THE INTENSITY FORECASTING EXPERIMENT

A NOAA Multiyear Field Program for Improving Tropical Cyclone Intensity Forecasts

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In probing the whole life cycle of these storms—not just mature hurricanes—IFEX is taking a new approach to developing physical understanding and forecast abilities as well as testing and enhancing real-time observational capabilities.

MOTIVATION FOR IFEX. One of the key activities in the National Oceanic and Atmospheric Administration's (NOAA's) strategic plan is to improve the understanding and prediction of tropical cyclones (TCs). The NOAA National Hurricane Center (NHC), a part of the National Centers for Environmental Prediction (NCEP), is responsible for forecasting TCs in the Atlantic and east Pacific basins, while NCEP's Environmental Modeling Center (EMC) develops the numerical model guidance for the forecasters. With support from NOAA's Hurricane Research Division (HRD) and others in the research community, continual progress has been made in improving forecasts of the TC track over the past 30 years (Franklin et al. 2003a; Aberson 2001). Advancements in state-of-the-art global and regional modeling systems at EMC and other operational numerical weather prediction centers have led to improvements in track skill over the past three decades, including a significant acceleration in improvements over the past decade. These advancements include improved assimilation of satellite and

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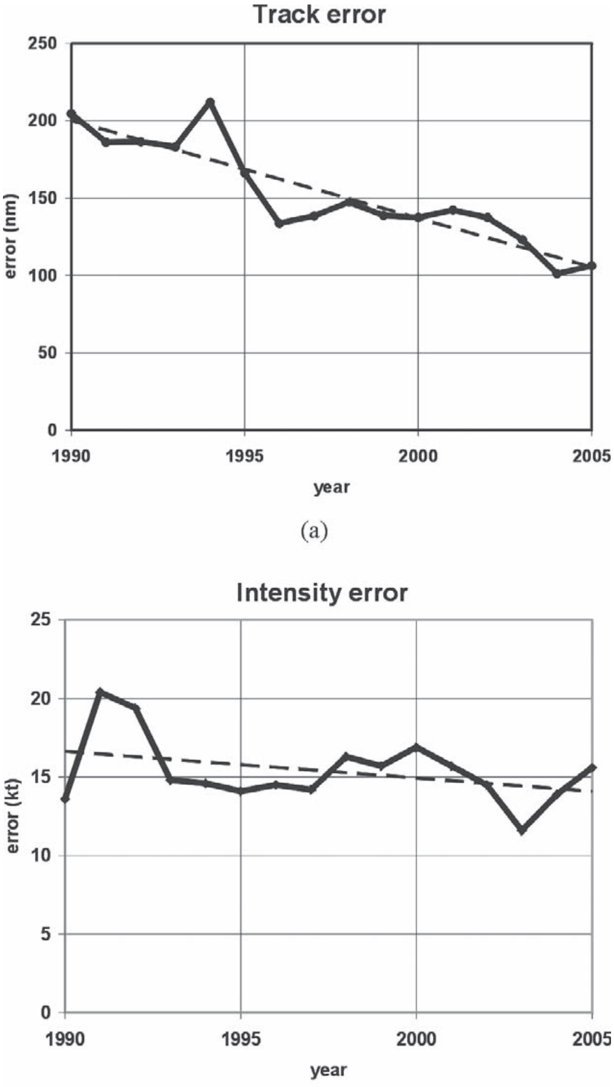
aircraft observations, better representation of the hurricane vortex, improved representation of tropical physics, and advancements in higher-resolution atmosphere–ocean coupled hurricane modeling.

Despite these advancements in the modeling systems, there has been much less improvement in forecasts of TC intensity (DeMaria et al. 2005; DeMaria and Gross 2003). For example, Fig. 1 shows that the official 48-h track forecast errors have decreased by nearly 45% during the past 15 yr (3% yr^{-1}), while official 48-h intensity forecast errors have decreased by only 17% (1.1% yr^{-1}). The modest improvement in intensity forecasting is the result of many factors, including 1) deficiencies in systematically collecting inner-core data to provide real-time estimates of TC intensity and structure to the forecasters at NHC and for assimilation into the numerical models at EMC and elsewhere; 2) limitations in the numerical models themselves, such as insufficient computing resources to run operational forecast models at high horizontal and vertical resolution, inadequate specification of the TC vortex in the initial conditions of the numerical models, and deficient representation of physical processes; and 3) gaps in our understanding of the physics of TCs and their interaction with the environment. Improvements in intensity forecasts will rely heavily on the use of improved numerical modeling systems, which in turn will rely on high-quality observational datasets for assimilation and validation.



(a)

(b)

Fig. 1. Annually averaged official NHC 48-h forecast errors for TC (a) track (nmi) and (b) intensity (kt) for TCs in the Atlantic basin from 1990 to 2005.

The next-generation NOAA operational tropical cyclone model, the Hurricane Weather Research and Forecasting model (HWRF; Surgi et al. 2006), is currently under development at EMC and will become operational in 2007. The HWRF is a coupled atmosphere–ocean–hurricane prediction system that is being coupled with EMC's operational wave model and land surface model to improve forecasts for TC intensity, structure, waves, storm surge, and rainfall. The HWRF prediction system will run at high resolution (≈9 km grid length initially), using advanced data assimilation techniques making use of NOAA's real-time radar observations to provide an initial three-dimensional description of the hurricane core circulation, and advanced physics that are improved over those used in previous operational tropical cyclone models such as the Geophysical Fluid Dynamics Laboratory (GFDL) model. In order to produce better forecasts of TC intensity, however, new data assimilation techniques must be developed and refined, physical parameterizations must be improved and adapted for both the TC storm–scale circulation and environment, and the models must be reliably evaluated against detailed observations from a variety of TCs and their surrounding environments. In addition to these modeling system upgrades, more accurate intensity forecasts will rely on more accurate real-time observations of the intensity and structure of TCs that are adequately separated in time and space for initialization of successive model forecasts. Some of these observations will be from satellite platforms while others, particularly within the TC core, will come from airborne measurements.

GOALS OF IFEX. With these observational requirements in mind, HRD has worked to address NHC and EMC objectives by devising the following set of goals for IFEX:

- Goal 1—Collect observations that span the TC life cycle in a variety of environments;
- Goal 2—Develop and refine measurement technologies that provide improved real-time monitoring of TC intensity, structure, and environment;
- Goal 3—Improve our understanding of the physical processes important in intensity change for a TC at all stages of its life cycle.

The first goal is primarily derived from the need to improve the representation of TCs in numerical models. By employing a strategy that focuses on collecting observations at all stages of the TC life cycle, IFEX provides measurements that can be used to help develop the HWRF data assimilation to improve the initialization of the hurricane core circulation in the model. Such an emphasis represents a departure from previous field experiments conducted by HRD. The distribution of flights, stratified by the TC life cycle stage, involving the NOAA WP-3D aircraft (hereafter NOAA P-3) from 1976 to 2004 is heavily skewed toward mature tropical cyclones, with 90% of the flights in systems that were already either tropical storms or hurricanes. Therefore, one of the goals of IFEX is to collect more observations at the earlier stages of the TC life cycle (i.e., from predepression to tropical depression and tropical storm stages). Another goal is to collect observations of the atmosphere and ocean within the TC and its periphery in a variety of atmospheric–oceanic conditions (e.g., atmospheric shear and humidity environments, mesoscale ocean features, etc.). These observations will also be used to develop an evaluation and validation package for the high-resolution HWRF and enhance the ability to assess the influence of these features on observed and modeled TC intensity and structure changes.

The second goal is primarily targeted toward improving the real-time assessment of the TC intensity and structure. A variety of instruments are available to estimate the wind, temperature, pressure, and moisture fields within TCs. Some of these instruments were available for many years, but are just now showing promise for real-time applications, such as airborne Doppler radar, which provides estimates of the three-dimensional fields of wind and reflectivity within the TC core, and the Stepped-Frequency Microwave Radiometer (SFMR), which measures brightness temperatures in the microwave portion of the electromagnetic spectrum sensitive to foaminess of the sea surface to estimate rain rate and wind speed at the surface. Other instruments have only become available recently (e.g., a newly engineered dropsonde), but offer the opportunity for more reliable observations in the high-wind, high-gradient environments of the TC. In addition, new techniques for transmitting, quality assuring, and displaying the data from these instruments in real time have been developed and demonstrated to the NHC. The primary example is the development of high-speed satellite communication (SATCOM) techniques developed by NOAA/National Environmental Satellite, Data, and Information Service (NESDIS) and Remote Sensing Solutions, Inc., that allow larger volumes of data to be transmitted to and from the aircraft in real time compared to previous years, despite bandwidth limitations (peak bandwidth of 9,600 baud). These instruments and techniques provide the potential for improving the assessment of the intensity and structure of TCs in real time and transmitting this data to NCEP for assimilation into the HWRF.

A final goal of IFEX is to improve our understanding of various physical processes important in governing TC intensity change at all stages of the TC life cycle. Specific topics that are targeted include convective–mesoscale interactions in tropical cyclogenesis; the role of shear and humidity in genesis and intensity change; the phase changes of moisture; the surface fluxes of heat, moisture, and momentum; the role of atmosphere–ocean feedbacks; and structural changes during landfall and extratropical transition. Improvements in the understanding of these processes can lead to better intensity forecasts by improving how they are represented and parameterized in HWRF, and they may also lead to refinements in existing algorithms for predicting intensity change [e.g., the Statistical Hurricane Intensity Prediction Scheme (SHIPS); DeMaria et al. 2005.]

IFEX 2005 ACCOMPLISHMENTS. The 2005 Atlantic hurricane season was historic in terms of the number and intensity of tropical cyclones in the Atlantic basin, and the number of IFEX missions was commensurate with the amount of activity during the season. There were 45 NOAA P-3 and 48 NOAA G-IV research and operationally tasked missions flown in a total of 14 different tropical cyclones or incipient tropical cyclones, with nearly 2,500 dropsondes released (Table 1). The high number of dropsondes released in 2005, which represents a significant increase over previous years (e.g., 815 in 2003 and 1,384 in 2004), is partly attributable to the very active 2005 season and partly to the collaboration with several partnering experiments (described below). A total of 220 NOAA P-3 and 44 G-IV research flight hours were used, while 186 NOAA P-3 and 388 G-IV operational flight hours were used for NHC-tasked missions. In addition to the

Table 1. Listing of 2005 NOAA flights and those jointly involving NOAA and its partners, NASA, and NSF (includes research and operationally tasked missions).

Storm/ system	2005 Dates	Aircraft[a] (No.)	Mission types[b]	Dropsondes	Comments
Arlene	9–10 Jun	N43(1), N49(2)	SFMR, SURV	79	Early season Gulf coast TC
Cindy	4–5 Jul	N42(1), N49(1)	SFMR, SURV	30	Another Gulf coast TC
Dennis	5–10 Jul	N42(2), N43(4), N49(4), ER2(3)	FM, SFMR, SURV, TCSP, LFALL	242	Almost complete life cycle studied
Wave Pre-Eugene	14–16 Jul	N42(3), N43(2), ER2(2)	GEN, TCSP	126	Good pregenesis case in east Pacific
Emily	16–18 Jul	N43(1), N49(2), ER2(1)	SFMR, SURV, CDO, FIX, TCSP	123	Inner-core G-IV test; notable ER2 flight
Franklin	23 Jul	N49(1)	CDO	12	Inner-core G-IV test
TD 7 Gert	23–25 Jul	N42(1), N43(3), N49(1), ER2(3)	GEN, TCSP, SURV	85	Good genesis case; wave to TS
Irene	7–8 Aug 12–13 Aug	N49(4)	SURV, SALEX	119	Good SALEX developing case
Katrina	24–29 Aug	N43(4), N49(6), NRL(2)	SFMR, SURV, IFEX, RAINEX, LFALL	302	Rapid strengthening to category 5; pre- and postlandfall
TD 16 Ophelia	6–17 Sep	N42(8), N43(5), N49(7), NRL(3)	FIX, SFMR, FM, ET, OW, SURV, RAINEX	462	Life cycle—TD to hurricane; ET; Aerosonde
Rita	19–23 Sep	N42(2), N43(5), N49(8), NRL(4)	SFMR, SURV, OW, FM, RAINEX, OCEAN	503	Category 5; classic concentric eyewall; Good three-plane RAINEX; prestorm, in-storm, and poststorm sampling of upper-ocean structure
Wave	27–28 Sep	N49(2)	SALEX	61	Good SALEX nondeveloping case
Wilma	18–24 Oct	N42(3), N49(9)	SFMR, SURV	308	Late-season intense storm
Gamma	19 Nov	N49(1)	SURV	22	End of season surprise
Totals	—	**N42(20), N43(25), N49(48), ER2(9), NRL(9)**	—	**2474**[c]	—

[a] Aircraft: N42 and N43—NOAA P3s, N49—NOAA G-IV, ER2—NASA ER2 (TCSP), NRL—Navy P3 (RAINEX).

[b] Mission types: SFMR—NHC-tasked mission to map surface winds, FIX—Operational center fix mission, SURV—G-IV operational synoptic surveillance, GEN—tropical cyclogenesis experiment, FM—frequent-monitoring experiment, LFALL—landfall or postlandfall experiment, ET—extratropical transition experiment, SALEX—Saharan Air Layer Experiment, OCEAN—ocean feedback experiment, CDO—test of inner core G-IV mission, TCSP—NASA involved mission and coordination with ER-2, OW—NESDIS Ocean Winds, RAINEX—collaboration with NSF-sponsored program and coordination with NRL P3.

[c] Total dropsondes include those released from the NOAA P3s, NOAA G-IV, and NRL P3.

flights by the NOAA aircraft, many of these flights were augmented by aircraft from operational Air Force Reserve WC-130 reconnaissance flights. Additional information describing IFEX is available in an online calendar at www.aoml.noaa.gov/hrd/Storm_pages/ifex2005/ifex_cal.html, which covers the times that IFEX missions were flown in 2005. It includes a daily Web log of the field activities and mission summaries for the NOAA P-3 and G-IV research flights.

One of the unique aspects of IFEX in 2005 was the large number of experiments that were partnered with IFEX. These experiments were the National Aeronautics and Space Administration (NASA) Tropical Cloud Systems and Processes (ICSP) project, which provided the high-altitude NASA ER-2 aircraft, the National Science Foundation (NSF) Hurricane Rainband and Intensity Change Experiment (RAINEX) project, which provided the Naval Research Laboratory (NRL) P-3 and additional dropsondes, and NOAA's Ocean Winds and Synoptic Surveillance experiments. The primary goal of TCSP is to increase the overall understanding of TC genesis and intensity change and conduct satellite and aircraft remote sensor data assimilation and validation studies pertaining to the development of TCs, while the primary goal of RAINEX is to investigate the interactions between a TC's inner core and outer rainbands and the role of these interactions in storm structure and intensity change. Further discussion of the TCSP and RAINEX experiments appear in companion papers. The main objective of the Ocean Winds experiment is to further the understanding of ocean surface wind vector retrievals in high wind speed conditions and in the presence of rain for all wind speeds from microwave remote-sensing measurements. The Synoptic Surveillance experiment goals are to provide operational dropsonde data to hurricane specialists at NHC, to assimilate these data into the operational global model at EMC, and to investigate sampling strategies to provide the greatest forecast improvement given limited aerial coverage and dropsondes.

Many of the IFEX goals were advanced during the 2005 hurricane season. A summary of these activities is included below.

Goal 1: Observations of tropical cyclones at various life cycle stages. For 2005, nearly 25% of the flights were in tropical cyclones either in the depression or predepression stage, a much larger proportion compared with previous years. Many of these observations were collected as a part of the frequent-monitoring experiment.

FREQUENT-MONITORING EXPERIMENT. This experiment was designed to provide airborne Doppler datasets at all stages of a TC's life cycle 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 h (depression to weak hurricane stage) or 24 h (mature hurricane stage) to provide the maximum possible temporal resolution over the lifetime of the storm. The flight patterns were designed to be flown in either research or operationally tasked missions. With this flight strategy, five of the TCs had flights in them for most or all of their life cycle:

- Dennis (tropical storm to landfall)—NOAA P-3s and G-IV together with NASA ER-2 (TCSP);
- Gert (tropical disturbance to landfall)—NOAA P-3s together with NASA ER-2 (TCSP);
- Katrina (tropical storm to landfall)—NOAA P-3s, G-IV together with NRL P-3 (RAINEX);
- Ophelia (tropical depression to extratropical transition)—NOAA P-3s, G-IV together with NRL P-3 (RAINEX); and
- Rita (tropical storm to hours before landfall)—NOAA P-3s, G-IV together with NRL P-3 (RAINEX).

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

Other research projects occurred during the same time that the frequent-monitoring experiments were flown. These included the NOAA/NESDIS Ocean Winds and Rain Experiment, which was designed to improve the understanding of microwave remote sensing of the ocean surface wind field in high-wind and heavy-rainfall conditions, and the NSF-sponsored RAINEX, which was designed to document the dynamic interaction between a hurricane's eyewall and rainbands to determine the role this interaction has on the evolution of the structure and intensity of the storm. By partnering with these projects, several excellent datasets were collected in Hurricanes Katrina, Ophelia, and Rita that should enhance the objectives of the frequent-monitoring experiment.

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 tropical cyclone intensity and structure.

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 (Marks and Houze 1984). In the years immediately following, analyses of vertical wind directly above and below the aircraft at vertical incidence (Marks and Houze 1987), and three-dimensional analyses of winds (Marks et al. 1992), were produced (see review by Marks 2003). However, these early airborne Doppler 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 hurricane center, quality control (QC) required more than a week. While there is no substitute for careful QC by an experienced scientist in a research setting, operational demands require an automatic, objective way to process the Doppler data for real-time use.

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. The main QC requirements for producing a reliable analysis are 1) removing the projection of aircraft motions from the observed radial velocities, 2) dealiasing the observed radial velocities, 3) removing noisy velocity data (e.g., gates with high spectral width), and 4) removing bins contaminated by sea surface reflection of both the main and sidelobes. After a passage through a TC center, the package performs QC on each sweep of the Doppler radial velocity, and then interpolates that sweep to two types of grids. After all sweeps are interpolated, the package synthesizes a wind analysis for each type of grid. The first grid is a two-dimensional vertical cross section extending outward from the storm center, with a horizontal resolution of 1.5 km and a vertical resolution of 150 m. The second is a three-dimensional analysis of winds near the flight track (e.g., Gamache 1997; Gao et al. 1999), with a horizontal resolution of 3–5 km and a vertical resolution of 0.5 km. 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. 2). As can be seen from Fig. 2, 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 versus the west side of the storm)

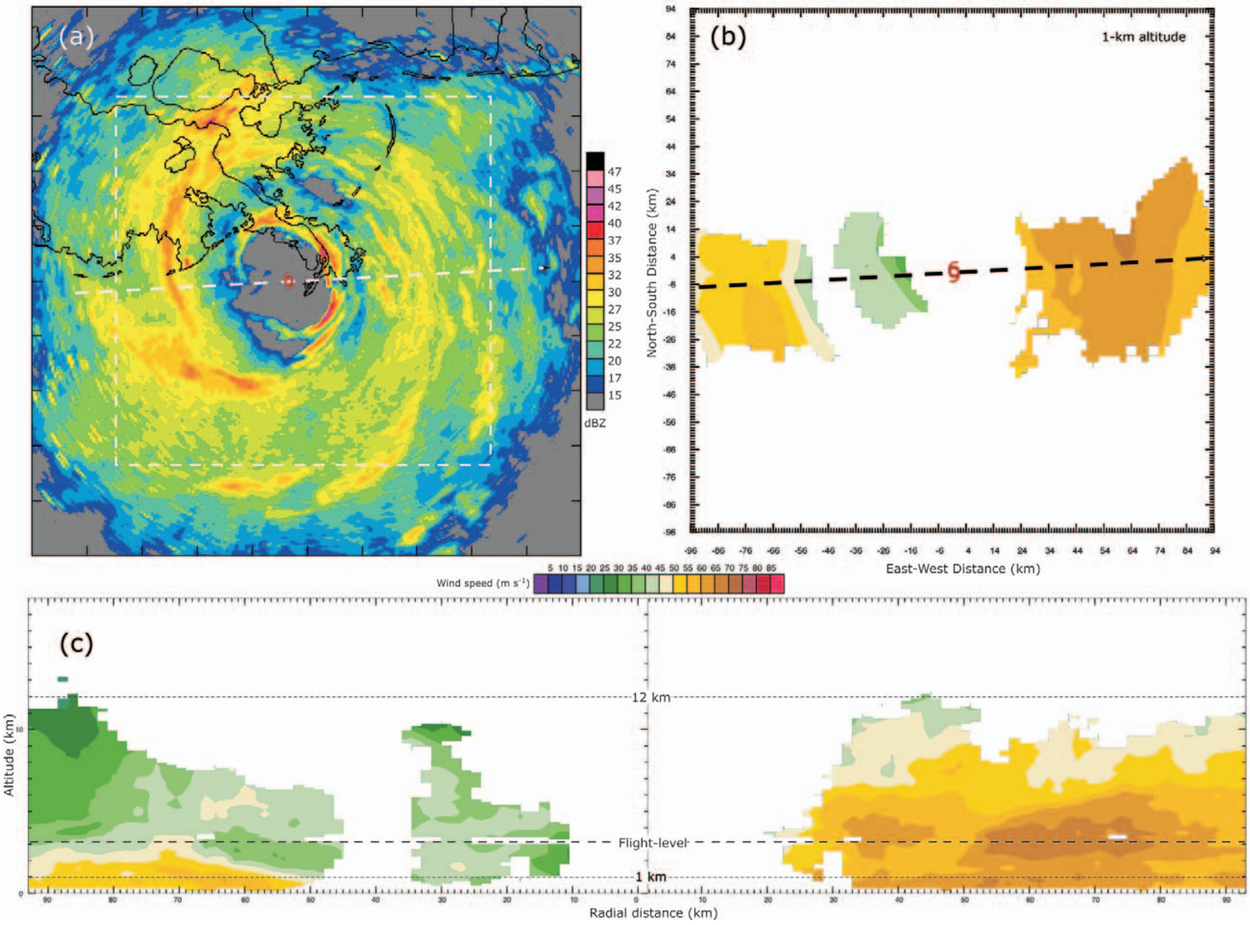


FIG. 2. (a) Radar-reflectivity depiction (shaded, dBZ) of Hurricane Katrina in horizontal plan view at 1021 UTC 29 Aug 2005 from lower-fuselage radar. Dashed box in (a) denotes analysis domain; (b) horizontal analysis of total wind speed at 1-km level (shaded, m s^{-1}) obtained from airborne Doppler data collected on N43RF during a pass through Hurricane Katrina centered at 1020 UTC 29 Aug; (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.

can be obtained from these analyses. This information proved helpful to the forecasters at NHC for short-term forecasts of surface winds in a landfalling situation; and it was used to help determine the best-track intensity and structure of storms like Katrina.

SFMR ALGORITHM REFINEMENT.

Estimating hurricane surface wind maxima and distributions is a top priority of the NHC. Until recently, surface wind estimates were based largely on 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 an 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. 3a). While there is some uncertainty in the relationship between rain-rate and wind speed anomalies in heavy rains at weak to moderate wind speeds (e.g., spikes in rain rate and winds, Fig. 3a), this issue does not appear in stronger winds. Furthermore, at least some increase in surface wind speed would be expected in rainbands, and evidently exists at flight level in Fig. 3a. Despite these uncertainties, SFMR measurements provide an independent estimate of surface winds with less uncertainty than flight-level wind reductions and better coverage than GPS dropsondes. Consequently, they have become an important data source for NHC to diagnose the surface wind maxima and distribution. Beginning in 2004, a SFMR flew on one of the NOAA P-3s for operational surface wind measurements, and in 2005 SFMRs were installed on both P-3s.

Previous studies comparing SFMR-measured winds with independent measurements from GPS dropsondes (Uhlhorn and Black 2003) indicate good agreement for most wind speeds. However, in 2004 comparisons between the SFMR winds and surface winds deduced from GPS dropsonde averages over the lowest 150 m indicated a low bias at high wind speeds (i.e., >50 m s^{-1}). The active 2005 Atlantic hurricane season provided ample opportunity to evaluate the SFMR's performance over the entire range of expected surface wind speeds (10–70 m s^{-1}). In particular, measurements were obtained from flights into category-5 Hurricanes Katrina and Rita. These concurrent measurements, coupled with improvements to the GPS dropsondes that enhanced their reliability in high wind speeds, enabled refinement of the geophysical model to remove the low bias of the SFMR for surface wind speeds >50 m s^{-1} (Fig. 3b).

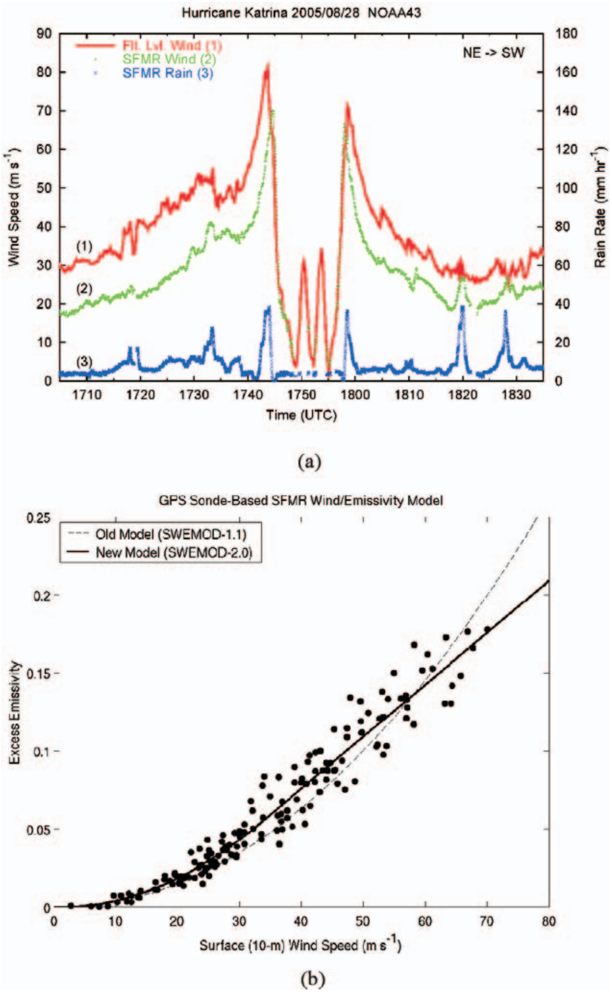
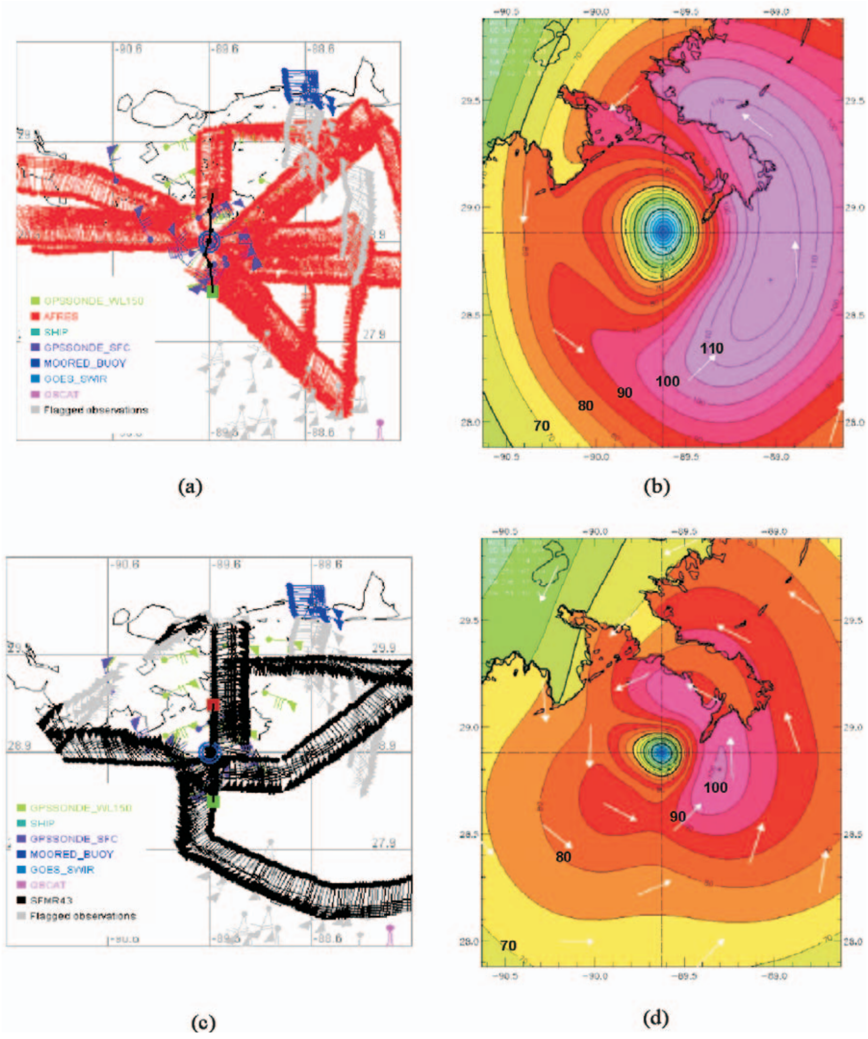


Fig. 3. (a) Time series of flight-level wind speed (red, m s^{-1}), SFMR surface winds (green, m s^{-1}), and rain rate (blue, mm h^{-1}) from 1705 to 1835 UTC 28 Aug in Hurricane Katrina; (b) scatterplot of emissivity measured by the SFMR compared with the wind speeds measured by dropsondes in the lowest 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).

NCAR GPS DROPWINDSONDE IMPROVEMENTS.

One of the primary instruments used on all aircraft involved in IFEX- and NHC-tasked missions are the NCAR GPS dropwindsondes (also called dropsondes; Hock and Franklin 1999). A record number of dropsondes were released from the three NOAA aircraft during the 2005 hurricane season. About 1,000 of the ~2,500 sondes were dropped from the NOAA P-3s within 300 km of the center of circulation of the TCs sampled. About 200 of these sondes were in support of the NSF-sponsored RAINEX program. Several hundred of the dropsondes that NOAA released were from a generous transfer from the Air Force Reserve's inventory.

Since its inception in 1997, the GPS dropsondes 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. 2003b). Once this failure occurs, winds can no longer be calculated, thereby eliminating the possibility of reporting standard 10-m-high winds. 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 from the NOAA and NRL aircraft, many 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.



(a)

(b)

(c)

(d)

Fig. 4. (a) Plot of wind observations from a variety of platforms (indicated by legend) during the 0700–1131 UTC time window used to create surface wind analysis. Air Force flight-level winds are included, but no SFMR winds; (b) surface wind analysis (shaded, kt) generated by H*Wind for Hurricane Katrina at 0930 UTC 29 Aug using measurements in (a); (c) as in (a), but for measurements from NOAA P-3. SFMR winds are included, but no Air Force or NOAA flight-level winds. (d) Surface wind analysis generated by H*Wind at 0930 UTC 29 Aug using measurements in (c).

SYNTHESIS OF OBSERVATIONS FOR SURFACE WIND STRUCTURE.

One of the most important tasks for the hurricane specialists at NHC during a landfalling TC is to identify the magnitude of the peak surface wind and to specify the location of the 64-, 50-, and 34-kt wind radii as a function of storm quadrant. There are a variety of data sources available to aid the specialist in this diagnosis, including wind estimates from aircraft flight level, SFMR, satellites, and buoys. The availability of such a large amount and variety of wind estimates requires a significant commitment of time to synthesize the data to produce surface wind distributions. During the 2005 hurricane season, HRD scientists were frequently at NHC to assist the specialists by providing a synthesis and interpretation of the various data sources for identifying the surface wind structure. The primary analysis tool used by the HRD scientists was the H*Wind system. Observations are quality controlled, and objectively analyzed, and then experimental analysis products are placed on the Web in near–real time (see online at www.aoml.noaa.gov/hrd/Storm_pages/katrina2005/wind.html; Powell et al. 1996, 1998). The availability of datasets such as the SFMR and Doppler winds in real time in 2005 provided more reliable surface wind estimates and analyses.

Figure 4 illustrates an example of the impact of these observations on surface wind analyses through comparisons of analyses using traditional data sources versus analyses using these new data sources in Hurricane Katrina just prior to landfall on the Gulf Coast. This figure shows an analysis using the traditional surface-reduced flight-level winds from Air Force reconnaissance aircraft (Fig. 4a), which shows a north–south swath of winds >55 m s^{-1} (Fig. 4b). However, when data from the SFMR are used (Fig. 4c), the peak winds decrease to 50 m s^{-1}, and the area encountering winds >50 m s^{-1} shrinks considerably (Fig. 4d). While some of the differences between these two analyses is likely attributable to the fact that data from two different aircraft are used, the use of SFMR data in the analysis in Fig. 4c clearly has an impact in reducing the magnitude and areal coverage of peak winds. These lower wind speeds were later confirmed by dropsonde and airborne Doppler radar measurements (cf. Fig. 2), and were part of the reason why NHC eventually downgraded the strength of Katrina to a category 3 at landfall (Knabb et al. 2005). The assistance provided by the HRD scientists from synthesizing the various data sources aided the specialists in diagnosing the surface wind speed and structure.

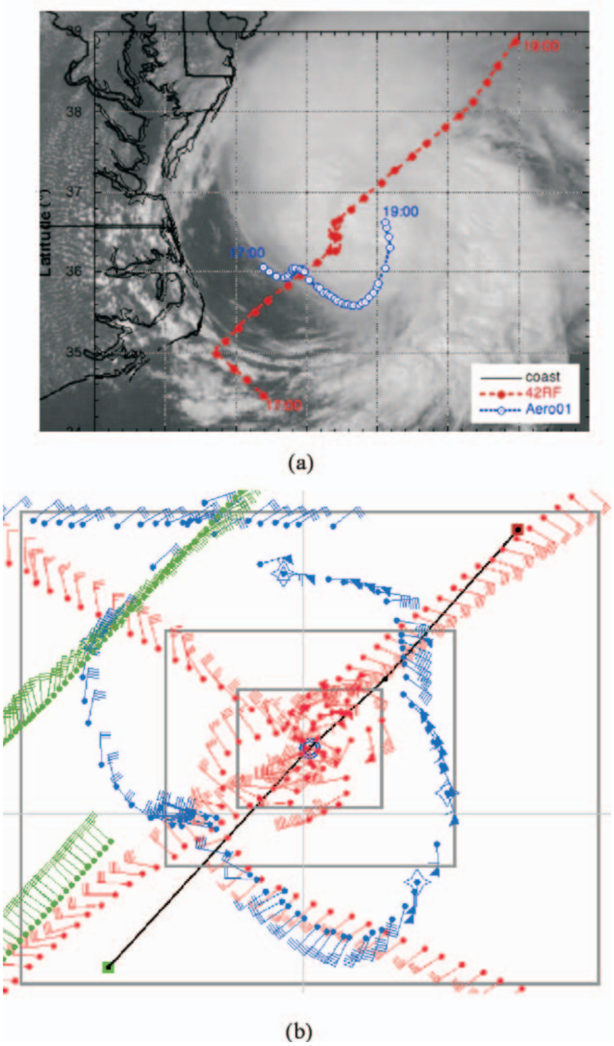


Fig. 5. (a) *GOES-12* visible satellite image valid at 19 UTC 16 Sep 2005 for Tropical Storm Ophelia. Flight tracks of Aerosonde (blue) and N42RF P-3 (red) from 1700 to 1900 UTC overlain; (b) storm relative winds (kt, flag is 50 kt) from surface-reduced Aerosonde winds (blue), N42RF SFMR winds (red), and a moored buoy (green) for 1200 UTC 16–0000 UTC 17 Sep time window. Diagonal line indicates position of storm at various times: 1200 UTC 16 Sep (green square), 1755 UTC 16 Sep (blue circle), and 0000 UTC 17 Sep (red square).

USE OF UNMANNED AERIAL VEHICLES. On 16 September 2005, the government 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. 5). 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, simultaneous 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, and were the strongest winds observed in Ophelia on this day. SFMR winds southwest of the center were collected within 10 min of Aerosonde observations. Excellent agreement was found between buoy, SFMR, and Aerosonde winds adjusted to surface values (Fig. 5).

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 datasets has the potential of improving the understanding of surface and boundary layer fluxes in TCs. The Ophelia Aerosonde dataset 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.

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 life cycle, from tropical cyclogenesis to a mature storm to landfall or extratropical transition.

TROPICAL CYCLOGENESIS EXPERIMENT. 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 midtroposphere 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. Measurements of microphysics quantities (e.g., hydrometeor concentrations, vertical motion, etc.) will also improve our understanding of the phase changes of moisture.

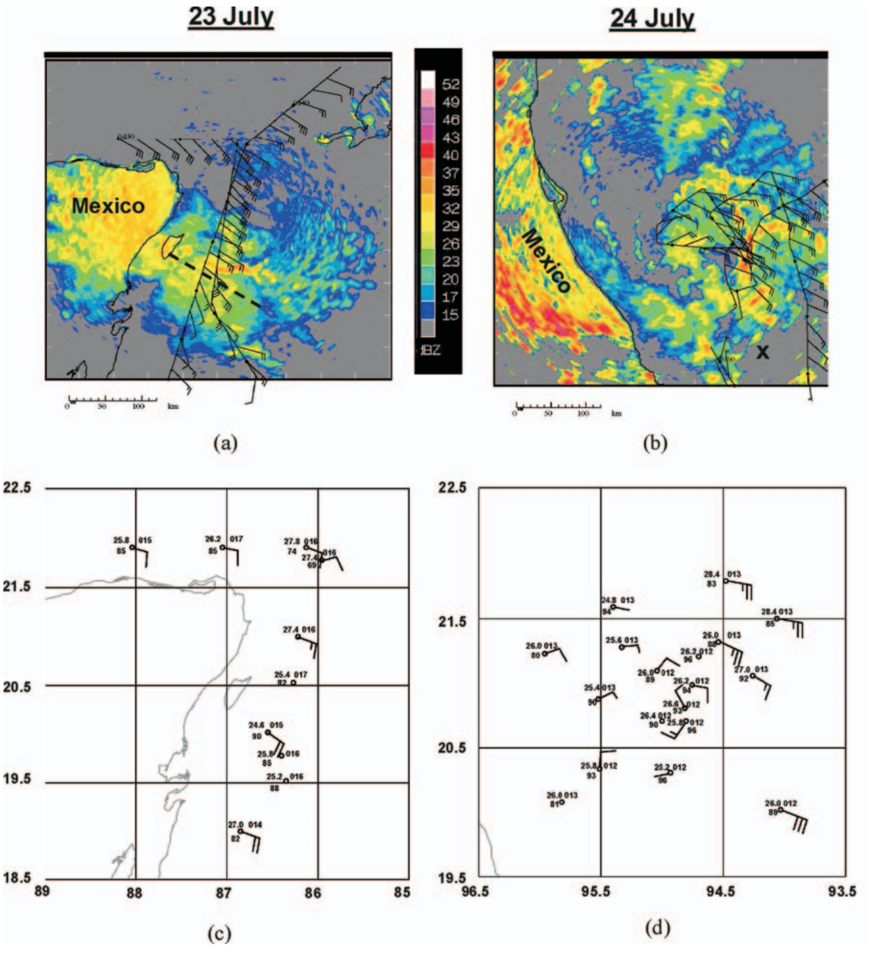


FIG. 6. (a) Plot of P-3 lower-fuselage reflectivity (shaded, dBZ) from 0205 UTC 23 Jul for a system that developed into Tropical Storm Gert. Flight-level winds (m s^{-1}; full barb is 5 m s^{-1}) are overlain. Area of image labeled "Mexico" denotes regions of significant ground clutter on the lower fuselage reflectivity image. Dashed line indicates axis of cyclonic shear in flight-level winds. (b) As in (a), but when system was a tropical storm, valid 0547 UTC 24 Jul. The "X" indicates approximate center of circulation in flight-level data. (c) Plot of surface winds (m s^{-1}, full barb is 5 m s^{-1}), temperature (°C), relative humidity (%), and surface pressure (hPa, standard convention) measured by dropsondes during flight shown in (a). (d) As in (c), but for flight shown in (b).

There were two cases in 2005 for which the tropical cyclogenesis experiment was flown: a tropical disturbance in the east Pacific, which eventually 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 life cycle, 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 nonprecipitating hydrometeors from the P-3s, 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. A comparison of 4-km flight-level and surface winds during the 24-h time period during which cyclogenesis occurred (Fig. 6) indicates that the system transitioned from a region of cyclonic shear vorticity in the midtroposphere with no discernable surface circulation on 23 July to a closed midlevel and surface circulation by 24 July. The measurements provided by these flights should help to elucidate the mechanisms underlying the convective and mesoscale interactions important in tropical cyclogenesis.

SAHARAN AIR LAYER EXPERIMENT (SALEX). The main goals of SALEX are to better understand and predict how the dry, midlevel easterly jet, and suspended mineral dust from the Saharan Air Layer (SAL) affect Atlantic TC intensity change. To assess the impact of these 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. 7a). The GPS dropsonde locations were selected using real-time Geostationary Operational Environmental Satellite (GOES) SAL tracking imagery from University of Wisconsin–Madison (UW) Cooperative Institute for Meteorological Satellite Studies (CIMSS) (Dunion and Velden 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 G-IV SALEX missions included four flights on two separate disturbances. The first disturbance had two missions that targeted a SAL outbreak interacting with Tropical Storm Irene (Fig. 7b). The second also consisted of two missions and targeted two tropical waves that were interacting with the SAL, one of which developed into Tropical Depression 19 a few days after the missions were completed.

OCEANIC INTERACTION EXPERIMENT. A particular area of research that has been identified to improve TC intensity forecasts is a better understanding of the interaction between the atmosphere and ocean during passage of a tropical cyclone. It is well known that TCs

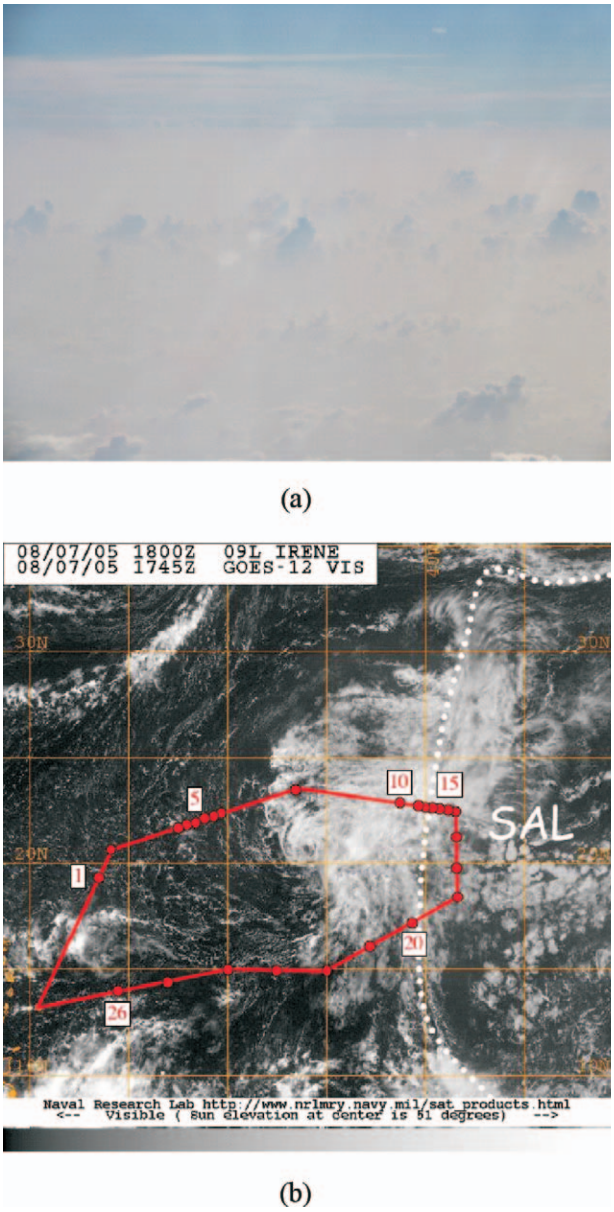


FIG. 7. (a) Photo taken from the NOAA G-IV on 27 Sep 2005 during a SALEX mission. At this time (~1820 UTC), the G-IV was cruising at 45,000 ft and was overflying a SAL outbreak in the central Atlantic. Vast amounts of suspended mineral dust (seen as a milky white haze) are evident in the photo. (b) *GOES-12*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

produce a cold wake due to entrainment mixing in response 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 (Chang and Anthes 1978). More recent research has documented the possible impact of oceanic warm-core eddies where OMLs are considerably deeper [e.g., as observed during the passage of Hurricane Opal (Shay et al. 2000) and Typhoon Maemi (Liu et al. 2005)]. The upper-ocean cooling during TC passage is considerably less in warm eddies and the Loop Current in the Gulf of Mexico 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 will aid in the intensification of the TC, and in some cases rapidly deepen the TC.

A number of experiments over the past several years have attempted to document this interaction by deploying expendable ocean probes before, during, and after the passage of a storm to document the evolution of upper-ocean momentum and thermodynamic fields (e.g., Shay 2001; Jacob and Shay 2003). Given its nearly annual cycle (Maul 1977), particular attention has recently been given to highly variable oceanic regimes, such as warm eddies and the Loop Current in the Gulf of Mexico. One such 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 the category-5 winds (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. 8). 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, under favorable atmospheric conditions, likely played an important role in causing Rita to reach 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.

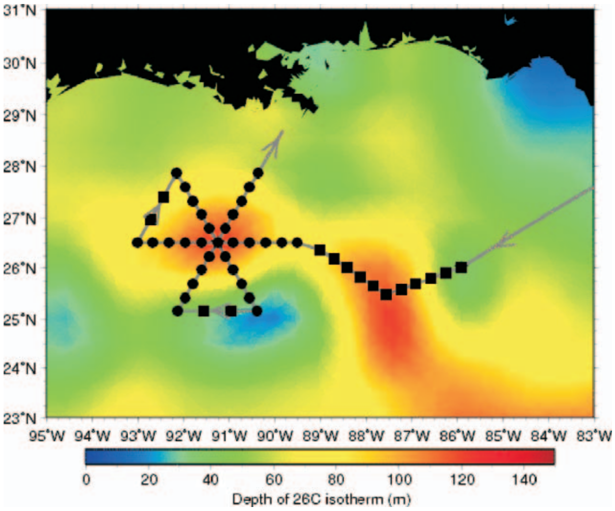


Fig. 8. Post-Katrina (pre-Rita) sampling pattern from the NOAA P-3 using a combination of Airborne Expendable Conductivity–Temperature–Depth (AXCTD, circles), Airborne Expendable Current Profiler (AXCP, circles), and Airborne Expendable Bathythermograph (AXBT, boxes) probes on 15 Sep relative to the depth of the 26°C isotherm based on an analysis of satellite altimeter measurements with a seasonal climatology. Note the same pattern was flown after Rita's passage on 26 Sep.

Preliminary analysis of the data (not shown) revealed significant cooling of more than 5°C between the warm core eddy and Loop Current as a cold core eddy observed southeast of the warm core eddy on 15 September (cf. Fig. 8) advected cyclonically around it on 26 September. By contrast, the observed thermal structure within the Loop Current and warm core eddy (not shown) revealed cooling of less than 1°C 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 (i.e., Isidore and Lili; Uhlhorn and Shay 2004). Perhaps more important was the separation of the warm eddy from the Loop Current and the net movement of the eddy of about 120 km toward the west. This translation speed of ~12 km day^{-1} was almost twice the usual speed of 3 to 5 km day^{-1} (Elliot 1982). 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 prestorm variability to fully understand the oceanic response to atmospheric forcing as well as the atmospheric response to oceanic forcing. Such gridded oceanic datasets are important to evaluate the model initialization fields as well as the oceanic response from operational coupled models.

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.

There were two research flights into Hurricane Dennis on 10 July 2005 (Fig. 9a), staggered to observe the hurricane's evolution as it made landfall and moved inland. These two flights presented a rare opportunity to study the decay of a strong hurricane as it moved inland. Ground-based and airborne Doppler radar data should provide both three-dimensional wind fields as well as vertical profiles of the wind offshore and over land. Contributions to the evaluation of SFMR winds near the coast will come from comparing the dropsonde data, especially in the flow from land to sea west of the center, where SFMR winds were 10 m s^{-1} greater than the flight level winds at 4-km altitude. These data will also provide a context for the tower teams to interpret their detailed time series of near-surface winds.

A research mission into Hurricane Katrina on 29 August 2005 collected data along the coast and over the Mississippi River delta to document the wind field of this devastating storm. Figure 9b shows the NOAA P-3 flight track and the locations of the surface wind towers. High-resolution airborne Doppler radar, GPS dropsonde and SFMR data were collected in the onshore wind maximum as well as over Lake Ponchartrain.

The data collected during the landfall missions were used in real-time landfall and postlandfall wind analyses using H*WIND. 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. Furthermore, a Dennis dataset will be used to validate forecasts from an empirical inland wind decay model (DeMaria et al. 2006)

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 often expanded warnings must be issued for impacts such as freshwater floods and high seas. Though the mean sea level pressure generally rises and maximum surface wind speeds decay, the cyclone sometimes rapidly re-

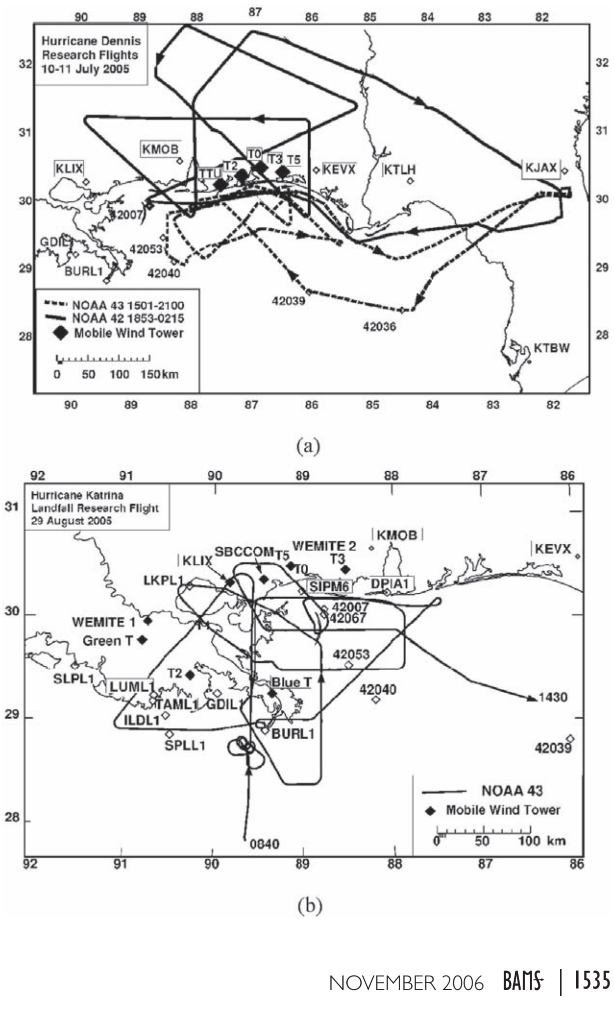


FIG. 9. **NOAA landfall flights in 2005. (a) Landfall and post-landfall flights in Hurricane Dennis, 10 Jul 2005. Dashed line denotes NOAA 42 track, from 1853 to 0215 UTC and solid line denotes track of NOAA 43, from 1501 to 2100 UTC. Solid diamonds indicate locations of mobile wind towers operated by Texas Tech University (TTU) and the Florida Coastal Monitoring Program (T0–T5). Open diamonds show fixed marine observing platforms and WSR-88D radars. (b) Landfall flight in Hurricane Katrina, 29 Aug 2005. Solid line indicates track of NOAA 43 from 0830 to 1430 UTC. WSR-88D radars and marine observing sites shown as in Fig. 10a. Solid diamonds indicate mobile towers from TTU (WEMITE and SBCCOM), the Florida Coastal Monitoring Program (T0–T5), and the University of Louisiana at Monroe (blue and green).**

intensifies 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 a 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 the Arctic region north of Norway a week later.

FUTURE PLANS FOR IFEX. For 2006, the major goals for IFEX remain the same. The upcoming African Monsoon Multidisciplinary Analyses (AMMA) international field program and NASA AMMA (NAMMA) supporting campaign that are planned for 2006 present a rare opportunity for IFEX to expand its research focus farther east into the central and possibly eastern North Atlantic. Specific objectives will include investigating the SAL and its interactions with TCs and studying the early, mature, and decay phases of the TC life cycle using the SFMR, airborne Doppler radar, GPS dropsondes, and unmanned aerial vehicles (UAVs). IFEX will use the data collected during several of the G-IV and NOAA *P-3* missions to assess and potentially improve the representation of humidity in NOAA's GFS model and to examine the impacts of this improved humidity representation on forecasts of TC track and intensity.

IFEX plans to coordinate its G-IV, P-3, and Aerosonde missions with other research aircraft operating during AMMA and NAMMA (e.g., the North Dakota DC-8 and French Falcon). Such a coordinated effort will provide an expanded domain of aircraft coverage between continental North Africa (French Falcon aircraft) and the tropical eastern (DC-8 and French Falcon), central (G-IV), and western (G-IV, WP-3D, and Aerosonde) North Atlantic. Additionally, a number of remote sensing and in situ platforms will contribute to this coordinated effort providing a truly unique dataset for advancing our understanding and prediction of TC intensity change in the North Atlantic.

While IFEX made several accomplishments this year, there are some improvements that could be made to better ensure that mission design, real-time decisions, flight patterns, and subsequent research activities will best address IFEX goals. Communication among the various partnering organizations (i.e., NOAA HRD, NHC, and EMC) will be emphasized not just before the field program, but during and afterward as well. By working together through the planning, execution, and analysis and research processes, NOAA has an excellent opportunity to improve our forecasts of tropical cyclone intensity.

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Many scientists were instrumental in facilitating the partnerships among the various experiments. The idea and execution of IFEX would not have been possible without the guidance and encouragement of Frank Marks of HRD, and the rest of the staff at HRD, who contributed enormous time and effort, as always, to ensure a successful completion of the field efforts. Many valuable interactions occurred with scientists associated with the NASA TCSP project: Ramesh Kakar, Jeff Halverson, Robbie Hood, Gerry Heymsfield, and Ed Zipser, and the NSF-sponsored RAINEX project: Bob Houze, Shuyi Chen, Brad Smull, Dave Jorgensen, Wen-Chau Lee, Jim Moore, Greg Stossmeister, and Jose Meitin. Dave Raymond also provided valuable expertise and insight for mission and science planning for the IFEX–TCSP partnership. Jodi Brewster and Benjamin Jaimes helped with the AXCP processing, while Tom Cook postprocessed the data.

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