**16. Tropical Cyclone Landfall Experiment**

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**Links to the IFEX:**

These modules support the following NOAA IFEX goals:

* **Goal 1**: Collect observations that span the TC lifecycle in a variety of environments for model initialization and evaluation;
* **Goal 3**: Improve our understanding of the physical processes important in intensity change for a TC at all stages of its lifecycle.

**Motivation:**

The lifecycle of a TC often ends when it makes landfall and decays as it moves inland. During a hurricane threat, an average of 300 nm (550 km) of coastline is placed under a hurricane warning, which costs approximately $150-300 million in preparation per event. The size of the warned area depends on the extent of hurricane and tropical storm-force wind speeds at the surface, evacuation lead-times, and the storm track forecast. Research has helped reduce uncertainties in the track and landfall forecasts, and now one of the goals of the IFEX is to improve the accuracy of the surface wind fields in TCs, especially near and after landfall. Improvements in track forecasts and surface wind field analyses could produce more accurate hurricane warning areas thereby optimizing the cost of hurricane landfall preparations. In addition to the surface wind field, the forecast of severe weather embedded within a landfalling TC is particularly difficult. Recent studies have highlighted the front-right quadrant of a landfalling TC as a region of increased severe weather risk, particularly TC tornadoes (e.g., Schultz and Cecil 2009). However, some landfalling TCs are associated with more severe weather than others, which has prompted the HRD to explore how numerical modeling (e.g., the HWRF model) can improve severe weather forecasts issued by the NHC and the SPC prior to, during, and after TC landfall. This experiment can help guide research at the HRD by providing real-time observations of severe weather to verify the HWRF model.

There are still uncertainties in deriving surface wind estimates from flight-level and SFMR wind speeds collected near the coast. Changing bathymetry could alter the breaking wave field, which could change the roughness length at higher wind speeds and microwave emissions. Evaluation of these effects may lead to adjustments to the operational surface wind speed algorithms.

Analysis of Doppler radar, GPS dropwindsonde, SFMR, flight-level and SRA or AWRAP data collected during hurricane flights can help achieve the IFEX goals for the 2015 Hurricane Field Program. A major goal of the IFEX is to capture the lifecycle of a TC and, while landfall typically occurs at the end of the TC lifecycle, the same data collection strategies developed for mature hurricanes over the open ocean can also be applied at landfall. Subsets of the collected data can be transmitted to the NHC and to the EMC, for assimilation into the HWRF model. Doppler and GPS dropwindsonde data can be analyzed to derive three-dimensional wind fields to compare with the HWRF output and data from the SRA can be compared to the HWRF wave fields. In addition to shear and heat flux from the ocean, landfalling hurricanes experience other conditions that may affect intensity change. These include changes in ocean wave action in shallow waters, change in surface roughness, drier and/or cooler inflow from the land, and topographical impacts. Radar, dropwindsonde, and SFMR data can help observe and analyze those conditions. Decay over land is also important, and data collected during and shortly after landfall should help refine both operational statistical models (such as the Kaplan/DeMaria decay model) and numerical models like HWRF.

The HRD has developed a real-time surface-wind analysis system to aid the NHC in the preparation of warnings and advisories in TCs. In the past, the wind analyses produced using the HRD analysis package have been used both for post-storm damage assessment by emergency management officials and by researchers seeking to validate their model analyses and forecasts. In addition, these wind analyses also have the potential to be employed for use in the initialization of real-time storm surge models.

As a TC approaches the coast, surface marine wind observations are normally only available in real time from National Data Buoy Center moored buoys, Coastal-Marine Automated Network (C-MAN) platforms, and a few ships. Surface wind estimates must therefore be based primarily on aircraft measurements. Low-level (<5,000 ft. [1.5 km] altitude) NOAA and AFRES aircraft flight-level wind speeds are adjusted to estimate surface wind speeds. These adjusted wind speeds, along with C-SCAT and SFMR wind estimates, are combined with actual surface observations to produce surface wind analyses. These surface wind analyses were initially completed after the landfall of Hurricane Hugo in South Carolina and of Hurricane Andrew in South Florida in support of post-landfall damage surveys conducted by FEMA. In recent years, these analyses have been produced in real time for use by the NHC for many of the TCs that have affected the Western Atlantic basin, including such notable landfalling storms as Opal (1995), Fran (1996), Georges (1998), Bret, Floyd (1999), Isidore (2003), Frances, Ivan, Jeanne (2004), Dennis (2005), Katrina (2005), Rita (2005), Wilma (2005), Ike (2008), Irene (2011) and Isaac (2012). Dual-Doppler analysis provides a complete description of the wind field in the core and, recently, the analysis techniques have been streamlined so that these real-time wind analyses can be computed aboard the aircraft and wind fields at selected levels transmitted from the aircraft to the NHC and the NCEP. These wind fields are also quite useful for post-storm analysis.

Severe weather, including the potential for tornadoes, is often associated with landfalling TCs. The basic dynamic and thermodynamic structures found in TC supercells are not well-understood. While some studies have found that TC tornadoes rely on some of the same factors as Great Plains tornadoes, some key differences exist, such as the height and amplitude of these vortices. Most TC tornadoes occur in the front-right quadrant of the TC primarily from 12 hours prior to 48 hours after landfall (Schultz and Cecil 2009). Additionally, the most damaging TC tornadoes occur in rain bands outside of the TC inner core (> 150 km). While TC tornadoes are typically weaker than their Great Plains counterparts, these TC tornadoes account for at least 10% of all tornado records from Louisiana to Maryland (Schultz and Cecil 2009). Unlike Great Plains tornadoes, TC tornadoes are typically associated with smaller values of CAPE. Instead of relying on high CAPE, TC tornadoes owe some of their existence to the friction-induced convergence that accompanies landfalling TCs. The sudden deceleration of the wind as it encounters the rougher land surface helps drive vertical motion, which promotes embedded mesovortices and severe weather.

Recent research efforts in coordination with the NHC and the SPC are focused on improving the prediction of TC tornadoes based on the HWRF model output prior to and during TC landfall. Unfortunately, the HWRF model does not possess a resolution fine enough to capture tornadoes. Instead, *signatures* of tornadoes (e.g., helicity, wind shear, vorticity, radar hook echoes) will be sought out in the flight data (e.g., Doppler, GPS dropwindsondes) and will be used to verify the HWRF model output. Since some landfalling TCs produce more tornadoes than others, one goal of this experiment is to better understand the structure and thermodynamical properties of tornado-inducing rainbands in landfalling TCs.

Recent GPS dropwindsonde data from near and inside the flight-level radius of maximum wind speeds (RMW) in strong hurricanes have shown remarkable variations of the wind with height. A common feature is a wind speed maximum at 300-500 m altitude. Theoretical and numerical modeling of the hurricane boundary layer suggests that the low-level jets are common features. The height of the jet varies by storm quadrant, and modeling indicates that this variation can be enhanced as a TC crosses land. In addition, GPS dropwindsonde data will provide critical observations of temperature and moisture associated with severe weather embedded within TC outer rain bands, which will help to provide a better picture of supercell structures within landfalling TCs.

While collection of dual-Doppler radar data by aircraft alone requires two P-3 aircraft flying in well-coordinated patterns, time series of dual-Doppler data sets have been collected by flying a single P-3 toward or away from a ground-based Doppler radar. In that pattern, the aircraft Doppler radar rays are approximately orthogonal to the ground-based Doppler radar rays, yielding true Dual-Doppler coverage. Starting in 1997, the Atlantic and Gulf coasts were covered by a network of Doppler radars (Weather Surveillance Radar 88 Doppler [WSR-88D]) deployed by the National Weather Service (NWS), Department of Defense, and Federal Aviation Administration. Each radar site transmits the base data (Level II) in near real time to a central site. These data are subsequently archived at the National Climatic Data Center. In precipitation or severe weather mode, the radars collect volume scans every 5-6 min.

If a significant TC moves within 215 nm (440 km) of the coast of the eastern or southern United States, then (resources permitting) a P-3 will obtain Doppler radar data to be combined with data from the closest WSR-88D radars in dual-Doppler analyses. The tail radar is tilted to point 20 degrees forward and aft from the track during successive sweeps (the fore-aft scanning technique [F/AST]). These analyses could resolve phenomena with time scales < 10 min, the time spanned by two WSR-88D volume scans. This time series of dual-Doppler analyses will be used to describe the storm core wind field and its evolution. The flight pattern is designed to obtain dual-Doppler analyses at intervals of 10-20 min in the core. Deploying dropwindsondes near the coast will augment the Doppler data, where knowledge of the boundary-layer structure is crucial for determining what happens to the wind field as a strong storm moves inland. Dropwindsondes will also be deployed in the eyewall in different quadrants of the TC. To augment the core analyses, dual-Doppler data can also be collected in the outer portions of the storm, beyond the range of the WSR-88D, because the alternating forward and aft scans in F/AST mode intersect at 40 degrees, sufficient for dual-Doppler synthesis of wind observations.

**Objectives:**

* Collect NOAA P-3 Doppler, flight-level, and SFMR surface wind data both within the inner-core (radius < 120 nm) and near storm (120 nm < radius < 240 nm) environment to help improve and validate real- time and post-storm surface wind estimates in tropical cyclones.
* Document the thermodynamic and kinematic changes in storm structure during and after landfall and improve our understanding of the factors that modulate changes in tropical cyclone intensity near the time of landfall.
* Collect observations that will aid in the evaluation of the current operational coupled model forecast system’s ability to predict the three-dimensional structure of tropical cyclones both at the time of landfall as well as after the cyclone has moved inland.
* Collect dynamic and thermodynamic data in outer rain bands (> 150 km from TC center) of tropical cyclones that are either likely to make landfall or to make a close enough approach to the coastline that they have the potential to produce tornadoes.

**Hypotheses:**

* It is possible to improve real-time surface wind estimates for landfalling tropical cyclones by obtaining in-situ inner-core and near storm wind data collected utilizing NOAA P-3 aircraft.
* The above landfall datasets can be used to validate statistical and numerical model landfall surface wind forecasts.
* Our understanding and ability to forecast changes in the structure and intensity of landfalling tropical cyclones can be enhanced utilizing the high-resolution kinematic and thermodynamic data sets collected during the aforementioned landfall research missions.
* Traditional environmental parameters (e.g., CAPE, vertical shear, helicity) will distinguish sectors of the storm that are most supportive of supercell development. Thus, the area coverage of SPC-issued severe weather watches may be optimized and the HWRF output can be validated based on datasets produced via the modules described in this experiment.

**Model Evaluation Component:**

Recent tropical cyclones (e.g., Irene [2011], Sandy [2012]) have produced over-land wind gusts that have often exceeded the values expected based upon both the simulated and observed maximum sustained wind. Thus, it is hypothesized that the collection of landfalling datasets such as those proposed for this experiment will help researchers evaluate the capability of the HWRF model to accurately predict both the maximum sustained wind and wind gusts of landfalling TCs. In addition, forecasts of TC tornadoes have generally depended on climatology even though some numerical models have the capability to resolve tornadic signatures within TCs. Thus, a goal of this experiment is to evaluate how accurately the HWRF model simulates the mesoscale convective features that are capable of producing tornadoes. Since the HWRF model resolution is currently too coarse to explicitly simulate TC tornadoes, the *signatures* of TC tornadoes will be analyzed in the landfalling datasets and compared with the HWRF output. This includes traditional environmental fields that are indicative of tornadoes, such as CAPE, vertical shear, and helicity.

**Mission Description:**

This is a ***multi-option*, *single-aircraft***experiment designed to study the changes in TC surface wind structure and to document TC supercell characteristics near and after landfall. All three modules described here could also be incorporated into operational surveillance or reconnaissance missions. It is designed for one or two single-aircraft missions with a P-3 when a hurricane or tropical storm moves within ~215 nm (400 km) of the U.S. coastline. The first of these two flights will typically consist of the Offshore Intense Convective module followed by either the Coastal Survey or Real-time modules. While the storm location relative to the coastline will dictate which combination of these modules will be flown, the Offshore Intense Convection module will generally precede all of the others.

Landfall flights may be coordinated with mobile observing systems that are sometimes deployed ahead of landfalling tropical cyclones. These additional observations could be particularly useful for: 1) documenting the inland decay of surface winds associated with TC landfall and 2) for identifying the location of any tornadoes that might be generated by the landfalling tropical cyclone.

The aircraft must have working lower fuselage and tail radars. The HRD should have access to a workstation on board, so radar and GPS dropwindsonde data can be analyzed and transmitted to the NHC. The SFMR should be operated, to provide estimates of wind speed at the surface. If the AWRAP or C-SCAT is on the aircraft then it should also be operated to provide another estimate of the surface wind speeds. If the SRA is working it also should collect wave and sweep heights to characterize the storm surge and breaking wave field near the coast. If the scanning LIDAR is available, then it should be operated to obtain wind profiles in the clear air regions, especially in the offshore flow. If the portable Doppler radars (Shared Mobile Atmospheric Research and Teaching Radar [SMART- R] and/or Doppler on Wheels [DOW]) and portable wind towers are deployed, they should be placed between ~65 and 130 km inland in the onshore flow regime as depicted in Fig. 3 if possible, to document the decay of the tropical cyclone wind field and to help identify any tornadoes that the landfalling tropical cyclone may produce. If possible, one of the DOWs should be positioned relative to the nearest WSR-88D such that the dual-Doppler lobes cover the largest area of onshore flow possible. In the schematic shown in Fig. 3, one of the DOWs is positioned north-west of the Melbourne WSR-88D so that one dual- Doppler lobe is over the coastal waters and the other covers the inland region. The profiler is positioned within the inland dual-Doppler lobe to provide independent observations of the boundary layer to anchor the dual-Doppler analysis.

All modules support real-time and post-storm surface wind analyses and the identification/verification of potential tornadoes produced by the landfalling tropical cyclone. The flight patterns will depend on the location and strength of the storm relative to surface observing platforms and coastal radars. The three modules can be easily incorporated into a tasked operational mission. In the case of the Offshore Intense Convection module, different legs of this module may be incorporated into legs of a figure-4 pattern if supercells are encountered (Fig. 1).

**Analysis Strategy:**

**1. Offshore Intense Convection Module**

The P-3 Doppler radar data will be carefully edited and then synthesized into a three-dimensional wind field. Dropsonde and flight-level data will be analyzed and combined with an available rawinsonde and surface (e.g. buoys, CMAN, etc.) observations to establish the dynamic and thermodynamic environment of the targeted cells. Any available land-based radar will be used to augment the cell evolution documented by the airborne radars. Observations of TC supercells will be used to validate HWRF output and will assess the HWRF model’s ability to predict signatures of tornadic activity. The supercell’s environment and structure will be used to verify the HWRF model output and will allow for a direct comparison with mid-latitude supercells.

**2. Coastal Survey module**:

In addition to the data processing described in modules 1 and 3, the Doppler radar swath data will be edited and synthesized into wind fields. The winds will be compared with GPS dropwindsondes and SFMR, AWRAP, and/or LIDAR data to characterize the differences between the onshore and offshore flow.

**3. Real-time module**:

Flight level, Doppler radar, dropsonde, and SFMR data transmitted in real time will be ingested into the HRD wind-analysis system archive, where the observations are standardized to average 1 minute data at a standard height of 10 m in an open exposure. These data, in addition to other surface data could then be combined to produce analyses of surface wind speed that could be provided to forecasters and/or emergency manager in real-time. The quality-controlled data will also be available for assimilation into models such as HWRF and to validate forecasts the sustained wind, wind gusts, and thermodynamic fields such temperature, moisture, and rainfall obtained utilizing both operational numerical models (e.g. HWRF) as well as statistical models (e.g. Kaplan/DeMaria decay, Rainfall clipper).