13. Tropical Cyclone Landfall Experiment

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Supported 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.

Program Significance:

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 WSRA 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 the 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 (1999), Floyd (1999), Isidore (2003), Frances (2004), Ivan (2004), 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 (> 95 nm [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 rainbands (> 90 nm [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 WSRA 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 the portable wind towers are deployed, they should be placed ~35-80 nm (65-130 km) inland in the onshore flow regime as depicted in Fig. 13-3, 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. 13-3, 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. 13-1).

1. Offshore Intense Convection Module

Description

This module focuses on the collection of dual-Doppler radar and vertical profiles of the lower atmosphere near intense convective cells (> 35 dBZ on the LF radar) located in an offshore outer rainband (> 90 nm [150 km] from the storm center) but embedded within the onshore flow. This module can be easily incorporated during either operational TD-R flights or the other two modules (i.e., Coastal Survey or Real-time modules) when a suitable outer rainband is encountered. Fig. 13-1 shows an example flight pattern along the Carolina coast. In order to provide adequate estimates of low-level vertical shear and instability, the aircraft should fly this module at an altitude of 10,000 ft. (3.0 km) or higher. The Doppler radar should operate in F/AST mode to provide wind estimates on each side of the aircraft track. **A minimum of 6 GPS dropwindsondes should be deployed**, although ideally ≥10 GPS dropwindsondes will be deployed if resources allow. If less than 10 GPS dropwindsondes are deployed in total, then at least 2 GPS sondes should be deployed on either side of the intense convection and at least 1 GPS dropwindsonde should be deployed each time the band-axis is crossed (at least 6 GPS dropwindsondes in total). For GPS dropwindsondes deployed in or near intense convection, getting as close as comfortably possible to the convection is preferred. The first flight leg should cross the target band ~10-13 nm (20-25 km) downwind of the intense convective cells and proceed until the aircraft is 13 nm (25 km) outside the rainband axis, deploying a GPS dropwindsonde at the band axis and end point. The aircraft then turns upwind and proceeds along a straight track parallel to the rain band axis, ideally deploying GPS dropwindsondes every 10-13 nm. The length of this leg can be adjusted as needed, but should be a minimum of 40 nm (75 km). When the aircraft is ~10-13 nm upwind of the target cells, the aircraft turns and proceeds along a track orthogonal to the band axis until the aircraft is 13 nm (25 km) inside the rainband axis. GPS dropwindsondes should be deployed at the initial and endpoints of this leg as well as at the band axis. Finally, the aircraft turns downwind and proceeds along a straight path parallel to the rain band axis, deploying GPS dropwindsondes every 10-13 nm. The end point of this final leg should be 10-13 nm downwind of the initial target cell to ensure adequate dual-Doppler radar coverage of all cells. From here other modules can be resumed. The total time to complete this module should not exceed 60 minutes, and in most case can be completed in less time.

Note: This module's flight pattern can be reversed depending either on the location of the intense cells relative to the aircraft's initial approach vector or the need for flight safety. This module could also be easily incorporate into any tasked operational or research missions in which an outer rainband (> 90 nm [150 km] from the storm center) with embedded intense convective cells (>35 dBZ on the LF radar) is encountered during ferry to or from the storm core. **In other words, this module is not strictly limited to the Landfall and Inland Decay Experiment.**

Significance

As tropical cyclones move inland and weaken, tornadoes also become a significant threat to society and one of the most difficult forecast problems. Since 2004, over 650 tornadoes have been spawned by 26 tropical cyclones impacting the U.S. coastline, resulting in 24 deaths, over 300 injuries, and more than $400 million in damage. Many of these tornadoes are spawned by ***miniature supercells***. Much of the forecast challenge is due to significant differences in structure, organization, and environment from the classic midlatitude supercell: the miniature supercells are shallower, weaker, shorter-lived, and less buoyant, but occur in a very moist, high-wind, high- rotation environment with more vertical wind shear. Furthermore, individual miniature supercells often occur in close proximity to one another along organized outer rain bands, whereas their midlatitude counterparts often occur in relative isolation. As a result, midlatitude conceptual models have shown very limited success when applied to tornado forecasting in tropical cyclones. Numerous studies have documented the onshore environmental conditions and evolution of miniature supercells associated with TC tornado outbreaks, but little is known about the ***offshore environment and cell evolution*** just prior to tornado outbreaks. The goal of the "Offshore Intense Convection" module is to document the structure, evolution, and low-level environment of the stronger convective cells (>35 dBZ) located offshore in an outer rainband (> 90 nm [150 km] from the TC center) that will soon move onshore and potentially spawn tornadoes. This goal is consistent with the three primary goals of the IFEX.

Analysis Strategy

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:

Description
When a TC is making landfall, the Coastal Survey module will provide information about the boundary layer in the onshore and offshore flow regimes. Fig. 13-2 shows an example of this pattern for a hurricane landfall near Melbourne, Florida. On the first coastal pass the P-3 would fly parallel 6-10 nm (10-15) km offshore to obtain SFMR surface wind speeds (leg 1-2 in Fig. 13-2). The track should be adjusted so that the SFMR footprint is out of the surf zone. The second pass should be as close to the coast as safety permits, to sample the boundary layer transitions at the coast in onshore and offshore flow (leg 3-4 in Fig. 13-2). The first pass should be at 5,000 ft. (1.5 km) or less, and the aircraft could climb to higher altitudes for the second pass. On both of these passes the aircraft should fly to 150 km or the radius of gale-force wind speeds and release GPS dropwindsondes at the RMW and at intervals of 7.5, 15, 30, 45, and 60 or 75 nm (12.5, 25, 50, 75, and 100 or 125 km) on either side of the storm track, to sample both onshore and offshore flow regimes. Three to four GPS dropwindsondes would be deployed quite near the coast, followed by 3-4 GPS dropwindsondes spaced every 20-30 km along the trajectory. The Doppler radar will be in F/AST mode, to provide wind estimates on either side of the aircraft track. This module could be flown when the hurricane is making landfall or just after the storm has moved inland. The pattern could be flown in ~2 h.

Analysis Strategy
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:

Description
The Real-time module combines passes over marine surface platforms with one or more figure-4 patterns in the core of the hurricane (Fig. 13-3). The aircraft flies at or below 5,000 ft. (1.5 km) (or the lowest level deemed to be safe by aircraft flight personnel), so that flight-level wind speeds can be adjusted to 30 ft. (10 m) to combine with measurements from marine surface platforms. Flight-level and GPS dropwindsonde data obtained near the platforms will be used to validate the adjustment method. Note that if the storm is outside of WSR-88D Doppler range then the figure-4 pattern could be repeated before returning home.

The landfall flight pattern should take advantage of buoys or C-MAN sites nearby, if those platforms are expected to experience wind speeds > 25 m s^{-1}. The aircraft descends at the initial point and begins a low- level figure-4 pattern, possibly modifying the legs to fly over the buoys (Fig. 13-3). The radar will be in F/AST mode. If time permits, the aircraft would make one more pass through the eye and then fly the Dual-Doppler option. In this example, the pattern would be completed in about 2.5 h. Dropwindsondes would be deployed near the buoys or C-MAN sites and at or just inside the flight-level RMW.

Note that the optimal volume scans for this pattern will be obtained when the storm is 35-80 nm (60-150 km) from the radar, because beyond 80 nm (150 km) the lowest WSR-88D scan will be above 5,000 ft. (1.5 km) which is too high to resolve the low-level wind field. Within 35 nm (60 km) the volume scan will be incomplete, because the WSR-88D does not scan above 19.5 degrees. It is essential that these passes be flown as straight as possible, because turns to fix the eye will degrade the Doppler radar coverage.

Analysis Strategy

Flight level, Doppler radar, GPS dropwindsonde, 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 observations could then be combined to produce analyses of surface wind speed and provided to forecasters and/or emergency manager in real-time. The quality-controlled data will also be available for assimilation into models such as the HWRF model and to validate surface wind field forecasts produced by both the statistical Kaplan/DeMaria decay model as well as the operational HWRF model.

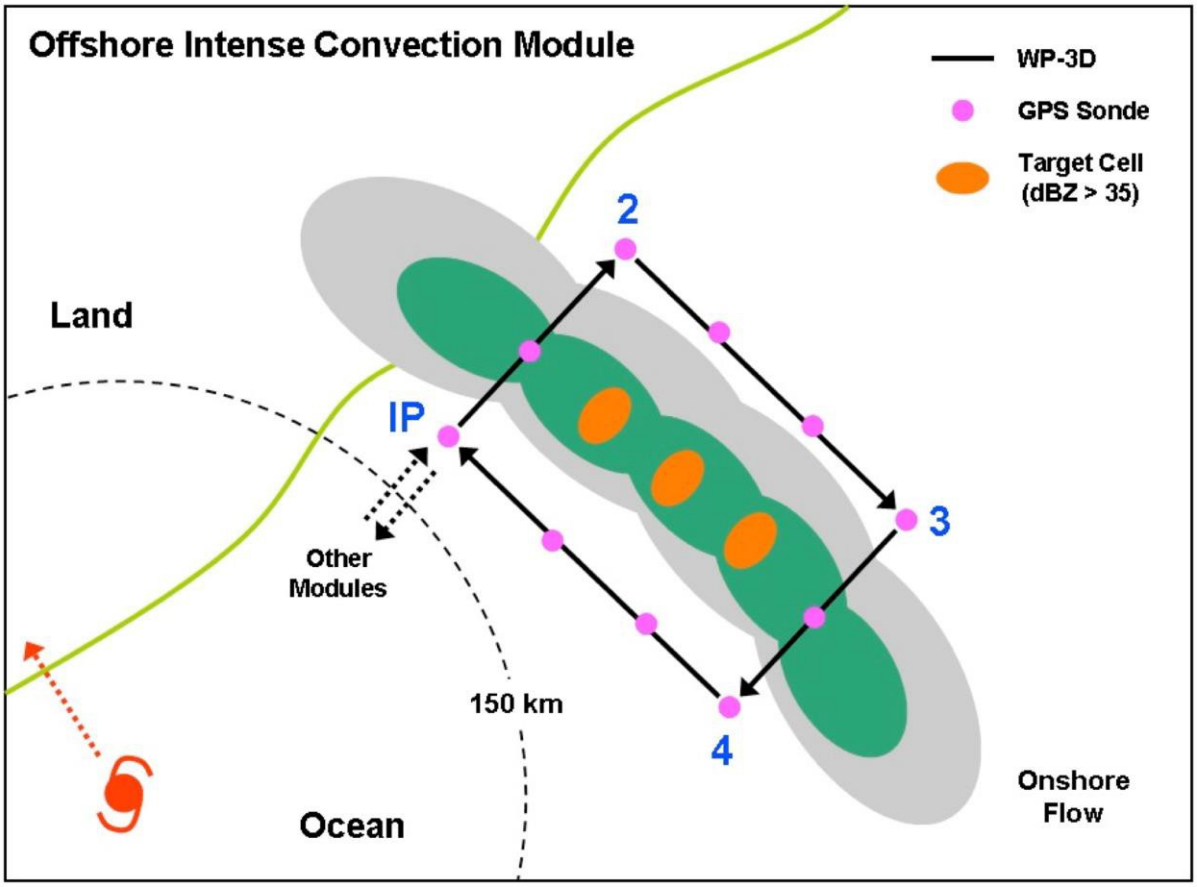

Fig. 13-1. Offshore Intense convection module.

Notes:

- The **IP** should be a minimum of 90 nm (150 km) from the storm center. The first leg (**IP-2**) starts 13 km (25 km) inside the rain band axis. Legs **IP-2** and **3-4** should be ~10-13 (20-25 km) downwind and upwind of the target cells to ensure adequate Doppler coverage. Legs **2-3** and **4-IP** should be 13 nm inside and outside the rain band axis. The length of legs **2-3** and **4-IP** can be adjusted but should be 40 nm (75 km) at a minimum.
- Deploy GPS dropwindsondes at the start or end points of each leg, at the band axis crossing points, and at ~10-13 nm intervals along each leg parallel to the band. The interval at which GPS dropwindsondes are deployed depends on how many are available, but **at least 2 GPS dropwindsondes should be deployed on either side of the convection and at least 1 dropwindsonde should be deployed each time the band-axis is crossed (for a minimum of 6 GPS dropwindsondes)**.
- Aircraft altitude should be at 10,000 ft. (3.0 km) or higher. Set airborne Doppler to scan in F/AST mode on all legs. Aircraft should avoid penetration of intense reflectivity regions (particularly over land).

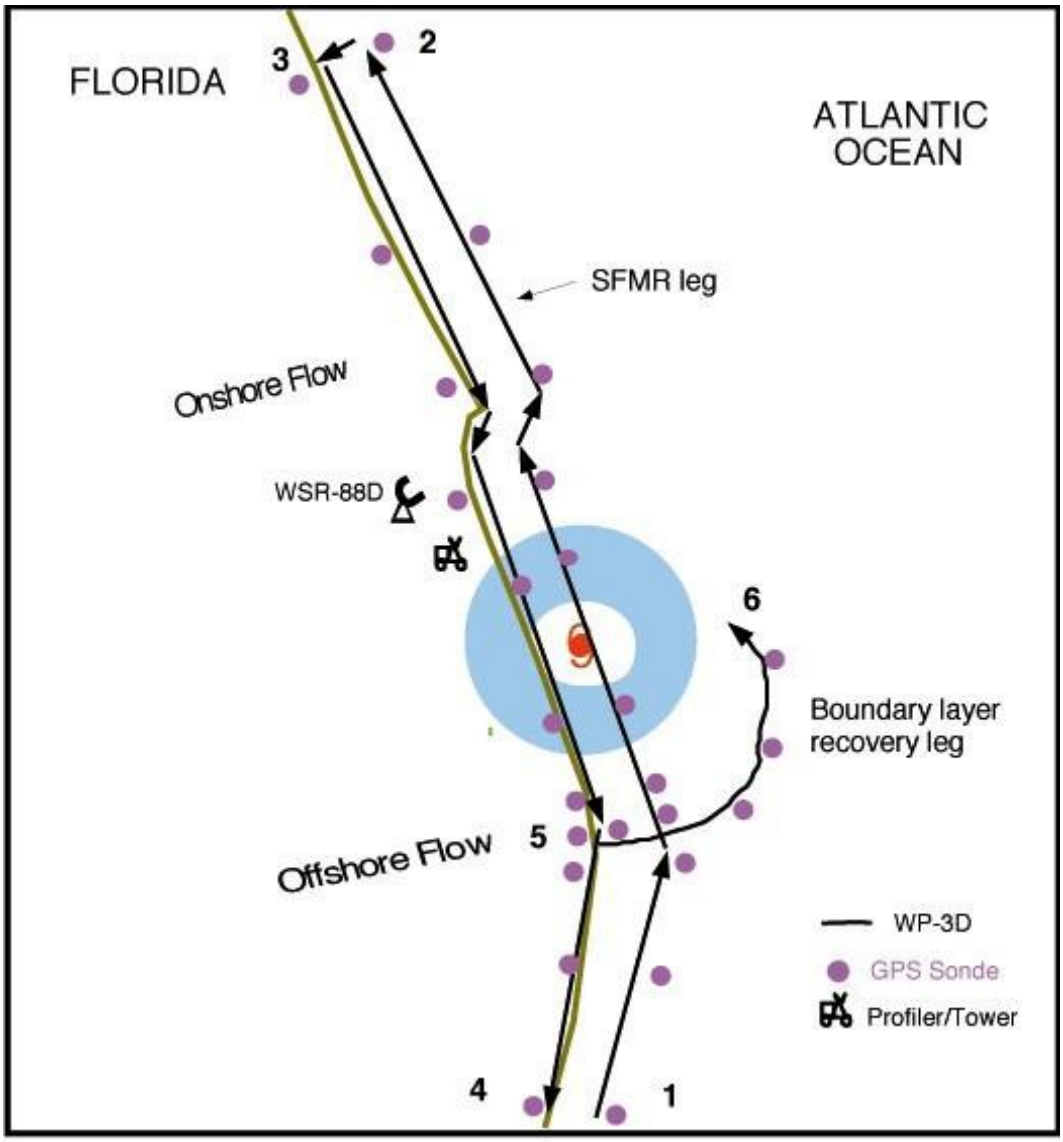

Fig. 13-2. Coastal Survey module.

Notes:

- First pass starts 80 nm (150 km) from center or at radius of gale-force wind speeds, whichever is closer. Pass from **1-2** should be 6-10 nm (10-15 km) offshore for optimum SFMR measurements. Release GPS dropwindsondes at RMW, and 7.5, 15, 30, 45, and 60 or 75 nm (12.5, 25, 50, 75, and 100 or 125 km) from RMW on either side of storm in legs **1-2** and **3-4**. GPS dropwindsondes should be deployed quickly at start of leg **5-6**, and then every 6-10 nm hereafter.
- Set airborne Doppler on all legs with single PRF > 2400 and 20% tilt. Aircraft should avoid penetration of intense reflectivity regions (particularly those over land)

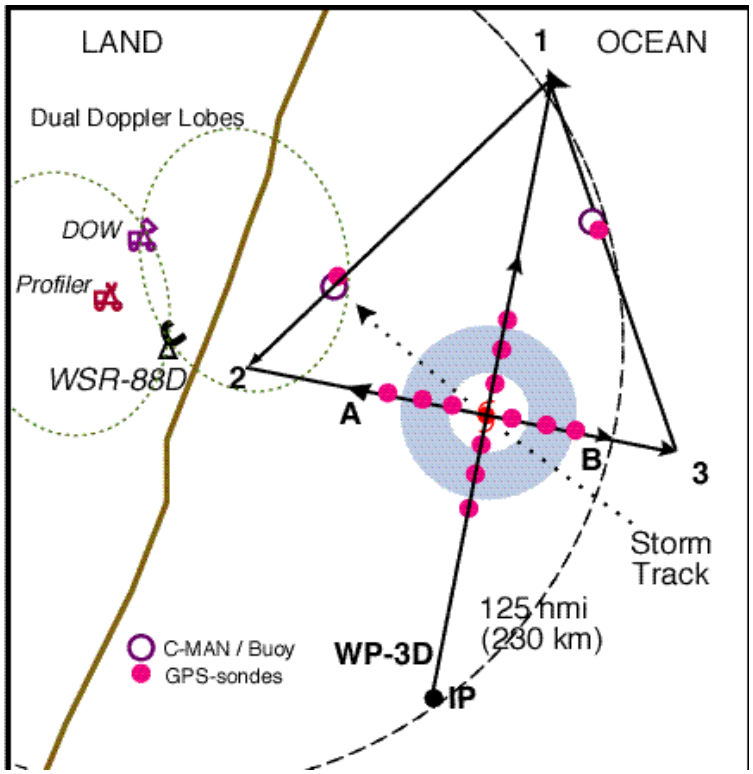

Fig. 13-3. Real-time module.

Notes:

- TAS calibration required. The legs through the eye may be flown along any compass heading along a radial from the ground-based radar. The **IP** is approximately 100 nm (185 km) from the storm center. Downwind legs may be adjusted to pass over buoys.
- P-3 should fly legs along the WSR-88D radials.

Aircraft should avoid penetration of intense reflectivity regions (particularly those over land).

- Wind center penetrations are optional.