## EXPERIMENT DESCRIPTION
## 12. Tropical Cyclone Landfall and Inland Decay

**Principal Investigators:** John Kaplan and Peter Dodge

**Links to IFEX:** These modules supports the following NOAA IFEX goals:

- **Goal 1**: Collect observations that span the TC lifecycle in a variety of environments;
- **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 about $50 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 forecast of the storm track. Research has helped reduce uncertainties in the track and landfall forecasts, and now one of the goals of IFEX is to improve the accuracy of the surface wind fields in TCs, especially near and after landfall. Improvements in diagnosing surface wind fields could decrease the uncertainty of the size of the hurricane warning area thereby reducing the cost of preparing for a landfalling hurricane.

There are still uncertainties in deriving surface wind estimates from flight-level and SFMR wind speeds collected near the coast. Changing bathymetry could change the breaking wave field, which could change both the roughness length at higher wind speeds as well as changing the microwave emissions. Evaluation of these effects may lead to adjustments to the operational surface wind speed algorithms. Data collected at the coast will also help to refine the Kaplan/DeMaria inland decay model that has been developed as part of a recently completed Joint Hurricane Testbed (JHT) project. Airborne Doppler radar data will also be transmitted to NCEP as part of another completed JHT project to assimilate radar data into the HWRF model.

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 2012 Hurricane Field Program. A major goal is to capture the lifecycle of a TC and while landfall is usually at the end of the lifecycle the same data collection strategies developed for mature hurricanes over the open ocean can also be applied at landfall. Subsets of the data collected can be transmitted to NHC and to EMC, for assimilation into HWRF. The Doppler and GPS dropwindsonde data can be analyzed to derive three-dimensional wind fields to compare with output from the HWRF and data from the SRA can be compared to HWRF wave fields. In addition to shear and heat flux from the ocean, hurricanes at landfall experience other conditions that may affect intensity change. These include change in ocean wave action in shallow waters, change in surface roughness, drier and cooler inflow from the land, and topography. Radar, dropwindsonde, and SFMR data can help define those conditions. Decay over land is also important and data collected during and shortly after landfall should help refine both operational statistical decay models (such as the Kaplan/DeMaria model) and 3-dimensional numerical models like HWRF.

HRD developed a real-time surface wind analysis system to aid NHC in the preparation of warnings and advisories in TCs. The surface wind analyses are now used for post-storm damage assessment by emergency management officials and to validate and calibrate the Kaplan/DeMaria decay model. These wind analyses could also be used to initialize the operational storm surge model in real time.

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 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 operational 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 and Floyd (1999), Isidore (2003) and Frances, Ivan and Jeanne (2004), and Dennis, Katrina, Rita and Wilma (2005).

Dual-Doppler analysis provides a complete description of the wind field in the core. Recently the analysis techniques have been streamlined so real-time wind analyses can be computed aboard the aircraft and wind fields at selected levels transmitted from the aircraft to NHC and NMC. These wind fields are also quite useful for post-storm analysis. An observational study of Hurricane Norbert (1984), using a PDD analysis of airborne radar data to estimate the kinematic wind field, found radial inflow at the front of the storm at low levels that switched to outflow at higher levels, indicative of the strong shear in the storm environment. Another study used PDD data collected in Hurricane Hugo near landfall to compare the vertical variation of wind speeds over water and land. The profiles showed that the strongest wind speeds are often not measured directly by reconnaissance aircraft.

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 hurricane crosses land.

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 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 (major hurricane) 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. The Doppler data will be augmented by deploying dropwindsondes near the coast, 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 hurricane. 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< radius < 240) 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.

**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, in combination with high-resolution surface wind measurements collected by land based collection teams, can be used to validate statistical and 3-D 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.

The miniature supercells and/or tornadic cells exhibit many basic kinematic, thermodynamic, and dynamic structures as those found in severe thunderstorms across the Great Plains. Traditional environmental parameters (such as CAPE and vertical shear) may be used to distinguish those sectors of the storm most supportive of supercell development and thus narrow the scope of any severe weather watches.

**Mission Description:** This is a *multi-option*, *single-aircraft* experiment designed to study the changes in TC surface wind structure near and after landfall. It has several modules that 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 moves within 215 nm (400 km) of the U.S. coastline. The first of these 2 flights will typically consist of the real-time module followed by SFMR and/or Coastal Wind Profile modules. A second flight could complete the post-landfall module. If the storm either moves parallel to the coastline or moves slowly inland and resources permit, it may be repeated with a second flight. While the storm location relative to the coastline will dictate which combination of these modules will be flown, the real-time module will generally precede all of the others.

This experiment should only be flown in a major hurricane, In addition, specific landfall flights will only be requested if the mobile observing systems are also deployed. These additional observations are especially important to document the inland decay of a major hurricane.

The aircraft must have working lower fuselage and tail radars. The HRD workstation should be on board, so radar and GPS dropwindsonde data can be analyzed and transmitted to 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 some of the portable Doppler radars (Shared Mobile Atmospheric Research and Teaching Radar [SMART-R] and/or Doppler on Wheels [DOW]), portable profilers and portable wind towers are deployed between ~65 and 130 km inland in the onshore flow regime as depicted in Fig. 12-1, this will provide valuable data for the inland decay model.  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. 12-1, 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 in 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.  The flight patterns will depend on the location and strength of the storm relative to surface observing platforms and coastal radars. The first two modules could be easily incorporated into a tasked operational mission. The other two modules are suited to research missions, where the patterns are not constrained by fix or gale-force wind radii requirements.

**Real-time module**: The real-time module combines passes over marine surface platforms with one or more figure-4 patterns in the core of the hurricane (Fig. 12-1.) The aircraft flies at or below 5,000 ft (1.5 km), 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 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 $ms^{-1}$. 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. 12-1). 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 additional dropwindsondes will be deployed at or just inside the flight-level RMW.

Note that the optimal volume scans for this pattern will be obtained when the storm is 32-80 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 32 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, dropsonde and SFMR data transmitted in real time will be ingested into the H*Wind 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 will be combined into analyses of surface wind speed that will be provided to forecasters, The quality controlled data will also be available for assimilation into models such as HWRF. The analyses can also be used to validate surface winds in model output fields, as explained in more detail in module 3.

**Coastal Survey module**: When the hurricane is making landfall, this module will provide information about the boundary layer in the onshore and offshore flow regimes. Figure 12-2 shows an example for a hurricane making landfall near Melbourne, Florida. On the first coastal pass the P-3 would fly parallel 10-15 km offshore to obtain SFMR surface wind speeds (1-2 in Fig. 12-2). The track should be adjusted so that the SFMR footprint is out of the surf zone. The second pass should as close to the coast as safety permits, to sample the boundary layer transitions at the coast in onshore and offshore flow (3-4 in Fig. 12-2). 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 dropwindsondes at the RMW and at intervals of 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. Finally, to better sample the adjustment of the off shore flow from land to ocean a short leg would be flown from the coast spiraling towards the storm center. Three to four dropwindsondes would be deployed quite near the coast, followed by 3-4 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 after the storm moves 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 dropsondes and SFMR, AWRAP and/or LIDAR data to characterize the differences between the onshore and offshore flow.

**Post Landfall Module:** This module is designed to collect kinematic and thermodynamic data ~1-2 h prior to and up to 6 h after a hurricane makes landfall. It is essential that ground-based measurements are obtained in conjunction with those that are being made by aircraft, since the primary goal is to determine the kinematic and thermodynamic changes that occur after a hurricane makes landfall throughout the depth of the lower troposphere.

The P-3 will fly a coastal survey pattern followed by a figure-4 pattern over land (Fig. 12-4) with ~ 150-km legs at an altitude of ~15,000 ft (5 km). The P-3 tail radar should be in F/AST mode. These data will aid in rainfall estimation and will help document the changes in vortex and rain band structure over land that are crucial to understanding the environment that supports tornado and mesovortex development.

Over land, available portable wind towers, mesonet stations, profilers and DOWs should be deployed along the path of the landfalling hurricane to identify the changes in storm structure as the hurricane moves inland. The wind towers and mesonet stations will obtain high-resolution surface wind, temperature, pressure, relative humidity, and perhaps rainfall measurements. If available, a profiler could be placed at the center of each line of mesonet stations. The profilers and RASS sounder will provide wind and temperature measurements within the lowest 3 and 1 km, respectively. Rain gauges should be located at each profiler and DOW site to obtain high-resolution rainfall measurements, both for calibrating the radar rainfall algorithms and for documentation of storm rainfall.

The first set of towers and mesonet stations should be placed as close as possible to the coastline (<10 km) to enable accurate documentation of the surface wind field just after landfall. Other towers or mesonet stations should be placed ~65 and 135 km inland respectively; however, these distances will vary depending upon the intensity and speed of motion of the landfalling storm as well as safety considerations. The spacing between the mesonet stations located within each group should be ~30 nm (50 km) perpendicular to the track to maximize the likelihood that one of the mesonet stations will be located near the RMW of the landfalling storm.

If the inland profilers are mobile, it will be possible to follow severe weather producing rain bands if safety and logistical considerations allow. The DOWs should be placed roughly halfway between the two rear lines of mesonet and profiler stations. The DOWs, in combination with the profilers with RASS, will aid in documenting the changes in kinematic and thermodynamic structure of the hurricane after landfall. An accurate analysis of such changes is crucial to learning more about the development of mesovortices and/or tornadoes spawned by landfalling hurricanes. They will also help document the changes in wind speeds within the PBL of a landfalling hurricane. Finally, the radars will aid in the measurement of the rainfall associated with the landfalling hurricane.

**Analysis Strategy:** Wind measurements for all landfalling cases for which simultaneous measurements were obtained by both NOAA-P3 aircraft and land-based collection teams will be converted to a uniform averaging time (1-min.), height (10-m), and exposure (Z0=0.01 or 0.03 m) using the methodology of Powell et al. (2009). The Kaplan/DeMaria empirical decay model will then be run for each of these cases and the surface wind forecasts from this model will be compared to the standardized surface winds at the appropriate observation location and time. Similar comparisons will also be made using the 3-D (e.g. HWRF or HWRF-X) numerical model surface wind forecasts. However, before such comparisons are made, the 3-D numerical model predicted winds will first need to be converted to open exposure or alternatively the observed surface winds will need to be standardized using the same exposure that was used in the 3-D model prediction at each surface observation location to enable a fair comparison to be made between the model predicted and observed wind.

**Offshore Intense Convection Module:** 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 rain band (>150 km from the storm center) but embedded within the onshore flow. This module can be easily incorporated during either the real-time module, the coastal survey module, or the onshore wind profile module when a qualified outer rain band is encountered. Figure 12-5 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 3000 m 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 10 GPS sondes should be deployed. The first flight leg should cross the target band ~20-25 km downwind of the intense convective cells and proceed until the aircraft is 25 km outside the rain band axis, deploying a GPS sonde at the band axis and end point. The aircraft then turns upwind and proceeds along a straight track parallel to the rain band axis, deploying GPS sondes every 20-25 km. This length of this leg can adjusted as needed, but should be a minimum of 75 km. When the aircraft is ~20-25 km upwind of the target cells, the aircraft turns and proceeds along a track orthogonal to the band axis until the aircraft is 25 km inside the rain band. GPS sondes 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 sondes every 20-25 km. The end point of this final leg should be ~20-25 km 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 min, and in most case can be completed in less time.

**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 rain band (>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 Intensity Forecasting Experiment (IFEX).

**<u>Note</u>:** 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 rain band (>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 <u>not</u> strictly limited to the Landfall and Inland Decay Experiment.**

**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 thermodynamic environment of the targeted cells. Any available land-based radar will be used to augment the cell evolution documented by the airborne radars. The cell's environments and structures will be compared with those of mid-latitude supercells.

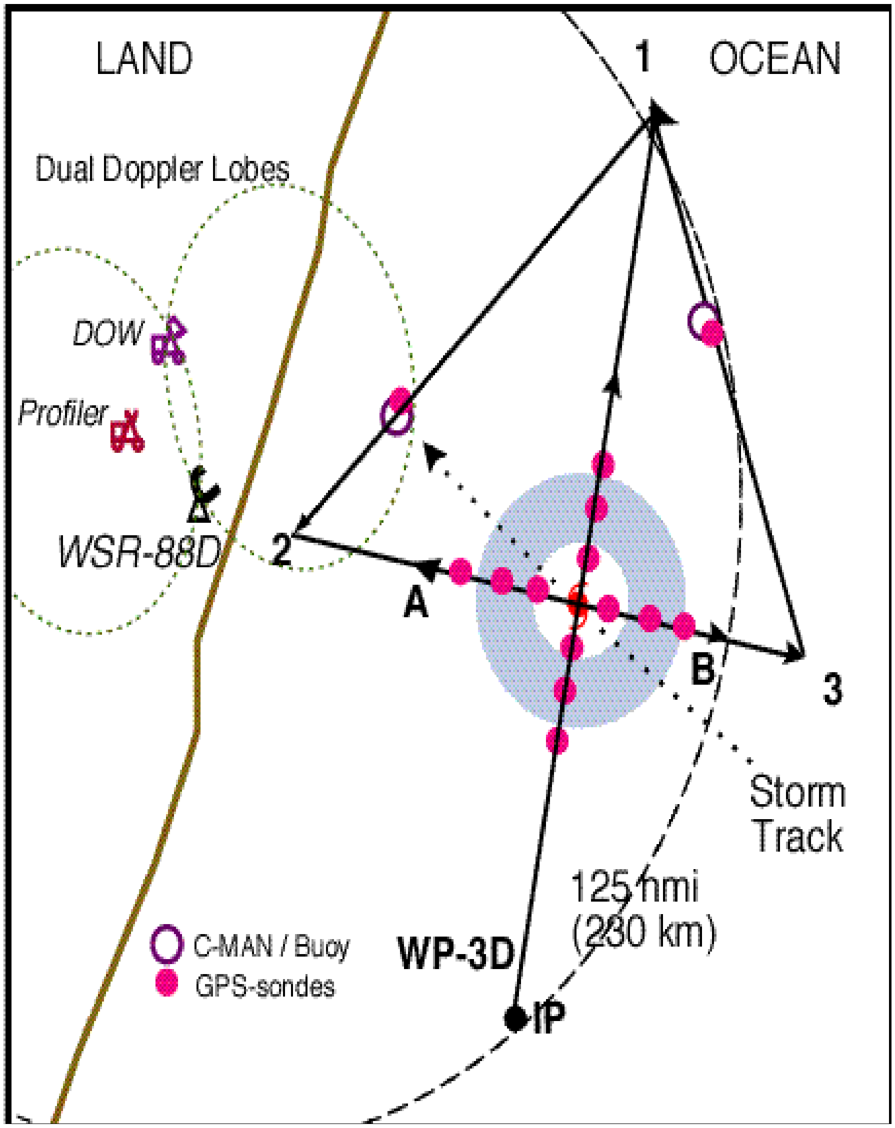


**Figure 12-1:** Real-time module.

- 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.
- Set airborne Doppler radar to F/AST on all legs. Aircraft should avoid penetration of intense reflectivity regions (particularly those over land).
- Wind center penetrations are optional.

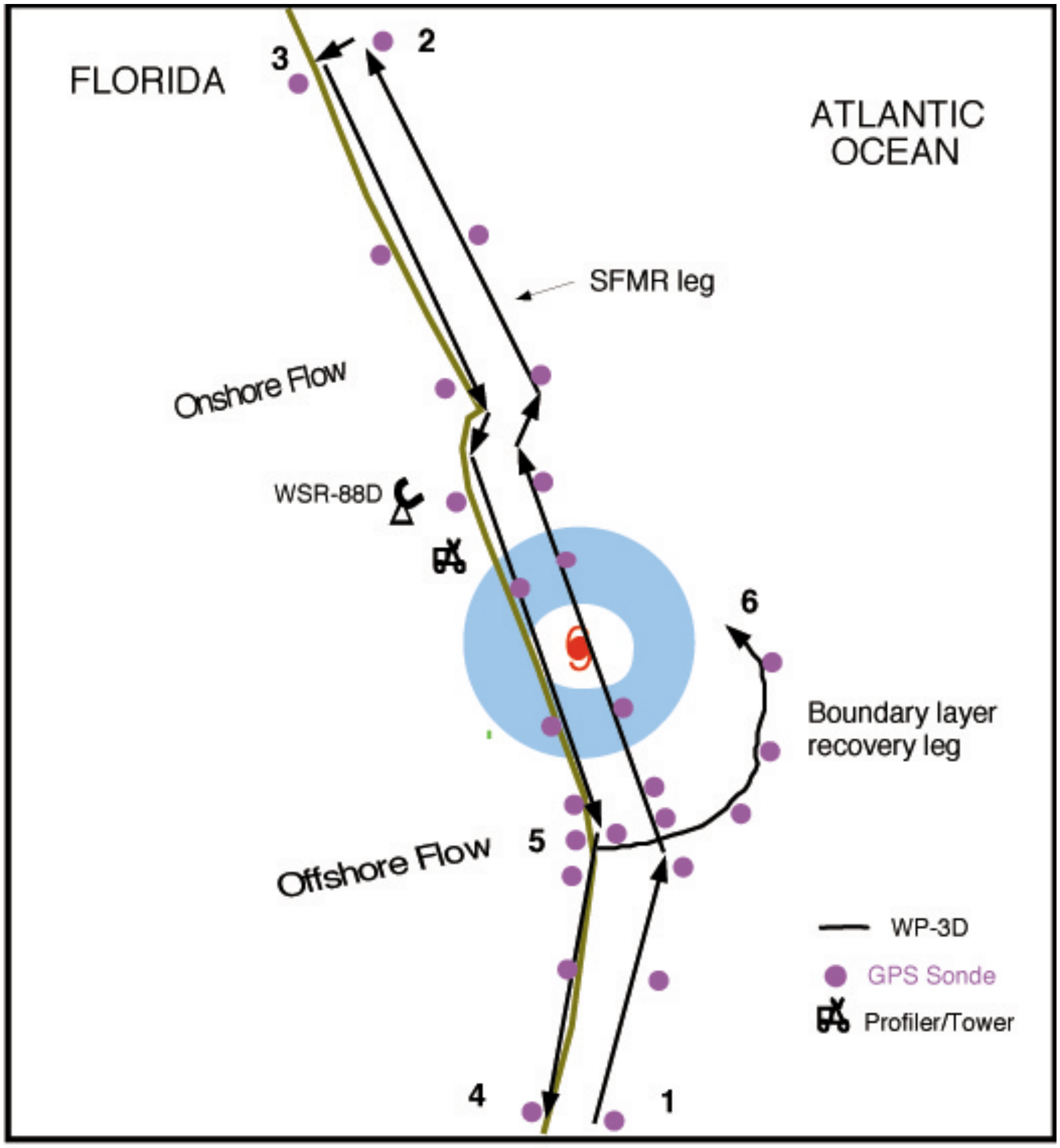


**Figure 12-2:** Coastal Survey pattern.

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

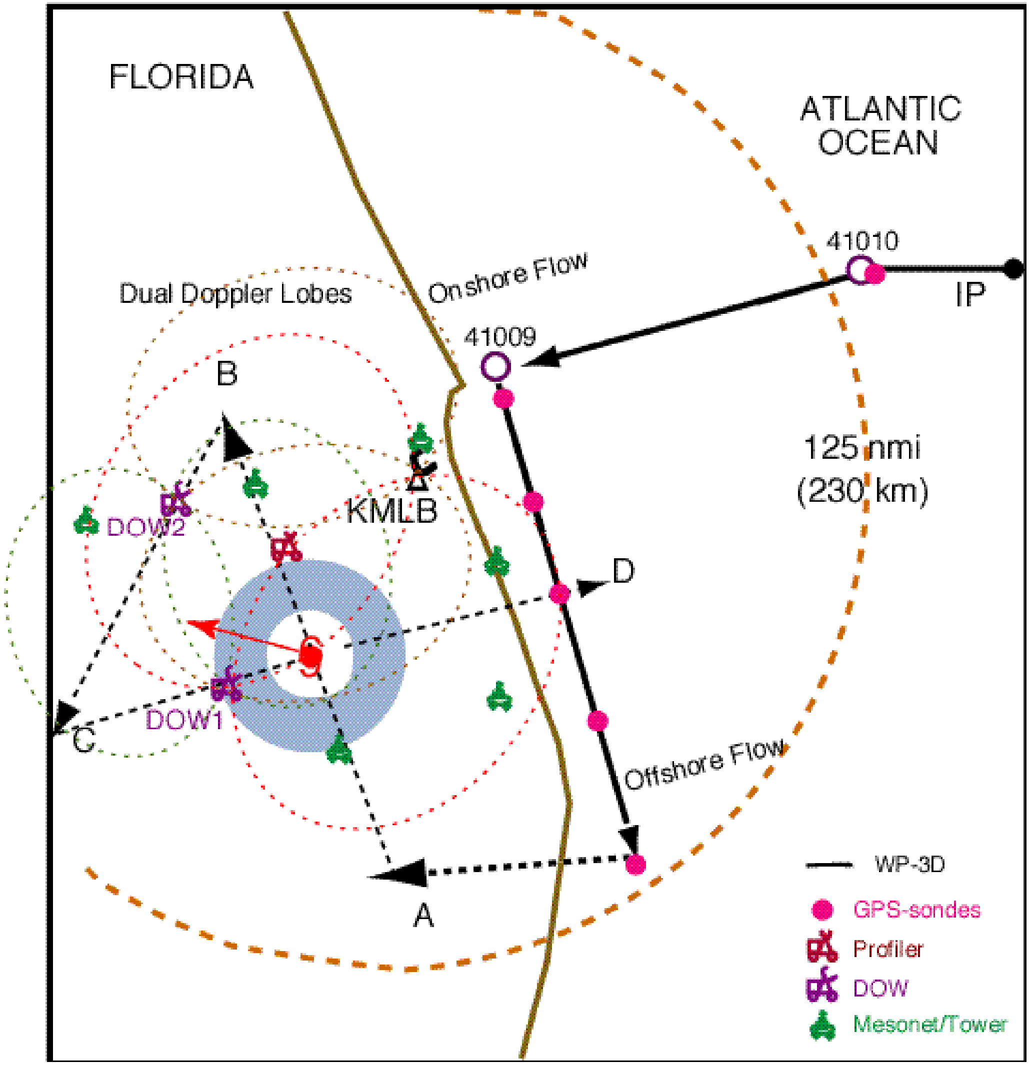


**Figure 12-3:** Post landfall module flight pattern.

- Coastal survey pattern (solid line) at ~10,000-15,000 ft (3-4 km) with dropwindsondes near buoys of opportunity and within 10-20 km of the shore in both the onshore and offshore flow
- Inland figure-4 pattern (dashed line) centered on the storm with leg lengths of ~80 nm (150 km) at an altitude of ~15,000 ft (5 km).
- P-3 should fly legs along the WSR-88D radials.
- Set airborne Doppler radar to F/AST on all legs.
- Aircraft should avoid penetration of intense reflectivity regions (particularly those over land).
- Wind center penetrations are optional.

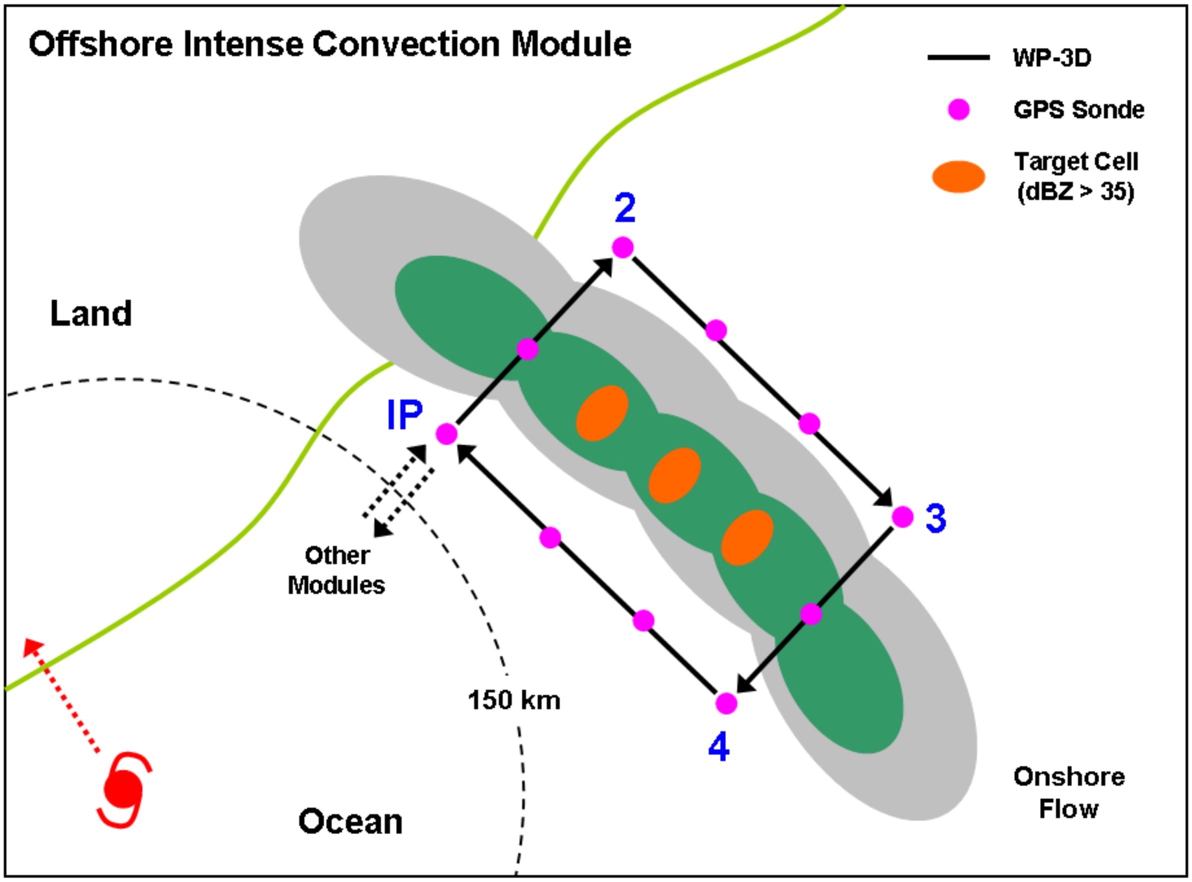


**Figure 12-4:** Offshore Intense Convection pattern.

The **IP** should be a minimum of 150 km from the storm center. The first leg (**IP-2**) starts 25 km inside the rain band axis. Legs **IP-2** and **3-4** should be ~20-25 km downwind and upwind of the target cells to ensure adequate Doppler coverage. Legs **2-3** and **4-IP** should be 25 km inside and outside the rain band axis. The length of legs **2-3** and **4-IP** can be adjusted but should be 75 km at minimum. Deploy dropwindsondes at the start or end points of each leg, at the band axis crossing points, and at ~20-25 km intervals along each leg parallel to the band. Aircraft altitude should be at 10,000 ft (3000 m) 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).