20. Hurricane Boundary Layer (HBL) Experiment

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Program Significance:
The near-surface inflow is a crucial region of a tropical cyclone (TC), since it is the area of the storm in direct contact with the ocean moisture and heat sources which power the storm (Zhang 2010; Wroe and Barnes 2003). The boundary layer has been identified in prior studies to be of critical importance to hurricane intensification (e.g., Emanuel 1997; Smith et al. 2009; Zhang and Marks 2015). Despite the critical nature of this environment, routine collection of kinematic and thermodynamic observations in the boundary layer remains elusive (Black et al. 2007). Currently, boundary layer observations, especially associated with turbulence, are very limited since the primary source of data is from point-source GPS dropsonde measurements (Zhang et al. 2013). The lack of data coverage at low levels is a primary reason why hurricane boundary layer structure and associated physical processes remain poorly represented in today's operational hurricane models (Zhang et al. 2012; Zhang et al. 2015).

Recent composite analysis of near-surface wind data has led to a more accurate description of general TC inflow characteristics, including asymmetries (Zhang and Uhlhorn 2012). However, it has also become clear that there are few individual cases that contain sufficient observations to develop an accurate synoptic view and comprehensive understanding of boundary layer inflow evolution as a TC intensifies or weakens, changes motion, experiences eyewall/rain-band cycles, and is impacted by shear to varying degrees. This experiment aims to fill this data gap.

Objectives:
The main objectives of the Hurricane Boundary Layer Experiment are to:
- Directly measure turbulent fluxes in the hurricane boundary layer;
- Characterize the distribution and variations of boundary layer heights in hurricanes;
- Identify and document the characteristics of organized eddy such as boundary-layer rolls;
- Quantify the capabilities of the operational hurricane models to accurately represent turbulent fluxes and boundary layer rolls.

Model Evaluation Component:
Turbulent fluxes are the key boundary layer conditions for numerical models. How energy is transported in the hurricane boundary layer is crucial to the hurricane maintenance and intensification. Boundary layer rolls are quasi-two dimensional features that can affect the surface flux transport and modulate the mean boundary layer structure. Observations that are collected during this experiment will be used to evaluate the robustness of the operational coupled model forecast system (e.g. HWRF) to represent turbulent mixing processes.

Mission Description:
This is a multi-option, single or multiple-aircraft experiment that is designed to measure both the mean and turbulent structure of the hurricane boundary layer. A combination of data sources from GPS sondes, AXBTs, high frequency turbulence sensors, Doppler Wind Lidar (DWL), on NOAA P3s and COYOTE unmanned aircraft are applied to determine the quantities listed in the above objectives. This experiment includes 3 modules: 1) stepped-descent module, 2) DWL boundary-layer module, 3)

boundary layer inflow module. Turbulence sensors on P3s need to be calibrated at the start of the field season as described in the turbulence calibration module.

Module/Option 1a: Stepped-descent module (40 minutes):

The module is flown between the eyewall and an outer rainband by NOAA P3s or COYOTE. It does not require any penetration of convective cells, the eyewall or convective rainbands. Preference is for a region that is either rain-free or stratiform rain only. For the simplest experiment 5 legs would be flown, each about 40 km or 5 minutes in duration (Figs. 20-1 and 20-2). The pattern would begin with a pass at 3 to 4 km altitude rapidly jettisoning 4 GPS sondes spaced approximately 10-km apart. During this pass 2-3 AXBT's would also be deployed to determine the SST. Airborne radiometers (SFMR) would also provide an estimate of surface wind speeds, and if there are enough scatterers in the volume the Doppler radar can be used to determine mesoscale wind and divergence. The first leg (at ~ 3 km altitude) can be done in conjunction with the standard figure-4 patterns.

The GPS sondes and Doppler wind lidar (DWL) are used to estimate the boundary layer height to the eyewall and the mean conditions of the boundary layer and the lower portion of the layer above. Because it is difficult to determine the height of the inflow layer at real time, the height of the maximum wind speed is defined to be top of the boundary layer, which is around 500 – 1000 m. The inflow layer top is expected to be 1-2 km in height. We can use the dropsonde and DWL data at the end of outbound radar leg to diagnose the boundary layer height. Then we turn back into the storm to do the stair-step. The aircraft would descend to 600 m above the inflow top (about 2400 m) and fly toward the eyewall along an approximate radial. This leg will cover 40 km or require about 5 minutes. The aircraft will then turn and descend ~500 m and fly out-bound for 5 minutes. Two more legs will be completed, each another 500 m below the previous pass. The last pass will be 700 to 800 m above the sea. If the aircrew deems it safe a final pass could be flown 400 to 500 m above the sea. All legs will finish with a turn upwind to keep the legs nearly vertically aligned and in the same portion of the TC. Time to complete the module is about 40 min including descents and turns.

These five passes and the GPS sondes will allow for a determination of the sensible and latent heat fluxes (total enthalpy flux) as a function of height and radial distance adjacent to the eyewall or a convective rainband from the top of the inflow layer to 500 m altitude. The combination of the vertical profiles of equivalent potential temperature (θe) and the determination of the fluxes at the top of the inflow layer will allow an estimate of the air-sea fluxes as a residual and directly through the application of the bulk aerodynamic formulae applying AXBT, SFMR, and 10 m observations obtained from the GPS sondes. The scheme will allow us to infer the magnitude of the transfer coefficients necessary to achieve energy balance, provide insight to the role of dissipative heating, and determine the role of entrainment of warmer θe through the top of the inflow layer.

Module/Option 1b: DWL Boundary-Layer Module:

The DWL on NOAA P3 aircraft measures three-dimensional wind velocities with ~50 m vertical resolution and ~2 km horizontal resolution (Pu et al, 2010). In the stare mode, the horizontal resolution in the marine boundary layer is on the order of a few meters. This is a new tool for boundary layer observations in addition to the existing GPS dropsonde and Doppler radar. Airborne Doppler radars provide three-dimensional wind estimates only where there is precipitation, whereas a DWL can provide wind estimates wherever there are aerosols and broken cloudiness.

This module is designed to complement standard operationally-tasked P-3 Tail Doppler Radar (TDR) missions. This module will target sampling of the kinematic structure of the boundary layer with focus on investigating the characteristics of the boundary layer height and coherent structures. The module can be combined with other experiments or modules, as it does not necessarily require a specific flight track. The DWL will scan in the following modes with downward looking direction. The first is a full scan mode. The second mode follows a sector scanning strategy that allows an increase in the horizontal resolution of the wind retrieval.

Module/Option 1c: Boundary-layer inflow module:

This module is designed to complement standard operationally-tasked P-3 Tail Doppler Radar (TDR) missions by obtaining near-surface wind vector data from GPS dropwindsondes where Doppler winds are not readily available.

The flight pattern is consistent with a typical rotated "alpha" (Figure-4) pattern flown for TDR missions (Fig. 20-3). The rotated pattern (as opposed to the repeated alpha pattern) is preferable to better resolve higher (than 1) wavenumber asymmetric wind field structure. In addition, it is requested to fly the pattern as orthogonal pairs of radials, rather than rotating radials by 45 deg. as the flight proceeds. The initial (IP) and final (FP) points of the pattern are arbitrary. Required instrumentation consists of expendable probes (34 dropwindsondes and 16 AXBTs) as depicted in Fig. 20-3. Note that in particular, high-resolution sampling (3 sondes spaced ~1 min apart) is requested across the radius of maximum wind (RMW) on a pair of orthogonal radii to help better estimate boundary layer gradient winds. Center drops are requested on the first and last pass through the eye. The COYOTE can be flown along the inflow trajectory along with this module for P3 aircraft.

Turbulence Calibration Module (2-3 hours)

The calibration module only needs be executed on separate flights at beginning of the field season. The following maneuvers are requested for turbulence sensors calibration:

1). Dynamic Yaw--2 sets: First set, vary sideslip angle (beta) by +/- 4 degrees. This maneuver requires 5 full sinusoids, with one consisting of left 4 degrees, back through center, right 4 degrees, back to center--one sinusoid. Second set, set angle variation, and perform faster roughly +/- 2.5 degree variation with 25 sec period.

2). Acceleration/Deceleration (AC/DC) run--1 set: Start at normal flight speed, slow to minimum sustainable flight speed, increase to maximum flight speed, slow minimum flight speed, return to normal speed. Try to maintain constant altitude (vary angle of attack).

3). Wind Circles: Two 360° standard rate turns: first clockwise, then counter-clockwise. We need 360° of data to be in a coordinated turn, so after the pilot enters the turn and it is coordinated, only then 'start the clock'.

4). Wind box: Straight and level box, 2 min on each side, standard rate 90° turn on the corners. The box consists of 4 two-minute legs, with 90 degree standard rate turns after the completion of each leg. The box should be set up to fly one leg into, the next cross, the third out of, and the fourth cross wind direction. Indicated airspeed should be 210-220 kt.

5). Pitch (angle of attack) maneuvers--2 sets of 5: Five sinusoids with angle attack variations of +/-5 to 7 degrees. One complete sinusoid should have a period of 15 to 20 seconds. Upon completion of one set, fly straight and level roughly 2 minutes and begin second set.

All of these maneuvers should be aligned with the wind. The boxes should have legs parallel and perpendicular to the wind. The calibrations should be completed at the mean radar altitude where the measurements were conducted or roughly 1,500 ft (500 m). The maneuvers should be conducted in smooth air (as smooth as possible).

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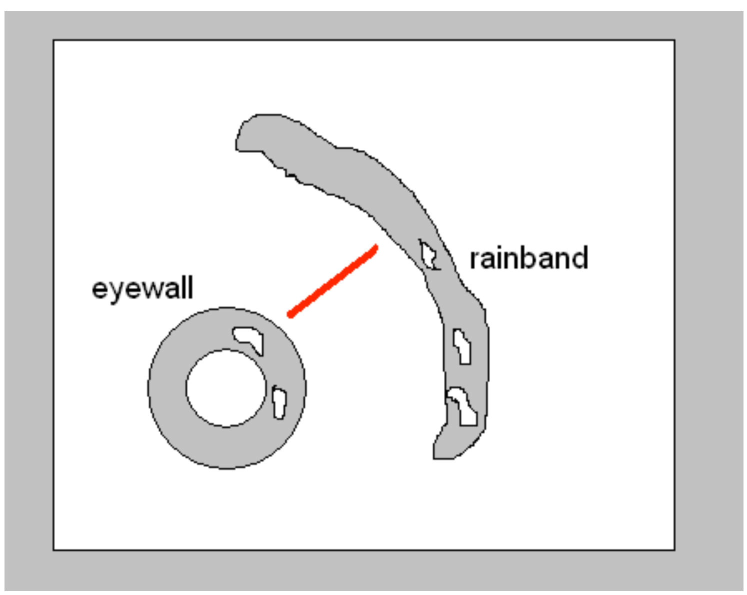

Figure 20-1: *Plan view of the preferred location for the stepped-descent module. Red line shows aircraft track.*

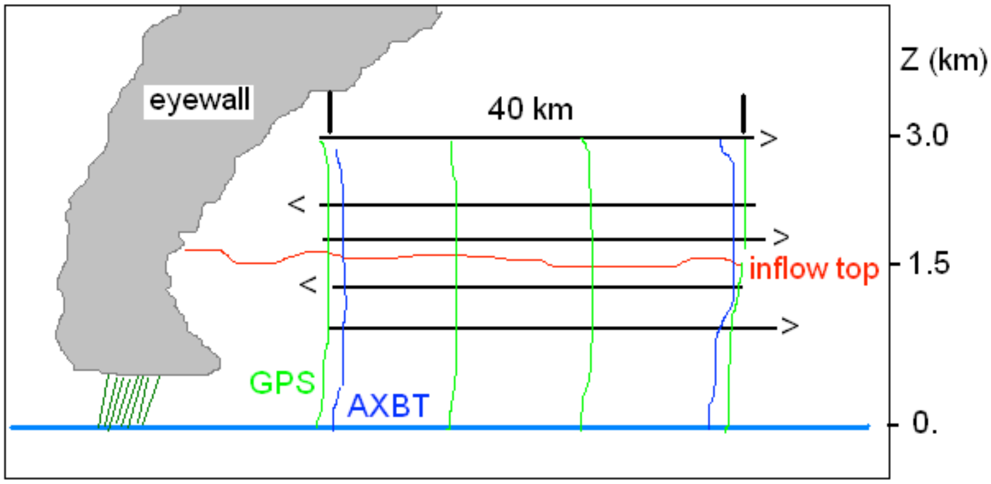

Figure 20-2: *Vertical cross-section of the stepped-descent module.*

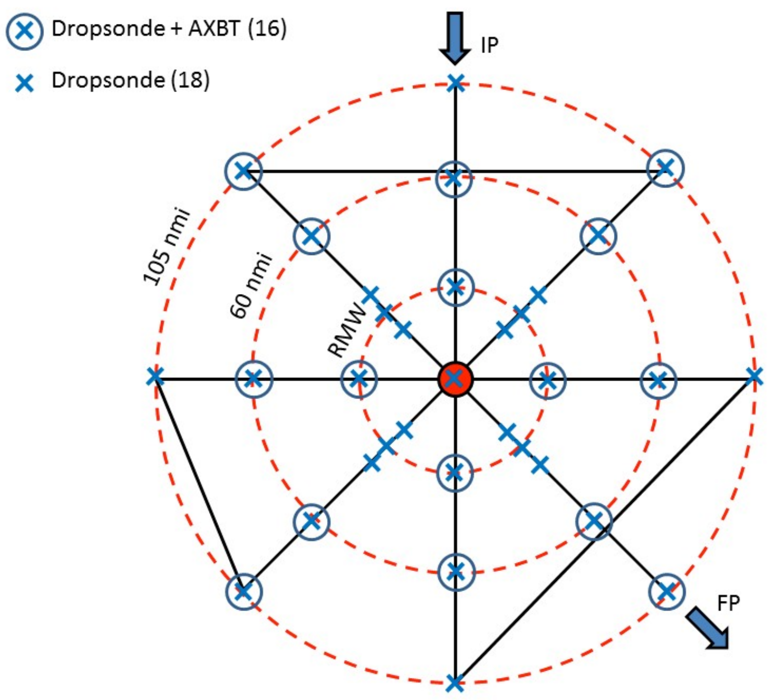

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Figure 20-3: *Boundary Layer Inflow Module. GPS dropwindsondes (34 total) are deployed at 105 nmi and 60 nmi radii and at the radius of maximum wind along each of 8 radial legs (rotated alpha/Figure-4 pattern). On 4 of the 8 passes across the RMW, rapid deployment (~1 min spacing) of 3 sondes is requested. Center drops are requested on the initial and final pass through the eye. AXBT (16 total) deployments are paired with dropsondes at the indicated locations. Flight altitude* *is as required for the parent TDR mission, and initial and final points of the pattern are dictated by these same TDR mission requirements.*