MATURE STAGE EXPERIMENT
Science Description

Experiment/Module: Hurricane boundary layer (HBL)

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Requirements: Categories 2–5 (*Note that this module can be conducted in any strength storm if needed*)

Plain Language Description: The atmospheric boundary layer is a crucial region of a tropical cyclone (TC), because it is the area of the storm in direct contact with the ocean moisture and heat sources which power the storm. This module aims to collect observational data to improve our understanding of physical processes in the boundary layer that control the TC intensity change. These data can be used to evaluate and improve the performance of TC forecast models.

Mature Stage Science Objective(s) Addressed:

1) Collect observations targeted at better understanding internal processes contributing to mature hurricane structure and intensity change [*APHEX Goals 1, 3*].
2) Collect observations targeted at better understanding the response of mature hurricanes to their changing environment, including changes in vertical wind shear, moisture and underlying oceanic conditions [*APHEX Goals 1, 3*].

Motivation: The atmospheric boundary layer is a crucial region of a TC, since it is the area of the storm in direct contact with the ocean moisture and heat sources which power the storm. The boundary layer has been identified in prior studies to be of critical importance to TC intensity and intensity change (e.g., Smith et al. 2009; Tang and Emanuel 2010; Riemer et al. 2010; Bryan 2012; Cione et al. 2013; Zhang and Rogers 2019; Chen et al. 2019). Despite the critical nature of this environment, routine collection of kinematic and thermodynamic observations in the boundary layer remains elusive. The optimal successful experiment will yield a synoptic view of the boundary layer over a series of consecutive missions. Our research goal of this module is to better understand details of the boundary layer structure and evolution before and during TC intensification. While the research plans focus on analyzing in-situ data collected by this module, these plans will be of value to remote sensing research (e.g., Synthetic Aperture Radar, Compact Raman Lidar, and Doppler radar) on boundary layer processes in TCs.

Background: An improved knowledge of mechanisms across the boundary layer is essential for interpreting physical processes that are tied to TC intensity change. Recent composite analyses of dropsonde data have improved our understanding of general TC boundary layer characteristics, including asymmetries (Bell and Montgomery 2008; Zhang et al. 2011, 2013, 2020; Zhang and

Uhlhorn 2012; Wadler et al. 2022). However, it has also become clear that there are few individual cases that contain enough observations to develop an accurate view and comprehensive understanding of boundary layer evolution as a TC intensifies, especially in a sheared environment (e.g., Chen et al. 2021; Rogers et al. 2015; Zhang et al. 2017b; Wadler et al. 2018, 2021a,b). In addition, the TC diurnal cycle modulates inflow strength and moist entropy in the TC near environment (R~150-300 km) that can affect storm intensity (Dunion et al. 2019). These diurnal fluctuations promote a stronger, deeper boundary layer at night and weaker, shallower boundary layer during the day in mature storms (Zhang et al. 2020). It remains to be understood how the boundary layer structure varies with the diurnal cycle during a TC's lifecycle. This HBL module aims to fill these data gaps.

Coherent structures in the hurricane boundary layer such as roll vortices are known to have a significant impact on turbulent transport and wind distribution (Foster 2005; Zhu 2008; Gao and Ginis 2015). The roll contribution to turbulent transport is non-gradient. Satellite SAR provides ultra-high resolution (~25 m) measurements of microwave normalized radar backscatter cross-section (NRCS) off the ocean surface with swath widths up to 400 km. This backscatter can be used to calculate 1 km resolution surface wind vectors up to ~ 80 m s^{-1} that can be used to diagnose aspects of the boundary layer flow. The NRCS also detects the surface imprints of the rolls (Zhang et al. 2008; Foster 2013; Huang et al. 2018). Coincident flight level, SFMR and dropsonde data are needed to calibrate and validate analysis techniques using Synthetic Aperture Radar data, for wind vector retrieval and models for roll structure and dynamics. This HBL module aims to collect the needed collocated observations.

Specific questions we wish to answer are:

1. How are boundary-layer inflow and thermodynamic fields related before TC intensification?
2. How do boundary layer height scales evolve before and during TC intensification?
3. How might environmental shear modulate the boundary layer asymmetry during TC intensity change?
4. What is the role of boundary layer recovery in TC intensity change in shear?
5. What is the relative importance of boundary layer recovery for TCs near landfall compared to over ocean?

Goal(s): To better understand details of boundary layer structure and evolution before and during TC intensification.

Hypotheses:

1. TCs that have a deeper boundary layer, stronger inflow, larger boundary-layer convergence, larger surface enthalpy fluxes, and less degree of asymmetry in boundary-layer enthalpy and inflow, tend to intensify faster in a sheared environment.

2. The inflow strength and moist entropy in the boundary layer of the TC outer core region vary with a diurnal cycle and modulate the intensity change.
3. Boundary layer recovery is a key process for convection development in intensifying TCs in shear.
4. The thermodynamic boundary layer structure of a TC, whose outer rain bands already experience land effect, may be primarily determined by the coastal SST response over the shelf.

Objectives:
1. Collect aircraft observations in the boundary layer before and during TC intensification to identify key boundary-layer structure and dynamics that are tied to TC intensity change.
2. Collect collocated aircraft and satellite observations to document surface wind distribution and characteristics of boundary-layer rolls in TCs.
3. Use observational data collected in this module to evaluate TC model simulations and forecasts.

Aircraft Pattern/Module Descriptions (see *Flight Pattern* document for more detailed information):

P-3 Pattern #1: Rotated Figure-4
For early stage TCs, this module complements standard Tail Doppler Radar missions. Dropsondes are deployed at the storm center, 105 n mi (end point) and 60 n mi radii, and the radius of maximum wind (RMW) along each of 8 radial legs (rotated Figure-4 pattern). For potential or imminent downshear reformation cases, this module would be adjusted to the rotated Figure-4 pattern focusing more on the midlevel TC center in the downshear side.

P-3 Pattern #2: Butterfly
For early stage TCs, this module complements standard Tail Doppler Radar missions. Dropsondes are deployed at the storm center, 105 n mi radii (i.e., end point), the RMW, and the mid-point between the RMW along each of 6 radial legs (Butterfly pattern).

P-3 Pattern #3: Circumnavigation
For early stage TCs, this module complements standard Tail Doppler Radar missions. Dropsondes are deployed at the storm center, the end points of Figure-4 (105 n mi), vertices of the octagon, and the RMW.

Links to Other Mature Stage Experiments/Modules: The HBL module can be flown in conjunction with the following Mature Stage experiments: TDR Experiment, RICO SUAVE, Ocean Observing, End Stage, Ventilation, Early Stage Experiment, and Sustained and Targeted Ocean Observations.

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Analysis Strategy: This module seeks to observe the characteristics of the TC boundary layer during TC intensity change. Dropsonde, AXBT and Doppler radar profile data will be analyzed. The combo AXBT, dropsonde, and ocean surface wind will be used to derive the surface fluxes. The dropsonde data will be analyzed in both an axisymmetric and asymmetric (e.g., shear-relative quadrant) framework. Optionally, small uncrewed aircraft systems (sUAS) can be utilized in conjunction with these instruments to augment the boundary layer measurements (see RICO SUAVE experiment). In the axisymmetric and shear quadrant framework, the dropsonde data will be azimuthally averaged at a given radius where dropsonde data are collected. Radius-height plots of the azimuthally averaged tangential and radial velocities, equivalent potential temperature and virtual potential temperature will be made. Boundary layer height scales will be estimated based on the method used by Zhang et al. (2011). The dropsonde measured data will also be plotted as a function of radius and azimuth at each altitude before and during the TC intensification in shear.

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