

EARLY STAGE EXPERIMENT
Science Description

Experiment/Module: Hurricane boundary layer (HBL)

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Requirements: TD, TS, Category 1

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 BL that control the TC intensity change. These data can be used to evaluate and improve the performance of TC forecast models.

Early Stage Science Objective(s) Addressed:

1. Collect datasets that can be used to improve the understanding of intensity change processes, as well as the initialization and evaluation of 3-D numerical models, particularly for TCs experiencing moderate vertical wind shear [*APHEX Goals 1, 3*].
2. Collect observations targeted at better understanding internal processes contributing to hurricane structure and intensity change [*APHEX Goals 1, 3*].
3. Test new (or improved) technologies with the potential to fill gaps, both spatially and temporally, in the existing suite of airborne measurements in early stage TCs. These measurements include improved three-dimensional representation of the TC wind field, more spatially dense thermodynamic sampling of the boundary layer, and more accurate measurements of ocean surface winds [*APHEX Goal 2*].

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 (Smith et al. 2009; Tang and Emanuel 2010; Riemer et al. 2010; Bryan 2012; Cione et al. 2013; Zhang et al. 2017a; Zhang and Rogers 2019; Chen et al. 2019, 2021). 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

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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; Zhang and Uhlhorn 2012). 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., Rogers et al. 2015; Zhang et al. 2017b; Wadler et al. 2018, 2021). 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 the early stage of 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 SAR analysis techniques such as 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?

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

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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.

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).

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 octagon, and the RMW.

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Links to Other Early Stage Experiments/Modules: The boundary layer module can be flown in conjunction with the following Early Stage experiments: TDR Experiment and sUAS modules.

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 RICOSUAVE 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.

Model Reanalysis and Evaluation Strategy: Quality controlled observations collected by this module will be used in the assimilation system to create a model reanalysis. The observations will also be used to evaluate the TC models' prediction of boundary layer structure and evolution prior to the TC rapid intensity change.

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