**Chapter 1: TCI Project Overview**

**Project Goals and Purpose**

The goal of the Tropical Cyclone Intensity (TCI) initiative is to improve the prediction of tropical cyclone (TC) intensity and structure change. The specific focus is an improved understanding of TC upper-level outflow layer processes and dynamics. This will be investigated in a comprehensive manner using the observations obtained during the TCI field phase in 2015 and high-resolution tropical cyclone models. Our ultimate goal is to improve the prediction of tropical cyclone intensity change, especially rapid intensification (RI) and rapid decay (RD) as well as TC structural changes that are hypothesized to occur through synergistic interactions with outflow.

Accurate prediction of tropical cyclone intensity remains one of the greatest challenges in meteorology today. Previous research programs and field campaigns (e.g., CBLAST, 2002-2004; TCSP, 2005; NAMMA, 2006; TPARC/TCS08, 2008; ITOP/TCS10, 2010, GRIP, 2010, HS3, 2012-2014) have focused on mechanisms in the boundary layer, mid-troposphere and convection, large-scale environment, and ocean mixed layer, all of which impact TC development and intensification to varying degrees. However, the upper-level TC outflow region (Fig. 1) remains relatively unexplored. This is thought to be a critical region as changes in the TC outflow can directly cause changes in the TC secondary (in-up-out) circulation. TCs intensify through enhanced radial inflow, which subsequently allows for more heat, moisture and high angular momentum air to be transported into the inner-core, which in turn allows for more vigorous deep convection there. Balance must be maintained between the inflow, upward, and outflow branches of the secondary circulation, and therefore changes in one branch will directly impact the other branches. Remote sensing and in-situ dropsonde (providing relatively rare direct wind, temperature and humidity) measurements of the outflow layer taken during TCI will provide a great opportunity to understand the role of this largely unexplored portion of a TC.

*Figure 1: Tropical cyclone schematic depicting the 3-D flow (including primary and secondary circulations), as well as the focal region (yellow box) for recent field campaigns. (From NASA)*

**Science Objectives**

The importance of the hurricane outflow layer in affecting both storm motion (Flatau and Stevens 1993) and structure (Holland and Merrill 1984) has been known for some time. Past observational studies have documented that intensifying TCs have outflows that link to the synoptic-scale upper-level flow, while non-intensifying TCs have no such link (Merrill 1988). Recent research has further demonstrated that intensification is favored in regions where the upper-level inertial stability is small (Rappin et al. 2011). Additionally, eddy flux convergences of absolute angular momentum at upper levels from mid-latitude troughs can further affect the outflow layer structure and TC intensity changes in these low inertial stability regions (Merrill 1989; Molinari and Vollaro 1989). The induced secondary circulation from the upper-level outflow can be important depending on the outflow layer characteristics. Of special interest to TCI is the characteristic for the majority of TC outflow to occur in the form of outflow jets directed preferentially in different quadrants of the TC depending on the nature of the environmental interactions. Additionally, there is evidence suggesting that outflow layer advective processes may alter the outflow layer moisture distribution, including linkages via forced subsidence with mid- and low-level moisture variations.

Rapid intensification events are typically associated with expansion and/or intensification of the TC’s upper-level outflow structure in the form of outflow jet streaks, as inferred from geostationary satellite cloud-track winds. Indeed, continuity demands that the upper-level outflow branch of the TC’s secondary circulation increase in concert with the increasing inner-core ascent and boundary layer inflow of the intensifying vortex. However, it is unknown whether the outflow branch and/or the inflow/ascent branch drive the intensification of the secondary circulation and the associated spin-up of the TC inner core.

There are two conceptual paradigms concerning the role of the outflow branch in driving the secondary circulation. The first paradigm is the concept of *active outflow*, in which an environmental feature such an upper-level trough forces the TC outflow layer to change, inducing subsequent changes in the inflow/ascent branch of the secondary circulation. For example, Nong and Emanuel (2003) advocate that vortex internal processes (e.g. eyewall replacement cycles) respond to external forcing by the outflow layer. In this sense, the outflow layer actively forces changes in the low level vortex. The second paradigm is the concept of *passive outflow*, in which changes in the inner core convection and inflow layer govern the secondary circulation, inducing subsequent changes in the outflow branch of the secondary circulation. Along these lines, Sang et al. (2008) advocate that deep convection and boundary layer processes are dominant, and that the outflow layer responds passively to these processes.

In nature, the rapid intensification of a TC likely does not take place in a purely active or passive outflow scenario, but rather changes to *both* the outflow and inflow/ascent branches drive the evolution of the secondary circulation. The relative roles of the outflow and inflow/ascent branches in driving the time-evolution of the secondary circulation are poorly understood, both in general and on a storm-by-storm basis. New research is required to elucidate the connections between the outflow and inflow/ascent branches of the secondary circulation, and how they vary as a function of the vortex characteristics and TC environmental characteristics in realistic scenarios.

We have identified three key TCI science hypotheses focused on the TC outflow layer.

1. Tropical cyclone intensity is primarily influenced by environmental effects and interaction with the TC. Processes that are thought to be especially relevant for this hypothesis include: eddy angular momentum fluxes, spatial and temporal organization of outflow owing to environmental potential vorticity, and the feedback between the outflow and environment via secondary circulations. Observations of outflow thermodynamic and kinematic characteristics are especially important for this hypothesis. Observations at the interface between the outflow and upper-level environmental features will be crucial. The interactions of mid-latitude troughs, upper-level closed cyclonic circulations, and pre-existing convective outflow will be important.
2. Tropical cyclone intensity is primarily influenced by internally-forced outflow. Processes that are thought to be especially relevant for this hypothesis include: diurnal forcing of convection, diabatic forcing of the outflow layer, outflow self-stratification, and cloud-radiative interactions with the outflow layer. Observations of thermodynamic and kinematic properties of the inflow and ascent branches of the secondary circulation, as well as the air-sea interface, are relevant for this hypothesis.
3. The predictability of tropical cyclone intensity, structure, and its outflow can be enhanced through assimilation of TCI observations in sensitive regions in the inner core, environment, and outflow regions. Observations within and outside sensitive regions will be important to assess and understand the impact. Initial condition sensitivity can be assessed using ensemble-or adjoint-based methods.

**Overview of project observing systems**

TCI is an Office of Naval Research Direct Research Initiative collaborative experiment with the Naval Research Laboratory, industry, and Universities. The TCI experiment will take place over the Atlantic, Gulf of Mexico, and potentially the Eastern Pacific when a storm is approximately in range (within 900 nm) of an aircraft site. Key field observations will be taken from the NASA WB-57 aircraft. The sensors carried by the WB-57 are expected to include the High Definition Sounding System (HDSS) Dropsondes and the Hurricane Imaging Radiometer (HIRAD). The HDSS deploys eXpendable Digital Dropsondes (XDD) with a dual Automated Dropsonde Dispenser (ADD) to measure air temperature, pressure, relative humidity, horizontal wind speed, wind direction, and sea-surface temperature. HIRAD is an airborne passive microwave radiometer to collect ocean surface wind speeds in tropical cyclones.

The HDSS can deploy 90 sondes per flight and has 4 antenna mounted on the aircraft for communication to the aircraft. Satellite communication links to ground teams to control the HDSS payload and retrieve sounding data. The data will then be presented in quick-look Skew-T format and will be post-processed once the aircraft lands. There are approximately 1000 sondes available for use during TCI. Additionally, Dual High Definition (HD) Airborne Cloud Imager (ACI) cameras are mounted forward and aft to capture XDDs leaving the drop tubes and record daytime clouds.

HIRAD is an airborne C-band passive microwave radiometer designed to retrieve ocean surface wind speeds in hurricanes. Its view of a wide swath (~50-75 km wide, when flown on high-altitude aircraft around 60,000 feet) enables mapping of the hurricane’s wind field. Wind speeds can be retrieved over a range from approximately 15 m/s to greater than 70 m/s. That is, HIRAD is appropriate for mapping the surface wind speed in tropical storms and hurricanes, up through category five.

**References**

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