MATURE STAGE EXPERIMENT
Science Description

Experiment/Module: Rainband and Secondary Eyewall Formation (SEF) Module

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Requirements: Categories 2–5

Plain Language Description: This module will sample the structure of long, spiral bands of rainfall (rainbands) that often extend outward from the eyewall of strong hurricanes out to very large distances from the center. These rainbands, often containing mixtures of strong thunderstorms and lighter rainfall that can cover huge areas, are thought to affect the structure and intensity of the hurricane within which they are embedded. The data from this module will seek to explore these structures and their potential relationship with hurricane structure and evolution.

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: Mature TCs often have an organized rainband complex outside of the eyewall (e.g., Willoughby et al. 1984). This prominent complex contains multiple spiral rainbands that make up much of the storm's area and total precipitation, and thus has impacts on the evolution of storm intensity, internal structure, and size; but the exact impacts are not yet fully known. The rainband complex involves an interaction of processes occurring on scales ranging from the microscale to the environment scale. Some previous studies suggest that the rainband complex can have competing effects, such as having different pathways for strengthening or weakening the TC intensity and potentially leading to the formation of a secondary eyewall. Better and more observations of rainbands are needed to examine their impacts, improve model representation, and improve forecasts of storm evolution.

Background: Willoughby et al. (1984) described rainbands that organize into a Stationary Band Complex (SBC) when the storm is embedded in environmental wind shear. The SBC is a wavenumber-1 structure that remains quasi-stationary relative to the storm center despite the storm motion. Hence and Houze (2012) confirmed the SBC precipitation structures in a climatology of TC rainbands observed by the TRMM Precipitation Radar. In this complex, isolated or connected convective cells are initiated and grow in the right-of-shear half (Didlake and Houze 2013a; Riemer 2016). Downwind in the left-of-shear half, the rainband complex is predominantly stratiform precipitation. Here, ice crystals produced by the upwind active convection are advected downwind and fall out in a broad, increasingly homogeneous precipitation band (May and Holland 1999; Didlake and Houze 2013b). When the environmental wind shear is weak, a stationary rainband complex can still form and have the same organization relative to the storm track motion vector (Corbosiero and Molinari 2003).

Barnes et al. (1983) showed that upwind convective cells are sustained by low-level inflow of high-θ_e air that turns upward into an intense buoyant updraft. This in-up-out circulation is the most frequently occurring circulation pattern in convective rainband updrafts and occurs most frequently in the downshear storm quadrants (Barron et al. 2022). These updrafts can build a midlevel tangential wind jet (Hence and Houze 2008). Downdrafts driven by negative buoyancy and precipitation drag can bring low-θ_e air downward into the boundary layer on the radially inward side of the rainband (Powell 1990a,b; Didlake and Houze 2009; Alland et al. 2021a, b), which possibly ventilates the eyewall circulation and decreases storm intensity. Modeling studies showed evidence of this ventilation pathway by the rainband complex (e.g., Wang 2009; Sawada and Iwasaki 2010a,b; Li and Wang 2012a). Convective cell updrafts tend to become more buoyant with increasing radius due to the increasing background convective available potential energy (Didlake and Houze 2013a; Bogner et al. 2000). Other observational studies also document varying structures and circulation patterns for rainband convective cells occurring at larger radii, suggesting that buoyancy effects rather than effects of the vortex shaped their convective-scale structures (Barnes et al. 1991; Yu and Tsai 2013; Tang et al. 2014, 2018).

Past observations and modeling studies (May et al. 1994; May and Holland 1999; Franklin et al. 2006) show that downwind stratiform portions of a rainband complex exhibit weak vertical velocities that are organized into net upward transport in mid- and upper levels and net downward transport in lower levels. Didlake and Houze (2013b) found in Hurricane Rita that within the stratiform cloud layer, upward transport associated with latent heating travelled radially outward along lines of constant angular momentum. Beneath the cloud layer, latent cooling from sublimation, melting, and evaporation created horizontal buoyancy gradients that induced a mesoscale descending inflow pattern similar to that of the trailing-stratiform region of a mesoscale convective system (Houze 2004). The mesoscale descending inflow advected angular momentum inward and contributed to the broadening of the storm's tangential wind field, as seen in Bell et al. (2012). In idealized model simulations, Moon and Nolan (2010) demonstrated that a similar midlevel inflow pattern occurs as a dynamic response to stratiform heating in a vortex circulation, and Yu and Didlake (2019) showed that this response is amplified when the rainband-like heating remains stationary relative to the vortex center.

A prominent rainband complex is often a precursor to secondary eyewall formation (SEF); Vaughan et al. (2020) found that 79% of SEF cases globally are preceded by the presence of an organized rainband complex. After SEF, an eyewall replacement cycle usually follows, which can lead to fluctuations in storm intensity (Sitkowski et al. 2011). Diabatic heating from rainband convection acts to spin up the outer core wind field, which generally precedes SEF (Smith et al. 2009; Rozoff et al. 2012; Zhang et al. 2017; Wunsch and Didlake 2018; Fischer et al. 2020). These local sources of enhanced vorticity and diabatic heating may also project onto the azimuthal mean. Several hypotheses have been proposed for how these azimuthally-averaged fields (that result from rainband convection) lead to boundary layer interactions and eventual SEF (Wu et al. 2011; Huang et al. 2012, 2018; Abarca and Montgomery 2013; Kepert 2013, 2018). One such hypothesis, supported by observations (Didlake et al. 2018) and modeling studies (Yu et al. 2021, 2022), involves a mesoscale descending inflow developing within the downwind stratiform portion of the rainband complex, which triggers new convective updrafts through mesoscale cold-pool dynamics. These updrafts then generate sufficient latent heating and potential vorticity that axisymmetrizes and forms the secondary eyewall.

Alternatively, SEF may also result from unbalanced boundary layer processes where agradient forcing in the boundary layer can induce a region of convergence outward of the primary eyewall and generate convection upward from the boundary in a thermodynamically favorable environment (Huang et al. 2012, 2018; Abarca et al. 2016). In a similar vein, unbalanced boundary layer processes may also lead to the generation of a corner-flow region at the base of the primary eyewall (e.g., Smith and Montgomery 2015; Fischer et al. 2020). The outflow emanating away from the base of the eyewall near the top of the boundary layer associated with this corner-flow can lead to a band of convergence and rainband development (Smith et al. 2021), and potentially SEF (Fischer et al. 2020). Considering the intrinsic unbalanced nature of the TC boundary layer, it is still unclear why such an SEF pathway is not observed more frequently or which environmental, vortex, and convective characteristics favor one SEF pathway over another.

Goal(s): To improve understanding of the dynamic and microphysical processes of the mature rainband complex and role in storm evolution.

Hypotheses:

1. The rainband complex has dynamical and microphysical structures that are repeated across mature storms. Certain patterns of the convective and stratiform rainband features can be tied to distinct trends in TC intensity and structure, and involve processes suggested by previous studies.
2. Specific patterns of rainband convection determine if secondary eyewall formation will occur based on the dynamical nature of the rainband structures. One hypothesized precursor pattern is a mesoscale descending inflow embedded within the downwind stratiform portion of a rainband complex. Such rainband convection could be tied to boundary layer processes that further strengthen the developing secondary eyewall.

Objectives:

1. Sample the wind and precipitation structures of both convective and stratiform regions of the rainband complex in varied storms across varied shear and moisture environments.
2. Sample the microphysics of the convective-to-stratiform transition and the downwind stratiform regions of the rainband complex.
3. Validate key features linked with different hypotheses of rainband-vortex interaction.
4. Identify which types of rainband structures, such as connected convective cells in the upwind rainband complex or a mesoscale descending inflow in the downwind stratiform complex, uniquely lead to secondary eyewall formation.

Aircraft Pattern/Module Descriptions (see *Flight Pattern* document for more detailed information): This module focuses on mature hurricanes (e.g., category 2 or stronger) with a well-defined eye (as seen in visible, infrared, and microwave satellite imagery) and a clear rainband complex (as seen in microwave satellite imagery or radar). Sampling can be achieved in combination with the P-3 Doppler Wind Lidar, sUAS, P-3 and G-IV dropsondes.

P-3 Pattern #1:
This is a stand-alone module that takes ~45 min to complete. The module is a curved leg that follows a curved rainband complex. This curved-leg module replaces a straight, downwind leg in the figure-4 or butterfly survey pattern, and can be performed multiple times in a mission. The module targets the middle or downwind stratiform regions of the complex.

G-IV Pattern #1:
This pattern is a circumnavigation that samples the TC environment outside of the rainband complex.

Links to Other Mature Stage Experiments/Modules: This module can generally be flown in conjunction with TDR Experiment survey patterns, with the addition of a spiral pattern added onto the survey. The module can also be flown in conjunction with the *Early Stage* Stratiform Spiral Module (SSM).

Analysis Strategy: Employing the RCM requires minor tweaks to existing survey patterns for the potential of large reward. The downwind legs of a survey pattern are typically a straight line after a radial cross, which sets up the next rotated radial cross in the shortest time possible. These legs usually cut through the rainband complex, capturing radar observations of the rainbands. But as a result of the straight-leg geometry, frequently only part of the spiral rainband complex lies within P3 Tail Doppler radar (TDR) range. The RCM ensures that the curved rainband complex remains within adequate range of the radar by using a curved flight path.

While a straight, level flight track is most optimal for TDR wind retrieval, the HRD wind retrieval algorithm is robust to small bank angles and can provide useful retrievals from minimally curved tracks. The RCM requires the smallest possible aircraft bank angle to effectively increase the amount of usable radar data. Lengths of the radial cross legs would need to be adjusted to match the planned endpoints of the RCM leg.

The RCM targets the midband convective-to-stratiform transition region and downwind stratiform regions of the rainband complex. In these regions, the convection becomes more organized into mesoscale structures that dynamically interact with the overall vortex and surrounding environment. Since downwind legs of regular survey patterns do not fully azimuthally cover the outer rainband regions, these survey patterns may be adjusted to ensure that the middle and downwind rainband portions are captured. This can be either beforehand if a microwave satellite overpass just prior to the mission reveals a clear rainband complex. Or it may be done in-flight if a rainband complex appears on LF or reconnaissance radar. The RCM may also be executed at the beginning or end of the mission if it can reasonably be added to the planned survey pattern.

The HRD wind retrieval software will be used to recover the wind and precipitation fields of the observed rainband complex. After several missions, the increased amount of rainband observations will be analyzed in both case studies and composite studies to better understand their role in TC evolution. Statistics from the composite studies will also be used for model evaluation.

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