2019 NOAA/AOML/HRD Hurricane Field Program - IFEX

MATURE STAGE EXPERIMENT
Science Description

Experiment/Module: Secondary Eyewall Formation Module

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Requirements: Categories 2–5

Mature Stage Science Objective(s) Addressed:

1) Collect observations targeted at better understanding internal processes contributing to mature hurricane structure and intensity change [*IFEX 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 [*IFEX Goals 1, 3*]

Motivation: Secondary eyewall formation (SEF) and eyewall replacement cycles (ERCs) frequently occur during the mature phase of the tropical cyclone (TC) lifecycle. These processes typically result in a halting of the intensification of a TC, and occasionally lead to a temporary weakening as the secondary eyewall becomes the dominant eyewall (Sitkowski et al., 2011). Additionally, they typically coincide with a significant broadening of the wind field, increasing the total kinetic energy of the storm and thus the risks from widespread wind damage and storm surge. Statistical analysis of a 10-year (1997-2007) dataset shows that 77% of major hurricanes (120 knots or higher) in the Atlantic Ocean, 56% in the eastern Pacific, 81% in the western Pacific, and 50% in the Southern Hemisphere underwent at least one ERC (Hawkins and Helveston, 2008). Despite the relative frequency of their occurrence, operational forecasting of SEF/ERCs remains a great challenge, partly since there is no consensus on the mechanisms responsible for SEF or ERC.

Background: There are a wide variety of studies that aim to understand SEF and ERC with different emphases on the internal dynamics and external environmental forcing. The axisymmetric balanced flow, constrained by heat and tangential momentum forcing, generally satisfies gradient wind and hydrostatic balance above the boundary layer (BL) (Abarca and Montgomery, 2013). From the perspective of diabatic forcing, Rozoff et al. (2012) proposed that a sustained azimuthal-mean latent heating outside of the primary eyewall could lead to SEF. This hypothesis was supported by the numerical simulations given by Zhu and Zhu (2014). In a similar sense, diabatic heating/cooling associated with rainbands plays an important role in the structure and intensity change of the storm (Wang 2009; Li et al 2014; Moon and Nolan 2010; Didlake and Houze, 2013a, b) and thus they may also contribute to the SEF/ERC. Didlake and Houze (2013a) proposed that there exists a critical zone where sufficiently high vertical shear of the radial wind can limit the altitude of the convectively induced supergradient flow, leading to low-level convergence in this radial zone and allowing the convection to develop into a secondary eyewall. Corbosiero and Torn (2016) proposed a hypothesis that an increase of convergence induced by the cold pool that formed from convectively-driven downdrafts and low-level radial inflow could enhance rainband convection and lead to SEF. Recently, Didlake et al. (2018) observed persistent widespread updrafts that were linked to mesoscale cold-pool dynamics in a broad stratiform rainband. They hypothesized that these mesoscale kinematics played a critical role in initiating axisymmetric SEF processes. The roles of convective and stratiform heating profiles in rainbands in modifying hurricane structure and intensity, and potentially SEF, is an area of ongoing research.

Montgomery and Kallenbach (1997) proposed that vortex Rossby wave (VRW) interaction with the mean flow may contribute to SEF. VRWs, supported by the radial vorticity gradient outside of the radius of the maximum wind (RMW), propagate from the primary eyewall radially outward until they reach their stagnation radius. At this stagnation radius, inward-moving cyclonic eddy momentum may contribute to SEF. The role of VRWs in SEF is further examined in high-resolution hurricane simulations by Abarca and Corbosiero (2011). Judt and Chen (2010), by contrast, downplayed the importance of VRWs, and instead attributed the large accumulation of convectively generated PV through eddy heating in the rainband region as an essential factor for SEF.

In contrast to the balanced arguments discussed above, unbalanced dynamics in the BL have also been recognized as an important element in SEF. In this framework, the axisymmetric flow in the BL does not satisfy gradient wind and thermal wind balance. Several studies (Wu et al., 2011; Huang et al., 2012; Abarca and Montgomery, 2013) have pointed out that the precursors of SEF include the broadening of the tangential wind field and the intensification of inflow in the BL, followed by development of supergradient winds and an enhanced horizontal convergence. In-situ observations also demonstrated this existence of supergradient flow (Didlake and Houze, 2011; Bell et al. 2012). Kepert (2013) specifically examined the role of the BL in a balanced vortex framework. He proposed that the BL contributed to the SEF and ERC through a positive feedback mechanism that involves a local enhancement of the radial gradient of vorticity, frictionally forced updraft and convection. Moon et al. (2010) attributed the local vorticity enhancement from processes such as rainband convection.

To test the varying mechanisms proposed to explain SEF and ERC, it is important to obtain kinematic and thermodynamic observations near the eyewall and rainbands. In particular, since most previous analyses focus on azimuthally averaged quantities, it is important to obtain adequate azimuthal and radial sampling both near the primary eyewall and a potentially-developing secondary eyewall. For example, Abarca et al. (2016) pointed out the lack of data particularly at radial distance between 120-200 km in Hurricane Edouard (2014). Additionally, some measure of kinematic and thermodynamic structures along a rainband/developing secondary eyewall can be used to evaluate the along-band structures and dynamics that may be associated with the pertinent axisymmetric features (Wang 2009; Moon and Nolan 2010; Didlake and Houze 2011, 2013a,b; Didlake et al. 2018). Observations sampled through this module can be used to evaluate the different proposed mechanisms of SEF and ERC. Data-impact studies on TC analyses and forecasts can also be conducted using the OSSE approach to find optimal sampling strategies for the prediction of SEF/ERC. If this module is flown every 12 h (e.g., in conjunction with the TDR experiment), then the temporal resolution will provide an opportunity to evaluate the importance of the various proposed mechanisms at different stages in the evolution of the secondary eyewall.

MATURE STAGE EXPERIMENT
Science Description

The dataset from this module eventually will benefit our understanding of the dynamic and physical processes that are responsible for SEF/ERC.

The main objectives of the SEF/ERC module are:

- Perform analyses with sampled observations to examine key factors that are responsible for SEF/ERCs;
- Validate key features linked with different hypotheses of SEF/ERCs using observations;
- Conduct OSE/OSSE studies to optimize sampling strategies for improving SEF/ERC predictions;
- Improve understanding of the dynamic and physical processes of SEF/ERCs.

Hypotheses:

1. Secondary eyewall formation may be determined by the dynamical nature of rainband convection. Different convective and stratiform rainband features have varied dynamics that may provide unique and important contributions to different but valid SEF processes. Such rainband convection could be tied to boundary layer feedback processes that further strengthen the developing secondary eyewall.
2. Secondary eyewall formation could be attributed to an unbalanced boundary layer (BL) spinup paradigm. The precursors of SEF include the broadening of the tangential wind field and the intensification of inflow in the BL, followed by development of supergradient winds and an enhanced horizontal convergence.

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. Sampling can be achieved in combination with the P-3 Doppler Wind Lidar, Coyote UAS, P-3 and G-IV dropsondes.

P-3 Pattern 1: This pattern is a combination of a Rotated Figure-4 with an inward spiral leg, where the spiral leg follows a prominent rainband complex that appears likely to initiate secondary eyewall formation.

P-3 Pattern 2: This pattern is a combination of a Rotated Figure-4 with a circumnavigation in the moat region, which targets both the moat and the strengthening secondary eyewall after it has apparently formed.

G-IV Pattern 1: This pattern is a circumnavigation that samples the TC environment outside of the rainband complex before or during secondary eyewall formation.

Links to Other Mature Stage Experiments/Modules: This module can generally be flown in conjunction with TDR Experiment survey patterns, with the addition of either a spiral pattern (Pre-SEF) or moat circumnavigation (Post-SEF) added onto the survey. The module can also be flown

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in conjunction with the following *Mature Stage* experiments: TCDC Experiment, TC in Shear Experiment, Synoptic Flow Experiment, and NESDIS Ocean Winds.

Analysis Strategy: Data collected by the pre-SEF module can be used to diagnose different roles in SEF. Specifically, rainband horizontal/vertical velocities can be calculated from Doppler radar and dropsonde measurements; gradient wind (and departures thereof) within and above the BL can be calculated from dropsondes; tangential winds and vorticity can be calculated from dropsonde, Doppler radar, flight-level, and DWL measurements; and moist static energy calculation, can be calculated from dropsondes. Observations that are collected can also be used to conduct data impact studies as well as provide insights for OSSE studies. Data measured by the post-SEF module would be useful to diagnose the formation and characteristics of the moat region and its role in ERC.

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