MATURE STAGE EXPERIMENT
Science Description

Experiment/Module: Ventilation Module

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Requirements: Categories 2–5

Plain Language Description: Ventilation occurs when drier and/or cooler environmental air intrudes into a vertically-sheared, tilted tropical cyclone (TC). Ventilation pathways include lateral intrusion (radial ventilation) and downward intrusion (downdraft ventilation) of dry and/or cool air. Both pathways may inhibit intensification. This module aims to collect observational data to study ventilation pathways, validate model simulations of ventilation in TCs, and assess the link between ventilation and intensity changes.

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: There are two main areas of motivation. First, ventilation has been predominately studied theoretically and in model simulations, and there has been less systematic evaluation of ventilation using aircraft observations. Such observations can help validate ventilation pathways in model simulations, including forecast models, and assess how ventilation affects TC intensity. Second, moderately-sheared TCs have a wide range of intensity change responses, which may be influenced by the variability in ventilation effectiveness associated with both environmental and internal factors. Understanding how ventilation differs among moderately-sheared TCs may provide insight into why certain TCs still intensify, while others do not, in such environments.

Background: Ventilation has been hypothesized to be an important control on TC intensity, linking how vertical wind shear and dry air in the environment affect TC convection and intensity change. There are two pathways by which ventilation may affect the TC. The first pathway is radial ventilation, where low-equivalent potential temperature (θ_e) air above the boundary layer is advected inward into the TC (Tang and Emanuel 2010; Alland et al. 2021a). Idealized simulations show this pathway occurs upshear, generally between 4–10-km height, and left-of-shear, generally between 1–4-km height (Alland et al. 2021a). Upshear, radial ventilation is associated with advection caused by the tilt of the vortex (Alland et al. 2021a), and left-of-shear, radial ventilation is associated with descending radial inflow in the stratiform rainband (also known as the stationary band complex) (Didlake and Houze 2013). The second pathway is downdraft ventilation, where low-θ_e air is deposited into the boundary layer through downdrafts (Riemer et al. 2010, 2013; Alland et al. 2021b). Idealized simulations show this pathway occurs left-of-shear and upshear, cyclonically downstream of the TC vertical tilt direction in the stratiform rainband (Alland et al.

2021b) and inner-core convection (Yu et al. 2023). Downdraft ventilation can be especially effective in weakening a TC if it occurs in or near the eyewall, and the low-θ_e air is entrained into the top of the inflow layer, since low-θ_e air has less opportunity to recover via surface fluxes (Wadler et al. 2021). Both ventilation pathways can reduce the inner-core vertical mass flux and inhibit intensification.

Ventilation, and its effects on TC intensity, likely depends on a number of factors, such as the vertical wind shear magnitude and structure (Tang and Emanuel 2012; Finocchio et al. 2016; Onderlinde and Nolan 2016; Ryglicki et al. 2019); the environmental moisture, particularly upshear (Zawislak et al. 2016; Rios-Berrios and Torn 2017); surface fluxes and the intensity/structure of the TC itself (Finocchio and Rios-Berrios 2021; Alland and Davis 2022); and others. A combination of these interacting factors may determine whether a TC is ultimately resilient and intensifies, through vortex realignment (Zhang and Tao 2013) or restructuring (Rios-Berrios et al. 2018).

Goal(s): The goals of this module are to better understand ventilation pathways, validate model simulations of ventilation in sheared TCs, and assess the link between ventilation and intensity changes.

Hypotheses:

1. Radial ventilation (the inward flux of relatively low-θ_e air) occurs upshear, generally between 4–10-km height, and left-of-shear, generally between 1–4-km height.
2. Upshear, radial ventilation is associated with direct advection by the tilted vortex, and left-of-shear, radial ventilation is associated with descending radial inflow in the stratiform rainband.
3. Downdraft ventilation (the downward flux of relatively low-θ_e air) occurs left-of-shear and upshear in the stratiform rainband and inner-core (eyewall) convection, depositing low-θ_e air into the inflow layer.
4. Upshear, radial ventilation is larger when the environment is drier and/or when the vortex tilt is larger.
5. Left-of-shear, radial ventilation is larger when the stratiform region of the stationary band complex is more established in moderately-sheared, tilted TCs.
6. Both radial and downdraft ventilation are more effective at inhibiting TC intensification when the TC is weaker (smaller surface fluxes), smaller, and/or when ventilation occurs closer to the eyewall.
7. Minimal ventilation increases the likelihood of rapid intensification.

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Objectives:

1. Collect observations to diagnose radial and downdraft ventilation.
2. Evaluate the radial and downdraft ventilation structure relative to pertinent aspects of the TC structure, like the stratiform rainband and TC tilt, and environment, like the vertical wind shear and moisture profile.
3. Compare observations of ventilation with model simulations from both idealized studies and real forecasts.
4. Connect ventilation to intensity changes via ventilation's effects on the convective structure and inner-core vertical mass flux.

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

G-IV Pattern #1: Double circumnavigation pattern with additional leg on the right-of-shear side. If hexagonal pattern, inner circumnavigation has added dropsonde releases at midpoints between vertices.

P-3 Pattern #1: Rotated figure-4 pattern centered on the estimated low-level center. For each leg, release dropsondes at 105 n mi (end point), 60 n mi, 30 n mi, and radius of maximum wind (RMW) along each of the radial legs.

P-3 Pattern #2: Butterfly pattern centered on the estimated low-level center. Dropsonde release pattern for each leg is the same as P-3 Pattern #1.

P-3 Pattern #3: Standard circumnavigation pattern with added drops at the RMW.

Coordination of aircraft: Ideally, the G-IV Pattern and one of the P-3 patterns should be flown as close in time to one another as possible.

Targets of interest and environmental setup: TCs in moderate vertical wind shear (4.5–11 m s^{-1}; Rios-Berrios and Torn 2017), TCs that are tilted, and TCs that have significant dry air (e.g., Saharan Air Layers) in their vicinity are of primary interest.

Links to Other Mature Stage Experiments/Modules: The Ventilation Module may be flown with any early- or mature-stage modules that contain a G-IV circumnavigation and P-3 rotated figure-4, butterfly, or circumnavigation patterns that provide sampling in all quadrants within ~105 n mi. Specific mature-stage modules include Tropical Cyclone Boundary Layer, Rainband and Secondary Eyewall Formation, Ocean Winds, and Tail Doppler Radar missions.

Analysis Strategy: The analysis strategy will make use of dropsonde and TDR data. It is necessary to have coincident wind and thermodynamic data to calculate the ventilation. Additionally, perturbations from azimuthal averages are required, so it is essential to have sampling in all sectors to be able to compute an accurate azimuthal average. In a frame of reference translating with the TC, the radial ventilation may be quantified as $u'\theta_e' > 0$ for $u' < 0$, and downdraft ventilation may be quantified as $w\theta_e' > 0$ for $w < 0$, where u is the radial wind, w is the vertical wind, and primes denote perturbations from the azimuthal mean. The ventilation structure will be studied through vertical profiles and horizontal plots of these ventilation quantities. The TDR will be used to examine the wind structure within the stratiform rainband, particularly the descending radial inflow and downdraft structures, and in the eyewall, particularly the downdraft structure on the upshear side. Additionally, the TDR will be used to estimate the vortex tilt and the inner-core vertical mass flux. Environmental moisture and vertical wind shear profiles will be estimated through G-IV drops on the periphery of the TC or, if not available, model analyses or short-term forecasts. When available from coincident experiments/modules (e.g., TCBL, Ocean Survey Experiment, and CHAOS), dropsondes, AXBTs, IRsondes, and saildrone data may be used to calculate surface enthalpy fluxes to assess recovery of low-θ_e air (e.g., Zhang et al. 2017).

Ventilation observations will be compared with forecast model output (e.g., HAFS) and other model simulations.

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