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 tropical cyclone (TC). Ventilation pathways include lateral intrusion (radial ventilation) and downward intrusion (downdraft ventilation) of dry and/or cool air. Both pathways may weaken a TC or delay its intensification. This module aims to collect observational data to study ventilation pathways, validate model simulations of ventilation in sheared 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, while ventilation has been studied theoretically and in model simulations, there has been less systematic evaluation of ventilation using observations, particularly 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. 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 vertical wind shear magnitude (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. Minimal ventilation, or resiliency against ventilation, increases the likelihood of rapid intensification.

Objectives:

1. Collect observations to diagnose radial and downdraft ventilation, specifically upshear and left-of-shear.

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 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 two additional radial legs offset from the center. Both circumnavigations are centered on the estimated low-level center. The outer circumnavigation is a standard octagonal circumnavigation at 1.75x the radius of the stationary band complex (r_{SBC}), or nominally 90 n mi (167 km) if r_{SBC} is unknown. The inner circumnavigation is also an octagonal circumnavigation at 1.25x r_{SBC}, or nominally 60 n mi (111 km) if r_{SBC} is unknown, with added sampling downshear-left to upshear-right. The inward leg is to the right-of-shear point midway between the radius of maximum wind (r_{max}) and r_{SBC}, or nominally 30 n mi (56 km). The outward leg is to the upshear vertex of the inner circumnavigation.

P-3 Pattern #1: Rotated figure-4 pattern centered on the estimated low-level center. For each leg, release dropsondes at $r_{\mathrm{SBC}} - 15$ n mi (28 km), r_{SBC}, and $r_{\mathrm{SBC}} + 15$ n mi (28 km), where the spacing can be adjusted based on the width of the stratiform rainband. Additionally, release a dropsonde just outside the eyewall, nominally at $r_{\mathrm{max}} + 5$ n mi (9 km).

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.

Coordination of aircraft: Ideally, the G-IV Pattern and either 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) 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 links with the following other mature-stage modules: the Rainband Complex Module, the Hurricane Boundary Layer Module, and the Research In Coordination with Operations Small Uncrewed Air Vehicle Experiment. Additionally, there are links to many of the goals and modules in the Analysis of Intensity Change Processes Experiment, so the Ventilation Module can be applied/adapted to early-stage TCs.

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 optimal to have sampling in all sectors at roughly constant radii 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, cross sections, 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, which is hypothesized to affect the ventilation structure, and the inner-core vertical mass flux, which is hypothesized to be affected by ventilation. 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 modules, AXBTs and IRsondes may be used to calculate surface enthalpy fluxes to assess recovery of low-θ_e air.

This analysis will be compared with idealized simulations of sheared TCs, and can be repeated for forecast model output (e.g., HWRF, HAFS, COAMPS-TC, MPAS) to compare with observations.

References:

Alland, J. J., and C. A. Davis, 2022: Effects of surface fluxes on ventilation pathways and the intensification of Hurricane Michael (2018). *J. Atmos. Sci.*, **79**, 1211–1229, https://doi.org/10.1175/JAS-D-21-0166.1.

——, B. H. Tang, K. L. Corbosiero, and G. H. Bryan, 2021a: Combined effects of midlevel dry air and vertical wind shear on tropical cyclone development. Part II: Radial ventilation. *J. Atmos. Sci.*, **78**, 783–796, https://doi.org/10.1175/JAS-D-20-0055.1.

——, ——, ——, and ——, 2021b: Combined effects of midlevel dry air and vertical wind shear on tropical cyclone development. Part I: Downdraft ventilation. *J. Atmos. Sci.*, **78**, 763–782, https://doi.org/10.1175/JAS-D-20-0054.1.

Didlake, A. C., and R. A. Houze, 2013: Dynamics of the stratiform sector of a tropical cyclone rainband. *J. Atmos. Sci.*, **70**, 1891–1911, https://doi.org/10.1175/JAS-D-12-0245.1.

Finocchio, P. M., and R. Rios-Berrios, 2021: The intensity- and size-dependent response of tropical cyclones to increasing vertical wind shear. *J. Atmos. Sci.*, **78**, 3673–3690, https://doi.org/10.1175/JAS-D-21-0126.1.

——, S. J. Majumdar, D. S. Nolan, and M. Iskandarani, 2016: Idealized tropical cyclone responses to the height and depth of environmental vertical wind shear. *Mon. Wea. Rev.*, **144**, 2155–2175, https://doi.org/10.1175/MWR-D-15-0320.1.

Onderlinde, M. J., and D. S. Nolan, 2016: Tropical cyclone–relative environmental helicity and the pathways to intensification in shear. *J. Atmos. Sci.*, **73**, 869–890, https://doi.org/10.1175/JAS-D-15-0261.1.

Riemer, M., M. T. Montgomery, and M. E. Nicholls, 2010: A new paradigm for intensity modification of tropical cyclones: Thermodynamic impact of vertical wind shear on the inflow layer. *Atmos. Chem. Phys.*, **10**, 3163–3188, https://doi.org/10.5194/acp-10-3163-2010.

——, ——, and ——, 2013: Further examination of the thermodynamic modification of the inflow layer of tropical cyclones by vertical wind shear. *Atmos. Chem. Phys.*, **13**, 327–346, https://doi.org/10.5194/acp-13-327-2013.

Rios-Berrios, R., and R. D. Torn, 2017: Climatological analysis of tropical cyclone intensity changes under moderate vertical wind shear. *Mon. Wea. Rev.*, **145**, 1717–1738, https://doi.org/10.1175/MWR-D-16-0350.1.

——, C. A. Davis, and R. D. Torn, 2018: A hypothesis for the intensification of tropical cyclones under moderate vertical wind shear. *J. Atmos. Sci.*, **75**, 4149–4173, https://doi.org/10.1175/JAS-D-18-0070.1.

Ryglicki, D. R., J. D. Doyle, D. Hodyss, J. H. Cossuth, Y. Jin, K. C. Viner, and J. M. Schmidt, 2019: The unexpected rapid intensification of tropical cyclones in moderate vertical wind shear. Part III: Outflow–environment interaction. *Mon. Wea. Rev.*, **147**, 2919–2940, https://doi.org/10.1175/MWR-D-18-0370.1.

Tang, B. H., and K. A. Emanuel, 2010: Midlevel ventilation's constraint on tropical cyclone intensity. *J. Atmos. Sci.*, **67**, 1817–1830, https://doi.org/10.1175/2010JAS3318.1.

——, and ——, 2012: A ventilation index for tropical cyclones. *Bull. Amer. Meteor. Soc.*, **93**, 1901–1912, https://doi.org/10.1175/BAMS-D-11-00165.1.

Wadler, J. B., D. S. Nolan, J. A. Zhang, and L. K. Shay, 2021: Thermodynamic characteristics of downdrafts in tropical cyclones as seen in idealized simulations of different intensities. *J. Atmos. Sci.*, **78**, 3503–3524, https://doi.org/10.1175/JAS-D-21-0006.1.

Zawislak, J., H. Jiang, G. R. Alvey, E. J. Zipser, R. F. Rogers, J. A. Zhang, and S. N. Stevenson, 2016: Observations of the structure and evolution of Hurricane Edouard (2014) during intensity change. Part I: Relationship between the thermodynamic structure and precipitation. *Mon. Wea. Rev.*, **144**, 3333–3354, https://doi.org/10.1175/MWR-D-16-0018.1.

Zhang, F., and D. Tao, 2013: Effects of vertical wind shear on the predictability of tropical cyclones. *J. Atmos. Sci.*, **70**, 975–983, https://doi.org/10.1175/JAS-D-12-0133.1.