2023 NOAA/AOML/HRD Hurricane Field Program - APHEX

EARLY STAGE EXPERIMENT
Science Description

Experiment/Module: Vortex Alignment Module (VAM)

Investigator(s): Michael Fischer, George Alvey, Robert Rogers, Jason Dunion, Paul Reasor, David Nolan (Univ. of Miami), Daniel Stern (NRL), Zeljka Stone (New Mexico Tech Univ.), David Raymond (New Mexico Tech Univ.), Stipo Sentic (New Mexico Tech Univ.), and David Schecter (NorthWest Research Associates)

Requirements: TD, TS, Category 1

Plain Language Description: In early-stage tropical cyclones (TCs), the rate at which a TC intensifies is strongly related to the vertical alignment of a storm's circulation. However, the physical processes responsible for changes in the alignment of a TC circulation are not well understood. This module aims to improve our understanding of the alignment process through the collection of relatively-high frequency observations of the three-dimensional TC structure.

Early Stage Science Objective(s) Addressed:

1. Collect datasets that can be used to improve the understanding of intensity change processes, as well as the initialization and evaluation of 3-D numerical models, particularly for TCs experiencing moderate vertical wind shear [*APHEX Goals 1, 3*].
2. Obtain a quantitative description of the kinematic and thermodynamic structure and evolution of intense convective systems (convective bursts) and the nearby environment to examine their role in TC intensity change [*APHEX Goals 1, 3*].
3. Test new (or improved) technologies with the potential to fill gaps, both spatially and temporally, in the existing suite of airborne measurements in early stage TCs. These measurements include improved three-dimensional representation of the TC wind field, more spatially dense thermodynamic sampling of the boundary layer, and more accurate measurements of ocean surface winds [*APHEX Goal 2*].

Motivation: TC intensity forecast errors are particularly large for events of rapid intensification (RI; Fischer et al. 2019; Trabing and Bell 2020). Although the environmental conditions favorable for RI are well known (Kaplan et al. 2010; Kaplan et al. 2015), storms that rapidly intensify are often located in similar environments as storms that intensify more gradually (e.g., Hendricks et al. 2010). In fact, the largest operational TC intensity forecast errors occur when storms are located in favorable environmental conditions, which suggests knowledge about the TC's vortex and convective structure are important for improved intensity forecasts (Trabing and Bell 2020).

Previous studies have found that an important structural prerequisite for a TC to undergo RI is the existence of a vertically-aligned vortex (Rios-Berrios et al. 2018; Tao and Zhang 2019; Schecter 2020; Alvey and Hazelton 2022; Schecter 2022; Fischer et al. 2023; Stone et al. 2023). However, early-stage TCs often have a wide range of vortex misalignment structures (Fischer et al. 2022) and the physical processes through which a misaligned vortex becomes aligned in nature are not well understood. One reason for this lack of clarity has been the identification of different alignment pathways in numerical modeling simulations and observational case studies. Nevertheless, these studies have largely agreed diabatic processes are important in modifying the local vorticity field during the alignment process. Thus, sampling the precipitation characteristics associated with aligning and non-aligning TCs can help elucidate the specific processes responsible for alignment and how these processes vary depending on the alignment pathway; however, this requires observing strategies tailored to sampling the rapid changes in the TC precipitation and vortex structure associated with changes in TC tilt.

This experiment is designed to better observe the precipitation and vortex processes that drive changes in the TC tilt structure compared to the observations available from standard flight patterns. In turn, an improved understanding of the factors dictating whether a given TC will undergo alignment may help provide advanced warning of subsequent TC intensification and possibly RI.

Background: Nearly all TCs are located in environments with some degree of vertical wind shear (e.g., Rios-Berrios and Torn 2017). The presence of a vertically sheared environmental flow has been shown to be largely unfavorable for TC development and intensification (DeMaria and Kaplan 1994; Riemer et al. 2010; Zhang and Tao 2013; Alland et al. 2021a, b). One reason shear is unfavorable for TC development is because a vertically sheared flow can differentially advect, or misalign, the mid–upper level TC vortex in the downshear direction away from the low-level vortex (e.g., Jones 1995; Reasor et al. 2004; Rios-Berrios et al. 2018; Alvey et al. 2020). In order to maintain thermal wind balance, a tilted TC vortex is characterized by thermal and vertical velocity azimuthal asymmetries, which induces an asymmetric TC precipitation structure (Jones 1995; Boehm and Bell 2021; Schecter 2022). Observational studies have demonstrated that TCs with relatively asymmetric precipitation structures tend to intensify at lesser rates than TCs with more symmetric precipitation structures (e.g., Rogers et al. 2013; Alvey et al. 2015; Tao et al. 2017; Fischer et al. 2018). Thus, the precipitation asymmetries associated with a tilted TC vortex are generally unfavorable for TC intensification (Miyamoto and Nolan 2018; Schecter and Menelaou 2020; Schecter 2022).

A vertically tilted vortex has also been shown to be unfavorable for TC intensification as it provides a pathway for low-entropy environmental air to enter the TC core (e.g., Davis and Ahijevych 2012; Chen et al. 2019; Alland et al. 2021b; Fischer et al. 2023). Such intrusions of low-entropy air can significantly erode the convective organization of the TC inner core, limiting intensification or even resulting in a weakening of the storm (e.g., Fischer et al. 2023). It is therefore not surprising that a number of studies have recently shown the importance of vortex alignment to promote not only a more symmetric precipitation structure, which is favorable for RI, but also increased resilience from surrounding environmental dry air and vertical wind shear (Chen et al. 2019, Alvey et al. 2020; Alvey and Hazelton 2022; Fischer et al. 2023). However, early-stage TCs are often associated with misaligned vortices (e.g., Fischer et al. 2022) and it remains unclear what factors dictate whether a given TC will experience a reduction in vortex tilt and intensify.

This lack of clarity can be partly attributed to findings that multiple pathways to alignment exist. For instance, modeling simulations have demonstrated that a cyclonic precession of the mid-level vortex toward the upshear region of the storm can lead to alignment as the vertically-sheared background flow advects the mid-level circulation toward the low-level TC center (Jones 1995; Finocchio et al. 2016; Munsell et al. 2017). Alternatively, the precession of a mid-level vortex into the upshear-left quadrant of the storm may also lead to alignment through a diabatic vortex merger process driven by strong convection and lower-tropospheric vortex stretching (Rios-Berrios et al. 2018). In other instances, vortex alignment can occur via a vortex reformation event, where robust convection and the associated stretching and tilting of vorticity lead to the generation of a new lower-tropospheric vortex near the location of the mid-level TC center (e.g., Chen et al. 2018; Rogers et al. 2020; Schecter 2020; Alvey et al. 2022; Stone et al. 2023) or the development of a new mid-level circulation above the low-level circulation (Miyamoto and Nolan 2018). Recent observational case studies have suggested increases in sustained convective activity, particularly those associated with a bottom-heavy mass flux profile, promote vortex alignment (e.g., Rogers et al. 2020; Alvey et al. 2022; Stone et al. 2023), but also point toward the need for observational analyses of higher temporal resolution to elucidate the dynamics associated with vortex alignment.

The characteristics of tropical precipitation have been demonstrated to be intimately connected to the thermodynamic characteristics of the environment (Raymond and Session 2007; Raymond et al. 2014; Raymond and Fuchs-Stone 2021). Similarly, the dynamics associated with vortex alignment have been hypothesized to be closely related to the local environmental thermodynamic characteristics, which are influenced by both the background, synoptic-scale environment as well as the balanced response to a misaligned TC vortex (e.g., Gjorgjievska and Raymond 2014; Schecter 2022). For example, Stone et al. (2023) hypothesized the presence of a robust mid-tropospheric vortex and the corresponding balanced thermal anomalies resulted in a region of lower instability-index and high saturation fraction values, which promoted convection characterized by a bottom-heavy vertical mass flux profile during the alignment of Tropical Storm Sally (2020). Similarly, Schecter (2022) found reductions in vortex misalignment and greater rates of TC intensification coincide with an increase in mid-tropospheric relative humidity and lower-tropospheric convective available potential energy (LCAPE) near the lower-tropospheric TC center. Because the local thermodynamic characteristics of the environment dictate the mode and vigor of precipitation and, furthermore, the magnitude of vorticity of an air parcel can only be changed through divergent processes (i.e., convection; Stone et al. 2023), to fully understand how vortex alignment is achieved in nature, it is essential that observations of both the local environment and the TC precipitation structure be collected. Environmental observations must also include details of the kinematic environment to elucidate how vortex misalignment is related to the vertical and horizontal structure of vertical wind shear. The collection of these observations will allow for an examination of how the environmental characteristics differ for aligning and non-aligning TCs, as well as an exploration of how the environment can influence the specific pathway by which vortex alignment is achieved.

Goal(s): Collect aircraft observations of the evolution of the TC vortex misalignment and precipitation structures (e.g., both areal coverage of precipitation and the mode of precipitation), and how the TC environment influences this evolution, at a greater temporal resolution than that achieved from standard flight patterns. These observations will allow for an improved understanding of the physical processes responsible for changes in the TC tilt structure. With repeated sampling, multi-case comparisons can be made for aligning and non-aligning TCs. If sufficient samples exist, aligning cases can be further partitioned by their alignment pathway (e.g., reformation vs. precession) to explore whether pathway-specific processes exist in nature.

Hypotheses:

1. TCs experiencing a reduction in vortex misalignment exhibit a greater areal coverage of convection in the region between the lower and mid-tropospheric TC centers compared to non-aligning TCs. This increase in convection is associated with a local thermodynamic environment that favors a bottom-heavy vertical mass flux profile and vortex stretching in the lower troposphere.
2. The type of alignment pathway is determined by the strength of the TC circulation and the local environmental conditions, which affects the vigor and spatial scale of convection. Specifically, the vortex reformation alignment pathway occurs preferentially in TCs with initially weak lower-tropospheric circulations and TCs located in environments of warm sea surface temperatures and relatively large lower-tropospheric instability. These conditions favor vigorous convection with significant vortex stretching in the lower troposphere near the location of the midlevel TC center. Alternatively, the vortex precession pathway to alignment occurs preferentially in TCs with stronger circulations, capable of greater coupling between the lower and midlevel circulations. Precession is also favored in cases with a greater frequency of stratiform precipitation and environments of weaker vertical wind shear, which provides less resistance to vortex precession.

Objectives:

1. Observe the evolution of the vortex tilt and precipitation structures in early-stage TCs by repeatedly sampling the low- and mid-level TC centers.
2. Identify how the local environment influences the TC tilt and precipitation structures, including whether certain environmental conditions favor one alignment pathway over another.

Aircraft Pattern/Module Descriptions (see *Flight Pattern* document for more detailed information): Missions will be targeted for early-stage TCs that have yet to vertically-align based on available observational and high-resolution numerical model forecast guidance. Due to the large uncertainty of when alignment occurs (or if it will occur at all) missions should target any early-stage, misaligned TC in at least moderately favorable environmental conditions (e.g., deep-layer shear < 20 kt) when possible (i.e., subject to range, timing, and other logistical constraints). This enables the documentation of TC structure during the time leading up to vortex alignment (if it indeed occurs). Ideally missions will continue every 12 to 24 h (or more frequent, depending on the *Scenario* below), as long as feasible.

P-3 Pattern #1: A standard Figure-4 pattern centered on the estimated low-level or mid-level center, oriented such that the radial passes are aligned along and perpendicular to the direction of vertical tilt of the circulation center. If possible, the first inbound-outbound center pass should be oriented (to the best it can be determined) along the direction of the low-level to mid-level center tilt. Adjust the pattern orientation in flight as necessary following a determination of the tilt orientation with TDR analyses. See the *Flight Pattern document* for how expendables are distributed. After completion of this pattern, it is preferred that P-3 Module #1 ("*Vortex Alignment Module*") be flown.

P-3 Pattern #2: A standard Butterfly pattern centered on the estimated low-level or mid-level center. The butterfly should be oriented such that the downshear / downtilt portion of the storm contains the most radial legs. If centered on the low-level center, legs in the downtilt direction may also be extended (and uptilt legs shortened to compensate) to account for misalignment and precipitation symmetry. See the *Flight Pattern document* for how expendables are distributed. After completion of this pattern, it is preferred that P-3 Module #1 ("*Vortex Alignment Module*") be flown.

P-3 Module #1 (*"Vortex Alignment Module"*): Follow the vortex tilt vector, beginning 25 n mi uptilt of the low-level (e.g., 2.0-km) or mid-level (e.g., 6.0-km) vortex center and ending 25 n mi downtilt of the mid-level/low-level vortex center, as identified from earlier TDR analyses. It is essential that the aircraft flies a sufficient distance (20–25 n mi) past both the low- and mid-level centers such that the TDR can sufficiently sample the respective circulations. Repeat this pattern for a total of at least two radial legs (one complete cycle), but repeated cycles are preferred. Dropsondes can be released during overpasses of the low-level center to identify the rate of TC intensity change. This module allows for high-temporal resolution analyses of the evolution of the TC tilt structure and the precipitation and kinematic processes associated with changes in vortex misalignment.

G-IV Pattern #1: A standard Figure-4 with Double Circumnavigation pattern with radial legs in the Figure-4 extending up to 150 n mi (275 km) and radii of 90 and 210 n mi (165 and 390 km) for the circumnavigations. If desired, the pattern can be centered on the estimated low-level or mid-level center, oriented such that the Figure-4 radial passes are aligned through approximately the upshear, downshear, left-of-shear, and right-of-shear directions, or oriented relative to the vertical tilt of the circulation. If time is not available to complete the full pattern, the Figure-4 is prioritized with either the inner or outer circumnavigation (preference to the inner circumnavigation). Dropsonde are released at each turn point, midpoint, and center on each pass of the Figure-4, and another at the midpoint of downwind leg; dropsondes also released at each turnpoint of the circumnavigations, with option to release in between each turnpoint to increase the density.

Scenario #1: Both P-3s (Back-to-Back) and G-IV ("Vortex Alignment Experiment")
This scenario aims to maximize the on-station time within a ~12–24 hr (ideally 16–20-hr) window in a misaligned TC via four consecutive flights. The G-IV will begin the sequence by flying G-IV Pattern #1 (Figure-4 with Double Circumnavigation) to observe the local thermodynamic and

kinematic environment, as well as the TC vortex structure. It is recommended that the Figure-4 component of the pattern be centered on the presumed mid-level TC center, typically found near the region of coldest infrared brightness temperatures as identified from satellite imagery. Otherwise, the Figure-4 can be centered on the low-level TC center with an effort to have one radial leg fly within TDR range (~15 n mi) of the mid-level TC center. If the on-station time needs to be shortened, it is recommended that the outer circumnavigation is not performed.

Within one hour of the departure of the G-IV from the storm environment, the first P-3 should arrive on station to begin sampling the TC, flying a single Figure-4 from P-3 Pattern #1, centered on the mid-level TC center. The location of the mid-level TC center will be identified from the initial G-IV mission. Following the completion of the Figure-4, the P-3 will fly Module #1 (*"Vortex Alignment Module"*) following the vortex tilt vector throughout the duration of the remaining on-station time. If vortex evolution is observed during Module #1, the azimuthal heading and radial leg length should be adjusted according to changes in the TC tilt structure, as identified from real-time TDR analyses. The second P-3 should be scheduled to arrive once the first P-3 departs the storm environment. The second P-3 mission should complete the same pattern as the first. Within one hour of the departure of the second P-3 from the storm environment, the second G-IV mission should begin sampling the storm, following the same pattern as the first G-IV mission.

Scenario #2: One P-3 and the G-IV, simultaneous

One P-3 will fly Pattern #1 (Figure-4) or Pattern #2 (Butterfly), followed by Module #1 (*"Vortex Alignment Module"*), depending on any operational tasking constraints. If existing constraints allow some flexibility, it is recommended that Pattern #1 or Pattern #2 be centered on the presumed mid-level TC center, typically found near the region of coldest infrared brightness temperatures as identified from satellite imagery.

In this scenario, the G-IV will also fly Pattern #1 (Figure-4 with Double Circumnavigation) to observe the local thermodynamic and kinematic environment, as well as the TC vortex structure. As with the P-3, it is recommended that the Figure-4 component of the pattern be centered on the presumed mid-level TC center, typically found near the region of coldest infrared brightness temperatures as identified from satellite imagery, or identified via TDR analyses from the concurrent P-3 mission. Otherwise, the Figure-4 can be centered on the low-level TC center with an effort to have one radial leg fly within TDR range (~15 n mi) of the mid-level TC center. If the on-station time needs to be shortened, it is recommended that the outer circumnavigation is not performed. If ongoing convection prevents the G-IV from flying the initial Figure-4 pattern passing over the TC center, the Figure-4 can be substituted with a box pattern about the TC center. Ideally, this substitute box pattern would have legs that pass within 30 n mi of the TC center location to maximize TDR coverage. This scenario leaves the possibility open to 12-hourly (twice-a-day) coordinated missions.

Scenario #3: Only one P-3 available (no G-IV)

When the G-IV and 2nd P-3 is not available for coordinated operations, either because of operational tasking requirements or aircraft unavailability, P-3 targeted observations in the near environment and inner core can still contribute towards the objectives of the experiment. In this scenario, it is preferred that the P-3 flies Module #1 (*"Vortex Alignment Module"*) after the completion of the any operational taskings and/or P-3 Pattern #1 or Pattern #2.

Links to Other Early Stage Experiments/Modules: The goals of this experiment synergize with those of *AIPEX*, *PREFORM*, and *FLAIMS*, as the observations collected here help characterize the TC vortex and inner core precipitation structures with relatively high temporal resolution. It is possible the goals of the present experiment can be met by flying P-3 Module #1 (*"Vortex Alignment Module"*) after a given pattern used to meet the goals of either AIPEX or PREFORM. Additionally, in the event that intense convection is ongoing during the alignment process, the *Convective Burst Module* could also be performed.

Analysis Strategy: The evolution of the TC tilt and precipitation structures will be determined from P-3 and G-IV TDR analyses, which are routinely created in real-time and are further post-processed after each season. The real-time TDR analyses are transmitted to hurricane specialists at the National Hurricane Center for additional situational awareness and are used in real-time data assimilation for select high-resolution numerical model guidance. Straight-and-level flight patterns are preferred, although the TDR analysis procedure is capable of handling small bank angles, which may be required to deviate around convection.

Ongoing work has demonstrated the vortex tilt structure can be inferred from individual TDR analyses (e.g., one radial pass through the center of the storm), provided sufficient data coverage exists in the analysis. To facilitate the identification of the low-level and mid-level centers for mission planning purposes, software is being developed which will generate text output on the aircraft of the geographic coordinates of the TC center at each height using an objective TC-center finding algorithm (documented in Fischer et al. 2022). The precipitation characteristics of the storm will be identified through a combination of TDR reflectivity and vertical velocity estimates. Previous work by Rogers et al. (2020) has demonstrated an objective precipitation partitioning algorithm can be applied to TDR analyses to identify changes in the mode of precipitation, which have been linked to changes in vortex alignment. Real-time graphics of the TDR-derived tilt and precipitation structure are routinely made available on the HRD web server (and can be found at: https://www.aoml.noaa.gov/ftp/pub/hrd/data/RTradar/).

The environmental characteristics will be identified through a combination of operational statistical guidance (e.g., the Statistical Hurricane Intensity Prediction Scheme; SHIPS) to identify aspects such as the synoptic scale shear, humidity, and sea surface temperature. Otherwise, high-altitude dropsonde observations from the G-IV will be used to determine additional parameters, such as tropospheric stability and humidity. Dropsonde observations from the G-IV are also routinely transmitted in real-time and assimilated into numerical model guidance.

References:

Alland, J. J., 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 I: Downdraft ventilation. *J. Atmos Sci.,* **78**, 763–782, doi: https://doi.org/10.1175/JAS-D-20-0054.1.

Alland, J. J., B. H. Tang, K. L. Corbosiero, and G. H. Bryan, 2021b: 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.

Alvey III, G. R., J. Zawislak, and E. Zipser, 2015: Precipitation Properties Observed during Tropical Cyclone Intensity Change. *Mon. Wea. Rev*., **143**, 4476–4492. doi: 10.1175/MWR-D-15-0065.1.

Alvey, G. R., III, E. Zipser, and J. Zawislak, 2020: How does Hurricane Edouard (2014) evolve toward symmetry before rapid intensification? A high-resolution ensemble study. *J. Atmos. Sci.*, **77**, 1329–1351, https://doi.org/10.1175/JAS-D-18-0355.1.

Alvey, G. R., III, M. Fischer, P. Reasor, J. Zawislak, and R. Rogers, 2022: Observed Processes Underlying the Favorable Vortex Repositioning Early in the Development of Hurricane Dorian (2019). *Mon. Wea. Rev.*, **150**, 193–213, doi:10.1175/MWR-D-21-0069.1.

Boehm, A. M., and M. M. Bell, 2021: Retrieved thermodynamic structure of Hurricane Rita (2005) from airborne multi–Doppler radar data. *J. Atmos. Sci.*, **78**, 1583–1605.

Chen, X., Y. Wang, J. Fang, and M. Xue, 2018b: A Numerical Study on Rapid Intensification of Typhoon Vicente (2012) in the South China Sea. Part II: Roles of Inner-core Processes. *J. Atmos. Sci.*, **75**, 235–255, doi:10.1175/JAS-D-17-0129.1.

Chen, X., J. A. Zhang, and F. D. Marks, 2019: A Thermodynamic Pathway Leading to Rapid Intensification of Tropical Cyclones in Shear. *Geo. Res. Lett*., **46**, 9241–9251.

Davis, C. A., and D. A. Ahijevych, 2012: Mesoscale structural evolution of three tropical weather systems observed during PREDICT. *J. Atmos. Sci.*, **69**, 1284–1305, https://doi.org/10.1175/JAS-D-11-0225.1.

DeMaria, M., and J. Kaplan, 1994: A Statistical Hurricane Intensity Prediction Scheme (SHIPS) for the Atlantic basin. *Wea. Forecasting*, **9**, 209–220.

Finocchio, P. M., 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.

Fischer, M. S., B. H. Tang, K. L. Corbosiero, and C. M. Rozoff, 2018: Normalized convective characteristics of tropical cyclone rapid intensification events in the North Atlantic and eastern North Pacific basins. *Mon. Wea. Rev.*, **146**, 1133–1155.

Fischer, M. S., B. H. Tang, and K. L. Corbosiero, 2019: A climatological analysis of tropical cyclone rapid intensification in environments of upper-tropospheric troughs. *Mon. Wea. Rev.*, **147**, 3693–3719.

Fischer, M. S., P. D., Reasor, R. F. Rogers, and J. F. Gamache, 2022: An analysis of tropical cyclone vortex and convective characteristics in relation to storm intensity using a novel airborne Doppler radar database. *Mon. Wea. Rev*., **150**, 2255–2278.

Fischer, M. S., P. D. Reasor, B. H. Tang, K. L. Corbosiero, R. D. Torn, and X. Chen, 2023: A tale of two vortex evolutions: Using a high-resolution ensemble to assess the impacts of ventilation on a tropical cyclone rapid intensification event. *Mon. Wea. Rev*., **151**, 297–320.

Gjorgjievska, S., and D. J. Raymond, 2014: Interaction between dynamics and thermodynamics during tropical cyclogenesis. *Atmos. Chem. Phys*., **14**, 3065–3082, https://doi.org/10.5194/acp-14-3065-2014.

Hendricks, E. A., M. S. Peng, B. Fu, and T. Li, 2010: Quantifying environmental control on tropical cyclone intensity change. *Mon. Wea. Rev*., **138**, 3243–3271, https://doi.org/10.1175/2010MWR3185.1.

Jones, S. C., 1995: The evolution of vortices in vertical shear. I: Initially barotropic vortices. *Quart. J. Roy. Meteor. Soc*., **121**, 821–851.

Kaplan, J., M. DeMaria, and J. A. Knaff, 2010: A revised tropical cyclone rapid intensification index for the Atlantic and eastern North Pacific basins. *Wea. Forecasting*, **25**, 220–241.

Kaplan, J., and Coauthors, 2015: Evaluating environmental impacts on tropical cyclone rapid intensification predictability utilizing statistical models. *Wea. Forecasting*, **30**, 1374–1396.

Miyamoto, Y., and D. S. Nolan, 2018: Structural changes preceding rapid intensification in tropical cyclones as shown in a large ensemble of idealized simulations. *J. Atmos. Sci.*, **75**, 555–569.

Munsell, E. B., F. Zhang, J. A. Sippel, S. A. Braun, and Y. Weng, 2017: Dynamics and predictability of the intensification of Hurricane Edouard (2014). *J. Atmos. Sci*., **74**, 573–595, https://doi.org/10.1175/JAS-D-16-0018.1.

Raymond, D. J., and S. L. Sessions, 2007: Evolution of convection during tropical cyclogenesis. *Geophys. Res. Lett*., **34**, L06811, https://doi.org/10.1029/2006GL028607.

Raymond, D. J., S. Gjorgjievska, S. Sessions, and Ž. Fuchs, 2014: Tropical cyclogenesis and mid-level vorticity. *Aust. Meteor. Oceanogr. J*., **64**, 11–25, https://doi.org/10.22499/2.6401.003.

Raymond, D. J., and Ž. Fuchs-Stone, 2021a: Emergent properties of convection in OTREC and PREDICT. *J. Geophys. Res. Atmos*., **126**, e2020JD033585, https://doi.org/10.1029/2020JD033585.

Reasor, P. D., M. T. Montgomery, and L. D. Grasso, 2004: A new look at the problem of tropical cyclones in vertical shear flow: Vortex resiliency. *J. Atmos. Sci*., **61**, 3–22.

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, doi:10.5194/acp-10-3163-2010.

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.

Rios-Berrios, R., 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, doi:10.1175/jas-d-18-0070.1.

Rogers, R., P. Reasor, and S. Lorsolo, 2013: Airborne Doppler observations of the inner-core structural differences between intensifying and steady-state tropical cyclones. *Mon. Wea. Rev.*, **141**, 2970–2991, doi: 10.1175/MWR-D-12-00357.1.

Rogers, R. F., P. D. Reasor, J. A. Zawislak, and L. T. Nguyen, 2020: Precipitation Processes and Vortex Alignment during the Intensification of a Weak Tropical Cyclone in Moderate Vertical Shear. *Mon. Wea. Rev.*, **148**, 1899–1929, https://doi.org/10.1175/MWR-D-19-0315.1.

Schecter, D. A., 2020: Distinct intensification pathways for a shallow-water vortex subjected to asymmetric “diabatic” forcing. *Dyn. Atmos. Oceans*, **91**, 101156, https://doi.org/10.1016/j.dynatmoce.2020.101156.

Schecter, D. A., and K. Menelaou, 2020: Development of a misaligned tropical cyclone. *J. Atmos. Sci.*, **77**, 79–111.

Schecter, D. A., 2022: Intensification of tilted tropical cyclones over relatively cool and warm oceans in idealized numerical simulations. *J. Atmos. Sci.*, **79**, 485–512.

Stone, Z., G. R. Alvey III, J. P. Dunion, Fischer, M. S., D. J. Raymond, R. F. Rogers, S. Sentic, and J. Zawislak, 2023: Thermodynamic contribution to vortex alignment and rapid intensification of Hurricane Sally (2020). *Mon. Wea. Rev*., **151**, 931–951.

Tao, C., H. Jiang, and J. Zawislak, 2017: The relative importance of stratiform and convective rainfall in rapidly intensifying tropical cyclones. *Mon. Wea. Rev.*, **145**, 795–809, https://doi.org/10.1175/MWR-D-16-0316.1.

Tao, D., and F. Zhang, 2019: Evolution of dynamic and thermodynamic structures before and during rapid intensification of tropical cyclones: Sensitivity to vertical wind shear. *Mon. Wea. Rev.*, **147**, 1171–1191.

Trabing, B. C., and M. M. Bell, 2020: Understanding error distributions of hurricane intensity forecasts during rapid intensity changes. *Wea. Forecasting*, **35**, 2219–2234.

Zhang, F., and D. Tao, 2013: Effects of vertical wind shear on the predictability of tropical cyclones. *J. Atmos. Sci.,* **70**, 975–983.