2023 NOAA/AOML/HRD Hurricane Field Program - APHEX

EARLY STAGE EXPERIMENT
Science Description

Experiment/Module: Convective Burst Structure and Evolution Module (CBM)

Investigator(s): Rob Rogers (PI), Trey Alvey, Robert Black, Hua Leighton, Xuejin Zhang, Michael Bell (CSU), Anthony Didlake (PSU), Jim Doyle (NRL), Dan Stern (NRL), Josh Wadler (ERAU)

Requirements: TD, TS, Category 1

Plain Language Description: This module samples the vertical motion and reflectivity structure of strong thunderstorm complexes at a high frequency, e.g., every 15–20 minutes, over a 1–2 h period, to observe how the structure of these systems change over time and as they move around the TC center, along with observing how those changes affect the structure and intensity of TCs.

Early Stage Science Objective(s) Addressed:

1. 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*].

Motivation: The objectives are to 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.

Background: It has long been known that deep convection is an integral component of TC structure. What has received greater attention in recent years is the potential role that deep convection, termed here "convective bursts" (CBs) and representing the peak updrafts and highest echo tops, plays in TC structure and intensity evolution. Various hypotheses have been posed that attempt to explain their contribution to TC intensification:

- Vortex gradient adjustment to the imposed diabatic heating in the high-inertial stability region inside the radius of maximum wind (RMW) (e.g., Shapiro and Willoughby 1982, Schubert and Hack 1982, Hack and Schubert 1986, Nolan and Grasso 2003, Nolan et al. 2007, Vigh and Schubert 2009, Pendergrass and Willoughby 2009, Rogers et al. 2013, 2015, 2016)
- Convergence of angular momentum surfaces in the lower troposphere and boundary layer (Smith and Montgomery 2016)
- Upper-level subsidence warming around the CB periphery (e.g., Heymsfield et al. 2001, Guimond et al. 2010, Rogers 2010, Zhang and Chen 2012, Chen and Zhang 2013, Chen and Gopal 2015)
- Stretching and axisymmetrization in vortical hot towers (Hendricks et al. 2004, Montgomery et al. 2006, Reasor et al. 2009)
- Vortex alignment/downshear reformation for weak, misaligned TCs (Reasor et al. 2009, Molinari and Vollaro 2010, Nguyen and Molinari 2012, Reasor and Eastin 2012, Stevenson et al. 2014, Rogers et al. 2015, 2020, Nguyen and Molinari 2015, Alvey et al. 2022, Stone et al. 2023).

While these studies have emphasized the role of deep convection in TC intensification, other studies have focused on the role of shallow to moderate convection, and even stratiform precipitation, in initiating TC intensification (Kieper and Jiang 2012, Zagrodnik and Jiang 2014, Tao and Jiang 2015, Tao et al. 2017, Nguyen et al. 2017, Rogers et al. 2020). Common to these and other studies (e.g., Miyamoto and Takemi 2015), though, is that TC intensification is favored when precipitation, including CBs, are preferentially located inside the RMW with a maximum azimuthal distribution.

Vertical shear is one factor that has been shown to be important in organizing precipitation, including CBs, azimuthally around the TC vortex. This has generally been attributed to the fact that vertical shear tilts the vortex, leading to preferred regions of vortex-scale low-level convergence and upward motion downshear and low-level divergence and subsidence upshear (Jones 1995, Bender 1997, Frank and Ritchie 2001, Black et al. 2002, Corbosiero and Molinari 2003, Rogers et al. 2003, Braun et al. 2006, Wu et al. 2006, Reasor et al. 2009, Reasor and Eastin 2012, Reasor et al. 2013, Dolling and Barnes 2014, DeHart et al. 2014). Recent composite studies of vortices in shear using airborne Doppler radar have shown that the shear-induced circulations are maximized downshear right (DSR) (low-level convergence/upward motion) and upshear left (USL) (low-level divergence/downward motion) (Reasor et al. 2013, DeHart et al. 2014). A similar composite methodology was performed in a CB-relative coordinate system (Wadler et al. 2018). This study found that the peak updraft magnitude and altitude for CBs was minimized DSR, consistent with the notion that this is the quadrant where CBs are initiated. The magnitude and altitude of the peak updraft increase in the DSL quadrant, as the CBs mature, and they reach their highest and strongest values USL. A similar shear-relative azimuthal relationship was found for echo top height. Significantly, when stratifying TCs by intensity change, it was found that the most significant differences in CB structure between intensifying and non-intensifying TCs were located in the USL quadrant. Intensifying TCs have CBs with stronger peak updrafts, at a higher altitude, with higher echo tops in the USL quadrant than non-intensifying TCs. This relationship suggests that the structure and evolution of CBs, which are to some extent a function of the local environment from which they initiate downshear and mature upshear — including convective available potential energy, midlevel humidity, and subsidence upshear (Zawislak et al. 2016, Rogers et al. 2016, Nguyen et al. 2017, 2019) — is an important factor to consider in assessing the potential for a TC to intensify.

It should be noted that the above descriptions presume that CBs do translate downwind, i.e., upshear. However, in some situations, mostly revealed from modeling studies (Munsell et al. 2017, Chen et al. 2017), CBs can remain "trapped" on the downshear side. In fact, cases where the CBs remain downshear were more likely to be associated with non-intensifying periods of TC evolution. This is consistent with the notion of greater azimuthal symmetry of diabatic heating being associated with TC intensification. CBs propagating into the upshear quadrants may also be related to a greater likelihood of vortex alignment, as revealed in the observational analysis of Hurricane Earl (2010; Rogers et al. 2015) and a WRF-ARW ensemble forecast of Edouard (2014; Munsell et al. 2017).

While much of the above discussion considers CB structure and evolution in a shear-relative context, there are instances where the TC is weak, likely mis-aligned, and likely will not see propagation of the CB from downshear to upshear. These scenarios are equally desirable for the CB module, as recent work has shown that vertical velocity and mass flux profiles vary as a function of the local thermodynamic environment in weak TCs (Rogers et al. 2020, Stone et al. 2023), with "top-heavy" mass flux profiles associated with lower midlevel relative humidity (< 60% in 4–8 km layer) and lower levels of static stability, and "bottom-heavy" mass flux profiles associated with higher midlevel relative humidity (> 80% in 4–8 km layer) and higher levels of static stability (Raymond et al. 2014; Sessions et al. 2015; Sentić et al. 2015; Raymond and Flores 2016; Raymond and Kilroy 2019; Raymond and Ž. Fuchs-Stone 2021a),. The differences in these profiles can impact the response of the TC to the latent heating within the CB. Therefore, obtaining measurements of the vertical velocity and reflectivity profiles at high temporal resolution are crucial to better understanding CB impacts on the developing TC circulation.

The results described above are valid for composites of many different CBs from many different TCs. They therefore lack the temporal continuity needed to measure the structure of specific individual (or groups of) CBs, and how they evolve in a shear-relative sense. The purpose of this module is to repeatedly sample individual (or groups of) CBs to provide this temporal continuity.

Goal(s): 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.

Hypotheses: The following hypotheses will guide the sampling strategies for CBs:

For stronger TCs (strong TS, Cat 1) in vertical shear:

1. CBs are preferentially initiated in the DSR quadrant; as such, the updraft maxima are likely to be weaker and at a lower altitude in this quadrant;
2. Traveling downwind into the DSL quadrant, peak updrafts will strengthen and be located at a higher altitude;
3. The strength of the CB in the USL quadrant (as measured by strength and height of peak updraft and echo top height relative to the DSL quadrant) will vary depending on the local, vortex-scale environment of the convection. This environment includes midlevel humidity, strength of subsidence upshear, and sea surface temperature (and CAPE) on the downshear side of the TC;
4. If the CB strength, as measured by peak updraft magnitude and altitude and echo top height, is higher USL than DSL, then the CB will persist on the upshear side with a mixture of convective and stratiform precipitation, and the TC will be more likely to intensify.
5. If CBs are primarily maximized DSL, the upshear will be more dominated by stratiform precipitation with downdrafts that are potentially detrimental to intensification.

For weaker TCs (TD, weak TS):

1. If the local thermodynamic environment of the CB is characterized by low relative humidity and static stability, the mass flux profile will peak at a relatively high altitude (> 5 km). In this situation the TC will be less likely to align and intensify.
2. If the local thermodynamic environment of the CB is characterized by high relative humidity and static stability, the mass flux profile will peak at a relatively low altitude (< 5 km). In this situation the TC will be more likely to align and intensify.

Objectives: The objectives of this module are to repeatedly sample the kinematic, thermodynamic, and reflectivity structure and evolution of individual convective bursts and their associated precipitation structures using airborne Doppler radar and dropsondes released from the P-3

1. Sampling will follow CBs as they translate azimuthally downwind in a shear-relative framework (where relevant)
2. Optimal additional measurements include:
    a. Deep-layer measurements of temperature and humidity in the local environment of the CBs from high-altitude aircraft will provide the thermodynamic context within the mid-and lower troposphere
    b. Measurements of sea-surface temperature and subsurface temperature profiles from ocean probes and/or IR dropsondes will provide context on the surface boundary

Aircraft Pattern/Module Descriptions (see *Flight Pattern* document for more detailed information): This is a stand-alone module that takes 1–2 h to complete. Execution is dependent on system attributes, aircraft fuel and weight restrictions, and proximity to the operations base. It can be flown separately within a mission designed to study local areas of convection or at the end of one of the survey patterns. Once a local area of intense convection is identified, the P-3 will transit at altitude (10–12 kft) to the nearest point just outside of the convective cores and sample the convective area. The sampling pattern will be a series of inbound/outbound radial penetrations or bowtie patterns (when sampling a CB near the radius of maximum wind of a tropical storm or hurricane). If the CB is at or near the RMW, repeated sampling can allow for a following of the burst around the storm. This is especially useful to sample the structural evolution of the burst as it moves around the storm. If the CB remains confined to the downshear side of the TC rather than translating upshear, the pattern should still be flown. This module can also be flown during the mature stage, in conjunction with the rainband module.

Links to Other Early Stage Experiments/Modules: CBM can be flown in conjunction with the following *Early Stage* experiments: *AIPEX*, *TDR Experiment*, *Stratiform Spiral Module (SSM)*, and NESDIS JPSS Satellite Validation Experiment. A crucial aspect of this module is that the kinematic and thermodynamic context of the vortex-scale structure is provided. Therefore, patterns that provide this context, through vortex survey patterns such as figure-4 and butterfly patterns, must be flown in conjunction with the CBM. AIPEX and the TDR Experiment are two good examples of this.

Analysis Strategy: Radar analyses will be performed for each radial pass through the CB, preferentially with a temporal spacing of 30 minutes or less. These analyses will provide high-frequency observations of the structure of the CB, as measured by the peak updraft magnitude and altitude and echo top heights. Additionally, the full spectrum of vertical velocity associated with each radar analysis will be evaluated using contoured frequency by altitude diagrams (CFADs; Yuter and Houze 1995) to obtain a more complete picture of the updraft and downdraft structure and evolution of the CB. Ideally a CB will be flown beginning with its initiation (likely to be downshear) and then followed around the storm as it travels through the downwind quadrants and into the upshear quadrants (or continuously sampled on the downshear side if it remains confined there). Dropsondes released at the starting and ending points of each radial leg will document the thermodynamic structure of the boundary layer radially bracketing the CB. A dropsonde will also be released within the CB, provided there is a region without heavy rain.

Optimally, the G-IV will be flying in the storm to provide deep-layer temperature and humidity profiles around the storm in addition to the P-3 dropsondes. If the G-IV is not available, the module could still be flown to examine the evolution using the Doppler radar and boundary layer thermodynamics from the P-3 dropsondes. Additionally, when multiple P-3 aircraft are available and sampling simultaneously, one aircraft can perform the radial penetrations as outlined above, while the other aircraft circumnavigates the CB outside the precipitation shield at the maximum allowable altitude (preferably ≥18 kft). Dropsondes should be released from the higher altitude aircraft at locations upwind and downwind from the CB.

In addition to the observational analysis described above, the high-resolution data collected in this module is planned to be embedded within the typical Hurricane Ensemble Data Assimilation System (HEDAS; e.g., Aksoy et al. 2013) framework to carry out storm-scale data assimilation that focuses specifically on the high-resolution analysis of the identified intense convective region. With current technology, a smaller domain with 1-km grid spacing will be nested within the HEDAS 3-km analysis domain, where the data will be assimilated for the duration of its collection (1–2 hours, at 5–10 min intervals). This is a typical setup that has been traditionally used in continental storm-scale radar data assimilation applications and has been shown to be effective to obtain realistic storm structures in analyses and short-range forecasts. With such high-resolution analyses, we hope to be able to obtain fully three-dimensional model representations of the observed convective regions for more detailed investigation, as well as investigate their short-range predictability. In an observing system experiment (OSE) mode, various assimilation experiments can also be devised to investigate hypothetical scenarios for how an observed convective region could interact with the surrounding vortex and impact its evolution. Dropsonde, superobbed Doppler, flight-level, and SFMR data will be transmitted over the GTS and assimilated in real time; full Doppler analyses and lower fuselage imagery will be available post-flight.

References:

Aksoy, A., S. D. Aberson, T. Vukicevic, K. J. Sellwood, S. Lorsolo, and X. Zhang (2013), Assimilation of high-resolution tropical cyclone observations with an ensemble Kalman filter using NOAA/AOML/HRD's HEDAS: Evaluation of the 2008–11 vortex-scale analyses, *Mon. Wea. Rev.*, **141**, 1842–1865, doi: http://dx.doi.org/10.1175/MWR-D-12-00194.1.

Alvey, G. R., 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, https://doi.org/10.1175/MWR-D-21-0069.1.

Bell, M. M., and M. T. Montgomery, 2019: Mesoscale processes during the genesis of hurricane Karl (2010). *Journal of the Atmospheric Sciences*, **76 (8)**, 2235–2255, https://doi.org/10.1175/JAS-D-18-0161.1.

Bender, M. A., 1997: The effect of relative flow on the asymmetric structure in the interior of hurricanes. *J. Atmos. Sci*., **54**, 703–724, doi:10.1175/1520-0469(1997)054<0703:TEORFO>2.0.CO;2.

Black, M. L., J. F. Gamache, F. D. Marks, C. E. Samsury, and H. E. Willoughby, 2002: Eastern Pacific Hurricanes Jimena of 1991 and Olivia of 1994: The effect of vertical shear on structure and intensity. *Mon. Wea. Rev*., **130**, 2291–2312, doi:10.1175/1520-0493(2002)130<2291:EPHJOA>2.0.CO;2.

Braun, S. A., M. T. Montgomery, and Z. Pu, 2006: High-resolution simulation of Hurricane Bonnie (1998). Part I: The organization of eyewall vertical motion. *J. Atmos. Sci*., **63**, 19–42, doi:10.1175/JAS3598.1.

Chen, H., and S. G. Gopalakrishnan, 2015: A study on the asymmetric rapid intensification of Hurricane Earl (2010) using the HWRF system. *J. Atmos. Sci*., **72**, 531–550, doi:10.1175/JAS-D-14-0097.1.

Chen, H., and D. L. Zhang, 2013: On the rapid intensification of Hurricane Wilma (2005). Part II: Convective bursts and the upper-level warm core. *J. Atmos. Sci*., **70**, 146–162, doi:10.1175/JAS-D-12-062.1.

Chen, H., S. Gopalakrishnan, J.A. Zhang, R.F. Rogers, Z. Zhang, and V. Tallapragada, 2017: Use of HWRF ensembles for providing improved understanding of hurricane RI problem: Case study of Hurricane Edouard (2014). *J. Atmos. Sci*., in review.

Corbosiero, K. L., and J. Molinari, 2003: The relationship between storm motion, vertical wind shear, and convective asymmetries in tropical cyclones. *J. Atmos. Sci*., **60**, 366–376, doi:10.1175/1520-0469(2003)060<0366:TRBSMV>2.0.CO;2.

DeHart, J. C., R. A. Houze Jr., and R. F. Rogers, 2014: Quadrant distribution of tropical cyclone inner-core kinematics in relation to environmental shear. *J. Atmos. Sci*., **71**, 2713–2732, doi:10.1175/JAS-D-13-0298.1.

Didlake, A. C., and R. A. Houze, 2013: Dynamics of the stratiform sector of a tropical cyclone rainband. *J. Atmos. Sci*, **70**, 1891–1911.

Didlake, A.C., P.D. Reasor, R.F. Rogers, and W. Lee, 2018: Dynamics of the Transition from Spiral Rainbands to a Secondary Eyewall in Hurricane Earl (2010). *J. Atmos. Sci.,* **75**, 2909–2929, https://doi.org/10.1175/JAS-D-17-0348.1

Dolling, K., and G. M. Barnes, 2014: The evolution of Hurricane Humberto (2001). *J. Atmos. Sci*., **71**, 1276–1291, doi:10.1175/JAS-D-13-0164.1.

Feng, Y.-C., and Bell, M. M, 2018: “Microphysical characteristics of an asymmetric eyewall in major Hurricane Harvey (2017)”. *Geophys. Res. Lett., doi: 10.1029/2018gl080770.*

Frank, W. M., and E. A. Ritchie, 2001: Effects of vertical wind shear on the intensity and structure of numerically simulated hurricanes. *Mon. Wea. Rev*., **129**, 2249–2269, doi:10.1175/1520-0493(2001)129<2249:EOVWSO>2.0.CO;2.

Foerster, A. M., M. M. Bell, P. A. Harr, and S. C. Jones, 2014: Observations of the eyewall structure of Typhoon Sinlaku (2008) during the transformation stage of extratropical transition. *Mon. Wea. Rev.*, **142**, 3372–3392.

Guimond, S. R., G. M. Heymsfield, and F. J. Turk, 2010: Multiscale observations of Hurricane Dennis (2005): The effects of hot towers on rapid intensification. *J. Atmos. Sci.*, **67**, 633–654, doi:10.1175/2009JAS3119.1.

Hack, J. J., and W. H. Schubert, 1986: Nonlinear response of atmospheric vortices to heating by organized cumulus convection. *J. Atmos. Sci.*, **43**, 1559–1573, doi:10.1175/1520-0469(1986)043<1559:NROAVT>2.0.CO;2.

Hendricks, E. A., M. T. Montgomery, and C. A. Davis, 2004: The role of "vortical" hot towers in the formation of Tropical Cyclone Diana (1984). *J. Atmos. Sci.*, **61**, 1209–1232, doi:10.1175/1520-0469(2004)061<1209:TROVHT>2.0.CO;2.

Heymsfield, G. M., J. B. Halverson, J. Simpson, L. Tian, and T. P. Bui, 2001: ER-2 Doppler radar investigations of the eyewall of Hurricane Bonnie during the Convection and Moisture Experiment-3. *J. Appl. Meteor.*, **40**, 1310–1330, doi:10.1175/1520-0450(2001)040<1310:EDRIOT>2.0.CO;2.

Houze, R. A., 1997: Stratiform precipitation in regions of convection: A meteorological paradox? *Bull. Amer. Meteor. Soc.*, **78**, 2179–2196.

Jones, S. C., 1995: The evolution of vortices in vertical shear. I: Initially barotropic vortices. *Quart. J. Roy. Meteor. Soc.*, **121**, 821–851, doi:10.1002/qj.49712152406.

Kieper, M. E., and H. Jiang, 2012: Predicting tropical cyclone rapid intensification using the 37 GHz ring pattern identified from passive microwave measurements. *Geophys. Res. Lett.*, **39**, L13804, doi:10.1029/2012GL052115.

Miyamoto, Y., and T. Takemi, 2015: A triggering mechanism for rapid intensification of tropical cyclones. *J. Atmos. Sci.*, **72**, 2666–2681, doi:10.1175/JAS-D-14-0193.1.

Molinari, J., and D. Vollaro, 2010: Rapid intensification of a sheared tropical storm. *Mon. Wea. Rev.*, **138**, 3869–3885, doi:10.1175/2010MWR3378.1.

Montgomery, M. T., M. Nicholls, T. Cram, and A. Saunders, 2006: A "vortical" hot tower route to tropical cyclogenesis. *J. Atmos. Sci.*, **63**, 355–386, doi:10.1175/JAS3604.1.

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, doi: 10.1175/JAS-D-16-0018.1.

Nguyen, L. T., and J. Molinari, 2012: Rapid intensification of a sheared, fast-moving hurricane over the Gulf Stream. *Mon. Wea. Rev.*, **140**, 3361–3378, doi:10.1175/MWR-D-11-00293.1.

Nguyen, L. T., and J. Molinari, 2015: Simulation of the downshear reformation of a tropical cyclone. *J. Atmos. Sci.*, **72**, 4529–4551, doi:10.1175/JAS-D-15-0036.1.

Nguyen, L.T., R.F. Rogers, and P.D. Reasor, 2017: Thermodynamic and kinematic influences on precipitation symmetry in sheared tropical cyclones: Bertha and Cristobal (2014). *Mon. Wea. Rev.*, in review.

Nolan, D. S., and L. D. Grasso, 2003: Nonhydrostatic, three-dimensional perturbations to balanced, hurricane-like vortices. Part II: Symmetric response and nonlinear simulations. *J. Atmos. Sci.*, **60**, 2717–2745, doi:10.1175/1520-0469(2003)060<2717:NTPTBH>2.0.CO;2.

Nolan, D. S., Y. Moon, and D. P. Stern, 2007: Tropical cyclone intensification from asymmetric convection: Energetics and efficiency. *J. Atmos. Sci*., **64**, 3377–3405, doi:10.1175/JAS3988.1.

Pendergrass, A. G., and H. E. Willoughby, 2009: Diabatically induced secondary flows in tropical cyclones. Part I: Quasi-steady forcing. *Mon. Wea. Rev*., **137**, 805–821, doi:10.1175/2008MWR2657.1.

Raymond, D. J., S. Gjorgjievska, S. L. Sessions, and Ž. Fuchs, 2014: Tropical cyclogenesis and mid-level vorticity. *Australian Meteorological and Oceanographic Journal*, **64**, 11–25.

Raymond, D. J., and M. M. Flores, 2016: Predicting convective rainfall over tropical oceans from environmental conditions. *Journal of Advances in Modeling Earth Systems*, **8** **(2)**, 703–718, https://doi.org/10.1002/2015MS000595.

Raymond, D. J., and G. Kilroy, 2019: Control of convection in high-resolution simulations of tropical cyclogenesis. *Journal of Advances in Modeling Earth Systems*, **11** **(6)**, 1582–1599, https://doi.org/https://doi.org/10.1029/2018MS001576.

Raymond, D. J., and Ž. Fuchs-Stone, 2021a: Emergent properties of convection in OTREC and PREDICT. *Journal of Geophysical Research: Atmospheres*, **126** **(4)**, e2020JD033 585, https://doi.org/https://doi.org/10.1029/2020JD033585, e2020JD033585 2020JD033585.

Reasor, P. D., and M. D. Eastin, 2012: Rapidly intensifying Hurricane Guillermo (1997). Part II: Resilience in shear. *Mon. Wea. Rev*., **140**, 425–444, doi:10.1175/MWR-D-11-00080.1.

Reasor, P. D., M. D. Eastin, and J. F. Gamache, 2009: Rapidly intensifying Hurricane Guillermo (1997). Part I: Low-wavenumber structure and evolution. *Mon. Wea. Rev*., **137**, 603–631, doi:10.1175/2008MWR2487.1.

Reasor, P. D., R. F. Rogers, and S. Lorsolo, 2013: Environmental flow impacts on tropical cyclone structure diagnosed from airborne Doppler radar composites. *Mon. Wea. Rev*., **141**, 2949–2969, doi:10.1175/MWR-D-12-00334.1.

Rogers, R.F., 2010: Convective-scale structure and evolution during a high-resolution simulation of tropical cyclone rapid intensification. *J. Atmos. Sci*., **67**, 44–70, doi:10.1175/2009JAS3122.1.

Rogers, R., S. S. Chen, J. E. Tenerelli, and H. E. Willoughby, 2003: A numerical study of the impact of vertical shear on the distribution of rainfall in Hurricane Bonnie (1998). *Mon. Wea. Rev*., **131**, 1577–1599, doi:10.1175//2546.1.

Rogers, R., P. D. 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., P. D. Reasor, and J. A. Zhang, 2015: Multiscale structure and evolution of Hurricane Earl (2010) during rapid intensification. *Mon. Wea. Rev*., **143**, 536–562, doi:10.1175/MWR-D-14-00175.1.

Rogers, R.F., J.A. Zhang, J. Zawislak, H. Jiang, G.R. Alvey III, E.J. Zipser, and S.N. Stevenson, 2016: Observations of the structure and evolution of Hurricane Edouard (2014) during intensity change. Part II: Kinematic structure and the distribution of deep convection. *Mon. Wea. Rev*., **144**, 3355-3376.

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.

Schubert, W. H., and J. J. Hack, 1982: Inertial stability and tropical cyclone development. *J. Atmos. Sci*., **39**, 1687–1697, doi:10.1175/1520-0469(1982)039<1687:ISATCD>2.0.CO;2.

Sentić, S., S. L. Sessions, and Ž. Fuchs, 2015: Diagnosing DYNAMO convection with weak temperature gradient simulations. *Journal of Advances in Modeling Earth Systems*, **7**, 1849 – 1871, https://doi.org/10.1002/2015MS000531.

Sessions, S. L., M. J. Herman, and S. Sentić, 2015: Convective response to changes in the thermodynamic environment in idealized weak temperature gradient simulations. *Journal of Advances in Modeling Earth Systems*, **7 (2)**, 712–738, https://doi.org/10.1002/2015MS000446.

Shapiro, L. J., and H. E. Willoughby, 1982: The response of balanced hurricanes to local sources of heat and momentum. *J. Atmos. Sci*., **39**, 378–394, doi:10.1175/1520-0469(1982)039<0378:TROBHT>2.0.CO;2.

Smith, R. K., and M. T. Montgomery, 2016: The efficiency of diabatic heating and tropical cyclone intensification. *Quart. J. Roy. Meteor. Soc*., **142**, 2081–2086, doi:10.1002/qj.2804.

Stevenson, S. N., K. L. Corbosiero, and J. Molinari, 2014: The convective evolution and rapid intensification of Hurricane Earl (2010). *Mon. Wea. Rev*., **142**, 4364–4380, doi:10.1175/MWR-D-14-00078.1.

Stone, Ž., G. R. Alvey, J. P. Dunion, M. S. Fischer, D. J. Raymond, R. F. Rogers, S. Sentić, and J. Zawislak, 2023: Thermodynamic Contribution to Vortex Alignment and Rapid Intensification of Hurricane Sally (2020). *Mon. Wea. Rev*., https://doi.org/10.1175/MWR-D-22-0201.1, in press.

Tao, C., and H. Jiang, 2015: Distributions of shallow to very deep precipitation–convection in rapidly intensifying tropical cyclones. *J. Climate*, **28**, 8791–8824, doi:10.1175/JCLI-D-14-00448.1.

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, doi: 10.1175/MWR-D-16-0316.1.

Vigh, J. L., and W. H. Schubert, 2009: Rapid development of the tropical cyclone warm core. *J. Atmos. Sci*., **66**, 3335–3350, doi:10.1175/2009JAS3092.1.

Wadler, J., R.F. Rogers, and P.D. Reasor, 2018:The Relationship between Spatial Variations in the Structure of Convective Bursts and Tropical Cyclone Intensification as Determined by Airborne Doppler Radar. Mon. Wea. Rev., 146, 761–780.

Wu, L., S. A. Braun, J. Halverson, and G. Heymsfield, 2006: A numerical study of Hurricane Erin (2001). Part I: Model verification and storm evolution. *J. Atmos. Sci*., **63**, 65–86, doi:10.1175/JAS3597.1.

Zagrodnik, J. P., and H. Jiang, 2014: Rainfall, convection, and latent heating distributions in rapidly intensifying tropical cyclones. *J. Atmos. Sci*., **71**, 2789–2809, doi:10.1175/JAS-D-13-0314.1.

Zawislak, J., H. Jiang, G. R. Alvey III, 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, doi:10.1175/MWR-D-16-0018.1.

Zhang, D.-L., and H. Chen, 2012: Importance of the upper level warm core in the rapid intensification of a tropical cyclone. *Geophys. Res. Lett*., **39**, L02806, doi:10.1029/2012GL052355.

Yuter, S. E., and R. A. Houze, 1995: Three-dimensional kinematic and microphysical evolution of Florida cumulonimbus. Part II: Frequency distributions of vertical velocity, reflectivity, and differential reflectivity. *Mon. Wea. Rev*., **123**, 1941–1963, doi:10.1175/1520-0493(1995)123<1941:TDKAME>2.0.CO;2.