Reply to "Comments on 'Multiscale Structure and Evolution of Hurricane Earl (2010) during Rapid Intensification'"

ROBERT F. ROGERS AND PAUL D. REASOR

NOAA/Atlantic Oceanographic and Meteorological Laboratory/Hurricane Research Division, Miami, Florida

JUN A. ZHANG

Cooperative Institute for Marine and Atmospheric Studies/Rosenstiel School of Marine and Atmospheric Science, and NOAA/Atlantic Oceanographic and Meteorological Laboratory/Hurricane Research Division, Miami, Florida

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Elsberry and Park (2017, hereafter EP17) propose an alternate explanation for the appearance of an aligned vortex during the second WP-3D mission in Hurricane Earl (2010), after the onset of rapid intensification (RI) as documented in Rogers et al. (2015, hereafter R15). EP17 argues that the interaction of the outflow of Hurricane Danielle to the north of Earl had a significant impact on the distribution of convection in Earl. Furthermore, the diurnal evolution of convection within Earl modulated the effective vertical shear experienced by Earl, with reduced shear during periods of the traditional diurnal maximum. EP17 states that this mechanism represents an environmental control that is distinct from the vortex alignment process described in R15.

There is no doubt that the temporally and spatially varying vertical shear plays a significant role in modulating the distribution of deep convection and the intensity evolution of tropical cyclones, including Earl. While the mechanism EP17 describes is certainly plausible, and they raise valid points regarding the limitations of the data and the value in considering additional data sources, we feel that EP17 overstates the degree to which R15 attributes the appearance of an aligned vortex after RI onset to "vortex alignment processes." Furthermore, one of the key points from R15 is that the RI of Earl results from physical processes spanning multiple scales, including environmental scale (e.g., vertical shear and sea surface temperature), vortex scale (e.g., potential vortex alignment), convective scale (e.g., convective bursts and their associated mesoscale convective systems), and boundary layer/turbulent scale (e.g., surface fluxes and development of supergradient flow). The mechanism described in EP17 (i.e., the potential reduction of environmental vertical shear from the development of diurnally modulated convection in a sheared vortex) is a perfect example of one such multiscale interaction. Finally, we suggest that their proposed mechanism actually is consistent with other mechanisms proposed in R15.

R15 did not propose a single mechanism to explain the appearance of an aligned vortex during the second WP-3D mission. Rather, R15 speculated (see section 5a in R15) that one (or more) of three possible mechanisms were at play:

1) the midlevel vortex precesses into the upshear quadrant (relative to the low-level vortex) and subsequently aligns with the low-level vortex;
2) the sustained organization of convection upshear left near the midlevel vorticity maximum promotes organization of vorticity underneath the midlevel vortex, through vorticity stretching in the lower troposphere (the formation of a single vorticity monopole also likely involves vortex symmetrization processes); or
3) the midlevel vorticity maximum is transient and plays no role in the development of the aligned vortex; rather, the low-level vortex builds upward with time.

EP17 focus on the first mechanism (i.e., precession) and argue that an alternate environmental control mechanism could be the primary means for achieving the vortex

Corresponding author e-mail: Robert Rogers, robert.rogers@noaa.gov

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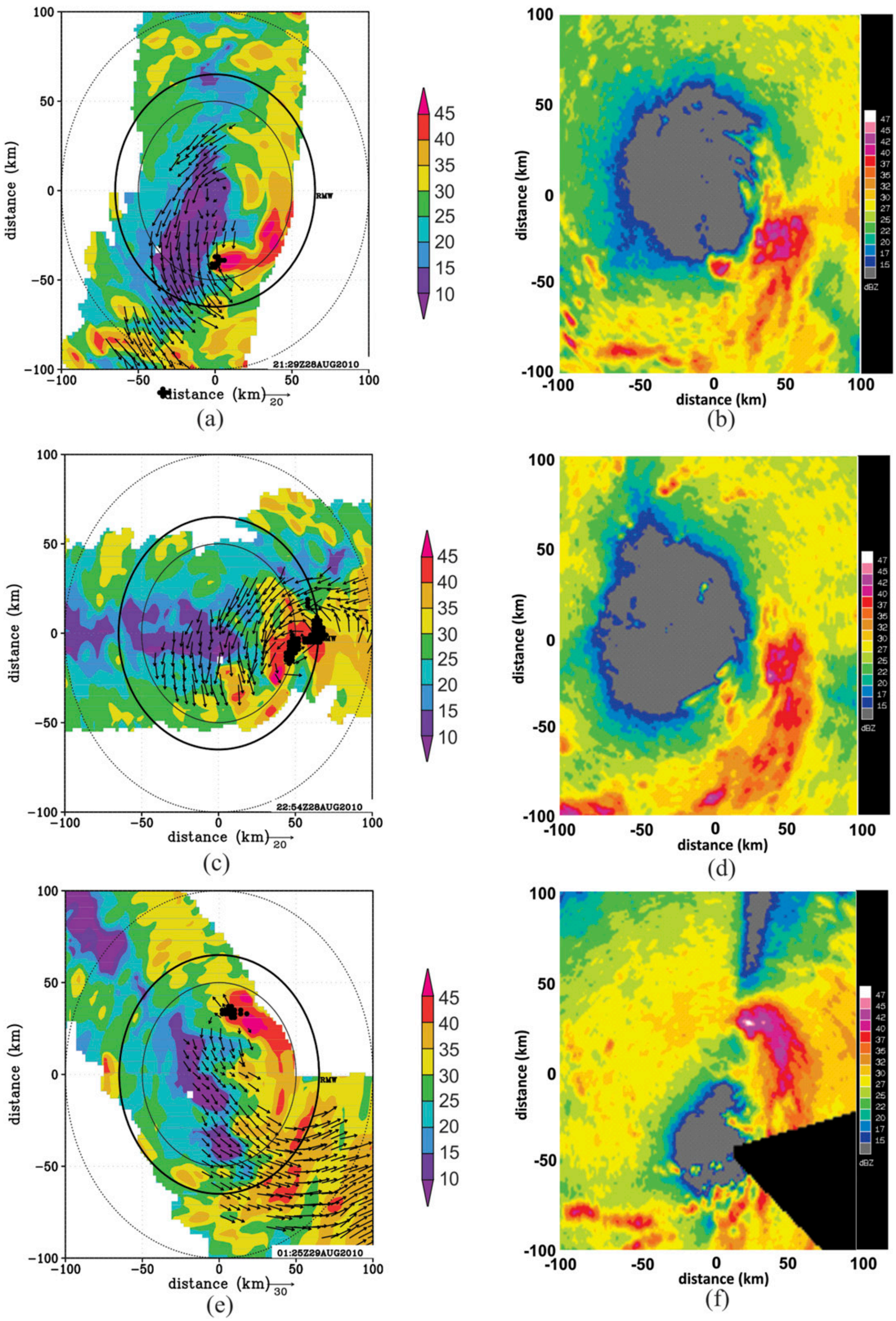

FIG. 1. (a) Reflectivity (shaded, dBZ) at 2-km altitude from tail Doppler radar during an individual radial pass through Earl centered at 2129 UTC 28 Aug. Vectors (m s^{-1}) show storm-relative flow at 8 km. Black dots denote locations of points flagged as convective bursts. RMW at 2-km altitude is indicated by the circle. (b) Storm-centered lower-fuselage reflectivity at 3.5 km from a single sweep at 2133 UTC. (c) As in (a), but for a pass centered at 2254 UTC 28 Aug. (d) As in (b), but for a sweep at 2247 UTC. (e) As in (a), but for a pass centered at 0125 UTC 29 Aug. (f) As in (b), but for a sweep at 0125 UTC and at ~2.5-km altitude. Domains in all images are 200 km on a side. (Reproduced from R15.)

alignment. As discussed in R15, all of these explanations are speculative, which EP17 correctly state is due to the fact that the aircraft missions are essentially spaced 12 h apart. As a result, the analyses shown in Fig. 10 of R15 (and Fig. 1 of EP17) lack the temporal continuity to be able to assess which of these three mechanisms is likely to be the one responsible for the appearance of an aligned vortex. While this is indeed a limitation of the dataset, there was another figure from R15 that showed the evolution of the deep convection at a higher temporal frequency. Figure 7 from R15 (reproduced as Fig. 1 here) shows the storm-relative flow at 8 km, reflectivity at 2 km from the tail Doppler radar (TDR), and locations of convective bursts (CBs) from *individual radial passes* during the first WP-3D mission. These radial passes were centered at 2129 and 2254 UTC 28 August and 0125 UTC 29 August (i.e., ~1.5–2.5 h apart) during this mission. These individual passes were merged to create the more complete horizontal coverage shown in Fig. 10 of R15 (and Fig. 1 of EP17). While the horizontal coverage in the individual radial passes from Fig. 1 is limited, there is a clear indication of a motion of the circulation center at 8 km from a location downshear left to one that is more left of shear and even upshear left.

Figure 1 also shows reflectivity from the lower fuselage (LF) radar on the P-3 for approximately the same times as the tail Doppler analyses from the radial passes. Both the TDR and LF reflectivity show localized areas of high reflectivity values, suggestive of deep convection, that follow a similar motion as the circulation center at 8 km (i.e., from the downshear-left to the upshear-left quadrants). Furthermore, separate papers from Stevenson et al. (2014), using lightning flash counts from the World Wide Lightning Location Network (WWLLN), and Susca-Lopata et al. (2015), using passive microwave satellite data, show a similar motion from the downshear-left quadrant around to the left-of-shear side and then to the upshear-left quadrant during the time of the first WP-3D mission and just afterward. These observations suggest that there is a distinct motion of both the deep convection (Stevenson et al. 2014; R15; Susca-Lopata et al. 2015) and 8-km circulation center (R15) that occurs prior to the onset of Earl's RI. Additionally, high-resolution HWRF simulations of Earl have documented a similar progression of the upper-level vortex relative to the lower-level vortex and emphasize the importance of eddy processes prior to and during the onset of RI (Chen and Gopalakrishnan 2015; Smith et al. 2017).

All of these results provide strong evidence that there is a coherent structure and evolution to the convection and midlevel vortex that appears related to the onset of RI, and they suggest the potential of a precession-type process occurring. However, lacking complete horizontal coverage and temporal continuity, a definitive assessment of the validity of this mechanism cannot be made. The two other mechanisms proposed in R15 (i.e., mechanisms 2 and 3 above) could also be responsible for the appearance of an aligned vortex by the time of the second WP-3D mission. Furthermore, in fact, the mechanism proposed by EP17 is broadly consistent with these two mechanisms. Specifically, mechanism 2 emphasizes the role of convection in increasing low-level vorticity underneath the existing midlevel circulation, while mechanism 3 states that the midlevel vortex plays no role, but the low-level vortex builds upward with time. Both of these mechanisms could occur in the presence of convection, either by increasing low-level vorticity underneath a midlevel vortex or by increasing midlevel vorticity above a low-level vortex.

What is unique about EP17's suggestion, and with which we agree, is the emphasis on the diurnal cycle of convection within Earl and its reduction of vertical shear in the inner core of Earl (as indicated by the CIMSS analysis that relies on cloud-drift winds). As mentioned above, though, this mechanism should be considered as a multiscale process, rather than an environmental control, since it describes the interaction of convection with environmental vertical shear.

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