5D.3 INVESTIGATION OF LIGHTNING STRUCTURE DURING THE RAPID INTENSIFICATION OF HURRICANE EARL (2010)

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1. INTRODUCTION

A clear relationship between lightning activity and tropical cyclone (TC) intensity change has not been established. The analysis of lightning in TCs over the open ocean is a relatively new research area. Although there are numerous regional lightning detection systems in many countries, a reliable, ground-based, continuous global lightning detection system did not exist until the mid-2000's. Prior to a continuous global lightning detection system, lightning data over the open ocean was limited to satellite observations that passed over the same area only once or twice per day. The World Wide Lightning Location Network (WWLLN; operated by the University of Washington) is a global, ground-based network presently consisting of more than 70 sensors that was established in the early 2000's (Lay et al. 2004), but fairly uniform global coverage was not available until about 2005 (DeMaria et al. 2012).

Lightning in TCs has been previously studied using regional lightning detection networks such as the National Lightning Detection Network (NLDN) (Molinari et al. 1999) and satellite-borne instruments like the Tropical Rainfall Measuring Mission (TRMM) satellite's Lightning Imaging Sensor (LIS) (Cecil et al. 2002). These studies have found a common radial distribution of lightning with three distinct regions: 1) a weak maximum in the eyewall region (< 100 km), 2) a clear minimum just outside the eyewall in the inner rainband region (100-120 km), and 3) a strong maximum in the outer rainbands (210-290 km) (Molinari et al. 1999). Examining the azimuthal distribution of lightning in 35 Atlantic basin TCs, Corbosiero and Molinari (2002, 2003; hereinafter CM02 and CM03) related lightning strike locations to both the directions of deep layer (850-200 hPa) vertical wind shear and storm motion, but ultimately determined the shear dominated the lightning distribution. When the shear exceed 5 m s^{-1}, more than 90% of the lightning occurred downshear, consistent with theoretical arguments that the shear tilts the TC vortex and induces a stronger diabatic secondary circulation downshear in an attempt to maintain balance and realign the vortex (Reasor et al. 2004). In the inner core (< 100 km), there was a slight preference for lightning to peak in the downshear left quadrant. Less than 10% of the inner core time periods examined had lightning peaks upshear, emphasizing how strongly the downshear quadrants dominate the lightning distribution.

In recent years, a few studies have begun to look at lightning structure and TC intensity trends using the WWLLN. Abarca et al. (2011) performed a similar study to CM02 and CM03 using the WWLLN with 24 TCs in the Atlantic basin. Comparable lightning patterns were found in relation to shear. This study also concluded that inner core lightning density has the potential to forecast intensity changes in TCs, with forecasts of weaker storms having more potential, as they tend to have larger lightning flash densities than stronger TCs. Price et al. (2009) analyzed the strongest TCs in all basins around the globe and found an increase in lightning activity one day prior to intensity peaks. Pan et al. (2010) limited their study to seven super typhoons in the Northwest Pacific and similarly noted lightning outbreaks in the eyewall several hours prior to peak intensity. In contrast, another study analyzing Atlantic basin TCs suggested an inner core lightning outbreak precedes weakening, and an outer rainband lightning outbreak is followed by intensification (DeMaria et al. 2012). Thomas et al. (2010) similarly found increased inner core lightning activity prior to, and during, periods of weakening in major Atlantic hurricanes. Molinari et al. (1999) proposed two intensity scenarios following an eyewall lightning outbreak. A TC may rapidly intensify if the eyewall lightning outbreak occurs while the TC is weakening, steady, or slowly deepening. In contrast, if the TC has been deepening for some time, an eyewall lightning outbreak may indicate that intensification is coming to an end.

Nearly all studies analyzing lightning in TCs agree that lightning data could help improve intensity forecasts, and it is well known that intensity forecasts have seen little progress over the past few decades (Rappaport et al. 2009). Since there is disagreement over whether a TC will intensify or weaken with an inner core lightning outbreak, there is a need to analyze this issue further. Lightning activity in TCs is very episodic (DeMaria et al. 2012), so analyzing composites of several TCs may hide important details. Thus, a detailed case study on lightning in an individual TC would add valuable further insight. This study will analyze Hurricane Earl (2010), a case in which an inner core lightning outbreak preceded a prolonged period of rapid intensification.

2. DATA AND METHODS

2.1 *Lightning*

The lightning detection system utilized in this study is the WWLLN (http://www.wwlln.com). At the time of writing, the WWLLN consists of more than 70 "time of arrival" sensors located around the globe that detect the very low frequency (VLF) radio waves of lightning sferics (Abarca et al. 2011). The VLF energy emitted by a lightning strike travels through the Earth-ionosphere waveguide where it is reflected back and forth to the

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Earth's surface until it reaches a sensor. This system allows for detection of strikes several thousands of kilometers from the sensor; however, the polarity of the strike is not retained since it is unknown how many times the energy is reflected between the ionosphere and Earth's surface. The WWLLN is able to capture both cloud-to-ground (CG) and intracloud (IC) strikes, although the detection efficiency (DE) of CG flashes is about twice the DE of IC flashes (Abarca et al. 2010).

While the global lightning DE is thought to be around 10% (Abarca et al. 2010), some regions have a higher DE than others. Most notably, Rudlosky and Shea (2013) found that the WWLLN DE is three times greater over the ocean than over land when comparing the detected WWLLN strikes to the LIS onboard the TRMM satellite. All locations with a DE greater than 20% were found over oceans. Abarca et al. (2011) found that even with a low DE, the WWLLN was able to capture the spatial structure of lightning in TCs quite well when compared to previous studies.

2.2 *Track and Intensity*

The lightning strike locations from the WWLLN were transformed into a storm-centered framework for analysis. The distance of each strike from the center was calculated using the National Hurricane Center (NHC) best track dataset linearly interpolated to one-minute resolution. The track interpolation to each minute is necessary to more accurately map lightning strikes near the core; the strike location relative to the TC center could change quadrants easily if only six-hourly, or interpolated one-hourly, track centers were used. Though the best track is known to miss the erratic behavior of TC movement, the authors found the lightning patterns, when linearly interpolating the best track to each minute, are very similar to other center location datasets with finer time resolution (e.g., flight reconnaissance data and the Hurricane Research Division's center fixes). The best tracks of Earl and Danielle are shown in Figure 1. Outflow from

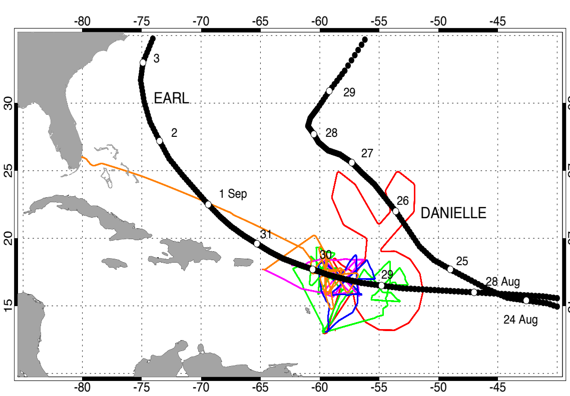

Figure 1. *Interpolated hourly best tracks for Hurricanes Earl and Danielle (2010). White circles indicate 0000 UTC each day. The colored lines are the aircraft flight tracks near the beginning of Earl's RI: NOAA49 (red), NOAA43 (green), NOAA42 (blue), USAF306 (magenta) and NASA DC-8 (orange).*

Danielle influenced the shear direction over Earl during the period of study.

Intensity measurements were also obtained from the best track dataset. Rapid intensification (RI) is defined by a 30-kt or greater wind increase in 24 h (Kaplan and DeMaria 2003). Earl began to rapidly intensify at 0600 UTC 29 August and continued intensifying until around 0000 UTC 31 August when an eyewall replacement cycle began (Cangialosi 2011). Over this period of RI, Earl went from a 55-kt tropical storm to a 115-kt major hurricane (Figure 2).

2.3 *Shear*

Similar to CM02 and CM03, this study will rotate the lightning into a shear-relative framework. Deep-layer vertical wind shear was calculated from 850-200 hPa by averaging over a 0-500 km radius from the TC center in order to remove the symmetric vortex. Table 1 shows the magnitude and direction of the shear from the Global Forecast System (GFS) 1°. The deep-layer vertical wind shear direction starts out from the northeast at the beginning of RI and switches to northwesterly toward the end of RI. Mean vertical wind shear is typically westerly to northwesterly during the summer for this region of the Atlantic basin (Chen et al. 2006). The somewhat unusual shear direction at the beginning of RI was the result of outflow from Hurricane Danielle located to the north of Earl (Figure 1).

	Magnitude (m s^{-1})	Direction (°)
18 UTC 28 Aug	7.29	25.59
00 UTC 29 Aug	8.41	45.29
06 UTC 29 Aug	**4.04**	**58.45**
12 UTC 29 Aug	**7.32**	**40.62**
18 UTC 29 Aug	**5.38**	**64.07**
00 UTC 30 Aug	**2.71**	**30.44**
06 UTC 30 Aug	**2.27**	**325.87**
12 UTC 30 Aug	**3.18**	**313.40**
18 UTC 30 Aug	**1.59**	**348.92**
00 UTC 31 Aug	7.00	328.92
06 UTC 31 Aug	7.42	267.07

Table 1. *The vertical wind shear magnitude and direction from the GFS 1° from 12 h prior to, and after, RI. The shear is calculated from 850-200 hPa in a 0-500 km radius from the TC center. Directions are meteorological. The bold dates indicate the RI period.*

2.4 *Aircraft Reconnaissance*

In addition to the spatial analysis of lightning in Earl, aircraft reconnaissance data was used to further analyze reasons for the observed lightning distribution. There was extensive flight coverage during the intensification of Earl. This study will utilize data from the NOAA P-3 aircraft (NOAA42 and NOAA43), United States Air Force C-130 aircraft (USAF306), and the NASA DC-8 aircraft flown in support of the NASA Genesis and Rapid Intensification Processes (GRIP) experiment. The flight tracks of these aircraft are overlaid on the best track in Figure 1.

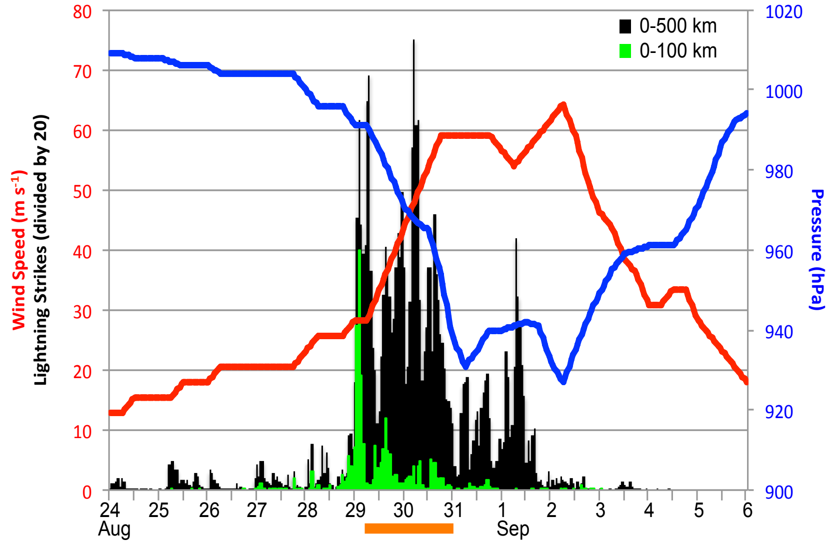

Figure 2. *Wind speed, pressure, and lightning strike counts in Hurricane Earl. The dates are labeled at 0000 UTC each day. Wind speed (m s^{-1}) is represented by the red line. Pressure (hPa) is represented by the blue line. Both pressure and winds are taken from the best track dataset. The black bars are the number of lightning strikes in the 0-500 km radius from the center and the green bars are the number of lightning strikes in the 0-100 km radius. The actual strike count corresponds to the left axis multiplied by 20. The orange line below the time axis indicates when RI occurred.*

3. RESULTS

3.1 *Lightning Evolution*

A remarkable 48,179 lightning strikes were captured by the WWLLN within a 500-km radius over the lifespan of Hurricane Earl. Only four of the 29 major Atlantic hurricanes from 2005-2013 recorded a greater total number of lightning strikes from the WWLLN within the same radius (Stevenson et al. 2014). Figure 2 shows the evolution of the lightning strikes in Earl from its pre-tropical depression stage to its extratropical stage. Earl's lightning was not very active until around 0100 UTC 29 August, when 800 lightning strikes occurred over the next hour in the inner core. Molinari et al. (2004) noted that the NLDN captured almost 900 strikes per hour in the inner core of Hurricane Danny (1997) while the TC was intensifying (see their Figure 3), the highest strike frequency of any inner core lightning outbreak within range of the NLDN from 1985-2001.

The inner core lightning burst in Earl preceded a 42-h period of RI (0600 UTC 29 August – 0000 UTC 31 August). While some studies have suggested inner core lightning is detrimental to intensification, Earl seems to suggest that inner core lightning could promote intensification. Aside from the pre-RI inner core lightning burst, the inner core did not experience any significant amount of lightning at any other time in the lifespan of Earl.

3.2 *Spatial Structure of Lightning*

Rotating the lightning into a shear-relative framework revealed atypical patterns in the spatial characteristics of the lightning. Fifty-percent of the inner core flashes were in the upshear left quadrant. As previously mentioned, CM03 found it extremely rare for lightning to peak in this particular quadrant (see their Figure 7); only 4% of the times they analyzed had an upshear left peak. About 60% of the inner core, upshear left lightning strikes in Hurricane Earl occurred in the six hours prior to RI.

Figure 3 shows the onset and progression of the inner core, upshear left lightning burst that preceded RI. The outbreak began around 2100 UTC 28 August left of shear, and increased in intensity as it rotated counterclockwise. The deep convection peaked in lightning production around 0130 UTC 29 August (green dots in Figure 3) and continued to rotate around the TC center though the upshear quadrants until about 0600 UTC 29 August. All of this inner core lightning was

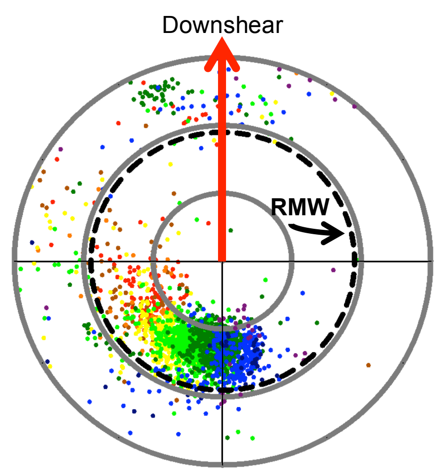

Figure 3. *Lightning strike locations in the inner core with respect to the GFS 1° shear vector from 2100 UTC 28 Aug – 0600 UTC 29 Aug. Range rings (grey) are every 50 km out to 150 km from the TC center. The dashed black line is the RMW. Colors indicate the hour the strikes occurred: 2100–2200 UTC (red), 2200–2300 UTC (brown), 2300–0000 UTC (orange), 0000–0100 UTC (yellow), 0100–0200 UTC (green), 0200–0300 UTC (dark green), 0300–0400 UTC (blue), 0400–0500 UTC (dark blue), and 0500–0600 UTC (purple).*

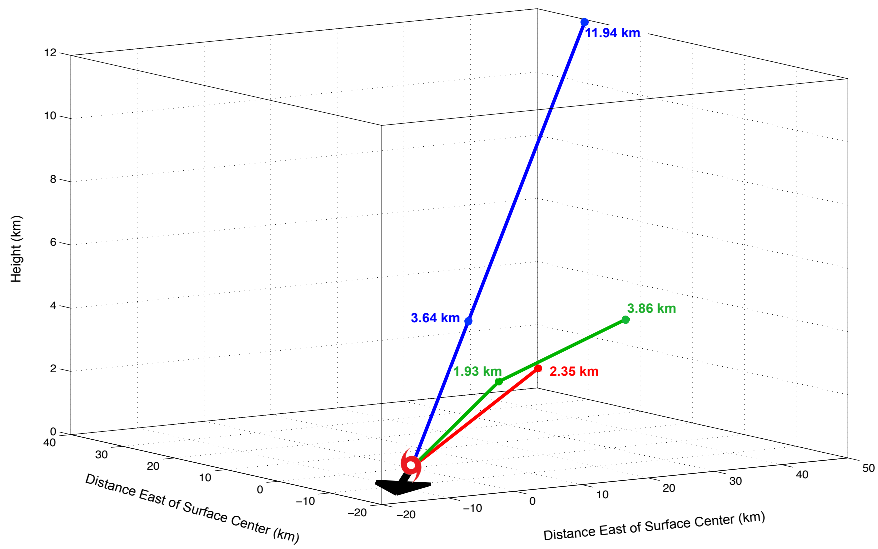

Figure 4. *Vortex tilt of Earl at three different times: 0000 UTC 29 Aug (red), 1200 UTC 29 Aug (green), and 2100 UTC 29 Aug (blue). The centers at each level are the D-value centers determined by aircraft flying through the storm. The red line is the NOAA43, the green line is a combination of NOAA42 and USAF306, and the blue line is a combination of NOAA43 and DC-8. The labeled points indicate the height at which the center value was measured. The tropical storm symbol denotes the interpolated best track surface center. The thick black arrow shows the direction of the shear from the GFS 1°.*

located inside the radius of maximum wind (RMW), which was calculated from flight-level data. Shapiro and Willoughby (1982) showed that a heating source (i.e., convection) near the RMW leads to the spin-up of tangential winds just inside the RMW (see their Figure 11). Musgrave et al. (2012) similarly showed that the tendency of tangential winds was dependent on the location of diabatic heating relative to the RMW, with diabatic heating located inside the RMW most likely to lead to intensification. Observational airborne Doppler radar (Rogers et al. 2013) and ground-based radar (Corbosiero et al. 2005) studies have shown that intensifying TCs tend to have convective bursts located inside the RMW. Convection, and thus lightning, inside the RMW promotes intensification by further enhancing the warm core through diabatic heating (Vigh and Schubert 2009).

3.3 *Vortex Structure*

Aircraft flying through TCs are able to locate the vortex center at that particular height using D-value measurements, the change in height along a constant pressure surface from the standard atmospheric height of that surface. At 0000 29 August, the NOAA P-3 measured a D-value center location at 2.35 km height that was 26 km upshear left from the interpolated best track surface center at the same time (Figure 4). This suggests the TC vortex was tilted upshear left, at least up to 2.35 km. Twelve hours later at 1200 UTC 29 August, just six hours after RI began, another NOAA P-3 and an Air Force C-130 flew at slightly different levels through the center. The D-value centers again showed an upshear left tilt of the vortex, with a magnitude of 38 km up to 3.86 km height. At 2100 UTC 29 August, the NASA DC-8 flew through the center at upper levels, coincident with another NOAA P-3 flight at lower levels. These two flights indicate the vortex was now tilted directly upshear, with a tilt magnitude of 59 km from the surface to 11.94 km height.

During the 21-h period shown in Figure 4, the tilt decreased over the lower layers of the storm. Between 1200 UTC and 2100 UTC 29 August, the tilt magnitude around the 3.5 km height decreased from 38 km to 26 km. The D-value evaluation of the vortex tilt in Earl also suggests the vortex was precessing counterclockwise (i.e., cyclonically) on the upshear side of the TC center. The red line in Figure 4 shows the vortex tilted upshear left, at least up to 2.35 km, 6 h before RI began. During the RI period, this vortex tilt rotated counterclockwise around the surface center (note the tilt progression from the red to green to blue lines in Figure 4) until its observed tilt was directly upshear at 2100 UTC 29 August.

Upshear tilt is atypical for a TC in an environment with moderate vertical wind shear, but it is consistent with the convective activity revealed by lightning locations in Earl. Theoretical work has shown vertical wind shear initially acts to tilt the TC vortex downshear, prompting eyewall convection to become asymmetric with a stronger diabatic secondary circulation downshear (Reasor et al. 2004). The downshear tilt of the vortex allows the upper- and lower-level cyclonic potential vorticity anomalies to interact in a manner that results in the cyclonic precession of the tilted vortex. If the vortex precesses upshear, the vertical wind shear would then act to reduce the tilt magnitude (Jones 1995). However, in several numerical modeling studies (Braun et al. 2006; Wu et al. 2006; Davis et al. 2008), the vortex has been found not to precess all the way around to upshear, but to reach a stable downshear left configuration, which is optimal for tilt reduction due to the mutual advection of the upper- and lower-level centers (Reasor et al. 2004).

Although continuous observations of vortex tilt are difficult to collect because aircraft need to observe a storm at multiple vertical levels, Reasor et al. (2000) and Reasor and Eastin (2012) were able to use airborne Doppler radar observations from Hurricane Olivia (1994) and Hurricane Guillermo (1997), respectively, to find downshear left tilted vortices. Additionally, Reasor et al. (2013) examined airborne Doppler radar data from 19 TCs; almost all of the cases had a vortex tilted downshear, unlike that found here in Earl. While observations were not available to discern if the vortex of Earl was initially tilted downshear, the observations suggest that the vortex tilt precessed cyclonically, and the tilt magnitude decreased while the vortex was tilted upshear. To our knowledge, this is the first study to capture the precession process in observations. Both the lightning movement in the inner core and the D-value evaluation of pressure centers at different levels suggest precession was occurring. Even with the limited data available, the tilt observed suggests the inner core lightning burst was tied to the direction of the tilt rather than the shear, consistent with Jones (1995).

3.4 *Flight-level Data*

One of the NOAA P-3 flight legs was used to examine the environmental characteristics in the vicinity of the inner core lightning burst. This leg flew at approximately 675 hPa from the downshear right quadrant, through the center, and out through the upshear left quadrant around 0000 UTC 29 August. Flight-level data revealed a transition from positive (outflow) to negative (inflow) radial winds in the region where the inner core lightning burst occurred, upshear left of the TC center (Figure 5b), implying convergence at flight level. Coincident with this radial wind sign reversal, a sharp gradient in equivalent potential temperature (θ_e) was found (Figure 5a). Corbosiero et al. (2005) similarly found that the maximum negative radial gradient in θ_e coincided with the location of the maximum eyewall updraft in Hurricane Elena (1985).

4. SUMMARY AND CONCLUSIONS

Continuous global lightning datasets are in the early stages of being feasible for research purposes. Although continental lightning detection networks have previously been used to investigate the lightning structure in TCs, few have examined lightning in tropical cyclones over the open ocean distant from large landmasses. Hurricane Earl (2010) provided such an opportunity for several reasons. The NASA GRIP field campaign, coincident with two other major field campaigns in the Atlantic basin, provided extensive flight coverage over the TC, and the WWLLN captured a large number of strikes in Hurricane Earl, well over 40,000. For a lightning detection network known to have a low global detection efficiency, this was a remarkable number of strikes.

With respect to the shear vector, most lightning occurred upshear left in the inner core (< 100 km). This inner core, upshear left maximum does not agree with previous studies that have found lightning peaks in this quadrant are rare. Nearly all of the inner core lightning occurred just prior to the period of RI. Using reconnaissance aircraft data, it was found that the inner core burst was aligned with the tilt direction of the vortex rather than with the direction of shear. During the inner

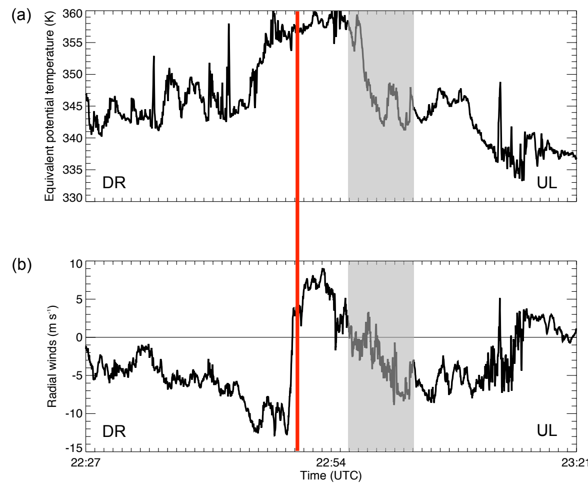

Figure 5. *Data from the NOAA43 showing (a) equivalent potential temperature (θ_e) and (b) radial winds along the leg from the downshear right to the upshear left quadrant at approximately 675 hPa. The grey shaded area is the approximate location of the inner core lightning burst. The red line indicates the time the D-value minimum was recorded for this flight leg.*

core convective burst, the vortex was tilted upshear and was precessing counterclockwise over a 21-h period just prior to, and during, the beginning of RI, just like the lightning burst. This is the first study, to our knowledge, that has shown vortex precession, with modest tilt reduction, from observations. Vortices are typically found to tilt in the downshear left position because this is believed to be the optimal configuration for tilt reduction in a sheared environment. Our results may suggest tilt configurations in a sheared environment vary depending on whether the TC is fully formed or in the process of developing. Data collected on a flight leg from the downshear right to upshear left quadrants of Earl showed that the upper shear quadrant was supportive of deep convection and lightning as a strong θ_e gradient was coincident with the implied convergence of radial winds in the region where the burst began.

The case of Hurricane Earl showed that an inner core lightning burst could precede a prolonged period or RI. This burst likely contributed to RI as it occurred inside the RMW: previous studies have shown that diabatic heating sources inside the RMW lead to a spin up of the tangential winds inside the RMW, intensifying the TC. While the lightning burst occurred in an unusual quadrant, upshear left, observations revealed this was consistent with the vortex tilt. Since Earl's vortex was tilted upshear left when the burst began, both the shear and diabatic heating associated with the upshear convection were likely acting the reduce the tilt. The alignment of the vortex in the vertical likely played a role in the subsequent period of RI.

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