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Tropical Cyclone Lightning Related to Polarimetric Radar Variables

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I. INTRODUCTION

Lightning within tropical cyclones has not been extensively studied. Lightning's intensity, location, and occurrence vary substantially within these storms. Here we present a study of the association between lightning strikes within tropical cyclone bounds and polarimetric radar data, to see how different radar variables may be related to lightning occurrence and characteristics.

This research is not the first of its type, but as with all knowledge there are areas that have not been totally filled in. "The mechanism responsible for the formation of the maximum flash density at the tropical cyclone periphery is not well understood as yet" (DeMaria et al. 2012). To address this outstanding topic, we have analyzed the polarimetric variables in coordination with lightning flash rates to identify possible mechanisms for the high flash density. It has been observed that high flash density is generally associated with stronger cells and deeper convection. Isolated strong cells in the outer rainbands are not uncommon and likely have a stronger updraft and more efficient charge separation. "In and near strong updrafts, flashes tend to be smaller and more frequent, while flashes far from strong vertical drafts exhibit the opposite tendency" (Lund et al. 2009). This would suggest that stronger updrafts should be associated with higher flash density.

In this research, we compared in-cloud (IC) lightning and cloud-to-ground (CG) lightning initiation points with the polarimetric radar variables. While looking at the lightning data overlaid on radar images, it is apparent that some cells do not exhibit the same degree of electrical activity as others. We individually examine these cells to find out why some are more active, with a focus on microphysical processes and distributions favorable for charge separation.

Hurricane Irene, which made landfall in North Carolina during August 2011, and Tropical Storm Gabrielle, which brushed Puerto Rico in early September 2013 as a tropical depression, will be the subjects of study in this research. Numerous datasets exist for these storms, including polarimetric radar and lightning data. The times of interest are a few hours before Irene's landfall, and during midday on the 5th of September for Gabrielle as the outer rainbands passed near the radar site. During these periods, the storms began interacting with land. In the case of Irene, the storm made a gradual landfall travelling almost parallel to the North Carolina coast. Gabrielle never made landfall on Puerto Rico, but sent several rain bands across the island during its passage.

II. DATA and METHODS

Lightning data was obtained from the Earth Networks Total Lightning Network (ENTLN), and polarimetric radar data was obtained from the National Climatic Data Center. The ENTLN supplies information on both CG and IC lightning strikes. The datasets of lightning included latitude and longitude of the strike based on the highest density of location points for a single strike. Also included are the amperage, time and type – whether CG or IC. Polarimetric radar data for Hurricane Irene was obtained from the Weather Surveillance Radar – 1988 Doppler (WSR-88D) location at Morehead City, North Carolina (KMHX), and data for Tropical Depression Gabrielle was obtained from the San Juan, Puerto Rico (TJUA) WSR-88D. Hurricane Irene passed almost directly over KMHX during landfall on August 27, 2011. Tropical Storm Gabrielle passed to the south and west of Puerto Rico, though many of the rainbands passed over the island and TJUA during the 5th and 6th of September, 2013.

Several software applications were used to analyze the data. All lightning data were originally in Microsoft Excel format. To more quickly sort and construct figures from the lightning data, we are using Interactive Data Language (IDL) programming. To view the NEXRAD radar data, we are using the Integrated Data Viewer (IDV) from UNIDATA, and the Weather and Climate Toolkit, distributed by the National Climatic Data Center. Both programs allow plotting of lightning strike locations over the radar images. For our three research questions, over-plotting analysis was used to determine which cells and what part of the cells were more electrically active, which can be compared to the polarimetric radar variables.

The following are the research questions we have sought to answer:

1) Does in-cloud (IC) lightning yield the same information as cloud-to-ground (CG) lightning?

To answer this question, IC and CG lightning data were analyzed in similar ways. We separated the data into five-minute bins by time period corresponding to five-minute radar sweeps. Thus, for every radar volume sweep, lightning strike locations were overlaid on radar data corresponding to the same period. The lightning data was also divided by separating IC from CG strikes and positive from negative strikes. By counting the number of strikes per period (corresponding to the radar volume sweep duration of five minutes), five minute flash rates were produced. This procedure was followed so later we could easily compare lightning occurrence and flash rate to the polarimetric radar variables.

2) What is the relationship between lightning flash rate and the polarimetric radar variables?

Values of polarimetric radar variables (reflectivity factor, differential reflectivity, correlation coefficient, specific differential phase) and their fluctuations are directly related to lightning flash rate and intensity. This analysis involved comparing the radar data and overlaid lightning points, examining polarimetric radar variables in areas with high and low flash rates, and relating our observations to storm structure.

3) Why do some storm cells within tropical cyclone rainbands exhibit substantial electrical activity while other nearby cells exhibit little to none?

In the research so far, it is apparent that while many storm cells within Irene and Gabrielle's rainbands were electrically active, some nearby cells showed little to no activity. We are continuing to examine the polarimetric radar data to look for differences in the radar variables between these cells. We want to find out why certain storm cells suddenly exhibit much more electrical activity than their neighbors. Comparing polarimetric radar data between cells should allow us to discover differences in precipitation particle distributions between storms, leading to more or less effective charge separation. For instance, we examined whether a large mass of graupel above the freezing level is associated with higher flash rates.

III. RESULTS

Under the first research question, we seek to understand the relationship between CG and IC lightning. With Hurricane Irene it was shown by graphing the number of IC and CG strikes that IC strikes were much more common (Figs. 1 and 2).

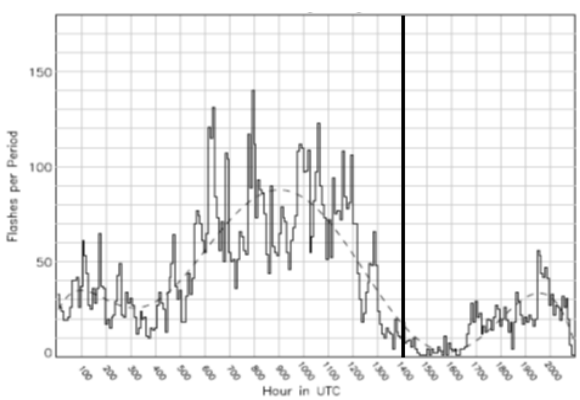

Figure 1. CG lightning flashes per five-minute period in Hurricane Irene, from 00 to 21 UTC on August 27, 2011. Vertical bar indicates the approximate time of landfall.

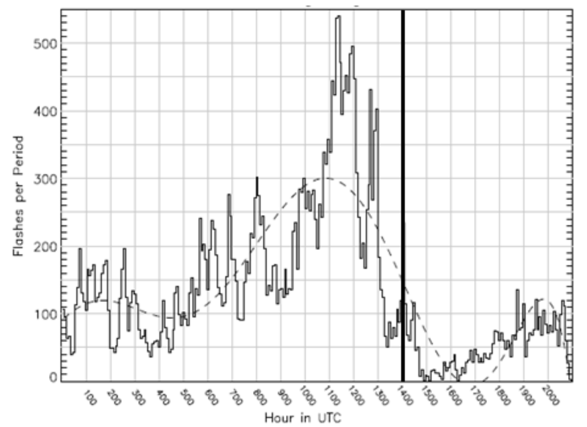

Figure 2. As in Fig. 1, except for IC lightning flashes.

This is possibly explained by the strength of the updraft within the rainband cells. Previous research (Lund et al. 2009) suggests that deep, rapidly rising updrafts produce more frequent flashes. Rapidly rising air in the storm core creates shear stress along the core edge; some of the rising particles get caught in shear-induced eddies. Naturally this separates charges as some of the particles are held back while others continue upward within the updraft. This produces an environment for frequent discharges between different layers of the cell (Lund et al 2009). According to Figures 1 and 2, high flash rates suggest predominantly IC strikes. If the updrafts are strong, it is more likely that IC strikes will be more prevalent.

The black line shown on Figs. 1 and 2. at 14 UTC indicates when Irene's eyewall began to make landfall. We observed that, though the IC flash rate showed a strong maximum in the hours prior to landfall, flash rates for CG and IC lightning dropped significantly as Irene moved inland. "…time variation of flash frequency over 300 km displayed one common behavior: a strong rise in flash rate in the hours prior to landfall" (Molinari et al. 1998). This lightning study done on several Atlantic and Gulf of Mexico cyclones confirms this observation in our research. However, after the above observation, the researchers stated, “The reasons for this behavior are unclear.” It is difficult to find substantial information on lightning activity during landfall from previous studies. Many ignore the data that exists after landfall altogether. “We confine our studies to hurricanes over the ocean” (Black et al. 1998). Future research should be focused on determining reasons for varying lightning flash rates around the time of landfall.

Fig. 3 identifies one of the challenges faced in analyzing data from Hurricane Irene. Most of the lightning data existed around 150 km from the radar site and from the hurricane’s eyewall (Fig. 3). Though we could not specify a reason, our data indicated few to no lightning strikes within the eye wall or nearby areas. Previous researchers mention similar observations within the eyewall and rainbands. “The most intense storms contained both very low lightning frequency and second highest frequency…. Moderate hurricane Gloria had virtually no lightning” (Molinari et al. 1998). Similarly, Squires et al. (2007) states that “the nature of lightning outbreaks in other tropical storms may vary, depending on the storm’s environment and strength.”

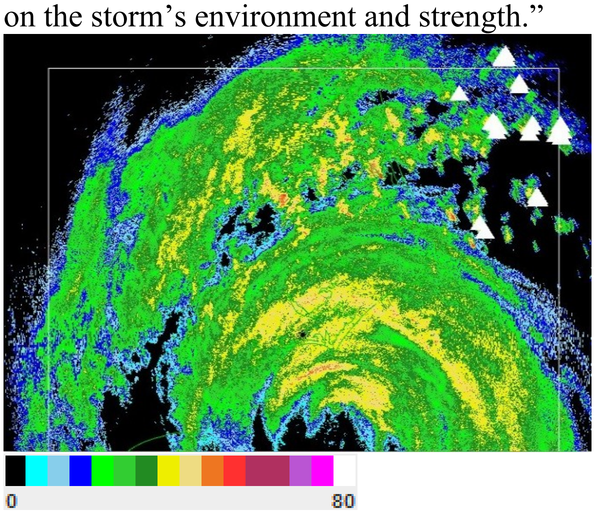

Figure 3. Hurricane Irene on August 27, 2011, at 0814 UTC. Reflectivity factor at elevation angle of 0.5 degrees with overlaid CG and IC (combined) lightning strikes shown with white triangles.

Convection in the outer rainbands was generally shallower than within the eyewall and spiral rainbands near the eyewall, evident by the greater area of high reflectivity near the eyewall. Many isolated cells in the rain-bands still had deep convection. According to previous research, the strong updraft in areas of deep convection separates charge (Lund et al. 2009). Positive charge builds up in the upper layers and negative in the middle layers of the cell; this promotes discharges within the cloud. Fig. 4 (below) shows an upper level sweep of differential reflectivity. This figure shows examples of depolarization. “Depolarization only affects the Z_{DR} product. If appears as radial spikes that can be either high or low Z_{DR} values” (WDTB 2013). The effect is caused by ice crystals canting at angles that align with an electrical field. In Figure 4, the black circles are areas of low Z_{DR}, or more vertically-oriented ice crystals, while red circles are high values that indicate horizontally-oriented crystals. Both are examples of depolarization because whether canted more vertically or horizontally, they indicate the presence of an electrical field.

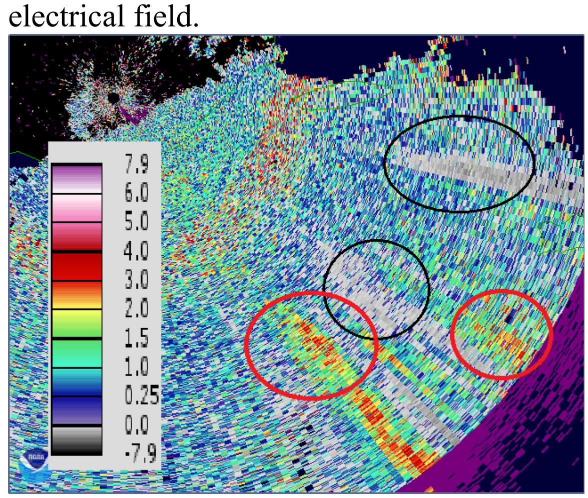

Figure 4. Tropical Cyclone Gabrielle on September 5, 2013, at 0402 UTC. Differential reflectivity at elevation angle of 4.0 degrees.

Tropical Depression Gabrielle exhibited a very different ratio between lightning types. During the study period, Irene displayed 33,526 IC strikes and 10,021 CG, or a 0.29:1 CG:IC ratio. Gabrielle displayed only 712 IC strikes but 17,390 CG, or a 24.4:1 CG:IC ratio. It is clear that Gabrielle showed a far greater percentage of CG strikes than IC compared to Irene. While reflectivity showed that Gabrielle had a significant number of deep convective cells, a 00 UTC sounding from TJUA on the 6th of September shows the freezing level was approximately 4700 meters (Fig. 5). This is shallower than the freezing level in Hurricane Irene (Fig. 6), which was at approximately 6200 meters. The sounding from Hurricane Irene (Fig. 6) was taken within the eyewall prior to landfall; this explains the high moisture and moist adiabatic temperature profile. The lower the freezing level, the greater the total graupel and ice crystal mass may be, all else equal, leading to more efficient charge separation and thus higher lightning flash rates.

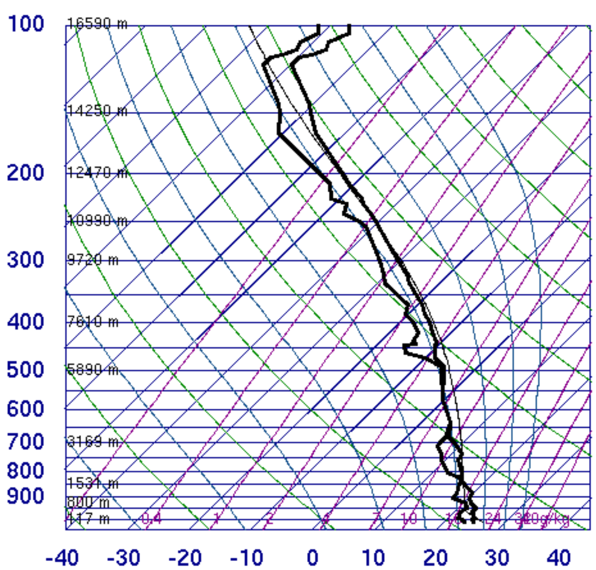

Figure 5. Skew-T diagram from San Juan, Puerto Rico, at 00 UTC on September 6, 2013

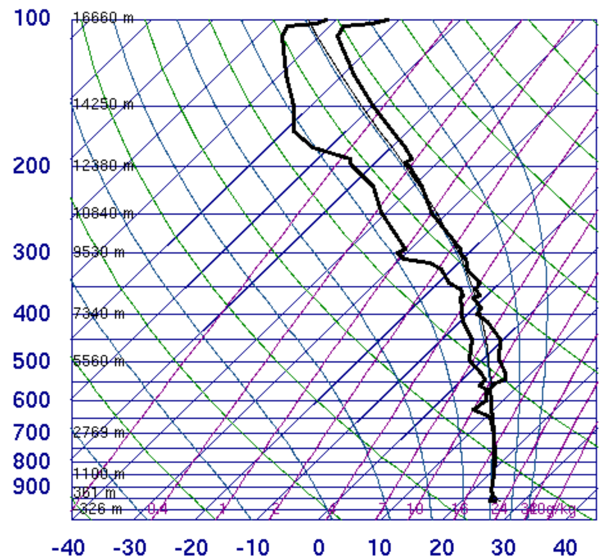

Figure 6. Skew-T diagram from Morehead City, North Carolina at 12 UTC on August 27, 2011

We also sought to use the polarimetric radar variables to explain the mechanisms responsible for high flash rates observed in certain cells. The proximity of lightning-saturated cells to the TJUA site within Gabrielle made it a better case to study for this purpose (Fig. 7). Cells with widespread moderate to strong reflectivity (>45 dBZ) exhibited a higher flash density of both CG and IC strikes than cells with low reflectivity (<32 dBZ).

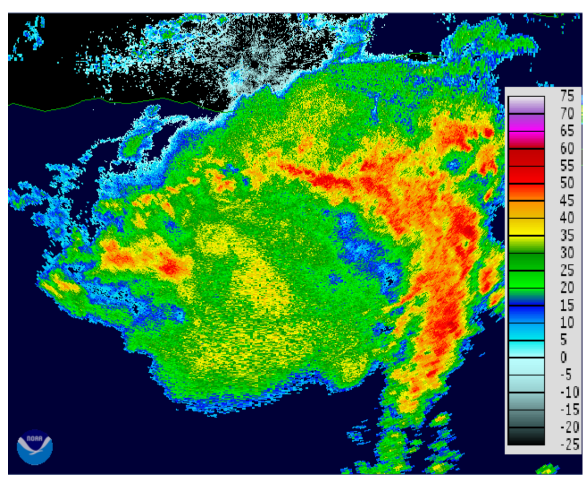

Figure 7. Tropical Cyclone Gabrielle on September 5, 2013, at 0402 UTC. Reflectivity factor at elevation angle of 0.5 degrees

We also looked for the freezing level within electrically active cells. Soundings taken near the storm showed that the freezing level was around 4700 meters. The polarimetric variables differential reflectivity (Z_{DR}) and copolar correlation coefficient (CC) confirmed that the freezing level was nearly the same height within the storm cells. Storms with strong updraft regions had a freezing level elevated above 4700 meters (Fig. 8).

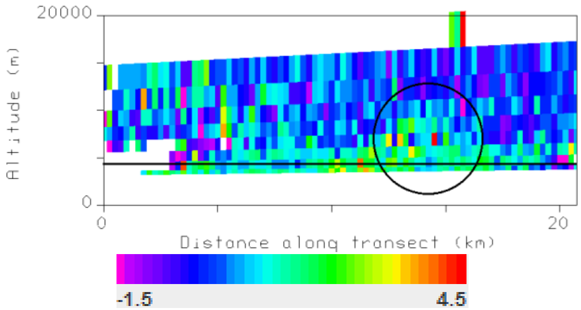

Figure 8. Differential reflectivity cross section from San Juan, Puerto Rico at 0755 UTC on September 5, 2013

This is because warm air from near the ground is caught in the updraft column and lofted past the environmental freezing level. Figure 8 shows a differential reflectivity cross section within a cell near the TJUA radar site; the dark straight line is drawn at approximately 4700 meters. The circled area points out the central updraft, seen as a plume of higher Z_{DR} values. High Z_{DR} indicates a particle with a component of the major axis oriented parallel with the ground, most likely large rain drops. The updraft locally elevates the ice crystal and graupel layer above the column of liquid drops. Through most of the rainbands below the freezing level, CC remained near 1.0, indicating uniform raindrops (Fig. 8). However, once the beam reached the freezing level, the CC dropped by approximately 0.1 as the beam encountered a layer of mixed particles (rain, ice crystals, ice pellets). The freezing level is outlined in black in Figure 9.

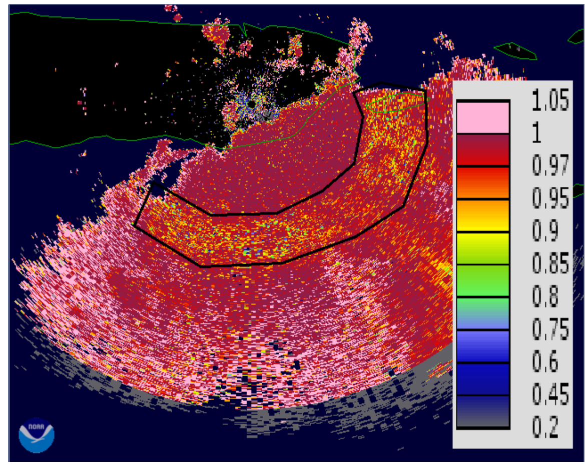

Figure 9. Tropical Cyclone Gabrielle on September 5, 2013, at 0402 UTC. Correlation Coefficient at elevation angle of 3.17 degrees

At this same height Z_{DR} fluctuated around 0 dB as particles became more spherical. This lower freezing level was one likely reason Gabrielle exhibited more electrical activity than Irene (Figs. 5 and 6).

Research question three dealt with cells that showed more electrical activity than neighboring cells. This phenomenon was more apparent in Irene where many cells would show no activity for long time periods if at all. When trying to examine these cells using polarimetric variables, there were often no variations from typical values. Because the lightning data for Irene corresponded with rainbands close to 150 km from the radar site, it is possible that any deviation in the polarimetric variables would fall within the noise at this distance, making an accurate assessment of the results difficult.

Within Gabrielle, it was rare to find a cell without electrical activity, but some cells and areas within cells did exhibit lower flash rates. The cells that were less active were usually smaller in diameter (<10 km) with reflectivity factor less than 50 dBZ. A strong updraft allows for more electrification; charge builds near the top and bottom of the cells and discharges readily to the ground or between layers within the cloud. Generally the larger the updraft volume, the larger the total mass of ice-phase particles in the storm, and the more likely it is to build up charge enough for significant flash density.

IV. CONCLUSIONS

Answering our research questions depended largely on the relation of flash rates to the polarimetric variables and to the freezing level, which was different for both cases. Reflectivity factor alone would have made the analysis less revealing. We found that flash rates decreased during land fall of Irene, and that in general, lightning did not exist near the eyewall. Gabrielle more consistently showed a non-zero flash rate. This could be due to the environment that the storms encountered as they intensified. When Saharan sand/dust is raised from the surface by turbulence, some may make it into the mid and upper atmosphere. The prevailing easterly winds at that latitude can carry the dust far from the coast of Africa. It has been hypothesized that Irene may have been affected by some of this Saharan dust prior to landfall. If this plume of Saharan dust and dry air became incorporated into Irene approaching the time of landfall, this may have significantly affected the hydrometeor distributions and thus the particle charging process in this storm. We also noted that the freezing level was lower in Gabrielle than in Irene. Although Irene was farther north, the freezing level was nearly 1500 meters higher than Gabrielle despite its lower latitude. There is still much to be learned about the third research question. We expect there may be some microphysical process we have not yet identified causing some cells to remain electrically inactive. In some cases, a cell does not produce lightning yet appears very similar to an active cell nearby. This research is ongoing.

ACKNOWLEDGMENTS

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