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Polarimetric Radar Analysis of the Microphysics of Charge Separation in an MCC Event on June 15, 2013

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Abstract

On June 15, 2013, a mesoscale convective complex (MCC) developed over northeast Oklahoma and tracked to southwest Illinois. This MCC brought large hail, heavy rain, and damaging wind to the area, including thunderstorm wind gusts to 75 mph, resulting in a loss of power. Although many studies have investigated MCC events, they have rarely compared their lightning structure with polarimetric radar variables. Here, polarimetric variables are used to analyze the storm's structure and show why some regions within the MCC exhibit substantial electrical activity while nearby areas exhibit little to none. Spectrum width is also examined in association with lightning occurrence. In some MCCs, it has been observed that an unusually high percentage of cloud-to-ground lightning has positive polarity. Polarimetrically-inferred precipitation processes will also be investigated relative to areas of positive-polarity lightning. These results may aid in understanding the microphysical structure of MCCs and provide information to aid aviation meteorologists. Using polarimetric radar to analyze this event will allow a better picture of MCC structure than satellite data or non-polarimetric radar data can provide, and may help develop future forecasting techniques.

Keywords: MCC, Lightning, Dual-polarization, Radar

1. Introduction

Many studies have examined the relationship between lightning and supercell storms, but little research has been conducted on the role of lightning in mesoscale convective complexes (MCCs). Criteria for a system to be considered an MCC are listed in Table 1.[2] The conceptual model is based on Houze et al. (1989) of midlatitude and tropical systems. In the vertical cross section, a general trend of upward motion is seen to begin in the boundary layer near the gust front and extend up through the convective region and to slope more gently into the trailing stratiform cloud at mid to upper levels. Superimposed on the general upflow within the convective region are intense, localized updrafts and downdrafts, associated with intense cells with the squall line. It is important to study MCCs since their large coverage and long duration cause widespread damage at the surface, whether in the form of flooding, wind, or hail, and may cause major problems for aviation[1] (e.g. freezing on the wing, severe turbulence). This research paper will focus on comparing dual polarization radar variables with lightning data to find possible microphysical associations with lightning. Using operational dual polarization radars, differential reflectivity (Z_{DR}) and copolar cross-correlation coefficient (ρ_{HV}) were examined for three different levels: the lowest radar tilt (0.54°), the melting layer, and the -30°C level derived from a nearby sounding. Each of these was compared to Cloud-to-

Table 1: Table displaying criteria for MCC classification

Criteria for Classification as an MCC		
A Mesoscale Convective Complex (MCC) is a MCS that meets the following satellite-based criteria established by Maddox (1980):		
Size	A.	Cloud shield with continuously low IR temperature ≤ -32°C must have an area ≥ 100,000 km^2 (*approximately half the size of the State of Kansas*)
	B.	Interior cold cloud region with temperature ≤ -52°C must have an area ≥ 50,000 km^2
Initiate	Size definitions A and B are first satisfied	
Duration	Size definitions A and B must be met for a period ≥ 6 hours	
Maximum Extent	Contiguous cold cloud shield IR temperature ≤ -32°C reaches maximum size	
Shape	Eccentricity (minor axis/major axis) ≥ 0.7 at time of maximum extent	
Terminate	Size and definition A and B no longer satisfied	

Ground (CG) and In-Cloud (IC) lightning for the three stages in the life cycle of an MCC.

The case of interest is an MCC on 15-16 June 2013. This system began in northeastern Oklahoma and moved northeast through Kansas, Missouri, and Illinois. The MCC produced small amounts of hail ranging from 2.54 to 4.45 cm in diameter and strong winds with values up to 38.6 m s^{-1} reported.[3] The synoptic setup included a 500 hPa shortwave present, high moisture content streaming into the area of interest at 700 hPa and strong instability present, with CAPE values greater than 1500 J/kg and minimal CIN, all ingredients often associated with MCCs (Fig. 1).[1]

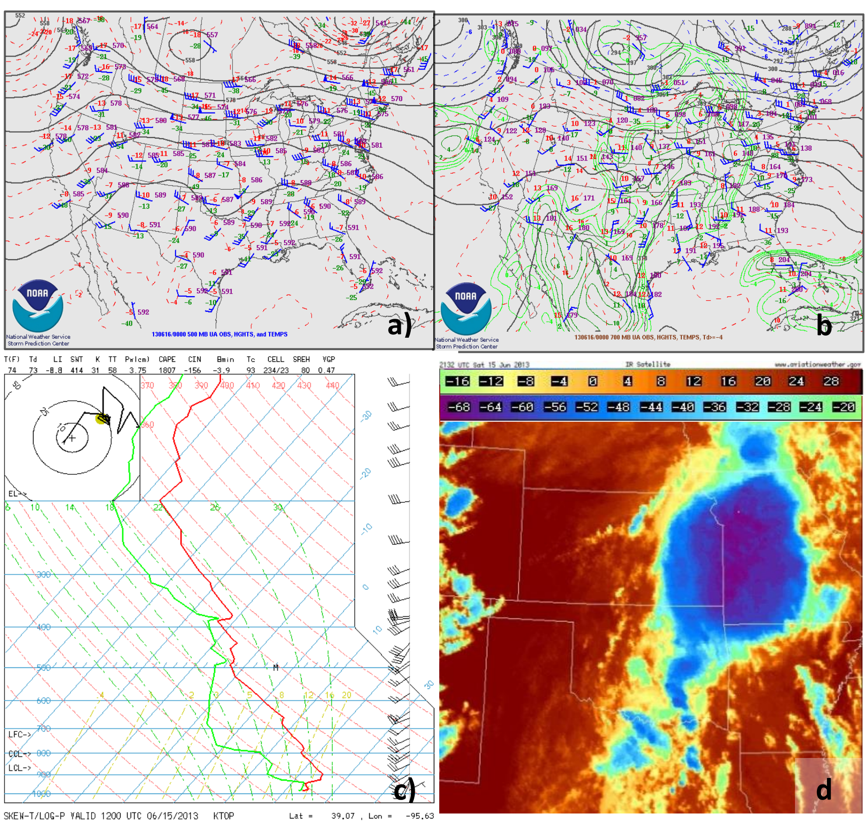

Figure 1: Environment of the MCC including a) 500 hPa chart at 0000 UTC showing a shortwave trough, b) 700 hPa chart at 0000 UTC showing available moisture in the area of the MCC, c) a skew-T diagram showing a CAPE value

of 1807 J/kg at 1200UTC on 15 June, and d) the IR imagery at 2132 UTC on 15 June showing cloud tops colder than -52° C.[4]

IR imagery also showed cloud tops colder than -52° C present. Using radar and satellite imagery, a specific time was assigned to each of the three stages of the MCC: developmental stage (1858 UTC on 15 June), mature stage (2232 UTC on 15 June) and dissipating stage (0103 UTC on 16 June), according to the stages in Maddox (1980).[5] The goal of this study is to help forecasters better understand and predict MCCs based on lightning data.

2. Data and Methods

Polarimetric radar datasets for three individual time steps were analyzed from Weather Surveillance Radar 1988-Doppler (WSR-88D) network radars. For each life cycle stage, two radars were used to achieve more accurate data collection, and are listed in Table 2. Lightning data were provided by the Earth Networks Total Lightning Network. It detects a broad frequency range extending from 1 Hz to 12 MHz, allowing detection of both IC and CG lightning. Total lightning data (CG and IC) were available from 1730 UTC on 15 June 2013 until 0200 UTC on 16 June 2013. To prevent overestimate of lightning strike points at a higher radar angle (>8°) during each 5-6 minute radar volume scans, lightning data were grouped into 3 min 38 s at each radar scan. Radar data were displayed using the Weather and Climate Toolkit software, and lightning data were displayed using shapefiles convert from ArcGIS software.

The focus of this study will be on three individual life cycle stages of the MCC: the developmental stage at 1858 UTC on 15 June 2013, the mature stage at 2232 UTC, and the dissipating stage at 0103 UTC on 16 June 2013. To ensure optimal data quality, two nearby radars were chosen to examine each stage, and vertical cross-sections were analyzed using GR2analyst. We examined polarimetric radar variable values and patterns associated with lightning characteristics, and the dominant polarity of lightning strikes in different MCC stages. When comparing the lightning data to the dual polarization parameters, radar parameter values in the pixel closest to each lighting point were used to calculate an average value of Z_{DR} and ρ_{HV}. Due to the large area of the MCC, using an average of the radar variable values as the method of data collection seemed like the best choice. Using Matlab, the values under the lightning points were extracted and the average calculated, as shown in Fig. 2.

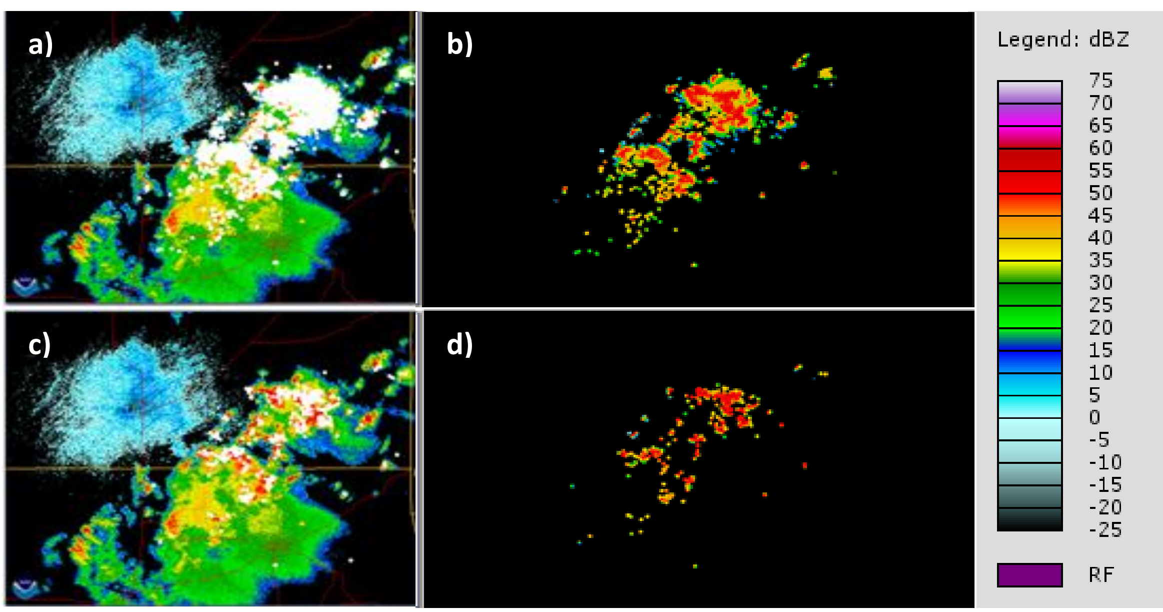

Figure 2: Example of the Matlab extraction process of reflectivity values for IC and CG lightning. Panels a) and b) show the original reflectivity with IC lightning (a) and CG lightning (b) strikes overlaid. Panels c) and d) show the extracted reflectivity values from each (c) IC lightning and (d) CG lightning strike.

Table 2: Table of radars analyzed representing each MCC stage.

MCC Stage	Radars used for Analysis
Developmental	KICT (Wichita, Kansas), KINX (Tulsa, Oklahoma)
Mature	KEAX (Kansas City/Pleasant Hill, Missouri), KSGF (Springfield, Missouri)
Dissipating	KLSX (St. Louis, Missouri), KILX (Lincoln, Illinois)

3. Reflectivity (Z_{HH})

During the developmental stage of the MCC (observed at 1856 from KICT and 1858 UTC from KINX), both radars indicated high Z_{HH} values (>55 dBZ) associated with intense lightning. The IC strikes predominate in the region of heavy convective showers where intense, localized updraft and downdrafts occurred throughout most of the high-reflectivity area[6], while CG strikes occurred more centrally within high-reflectivity regions (Fig. 3c and 3d). From KICT, the convective region was indicated by a thicker layer of Z_{HH} >55 dBZ; ~9.1 km deep (Fig. 3a), compared to the stratiform region which had a shallower reflectivity layer Z_{HH}> 45 dBZ; ~4.6 km deep (Fig. 3b), likely indicating weaker vertical motion. From KINX, the results were similar in the convective region, but the overall reflectivity slightly increased in the stratiform region due to the radar site being closer. The mature stage of the MCC was observed at 2232 UTC from KSGF and KEAX. Location of lightning strikes was similar to the developmental stage, with most lightning strikes in regions of Z_{HH} >55 dBZ along the edges of deeper updrafts. The trailing stratiform region had less strikes compared to the convective region--most strikes in the trailing stratiform region were in regions of higher reflectivity caused by mesoscale updraft. The mesoscale updraft likely increased water vapor and supercooled liquid water content (LWC) in the mixed-phase portion of the stratiform region resulting mixed phase precipitation processes above the melting level allowing local charging mechanisms (Ely et al 2008). In the dissipating stage observed at KSLX and KILX (0101 and 0103 UTC, respectively), the total number of lightning strikes had decreased dramatically.

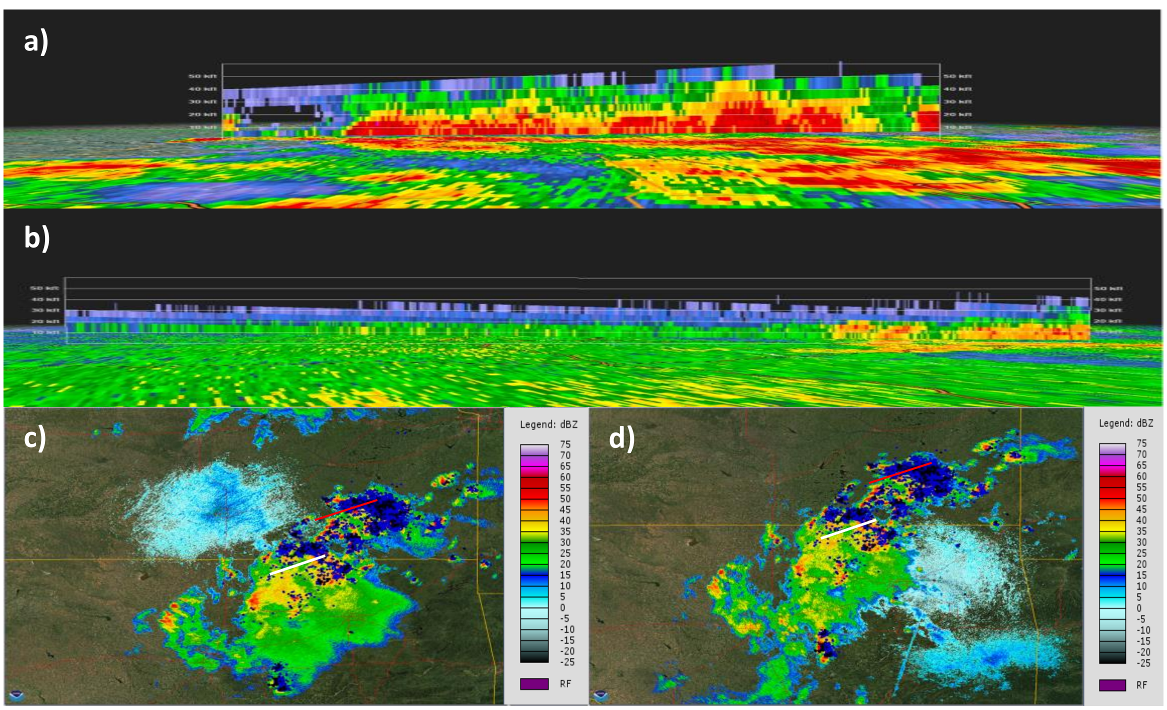

Figure 3: a) Vertical cross-section of reflectivity values through the convective region (red line) and b) trailing stratiform region (white line); c) Observations from KICT and d) KINX for IC lightning (blue dots) and CG lightning (black dots).

Most lightning strikes were within the region of deep reflectivity core (>55 dBZ) associated with heavy rainfall in the convective region, with few to no lightning strikes in the trailing stratiform region characterized by midlevel horizontal extensive layer[6]. Most lightning strikes corresponded to high reflectivity regions due to the presence of abundant ice crystals and mixed-phase particles inferred by Z_{DR} and K_{DP}. Interactions between the supercooled liquid water and the ice to form graupel in the mixed-phase region are believed to be responsible for producing the electrical charging that leads to lightning discharges in thunderstorms.[7] The trailing stratiform region is characterized by weaker reflectivity and a larger vertical shear in the horizontal flow. Ice particles produced in the convective region are transported by the front -to-rear flow into the stratiform region.[8] Ice particles in the stratiform region grow considerably by deposition and aggregation as they fall through the stratiform cloud; Rutledge and Houze (1987) indicated a riming process in the stratiform region, which was concentrated near the melting level.[9] This mechanism is likely of lesser importance in the stratiform region since only a very small amount of cloud water is present there. This may explain why the stratiform region has less-favorable conditions for lightning.

4. Specific Differential Phase (K_{DP})

Specific differential phase (K_{DP}) is used to estimate total LWC, high values of which are closely associated with updraft[13]. According to Loney et al. (2002) and Schlatter (2003), the K_{DP} column is associated with a high concentration of mixed-phase hydrometeors and is often collocated with high reflectivity.[10-11] Raindrops above the melting level in the K_{DP} column may indicate a mixed-phase hydrometeor layer which is favorable for lightning initiation. K_{DP} columns were persistent throughout the life of the MCC in the convective region. Most lightning strikes occurred close to high K_{DP} values (4 degree km^{-1}), which indicate locally high LWC. A well-defined K_{DP} column was evident in a vertical cross-section through the MCC's convective region. The region of high values (>2.5 degree km^{-1}) extends to a height of about 6 km with mostly lightning around associated with strong updraft (Fig.4). This was also the region of the highest lightning flash rate (2100 flashes/min). The trailing stratiform region had K_{DP} values <0.3 degree km^{-1} due to the lower concentration of liquid water. The convective region has its own distinct column and is clearly separated spatially from and trailing stratiform region, which did not have a deep column. K_{DP} may aid forecasters to see where the lightning flash rate is likely to be highest, but it also may have data quality issues with distance due to non-uniform beam filling.

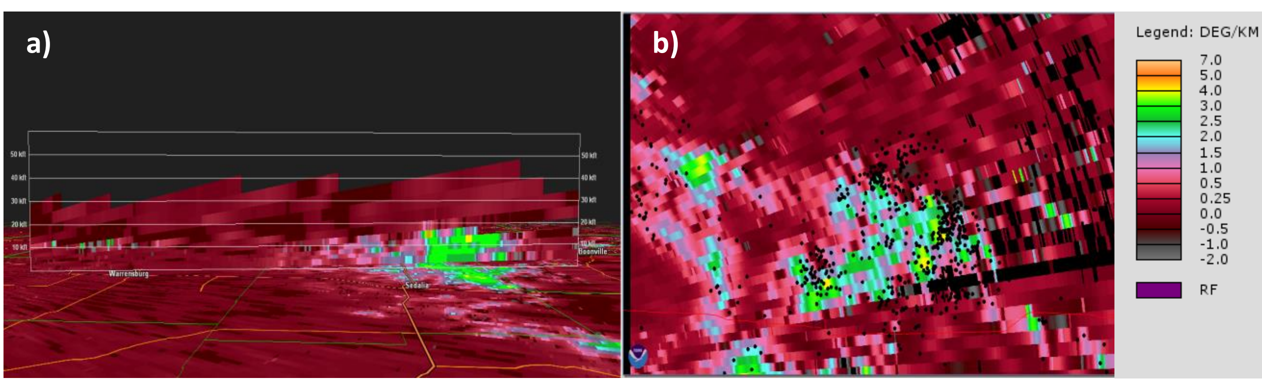

Figure 4: Panels a) and b) show vertical cross-section of K_{DP}, most lightning strikes (black dots) around high K_{DP} (both IC and CG).

5. Spectrum Width (σ_v)

Spectrum width (σ_v) can be used to identify regions of large-scale turbulence, and this signature adds information useful to the interpretation of radar data, which can aid the nowcaster of severe weather events. Lightning strikes were closely associated with high σ_v values. High σ_v values occurred within the area of strong updraft as identified by the other radar variables (Z_{DR}, Z_{HH}) in Fig. 5. This was also the region with highest lightning flash rate. A vertical cross-section shows higher σ_v value associated with the strong shear aloft during the developmental stage and a shallower column in the dissipating stage. The convective regions were generally associated with largest σ_v values;

most lightning strikes occurred near these areas of high σ_v. The trailing stratiform region was generally associated with lower σ_v values, with fewer lightning strikes. The use of σ_v data has historically been limited compared to Z_{HH} and Doppler velocity fields due in part to the relative difficulty in relating σ_v to meteorologically-significant phenomena. σ_v values are also easily corrupted, thus the use of σ_v may be less reliable and more prone to interpretation errors.[12]

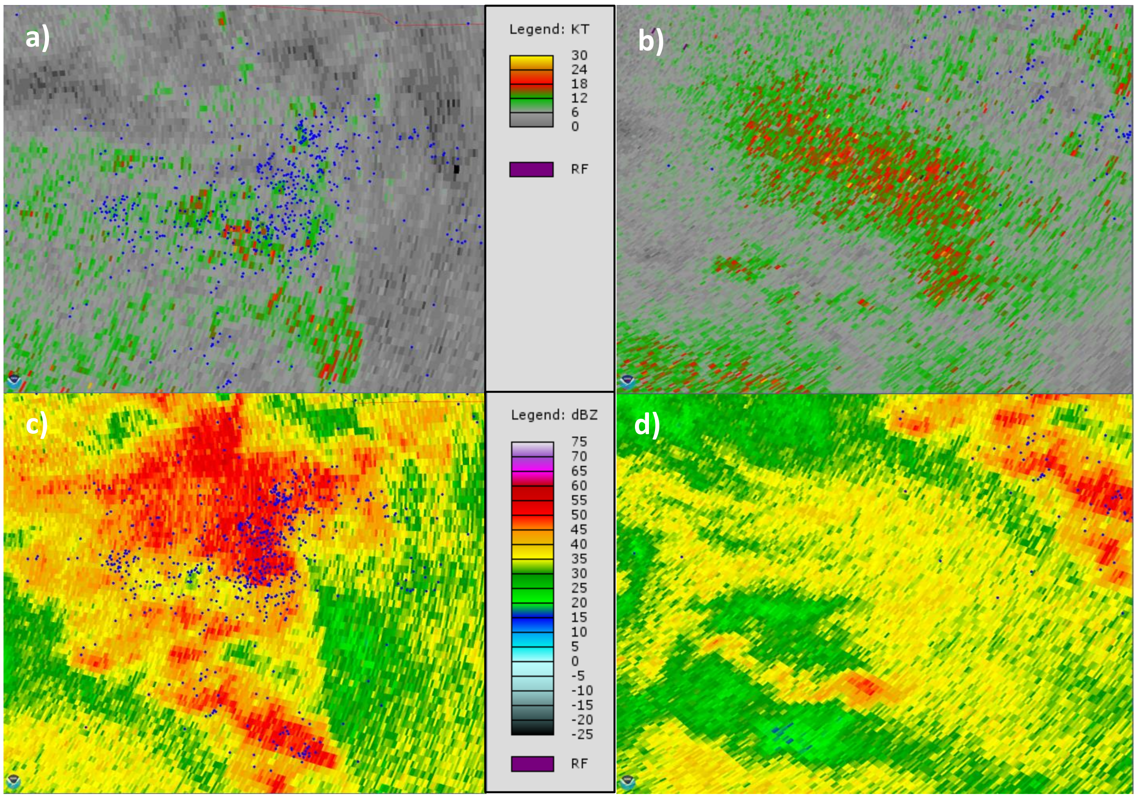

Figure 5: Most lightning strikes occurred over a) high spectrum width at northern part of the storm (blue dots = lightning strikes); Few lightning strikes associated with b) high spectrum width and weaker reflectivity at southern part of storm (blue dots = lightning strikes); c) Association between strong reflectivity and lightning in northern part of the storm (blue dots = lightning strikes); d) Few lightning strikes associated with southern part of storm in region of weaker reflectivity (blue dots = lightning strikes).

6. Differential Reflectivity (Z_{DR})

For all MCC stages, differential reflectivity (Z_{DR}) values were highest close to the surface and decreased with height. For CG lightning, Z_{DR} values were highest in the developmental stage with an average value in the lowest radar tilt (0.54°) of 1.88 dB. At the same tilt, the lowest average Z_{DR} value was observed during the mature stage (1.02 dB). IC lightning showed the same trend, but with smaller overall values for all levels compared to CG lightning. For IC lightning at the lowest tilt, the highest Z_{DR} values were found during the developmental stage, with an average Z_{DR} value of 1.79 dB, and the lowest values during the mature stage, with an average value of 0.92 dB (Fig. 6). Higher Z_{DR} values near the convective region and lower values in the stratiform region are due to stronger updraft in the convective region, associated with a larger average drop size and/or water-coated hailstones (e.g., Kumjian and Ryzhkov 2008).[13] Water coated hailstones will appear as large raindrops to the radar, and thus return a high Z_{DR} value. IC strikes were predominant in the edge of the high Z_{DR} region, and CG strikes also occurred in the vicinity of high Z_{DR} values. Fig. 6a of Loney et al. indicates maximum Z_{DR} values coincident with maximum upward motion in the updraft, which corresponds to our observation that most lightning strikes is not directly within the updraft.[10]

The slightly lower Z_{DR} surrounding the highest Z_{DR} values likely indicates mixed-phase hydrometeors if above the freezing level, which favors charge separation. So, the highest flash rates should be on the edges of the high Z_{DR} regions, as observed. Z_{DR} in the stratiform region exhibited lower values (1-2 dB) indicating less favorable conditions for lightning strikes; most strikes in the stratiform region were near high values of Z_{DR}. A vertical cross-section indicated the convective region had higher Z_{DR} values than the stratiform region, which indicated stronger updraft in the vicinity of lightning strikes.

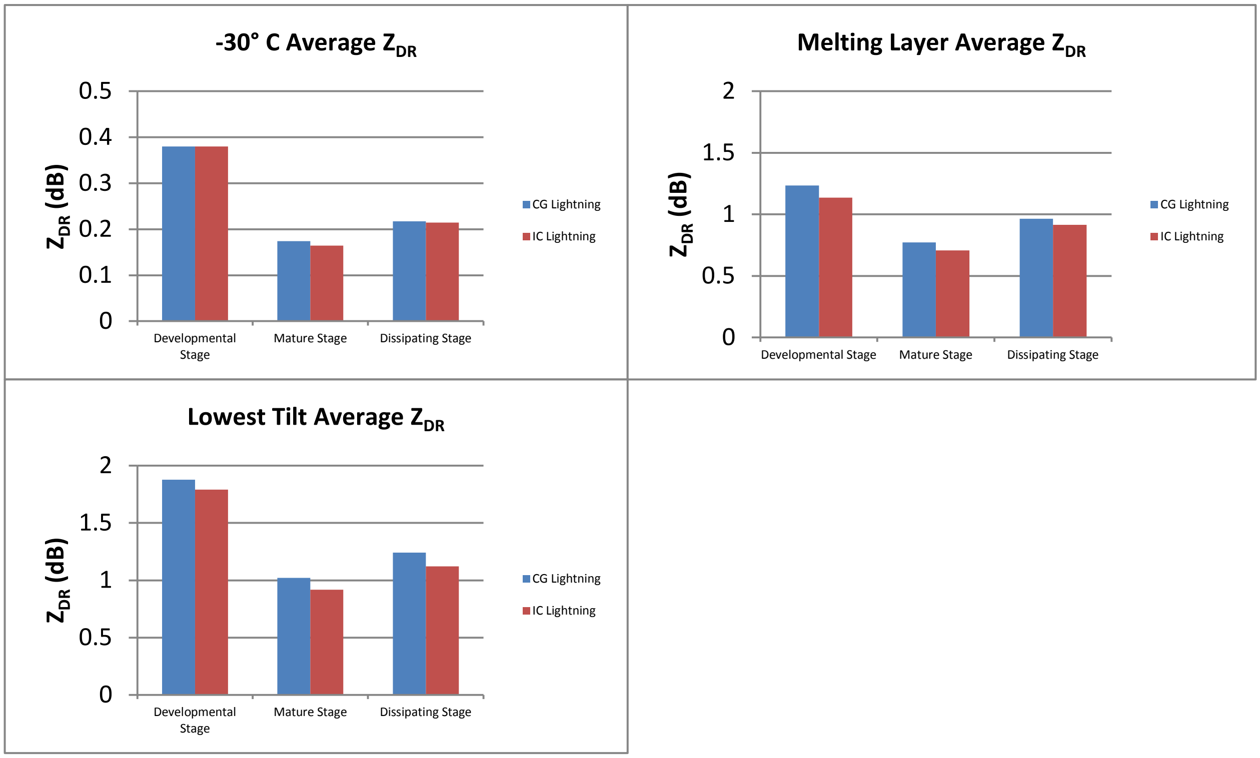

Figure 6: Average Z_{DR} of the three stages of an MCC for three different layers of the atmosphere: a) Lowest tilt, b) 0°C, and c) -30°C for CG and IC lightning.

7. Copolar Cross-Correlation Coefficient (ρ_{HV})

Copolar cross-correlation coefficient (ρ_{HV}) was not a good indicator of lighting flash rate far from the radar due to nearby strong convection which caused non-uniform beam filling [23]. Since the MCC covers a wide area, the possible height of lightning can also be analyzed using ρ_{HV}. The lowest values were found at the melting layer level for both CG and IC plots for all MCC stages. This is likely due to the mixed nature of the hydrometeors in the melting layer resulting in lower ρ_{HV} values[14]. This may indicate a favored height leading charge separation in MCC. Highest values of ρ_{HV} were at the -30° C level, due to the presence of many small, uniform ice crystals. At the -30° C level, out of the three MCC stages, the developmental stage had the lowest ρ_{HV} values with an average ρ_{HV} value of 0.97 for CG and IC lightning. This lower value during the developmental stage was likely due to the greater prevalence of hail. By the dissipating stage, ρ_{HV} values were highest, indicating more uniform raindrops. Comparing CG and IC lightning, CG lightning had slightly lower average ρ_{HV} than IC lightning for nearly all stages throughout the lifetime of the MCC (Fig. 7). A vertical cross-section also shows the convective region has a thicker layer of lower ρ_{HV} values, indicating a deeper mixed-phase hydrometeor layer than in the trailing stratiform region.

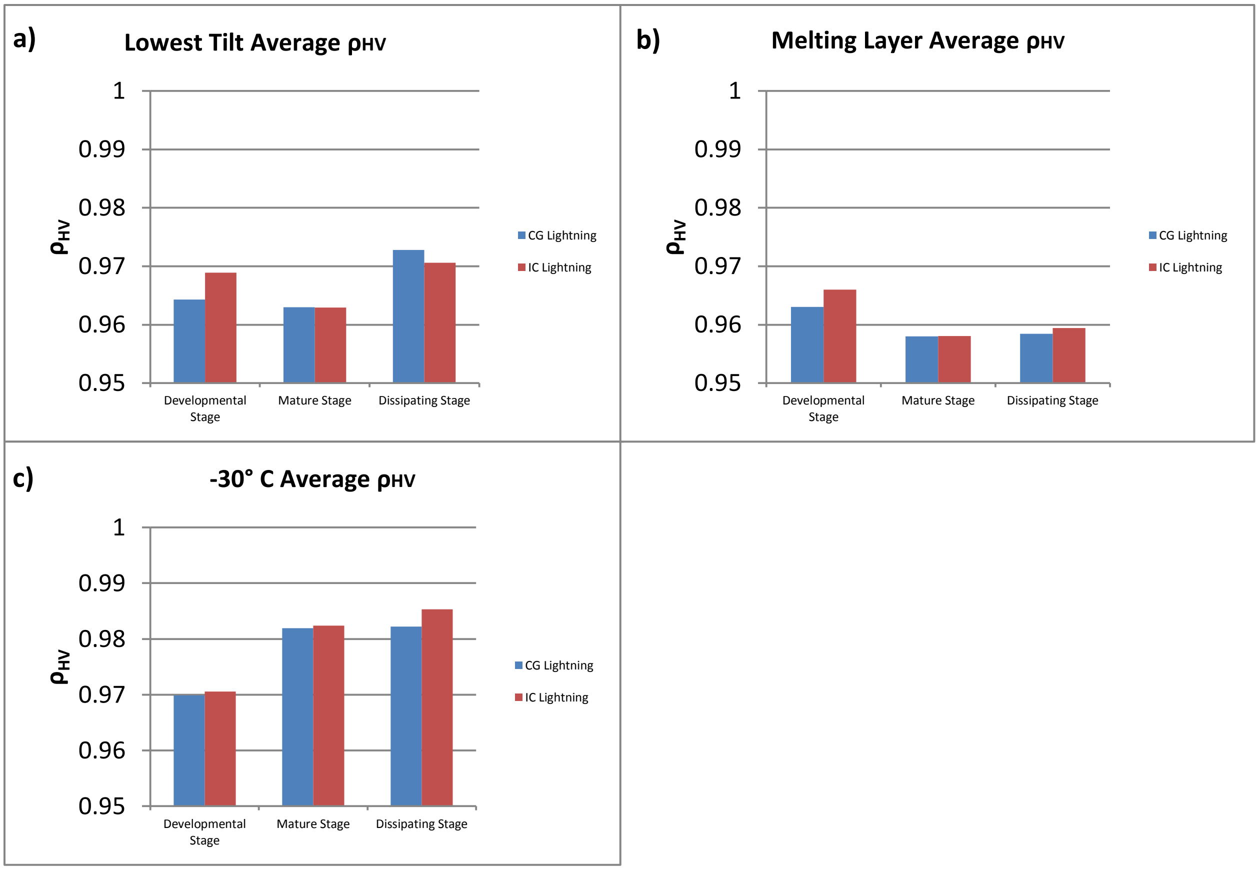

Figure 7: Average ρ_{HV} of the three stages of an MCC for three different layers of the atmosphere: a) Lowest tilt, b) 0°C, and c) -30°C for CG and IC lightning.

8. Polarity of Cloud-to-Ground Lightning in the MCC

Several studies of lightning characteristic indicate the polarity of lightning has a direct relationship between positive CG and storm severity (Rust et al 1985; MacGorman 1989). This relationship might provide a useful tool for nowcasting severe storms. The majority of CG flashes have net negative charge values across the contiguous United States,[15] and most warm-season storms throughout the CONUS generate mostly negative CG flashes.[16] Storms dominated by positive CG flashes vary regionally, and account for less than 10% -20% of all warm-season severe storms in the eastern and southern United States. Strong updrafts and associated high LWC in positive storms lead to positive charging of graupel and hail. Ice crystals take on negative charge during rebounding collisions via the non-inductive charging mechanism (NIC), resulting in a typical thunderstorm dipole structure producing negative flashes.[17-20] The differential fall speeds of ice particles and an accelerating updraft results in the storm-scale separation of positively-charged graupel and hail and negatively-charged ice crystals, forming an inverted dipole (Fig. 8). A more common NIC process is the negative charging of graupel and hail and positive charging of ice crystals, which is hypothesized to occur in storms with moderate updrafts and moderate LWC, resulting in the typical thunderstorm dipole and negative CG lightning.[16] Carey et. al (2008) shows significant regional variability in the percentage of positive CG lightning generated from severe storm in the warm season; the Great Plains and Midwest have a higher percentage of severe storms dominated by positive CG lightning.

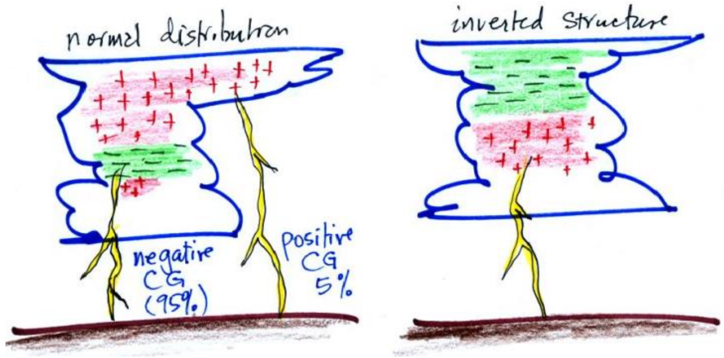

Figure 8: Example of the normal charge distrubtion (left) and inverted dipole structure (right).[21]

In the developmental stage of the MCC, positive lightning strikes were located centrally within the high reflectivity region and associated with high Z_{DR} values. These regions were associated with vigorous updraft. Negative strikes were scatter throughout the high-reflectivity region, but also occurred within areas of lower Z_{DR} values. In the MCC's mature stage, associations were similar to the developmental stage; lightning strikes (positive and negative) were decreasing throughout the trailing stratiform region likely due to change supply sources from leading-line convection to ice particle advection from the convective region (not shown). In the dissipating stage, positive strikes were sparse and associated with reflectivity >45 dBZ and Z_{DR} values of 1-2 dB, corresponding to strong updraft. Negative strikes were scatter throughout the region of reflectivity values >35 dBZ, and with a wider range of Z_{DR} values (0–3 dB).

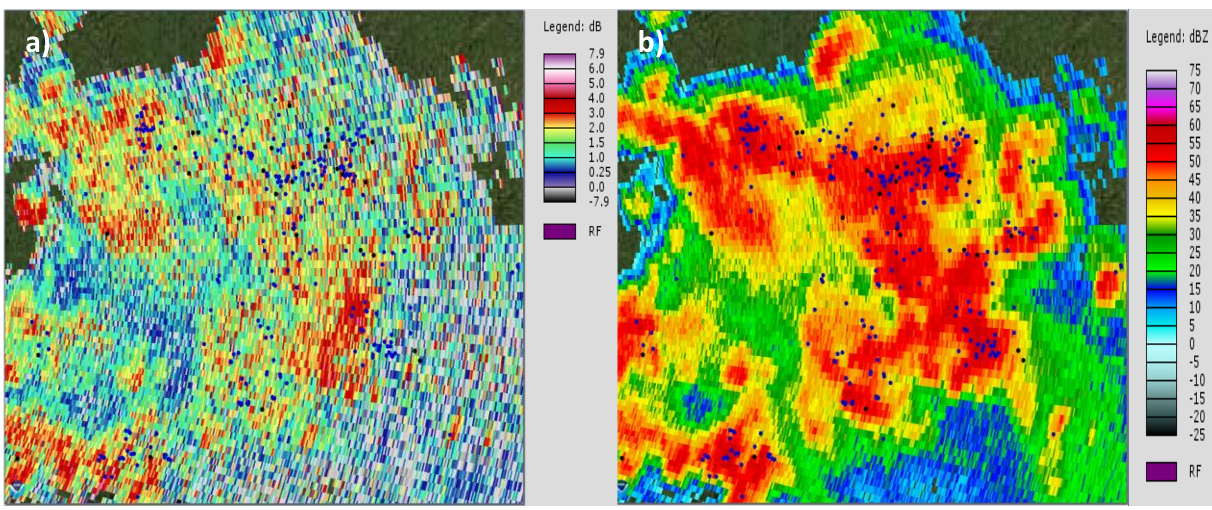

Figure 9: Polarity of the MCC associated with (a) high Z_{DR} and (b) high Z_{HH} (black = positive strikes; blue = negative strikes).

9. Conclusions and Future Research

The dual polarization variables show a clear connection between the convective region and lightning strikes, with CG lightning specifically focused in the areas of highest Z_{HH}, high Z_{DR}, lowest ρ_{HV}, and high K_{DP} values. This combination of values indicates a region of mixed-phase hydrometeors characterized by high LWC (e.g., Straka et al. 2000). IC lightning also tended to be located in similar regions, but scatter over a larger spatial area, causing smaller average values of the polarimetric variables when compared to CG lightning. Lightning strikes tended to occur near high spectrum width values, but a cluster of high spectrum width may indicate strong shear which may discourage lightning initiation. For the MCC event, positive lightning strikes were located centrally within the high-reflectivity region and associated with higher Z_{DR} values, and negative strikes were scattered throughout the high-reflectivity region, occurring within areas of lower Z_{DR} values.

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