4.6 ELECTRICAL AND POLARIMETRIC RADAR OBSERVATIONS OF A HP SUPERCELL ON 29-30 MAY 2004 DURING TELEX

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1. INTRODUCTION

Lightning holes, as first seen in lightning mapping array (LMA) data (Krehbiel et al. 2000), are characterized by a region of reduced lightning density that is surrounded by a ring of higher lightning density. Numerous other studies (e.g., Krehbiel et. al. 2002; Murphy et. al. 2005; MacGorman et. al. 2005; and many others) have also noted this feature. Most of these studies have linked the lightning hole to the bounded weak echo region (BWER) of supercell thunderstorms and believed that the lightning holes formed when precipitation particles were lofted out of the way of the updraft causing limited charging in this region and restricting lightning activity to the periphery of the updraft. All of these previous studies have developed conclusions on lightning hole formation based solely on reflectivity data. The primary goal of this paper is to show the evolution of a lightning hole that occurred during the 29-30 May 2004 high precipitation (HP) supercell relative to its polarimetric signatures and use that data to refine our knowledge of the microphysical processes in lightning hole regions.

The 29-30 May 2004 supercell was the only HP supercell to be observed during the Thunderstorm Electrification and Lightning Experiment (TELEX, MacGorman et al. 2008). Furthermore, we believe it to be the only HP supercell to be thoroughly sampled by an S-band polarimetric radar and LMA simultaneously. Polarimetric radar data were collected by a WSR-88D prototype (KOUN, Doviak et. al. 2000), and the Oklahoma Lightning Mapping Array (OK-LMA, Rison et al. 1999) provided three dimensional (3-D) VHF sources and densities of lightning activity. Two Shared Mobile Atmospheric Research and Teaching Radars (SMART-R, Biggerstaff et. al. 2005) provided good dual-Doppler data for a portion of the lifetime of the supercell. Finally, it was sampled electrically and thermodynamically by two electric field meters (EFM, Winn et. al. 1978) and dropsondes, respectively.

The 29-30 May 2004 supercell initiated along the dryline in western Oklahoma around 2200 UTC and progressed eastward towards central and eastern Oklahoma late into the evening hours. It came into the KOUN and OK-LMA ranges at approximately 2330 UTC. At this time it produced its first tornado. It eventually produced approximately 11 more tornadoes, and copious hail, as it propagated eastward passing 40 km north of the KOUN radar. This paper will focus on the 0000 UTC to 0100 UTC time period when the storm was going through its most mature stage.

2. OVERVIEW

2.1 Polarimetric Overview

Figure 1 shows the evolution of the polarimetric radar data during one evolution of a lightning hole studied in this paper. Reflectivity structure from 0018 UTC to 0052 UTC show classic supercell features. A well defined inflow notch can be seen on the east side of the hook echo region. Reflectivity in the hook echo region is near 50 to 55 dBZ. At upper elevations, a BWER extends from 7 km up to 10 km. Associated dual-Doppler updraft speeds exceed 50 m/s.

From 0018 UTC to 0034 UTC, a differential reflectivity (Z_{DR}) column (Bringi et. al. 1991; Brandes et al. 1995) appears on the edge of the inflow notch reaching values of ~3.5 dB. North and northwest of the Z_{DR} column, a Z_{DR} minimum is noted. A Z_{DR} minimum can also be seen in the inflow region. At 0039 UTC through 0050 UTC, a ring of high Z_{DR} becomes

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noticeable just upshear of the inflow region in the hook echo region. This ring extends well above the environmental freezing level up to about 7 km. This ring collapses around 0055 UTC.

To the west of the Z_{DR} column, a broad region of positive specific differential phase (K_{DP}) dominates the lower levels (~ 3 km). From 4 to 6 km, K_{DP} decreases to near zero in this region except for a small area to the southwest of the updraft region. This region is dominated by K_{DP} values of nearly 2.5 deg/km. This K_{DP} maximum persists through 0052 UTC.

The correlation coefficient (ρ_{hv}) for the updraft region rarely exceeds 0.98. For the most part, the values range from 0.9 to about 0.96. Just outside of this broad updraft region the ρ_{hv} are at or above 0.98. No evident evolution can be seen in the ρ_{hv} except for at 0039 UTC. At this time, a ring of low ρ_{hv} appears in the mid-levels (~ 4 to 6 km). Kumjian and Ryzhkov (2008) provide a more thorough overview of polarimetric signatures in supercells.

2.2 Dual-Doppler Overview

Figure 2 represents the evolution of the dual-Doppler data from 0018 UTC to 0052 UTC. At 0018 UTC, the supercell thunderstorm begins intensifying evident by a broad inflow notch in the reflectivity plots in the lower elevation angles and a bounded weak echo region (BWER) in the higher elevation angles. These reflectivity features are associated with a very concentrated updraft as depicted by the dual-Doppler analysis. This updraft persists and begins to take on a cyclonically curved look around 0038 UTC. At this time, a region of downdrafts can be seen beginning to entrain into the updraft signifying the beginning of the occlusion process. At 0050 UTC, the vertical velocity structure shows that the downdraft (most likely the rear flank downdraft (RFD)) begins wrapping around the updraft while downstream another updraft begins to form.

2.3 Lightning Overview

Figure 3 presents the evolution of the lightning source densities during the time period of this study. Lightning source densities are mainly confined above the environmental freezing level (4 km) prior to 0039 UTC. After 0039 UTC, two distinct source density regions develop below 3 km: (1) near the updraft and (2) downshear in the anvil. This paper will be focusing on the lightning activity in the updraft region. A lightning hole does not develop until 0039 UTC and persists for about 12 minutes, after which the lightning hole collapses and fills in with lightning VHF sources. Most of the lightning sources in the updraft region are located upshear of the updraft.

3. SYNTHESIS OF OBSERVATIONS

The following section will attempt to relate LMA, Polarimetric and Dual-Doppler data to the lightning hole region of the HP supercell

3.1 Below the freezing level (3 to 4 km)

Figures 4-6 overlay lightning densities with polarimetric data below the freezing level. Few VHF sources are occurring at or below 4 km from 0018 UTC to 0039 UTC (Figure 4). The few sources that are occurring are located in the anvil region (upshear and downshear), and within the hook echo of the storm with reflectivity ranging from 40 to 50 dBZ. Z_{DR} ranges from slightly negative to a maximum value of 1 dB. K_{DP} is near zero or slightly positive, and ρ_{hv} is approximately 0.95 to 0.97. The vertical velocity structure shows a strong updraft (~ 20 to 30 m/s) just to the south and east of the VHF source region. The sources are occurring along an interface between positive and negative vertical velocities.

At 0039 UTC, lightning density increases below the freezing level (Figure 5). A semi-circular region of VHF sources develops along the southern and western edges of the storm. The lightning sources follow an axis of reflectivity maximum (~ 50 to 55 dBZ) inside the hook echo region and extend back into the inflow region. A Z_{DR} ring is seen in this semi-circle region. The densest region of sources occurs where Z_{DR} is around 1 to 1.5 dB and the least dense region of lightning sources occurs where Z_{DR} is greater than 2 dB. K_{DP} is greater than 1.5 deg/km in this region of high source densities except where the high source densities occur in the inflow region. The ρ_{hv} ranges from 0.95 to 0.96 in the high source density region. At the center of the VHF source semi-circle, reflectivity is depressed to about 45 dBZ, Z_{DR} is around 0.75 to 1 dB, K_{DP} rapidly drops to around 0 deg/km, and the ρ_{hv} is 0.98 or greater. The vertical velocity shows a cyclonic curvature in the updraft with a region of

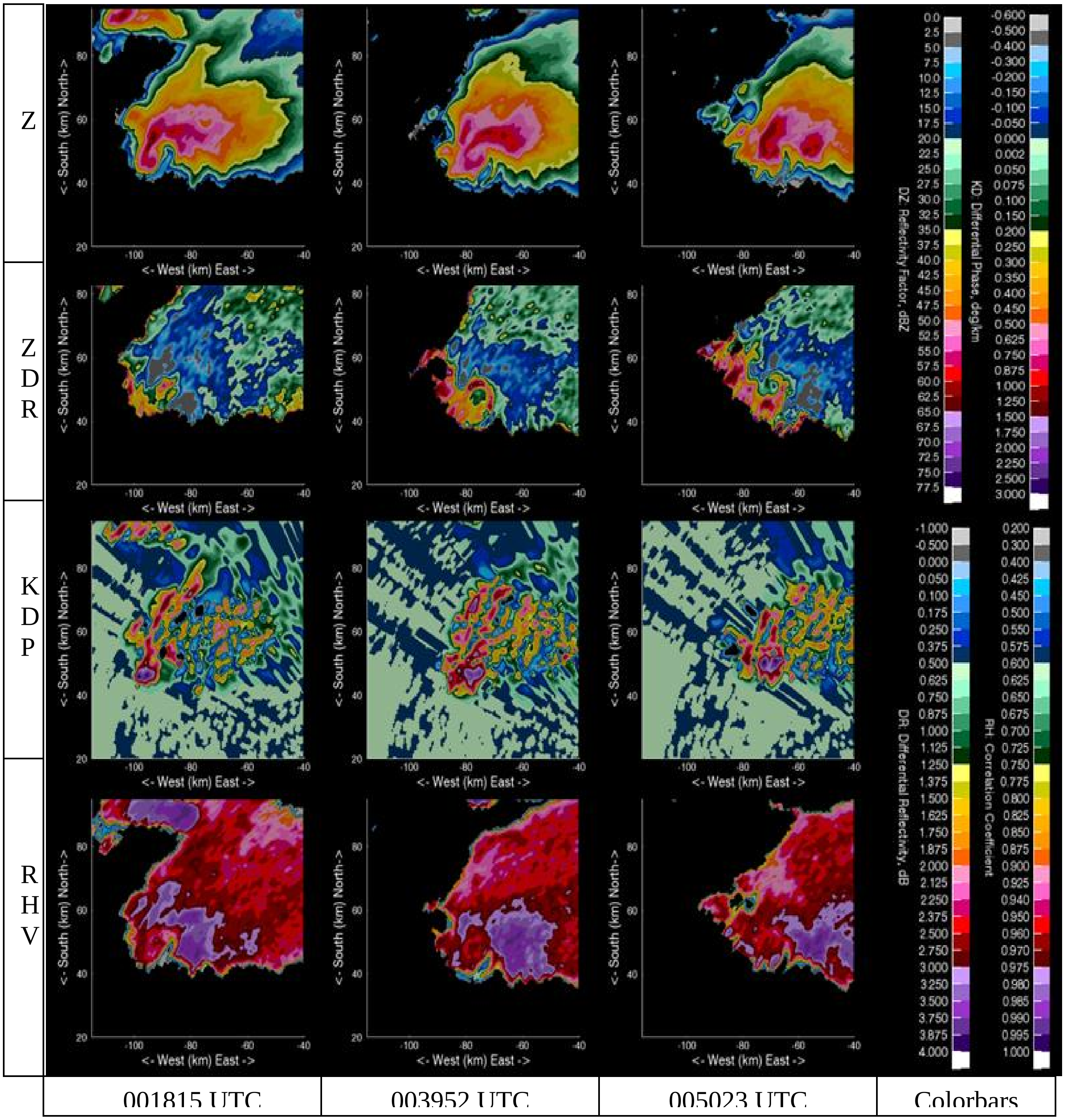

Figure 1. Polarimetric variables for the period from 001815 UTC to 005023 UTC. The top panel shows reflectivity. Note the classic supercell structures: hook echo, inflow notch, and anvil overhang. The panel below it shows differential reflectivity. Note the Z_{DR} column at 001815 UTC that evolves into a Z_{DR} ring at 003952 UTC and weakens at 005023 UTC. The panel below it shows K_{DP}. Note the regions of high K_{DP} in the southwest portion of the storm. The bottom panel shows ρ_{hv}. Note the regions of low ρ_{hv} (< 0.98) in the hook echo/updraft region and the ring of low ρ_{hv} at 003952 UTC. Colorbars for the variables are shown to the right.

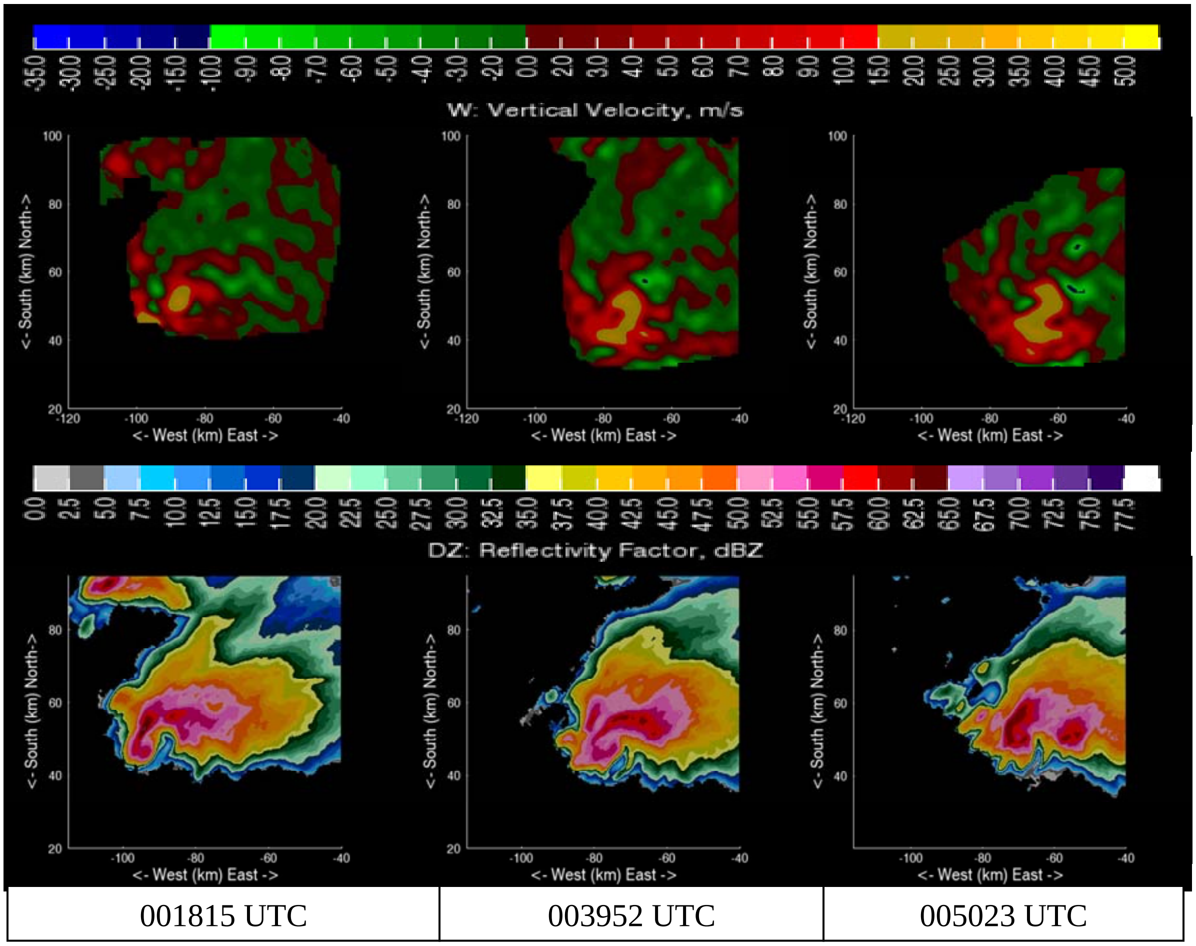

Figure 2. Dual Doppler derived vertical velocities (top panel) and reflectivity (bottom panel) showing the evolution of the vertical velocity field and reflectivity field for the time period from 0018 UTC to 0052 UTC at 4 km AGL. The evolution covers from the initiation of a new updraft through the occlusion process.

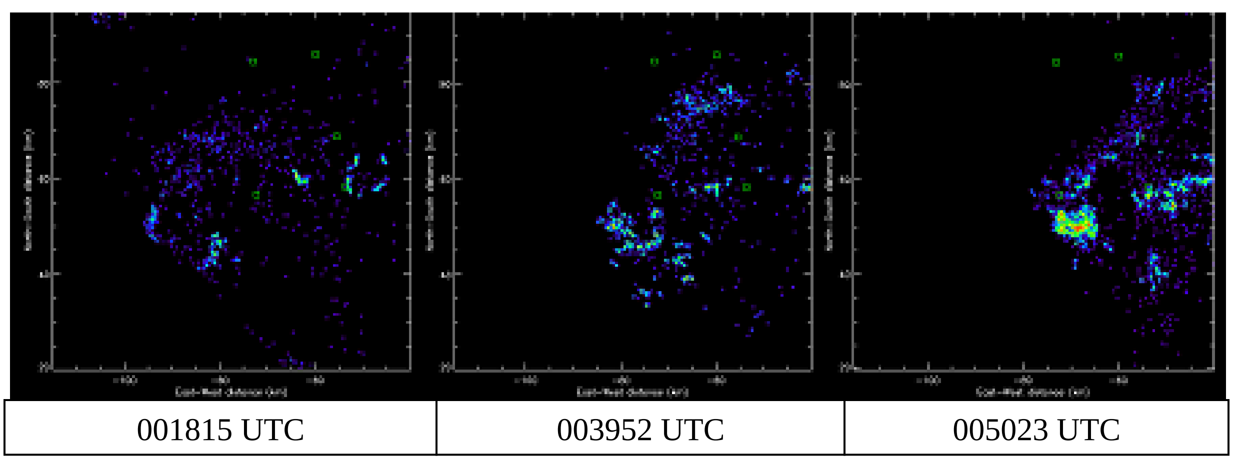

Figure 3. Lightning source densities from 001815 UTC to 003952 UTC at 4 km AGL. At 001815 UTC very little sources occurred at the 4 km level. A semi-circular ring forms at 003952 UTC and completely fills in at 005023 UTC. Also, note the increase in lightning source densities from 001815 UTC to 005023 UTC.

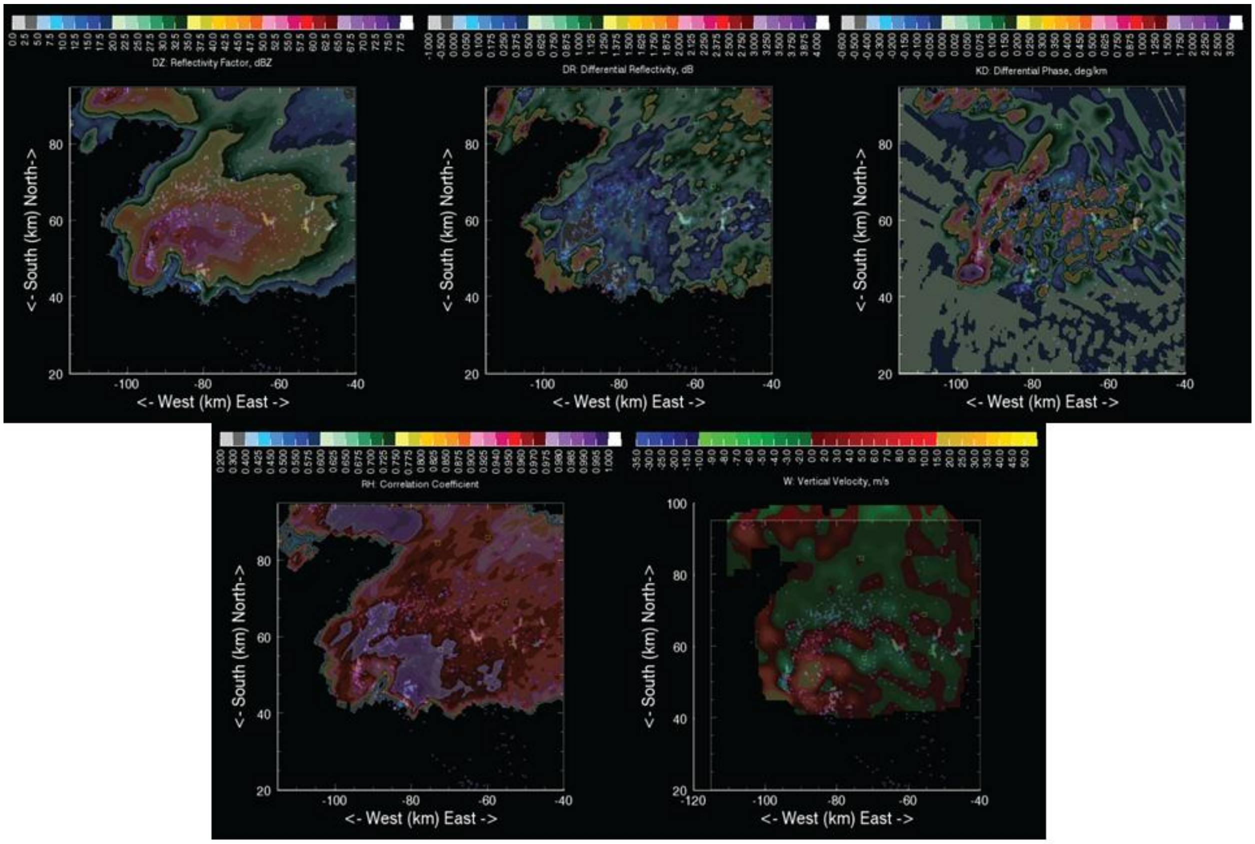

Figure 4. Lightning source densities and polarimetric signatures overlaid at 0018 UTC below the freezing level at 4 km. The top left panel shows the reflectivity. The top middle panel shows the Z_{DR}. The top right panel shows the K_{DP}. The bottom left panel shows the ρ_{hv}. The bottom right panel shows the vertical velocity field.

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downdrafts beginning to entrain on the backside of the updraft. The lightning sources seem to follow this downdraft entrainment path.

At 0050 UTC, the lighting source densities increase to a maximum, and the semi-circle feature fills in completely (Figure 6). The majority of the sources are confined to a reflectivity region of 50 dBZ or greater. Z_{DR} in this lightning density source region are at or below 1.5 dB with a Z_{DR} column forming east of the VHF source maximum. K_{DP} is above 1 deg/km, and ρ_{hv} is 0.95 to 0.97. In the vertical velocity field, the vast majority of the lightning sources are located in the downdraft region west of the new updraft formation.

3.2 Above the freezing level (5 to 6 km)

Above the freezing level, the lightning source density regions increased quite substantially. The majority of the area covered by large VHF source densities was located out in the anvil region. However, a secondary maximum was located in the updraft region of the storm. The focus of this section will be to look at the source densities in the updraft region. Figures 7-9 overlay lightning densities with polarimetric data above the freezing level.

At 0018 UTC, evidence of a BWER begins to take place at 5 and 6 km (Figure 7). The lightning activity in this region occurs just west of the BWER in a reflectivity maximum region near or above 50 dBZ. Z_{DR} ranges from 0 to 1 dB and VHF sources are located just southwest of a Z_{DR} column.

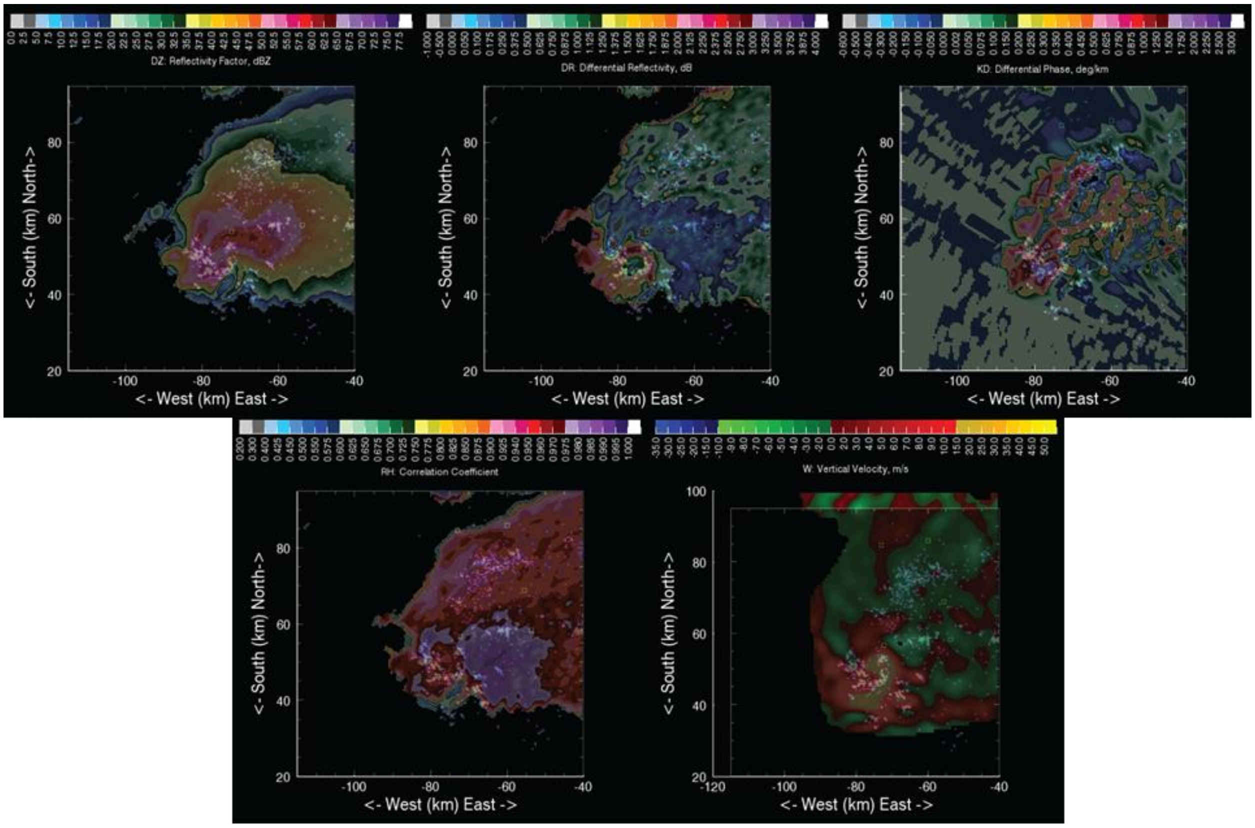

Figure 5. Same as Figure 4, but at 0039 UTC

Lightning sources are confined to a region north and east of a K_{DP} maximum within a K_{DP} range of 0.5 to 1.5 deg/km. The ρ_{hv} range from 0.9 to 0.95 and the source densities virtually cease when ρ_{hv} goes above 0.98. The vertical velocity fields show a few pockets of downdrafts located to the southwest of the main updraft. This is where the densest lightning activity occurs.

At 0039 UTC, a broad region of intense lightning source densities is located to the west of the BWER in a high reflectivity region and wrapped around a depressed reflectivity region into the inflow side of the storm at 5 km (Figure 8). Lightning density sources begin where Z_{DR} is slightly negative and extend into the Z_{DR} ring along the southern and eastern edges with values from 0.5 to 1 dB. The broad region of lightning densities begins where K_{DP} is negative and extends into the K_{DP} maximum of 2.5 deg/km. The ρ_{hv} is around 0.95 to 0.98. In the vertical velocity fields, no downdrafts occur within the lightning source regions but are following along a minimum in updraft velocity that is connected to a corridor of downdraft off to the northwest.

Toward the end of the updraft cycle at 0050 UTC, the lightning semi-circle fills in just like it did at the 3 and 4 km levels (Figure 9). The reflectivity in this region is above 50 dBZ. Z_{DR} ranges from slightly negative to around 1 dB and the Z_{DR} ring has substantially decreased in size and magnitude while a Z_{DR} maximum has developed to the south. The K_{DP} in this region ranges from 0.5 to about 2 deg/km. Lightning source densities are mainly confined to the regions of ρ_{hv} around 0.9 to 0.97. In the vertical velocity fields, the updrafts begin to weaken within the source density region as they evolve into downdrafts.

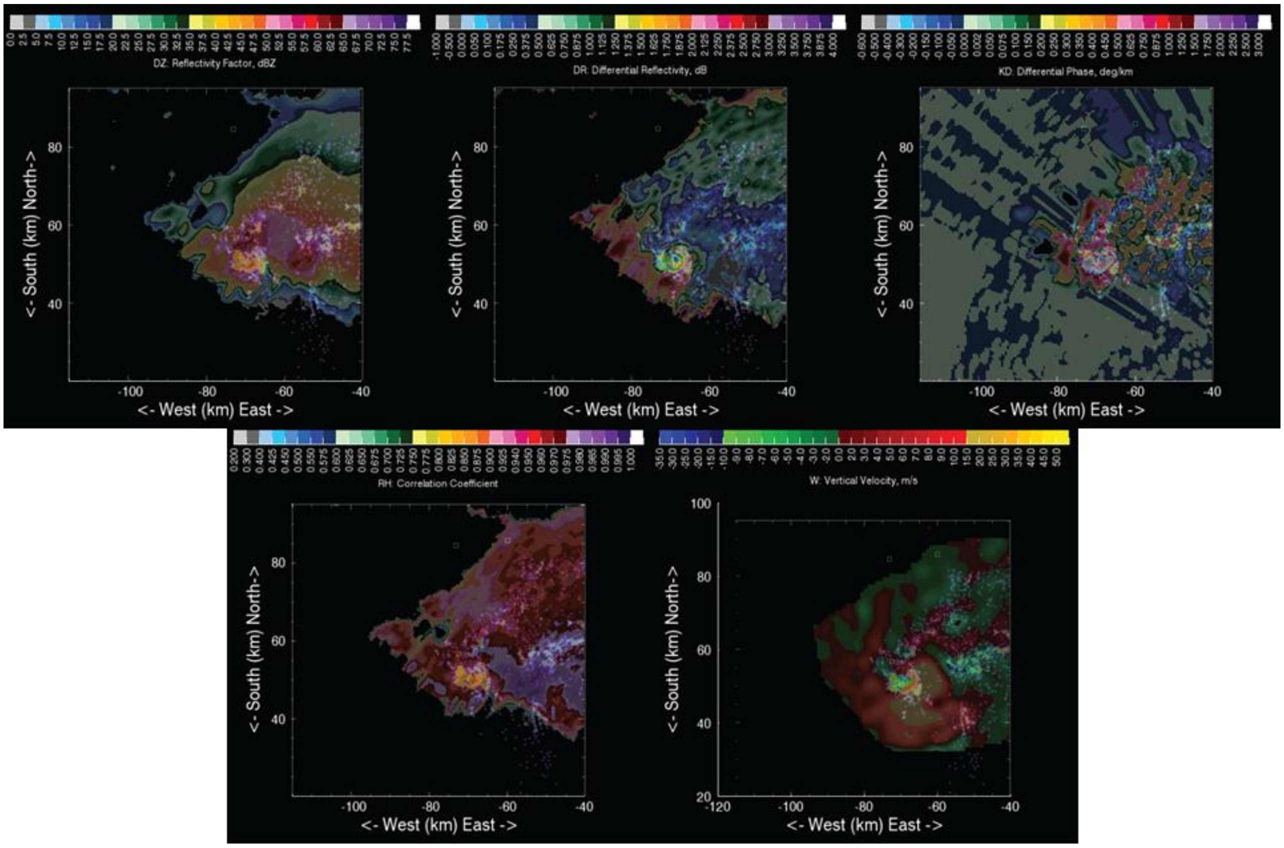

Figure 6. Same as Figures 4 and 5, but at 005023 UTC

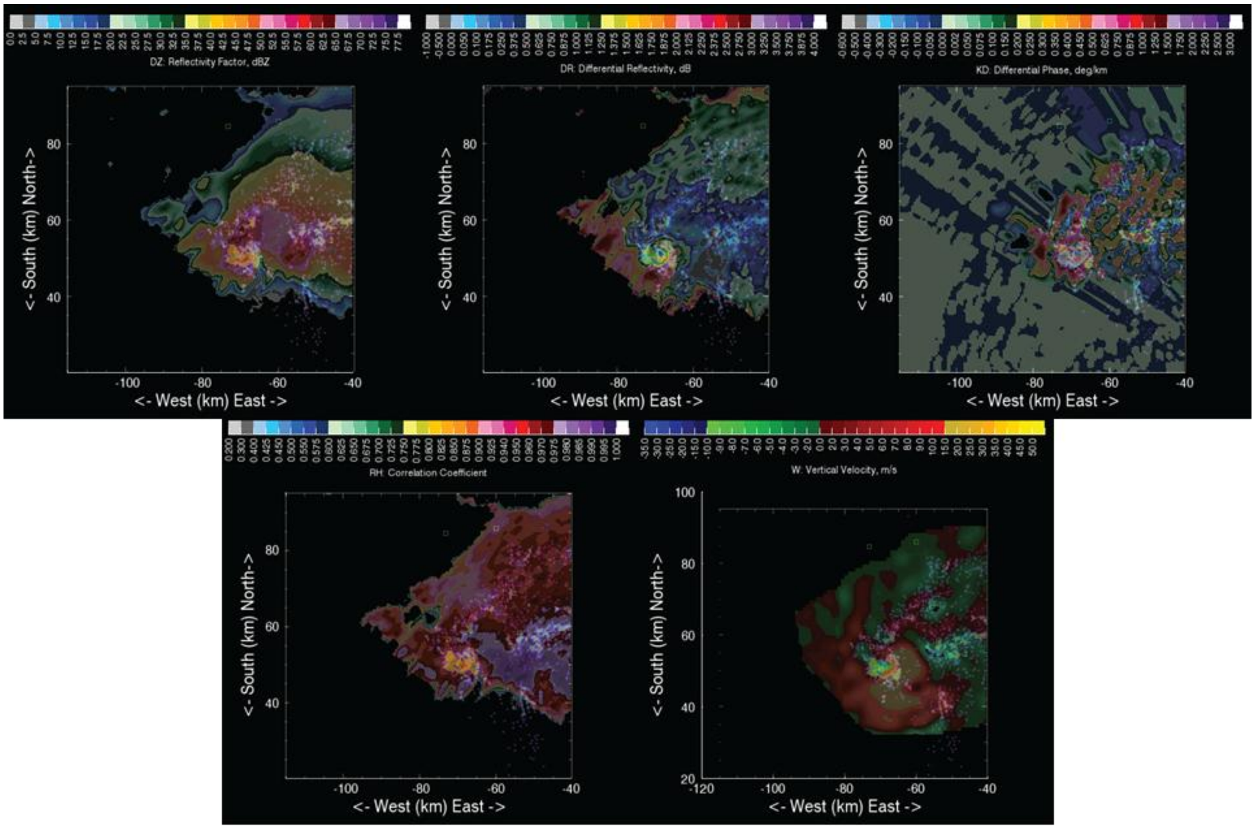

Figure 7. Lightning source densities overlaid with polarimetric variables above the freezing level at 5 km for 0018 UTC. The top panel shows reflectivity. The top middle panel shows Z_{DR}. The top right panel shows K_{DP}. The bottom left panel shows ρ_{hv}. The bottom right panel shows vertical velocity.

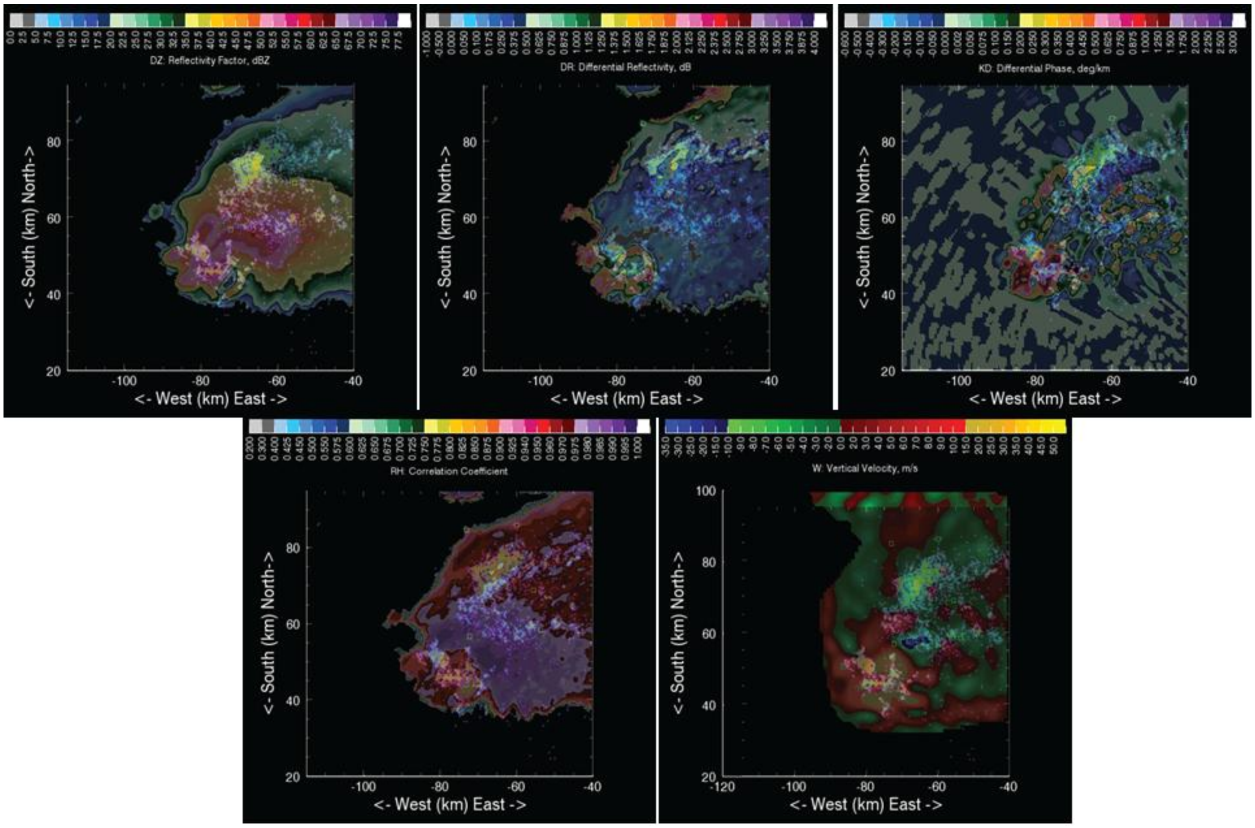

Figure 8. Same as Figure 7, except at 0039 UTC

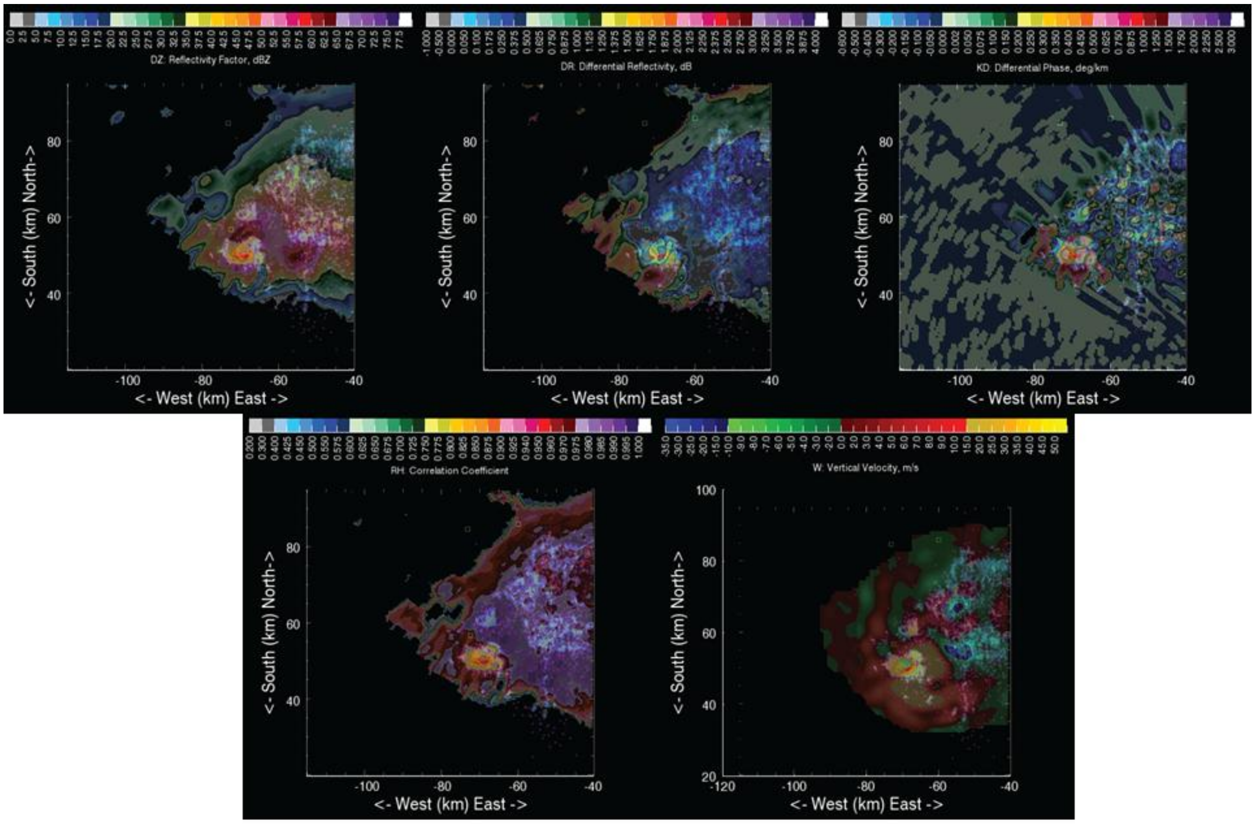

Figure 9. Same as in Figures 7 and 8, except at 005023 UTC

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4. DISCUSSION

The data presented here from the evolution of the lightning hole region of this HP supercell offer some invaluable insight as to the microphysics that occurred during this time.

In the early stages of the lightning hole formation, most of the activity was confined above the melting level (4 km) just off to the northwest of the main updraft. This region was characterized by high Z, low Z_{DR}, low K_{DP}, low ρ_{hv}, and weak updrafts or downdrafts. This type of signature can be associated with small hail or graupel (Straka et. al. 2000). At the lower levels a smaller region with these same characteristics existed and had much fewer VHF sources. The fact that the VHF sources were confined to the areas of graupel suggests that the riming graupel mechanism (Takahashi 1978) was responsible for the charging in this region that allowed the lightning channels to propagate through this region.

In the mature stages of the lightning hole, the VHF sources extended from the northwest along the southern end of the updraft and into the inflow region at both the upper and lower levels. The appearance of lightning sources at the lower levels suggests that charging had begun to occur there. The polarimetric variables and dual-Doppler data strongly suggest that graupel was the dominant hydrometeor along the path of the VHF sources at the lower levels. A new feature to note at 0039 UTC was the overlapping of the K_{DP} column with the graupel signature. The overlapping of the K_{DP} column with the graupel signatures suggests rime charging should have increased in this region. It may be possible that the overlapping of the K_{DP} column with the graupel signature may be responsible for the increased charging in this region leading to increased VHF sources.

The semi-circular feature of the VHF sources at 0039 UTC may be explained by the airflow and precipitation trajectories explained by Browning (1964). As the graupel forms in and above the updraft region, and becomes large enough, it falls out along the periphery of the updraft. As the graupel fall out, some become ingested back into the inflow of the updraft. The data suggests this is what happened because the graupel signatures occurred along the periphery of the updraft and eventually became associated with downdrafts. The graupel signatures could also been seen to have an “inflow” feature back into the updraft region along the southern side of the storm. This is the same region where the lightning VHF sources were propagating.

At 0052 UTC, the lightning hole had completely filled in. The polarimetric signatures in that region also suggest that graupel was the dominant hydrometeor. The dual-Doppler data also show that this region is dominated by downdrafts. Thus, it is hypothesized that this region had become dominated by graupel that had descended to lower levels and carried the charge it had acquired at the upper levels down to the lower levels and is thought to be responsible for the increased lightning activity at these lower levels.

5. CONCLUSIONS

The evolution of the lightning hole for the 29-30 May 2004 HP supercell was hypothesized to form via the formation and assumed trajectories of graupel in the updraft region. Graupel was formed as embryos were ingested into the updraft (Browning and Foote 1976; Tessendorf et al. 2005). After traversing through and exiting the updraft, these graupel particles became charged through the riming graupel charging mechanism. As these graupel particles fell around the southern periphery of the updraft and got entrained back into the inflow, they carried the charge they gained along this path. The lightning flashes that initiated above the updraft region were hypothesized to then follow this charged path and give the appearance of a lightning hole.

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