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An Analysis of Lightning Holes in Northern Alabama Severe Storms Using a Lightning Mapping Array and Dual-Polarization Radar

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Abstract - *Multiple severe storms that produced lightning holes were observed on 10 April 2009 in the Tennessee Valley. Two specific supercell storms from this day were analyzed, one non-tornadic storm that occurred in southern Tennessee and a tornadic storm that occurred in northern Alabama. Observational systems included the North Alabama Lightning Mapping Array (NALMA), the UAH Advanced Radar for Meteorological and Operational Research (ARMOR) C-band radar and the WSR-88D KHTX radar. These storms were approximately three hours apart, both displaying defined lightning holes. However, these two storms exhibited very different lightning and inferred charge structure although they were only a few hours and a few hundred kilometers apart. Lightning holes are hypothesized to be strongly correlated to the strength and size of the storms updraft. One scientific question that has yet to be fully addressed is "What is the minimum updraft speed required for a lightning hole to form?" In hopes of answering this question, multi-Doppler analysis was conducted on both storms. Updrafts of at least 20 m/s were present in the vicinity of the lightning holes of both the non-tornadic and tornadic storm, with updrafts of up to 30 m/s observed at higher levels in the storms.*

I. Background and Motivation

Lightning holes are an important research topic because of their potential impact on the lightning-tornadogenesis hypothesis and their general importance in relating electrical, kinematic and microphysical processes in tornadic storms. A lightning hole is a small region within a storm that is relatively free of in-cloud lightning activity [e.g., Murphy and Demetriades 2005]. These lightning-free regions (i.e., lightning holes) have been identified within LMA lightning source data since 1998 [Krehbiel et al. 2000]. However, few of these studies have documented lightning holes in severe storms in the southeastern United States [e.g., Goodman et al. 2005]. Lightning holes have also been referred to in the literature as lightning rings [e.g., Payne et al. 2010] when the emphasis is on the ring of higher lightning density instead of the lack of lightning activity in the center. Lightning holes are typically a transient feature having duration of less than 20 minutes and are approximately 5-10 km in diameter [Wiens et al. 2005; MacGorman et al. 2005]. In these studies, lightning holes are often found in the vicinity of supercell tornadoes, thus potentially contradicting the Armstrong and Glenn [2006] hypothesis that tornadogenesis and maintenance are caused by electrical forces associated with high flash rates in and around the tornado.

Lightning holes are typically affiliated with the extremely strong updraft and mesocyclone that are unique to severe storms. Large hail and tornadoes are usually present when lightning holes appear. Not coincidentally, in LMA studies thus far, scientists have only observed lightning holes in severe thunderstorms. It is important to note that the entire lightning hole is not well observed at any single altitude. Multiple levels within a thunderstorm must be analyzed in order to determine if a lightning hole is present.

An open scientific question is 'why do lightning holes exist?' The lightning hole probably exists for much of the same reason as the bounded weak echo region (BWER) exists in radar data. The hole is most likely due to short residence time of hydrometeors through the mixed-phase region in a very fast (> 20 m/s) updraft, which would cause a relative lack of precipitation growth and of charging from rebounding collisions between riming graupel and cloud ice [MacGorman et al. 2008]. Because of this very strong updraft, there is insufficient time for precipitation particles (of any type, including graupel/small hail) to grow and therefore there are fewer of these particles available for non-inductive charging (NIC) to occur in the BWER. Hence, there is little to no in situ charging going on in the BWER. Essentially, the BWER (and sometimes the associated lightning hole) is composed primarily of cloud liquid water, including supercooled water in the mixed phase zone. Supercooled cloud water alone is not sufficient for charging and hence there is little charge or lightning in what we see as the lightning hole. Not all lightning holes are associated with low reflectivity values (i.e., not all lightning holes are aligned with a BWER). Besides the short residence times for precipitation growth and charging, wet growth of large hail, which can occur in strong updrafts and large reflectivity, may also reduce the amount of charge separation in the lightning hole by drastically reducing the rebounding collisions between hail and ice particles [Steiger et al. 2007; Emersic et al. 2011].

This paper focuses on the 10 April 2009 case over Northern Alabama. This event provides an opportunity to compare and contrast the presence and characteristics of "lightning holes" between a tornadic and non-tornadic supercell. The non-tornadic supercell crossed southern Tennessee between the times of 17-18 UTC while the tornadic supercell spawned EF-3 damage and tracked across Marshall, Dekalb and Jackson counties from approximately 19 -20 UTC (Fig. 1 and Table I). Some questions about these two storms that we want to answer are: **1)** On what time and spatial scales were these lightning holes present? **2)** Were the lightning holes collocated with the BWER or were they displaced? And **3)** How strong of an updraft is needed for a lightning hole to form? These questions will be answered in both the results or conclusions sections.

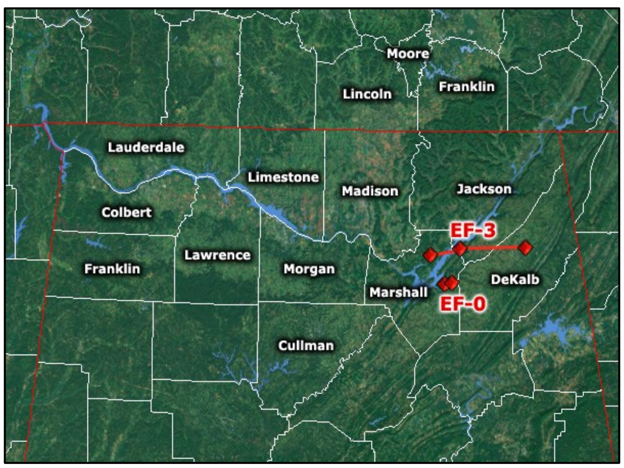

Fig. 1. *Tornado paths are marked on the map of the Huntsville county warning and forecast area (CWFA) from the 10 April 2009 event. The tornado analyzed for this event was the EF-3 that passed through Marshall, Jackson and DeKalb counties in northern Alabama. Details of the tornado are provided in Table I. Source: NOAA NWS HUN*

TABLE I. TORNADO CHARACTERISTICS FOR 10 APRIL 2009 EVENT (SOURCE: NOAA NWS HUN)

EF- Scale Rating	EF-3
Peak Wind	155 mph
Peak Path Width	½ mile
Path Length	28 miles

II. DATA AND METHODOLOGY

The relationship between lightning holes and storm kinematics will be analyzed in depth in this study. Multi-Doppler analysis of the UAH Advanced Radar for Meteorological and Operational Research (ARMOR) [Knupp et al. 2013] and KHTX radar was conducted on the 10 April 2009 case study over Northern Alabama to provide the three dimensional (3-D) wind field. In order to conduct the multi-Doppler analysis, the time consuming process of editing radar data had to be completed first. For example, Doppler velocities were unfolded via NCAR solo3 and artifacts such as 2nd trip echo and ground clutter were removed using both automated and manual techniques where appropriate. The multi-Doppler domain across northern Alabama can be seen in Fig. 2.

The multi-Doppler analysis will be combined with polarimetric techniques to provide information on storm kinematics and the location of tornadic debris. For example, the strength and volume of the updraft, rotational signatures and dual-polarization tornado debris signatures (DPTDS) [Schultz et al. 2012] will be analyzed with respect to possible surges in the lightning activity, which was observed by the Northern Alabama LMA (NALMA). ARMOR, which is a dual-polarization radar located at the Huntsville International Airport was used to analyze the tornadic storm for rotational signatures such as the presence of a strong mesocyclone (i.e., a strong updraft), a tornado vortex signature (TVS) and if the storm was exhibiting a tornado debris signature (TDS). According to Schultz et al. [2012] a TDS is defined by the presence of significant azimuthal shear (i.e., rotation) in the Doppler radial velocity (V_r), correlation coefficient (ρ_{hv}) less than 0.7, horizontal reflectivity (Z_h) greater than 30 dBZ and finally a near zero differential reflectivity (Z_{dr}). These four components of the TDS are shown in the results section. Radar data from ARMOR and KHTX both separately and when combined were used to determine if and when the storm exhibited a BWER. The location of the BWER was then compared to the location of the lightning hole around the same time.

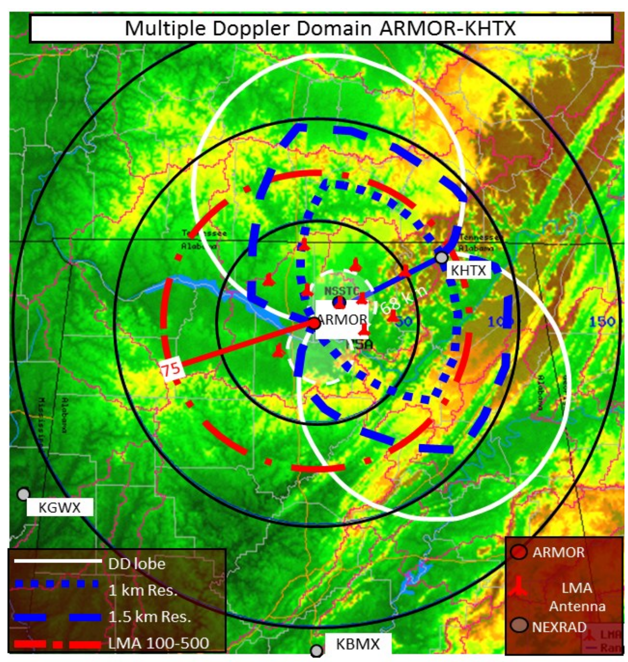

Fig. 2. *This image shows the multi-Doppler domain for the ARMOR and KHTX radars.*

III. RESULTS

10 April 2009: Non-tornadic storm

A lightning hole was present in the first severe storm (non-tornadic) approximately a few minutes after the lightning jump (Schultz et al. 2009) occurred (1728 UTC) and a defined bounded weak echo region (BWER) appeared in the radar data between 1727 and 1732 UTC (Fig. 3). From 1724 to 1728 UTC is when both the updraft and flash rate significantly increased and the lightning jump occurred. Between 1730 and 1733 UTC the lightning hole in this storm was beginning to form. By 1733 UTC, updrafts speeds of 25 m/s were observed at 2 km and updraft speeds of at least 30 m/s were observed at 6 km (Fig. 3). The lightning hole in this non-tornadic storm was present in the LMA data from approximately 1733 UTC until about 1747 UTC for a total duration of 14 minutes. An example of the lightning hole in LMA data between 1735 and 1737 UTC can be found in Fig. 4.

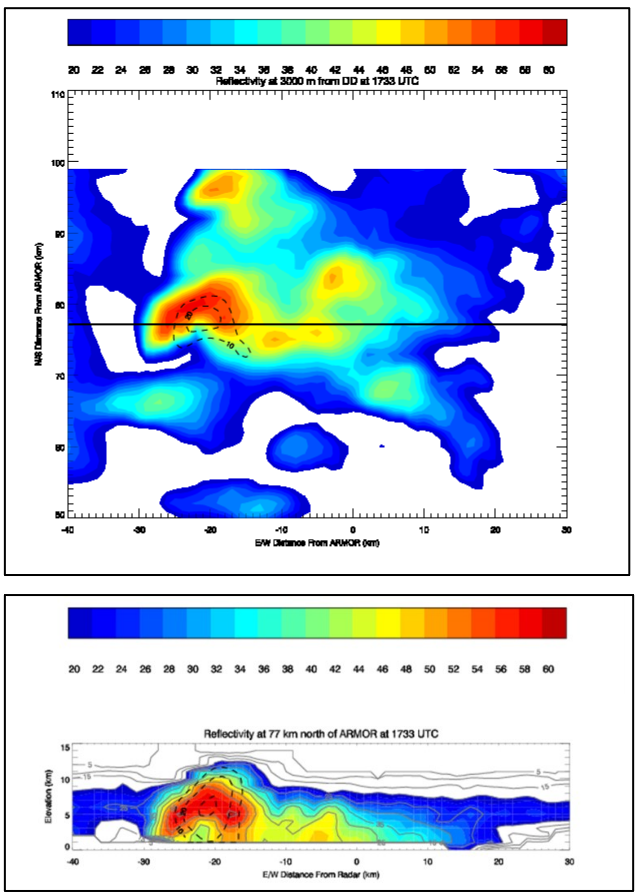

Fig. 3. *Gridded ARMOR/KHTX radar reflectivity and multi-Doppler inferred vertical motion at 1733 UTC on 10 April 2009 in a non-tornadic severe storm. Horizontal constant altitude plan position indicator (CAPPI) (top) of reflectivity (dBZ, color shaded) and vertical motion (m/s, dashed contours) at 3 km altitude while the east-west vertical cross-section of reflectivity (dBZ, color shaded) and vertical motion (m/s, dashed contours; bottom panel) is taken through the storm at 77 km north of ARMOR, showing the height of the BWER.*

Fig. 4 shows that this severe storm was highly sheared to the south and east with height, which is why there are a large number of LMA sources in that region. The black circle in this image indicates the presence of a lightning hole from 1735-1737 UTC. This non-tornadic storm is not only being studied for the presence of a lightning hole, but also the unique lightning structure and characteristics and how it compares to the structure of the lightning in the tornadic storm. By analyzing the height distribution of VHF sources in the histogram plot of Fig. 4 and the structure of individual intracloud flashes (e.g., Fig. 5), it can be inferred that the non-tornadic storm has a likely large and prominent positive charge region in the lower levels of the storm (~ 4 km).

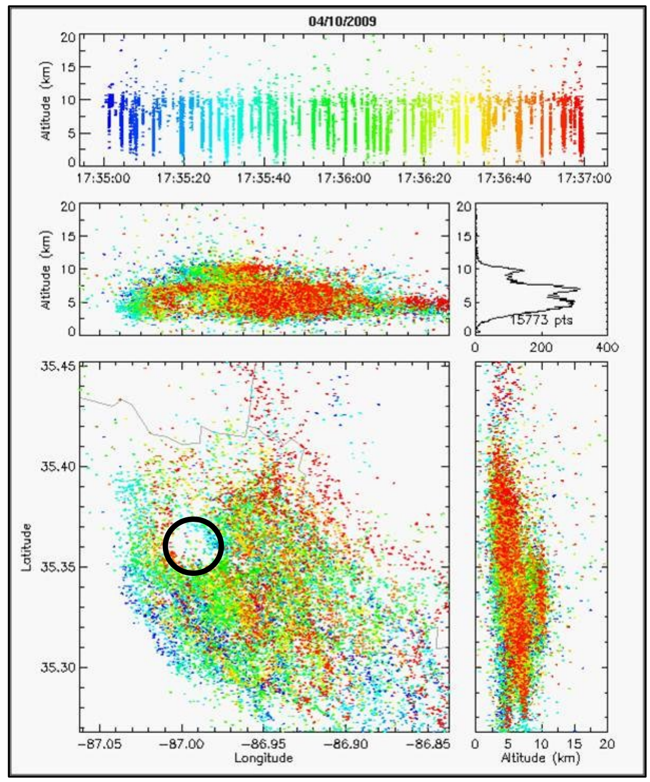

Fig. 4. *The non-tornadic supercell on April 10, 2009 was highly sheared to the south and east with height, which is why many LMA sources are in that region. A likely large positive charge region within this storm is evident at ~ 4km as seen in the histogram. The black circle is indicating the presence of a lightning hole from 1735-1737 UTC.*

This enhanced lower positive charge region is not typical of severe storms in Alabama. It is inferred that this is a lower positive charge region because negative polarity breakdown tends to be noisier than positive polarity breakdown at the radio frequencies used by the LMA, which results in more LMA sources that map negative breakdown [Rison et al. 1999]. More specifically, negative breakdown traveling through a positive charge region. When negative breakdown occurs, the electrons move away from the negative leader. The opposite occurs with positive breakdown, the electrons in that case move towards the positive leader, which in turn “blocks” the LMA from seeing that positive leader. Negative breakdown through positive charge regions is what is seen best by the LMA. Negative charge regions tend to have much fewer LMA sources associated with them. Using a program such as XLMA will give you a rough idea of the vertical charge structure based only on the altitude of the LMA sources. However, a flash-by-flash analysis of LMA data is probably the best way to determine charge regions within the thunderstorm [e.g., Wiens et al. 2005; Rust et al. 2005].

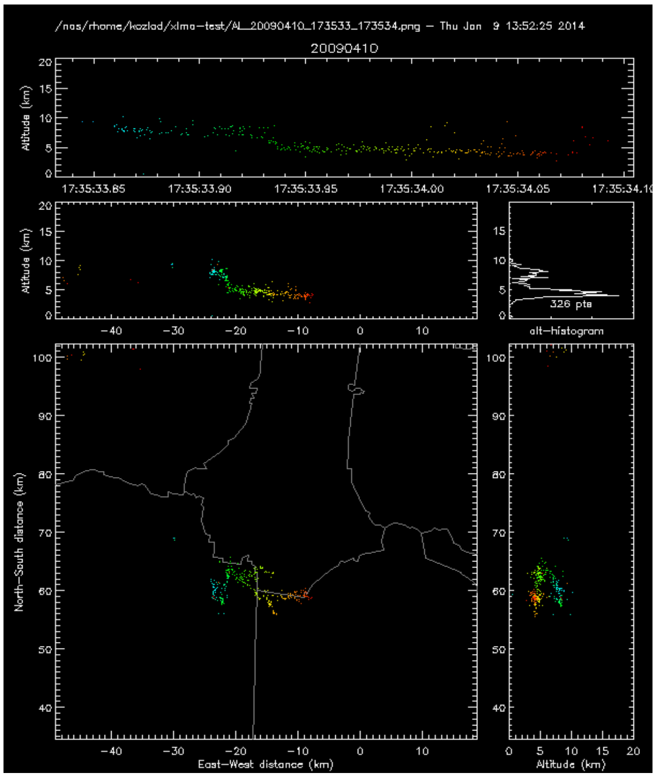

Fig. 5. *5-panel VHF source image from 17:35:33.83 to 17:35:34.1 UTC taken from XLMA showing a single intra-cloud (IC) flash from the non-tornadic storm. The LMA sources initiate around 8-9 km and then decrease in height to about 4-5 km. This lightning behavior shows more evidence of a likely low level (4 km) positive charge region (e.g., Wiens et al 2005; Rust et al. 2005).*

10 April 2009: Tornadic storm

The storm survey from the Huntsville National Weather Service (HUN NWS) states that the tornado touched down at 2007 UTC, but there is what appears to be a DPTDS in the radar volume at 20:04:34 UTC in the ARMOR data (Fig. 6). The DPTDS has vertical continuity, but is also in a region of significant attenuation. This debris is seen as high as 7.2 degrees elevation or 23,000 ft. (7 km) at 20:06:12 UTC. The first indication of damage was 2 miles south of Grant, AL (34.498231, -86.241621) and was mostly pine and deciduous trees. The NWS was able to survey a second point of damage, which was located 2 miles southeast of Grant (34.501278, -86.231477) and was comprised of trees and some fencing. This second point matches up well with the debris signature in this radar volume.

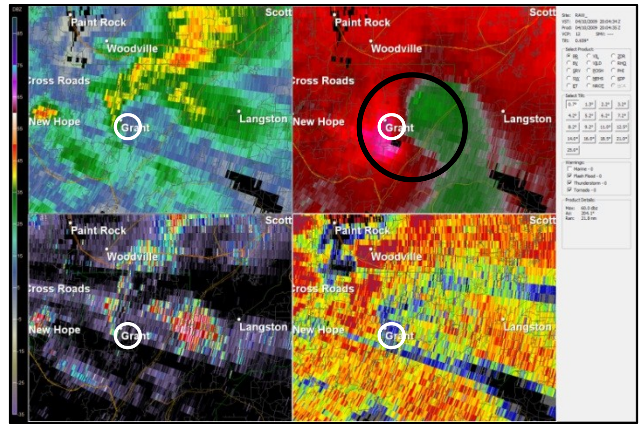

Fig. 6. *Image taken from GR2 Analyst for the April 10, 2009 tornadic supercell. ARMOR at 2004 UTC showing the presence of a TDS (indicated by the white circle) in the EF-3 storm doing damage near Grant, AL along with the presence of a mesocyclone (indicated by the black circle) at 0.7 degrees elevation. The TDS has vertical continuity, but is also in a region of significant attenuation. See Fig. 10 for the location of the lightning hole within this storm at this same time.*

Fig. 7. shows the 3-dimensional wind field at 1 km and low-level rotation associated with the tornado is clearly seen. The DPTDS signature (Fig. 6) and low-level rotation (Fig. 7) were preceded by a BWER and strong updraft at 2002 UTC (Fig. 8 and Fig. 9). A lightning hole was present in the tornadic storm from 2003-2005 UTC around the 2004 UTC ARMOR radar time (Fig. 10). This lightning hole was well correlated with the BWER and main updraft of the storm, as can be seen by comparing Figs. 9 and 10.

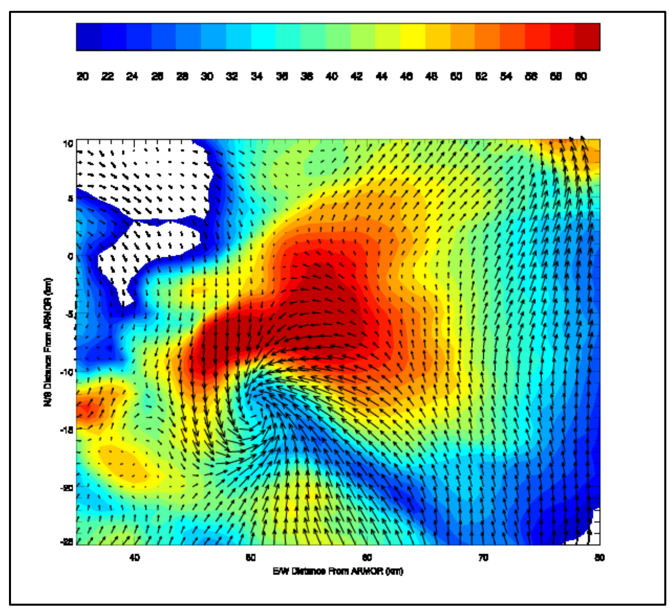

Fig. 7. *Multi-Doppler analysis at 2004 UTC at 1 km from ARMOR and KHTX of the tornadic storm on 10 April 2009. Horizontal CAPPI of reflectivity (dBZ color shaded) and horizontal wind vectors (black arrows). Low-level rotation associated with the tornado is evident.*

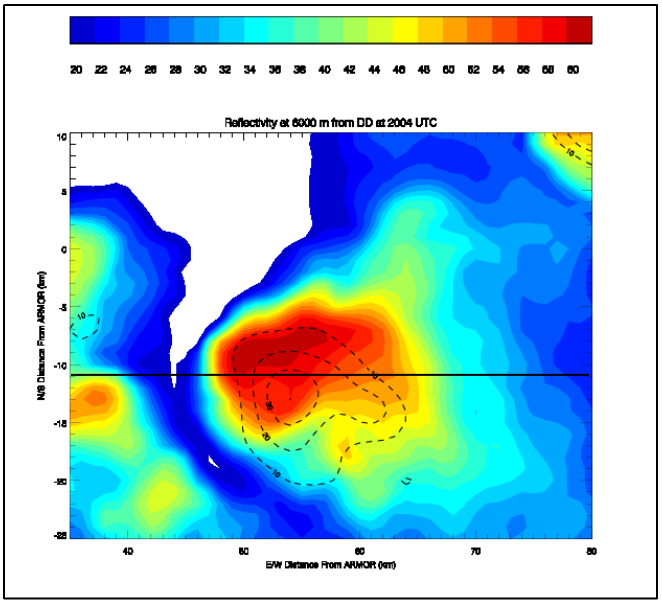

Fig. 8. *Gridded horizontal radar reflectivity at 6 km with updrafts speeds overlaid (black dashed lines). Seen here are updraft speeds as strong as 30 m/s in the tornadic storm.*

From the prior analysis and earlier discussion of what likely causes these lightning holes or minimums in lightning densities, it makes sense that there was a lightning hole (Fig. 10) present in this storm because of the strong updraft speeds observed at both the lower and mid-to-upper levels. At 3 km there were updraft speeds of at least 20 m/s and at 6 km to 9 km, updraft speeds of 30 m/s or greater were observed (Figs. 8 and 9). One of the questions needing to be answered is, what is the minimum updraft speed required for a lightning hole to form? In other studies, most results have shown that lightning holes are definitely present with a 20 m/s updraft [e.g., MacGorman et al. 2008]. Although research is still ongoing, the results presented herein appear to confirm these earlier studies.

Also seen in Fig. 10 is the very different charge structure present in the tornadic storm. The likely large positive charge region in this storm is located at 8 km (i.e., upper positive charge), which is a more normal charge structure seen in Alabama severe storms.

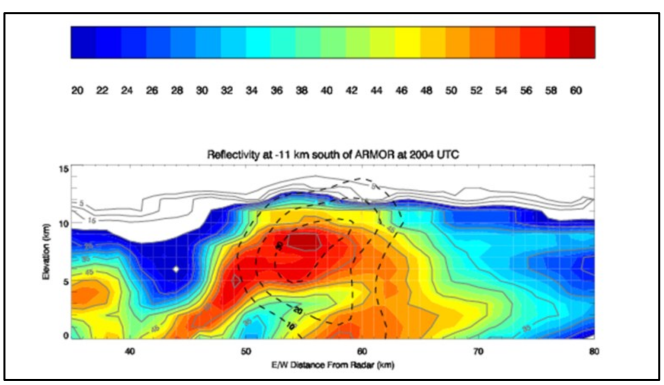

Fig. 9. *Cross section taken through the storm at -11km south of ARMOR to capture the height of the BWER with updraft speeds plotted in black dashed lines.*

The main positive region being located much lower in height (i.e., enhanced lower positive charge layer), which was seen in the earlier non-tornadic supercell (Figs. 4 and 5), is not typical for Alabama. Interestingly, there were at least two other nearby storms (not shown) in addition to the storm highlighted in Fig. 3 that occurred earlier in the day with the anomalous lower positive charge structure. All of these storms were within 100 to 200 km of each other. Storms prior to about 1830 UTC appeared to have anomalous charge structure (e.g., Fig. 4) while storms after 1830 UTC, including the tornadic storm (e.g., Fig. 10), were characterized by normal charge structure. Future research will include a more careful comparison of lightning type, charge structure, radar properties and environmental conditions between the two contrasting time periods on 10 April 2009.

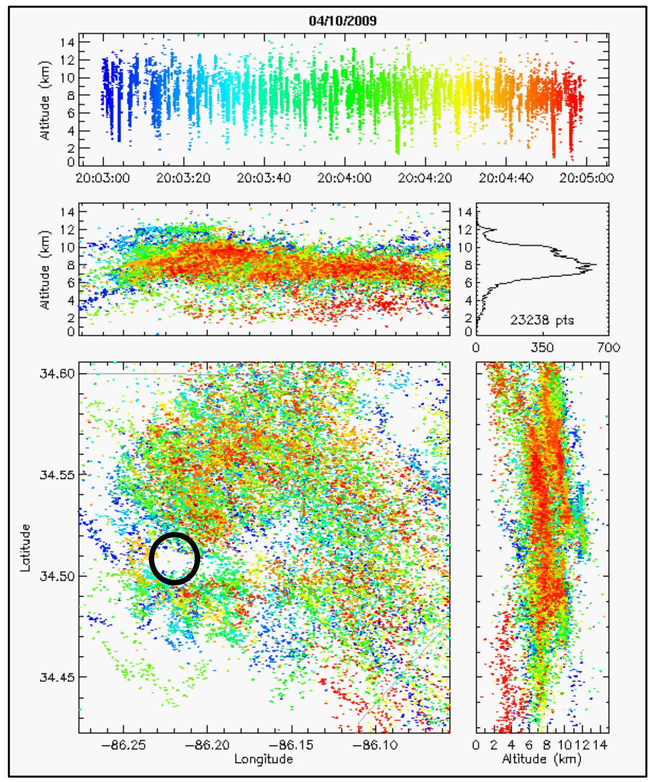

Fig 10. *LMA source data from 0 to 15 km and from 2003 to 2005 UTC surrounding the time of the 2004 UTC ARMOR radar volume from the tornadic supercell on 10 April 2009. Image taken from the XLMA viewing side of ANGEL. Based on comparison with radar data (seen in Figs. 5 and 6), the lightning hole appears to be collocated with the main updraft of the storm. At this time the lightning hole was approximately 3-4 km wide and 1-2 km in height. Also seen in this image is the very different charge structure of this tornadic storm compared to the earlier non-tornadic storm (c.f., Fig. 4).*

IV. CONCLUSIONS

This case study showed the severe storms on 10 April 2009 that produced lightning holes had updrafts of 20 m/s or greater which correlates well with findings from MacGorman et al. [2008] and other similar studies. The lightning hole in the non-tornadic storm was present for about 14 minutes of the storms' lifetime which agrees with previous research results as well. One thing that needs to be understood, is that not all lightning holes can be seen through the entire height of the storm (i.e., from 0 to 20 km). Lightning holes are a much more complicated feature within severe storms that must be analyzed over a short period of time (no longer than 3 or 4 minutes) and a small height range (anywhere from 2-3 km) at one time. There were certain times in the non-tornadic storm where the lightning hole was better defined than at other times. A comparison of the updraft speed to the lightning hole structure is currently being analyzed. Storms prior to about 1830 UTC appeared to have anomalous charge structure (i.e., enhanced low level positive charge layer) while storms after 1830 UTC, including the tornadic storm were characterized by normal charge structure (i.e., upper level positive charge layer). Updraft speeds of at least 20 m/s were present at low levels in both the non-tornadic and tornadic storm at the time lightning holes were present. Both of these storms also produced updraft speeds of up to 30 m/s observed at higher levels in the storms (5 km or greater). Further research is required to determine if 20 m/s is a minimum threshold for low level updraft speed prior to the formation of a lightning hole.

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