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THREE-DIMENSIONAL RADAR AND TOTAL LIGHTNING STRUCTURE OF MESOSCALE CONVECTIVE SYSTEMS

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1. INTRODUCTION

Mesoscale Convective Systems (MCSs) produce a significant fraction of the warm season rainfall, lightning and severe weather in the central United States. As a result, the concomitant kinematic, microphysical, electrical and lightning characteristics of MCSs over this region have received considerable research attention.

However, almost all studies of lightning in MCSs have analyzed primarily ground flashes in relation to storm structure. One exception is Mazur and Rust (1983), who observed the total lightning structure roughly perpendicular to a leading line, trailing stratiform MCS with radar. Total lightning flash density in the stratiform region was typically much smaller than in the convective cells. Lightning possessing radial extent in excess of 20 km tended to occur rearward of the deep convective cells and in the stratiform region.

Recently, lightning networks measuring the time of arrival of impulsive VHF radiation using GPS have been developed that provide an accurate and detailed depiction of three-dimensional lightning structure (e.g., Krehbiel et al. 2000). Herein, we report on unique observations of the total lightning structure of two leading line, trailing stratiform MCSs (Houze 1993) recorded by the Vaisala Dallas-Fort Worth (DFW) Lightning Detection and Ranging (LDAR II) research network during the 2002 warm season. The VHF derived three-dimensional lightning structure was placed in the context of DFW WSR-88D (KFWS) radar derived kinematic and precipitation organization, providing a fresh perspective on total lightning and inferred charge structure within MCSs. To our knowledge, these are the first such comprehensive observations of total lighting pathways within leading line, trailing stratiform MCSs.

2. DATA

We employed KFWS WSR-88D reflectivity and Doppler velocity; cloud-to-ground (CG) flash location, time, peak current and polarity from the National Lightning Detection Network (NLDN: owned and operated by Vaisala); and the time and three dimensional location of VHF sources associated with total lightning as measured by Vaisala's DFW LDAR II network. During the 2002 warm season, LDAR II data were available for two symmetric, leading line, trailing stratiform MCSs that passed directly over the network: 1) April 8 2002, 0000-0400 UTC and 2) June 16 2002, 0500-0700 UTC.

The DFW LDAR-II network is made up of 7 sensors with 20 to 30 km baselines (see Fig. 1b). Each sensor detects pulses of VHF radiation produced by electrical breakdown processes associated with lightning. The time of arrival of these pulses are used to reconstruct the path of individual lightning flashes (both in-cloud and cloud-to-ground = total lightning) in three dimensions. The DFW LDAR-II network can map lightning flashes in three dimensions within approximately 150 km of the center of the network, degrading in performance with increasing range.

During the April MCS case, two sensors in the northern and northeastern sectors of the network were malfunctioning such that only five sensors were available for detecting a lightning flash (Fig. 1a). Since a minimum of five sensors are required to locate a VHF source in time and space, the estimated flash detection efficiency was significantly impaired relative to optimal performance. For the April case, the estimated flash detection efficiency varied from 70% at the center of the network to 20% at a range of about 120 km from the center. Under optimal conditions (i.e., all 7 sensors functioning normally), the estimated flash detection efficiency within 120 km of the center would be >90%, as was the case for the June MCS. For typical conditions, the three dimensional location accuracy for individual VHF sources is better than 100 m within the network interior and better than 2 km out to a range of 150 km from the center of the network.

3. RESULTS AND DISCUSSION

The relationship between CG flash location, polarity and horizontal storm structure is depicted in Figs. 1a,b for the April and June MCSs respectively. As in past studies, the leading convective line for both MCSs contained significantly more CG flashes than the stratiform region (i.e., 6 and 12 times more for the April and June MCSs respectively). Interestingly, the June MCS (mean of 58.1 CG flashes min^{-1}) produced significantly more CG lightning overall than the April MCS (mean of 14.5 CG flashes min^{-1}). Consistent with earlier studies (Rutledge and MacGorman 1988), both MCSs generated a larger percentage of positive polarity CG flashes in the stratiform region (44.9% and 26.5% for the April and June MCSs respectively) than in the convective line (7.5% and 2.0% for the April and June

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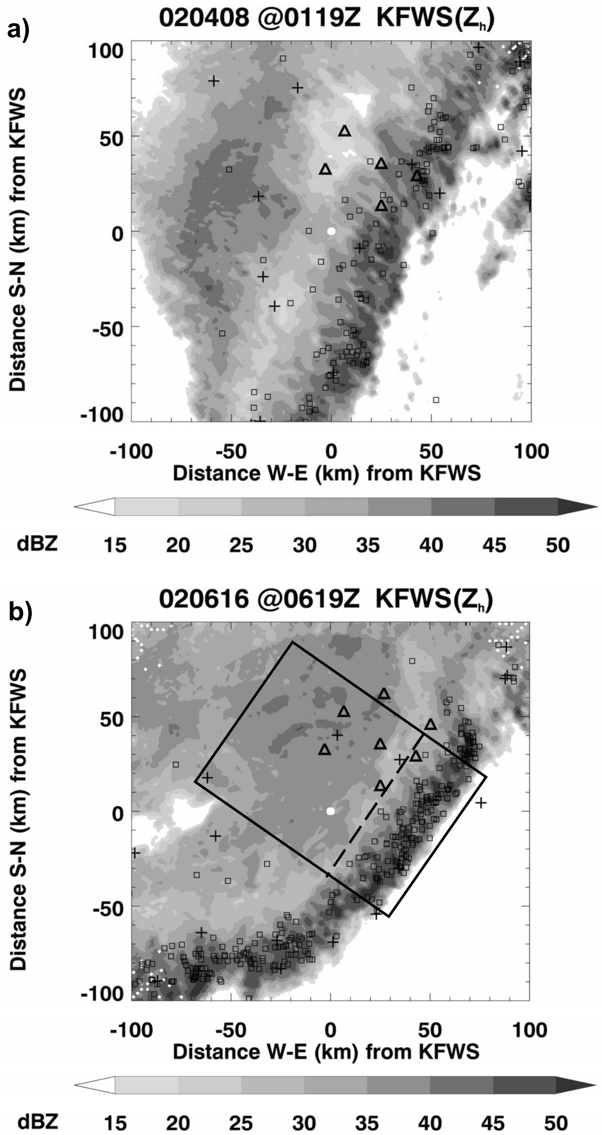

Figure 1. Low-level (2 km) horizontal cross-sections of Dallas-Fort Worth, Texas (KFWS) WSR-88D reflectivity (shaded as shown, dBZ) that depict two leading-line, trailing-stratiform, symmetric Mesoscale Convective Systems (MCSs). **a)** April 8, 2002 at 0119 UTC and **b)** June 16, 2002 at 0619 UTC. Cloud-to-ground (CG) lightning locations for a five-minute period centered on the radar time are shown. Positive (negative) polarity CG flashes are indicated by plus (box) symbols. For each panel, the triangles indicate the location of the VHF sensors in Vaisala's Dallas-Fort Worth LDAR II network that were operating nominally. All LDAR II (7) sensors were functioning on June 16, 2002. Network performance was degraded on April 8, 2002 with only the minimum required 5 sensors operating normally. The box in b) indicates the averaging region for the mean vertical velocity profiles in Fig. 2. Forward (rearward) of the dashed line is the convective (stratiform) region.

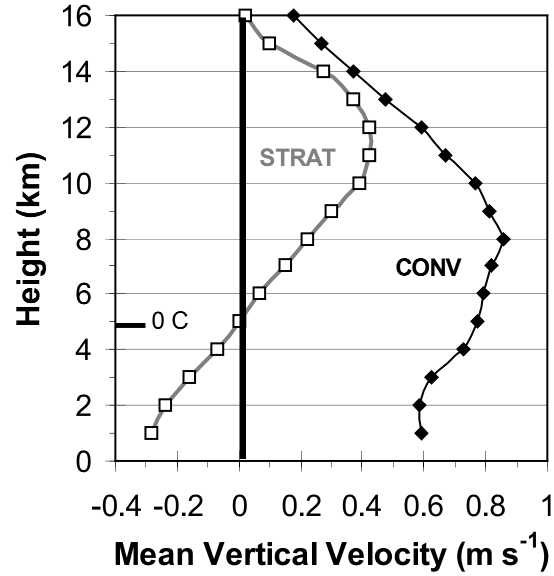

Figure 2. Vertical profile of the mean vertical velocity (m s^{-1}) in the convective (CONV, diamonds) and stratiform (STRAT, open squares) regions of an MCS on June 16, 2002 at 0619 UTC as derived from synthetic dual-Doppler analysis (e.g., Bluestein et al. 1994) of KFWS single-Doppler radial velocity data. See Fig. 1b for a graphical depiction of the averaging regions.

MCSs respectively). As in Petersen and Rutledge (1992), the mean positive peak currents were significantly larger in the stratiform region (43.0 and 31.5 kA for the April and June MCSs respectively) than the convective line (20.2 kA and 22.8 kA for the April and June MCSs respectively). In all respects, the horizontal radar structure and CG lightning properties of both the April and June 2002 cases were "typical" for leading line, trailing stratiform MCSs in the central United States and elsewhere.

Hypotheses for the presence of small numbers but large percentages of positive polarity ground flashes in the trailing stratiform region fall into one of two categories: 1) advection mechanism (e.g., Rutledge and MacGorman 1988) and 2) in-situ mechanism (e.g., Engholm et al. 1990; Rutledge et al. 1990). As proposed, the in-situ hypothesis requires the presence of a mesoscale updraft of sufficient strength to provide supercooled water for the local generation and separation of negative over positive charge by the non-inductive mechanism (NIC) (e.g., Saunders et al. 1991).

Consistent with conceptual models (Houze 1993), such a mesoscale updraft (0 to 0.4 m s^{-1}) was present above the melting level and to the rear of the convective line above the bright band in the June MCS (Fig. 2 and Fig. 1b). The advection mechanism requires the rearward transport of positive charged hydrometeors from the upper level positive charge center of the convective line. As in most MCSs, storm relative front-to-rear flow was present behind the convective line above 0°C (≈ -10 m s^{-1}; not shown). Therefore, the basic requirements for each hypothesis were in place.

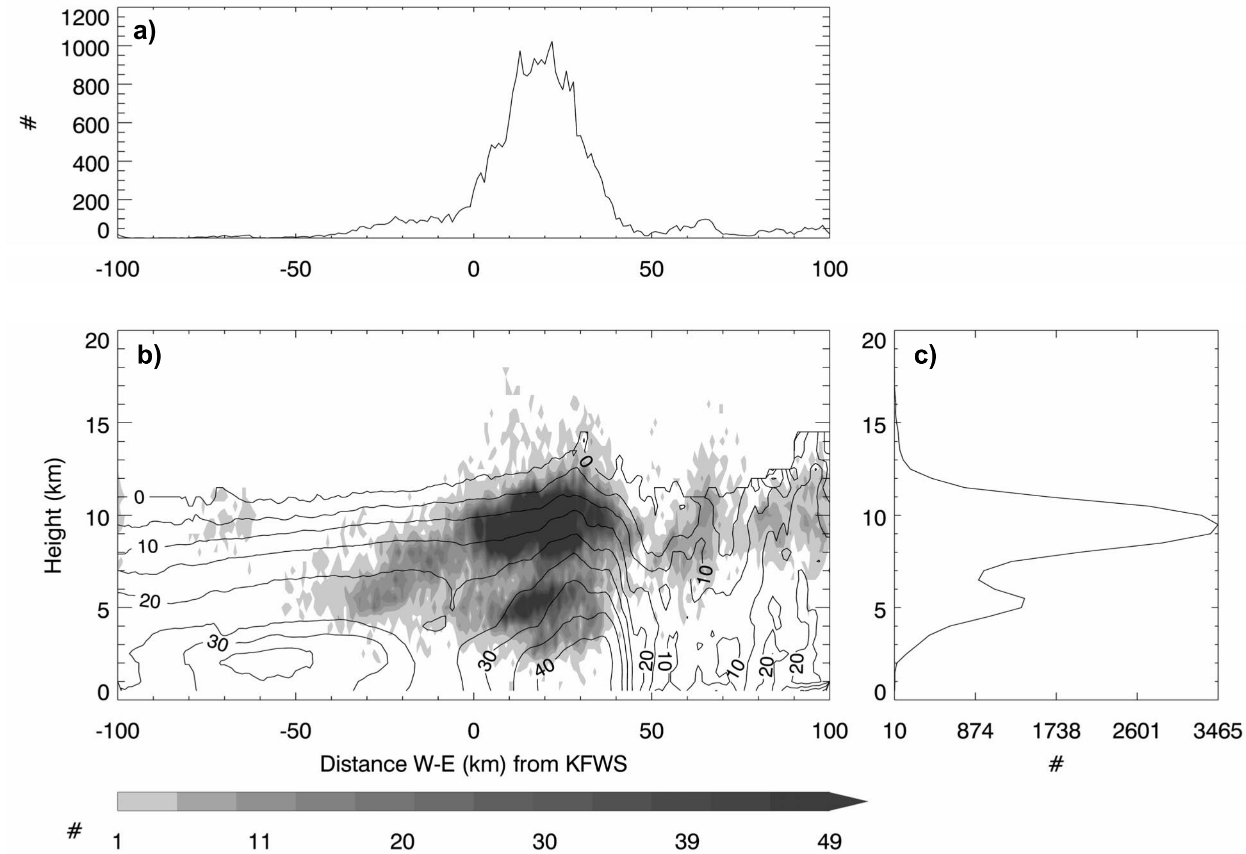

Figure 3. Line normal, vertical composites of radar reflectivity and total lightning structure of an MCS over Dallas-Fort Worth on 8 April 2002 at 0119 UTC. **a)** VHF source density as a function of line normal distance through the MCS, **b)** line normal, vertical composite of mean radar reflectivity (contoured, starting at 0 dBZ every 10 dBZ) and VHF source density (#, shaded as shown), **c)** VHF source density as a function of height in the MCS. To obtain the line normal, vertical MCS composite structure, the Cartesian KFWS radar (LDAR II VHF source) data were rotated 20° counter-clockwise (see Fig. 1a) and then averaged (summed) along the line-parallel direction.

Line normal, vertical composites of total lightning VHF source density and hence lightning pathways for the April and June MCSs are placed in the context of line normal vertical radar structure in Figs. 3 and 4 respectively. Similar to the radar study of Mazur and Rust (1983), an overwhelming majority of VHF sources occurred in the convective line of both MCSs (Fig. 3a,b and 4a,b). Averaged over the sampling period, roughly 6 (10) times as many VHF total lightning sources occurred in the convective region compared to the stratiform region for the April (June) MCS.

In each composite, VHF lightning sources in the convective line clustered into a vertical dipole (Figs. 3b and 4b). The two VHF source maxima are located at roughly similar altitudes in each case: 1) an upper lightning center at 9.5 km, and 2) a mid-level lightning center at about 5 km (Figs. 3b,c and 4b,c). Krehbiel et al. (2000) found comparable lightning dipoles at similar heights within thunderstorms over central Oklahoma. The upper (mid-level) VHF source maximum was interpreted to be associated with the upper-level positive (mid-level negative) charge center of a thunderstorm tripole (Shao and Krehbiel 1996).

VHF lightning sources associated with the inferred upper level positive charge center of the convective region sloped rearward (by ≈ 40- 50 km) and downward (by ≈ 4-5 km) through the transition zone to the stratiform region, settling above the radar brightband (Figs. 3b, 4b). This sloping lightning pathway was a persistent feature of both MCSs. A comparable sloping structure was present in nearly *every* five-minute line normal composite of VHF sources for the entire four (two) hour sampling period of the April (June) MCS. The sloping pathway of the VHF sources in both MCSs is *remarkably* similar to trajectories taken by hydrometeors (i.e., aggregates) from upper reaches of convective cells to the stratiform region in the front-to-rear flow, which continue to grow via deposition in the mesoscale updraft, further aggregate and then melt below 0° C, hence forming the radar bright band (e.g., Houze 1993). Since a typical fall speed for aggregates is ≈ 1 m s^{-1} and the front-to-rear flow along the trajectory was ≈ 10 m s^{-1} (i.e., 10:1, horizontal-to-vertical), it is feasible that the primary lightning pathway rearward of the convective line, which also sloped rearward-to-downward at 10:1, followed the identical trajectory as aggregates.

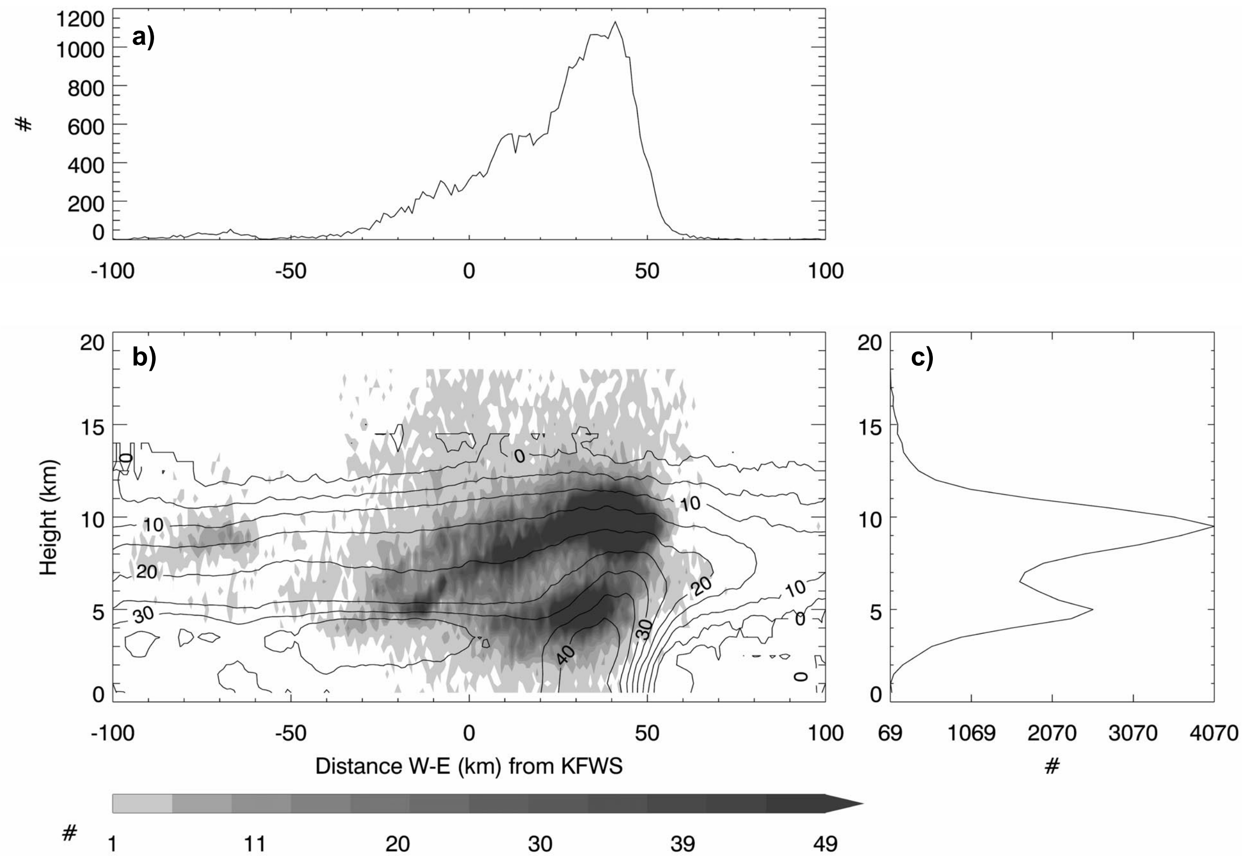

Figure 4. Same as Fig. 3 except for an MCS over Dallas-Fort Worth on 16 June 2002 at 0619 UTC. Rotation angle prior to compositing was 40° (see Fig. 1b).

One interpretation of these results is that aggregates were advected rearward from the convective line transporting net positive charge along the sloping trajectory. Since lightning propagates preferentially through space charge (Williams et al. 1985) and VHF radiation sources radiate strongly where the breakdown process is of negative polarity through positive charge (Thomas et al. 2001), our observations support this interpretation. Although supporting the advection mechanism, our data are also consistent with the positive charging of aggregates along this sloping trajectory via NIC in the mesoscale updraft rearward of the transition zone downdraft. Positive charge on aggregates could then separate from negative charge on smaller ice crystals due to differential sedimentation, resulting in negative over positive charge.

The 2-D modeling study of the electrification of stratiform regions in symmetric MCSs by Schuur and Rutledge (2000) demonstrated that both mechanisms likely contribute. The trajectory of aggregates in their study is identical to our sloping lightning path. When they used the Type "A" (i.e., symmetric MCS) electrical sounding from Marshall and Rust (1993) to initialize their charge advection profile, placed positive charge on aggregates, and then allowed in-situ charge generation according to the NIC laboratory experiments of Saunders et al. (1991), Schuur and Rutledge (2000) obtained a sloping trajectory of significant positive charge density that is surprisingly similar in size, location, shape and slope to the sloping lightning pathway from the inferred upper positive charge region above the convection to the region just above the bright band (Figs. 3b, 4b).

Another interesting feature in the composite maps was the weak but measurable secondary maxima in VHF source density 60-80 km (80-120 km) rearward of the convective line at altitudes of 8-11 km (7-10 km) in the April (June) MCS as seen in Figs. 3a,b (4a,b). The secondary maxima appear to be distinct from the sloping trajectory discussed above and were present in many five-minute composites. The synthetic dual-Doppler analysis did reveal a mesoscale updraft at these ranges and altitudes in the June MCS.

Finally, note that the lightning dipole was tilted in the downstream direction in the June MCS. This was consistent with a prominent forward anvil and an increased occurrence of positive CG flashes ahead of the convective line (Figs. 1b and 4b). Also notice that the source density maxima in the convective line of the April MCS are shifted slightly rearward (upstream) toward more moderate reflectivities and mature convection, similar to Mazur and Rust (1983).

4. REFERENCES – are available upon request.