2.2 ONE SEVERE STORM WITH TWO DISTINCT ELECTRICAL REGIMES DURING ITS LIFETIME: IMPLICATIONS FOR NOWCASTING SEVERE WEATHER WITH LIGHTNING DATA

Timothy J. Lang and Steven A. Rutledge
Department of Atmospheric Science, Colorado State University, Fort Collins, CO

1. Introduction

In the past decade or so there have been numerous efforts to link lightning behavior in thunderstorms and the occurrence of severe weather such as large hail, strong winds, and tornadoes. Some studies have demonstrated a propensity for the production of unusually high numbers of positive cloud-to-ground (+CG) lightning flashes by some severe thunderstorms (e.g., Rust el al. 1981a,b; Stolzenburg 1994; Carey and Rutledge 1998). A more recent statistical study (Carey et al. 2003), however, found that such a phenomenon was mainly confined to the central plains of the United States, and that even there the percentage of severe storms that feature mostly +CG lightning is less than 50%. In central plains storms, Lang et al. (2000) and Lang and Rutledge (2002) found many intense or severe storms were linked more by a lack of negative CG (-CG) lightning than the occurrence of +CGs. Indeed, a more promising metric of severity appears to be total flash rate (CG plus intracloud, or IC, lightning). For example, Williams et al. (1999) found that total flash rate, as measured by a time-of-arrival VHF lightning mapper, often increased rapidly 5-20 min prior to the occurrence of severe weather in Florida thunderstorms. In addition, Hamlin (2004) found that the vertical distribution of VHF electrical activity can change prior to severe weather, with surges in convective strength leading to VHF activity at higher altitudes for short periods of time beforehand.

However, there remains a great level of uncertainty in all of these findings due to the small number of statistical and case studies. Also, few studies have examined the issue of using lightning data for nowcasting severe weather within the convective elements of a mesoscale convective systems (MCS). Therefore, in the spirit of making an incremental improvement to our understanding we offer a case study of a small but severe asymmetric MCS that passed through eastern Colorado and western Kansas on 11-12 June 2000. This system was monitored by two research polarimetric Doppler radars and a NEXRAD Doppler radar, as well as a VHF-based lightning mapping network and the National Lightning Detection Network (NLDN), as part of the Severe Thunderstorm Electrification and Precipitation Study (STEPS; Lang et al. 2004a). The MCS produced severe-sized hail and severe winds throughout much of the ~5-hour period of study, from 2100 UTC on 11 June to 0150 UTC on 12 June. However, the electrical behavior of the storm varied significantly during this time period, in terms of both total and CG flash rate as well as vertical distribution of VHF sources.

This study is ongoing and we report only partial results here. Mainly, we will examine what aspects of the lightning in this system show promise in anticipating severe weather. In particular, we will examine CG

Corresponding author address
Timothy Lang
Department of Atmospheric Science
Colorado State University
Fort Collins, CO 80523
970-491-6944
tlang@atmos.colostate.edu

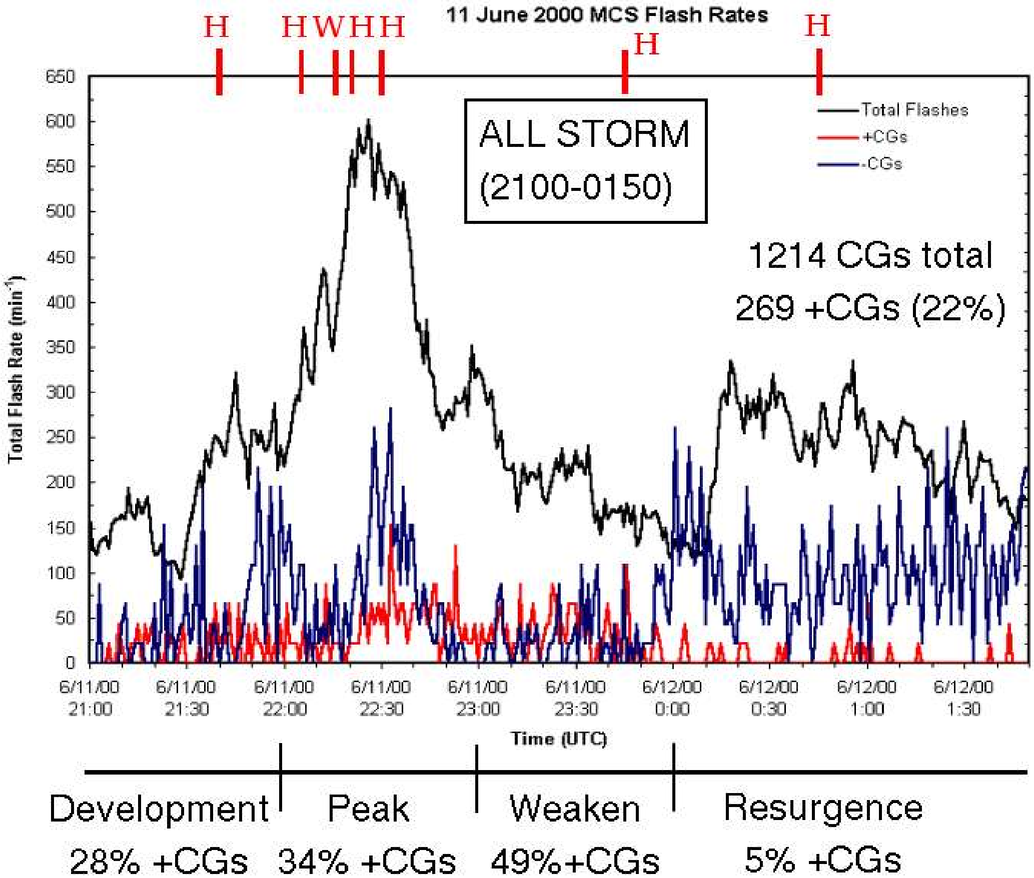

Figure 1. Total and CG lightning flash rates for the 11 June 2000 storm. Also shown are basic CG flash statistics and the times and types of severe weather (H - Hail, W - Wind).

flash rate and polarity, total flash rate, and vertical distribution of VHF activity prior to the onset of severe weather. Also, we will diagnose aspects of the microphysical structure of the MCS that are relevant to understanding the lightning behavior. We approach this problem from two different angles – examining the entire MCS, and examining individual cells associated with severe weather.

2. Lightning activity in the entire MCS

Figure 1 shows total, -CG, and +CG lightning flash rates for the entire MCS, during the analysis period (2100-0150 UTC). Also shown are basic CG flash statistics for this period, as well as the times and types of severe weather associated with the MCS. Total lightning comes from analysis of the VHF lightning mapper (the New Mexico Tech Lightning Mapping Array, or LMA) that was available during STEPS. Total flash rates are determined by the flash identification algorithm of Thomas et al. (2003), that runs in the xlma software developed at New Mexico Tech. This software also allows for the exclusion of other storms from the analysis, so that the flash rates correspond to the MCS only. Though a detailed quality control study of the flash sorting algorithm has not been performed, based on comparisons with manual sorting efforts and other lightning metrics (e.g., number of LMA sources per unit time), we believe that at a bare minimum it adequately captures order of magnitude flash rates as well as the overall

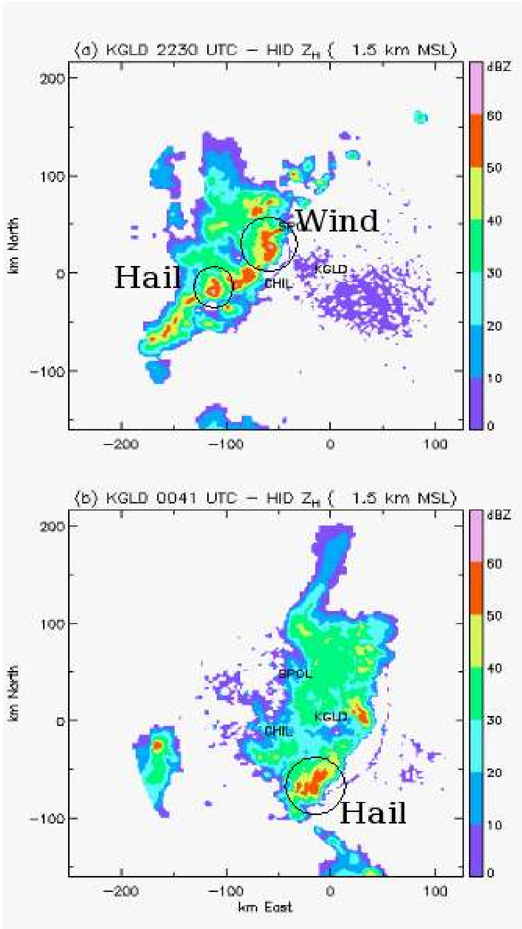

Figure 2. KGLD reflectivity for the 11 June 2000 storm at 2230 (a) and 0041 UTC (b). Also indicated are the cells associated with the severe weather studied in Section 3.

trends in flash activity. As noted in Lang et al. (2004b), the MCS was close to the LMA during the 5-h analysis time and therefore LMA spatial resolution and coverage were adequate for our purposes. CG flash rates were determined from the NLDN, with strike locations compared with VHF source distributions to ensure that we were counting only CGs associated with the MCS. As the MCS was relatively isolated from surrounding convection, this was neither a difficult nor ambiguous task. Severe weather reports came from the National Climate Data Center and included latitude and longitude locations, so that reports could be accurately matched to the MCS.

As Fig. 1 demonstrates, there were two convective peaks in this MCS, both associated with severe weather. One occurred around 2230 UTC on 11 June. During this time period total flash rate peaked near 600 min^{-1}, with -CG flash rates between 10 and 15 min^{-1}, and +CG flash rates between 5 and 10 min^{-1}. Over the 2200 hour roughly 1/3 of all CGs were positive. Severe weather reports during this time period included up to 1.5-inch diameter hail and wind gusts up to 57 knots. The second convective peak occurred after 0000 UTC on 12 June. Here -CG rates again peaked between 10 and 15 min^{-1}. However total flash rates were lower, though still high (~300 min^{-1}). Interestingly, during the 0000-0150 UTC time period only 5% of all CGs were positive. There was a single severe weather report of 0.88-inch hail at 0045 UTC.

Figure 2 shows low-level horizontal cross-sections of Goodland, KS (KGLD), NEXRAD radar reflectivity at 2230 (a) and 0041 UTC (b). Also indicated on these plots are the cells associated with severe weather. These will be examined in more detail in Section 3. At the earlier time, convection was active all along the leading line of the MCS, and a nascent stratiform region was developing rearward of this line. By the later time period, the strongest (and severe) convection was toward the southern portion of the MCS, while the mature stratiform region was mainly northward of this convection, identifying this system as an asymmetric MCS.

Figure 3 shows time height distributions of VHF sources for the entire MCS, as well as portions of the MCS identified as convective, stratiform, and transition. This partitioning was performed by examining KGLD radar data that was gridded to a 2 km by 2 km by 0.5 km (vertical) Cartesian grid. This radar was able to scan the entire MCS during the 2100-0150 UTC time period. We distinguished convective

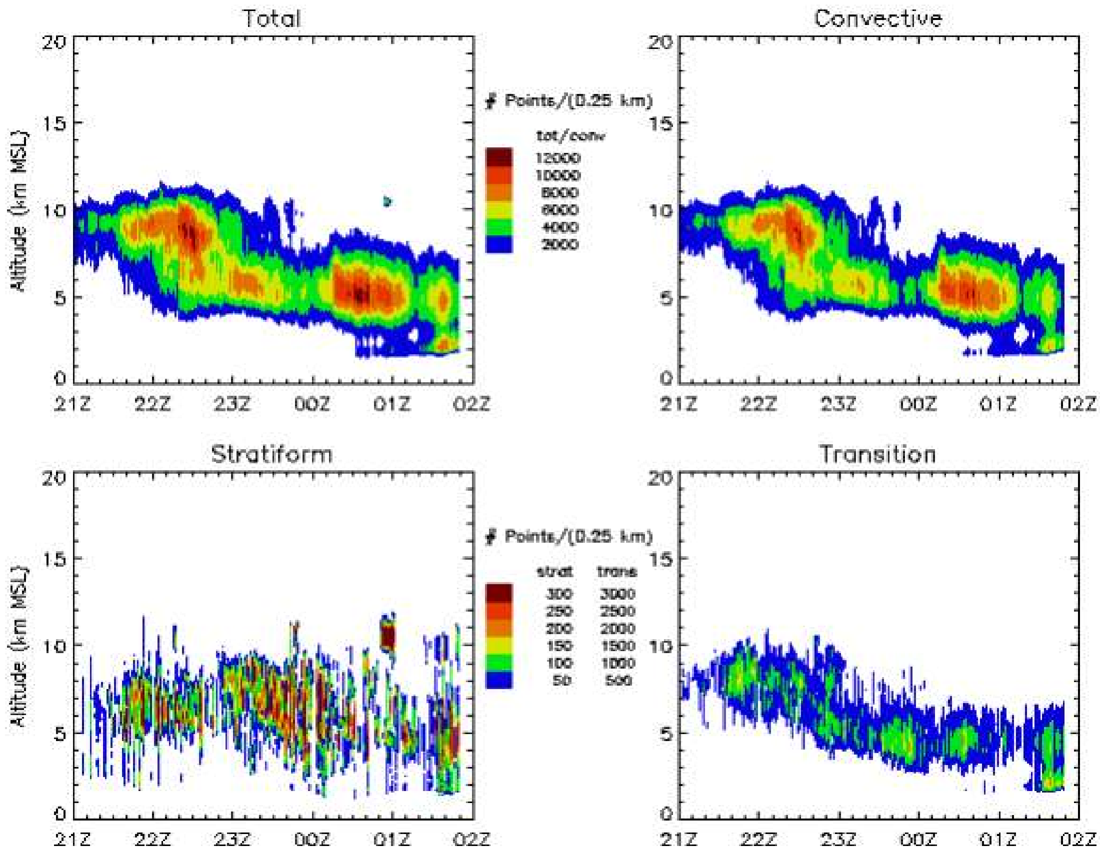

Figure 3. Time-height plot of VHF source density for four different regions of the 11 June 2000 storm.

regions by looking for 30 dBZ at 6 km MSL (-10 °C). Transition areas were those non-convective regions within 10 km of a convective gridpoint. Stratiform echoes were those not meeting either criteria. If a VHF source was located within a particular region (e.g., convective), it was assigned to that region (e.g., became a convective VHF source). This partitioning is different and simpler than other automated algorithms (e.g., Steiner et al. 1995). However, it performed much better than these other algorithms, which failed on the intense stratiform echo in this storm and mis-classified it as convective. Note that our criteria bias our convective classification results toward convection that is likely producing lightning, not electrically quiet decaying or weak convection, which will usually get placed within the transition or stratiform regions. That is by design, since this is a lightning study.

From Fig. 3 it is apparent that the convective line dominated the electrical behavior of this MCS. Prior to 2200 UTC, VHF activity was mainly confined to the upper regions of the storm, around 9 km MSL. From Rison et al. (1999), we know that VHF activity is primarily caused by negative breakdown within regions of positive charge. Based on Fig. 3 and evaluations of selected individual flashes, the gross charge structure of the convective portion of this MCS prior to 2200 appears to include positive charge near 9 km MSL. However, after 2200 there is a broadening of the vertical distribution in the convective line, with

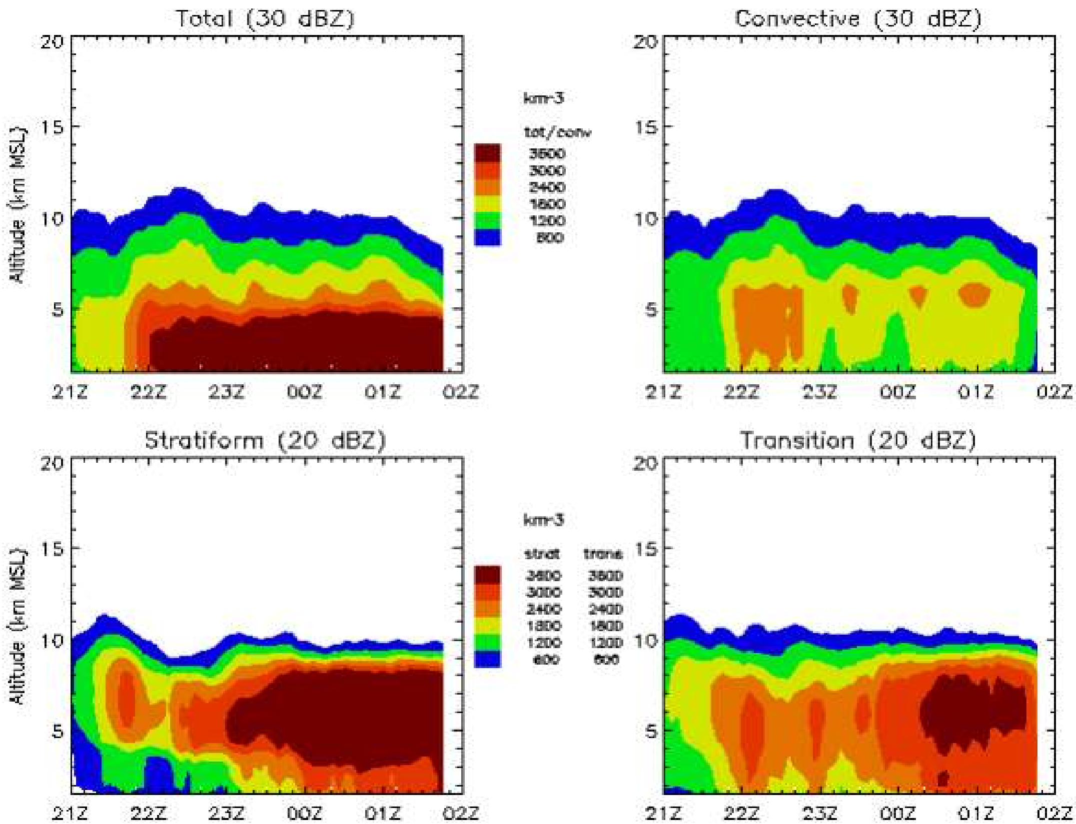

Figure 4. Time-height plot of 20+ or 30+ dBZ echo volume from the KGLD radar for four different regions of the 11 June 2000 storm.

increasingly more sources at lower altitudes and an evental dropoff in sources aloft. This broadening coincides with the general increase in total flash rate around this time. Indeed, after 2300 most LMA activity is centered in the 5-6 km MSL range. This is also true during the second convective surge after 0000 UTC. This latter distribution (as well as an examination of individual flashes) is most consistent with lower positive positive charge at 5-6 km.

In Fig. 4 we plot time-height contours of echo volumes containing 30+ dBZ reflectivity for the entire MCS and the convective region, as well as 20+ dBZ for the stratiform and transition regions. The data come from the KGLD radar. Note in the convective plot that there is an increase in 30+ dBZ volume near 5-6 km MSL around the time of the broadening of the vertical distribution of VHF sources, and that a maximum near this altitude continues for much of the storm' slater lifecycle. At this altitude (colder than 0 °C), the most likely contributor to reflectivities of this magnitude is graupel and hail. This inference will be confirmed using polarimetric-radar-based hydrometeor identification on indivudal cells in Section 3. We suspect that the development of significant quantities of graupel near 5-6 km MSL led to the change in charge structure and lightning distribution over the lifetime of this MCS.

3. Lightning Activity in Individual Cells

It is instructive to examine the lightning behavior in individual cells associated with

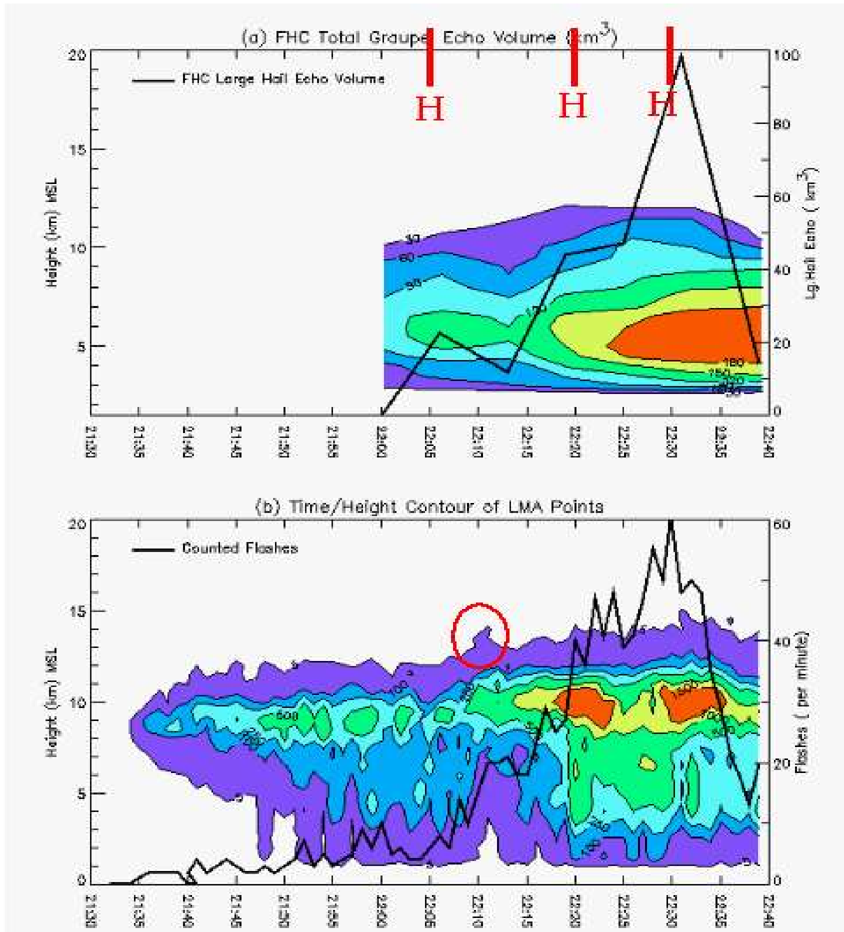

Figure 5. (a) Total graupel echo volume and large hail echo volume for the cells associated with hail reports at 2205, 2220, and 2230 UTC. Data from S-Pol (no coverage prior to 2200). (b) VHF source density and total flash rate for the same cells.The red ellipse indicates an increase in high-altitude VHF sources prior to severe weather.

severe weather. This is more problematic in an MCS case because of the close proximity of cells to one another, making it difficult to separate out the radar and lightning analyses. In addition, there is more ambiguity in the assignment of severe weather to particular cells. However, the LMA and polarimetric radar provide a method for increasing our confidence in these efforts, particularly for severe hail reports. Polarimetric radar were used to identify areas of rain, small (D < 2 cm) and large hail, as well as graupel using a fuzzy-logic-based hydrometeor classification scheme (FHC) based on Liu and Chandrasekar (2000) and Straka et al. (2000). Using polarimetric radar data from this case, the cell that had the most robust (largest volume and most vertical development) large hail signal closest in both space and time to the severe hail report was considered the most likely cell to be responsible for that report. Also, VHF source spatial density can be plotted against radar data to help isolate the proper cells from the lightning perspective.

Figure 5 shows a time series of VHF source density, total flash rate, and FHC

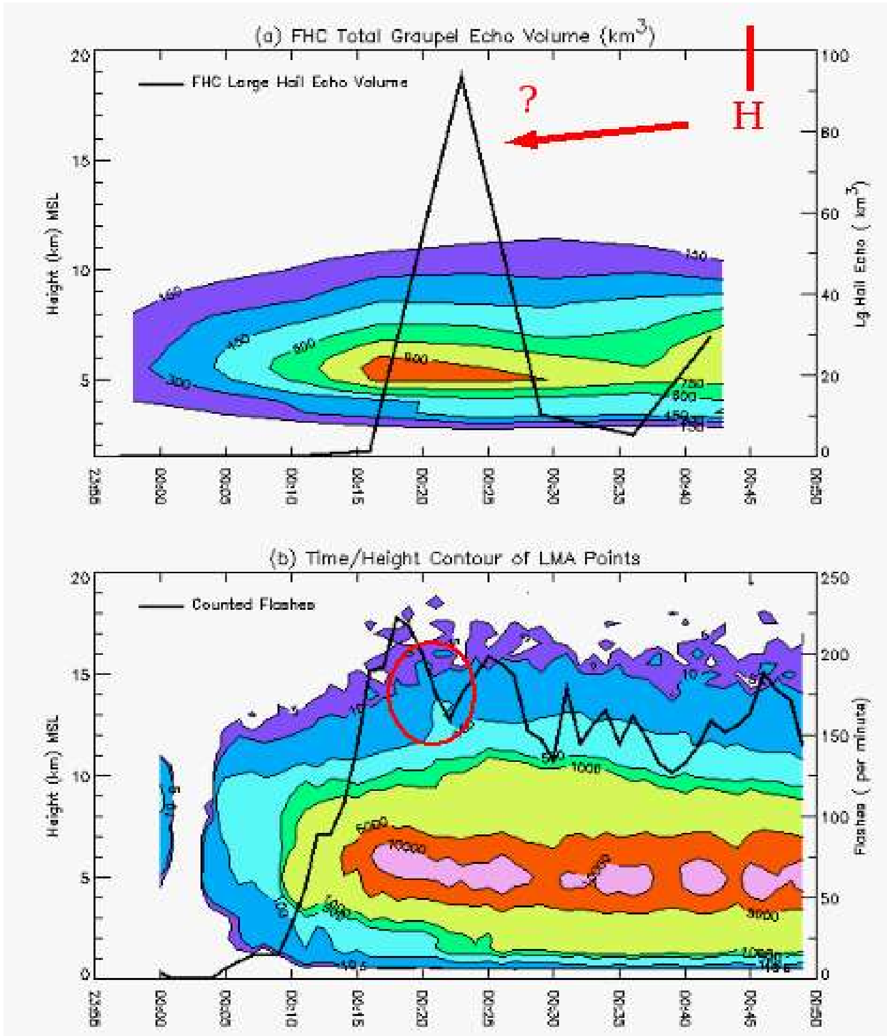

Figure 6. Same as Fig. 5 but for the cells associated with hail at 0045 UTC. Note no S-Pol volumes start after 0043 UTC.

graupel and hail (from S-Pol radar data) for a complex of two cells that produced severe-sized hail at 2205, 2220, and 2230 UTC. Figure 6 shows the same but for a cell complex that produced severe-sized hail at 0045 UTC. The delineation of these cell complexes are indicated in Figure 2. For both cell complexes, most hail reports are preceded by a rapid increase in total flash rate, an increase in LMA source density, and a minor spike in LMA sources far aloft similar to those identified by Hamlin (2004). There is an exception with the 2205 UTC hail report, which showed very little lightning change prior to the report. Indeed, the cell complex did not seem very electrically intense at all at or prior to this time. However, polarimetric FHC does indicate a fairly robust large hail signature near the severe weather location in the 2206 UTC S-Pol radar volume, so it is difficult to rule out that the timing and location for the report are roughly accurate, and that for this one report lightning data provided very little information for nowcasting the large hail.

Note that, though there is an increase in hail after 0040, the most robust polarimetric hail signal in the 0000-0050 UTC period occurs near 0025 UTC. The location of the surface hail report is most consistent with the cell location at this time rather than at 0045 UTC. It is unclear whether there was no report for this earlier time, or whether the 0045 report is late by up to 20 min. Nevertheless, our basic inferences regarding total lightning behavior stand, though the lead time provided by lightning data is substantially less if large hail fell at 0025 UTC.

Table 1 lists CG flash rates for these cells. Here, the results are far more ambiguous. Both severe complexes indicated a slight increase in -CG flash rates prior to theonset of severe weather, with little in the way of +CG activity, but flash rates are under 1 min^{-1} for the most part. The exception was the -CG flurry during the 0040-0050 UTC time period. However, LMA and NLDN data indicated that these flashes were mainly originating within decaying convection to the north of the hail-producing convection. Indeed, similar to Lang et al. (2000) and Lang and Rutledge (2002), these cell complexes were associated with few CGs overall. As it turns out, the large number of +CGs around 2230 UTC (Fig. 1) mainly were produced by the set of cells in the northern end of the convective line (Fig. 2). This northern area saw the severe wind report at 2217 UTC. For brevity, and due to the lack of polarimetric radar coverage of this part of the storm, we omit a plot of the electrical observations for the +CG/wind cells, but the wind report was still preceded by increases in total flash rate and in VHF source density similar to those shown in Figs. 5 and 6. However, this northern complex was associated with >50% +CGs, and CG flash rates between 1 and 2 min^{-1}, thus underscoring the ambiguity of using CG data for nowcasting severe weather.

Figures 5 and 6 also demonstrate the link between graupel at 5-6 km MSL and the development of significant VHF activity in this region. Figure 5 shows the downward broadening of VHF activity from the 9 km MSL peak when significant graupel began appearing at lower altitudes. In Fig. 6, the peak graupel and VHF density contours are nearly collocated in time and space. These results for individual cell complexes support the inferences made for the entire MCS based on Figs. 3 and 4.

Time	***+CG***	***-CG***	***Time***	***+CG***	***-CG***
21:30	0	0	00:00	0	0
21:40	0	0	00:10	0	0
21:50	0	9	00:20	1	4
22:00	0	5	00:30	2	2
22:10	0	1	00:40	0	15
22:20	0	0			
22:30	2	1			

Table 1. CG flashes per 10-minutes for the severe cells shown in Figs. 5 and 6. Severe weather times are 2205, 2220, 2230, and 0045 UTC.

4. Conclusions

The conclusions of this study are similar to those of prior studies. Namely, severe weather is preceded by several minutes by increases in total lightning flash rate, VHF source density as measured by a lightning mapper, and minor spikes in VHF activity far aloft. The association between cloud-to-ground lightning activity and severe weather is found to be ambiguous, consistent with previous studies. The observed changes in the gross vertical distribution of VHF sources prior to severe weather could be important, for the following reason.

It is apparent from this study that the development of significant amounts of graupel at low levels can re-arrange gross charge structure and lightning distribution in the vertical as revealed by VHF lightning mapper data. This suggests that the graupel is acquiring net positive charge in the 5-6 km MSL layer (-10 ° C). This is right on the border of charge reversal based on temperature in Takahashi (1978), and could correspond either to a relatively low or relatively high liquid water content (LWC). However, according to Saunders et al. (1991), positive charging of the graupel would require a relatively higher LWC (~1 g m^{-3} and greater). Microphysically, a higher LWC within this region would be consistent with the observed development of large amounts of graupel (and by extension, hail), since this would mean more supercooled water available for riming.

From a forecast perspective, the development of significant quantities of graupel in a high LWC environment is an important hail precursor, as seen in Figs. 5 and 6. Based on non-inductive charging theory, the vertical distribution of lightning should reveal this development of precipitation-sized ice, as observed in this case. Thus, this study indicates that VHF lightning data could be used as a proxy for the production and location of significant amounts of graupel in a high LWC environment, and thus potentially could improve lead times in severe weather warnings for large hail. This hypothesis deserves further testing and refinement. Also, the relative utility of lightning data versus radar data for diagnosing graupel is an open question, but it deserves further research due to proposed upgrades to the current NWS observing network, including polarimetric NEXRAD and satellite-based lightning detectors.

Acknowledgments

KGLD and S-Pol radar data were obtained from NCAR. LMA data and software came from New Mexico Tech. NLDN data came from Vaisala. This research was supported by NSF through grant ATM-030930.

References

Carey, L. D., and S. A. Rutledge, 1998: Electrical and multiparameter radar observations of a severe hailstorm. *J. Geophys. Res.*, **103**, 13979-14000.

Carey, L. D., S. A. Rutledge, and W. A. Petersen, 2003: The relationship between severe storm reports and cloud-to-ground lightning in the contiguous United States from 1989 to 1998. *Mon. Wea. Rev.*, **131**, 1211-1228.

Hamlin, T. D., 2004: The New Mexico Tech Lightning Mapping Array. Ph.D. Dissertation, New Mexico Institute of Mining and Technology, 183 pp.

Lang, T. J., L. J. Miller, M. Weisman, S. A. Rutledge, L. J. Barker III, V. N. Bringi, V. Chandrasekar, A. Detwiler, N. Doesken, J. Helsdon, C. Knight, P. Krehbiel, W. A. Lyons, D. MacGorman, E. Rasmussen, W. Rison, W. D. Rust, and R. J. Thomas, 2004a: The Severe Thunderstorm Electrification and Precipitation Study. *Bull. Amer. Meteor. Soc.*, **85**, 1107-1125.

Lang, T. J., and S. A. Rutledge, 2002: Relationships between convective storm kinematics, precipitation, and lightning. *Mon. Wea. Rev.*, **130**, 2492-2506.

Lang, T. J., S. A. Rutledge, J. E. Dye, M. Venticinque, P. Laroche, and E. Defer, 2000: Anomalously low negative cloud-to-ground lightning flash rates in intense convective storms observed during STERAO-A. *Mon. Wea. Rev.*, **128**, 160-173.

Lang, T. J., S. A. Rutledge, and K. C. Wiens, 2004b: Origins of positive cloud-to-ground lightning flashes in the stratiform region of a mesoscale convective system. *Geophys. Res. Lett.*, **31**, DOI:10.1029/2004GL019823.

Liu, H., and V. Chandrasekar, 2000: Classification of hydrometeors based on polarimetric radar measurements: Development of fuzzy logic and neuro-fuzzy systems and in situ verification. *J. Atmos. Oceanic Technol.*, **17**, 140-164.

Rison, W., R. J. Thomas, P. R. Krehbiel, T. Hamlin, and J. Harlin, 1999: A GPS-based three-dimensional lightning mapping system: Initial observations in New Mexico. *Geophys. Res. Lett.*, **26**, 3573-3576.

Rust, W. D., D. R. MacGorman, and R. T. Arnold, 1981a: Positive cloud-to-ground lightning flashes in severe storms. *Geophys. Res. Lett.*, **8**, 791-794.

Rust, W. D., D. R. MacGorman, and R. T. Arnold, 1981b: Research on the electrical properties of severe thunderstorms in the Great Plains. *Bull. Amer. Meteor. Soc.*, **62**, 1286-1293.

Saunders, C. P. R., W. D. Keith, and R. P. Mitzeva, 1991: The effect of liquid water on thunderstorm charging, *J. Geophys. Res.*, **96**, 11007-11017.

Steiner, M., R. A. Houze Jr., and S. E. Yuter, 1995: Climatological characterization of three-dimensional storm structure from operational radar and rain gauge data. *J. Appl. Meteor.*, **34**, 1978-2007.

Stolzenburg, M., 1994: Observations of high ground flash densities of positive lightning in summertime thunderstorms. *Mon. Wea. Rev.*, **122**, 1740-1750.

Straka, J.M., D.S. Zrnic, and A.V. Ryzhkov, 2000: Bulk hydrometeor classification and quantification using polarimetric radar data: Synthesis of relations. *J. Appl. Meteor.*, **39**, 1341-1372.

Takahashi, T., 1978: Riming electrification as a charge generation mechanism in thunderstorms. *J. Atmos. Sci.*, **35**, 1536-1548.

Thomas, R., P. Krehbiel, W. Rison, J. Harlin, T. Hamlin, and N. Campbell, 2003: The LMA flash algorithm. *Proc. 12th Int. Conf. on Atmospheric Electricity*, Versailles, France, International Commission on Atmospheric Electricity, 655-656.

Williams, E. R., B. Boldi, A. Matlin, M. Weber, S. Hodanish, D. Sharp, S. Goodman, R. Raghavan, and D. Buechler, 1999: The behavior of total lightning activity in severe Florida thunderstorms. *Atmos. Res.*, **51**, 245-265.