Total Lightning Signatures of Thunderstorm Intensity over North Texas.
Part I: Supercells

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ABSTRACT

It is shown that total lightning mapping, along with radar and National Lightning Detection Network (NLDN) cloud-to-ground lightning data, can be used to diagnose the severity of a thunderstorm. Analysis of supercells, some of which were tornadic, on 13 October 2001 over Dallas–Fort Worth, Texas, shows that Lightning Detection and Ranging (LDAR II) lightning source heights (quartile, median, and 95th percentile heights) increased as the storms intensified. Most of the total (cloud to ground and intracloud) lightning occurred where reflectivity cores extended upward, within regions of strong reflectivity gradient rather than in reflectivity cores. A total lightning hole was associated with an intense, nontornadic supercell on 6 April 2003. None of the supercells on 13 October 2001 exhibited a lightning hole. During tornadogenesis, the radar and LDAR II data indicated updraft weakening. The height of the 30-dBZ radar top began to descend approximately 10 min (2 volume scans) before tornado touchdown in one storm. Total lightning and cloud-to-ground flash rates decreased by up to a factor of 5 to a minimum during an F2 tornado touchdown associated with this storm. LDAR II source heights all showed descent by 2–4 km during a 25-min period prior to and during this tornado touchdown. This drastic trend of decreasing source heights prior to and during tornado touchdown was observed in two storms, but did not occur in nontornadic supercells, suggesting that these parameters can be useful to forecasters. These observations agree with tornadogenesis theory that as the updraft weakens, the mesocyclone can divide (into an updraft and downdraft) and become tornadic.

1. Introduction

Lightning can be used with radar observations to characterize thunderstorms and to warn people of imminent severe weather. Combined, these two datasets form a strong foundation for the short-term forecasting of convective weather. Also, relationships between radar and lightning characteristics give insight into how a thunderstorm’s dynamics and electrification processes operate. The advent of the Weather Surveillance Radar-1988 Doppler (WSR-88D) nationwide (throughout the United States) radar system, the National Lightning Detection Network (NLDN), and three-dimensional lightning mapping systems [here the Lightning Detection and Ranging Dallas–Fort Worth (LDAR II) network is used] allows scientists to dissect thunderstorms and explore relationships between observables.

Some of the most comprehensive work detailing the electrical structure of isolated storms and mesoscale convective systems (MCSs) is discussed by Stolzenburg et al. (1998a–c) and reveals a more complex charge structure than the classic tripole (Williams 1989). Within convective updrafts, the basic charge structure has four charge regions, alternating in polarity, and the lowest is positive. It is believed that these charge regions develop through a noninductive charging mechanism (Takahashi 1978) that is dependent on cloud temperature and the riming rate of graupel (which is directly

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related to the updraft speed). Outside updrafts there are typically at least six charge regions, alternating in polarity, with the lowest again being positive. Among the three storm types examined by Stolzenburg et al. (MCS, supercell, and isolated New Mexican convection), there are differences in the heights and temperatures at which the four charge regions are found in updrafts. The charge regions are higher in altitude when the balloon ascent rate (a proxy for updraft strength) is greater. Hence, charge regions detected by VHF networks like LDAR II (Rison et al. 1999; Coleman et al. 2000; Bruning et al. 2002; Detwiler et al. 2002; Wiens et al. 2005) are expected to ascend when a thunderstorm’s updraft intensifies.

Supercells are prolific lightning producers, and some studies suggest they may have unique lightning characteristics that may help predict the severe weather that can accompany them. MacGorman et al. (1989) found that the ground stroke rate and flash multiplicity (number of strokes per flash) increased after the tornadic stage of a storm ended. The ground flash rate was negatively correlated with cyclonic shear. However, there was a strong correlation between intracloud (IC) flash rate and cyclonic shear at 1.5-km altitude (low-level cyclonic shear and storm updraft strength are assumed to be directly related). To explain this, MacGorman et al. proposed the elevated charge region hypothesis: As a storm’s updraft intensifies, the main negative charge region is lifted and brought closer to the main positive charge region typically located higher in the storm, and IC flashes become more frequent and cloud-to-ground (CG) flash rates decrease; when the updraft weakens, CG flash rates increase as the lower negative charge region descends. Charge regions have been shown to become elevated in a simulated supercell updraft (Ziegler et al. 2003). MacGorman and Nielsen (1991) showed the opposite relationship for CG flash rates in the “Edmond storm”: as low-level cyclonic shear initially increased, negative CG lightning flash rates also increased. Numerical simulations by Mansell et al. (2002) strongly suggest that the development of a lower positive (negative) charge region plays a key role in \(-\)CG flash rates, which shows processes controlling these flash rates are more complicated than those associated with the elevated charge region hypothesis. It is clear that robust relationships between storm dynamics, severe weather, and lightning activity (especially CG) have not been found. The major purpose of this study is to better understand how we can use total lightning information in determining storm intensity and to observe if storm cell lightning characteristics can be used to predict severe weather at the ground. Comparisons between charge region heights (revealed by lightning mapping), IC and CG flash rates, IC:CG ratios, and radar characteristics are made to test the hypothesis that lightning characteristics are directly related to storm strength.

Lightning “jumps” [total flash rate increasing rapidly; Williams et al. (1999)] and “holes” [areas of weak total lightning density values surrounded by an annulus of larger values; Krehbiel et al. (2000); Lang et al. (2004)] have been noted in severe thunderstorms. Results from the North Alabama and New Mexico Institute of Mining and Technology (New Mexico Tech) Lightning Mapping Array (LMA) networks (McCaul et al. 2002; Wiens et al. 2005) show lightning jumps coincident with storm intensification prior to and during tornadogenesis, and lightning holes collocated with a bounded weak echo region in the updraft in tornadic storms, while being absent in nontornadic supercells. The tornadic storm analyzed by Wiens et al. (2005) had total lightning rates approaching 300 flashes per minute (mostly IC lightning). Mathematical analysis by Baker et al. (1995) shows that total flash rate is strongly dependent on storm updraft speed. Hence, lightning jumps can be proxies for increases in updraft strength.

Relations between CG flash rates, polarity, and tornado development vary widely (Bluestein and MacGorman 1998). Perez et al. (1997) show that out of 42 F4–F5 tornadoes, 31 (74%) have a peak CG rate preceding tornado formation (an average of 17 min before touchdown), 6 (14%) have polarity reversals from predominantly positive to negative, and 20 (48%) storms show a decrease in CG activity coincident with tornado touchdown. Using CG data to discriminate between severe and nonsevere thunderstorms may be regionally dependent. Indeed, Carey and Rutledge (2003) show that differences in CG characteristics between severe and nonsevere storms are less clear in southern plains compared to northern plains storms (e.g., the difference in the mean percentage of +CG lightning values between severe and nonsevere is <5% near Dallas, Texas, and >30% in northern Nebraska using their Figs. 6 and 7).

In comparing lightning in a supercell to a multicell storm, Ray et al. (1987) show the following: 1) lightning tended to be downshear of the main updraft (with weak echo region) and reflectivity core in the supercell, while in the multicell storm the activity was concentrated in the updraft and reflectivity core; and 2) the distribution of lightning with height was unimodal with a peak at approximately 8 km \((-30^\circ\text{C environmental temperature})\) in the supercell while for the multicell it was bimodal, with modes at 6 and 11 km \((-10^\circ\text{C} \text{ and } -40^\circ\text{C}, \text{ respectively})\). From their observations, Ray et al. conclude that the magnitudes and vertical shears of the environmental wind are key parameters in lightning lo-
cation (as shown by the distribution of VHF impulses) relative to severe storm structure. The lightning data from the LDAR II overlaid on radar reflectivity data for the supercell storms in this study will be used to test the conclusions regarding the spatial patterns discussed by Ray et al.

An MCS moved through the Dallas–Fort Worth area late on 12 October to early 13 October 2001. Embedded in this system were several supercells, a few of which were severe, producing strong F2 tornadoes and large hail. Intense, isolated supercells (nontornadic, but with large hail) occurred near Dallas on 6 April 2003. These events provide an excellent opportunity to compare severe storm reports, and radar and lightning data from the NLDN and LDAR II, to test the hypothesis that there are spatial–temporal signatures in the lightning data that are related to storm intensity and can assist in predicting severe weather.

2. Data and methodology

The radar data used in this study were from the Dallas–Fort Worth WSR-88D (KFWS), obtained from the National Climatic Data Center (NCDC). To analyze the collected data initially, the Warning Decision Support System-Integrated Information (WDSS-II) software (Hondl 2003) provided by the National Severe Storms Laboratory (NSSL) was used. This software has algorithms that identify, track [storm cell identification and tracking (SCIT) algorithm; Johnson et al. (1998)], and quantitatively describe the state of storm cells [hail detection algorithm (HDA), Witt et al. (1998); mesocyclone detection algorithm (MDA), Stumpf et al. (1998)]. The Dallas–Fort Worth (FWD) sounding was used to obtain temperature level data to import into the HDA. Storm cells, and hence lightning data, were analyzed only within a range of 30–100 km from the KFWS radar site (see Fig. 1) due to the cone-of-silence and beam-elevation effects (lowest tilt beam is above the melting level at far ranges, and this causes systematic error in the HDA), and the decreasing location accuracy and detection efficiency of the LDAR II instrument beyond 150 km from the network center. Note that the radar is approximately 45 km to the southwest of the LDAR II network center. Radar data were also converted from a polar to a Cartesian grid space using the REORDER software (Oye and Case 1995). The horizontal and vertical grid spacings were set at 1.0 and 0.5 km, respectively. In this way, lightning data (LDAR II source points, CG flash locations) were overlaid onto radar reflectivity values using data from within each volume scan time interval.

The CG lightning data used in this study were from the NLDN. These data were obtained from Vaisala, Inc., of Tucson, Arizona. The network consists of over 100 sensors across the United States (Orville and Huffines 1999). The NLDN was given an upgrade in 1994 (Cummins et al. 1998). This upgrade included a combination of Improved Accuracy from Combined Technology (IMPACT) and time-of-arrival (TOA) sensors. The upgrade resulted in improving the median location accuracy to 500 m and the expected flash detection efficiency to ~85% for events with peak currents above 5 kA. The NLDN underwent another upgrade in 2002–03 to improve the detection efficiency and location accuracy at the network boundary (Cummins et al. 2006). The CG lightning characteristics that were analyzed from these data include negative and positive flash density, percent positive flashes, median peak current for each polarity, and mean multiplicity for each polarity.

Total lightning flash data over the Dallas–Fort Worth area were from the VHF lightning mapping instrumentation known as the LDAR II network operated and maintained by Vaisala, Inc. (it is assumed the instrument detects both IC and portions of CG flashes; hence, total flashes were detected). Because VHF impulses are of short duration and have line-of-sight
propagation, they are shown as point sources located in three dimensions (thousands of which can compose a single flash). The LDAR II uses the TOA technique described by Rakov and Uman (2003, 562–565). This network is comprised of seven sensors with 20–30-km baselines centered on the Dallas–Fort Worth International Airport (DFW; Fig. 1). The regional LDAR II network accurately maps lightning flashes in four dimensions within approximately 150 km of the center of the network, degrading in performance with increasing range (Demetriades et al. 2001; Carey et al. 2005). The expected lightning flash detection efficiency is typically greater than 95% within 30 km (the interior of the network) from DFW, and greater than 90% out to a range of 100 km. Significantly smaller detection efficiencies were estimated at these ranges for 6 April 2003 (only six sensors were operable). Expected three-dimensional location accuracy for individual pulses of radiation is between 100 and 200 m within the interior of the network and better than 2 km to a range of 150 km (Carey et al. 2005). Thomas et al. (2004) thoroughly discuss the accuracy of a similar system, the LMA operated by New Mexico Tech. For example, they show that range and altitude errors increase as the range squared. During the LDAR II data processing a filtering algorithm was used to remove isolated points likely to be outliers and not flashes. LDAR II VHF sources were grouped into flashes according to temporal and spatial restrictions using a modified version of an algorithm created by NASA. The constraints used to determine if a source point was part of a flash were as follows: a maximum of 3 s for the duration of the flash, maximum time lag of 0.5 s between points in a flash, maximum time delay of 0.03 s between points in a flash branch, and adjacent points must be within 5 km of each other to be considered part of the same flash. Flashes must comprise at least three source points.

Comparatively few sources are observed from CG processes because of how IC and CG channels radiate differently [CG strokes radiate as long antennas/lower frequency than the short breakdown processes associated with IC flashes; Cummins et al. (2000)]]. The total source density is thus dominated by the in-cloud portion of the total lightning flashes. VHF TOA lightning detection systems like LDAR II detect more sources from lightning traveling into/through positive charge regions than negative charge regions because negative polarity breakdown into positive charge regions is noisier (speculated more intermittent pulses) at radio frequencies than positive breakdown into negative charge regions (Rison et al. 1999).

To compare the lightning and radar characteristics of storm cells, lightning data (CG and total) within 5-, 10-, and 20-km horizontal distances of the radar-defined cell or mesocyclone (cell/mesocyclone locations given by WDSS-II) were analyzed for each radar volume scan (interval of approximately 5 min). The 10-km results primarily will be shown as most lightning from the storms of interest were contained within this distance without contamination from nearby cells. This resulted in cylindrical volumes of total lightning data from LDAR II. The radar and lightning characteristics analyzed included the following: storm cell maximum reflectivity; maximum reflectivity height; radar top (maximum height of the 30-dBZ contour); severe hail index (SHI); vertically integrated liquid (VIL); low-level mesocyclone diameter; mesocyclone strength index (MSI); lower quartile, median, and 95th percentile (defined as the lightning-based storm top) and modal LDAR II source heights; total number of sources within the cylindrical volume; number of flashes from sources (total flash rate); and the IC:CG ratio. To calculate a cell’s flash rate, the flash origins were determined using a larger domain (i.e., 60 km × 60 km box centered on the cell/mesocyclone) and then the number of origins within 10 km of the cell/mesocyclone location was summed. Refer to Johnson et al. (1998), Witt et al. (1998), and Stumpf et al. (1998) for how the storm cell radar characteristics were calculated. The VIL and SHI are determined by vertically integrating a measure of reflectivity throughout the whole depth and above the melting level of the storm, respectively. The MSI is a measure of mesocyclone rotation; the algorithm vertically integrates rotation strength ranks from all levels sampled of the cell, which is then normalized by the depth of the mesocyclone.

To obtain a four-dimensional (x, y, z, and t) representation of a storm’s radar and lightning structure, the following projections of the data were produced on a single plot: time–height, x distance–height, y distance–height, and x–y distance (see Fig. 2). The time period of the lightning data corresponds to the radar volume scan time interval (approximately 5 min). The x and y distances represent the directions west–east and south–north, respectively, in the plots. The LDAR II source density was computed at 1-km resolution in all spatial dimensions, and the time–height panels were constructed using 5-s time resolution. Source data were plotted within a 60 km × 60 km × 20 km volume (most lightning was detected within 20 km of mean sea level) centered horizontally on the storm. Projections were taken onto the horizontal and vertical planes and plotted as two-dimensional source densities.

The radar reflectivity vertical and horizontal projections were constructed using a similar method, but the
FIG. 2. LDAR II source density and mean radar reflectivity (mean above the melting level) of a supercell on 13 Oct 2001 (5-min period). (a) Time (UTC)-vs-height display of lightning source density at 5-s and 1-km resolutions. (d) The plan-view projection of mean reflectivity (contour interval is 5 dBZ for values of 20 dBZ and greater) overlaid on source density (color bar gives values in sources per square kilometer). The resolution of the LDAR II and radar data is 1 km. The asterisk at the center is the location of the radar-detected mesocyclone (at $-65, 61$ km) by WDSS-II. Vertical projections of source density and mean reflectivity for (b) west–east and (e) south–north projections. The height resolutions of the LDAR II and radar data are 1 and 0.5 km, respectively. The color bar is not associated with these panels or the time–height panel. (c) A normalized height histogram of the number of sources and flash origins (shaded) at 1-km intervals. Environmental temperature levels are plotted as bars, and the total numbers of sources, flashes, and modal source height (km) are given above the histogram. The “H” in the panels represents the time and location of a severe hail report. The axes are labeled as distances ($x$: west–east; $y$: south–north) from the KFWS radar (located at 0, 0 km), and in the vertical direction are heights (km) MSL.
values shown are the mean reflectivity for each cuboid. To calculate mean reflectivity, the linear values were averaged and then converted to dBZ units. Note that a cuboid is a volume of space determined by the resolution of the projection and the depth into the projection. For example, when plotting the south–north vertical radar projections, each plotted value (at height z and distance y) is the mean of all values along x. The mean reflectivity values were conditional in that only points in the cuboids that had reflectivity values above 0 dBZ were used. For the horizontal projections, only points above the melting level were used to calculate the mean reflectivity. This was done to test the idea that lightning production is highly dependent on the existence of hydrometeors above the melting level in a thunderstorm via the noninductive charging mechanism.

The total lightning (LDAR II) and radar reflectivity history following a storm cell will be shown in a time–height display (e.g., Fig. 10). For each radar volume scan, the mean reflectivity of a storm was calculated for each height at 0.5-km intervals. Only values within 20 km in horizontal distance of the storm’s mesocyclone location, determined from WDSS-II, were used to calculate the mean reflectivity at each height for each volume scan. Contours of the total number of LDAR II sources in each 1-km height interval within 20-km horizontal distance of the storm’s mesocyclone for each radar volume scan interval were overlaid on the radar data.

3. Lightning and radar reflectivity overlays of supercell thunderstorms

a. 13 October 2001

Figure 2 shows projections of the total lightning source density and mean reflectivity of a supercell on 13 October 2001. The LDAR II and WSR-88D data shown were from the time period 0015:37–0020:34 UTC. The height of maximum lightning activity remained constant near 10 km MSL during the 5-min period shown (see time–height panel). The plan view radar structure shows large reflectivity gradients, especially on the southwestern side of the supercell, and the shape of the southern portion of the 55-dBZ contour (which encompasses the hail report) is suggestive of a hook, two classic signatures of a mature supercell. The reflectivity contours tilted downshear (0000 UTC proximity sounding at FWD indicated west-southwesterly wind shear) in the west–east vertical projection. Reflectivity values greater than 40 dBZ extended higher than 10 km MSL (above the −40°C isotherm). Both vertical projections indicate reflectivity maxima (55 dBZ) aloft above the hail report. The hail report in the south–north projection was within a weak reflectivity echo region.

The greatest LDAR II source density values in all projections were within areas of the reflectivity gradient. The areas of maximum lightning activity in the vertical projections were above where the reflectivity core extended upward at x, y position (−62, 56 km). The source density maximum in the plan view was 5 km to the east of the greatest 40-dBZ echo height (12 km MSL) located at (−64, 56 km) in Fig. 3. The strongest updraft, ideal for charge separation and lightning, was likely near this echo-height peak. The modes in the vertical distributions of lightning sources and flash origins were at 10 and 11 km MSL, respectively. A total of 3846 sources composing 222 flashes were included in this plot (an average of 17 sources per flash).

Note the lack of lightning activity in the rear part of the storm (southwest side in Fig. 2). Also note the absence of any activity just southwest of the hail report, where the mean reflectivity was over 55 dBZ. The majority of the lightning activity most likely occurred between the main updraft and the forward-flank downdraft of the supercell according to the above interpretations of Figs. 2 and 3 [see Lemon and Doswell (1979) for locations of vertical drafts in an ideal mature supercell].

This supercell produced a strong F2 tornado (NCDC 2001) between 0100 and 0105 UTC (Fig. 4). The reflectivity structure of the supercell shows that it had weakened compared with 40 min earlier (Fig. 2). The reflectivity did not extend upward as high; the 40-dBZ contour in the vertical projections extended only to about 7 km MSL as opposed to being above 10 km in Fig. 2. Another indication that this was a weaker storm than earlier was that the maximum mean reflectivity (plan view) in the cell was a small area of 50–55 dBZ, while Fig. 2 shows a larger area of greater than 55 dBZ. There was more lightning activity (more sources) at lower levels (near x = −18 km in the west–east projection below 5 km MSL) as well, supporting the idea that the storm had become less intense (weaker updrafts can lead to lower charge regions). This also could be a result from the storm being 30 km closer to the center of the LDAR II network (effect of less source attenuation closer to the network).

The mean reflectivity tilted downshear once again, and the maximum LDAR II source density was above the reflectivity upward protrusion at x = −17 km in the x-height projection (Fig. 4). The peak number of sources was located at 10 km MSL (above the −40°C isotherm), and there were two modes in the height histogram of flash origins: 4 (near the melting level) and
10 km MSL. The vertical projections show that the lower origin mode was likely associated with another storm in the southeastern portion of the plan view. There were 9159 sources that composed 196 flashes in this plot (about 47 sources per flash).

The tornado’s path was in the rear flank of the supercell (see plan view in Fig. 4). The tornado was reported to occur throughout this volume scan time interval, and there were no abrupt changes in the altitude of maximum lightning activity according to the time–height panel. A hook was apparent in the mean reflectivity [observe the 35-dBZ contour at (−25, 72 km)]. The WDSS-II indicated that a mesocyclone was near the hook region, along with the tornado path. As in Fig. 2,
notice that most of the lightning activity in the plan view occurred in areas of mean reflectivity gradient downshear of the low-level echo centroid.

b. 6 April 2003

Three intense, isolated supercells moved through the Dallas–Fort Worth region early on 6 April 2003. A supercell, which produced 5-cm-diameter hail (SPC 2005), is shown in Fig. 5. As first documented by Murphy and Demetriades (2005) for this storm, the most striking feature in the plan view is that of a “lightning hole” (a source density minimum surrounded by greater source density values) located at (41, 51 km) 5 km to the northwest of the radar-indicated mesocyclone.
clone. This hole was a persistent feature for at least an hour of the storm’s lifetime (from 0330 to 0430 UTC 6 April). Source density values were over a factor of 5 less in the hole compared to the large density annulus surrounding it. An asymmetry was apparent: the largest source density values were in the southern half of the annulus. The mean reflectivity does not show the same pattern. An enhanced reflectivity contour (>55 dBZ) had a sideways-S shape (also noted by Murphy and Demetriades). The lightning hole was near the western notch in this reflectivity pattern.

Maximum LDAR II source density values in Fig. 5 were located above where the reflectivity contours extended upward as with the 13 October 2001 supercells.
Maximum source density was colocated with the greatest 40-dBZ echo height [near the mesocyclone location at (46, 47 km); not shown]. The 8 and 10 km MSL 40-dBZ height contours had a shape similar to that of the largest source density contour. The source density contours sloped downward to the west and north of the storm in the vertical projections in Fig. 5, following the reflectivity contours. The lightning layer was thickest near the center of the storm in the south–north vertical projection (at $y = 47$ km), gradually becoming thinner farther to the north. There was one mode in the vertical distribution of the source density, located at 8 km MSL. The reflectivity field indicated a similar tilt to the storm’s core in the downshear direction as shown for the 13 October 2001 supercells, revealing the effect of strong environmental vertical wind shear (southwesterly).

Figure 6 shows the same storm discussed above, but approximately 30 min before that shown in Fig. 5. The lightning hole was not as distinct; its approximate diameter (defined as the distance between areas of a large source density gradient on opposite sides of the hole) was 1.5 km compared to the 4-km-diameter hole shown in Fig. 5. A weak source density region, analogous to the weak echo region (WER) in reflectivity data sometimes present in strong supercells (e.g., Weisman and Klemp 1986), is shown in the west–east vertical projection in Fig. 6. This feature was located in a region of enhanced reflectivity aloft ($>55$ dBZ) at $x, z = (17, 6$ km). This location was consistent with that of the mesocyclone indicated in the plan view at (15, 46). The lightning hole was within a circular area of large mean reflectivity values ($>55$ dBZ) in the plan view (note that large source density was also located in the $>55$ dBZ region). The largest source densities were once again in the southern and eastern parts of the annulus surrounding the hole (asymmetric). Similar relationships were found by restricting the radar and lightning data to a vertical cross section (not shown) through the storm center. The weak source density region was colocated with large reflectivity values, but a bounded weak echo region (BWER; Weisman and Klemp 1986) in the reflectivity field was located 3 km beneath this feature in the west–east cross section.

4. Time series of radar and lightning characteristics during tornadic supercells

As was shown in Figs. 2–6, the areas of maximum total lightning activity were approximately above where the reflectivity extended upward, which is representative of a strong updraft. The source density contours were also at relatively higher altitudes at these locations in the vertical projections. Comparing the vertical projections of Figs. 2 and 4 also shows that the altitudes of the source density contours were higher in the more intense storm (Fig. 2). Hence, a plausible hypothesis is that lightning heights computed from LDAR II source data can be used to diagnose storm (updraft) intensity. These were calculated by finding the 95th percentile (lightning-based storm top analogous to radar echo top), modal, median, and lower quartile heights of all LDAR II sources located within 10 km of the radar-defined mesocyclone for each radar volume scan time interval. Figure 7 reaffirms that the tornadic storm discussed in section 3 reached its peak lightning-inferred intensity (Ltop of 15 km, mode of 12 km, median of 12 km, and lower quartile height of 11 km MSL) about 12 min prior to the report of the first tornado (F2) touchdown at 0005 UTC. Descent in the heights began at 0043 UTC and reached a minimum during the second tornado (F2) at 0108 UTC. The two severe hail reports (at 0015 and 0144 UTC) occurred when the storm cell was relatively intense (lightning heights greater), and this agrees with the storm structure shown in Fig. 2.

To test the idea that the storm was weakening during tornadogenesis, the radar-derived storm cell and mesocyclone diagnostics given in WDSS-II were examined. Figures 8 and 9 show that most radar characteristics decreased to minimum values during the tornadoes. Radar top peaked at 12 km MSL about 7 min before the first tornado and decreased to a minimum of 6 km during the middle of the second tornado. This characteristic had more variation than did the lightning top during the first 35 min shown. The severe hail index (SHI), which is an integration of the reflectivity above the melting level, reached an absolute maximum near 0018 UTC, more than 30 min before the first tornado was reported, followed by a secondary maximum at 0038 UTC, and then decreased to a value near 0 during the second tornado. The VIL and MSI followed a similar trend, reaching relative minimum values during the second tornado report.

The significant updraft weakening of the storm during tornadogenesis is prominent in Fig. 10. The vertical extent of the mean reflectivity [the vertical extent of the graupel echo volume was closely related to updraft intensity in Wiens et al. (2005)] peaked at 0043 UTC, about 7 min or over one volume scan before the first tornado touchdown. The height of the 30-dBZ contour was 13 km, and descended to 7 km MSL during the second tornado associated with this supercell (0108 UTC). The height of the maximum LDAR II source density [denoted by the 1600 and 800 sources km$^{-1}$ (5 min)$^{-1}$ contours] had a trend similar to the radar contours and also reached a minimum during the second
tornado. There was a secondary intensification of the storm’s inferred updraft apparent at 0122 UTC, preceding a severe hail report at 0145 UTC. The area of >55 dBZ reflectivity below 3 km at 0122 UTC was a probable measurement error (mean reflectivity values were near 75 dBZ associated with this storm; these had no time continuity with measurements before and after this time).

Intense lightning flash rates associated with this supercell also occurred before the tornado reports (Fig. 11). Shortly before the first tornado, the total (IC and CG) flash rate peaked at 130 flashes per approximate
5-min volume scan (at 0048 UTC), and the −CG flash rate reached a maximum value of 60 flashes (5 min)\(^{-1}\) (at 0038 UTC). Both rates decreased before and during the tornadoes to a minimum during the second F2 tornado that was 20% or less of the peak values. McCormick (2003) analyzed this same supercell and found similar results with her methods. The total flash rate peaked again near the end of the second tornado (0117 UTC). The IC:CG values were near 10 in the initial stage of the storm, decreased to a minimum at the same time the −CG flash rate peaked (0038 UTC), reached a maximum value of 20 during the second F2 tornado.

The second tornadic storm’s vertical radar structure indicated a more intense storm prior to the tornado report (Fig. 13). The 45-dBZ contour reached its highest extent of 6.5 km MSL near 0256 UTC, approximately 20 min before the tornado touchdown. The storm was going through a collapse phase during tornadogenesis, which was consistent with the findings for
the tornadic storm in Fig. 10 (albeit more gradual in Fig. 13). The height of maximum source density [800 sources km\(^{-1}\) (5 min\(^{-1}\)] followed a similar trend, decreasing during and after the tornado.

Negative CG rates during the second tornadic storm (Fig. 14) peaked near 75 flashes (5 min\(^{-1}\)) at 0237 UTC and decreased to 0 by 0401 UTC. The peak +CG rate occurred more than 30 min prior to tornado touchdown, consistent with the trends for the first tornadic storm. The total flash rate, however, showed an increase to near 110 flashes (5 min\(^{-1}\)) well after the tornado. There was no rapid decrease in total flash rate associated with the tornado as in the earlier tornadic storm. The percentage of positive CG flashes increased preceding the tornado, and attained a relative maximum of 40% 6 min after the tornado. Percent positive values reached 100% at 0401 UTC, but this included only two +CG flashes. The behavior of the IC:CG ratio
was also different for this storm compared to the previous tornadic storm (Fig. 11). The ratio was lower (<5) preceding and during the tornado, but then increased rapidly to near 35 at 0406 UTC, well after the tornado and when Fig. 13 indicated a weaker storm cell. Note the CG rate was near 0 at this time (much smaller than earlier in the storm), contributing to such a large ratio.

5. Relationships between lightning and radar storm characteristics

The previous results indicate that storm radar reflectivity and lightning characteristics are related. Larger values and higher extent of reflectivity contours occur near the same time as when lightning heights and flash rates are greater (e.g., cf. Figs. 7 and 10 and 12 and 13). This section uses correlation analysis to test the hypothesis that if radar characteristics indicate a storm’s updraft is becoming more intense, there is a corresponding signal in the lightning characteristics. The support of this hypothesis indicates that storm dynamics, microphysics, and electrification are related and that lightning can be used to diagnose and predict storm evolution, an idea that has been tested by many lightning studies (e.g., MacGorman et al. 1989; Carey and Rutledge 1998; Harlin et al. 2000; Lang and Rutledge 2002; MacGorman et al. 2002). This study is different from the aforementioned ones in that it uses cell characteristics from WDSS-II and LDAR II source heights as a measure of storm updraft strength.

Correlations between lightning and radar characteristics calculated for each volume scan during a supercell’s evolution (first tornadic storm discussed, which occurred between 0005 and 0200 UTC 13 October 2001) are shown in Table 1. The lightning-based storm top (Ltop) was statistically significantly correlated with the radar measures of storm strength. The VIL–Ltop correlation coefficient was the largest at 0.82 while the Ltop correlation with maximum reflectivity height was the smallest (0.44). The number of flashes determined from the source data (nfl; total flash rate) was also positively correlated with these measures, and its highest r value was with VIL (0.52). The relationship between maximum reflectivity height and the flash rate was the weakest with r = 0.11. Wiens et al. (2005) show very strong correlations between total flash rate and graupel echo volume (r = 0.95). Their higher correlations support the dependence of lightning development on the existence of graupel. These results support the hypothesis that some of the lightning characteristics used in this study can indicate storm strength.

![Figure 14](image1.png)

Fig. 14. Same as in Fig. 11 but for a different tornadic supercell on 13 Oct 2001.
To test the sensitivity of these relationships, the same correlations were repeated using different cell radii (5 and 20 km) to calculate the lightning statistics (not shown). Most of the correlations shown in Table 1 were positive for the other radii, and the majority of them were statistically significant. Once again the VIL–Ltop correlation was the strongest for both the 5- and 20-km analysis radii.

Surprisingly, the SHI–nfl correlation \( r = 0.24 \) was less than that between VIL and the total flash rate \( r = 0.52 \). One might expect SHI to be better correlated with total flash rate as it is a measure of the reflectivity only above the melting level (and weighted to indicate the presence of graupel and hail particles) while VIL represents an integration of reflectivity throughout the whole storm depth. However, such was not the case. Similar correlation analysis between the radar characteristics and lightning top for the second tornadic storm discussed (occurred between 0224 and 0423 UTC) was consistent with the above results \( r = 0.86 \) between VIL and \( \text{Ltop} \).

The correlations with total flash rate, however, were insignificant and mostly negative.

6. Nontornadic supercell characteristic trends

a. 13 October 2001

To observe if the above signatures associated with the 13 October 2001 tornadic supercells may have been unique to a tornadic storm, radar and lightning data were analyzed from a nontornadic supercell from the same day (from 0050:15 to 0154:37 UTC). The lightning heights show a general upward trend during this period (Fig. 15). The lightning storm top was 12.5 km MSL at 0053 UTC, and reached a maximum value at 0142 UTC of 14.5 km.

The mean reflectivity history of the nontornadic supercell shows an increase in the vertical extent of the storm to a maximum at 0132 UTC (Fig. 16). The maximum height of the 30-dBZ contour increased from 10 km at 0102 UTC to higher than 14 km MSL at 0132 UTC. There was a corresponding increase in the height of the enhanced LDAR II source density [3200 sources \( \text{km}^{-1} \) \( (5 \text{ min})^{-1} \) contour], but the trend was not as drastic as with the tornadic storms shown in Figs. 10 and 13. Surprisingly, the maximum source density shown in Fig. 16 [6400 sources \( \text{km}^{-1} \) \( (5 \text{ min})^{-1} \)] occurred at 0102 UTC when the radar reflectivity contours were at lower altitudes (indicative of weaker updraft than at 0132 UTC). The storm was closer to the network earlier in the period, which can partially explain this early maximum source density. Comparing Figs. 10, 13, and 16 shows that the maximum contoured source densities were greater for the nontornadic supercell (6400 versus 1600 sources). This was likely because the nontornadic storm shown in Fig. 16 traversed closer to the LDAR II network (higher source detection efficiency) than the tornadic supercells (mean distance from the network throughout each storm’s lifetime = 91 km for the tornadic storms and 39 km for the nontornadic storm).

b. 6 April 2003

The hail-producing (nontornadic) supercell of 6 April 2003 had no significant variations in the lightning heights during the analysis period (Fig. 17), unlike those for the tornadic storms shown in Figs. 7 and 12.

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### Table 1. Correlation analysis of radar and lightning characteristics for the first 13 Oct 2001 tornadic supercell discussed. The linear correlation coefficient is given by \( r \), and the correlations that are statistically significant at the \( p = 0.05 \) level are marked by an asterisk. The characteristics shown include maximum reflectivity (maxz); maximum reflectivity height (maxzht); radar top (rtop); SHI, VIL, MSI, 95th percentile height of LDAR II sources (Ltop), and number of total flashes (flash rate; nfl). The LDAR II characteristics were calculated using data within 10 km of the mesocyclone.

<table>
<thead>
<tr>
<th>Analysis</th>
<th>( r )</th>
</tr>
</thead>
<tbody>
<tr>
<td>maxz-Ltop</td>
<td>0.70*</td>
</tr>
<tr>
<td>maxz-nfl</td>
<td>0.27</td>
</tr>
<tr>
<td>maxzht-Ltop</td>
<td>0.44*</td>
</tr>
<tr>
<td>maxzht-nfl</td>
<td>0.11</td>
</tr>
<tr>
<td>rtop-Ltop</td>
<td>0.52*</td>
</tr>
<tr>
<td>rtop-nfl</td>
<td>0.44*</td>
</tr>
<tr>
<td>shi-Ltop</td>
<td>0.69*</td>
</tr>
<tr>
<td>shi-nfl</td>
<td>0.24</td>
</tr>
<tr>
<td>vil-Ltop</td>
<td>0.82*</td>
</tr>
<tr>
<td>vil-nfl</td>
<td>0.52</td>
</tr>
<tr>
<td>msi-Ltop</td>
<td>0.57*</td>
</tr>
<tr>
<td>msi-nfl</td>
<td>0.32</td>
</tr>
</tbody>
</table>

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Fig. 15. Same as in Fig. 7 but for a nontornadic supercell on 13 Oct 2001. There were no severe storm reports associated with this storm.
Figure 17 shows the lightning top (95th percentile source height) remained near 11 km MSL for the hour analyzed. The lower heights (quartile, median, and modal heights) show some minor changes, with maximum lower quartile and modal heights (8 and 9 km MSL, respectively) near the time of the hail report. LDAR II source data within 20 km of the mesocyclone were used to calculate the characteristics shown in Fig. 17 because the mesocyclone location given by WDSS-II was typically on the south side of the storm and a significant fraction of the data would have been missed if a radius of 10 km was used as in Fig. 7. This storm was also well isolated from other storms, minimizing contamination.

7. Discussion and conclusions

The horizontal projections in Figs. 2 and 4–6 show that most lightning occurs where there are gradients of mean cold cloud (above melting level) radar reflectivity. Examining data within the layer where most of the lightning occurred in Fig. 2 (between 9 and 14 km MSL; Fig. 18) also shows that the greatest density of LDAR II sources were in the reflectivity gradient [agreeing with the results from Ray et al. (1987)]. Rust et al. (1982) and Proctor (1991) show that lightning origins occur at the edges of high radar reflectivity precipitation cores, where the reflectivity and vertical velocity horizontal gradients are large. Dye et al. (1986) explain why lightning is unlikely to originate within a strong reflectivity core: the particle interactions responsible for net precipitation charging and ultimately lightning initiation occur in an updraft, but at the core of the updraft where speeds at 7-km altitude are generally at least 10–15 m s⁻¹ even the largest particles would be carried upward. The greatest charge separation occurs at the periphery of the updraft where there are horizontal gradients in vertical velocity (where typically lighter positively charged ice crystals are lofted to form a higher positive charge center while heavier negatively charged graupel particles descend to form a lower negative charge region and a strong electric field develops between the two). During the early stages of a supercell, as shown in Figs. 2 and 18, precipitation particles grow rapidly within the updraft and can create a region of large reflectivity near the updraft location in the plan view. Hence, horizontal gradients in radar reflectivity...
may be used as a proxy for vertical velocity gradients. Maximum source density values in the west–east vertical projection of Fig. 18 existed where the reflectivity contours were nearly vertical at $x = -60$ km immediately to the east of an upward bulge in the contours (note the shape of the 30-dBZ contour inferring updraft location). These observations support the hypothesis that the greatest charge separation and lightning occur on the edges of an updraft.

Environmental wind shear also likely has a role to play in the distribution of total lightning activity relative to the mean reflectivity thunderstorm structure. The positively charged ice crystals aloft were likely advected east-northeastward for both the 13 October 2001
and 6 April 2003 supercells, and lightning propagated into these advected charge regions downstream of the reflectivity cores.

The maximum LDAR II source density values in the vertical projections of Figs. 2–6 are located in the reflectivity gradient above where the reflectivity contours protrude vertically. The plan view in Fig. 3 shows the peak source density is within 5 km of the maximum 40-dBZ echo height (near the inferred updraft), within the horizontal echo height gradient agreeing with the above conclusions. The area of maximum source density is thickest (largest vertical distance enclosed by a source density contour) within and above these upward reflectivity bulges in the vertical projections, indicating more charge within a thicker layer and/or the merging of multiple charge layers by a strong updraft.

Only the 6 April 2003 supercell exhibited the total lightning holes (Figs. 5 and 6) as discussed by Krehbiel et al. (2000), McCaul et al. (2002), and Wiens et al. (2005). The lightning hole is associated with large values of mean reflectivity in this study (the collocation with large reflectivity values occurred for all the volume scans analyzed). Murphy and Demetriades (2005) explain that storms with intense updrafts and large hail, such as the 6 April supercell, can develop a condition within the updraft region unfavorable to noninductive charge separation and, hence, lightning. Under these conditions, the graupel and hail particles become heavily coated with liquid water (wet growth), decreasing the number of effective rebounding collisions, which can lead to charge separation [Saunders and Brooks (1992) show charge transfer values are insignificant during wet growth]. High reflectivity values can also be associated with relatively low concentrations of large hail particles, a condition also unfavorable for noninductive charging (reduced total surface area) and lightning (Williams 2001).

The lightning hole was also collocated with significant reflectivity within the 2–6 and 6–10 km MSL layers of the storm (not shown). The diameter of the lightning holes in Figs. 5 and 6 are consistent with typical thunderstorm updrafts [1–10 km; Weisman and Klemp (1986)]. The weak source density region in the vertical projection of Fig. 6 is in the vicinity of the radar-detected mesocyclone, which also supports the hypothesis that the lightning hole is created by an intense updraft. The lightning hole and the maximum 40-dBZ echo height are not collocated (not shown), which is inconsistent with the above hypothesis (this may be the result of storm tilting). Examining total (0–20 km MSL) and low-level lightning (0–6 and 0–10 km MSL) from the 13 October 2001 supercells did not reveal a lightning hole as described above. Analyzing the total lightning from the 13 October tornadic storms with shorter integration times (2 min) did not show a lightning hole signature either (holes may appear when shorter integration times are used as the effect of storm advection is reduced). Hence, lightning holes are not necessary features of supercell storms.

The modes in the height histograms of LDAR II sources (Figs. 2–6), which are hypothesized to be the locations of major positive charge regions, are located at environmental temperatures near or below −40°C. Particle charging likely occurred a few kilometers below this level, with the lighter ice crystals [typically positively charged after collisions with graupel; Saunders (1993)] ascending to form a reservoir of positive charge near the −40°C isotherm level. Figures 2 and 6 also show that the distributions of flash origins (shaded in the histogram) peak on the edges of source modes. Electric fields are at maximum values between oppositely charged regions. Lightning is initiated where the electric field is the strongest [MacGorman and Rust 1998, p. 203]. If it is assumed that the main negative charge region is located near the minima in the source height distributions [since positive breakdown into negative charge regions is not well detected by VHF TOA systems (Rison et al. 1999)], the hypothesis that the source modes represent positive charge regions is supported as the maxima in the number of flash origins are located between oppositely charged regions. However, the flash origin modes in Figs. 4 and 5 are also where the source modes are located, contrary to this hypothesis. This can be a consequence of the low resolution used to construct the histogram (1 km).

The lightning heights (lower quartile, median, 95th percentile, and modal heights) calculated with the LDAR II data are useful indicators of storm updraft strength. Figures 7–9 show that when radar storm cell characteristics, such as the radar top, SHI, and VIL, indicate a stronger storm, the lightning heights are higher. The radar top has two maxima at 0043 and 0122 UTC, near the same times as when the lightning heights are at their highest. As a storm’s updraft intensifies, precipitation particles are lofted higher, especially the lighter ice crystals that are typically charged positively (Saunders 1993). Hence, the radar-top and LDAR II sources, which likely show where positive charge is in the storm, are at higher altitudes. Stolzenburg et al. (1998a–c) show by more direct means (electric field meter balloons) that charge regions are higher in altitude when the balloon ascent rate (a proxy for updraft strength) is larger. Changes in the altitude of VHF sources (which can map positive charge regions) have been associated with the updraft core (Dotzek et al. 2001). Significant lightning height fluctuations did not occur during the hour shown for the 6 April 2003 case.
(Fig. 17) because the storm was in a quasi-steady intense state. It formed and decayed outside the analysis time.

The lightning height statistics shown need to be examined with caution. Using a large database, Fig. 7 in Boccippio et al. (2001) shows a systematic increase in the altitude of maximum source density with increasing range from the Kennedy Space Center (KSC) LDAR network. The supercell in Fig. 7 steadily moved toward the center of the network with time from a range of 101 to 57 km (Fig. 19a). The heights show descent until 0108 UTC, and then increase to relative maximum values near 0122 UTC. The altitude error was not significant enough to mask the trends associated with this storm’s intensity variations (otherwise the LDAR II heights would have continually decreased during the period). Figure 19a shows a slight increase in distance from the network at 0127 UTC, but this occurred approximately 20 min after the lightning top began to ascend to a second relative maximum while the storm was moving toward the network. This shows the instrument effect cannot explain the variations during this period. The radar data support that the trends in Fig. 7 are true, as they show the cell was more intense when it was at a greater range (see Figs. 8–10 and 19a). The tornadic storm in Fig. 12 also moved closer to the network with time (Fig. 19b). The radar data in Fig. 13 support that the lightning height trends in Fig. 12 are true (decreasing with time after 0302 UTC) as the source density contours nearly parallel the reflectivity contours in the upper portions of the storm. Boccippio et al. (2001) show large altitude errors (greater than 2 km) are not likely within 150 km from the network (all of the supercells in Fig. 19 were within this range).

The aforementioned instrument effect can partially explain the increases in LDAR II source heights shown for the nontornadic storm in Fig. 15 as heights gradually increased as the storm moved farther from the network (cf. to Fig. 19c). However, Fig. 16 shows the storm intensified during this period as the vertical reflectivity extent also increased between 0053 and 0132 UTC. Note how the lightning top began to decrease after 0142 UTC, a trend similar to that of the 40-dBZ contour in Fig. 16, while the storm was moving away from the network. The LDAR II heights are capable of measuring storm intensity fluctuations, but their utility must be examined with respect to the increasing height error (positive bias) with range, especially for storms traversing large distances toward/away from the network.

Table 1 also supports the hypothesis that the lightning characteristics calculated in this study can be used as indicators of changes in storm intensity. Maximum reflectivity, maximum reflectivity height, radar top, SHI, VIL, and MSI show statistically significant positive correlations with the 95th percentile source height and total flash rate for a tornadic supercell. These results agree with those of Mazur et al. (1986), who show a storm’s maximum flash rate typically occurs when the
height of the storm core has peaked. The advantages of the characteristics calculated from LDAR II data are that the time and spatial resolution of the lightning data are better than for WSR-88D data (these characteristics can be calculated/updated every minute of the storm’s lifetime as opposed to the 5–6 min required for a radar volume scan).

The lightning and radar characteristics shown in Figs. 7–13 suggest a significant weakening in each tornadic supercell prior to and during the reported tornado touchdowns. Lightning heights show significant descent and radar characteristics like the SHI peak before the tornado touchdowns. Most of these indicators have their absolute minimum values during the second tornado in Fig. 7, rated F2. Figures 10 and 13 clearly show each tornadic storm is going through a collapse phase during tornadogenesis. Both −CG and total flash rates peaked prior to the F2 tornado and decreased by at least a factor of 5 to a minimum during the tornado in Fig. 11. Similar behavior in the −CG rate is observed for the second tornadic storm analyzed in Fig. 14 [which agrees with the results from Perez et al. (1997)], but the total flash rate trend is different (interactions with another cell likely affected this result). Comparing the plan views of Figs. 2 and 4, the WDSS-II–indicated mesocyclone becomes more separated from the total lightning activity during the tornadic stage of this storm. This may explain why the flash rates decreased substantially as only lightning data within 10 km of the mesocyclone were chosen to calculate the characteristics (Fig. 11). However, a similar analysis was conducted as shown in Fig. 11 using data within 20 km of the mesocyclone and found similar results. Recent studies show the rates of VHF emissions and total flashes tend to increase prior to tornado occurrence (Williams et al. 1999; MacGorman et al. 2002). A dramatic decrease in total flash rate has been observed near the same time as tornado touchdown and bounded weak echo region collapse in some Florida storms (Sharp 2005). Tornadoes occur during or shortly after updraft surges inferred from lightning in these studies.

Lemon and Doswell (1979) explain that tornado touchdown occurs when the updraft of an intense supercell weakens in magnitude and extent, and the downdraft (rear flank) of the storm intensifies. The mesocyclone becomes divided between the updraft and downdraft. This theory is supported by the observations in this study: most lightning and radar characteristics indicate the storm is indeed weakening (updraft decreasing intensity and/or downdraft overtaking the storm) while the tornadoes are on the ground in both tornadic storms examined. Conversely, the Lemon and Doswell theory combined with these observations support the hypothesis that the altitude of lightning activity as shown by the LDAR II source heights is related to the thunderstorm’s updraft strength. Caution must be taken in that there can be errors in the timing and location of the reported tornadoes. The non-tornadic supercells examined in this study show a gradual increase or no significant change in lightning heights throughout the period shown for each storm (Figs. 15 and 17). The lightning and radar trends shown for the tornadic storms are more abrupt and at least appear to be related to tornadogenesis. It is important to note that a high false alarm rate is still likely using lightning heights to predict tornadogenesis. The Lemon and Doswell hypothesis may be too simple to explain the development of the majority of tornadoes. However, total lightning data can significantly add to the forecaster’s situational awareness.

Total lightning (IC + CG) variations, especially changes in lightning heights and flash rates, have been shown to be useful in diagnosing supercell intensity changes in the limited number of cases presented. Used in conjunction with radar data, researchers and forecasters will have a better understanding of thunderstorm morphology and its relation to the occurrence of severe weather (tornado, large hail) at the ground. The advantages of volumetric LDAR II source data include higher temporal and spatial resolutions (especially at far ranges) compared to WSR-88D radar data. The National Weather Service in Birmingham, Alabama, has successfully used source data at 2-min resolution in their warning operations (S. Goodman, NASA/MSFC, 2005, personal communication). Future research will include calculating the total lightning characteristics used in this study every 2 min to observe if warning times can be increased compared to when using radar data alone. The lower limit for the time interval used for calculating total lightning characteristics requires further testing to determine the proper sampling of storms. (That is, can characteristics be calculated every 30 s? Probably not, as only a few flashes occur in this interval assuming a typical storm flash rate of 10 min−1.) LDAR II data are useful for these purposes within 150 km from the network; beyond this distance, range and altitude errors have significant effects (Boccippio et al. 2001; Thomas et al. 2004). The LDAR II source density is not very useful for comparing storm intensity at significantly different ranges as the number of detected sources decreases rapidly with distance from the network (see Fig. C3 in Carey et al. 2005). Finally, more storms need to be analyzed using these data to increase the sample size and gain confidence in the relationships between lightning development and storm intensity.
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REFERENCES


——, and Coauthors, 2002: Lightning relative to precipitation and tornadoes in a supercell storm during MEAPRS. Preprints,


Storm Prediction Center, cited 2005: Storm reports. [Available online at http://spc.noaa.gov/climo/]


