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Total Lightning Observations of Supercells over North Central Texas

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ABSTRACT

As part of a collaborative research project between Texas A&M University and the NOAA/NWS Fort Worth/Dallas Weather Forecast Office, total lightning observations from Vaisala's Dallas-Fort Worth (DFW) Lightning Detection and Ranging (LDAR II) network have been used to supplement Doppler radar measurements in the diagnosis of thunderstorm updraft strength and analysis of severe weather potential. More specifically, initial observations of severe convection over north-central Texas for three case dates have shown that total lightning flash extent density (FED) and gridded source density peaked prior to, or increased during reported severe weather events. Two lightning holes were observed with one supercell, and numerous FED notches were noted with other cells that likely indicated the updraft region of the thunderstorms. These signatures in the FED corresponded to weak echo regions on the KFWS WSR-88D radar reflectivity data. Additionally, lightning appendages developed for both right- and left- deviant cells prior to shifts in radar-inferred cell track, indicating a possible method for prediction of right or left hand deflections in supercell motion. A cell embedded within a linear MCS also developed a large notch in the FED data on its rear flank that persisted for over 25 min and preceded a severe wind report, indicating another potential forecasting application of total lightning data.

1. Introduction

The mission of the National Weather Service (NWS) is to issue weather forecasts and warnings for the United States "for the protection of life and property" (NWS 2005). During severe weather operations, NWS meteorologists use a warning decision process combining information from satellites, surface observations, computer models, upper air observations and Doppler weather radar. While the WSR-88D is relied upon heavily for information on the structure and evolution of severe convection; information on the electrical structure of the thunderstorm also may aid forecasters in the short-term prediction of severe weather events.

Forecasters at the National Weather Service Forecast Office in Fort Worth, TX (WFO FWD) have two sources of lightning information available for their use. The first is the National Lightning Detection Network (NLDN), a low-frequency (LF) network that detects cloud to ground (CG) lightning strikes. The network, owned by Vaisala, Inc. of Tucson, AZ provides data on CG strike location, polarity (positive or

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negative), multiplicity and peak current (e.g., Cummins et al. 1998). While this information is of value to forecasters, previous studies have shown that intra-cloud (IC) flash rates can be up to 30 times greater than CG rates (Lang et al. 2000). Wiens et al. (2005) found that for any given 1 min period, IC lightning accounted for over 95% of the total flash rate of a tornadic supercell.

To aid in the detection of IC flashes, forecasters at WFO FWD have access to information from the Dallas - Fort Worth (DFW) Lightning Detection and Ranging-II (LDAR) network, also owned and operated by Vaisala, Inc. This system, covering a limited geographic area around the DFW metroplex, detects very high frequency (VHF) energy sources which emit radiation in the lightning breakdown process. These sources can be compiled to provide information on the three dimensional electrical activity within a cell, comprised of both IC and CG flashes (Rison et al. 1999). It is this ability to detect both types of flashes that has led to VHF networks being called “total” lightning networks.

It is hypothesized that the amount of electrical activity within a convective cell is highly correlated with the strength of its updraft, and hence, severe potential. As the updraft strengthens, more cloud matter is lofted into the mixed phase region above the environmental freezing level, and the cell is able to produce ice particles of greater size, and in greater amounts. This results in greater charging within the cell, as collisions between graupel and smaller ice crystals increase, depositing charges of opposing signs on the two particles. Increases in this collisional charging in turn lead to increases in storm scale charge separation and lightning activity within the cell (Williams 2001). Carey and Rutledge (1996, 2000) found that the total flash rate was well correlated with graupel volume and mass in the mixed phase region of convective cells, a quantity that increases with increasing updraft strength (Williams 2001). Wiens et al. (2005) showed that total flash rate was well correlated with both inferred graupel echo and measured updraft velocity within a tornadic supercell observed during the Storm Electrification and Precipitation Study (STEPS) in 2000 (Lang et al. 2004).

In their study of severe convective cells over Florida, Williams et al. (1999) noted that total flash rates exceeded 60 flashes per minute (fpm), with some cells reaching values of 500 fpm. They also state that these values occurred as part of a lightning “jump”, where total flash rate values increased rapidly to peaks between 5-20 min prior to the severe weather event. Goodman et al. (2005) found similar trends in total flash rates for severe thunderstorms observed by the North Alabama Lightning Mapping Array (LMA), with peak flash rates in excess of 70 fpm for severe cells. Lightning jumps were found to occur 15-25 min prior to reported tornadoes, which matches with Williams’ results, as well as those of Bridenstine et al. (2005). Similarly, Gatlin and Goodman (2004) found that lightning jumps preceded tornadic activity by up to 20 min for cells observed by the North Alabama LMA. Gatlin and Goodman also noted that while trends in CG flash rate were similar to total flash rate trends, the signal of increased activity was clearer in the total lightning data. Steiger et al. (2007a) observed that source heights dropped during a 25-minute period prior to tornadogenesis with two supercells observed using the DFW LDAR network. This result was not observed with nontornadic supercells in the region, suggesting that the updraft may have weakened prior to tornadogenesis, in agreement with the theory suggested by Lemon and Doswell (1979).

Features in VHF source density plots also have been linked to severe convection. Lightning “holes”, or areas within a cell with little or no total lightning activity, have been observed in VHF source density plots of several supercells (e.g., Krehbiel et al. 2000; Goodman et al. 2005; MacGorman et al. 2005; Murphy and Demetriades 2005; Wiens et al. 2005). These features occur in an area of the supercell collocated with the updraft. Lang et al. (2004) found that a supercellular lightning hole during the STEPS project was associated with the bounded weak echo region (BWER), a radar indication of an updraft. Similar features such as hooks and notches in the lightning pattern also have been observed with supercells (Demetriades et al. 2002). It is currently hypothesized that these total lightning features indicate the updraft region of the storm, as supported by the observations of Williams et al. (1999), Goodman et al. (2005), and others.

While previous studies have focused on the use of total lightning flash rates, forecasters at WFO FWD do not have access to real time flash rates. Instead, forecasters use a product called flash extent density (FED). FED is a gridded measure of total lightning activity, created by counting the number of lightning flashes that cross through 1 km^2 in a given time interval (Lojou and Cummins 2005). FED data are displayed in plan view and are color-coded in a manner similar to radar reflectivity. These contoured displays have shown features that may be related to the structure and strength of the cell. Features such as lightning holes, hooks, and appendages (Demetriades et al. 2002, Lang et al. 2004, Murphy and Demetriades 2005) have been observed that may correspond to the updraft region of the cell and the BWER aloft (Krehbiel et al. 2000; MacGorman et al. 2005). Additionally, Steiger et al. (2007b) observed notches in VHF density plots on the rear flank of bowing line segments within a mesoscale convective system (MCS) over the DFW network. Features such as these rear notches may indicate the presence of a rear inflow jet and the possibility for severe downdraft winds within a line segment. While these qualitative features show promise as an additional source of information on the strength of the thunderstorm at a given moment, more analysis is needed to tie them to the timing and location of severe convective reports, storm structure and kinematics, as well as the WSR-88D derived signatures of cell strength. Particular emphasis is placed on examining FED appendages and lightning hooks; there are relatively few examples of them in the peer-reviewed literature as compared to lightning holes.

2. Data and methodology

VHF source data from the DFW LDAR network were obtained from Vaisala, Inc. The DFW LDAR network currently consists of 9 VHF sensors with baselines of ~20-30 km between sensors. However, on the dates included in this study, only the first 7 sensors were installed and in operation (Fig. 1). The DFW LDAR network detects VHF radiation emitted during the lightning breakdown process. Due to the very short duration of these emissions, they may be modeled as point sources of radiation (e.g., Mazur et al. 1997; Carey et al. 2005). The network operates within a frequency range from 60 – 66 MHz, corresponding to TV channel 3. Each sensor reports the time of the highest amplitude signal received in a 100 μs time interval. These data are collected at a central site, where the time of arrival of a source at multiple sensors can be used to determine the three dimensional location of the source. VHF detection networks are sensitive to both wholly IC flashes and the IC portions of CG flashes, leading to the term "total lightning" detection. It is believed that most sources are detected within the positively charged region of a thunderstorm, as lightning propagation there is noisier in VHF than propagation through negative charge regions (Rison et al. 1999).

Previous work has shown that the expected flash detection efficiency of the DFW LDAR network is estimated to be greater than 95% in the interior of the network, with a flash detection efficiency of greater than 90% out to a range of 120 km. The estimated location accuracy of individual VHF sources is within 200 m when the source is within 30 km radius of the network center at DFW International Airport (sensor site "A" in Fig. 1). Position errors for VHF sources are estimated to be less than 2 km out to a range of 150 km from the network center (Demetriades et al. 2002; Carey et al. 2005).

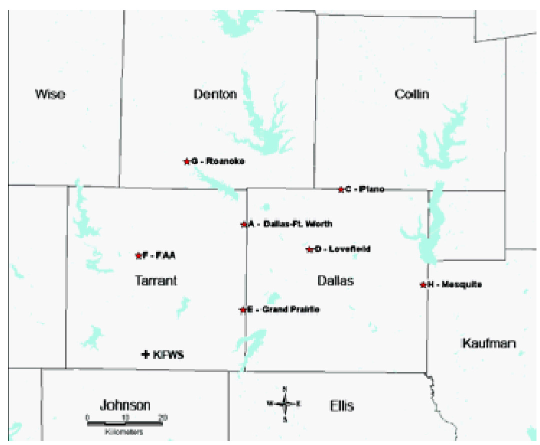

Figure 1. Location of the KFWS WSR-88D and the DFW LDAR network sensors that were active on the dates in this study. The center of the LDAR network is at DFW International Airport (sensor site "A"). [Adapted from Patrick and Demetriades (2005)]. *Click image to enlarge. View all images.*

Data from the DFW LDAR network are sent in real time to WFO FWD through the Southern Region Headquarters of the NWS. Forecasters then may access the data using the Display Two Dimensions (D2D) program that is part of the AWIPS used by the NWS. Currently there are three products shipped to the office by Vaisala: gridded source density (GSD), flash extent density (FED), and flash initiation density total (FIDT). All are density products, gridded into 1 km by 1 km horizontal bins.

GSD displays the number of VHF sources detected by the LDAR network within each 1 km grid box. It is available for seven altitudes, the first six of which are 3-km vertical intervals from 0-18 km. The final GSD image available is the total column value, displaying all sources detected within the horizontal grid box from the surface up to an altitude of 20 km.

Vaisala creates FED values after the raw VHF source data is run through a flash-grouping algorithm. This process applies a series of spatial and temporal criteria to the sources that are based upon the propagation speed of lightning processes measured by the LDAR network. By grouping together sources that meet the constraints of the flash algorithm individual lightning flashes can be reconstructed. Specific information on the Vaisala flash-grouping algorithm was not made available, although it is a modification of a flash-grouping algorithm created by NASA (McCormick 2003). Once individual flashes have been recreated the total number of flashes passing through each 1 km grid box are summed to produce the FED value for that grid box (Lojou and Cummins 2005). FED is only available for the full 0-20 km column, and has units of flashes min^{-1} km^{-2}. It is important to note that each flash passing through a grid box counts only once. If a flash has multiple branches passing through the same grid box, the first one will be counted and subsequent branches will be disregarded. FIDT is a product similar to GSD, however the sources are filtered such that only those VHF sources identified by the flash algorithm as being the first source within a flash are included.

Currently, FED is the preferred product for operational use of total lightning data at WFO FWD, as it is less susceptible to the decrease in source detection efficiency with increasing range from the network than simple source density plots (Carey et al. 2005). This comparative advantage of FED results from the use of the flash grouping algorithm. While decreasing detection efficiency results in fewer sources being detected, flashes still will be plotted as long as the remaining sources meet the temporal and spatial criteria of the algorithm.

Radar observations of storm structure, evolution, and movement were taken from the Ft. Worth/Dallas (KFWS) WSR-88D, located approximately 44 km southwest of the LDAR network center (Fig. 1). The radar was operated in Volume Coverage Pattern (VCP) 11 on all three case dates. This mode of operation samples the atmosphere at 14 elevation angles between 0.5°-19.5°. Due to the number of samples taken, the update time between images is approximately 5 min (OFCM 2006). This means that there are roughly two LDAR images produced for each radar scan update.

Reports of severe weather events were taken from the official *Storm Data* publications for April 2005 and April 2007, available from NCDC. While these reports are generally in good agreement in timing and location with respect to cell locations from the KFWS radar data, the times listed may be up to 5 or 10 min off of the actual event time because of the nature of the reporting method, as discussed in Witt et al. (1998).

Quantitative analysis of the LDAR products available at WFO FWD was conducted using the Interactive Data Language (IDL). Each file, containing 2 min of LDAR data was read in by IDL and the highest FED and GSD values within 15km of the radar derived cell location were returned. The maximum FED and GSD values for each cell then were plotted in time series using Microsoft Excel.

In addition to the quantitative analysis included in this work, qualitative analysis of FED images was performed to evaluate the usefulness of these displays in evaluating storm structure and evolution. Specifically, FED features such as lightning holes, hooks, and notches (e.g., Krehbiel et al. 2000; Demetriades et al. 2002, MacGorman et al. 2005; Wiens et al. 2005) were compared to radar reflectivity and velocity images obtained from the KFWS radar. This analysis has an analog in the early research using radar, such as the observation that hook echoes were a signal of tornadic potential with a thunderstorm, as was first proposed by Stout and Huff (1953). All images of FED were displayed using the Weather Event Simulator (WES), a version of AWIPS that is used for forecaster training within the NWS (Magsig 2004). The displays of LDAR data within WES are identical to those presented to forecasters in real time within AWIPS.

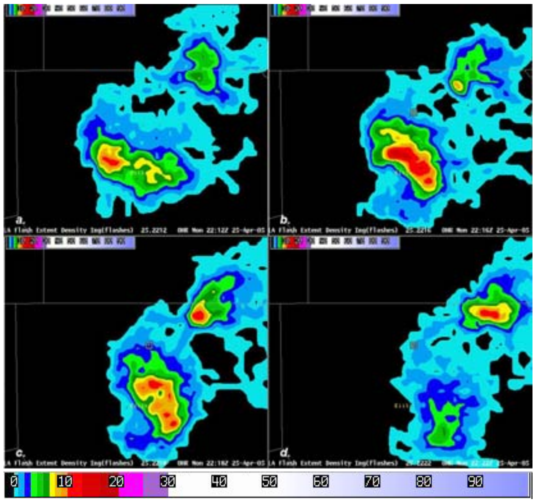

Figure 2. Right hand shift in FED (flashes min^{-1} km^{-2}, colors as shown) track for cell two on 25 April 2005. Times in UTC are: a) 2212, b) 2216, c) 2218, and d) 2222. *Click image to enlarge.*

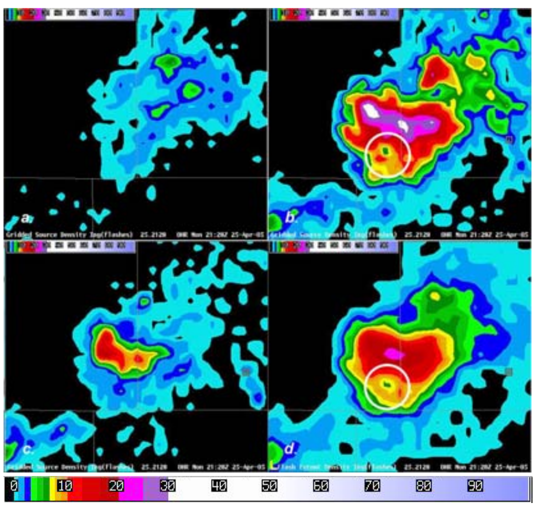

Figure 3. FED (convention as in Fig. 2) and GSD (sources min^{-1} km^{-2}, colors as shown) images of cell one lightning hole (circled) at 2128 UTC on 25 April 2005. Images are: a) 0-3 km GSD, b) 3-6 km GSD, c) 6-9 km GSD, and d) FED. *Click image to enlarge.*

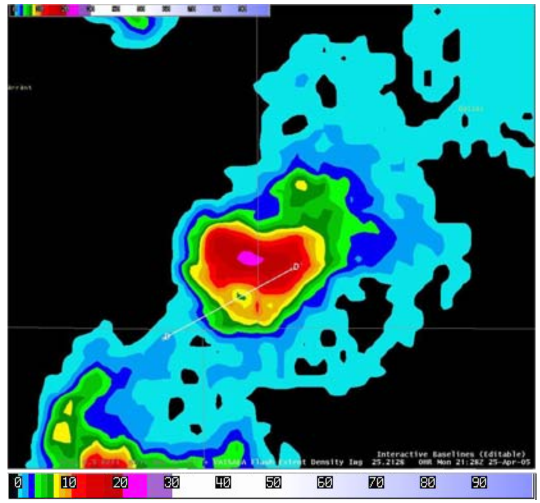

Figure 4. FED (convention as in Fig. 2) image of cell one lightning hole at 2128 UTC on 25 April 2005. Diagonal line "D" denotes the location of the radar vertical cross section shown in Fig. 6. *Click image to enlarge.*

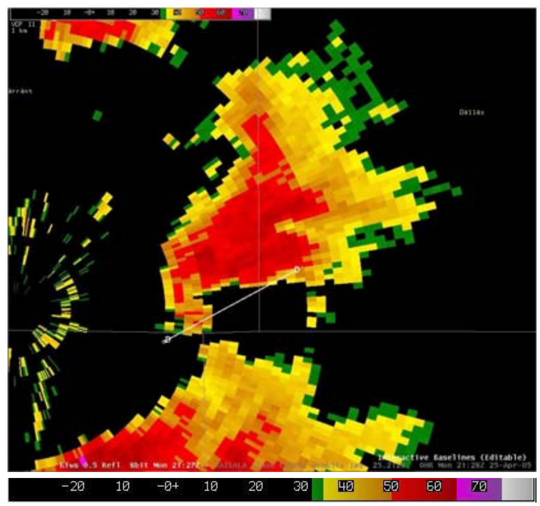

Figure 5. 0.5° Radar reflectivity (dBZ, colors as shown) image at 2127 UTC on 25 April 2005, corresponding to lightning hole at 2128 UTC. Line "D" denotes the location of the vertical cross section in Fig. 6. *Click image to enlarge.*

3. Results

On the afternoon of 25 April 2005, numerous showers and thunderstorms formed along a dryline west of the DFW metroplex, including two tornadic supercells that moved across portions of Tarrant, Dallas, Johnson, and Ellis Counties (all counties referenced in this section can be found on the LDAR network map in Fig. 1, unless otherwise noted). On 5 April 2005, a broken line of thunderstorms developed in the afternoon hours across sections of Collin, Denton, Dallas, and Ellis Counties. Within this line, a leftward deviant supercell moved across Dallas County and produced several reports of severe weather. The final case presented is from 13 April 2007, when a linear MCS moved across the DFW metroplex, including an embedded supercell that crossed northern Tarrant and Dallas Counties. The supercell was responsible for several reports of tornadoes and large hail across the network domain.

a. 25 April 2005

On this date, an eastward advancing dryline was located just to the west of the DFW metroplex by mid afternoon. Several cells initiated along this boundary, including the two supercells discussed herein. At 2100 UTC, these two cells were located in eastern Tarrant and central Johnson County, and moved southeastward into Dallas and Ellis Counties during the analysis period. By 2300 UTC, the northern cell (cell one) had begun to dissipate, and cell two (southern cell) had moved into northeastern Navarro County (unlabeled county immediately southeast of Ellis County in Fig. 1).

The FED of cell one, the northern (Tarrant County) storm, exhibited a rightward shift in direction between 2112-2118 UTC. This shift of FED to the right of the previous storm track corresponded to a similar shift in radar reflectivity, and is discussed in detail in Patrick and Demetriades (2005). The FED maximum of cell two, the southern (Johnson County) storm, also turned to the right, later in the study period, between 2210-2222 UTC (Fig. 2). However, this shift in FED maximum lagged behind the shift in radar reflectivity, which began around 2200 UTC (not shown). Cell one displayed a minimum in FED and GSD in southeastern Tarrant County at 2128 UTC (Figs. 3 and 4). This lightning hole was located 5 km to the east of a well-pronounced hook shaped echo at low levels in the KFWS radar reflectivity data (Fig. 5). A north-south cross section of radar data through this FED minimum shows that it corresponded to an area of relatively low radar reflectivity values up to an altitude of 2 to 3 km AGL (Fig. 6). This vaulted shape corresponded to a radar reflectivity weak echo region (WER) (Fig. 5) at low elevation angles and a BWER aloft (not shown), which are radar indications of a strong updraft. Another similar area of minimum FED at 2234 UTC corresponded to an area where no sources were present in the GSD data (Fig. 7). This region also corresponded to an area of weak KFWS reflectivity (25.5 - 27.5 dBZ) at the 5.3° and 6.0° elevation angles, at altitudes of 7.2 km (23.7 kft) and 8.3 km (27.4 kft) above ground level (AGL) (not shown). However, this lightning minimum corresponded to relatively high values of radar reflectivity (~55 dBZ) on the 0.5° and 1.5° elevation at altitudes of approximately 1.1 km (3.7 kft) and 2.6 km (8.5 kft, not shown). Each minimum in lightning activity was observed on only one two-minute image of either FED or GSD. However, each minimum was followed by a notch in the FED and GSD data that persisted for several images, corresponding to the updraft region of the cell as inferred from KFWS imagery. Examples of these notches are indicated with white arrows in Fig. 8.

Lightning appendages on cell one appeared in FED and GSD displays at several points in the storm's evolution: at 2116 UTC (Fig. 7c in Patrick and Demetriades 2005), and again between 2132-2144 UTC (Fig. 8). No similar features were observed in the FED or GSD images of the second cell. At 2158 UTC, another appendage formed on the southern edge of the FED maximum from cell one (Fig. 9). This appendage evolved over the next five FED images into a separate area of relatively high values separate from cell one. During this time, the maximum FED value observed with this new feature was between 14 and 16 flashes min^{-1} km^{-2}. Cell one displayed a decrease in both the value and extent of the FED maxima during this ten-minute period. At 2210 UTC, the two FED maxima merged on the D2D display into one feature. FED values associated with the merged feature began to increase at 2216 UTC on the southwest side of the cell, with FED values approaching 9 flashes min^{-1} km^{-2}. This intensification continued until a maximum of over 17 flashes min^{-1} km^{-2} was observed at 2226 UTC. This feature also was evident in the GSD display, where it first appeared on the 2154 UTC image (Fig. 10).

The maximum FED values (MxFED) associated with cell one during the study period are plotted in Fig. 11. This time series plot displays the maximum value of FED within a specified radius around the radar derived cell location, which for the cells on this date was 15 km. A sharp drop in MxFED occurred at 2108 UTC, with the value dropping from 16.5 flashes min^{-1} km^{-2} at 2104 UTC to a minimum value of 8.5 flashes min^{-1} km^{-2} at 2108 UTC. MxFED increased over the next two time intervals, reaching 17.5 flashes min^{-1} km^{-2} at 2112 UTC. The drop in MxFED at 2108 UTC occurred 6 min prior to a tornado reported with this cell along Interstate 35 in south Ft. Worth. MxFED increased during the period from 2114 through 2130, reaching a value of 24.5 flashes min^{-1} km^{-2} at 2130. A dip in MxFED occurred at 2132, with a value of 23 flashes min^{-1} km^{-2}, before quickly increasing to 31.5 flashes min^{-1} km^{-2} at 2136. A tornado was reported in the town of Mansfield, in southeast Tarrant County, at 2130 UTC, during the time of increasing MxFED, MxFED remained above 30 flashes min^{-1} km^{-2} until 2146, with the exception of a sharp drop in at 2142 UTC to 22.5 flashes min^{-1} km^{-2}. Another tornado was reported with this cell south of Cedar Hill, in southwestern Dallas County, at 2135 UTC (NCDC 2005). Another FED "jump" was observed just after 2200 UTC. FED increased between 2200-2204 UTC, reaching a maximum value in excess of 20 flashes min^{-1} km^{-2}. MxFED dropped below 10 flashes min^{-1} km^{-2} at 2206 UTC, and continued to diminish as a second FED maximum (discussed previously) approached from the southwest. No severe

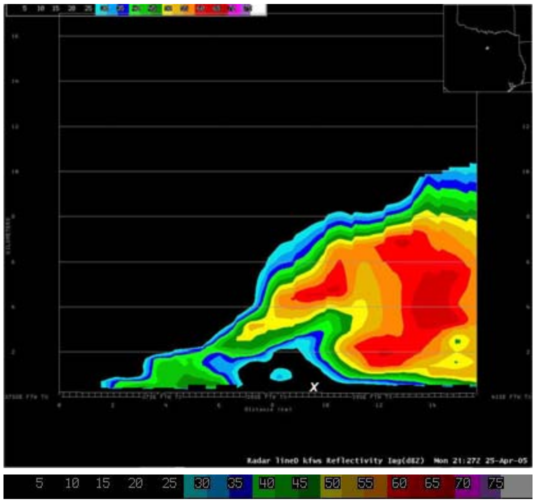

Figure 6. Radar reflectivity vertical cross section (line "D") at 2127 UTC on 25 April 2005. The position of the lightning hole from Fig. 4 is marked with a white X along the horizontal axis. Note the weak echo region that extends upward 2-3 km in the location of the lightning hole. *Click image to enlarge.*

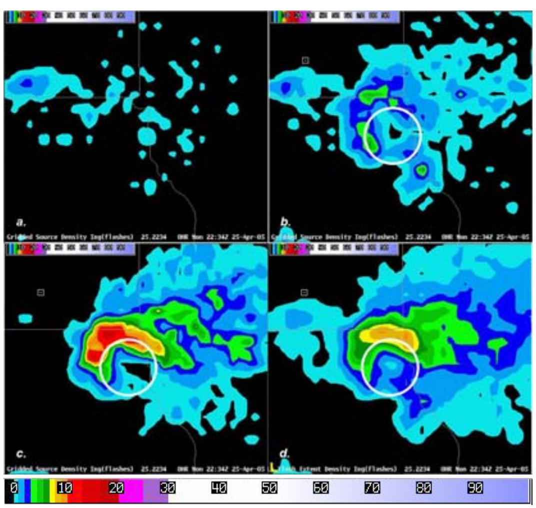

Figure 7. GSD and FED (conventions as in Fig. 3) images of second cell one lightning hole (circled) at 2234 UTC, 25 April 2005. Images are: a) 0-3 km GSD, b) 3-6 km GSD, c) 6-9 km GSD, and d) FED. *Click image to enlarge.*

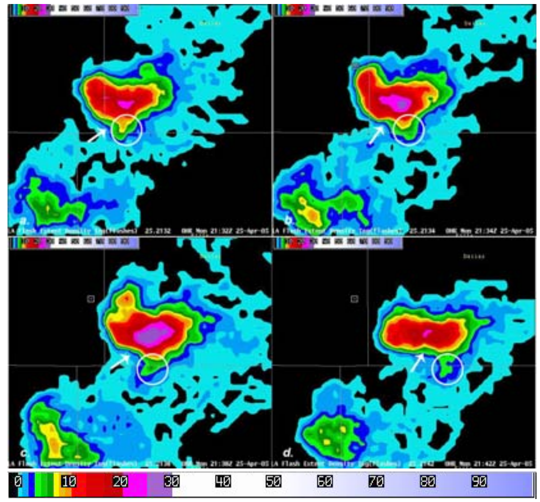

Figure 8. FED (convention as in Fig. 2) time series of cell one leading appendage (circled) from 25 April 2005. Times are: a) 2132 UTC, b) 2134 UTC, c) 2138 UTC, and d) 2142 UTC. Updraft notches are marked with white arrows. *Click image to enlarge.*

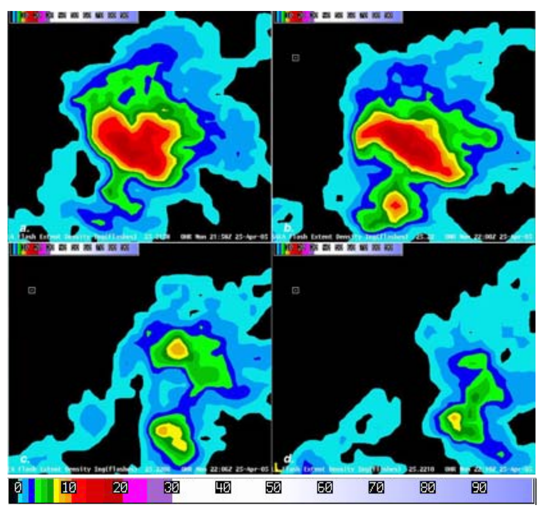

Figure 9. New FED (convention as in Fig. 2) maxima developing to the south of, and then merging with, cell one. Times are: a) 2158 UTC, b) 2200 UTC, c) 2206 UTC, and d) 2210 UTC on 25 April 2005. *Click image to enlarge.*

weather was reported during this time, despite the cell being located in a well-populated region just to the south of the Dallas metro area. Another period of increasing MxFED values occurred between 2214-2226 UTC, with the exception of a short dip in values at 2220 UTC, roughly at the same time as the report of severe hail in the community of Ferris mentioned previously. After 2226 UTC, MxFED begin to decrease as the cell weakened considerably on KFWS reflectivity images.

Trends in MxGSD for cell one were similar to those of MxFED (Fig. 11), however an area of relatively high GSD (mentioned previously) was apparent at 2154 UTC (Fig. 10), 4 min prior to being a prominent feature in the FED display. The two GSD maxima remained distinct until merging at 2216 UTC. GSD peaked at just over 30 sources min^{-1} km^{-2} at 2226 UTC, corresponding to the time of highest FED.

The time evolution of FED and GSD values for cell two are shown in Fig. 12. At 2128 UTC, FED for cell two reached a maximum of 17 flashes min^{-1} km^{-2} just to the east of Alvarado (image not shown, see Fig. 12 for time series).

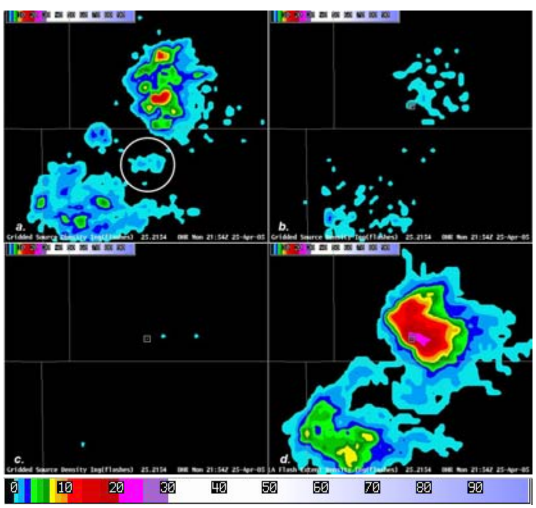

Figure 10. Comparison of GSD and FED (conventions as in Fig. 3) images at 2154 UTC, 25 April 2005. Images are: a) 6-9 km GSD, b) 9-12 km GSD, c) 12-15 km GSD, and d) FED. Note the highlighted region in a), this feature evolved into the second maximum of FED displayed in Fig. 9, although it was not a distinct feature in FED until 2158 UTC, 4 min after appearing on the GSD display.

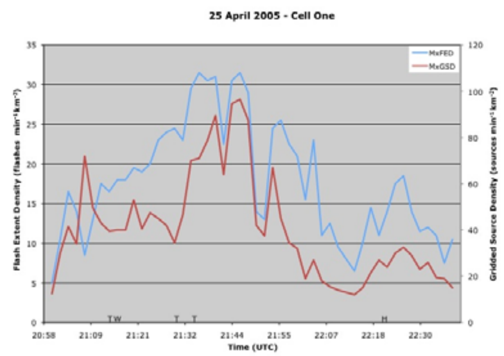

Figure 11. Time series of MxFED (flashes min^{-1} km^{-2}) and GSD (sources min^{-1} km^{-2}) for cell one on 25 April 2005. The x-axis represents severe weather reports, with tornadoes labeled as "T", hail reports labeled as "H", and wind gusts labeled as "W". *Click image to enlarge.*

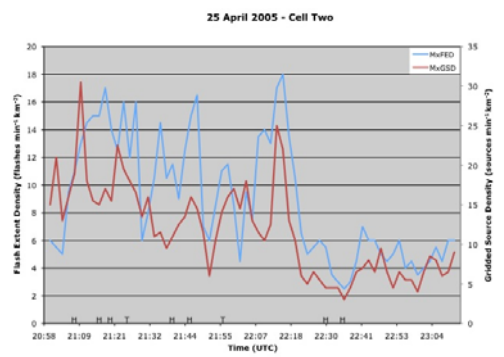

Figure 12. As in Fig. 11, but for cell two on 25 April 2005. *Click image to enlarge.*

At 2130 the maximum FED dropped to 6 flashes min^{-1} km^{-2} before increasing again at 2132 UTC. Storm reports show that large hail reaching 7.0 cm (2.75 in) was observed in Keene at 2120 UTC (NCDC 2005). A tornado was reported 1 mile west of Alvarado at 2125 UTC, and 2.50 cm (1.00 in) hail was reported in Alvarado at 2130 UTC (NCDC 2005). FED increased again with this cell, in western Ellis County from 2142-2148 UTC, peaking at 16.5 flashes min^{-1} km^{-2} at 2148 UTC. At 2150 UTC, FED dropped significantly, with an MxFED of only 6 flashes min^{-1} km^{-2}. Severe hail reaching 4.5 cm (1.75 in) in diameter was reported in Venus at 2140 UTC, and 2.50 cm (1.00 in) hail was reported in Alvarado at 2145 UTC. A tornado also was reported near Maypearl at 2156 UTC (NCDC 2005).

b. 5 April 2005

At 2200 UTC on 5 April 2005, a solid line of thunderstorms extended from southern Oklahoma southward into Collin County. Convection extended further south and west as a broken line of cells from Collin to Bosque Counties (located to the southwest of Johnson County in Fig. 1). The primary cell of interest on this date formed at approximately 2254 UTC near the confluence of Tarrant, Dallas and Ellis Counties. This cell began to split at 2309 UTC on the KFWS imagery. The left-split rapidly moved northeastward across Dallas County before merging with another cell in far eastern Collin County at ~2348 UTC (Fig. 13).

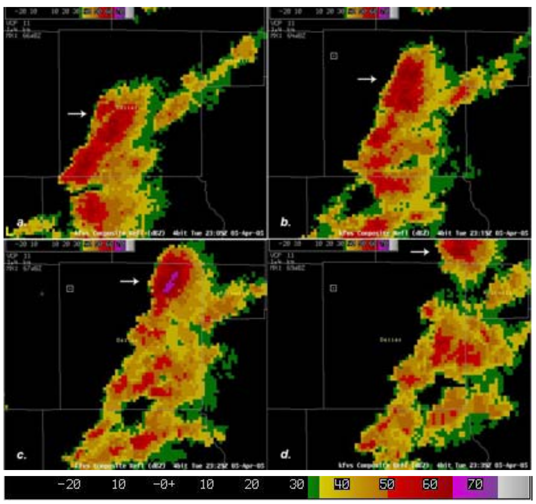

Figure 13. Evolution of left-moving supercell on 5 April 2005 from KFWS composite reflectivity (dBZ, colors as shown). Position of this cell is displayed at a) 2309 UTC, b) 2319 UTC, c) 2329 UTC, and d) 2339 UTC. *Click image to enlarge.*

The left-moving supercell in this case displayed lightning appendages on the left flank of the cell similar to those seen on the right flank of the northern cell from April 25. The first appendage developed at 2314 UTC and became more pronounced on the 2316 UTC image (Fig. 14). The radar data show that the cell track shifted to the left between 2319-2324 UTC, just after the development of this feature (Fig. 15). A second appendage and an associated FED notch developed at 2328 UTC (Fig. 16). After each of these appendages developed, the FED values appeared to turn towards them and the higher FED shifted farther to the left.

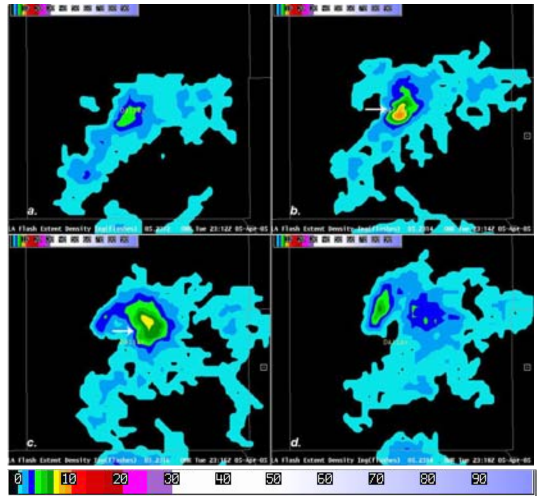

Figure 14. Development of leading appendage on the left moving supercell and subsequent shift of FED maximum at a) 2312 UTC, b) 2314 UTC, c) 2316 UTC, and (d) 2318 UTC on 5 April 2005. Updraft notches are marked with white arrows. FED convention as in Fig. 2. *Click image to enlarge.*

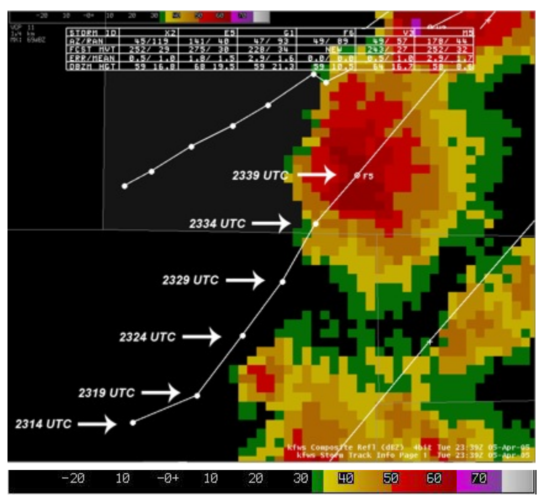

Figure 15. KFWS composite reflectivity of left-moving supercell (labeled as "F5"), 2339 UTC, 5 April 2005. Dots indicate radar derived cell locations at each of the times labeled. White line denotes the cell track from the WSR-88D storm tracking algorithm. Note the leftward turn between 2319-2324 UTC, after the development of the FED appendage from 2314-2318 UTC (Fig. 14). *Click image to enlarge.*

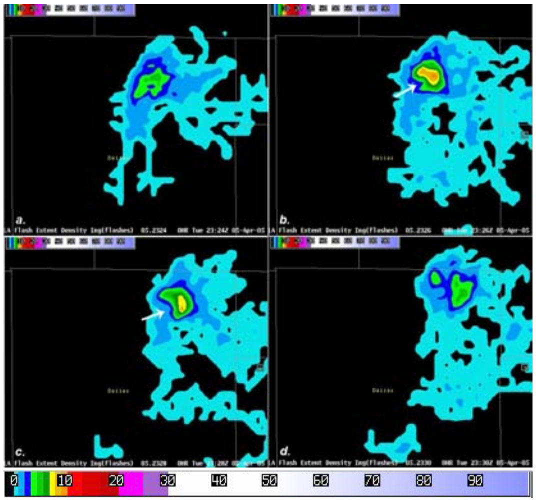

Figure 16. Development of second leading FED appendage associated with the left-moving supercell from 5 April 2005. Times are: a) 2324 UTC, b) 2326 UTC, c) 2328 UTC, and d) 2330 UTC. Updraft notches are marked with arrows. FED convention as in Fig. 2. *Click image to enlarge.*

This left-moving supercell exhibited updraft signatures in FED and GSD images that were similar to those of the northern supercell from 25 April. Several FED notches were noted with this cell, corresponding to tight radar reflectivity gradients on its northwestern side (Figs. 14 and 15). FED values were much lower than those from the 25 April northern supercell, but two distinct peaks in lightning activity were noted. The first occurred at 2314 UTC with an MxFED of 10.5 flashes min^{-1} km^{-2} and an MxGSD of 40 sources min^{-1} km^{-2} (Fig. 17). MxFED associated with this cell peaked again at 10.5 flashes min^{-1} km^{-2} over northeastern Dallas County at 2326 UTC (Fig. 17). At 2322 UTC 2.50 cm (1.00 in) hail was reported in the Lake Highlands area of Dallas, near White Rock Lake, and 3.75 cm (1.50 in) hail was reported 3.2 km (2 mi) north of Garland at 2336 UTC (NCDC 2005). Hail to 2.50 cm (1.00 in) was reported in Blue Ridge, in eastern Collin County at 2350 UTC, immediately after the merger of the left moving supercell with another thunderstorm in the line (NCDC 2005).

While there was some increase in FED values associated with the new merged cell prior to the latter hail event, an apparent loss of LDAR data at 2338 UTC (manifested as a significant drop in FED and GSD values across all cells in the LDAR II network domain for one two min period) makes it difficult to analyze lightning activity prior to the severe hail report at 2350 UTC. A third, smaller cell began to develop northeast of DeSoto in Dallas County at approximately 2334 UTC. This cell had a peak in FED between 13.5-18 flashes min^{-1} km^{-1} just to the west of Mesquite at 2340 UTC, but no severe weather was reported at the time. Lightning analysis of this cell also is hampered by the apparent data loss mentioned previously, but after dropping off from 2340 UTC, FED on the northeast side of this cell begin to rise again at 2358 UTC in northeastern Rockwall County. FED peaked between 13.5-18 flashes min^{-1} km^{-2} (the highest values seen on this date) at 0002 UTC (not shown). FED declined for this cell at 0004 UTC, matching the last available FED image. Although this cell showed higher values of FED than the supercell emphasized in this case, it produced no reported severe weather.

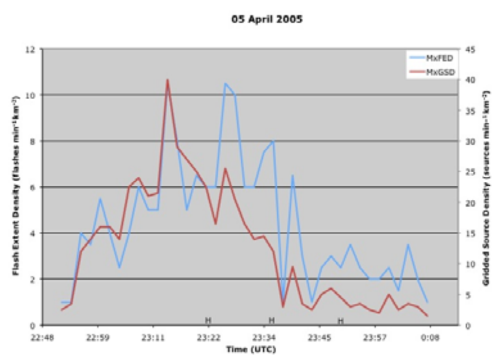

Figure 17. As in Fig. 11 but for the left-moving supercell on 5 April 2005. *Click image to enlarge.*

c. 13 April 2007

A broken line of discrete cells formed on a dryline west of the Dallas-Fort Worth Metroplex, soon evolving into a contiguous linear MCS. At the center of the line, an embedded supercell developed and moved across Tarrant and Dallas Counties, producing several reports of tornadoes and hail up to 7.50 cm (3.00 in) in diameter. Due to a lack of network communications, only data after 2300 UTC were considered in this study. Additionally, at 2336 UTC, values of FED and GSD began to decrease for all cells, until all VHF data across the network were gone after 23:40 UTC (not shown). Thereafter, FED increased slowly through 2354 UTC, returning to magnitudes evident before the data loss. The data dropout occurred as areas of strong convection crossed several of the sensor sites.

The first feature of interest appeared at 2316 UTC in southern Denton County. A large “hook” appendage developed on the southern edge of a large FED maximum (Fig. 18). The FED minimum encircled by this appendage was located in an area with radar reflectivity of 40-45 dBZ (Fig. 19). An area of cyclonic rotation and a radar hook echo developed on the southern end of this storm by 2332 UTC (Figs. 20 and 21), indicating tornado potential. This feature quickly dissipated during the next two radar volume scans as convection to the south of this cell rapidly moved eastward.

At 2324 UTC, a notch began to develop on the west side of the FED maximum located in Denton County (Fig. 22). This feature persisted into the network data loss period between 2336-2352 UTC. Afterward, the feature became most pronounced on the 2354 UTC FED image as a sharp notch of low values extending into the large maximum that had crossed into Collin County (Fig. 23). At 2347 UTC, KFWS radar data showed outbound velocities of over 40 m s^{-1} (80 kt) in southeastern Denton County at approximately 6.4 km (21.0 kft) AGL. Outbound velocities at approximately 3.9 km (13.0 kft) and 3.0 km (10.0 kft) AGL were 38.5 and 27 m s^{-1} (77 and 54 kt), respectively. The 4.3° and 3.4° tilts at this time also show a slight bow in reflectivity in this area. At 0001 UTC, the bowing reflectivity was observed on the 2.4° and 1.5° tilts, and outbound velocities from the 2.4° tilt had increased from 27 m s^{-1} (54 kt) at 2347 UTC to to >32 m s^{-1} (64 kt). Outbound velocities in this area on the 1.5-degree scan were greater than 25.5 m s^{-1} (51 kt), at an altitude of approximately 2.1 km (7.1 kft) AGL (Fig. 24). A wind gust of 25 m s^{-1} (50 kt) was reported 1.4 km (0.9 mi) northeast of Allen in south central Collin County at 0015 UTC (NCDC 2007).

Another bounded FED minimum appeared in Dallas County at 2354 UTC, associated with the embedded supercell (Fig. 25). This feature was located in an area of relatively low reflectivity values, south of a tight reflectivity gradient and east of a radar hook echo that developed by the time of the 2356 UTC 0.5° KFWS reflectivity image (Fig. 26). A strong signature of cyclonic rotation persisted in this area for several volume scans, as shown on the 2356 UTC velocity image (Fig. 27). At 0000 UTC 06 April, a tornado was reported in the Forest Hills area of northeast Dallas (NCDC 2007).

MxFED for the embedded supercell that crossed Tarrant and Dallas Counties, are shown in Fig. 28. Values increased to an initial peak of 10 flashes min^{-1} km^{-2} at 2314 UTC. This cell produced a tornado, rated EF-1 on the enhanced Fujita scale (WSEC 2006), in Haltom City from 2309-2315 UTC, with one fatality at a lumberyard. This cell also produced several reports of severe hail during this period, including 6.35 cm (2.50 in) diameter hail in Saginaw at 2303 UTC. Baseball sized hail (7.0 cm, 2.75 in) was observed at WFO FWD in northeast Fort Worth, at 2306 UTC, and 4.5 cm (1.75 in) hail damaged many vehicles at North East Mall in Hurst at ~2315 UTC. MxFED increased to 14.5 flashes min^{-1} km^{-2} at 2326 UTC before dropping to only 3 flashes min^{-1} km^{-2} at 2332 UTC. At 2336 UTC MxFED reached 22.5 flashes min^{-1} km^{-2}, the highest value observed before the loss of LDAR data at approximately 2338 UTC. Hail 7.60 cm (3.00 in) in diameter was reported in Colleyville, in northeast Tarrant County, at 2332 UTC. After LDAR data resumed, MxFED at 2354 UTC was 23.5 flashes min^{-1} km^{-2}, the highest value reported with this cell. MxFED then decreased sharply into the second period of missing data, to only 12.5 flashes min^{-1} km^{-2} at 0000 UTC, the time of the aforementioned northeast Dallas tornado. MxFED then decreased through the remainder of the supercell’s lifetime.

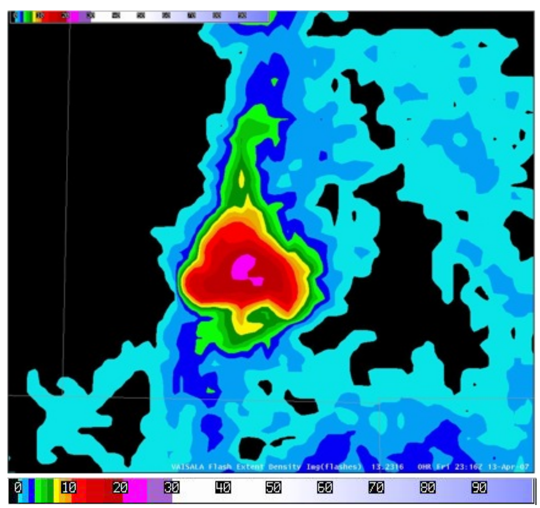

Figure 18. Hook shaped FED (convention as in Fig. 2) appendage in Denton County, TX, 2316 UTC, 13 April 2007. *Click image to enlarge.*

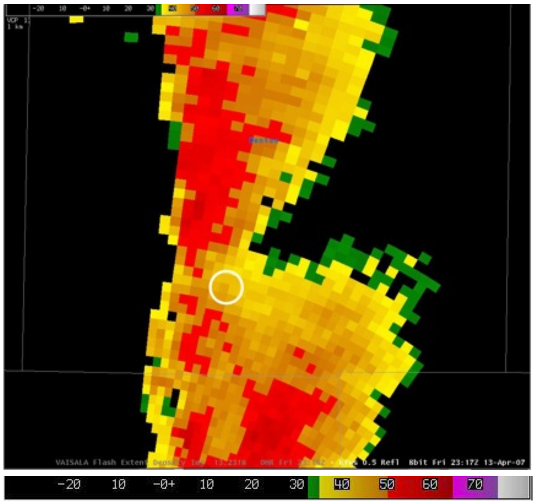

Figure 19. KFWS 0.5° reflectivity image from 2317 UTC on 13 April 2007 (dBZ, colors as shown). Highlighted area is encircled by the FED hook appendage in Fig. 18. *Click image to enlarge.*

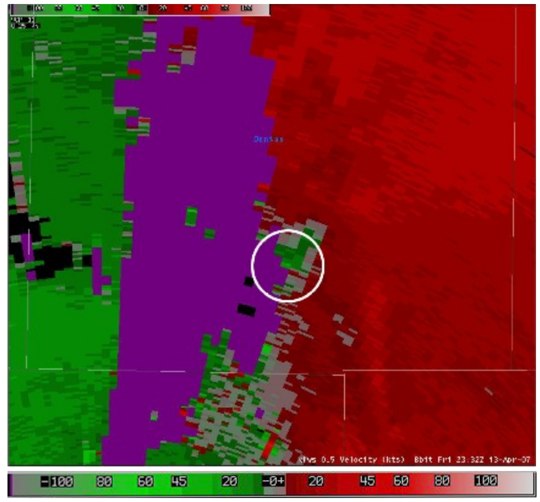

Figure 21. KFWS 0.5° radial velocity (kt) image from 2332 UTC on 13 April 2007. Highlighted region is the same as that in Fig. 20, ~60 km northeast of the radar site. Note the velocity couplet collocated with the hook echo shown in Fig. 20. *Click image to enlarge.*

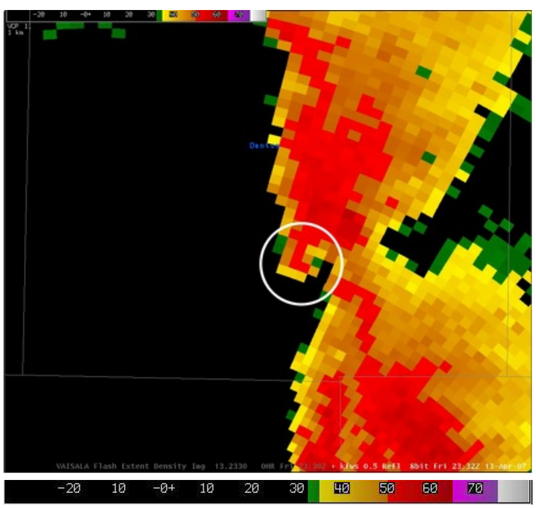

Figure 20. As in Fig. 19, but for 2332 UTC, showing a radar hook echo (circled) that developed in southern Denton County, TX. *Click image to enlarge.*

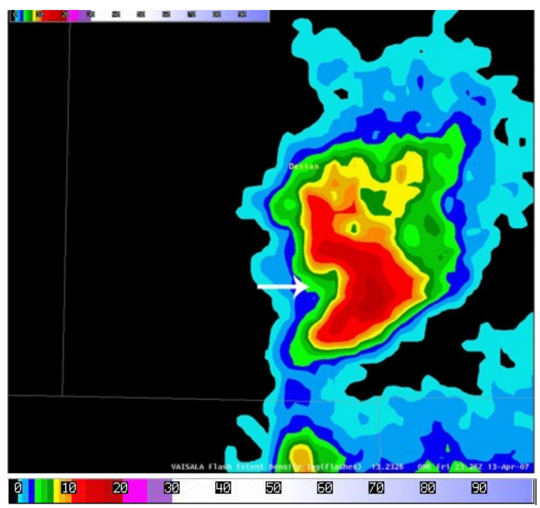

Figure 22. FED (convention as in Fig. 2) notch developing at 2326 UTC on 13 April 2007 on the rear flank of a cell in Denton County. *Click image to enlarge.*

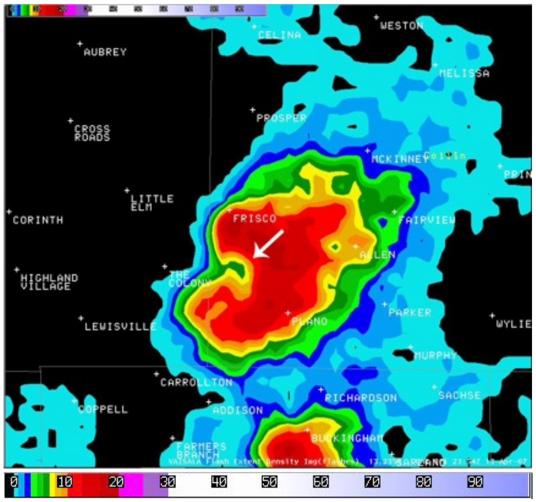

Figure 23. FED (convention as in Fig. 2) notch from the Denton County cell at 2354 UTC on 13 April 2007. A severe wind report was recorded just north of the town of Allen (located on the east side of the FED core) at 0015 UTC. *Click image to enlarge.*

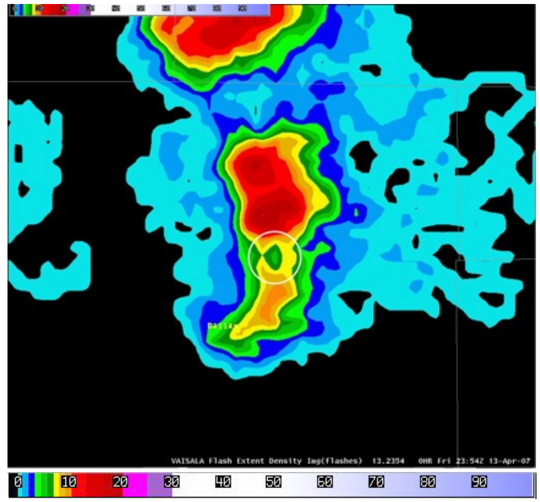

Figure 25. FED (convention as in Fig. 2) minimum associated with the embedded supercell in Dallas County at 2354 UTC on 13 April 2007. *Click image to enlarge.*

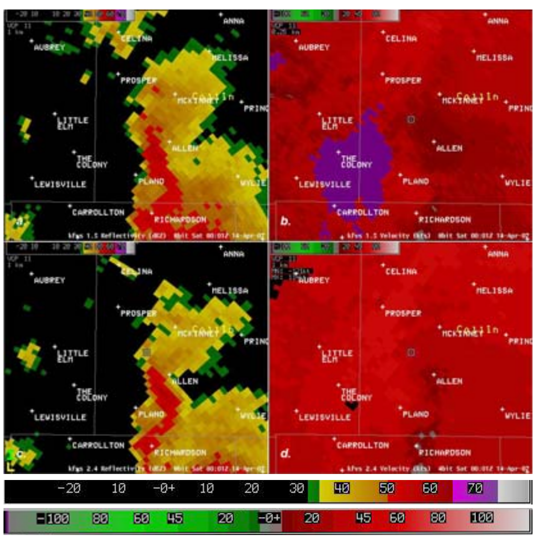

Figure 24. KFWS radar reflectivity (dBZ, upper color bar) and velocity (kt, lower color bar) images from 0001 UTC 14 April 2007, showing bowing reflectivity and strong straight line winds just to the west of the town of Allen. Images are 0.5°: a) reflectivity and b) radial velocity, and 2.4°: c) radial velocity and d) reflectivity. *Click image to enlarge.*

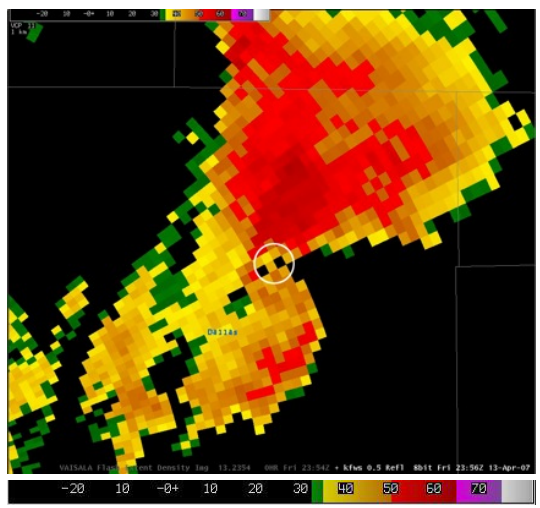

Figure 26. KFWS 0.5° reflectivity (dBZ, colors as shown) image from 2356 UTC on 13 April 2007. Highlighted location is the position of the FED minimum shown in Fig. 25, just to the east of a reflectivity hook echo. *Click image to enlarge.*

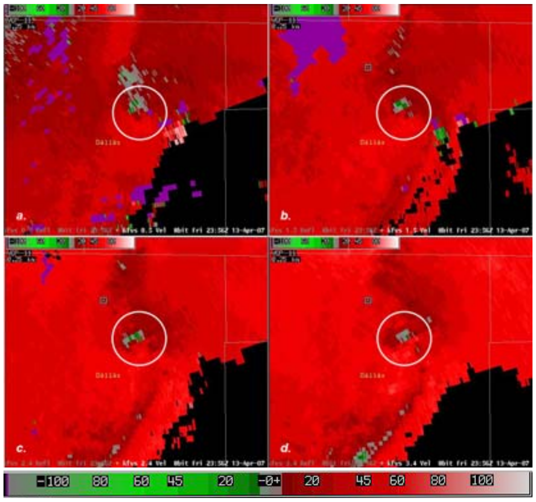

Figure 27. Display of KFWS radial velocities from 4 different elevation angles (kt, colors as shown) over Dallas County at 2356 UTC on 13 April 2007: a) 0.5°, b) 1.5°, c) 2.4° and d) 3.4°. Encircled region is the location of the FED minimum shown in Fig. 25. *Click image to enlarge.*

MxGSD values for this cell are shown in Fig. 28. The three sharp MxGSD spikes were present in the source density plots as well. Following the LDAR data blackout, MxGSD for this storm was 30.5 flashes min^{-1} km^{-2}. MxGSD decreased thereafter as the storm it moved farther from the center of the LDAR network.

4. Discussion

a. Lightning holes, hooks and notches

Displays of FED and GSD have shown the ability of total lightning data to highlight key characteristics of supercell structure on the dates examined in this study. FED and GSD imagery successfully highlight the radar inferred updraft regions of the cells, as shown by the lightning holes present at two separate times with the northern cell on 25 April 2005. The radar reflectivity cross section through the first lightning hole clearly shows the vaulted shape of a BWER. Although both lightning holes were apparent only on one image of either FED or GSD, they evolved into persistent notches in the lightning data at the same location in the storm as the reflectivity hook echo or updraft notch, similar to the lightning notch described in Demetriades et al. (2002). The embedded supercell from 13 April 2007 also displayed a local FED minimum at 2354 UTC, clearly associated with the updraft region. Although this feature appears to be visually similar to the lightning hole seen with the northern supercell on 25 April 2005, this may be a consequence of its location between the two FED maxima associated with the convective core of the former supercell and the flanking line to the south. Regardless of whether this feature is a true lightning hole, it can bring the forecaster's attention to the updraft region associated with the main cell. Additionally, the lightning "hook" and associated FED minima that developed along the convective line in Denton County at 2316 UTC appear to indicate a strong updraft with the echo just to the north of the main supercell.

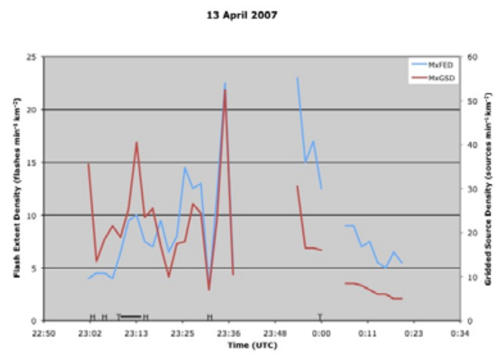

Figure 28. As in Fig. 11, but for the embedded supercell on 13 April 2007. The black bar represents the Haltom City tornado lifespan (EF-1, one fatality). *Click image to enlarge.*

On 5 April 2005, similar FED updraft notches were present in FED imagery of the left moving supercell that crossed Dallas County. In this case, the FED provides even greater benefit, as this cell tended not to have a well-defined radar hook echo around the updraft region. The presence of the updraft notch in FED, in addition to the tight radar reflectivity gradient on the northwest side of this supercell, highlighted it as a left moving storm, despite the lack of the mirrored form of a "classic" supercell shape (Lemon and Doswell 1979). As a consequence of these results and those of other studies discussed earlier, it appears that forecasters can use total lightning data displayed within D2D as a secondary indication of a strong updraft; as regions of a cell that are relatively free of IC lightning have shown a strong correlation with the thunderstorm updraft (Krehbiel et al. 2000; Goodman et al. 2005; Murphy and Demetriades 2005; Wiens et al. 2005).

Similarly, the rear notch in FED associated with the cell moving across southern Denton and Collin Counties on 13 April 2007 highlights an apparent rear inflow jet in this part of the convective line, similar to the results of Steiger et al. (2007b). This notch formed at 2124 UTC and became most pronounced at 2354. Its developemtn preceded the descent of strong outbound radar velocities to low levels in the KFWS volume scans. No rear inflow notches readily were apparent in radar reflectivity data during this time period. The occurrence of a severe wind gust near Allen, in southern Collin County at 0015 UTC, suggests that this rear notch *may* be an FED signature of the potential for severe downdraft gusts associated with a linear MCS as in Steiger et al. (2007b). This feature is not to be confused with the "updraft" notches also described herein. The rear FED notch from 13 April 2007 is a much larger and more pronounced feature than the updraft notches, and not located in an area of the cell that would suggest an updraft. More cases involving linear systems with damaging winds need to be investigated to determine whether this is an isolated feature or a reliable indication of severe weather potential.

b. FED appendages

FED appendages appeared to signal a tendency for deviant cell motion. On 25 April 2005, the northern supercell developed two of them during its lifetime that appear just to the east of the updraft region. These features formed at 2116 UTC and again between 2132-2144 UTC. In both episodes, the storm was in the process of shifting to the right of its previous track. Right-moving supercells were favored on this day based on the veering characteristics of the low-level winds in the 1900 UTC sounding from WFO FWD (not shown). Two similar appendages also formed with the left moving supercell from 5 April 2005. Again, each appendage developed at approximately the same time as the cell motion became more deviant, this time to the left. After the development of each appendage, MxFED appeared to "roll" towards the appendage, collocating the highest FED values with the strongest reflectivity gradient in the supercell. This tendency appears to follow the observation from Steiger (2007a) that the highest FED is found with the strongest reflectivity gradient.

These observations suggest that FED not only indicates supercellular updraft regions, but also may indicate new updraft development on the preferred side, leading to a propagational shift in storm track. This ability to highlight updraft development and propagation on a timescale faster than the WSR-88D update interval (2 min vs 5 min) makes LDAR data an important resource for forecasters to maintain situational awareness during warning operations.

c. FED and GSD comparison

Each lightning hole on 25 April 2005 was far more evident in GSD imagery than in FED, as the method by which FED is calculated tends to fill in bounded areas without VHF sources. This advantage of GSD over FED is good reason for forecasters to check both products, at least at distances close enough to the LDAR network that GSD data are not degraded significantly by decreasing detection efficiency. Carey et al. (2005) evaluated DFW LDAR data for one case date in 2004, estimating that source detection efficiency decreased to 10% at a range of 50 km from the center of the network.

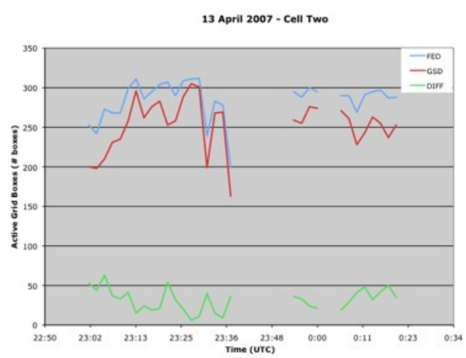

Figure 29. Total number of grid boxes containing FED or GSD data for the embedded supercell on 13 April 2007. Also plotted is the difference between the two, labeled as "DIFF." *Click image to enlarge.*

An example of decreasing source density performance is shown in Fig. 29. The total number of 1-km by 1-km grid boxes containing FED or GSD data for the supercell on 13 April 2007 are plotted, along with the difference between them, labeled DIFF. DIFF decreased during the first half of the cell tracking period, with the lowest values between 2320-2335 UTC. After LDAR data resumed at 2354 UTC, DIFF increased again. The period of low DIFF corresponded to the time when the cell passed closest to the network center (Fig. 1). While the cell was farther away, fewer sources were detected, thus the number of grid boxes containing GSD data decreased. FED, however, is created using output from a flash algorithm, and therefore is able to recreate flashes as long as the temporal and spatial criteria between sources still are met. This relative advantage of FED over GSD makes it the preferred product for display in AWIPS at WFO FWD.

d. FED trends and severe weather

The results of this study also appear to support the hypothesis that trends in FED intensity may indicate severe weather potential in a storm. Several efforts have been made to correlate changes in total lightning flash rates with the occurrence of severe weather (Williams et al. 1999; Goodman et al. 2005; Bridenstine et al. 2005; Steiger et al. 2007a,b), with some interesting results in regard to spikes in total flash rate and changes in altitude of lightning activity.

Although FED values cannot be considered interchangeable with flash rates, they do appear to show similar trends with respect to severe weather reports. Jumps in FED on 25 April 2005 appeared for each supercell before reports of tornadoes and large hail. FED increased sharply for cell two, 9 min prior to the first reported tornado, then 14 min before the second tornado. Lead times were lower for the northern cell, with an FED jump beginning at 2108 UTC, 6 min prior to a reported tornado in southern Tarrant County. A peak in lightning activity occurred at 2130 UTC, simultaneous with the reported tornado in Mansfield, although an increase in MxFED from 2124-2126 UTC was noticeably greater than the overlying upward trend from 2114-2130 UTC. Another tornado was reported south of Cedar Hill in Dallas County at 2135 UTC (NCDC 2005), although radar reflectivity data from KFWS suggests that it probably occurred closer to 2145 UTC. A jump in FED values began at 2132 UTC, indicating a possible lead time for this event of up to 13 min. Severe hail tended to occur either during or just after a lightning jump, as did those of the left moving supercell on 5 April 2005, which showed two distinct spikes in lightning activity 8 and 10 min prior to each severe hail report in Dallas County. This supports the idea that total lightning activity is related to the strength of the updraft, as an intensifying updraft would indicate a greater threat of severe hail.

e. Network performance

The usefulness of the LDAR data appears to depend highly upon both the distance of the cell from the network and the performance of the network on a given day. On 25 April 2005, the southern storm consistently displayed much lower values of FED and GSD than the northern storm, despite having higher values of radar reflectivity and more severe weather reports. Additionally, one sensor within the network stopped reporting from ~2045-2100 UTC. This data loss dramatically decreased FED and GSD for the same time period, much greater in extent than any of the decreases in activity associated with the lightning jumps mentioned previously (Fig. 30). Another such example occurred in the 13 April 2007 case, when FED and GSD data disappeared and returned for all cells between 2336-2354 UTC. While sharp decreases in FED for *one particular* storm could indicate an imminent severe weather event; a similar decrease with *all* cells is more likely a secular network detection issue instead.

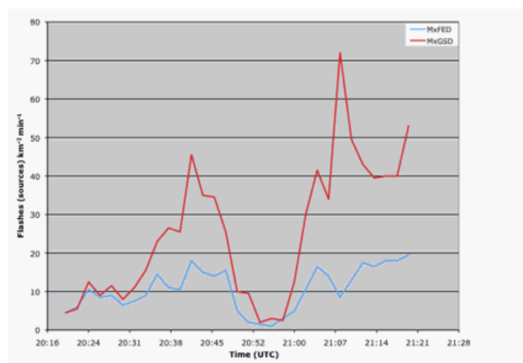

Figure 30. Time series of FED (flashes min^{-1} km^{-2}) and GSD (sources min^{-1} km^{-2}) data illustrating apparent LDAR network "brownout" from 2045 UTC to 2100 UTC on 25 April 2005. MxFED and MxGSD data are displayed from cell one. *Click image to enlarge.*

Because detection efficiency can vary day to day with network sensor status, forecasters should be aware of any situations (maintenance, communication problems, etc.) that would affect the data, so that artificial signals are not treated as indicating actual convective trends or severe potential within a given cell.

While there is encouraging evidence that lightning trends can aid the warning decision process, the FED for each cell varied considerably during its lifetime. In the case of April 5, the cell with the highest FED showed FED spikes without producing any severe weather, indicating that there may be other considerations beyond the maximum flash rate or MxFED. More research is needed to quantify what rates of change of total flash rate or FED are significant in order to reduce the false alarm potential associated with jumps in those data.

Data from the North Alabama LMA are being used to develop a lightning jump algorithm that may predict tornado potential based on total flash rate. Early results from that work have shown probabilities of detection and critical success index values that compare favorably to the performance of the operational tornado vortex signature (TVS) algorithm of the WSR-88D (Gatlin and Goodman 2008). Perhaps the greatest benefit of total lightning trend data, on days with widespread convection, is to highlight specific storms that may be more likely to produce severe weather, which the warning forecaster then could monitor with greater emphasis (Goodman et al. 2005).

f. LDAR vs. WSR-88D

The LDAR network has two relative advantages with regard to the WSR-88D that make it an important tool in the analysis of severe convection. The first is its rapid update cycle, 2 min at WFO FWD, producing images twice as fast as VCP 12 (the shortest WSR-88D scanning strategy). This cycle also is flexible; if desired, total lightning parameters could be updated with even higher frequency in situations where cells produce large amounts of lightning. Also, when the radar and LDAR networks are located in close proximity, as is the case here, the LDAR network can be utilized at very close range, where radar sampling is truncated (the "cone of silence") above a beam elevation angle of 19.5°. By contrast, LDAR data improves as the cells move within the network, where detection efficiency and location accuracy are highest (Carey et al. 2005). As such, LDAR performance can increase as radar performance decreases. This relationship between the two observing systems, coupled with the ability of the LDAR to show important information on cell structure and intensity, make total lightning data an important complement to the WSR-88D in the warning decision process.

The results of this study support the conclusion that FED is the preferred product for displaying total lightning information in plan view, while the total lightning flash rate is the better product for tracking values in real time. The superiority of either during NWS warning operations remains to be decided. The most obvious answer, and probably the best, is to use both. While future work may refine the definition of lightning jumps and the ability to diagnose them in real time, plan view FED displays were very effective in highlighting the most active storms, as well as important information on their structure and movement. This situation has a direct analog in the use of radar data. While numerous algorithms and indices have been developed to diagnose the strength of a storm, meteorologists still rely heavily on displays of reflectivity and velocity data and their qualitative interpretation (e.g., hook echo, WER, notches, velocity couplets) during warning operations. A similarly balanced approach between qualitative and quantitative measures of total lightning should provide the greatest added benefit to warning forecasters.

5. Summary

1) Qualitative displays of total lightning data, including both FED and GSD, can be used by forecasters as indicators of the presence of a strong updraft within a storm. Regions of little total lightning activity within a cell, including features such as lightning holes and updraft notches, have been observed with strong updrafts on each of the three case dates herein.

2) FED appendages were observed with multiple supercells prior to and during shifts in storm track in radar reflectivity images. These appendages may be an indicator of updraft redevelopment on the preferred flank, suggesting the potential for deviant storm movement. Forecasters using LDAR or other VHF total lightning mapping data in real time should be aware of these features, as they may signal a change in storm motion before the next radar volume scan is available.

3) FED "jumps", or sharp increases in MxFED, occurred prior to tornadogenesis with several supercells examined here. These jumps occurred up to 14 min before the reported

tornado time. Additionally, FED jumps were associated with numerous reports of severe hail in both tornadic and nontornadic thunderstorms. These jumps may indicate strengthening updrafts, so that forecasters should be aware of the increased potential for severe weather with the associated storm. However, there was significant FED variability throughout each cell's lifetime. Further research is needed to differentiate true FED jumps from changes that are not important indicators of cell intensity.

4) The ability of FED to highlight changes in cell intensity and movement make it an important addition to the WSR-88D data used during warning operations. This is especially true in situations where the radar may not sample a storm adequately, at very close range, or if the radar is inoperative.

5) LDAR network performance appears to depend upon both the distance of the cell from the network and the operational status of the sensors. Forecasters must understand strengths and weaknesses of the LDAR data, as well as remain aware of changes in the status of the network that may affect performance, in order to avoid misinterpreting secular artifacts as changes in the electrical structure of a thunderstorm.

Although the results of this study have shown great promise for the ability of total lightning data to improve the warning decision process, many more cases need investigation to determine how such data is most useful to forecasters in real time. Two new sensors added to the DFW LDAR network after the dates in this study should improve network performance. Severe weather cases occurring after this upgrade should be assessed for changes in network performance. More research is also needed to determine if the FED rear notch is a prior indicator of severe nontornadic winds. Several such events occurred in the DFW metroplex in the spring of 2008.

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REVIEWER COMMENTS

[Authors' responses in *blue italics.*]

REVIEWER A (Brian Curran):

Initial Review:

Recommendation: Accept with major revisions

Substantive comments: The proposed article provides observations of total lightning in supercellular and multicellular convection over north Texas and the use of these data in the warning decision process. An opportunity exists here to demonstrate how these data were used in an operational warning setting. I do not believe the authors have considered this opportunity sufficiently and I recommend that the authors explore further how these data were used in acquiring and maintaining appropriate situational awareness and in demonstrating the impacts these data had on the warning decision process before acceptance for publication in EJSSM.

The authors do not demonstrate how total lightning data were used in warning operations at NWS WFO Fort Worth during the period of study. For instance, in the fourth paragraph of the Discussion and Conclusions section of the paper, the authors write, "…it appears that forecaster can use lightning data in D2D as a secondary indication of the presence of a strong updraft…". The forecasters can use the data, but did they? In the sixth paragraph the authors write, "[t]his ability to highlight updraft development and propagation on a timescale faster than the update time of the WSR-88D makes the LDAR data an important resource for forecasters to maintain situational awareness during warning operations." Did the forecasters make use of this resource and did it add value to the forecasters' situational awareness? Lastly, in the eighth paragraph the authors write, "…forecasters at WFO FWD must be educated on both the strengths and weaknesses of the LDAR data if they are to be able to accurately apply the lightning data into the warning decision process in real time." What level of training did the forecast staff receive? How was this accuracy measured? What defines "accurate use" of LDAR data?

If it was the intent of the authors to demonstrate the use of total lightning data in warning operations as stated in the last paragraph of the Introduction section, then more work must be done to show how these data were used operationally. Did the integration of lightning data into the warning decision environment improve forecasters' situational awareness? Did this integration translate into warnings with longer lead times and with less uncertainty? Was total lightning information included in other WFO FWD products and services, such as warnings, follow-up statements, and forecast discussions? Did the authors take post-event surveys of the forecast staff, specifically asking the staff whether the additional information provided by total lightning data added value to the warning decision process? If, however, the intent is to demonstrate potential uses in an operational setting, then the authors should revise the article to make this intent clearer to the reader. The case studies presented can then be used to justify further investigation of total lightning in an operational setting.

The text of the article has been revised heavily from the original draft. While I believe that the new text makes many of the changes requested from the original draft, it is simply not possible to respond to each of the minor edits, as some of the sentences have been removed. I will address those that are still relevant to the new text.

The objective of this paper was to show the potential benefits of using LDAR data in the warning decision process. I believe that the new text is clearer in making this distinction.

Lastly, I believe this paper would have benefited from a critical internal review prior to submission. A "fresh set of eyes" would have captured many of the issues outlined under the technical comments section.

[Minor comments omitted...]

REVIEWER B (Ted Mansell):

Initial Review:

Recommendation: Revisions required

Summary: The paper reports on lightning data as used in now-casting products for a few severe storms. As such, the paper has interest at an anecdotal level more than a scientific level, which can be acceptable to incite interest. I think the science value of the paper is lacking, however, and could be improved by enhancing the data presentation and the making the information in the text more accessible (as well as allowing more data to be presented). The topic may be more suitable for submission to *Weather and Forecasting* rather than EJSSM.

The formatting of the submitted paper is not typical manuscript form, which makes commenting a bit more of a hassle.

Major Points:
1. It would be nice to see a full integration of GSD (0-15km) next to FED. How do they compare for structure?

Unfortunately it would be very difficult for me to recreate images for this text, as I no longer have access to my computer used to create them at Texas A&M. I believe that the images presented do give a slight indication as to what the GSD figures would look like. A total column GSD image looks very similar to FED, but has a much more grainy appearance.

2. I can understand wanting to limit the data sources to what were available to the forecast office, but why not be able to look back in more detail? There may be some characteristics that could be important but were not captured in the operational products. In other words, what might be added or substituted that could enhance the utility of the data to a forecaster?

I have added the time series plots of the maximum FED and GSD values associated with the cells under review. This information is not currently available to forecasters, and I believe that there is a fair amount of discussion in the new text comparing the operational and non-operational products.

3. [Former] P1,c1,par2: But the flash grouping algorithm (which was not given), can also have results that vary with range (detection efficiency and location accuracy), so please explain why you think FED is preferable over GSD. GSD can be vertically integrated just as well as FED.

The new text covers differences in the GSD and FED products with respect to range limitations that I believe more accurately describes the apparent FED advantage than the original document (Data and Methodology section, p. 9).

4. The text contains many mentions of changes in flash density and severe weather events. This information could be more coherently presented in time-series plots of maximum FED for a given cell, and then indicate on the plot when severe events were reported (and what type). Given a long-enough time-series, one could more readily evaluate whether there is a distinct signature in the lightning or not. As it is, the information is very anecdotal with little sense of what the lightning is doing the rest of the time, resulting in an impression of cherry-picked moments. This would mainly involve going through the 2-minute images and picking out the max value of FED and/or GSD for each cell and plotting it. (It is easy to imagine having a point and click capability like this for a forecaster display, so I think this is also relevant to what could be done in operations.)

An additional approach might be to create a table of "significant" lightning changes (increase/decrease) and what severe events (if any) were concurrent or subsequent.

Time series plots of maximum FED and GSD values for the cells were computed as part of my thesis work (done after the original text was written). I have adapted the figures from my thesis for this work and have included them. The maximum FED plots have markers denoting the time of severe weather events with each cell. I agree that a point and click function to interrogate a cell's lightning activity would be useful.

[Minor comments omitted...]

Second Review:

Recommendation: Revisions required

Summary: The paper reports on lightning data as used in now-casting products for a few severe storms. The paper is definitely improved over its original form.

Major Points: The patterns in lightning seem to me to be the chief interest of this paper. The (welcome) addition of the time series plots of flash/source rate suggest that sharp changes in rates are not very well correlated to severe events, at least not in any consistent way. The only rated tornado (EF1 on 13 April) has too much missing lightning data to draw any conclusions. Did the tornado reports from 25 April 2005 have damage ratings? If not, how should they be considered as far as severe events, since plenty of tornado reports are inaccurate?

All of the tornadoes reported with the April 25, 2005 storms were rated as F0 on the Fujita scale. Only the tornado that occurred near the town of Maypearl, TX (associated with cell two, the southern supercell) produced measured damage according to Storm Data for that month.

Basically I think summary point number 3 could say that these cases don't provide much help in evaluating the usefulness [of] lightning jumps. The last sentence in point 3 is, in my opinion, the key point: When I look at the time series, I don't see anything consistent between the FED/GSD rates and the severe reports.

It is possible that a better estimate of total flash rate for a cell would show something more consistent, but I would question how comparable the 1x1 km FED is to a cell-based total flash rate. In high flash rate storms, flashes may occupy only a fraction of the convective region and the total flash rate would not be well represented by FED. But cell-based total flash rate may be too difficult to automate, as cell ID and tracking is already difficult enough. I'm not asking you to go back and try to get a better flash rate -- that is future work -- but to consider the possibility that the products shown don't seem to have a strong signal.

I agree that it is difficult to determine a relationship between a severe weather event and a particular change in a cell's FED value. Further work is needed to establish the criteria to define a "lightning jump" in FED so that a more careful review of cell total lightning trends can be done. However, I do believe that there is still benefit to using the total lightning data to determine which cells may be more intense at a particular time, particularly in regards to the data currently available in AWIPS.

[Minor comments omitted...]

REVIEWER C (Ronald L. Holle):

Initial Review:

Recommendation: Accept with minor revisions

Summary: I have reviewed the paper "Total lightning observations of supercells over North Central Texas" by McKinney et al. The paper may be acceptable with minor revisions, but send the revised manuscript back to me for further review.

This paper uses operational radar and total lightning data to show the relationship with severe weather in several cases; many of the comparisons are interesting and combine datasets in ways that are not often published for the operational meteorological community. However, there are two substantive issues that need attention. First, section 3, titled Results, has a lack of time series that is a significant gap in the presentation. At present, all of the time series for cases are 'not shown', so some sample time series would greatly enhance the reader's ability to synthesize the results. Second, section 4, titled Discussion and Conclusions, is very long and needs to be made more useful for the reader to understand the main results.

Substantive comments:
Section 3, Results: During the discussions of the individual cases in section 3, it is very difficult to understand the relationships among FED, GSD, radar, and severe weather with respect to time. The spatial features were shown, but not the temporal, since all time relationships in the paper were 'not shown'. At least for some of the cases, there needs to be time series that relate datasets with each other. They don't need to be complicated, but are important for the reader to help understand the events. Two examples:
-- [Former] Page 6, left column, the lack of time series makes it difficult to grasp the main points, and I essentially gave up trying to figure out how the lightning, radar, and severe weather fields related in time.
-- [Former] Page 12, right column: There is a great deal of discussion of the trends and spikes as being important, but none of them have been shown. The reader is left with a very diffuse idea of the temporal sequences at this point.

Time series plots of maximum FED and GSD values for each cell have been added to the text. I believe that these will fix most of the concerns with continuity through the results section of the text.

Section 4, Discussion and Conclusions: There are interpretations and results that seem to be new and were not mentioned in the original conclusions from the cases in section 3. As a result, section 4 is nearly as long as the text in the original results of section 3. It would be best if 1) new interpretations were moved to the place where the results were first discussed in section 3, 2) section 4 only included cross-case comparisons, and 3) a short conclusion section was separated from section 4. In the present form, the reader has no single place to find a summary of the paper.

[*Editor's note: The authors added a summary section per this reviewer's request.*]

[Minor comments omitted...]

Features such as appendages and notches have been highlighted in the figures with circles and arrows to make them more apparent to the readers.

The references section has been edited to fix formatting issues mentioned from the first draft of the text.

Due to the amount of changes that were made between the first and second drafts of the text, I have not included a response for each of the minor edits requested. I believe that the revised text does address each of them though.

Second Review:

Recommendation: Accept

Summary: I have reviewed the revised paper "Total lightning observations of supercells over North Central Texas" by McKinney et al. I accept the revised paper, and do not need to see it again unless there are substantial revisions. A few remaining comments can be accommodated if possible.

I very much appreciate the issues with Ike that have arisen with the first author, and commend him for persevering toward publication. [*Editor's note: Substantial delays in the revision/review stage occurred because of direct impact of Hurricane Ike on the lead author's home area, and were accommodated by EJSSM.*] The time delay is not an issue. The manuscript has been revised more substantially than expected, and I thank the authors for placing so much time and effort into improving the text. This study is one of the first formal papers to document the use of total lightning in a detailed manner, and as mentioned on page 11, the documentation here of total lightning features has a parallel in the early radar studies of severe weather. The introduction now establishes the basis for this new study, and the summary and conclusions are more direct than the early version. The addition of time series is very welcome, although they could be combined to reduce the length of the paper.

Substantive comments:

The addition of the time series makes the results easier to understand than before, and I recommend that they be kept. One way to reduce the number of figures is to combine time series for the same periods onto one graph, such as putting Figures 11 and 12 on one, with one scale on the left and the other on the right. The same could be done for Figures 13-14, 19-20, and 31-32.

The time series plots of maximum flash extent density and gridded source density for each cell have been combined, cutting down the total number of figures within the text.

The long section 4 titled Discussion has a good deal of important content. It would seem helpful for the reader to have subsections such as a. Notches and hooks at the start of section 4, b. Appendages and holes starting on the top of page 24, c. FED trends on page 26, d. Network performance on page 27, and e. LDAR compared with WSR-88D on at the end of page 28. Perhaps these are not correct or sufficiently exclusive titles, but some structure such as this would help divide the section 4 discussion.

Section four (discussion) has been subdivided as suggested to allow for easier reading.

[Minor comments omitted...]