6R.6 THE COMPLEMENTARY USE OF TITAN-DERIVED RADAR AND TOTAL LIGHTNING THUNDERSTORM CELLS

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1. INTRODUCTION

The identification and trending of thunderstorm characteristics are key components of the nowcasting process. Historically, radar-identified storm attributes have been used most effectively for this process because of the WSR-88D's extensive coverage across the United States and familiarity of use by forecasters. With the advent of lightning mapping array technology, total lightning (cloud plus cloud-to-ground) data is available for operational nowcasting use in many locations across the National Weather Service's (NWS) Southern region. This paper explores the complementary use of radar- and lightning-derived thunderstorm attributes using Thunderstorm, Identification, Tracking, Analysis and Nowcasting (TITAN) as a prognostic tool (Dixon and Wiener, 1993). The results from several storm events serve as the preliminary analysis necessary to introduce total lightning information into the NCAR Auto-Nowcast system (ANC; Mueller et al., 2003). The ANC is an interactive software package that integrates multiple meteorological datasets in real-time and uses fuzzy logic to combine them and create 60-minute forecasts of thunderstorm initiation, growth and decay every 5 minutes. The forecasting potential of lightning cell trends and their relation to radar reflectivity cells must be fully understood for optimal automated operational deployment in the ANC.

Total lightning data has been provided across the Dallas-Ft. Worth area since 2001 via Vaisala Inc.'s second-generation Lightning Detection and Ranging (LDAR II) VHF time-of-arrival research network (Demetriades et al., 2002). The LDAR-II is an array of 7 sensors centered at Dallas-Ft. Worth International Airport with an average radial baseline of 20 to 30 km (Fig. 1). They detect pulses of radiation produced by the electrical breakdown processes of lightning in a 5 MHz band centered at 61 to 64 MHz. The expected VHF source point accuracy is better than 100 m within the network and better than 2 km out to a range of 150 km. In addition, the ANC has been running operationally in the NWS Ft. Worth, TX forecast office since March 2005 (Nelson et al. 2005). Our dataset includes 15 thunderstorms from six different events from April to July 2005 within the NWS Ft. Worth county warning area (CWA; Fig. 2).

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2. DESCRIPTION OF THE DATA

2.1 *Radar Reflectivity*

The NWS Ft. Worth CWA is well covered by a mosaic of five S-band (10 cm wavelength) NEXRAD WSR-88D radars: KFWS, KDYX, KFDR, KGRK and KSHV. Reflectivity data are updated every 5 to 7 minutes depending on which volume scan strategy is utilized at the time. TITAN is run on a 2.5 km-to-troposphere composite reflectivity corrected for brightband contamination. The minimum storm size area used in the study for identifying radar reflectivity cells is 10 km² and the threshold reflectivity values used are 35 and 45 dBZ.

2.2 *Flash Extent Density*

Our study of total lightning derived thunderstorm cells utilizes Flash Extent Density (FED; Lojou and Cummins, 2005). It employs a "branched segment" reconstruction of the lightning flash using temporal and spatial constraints upon VHF sources created by the electrical breakdown in the propagation of negative leaders. FED helps to normalize the effect of decreasing VHF source detection efficiency with range because flash detection efficiency decreases at a much slower rate with increasing distance from the center of the LDAR II network. Flash detection efficiency is 100% within the network and better than 90% out to 120 km. A 1 km^2 grid box obtains a "hit" if the reconstructed flash passes thru its boundaries. Figure 3 illustrates the similarity of FED shape and appearance to that of traditional radar reflectivity. The FED's temporal resolution for this study is 4 minutes. These characteristics make FED ideal to use for lightning cell identification by adjusting the thresholds used in TITAN. The minimum storm size area used in the study for the FED lightning cells is 10 km² and the threshold FED values used are 0.25 and 1.0. The threshold FED values are chosen to best coincide with the 35 and 45 dBZ reflectivity cells respectively.

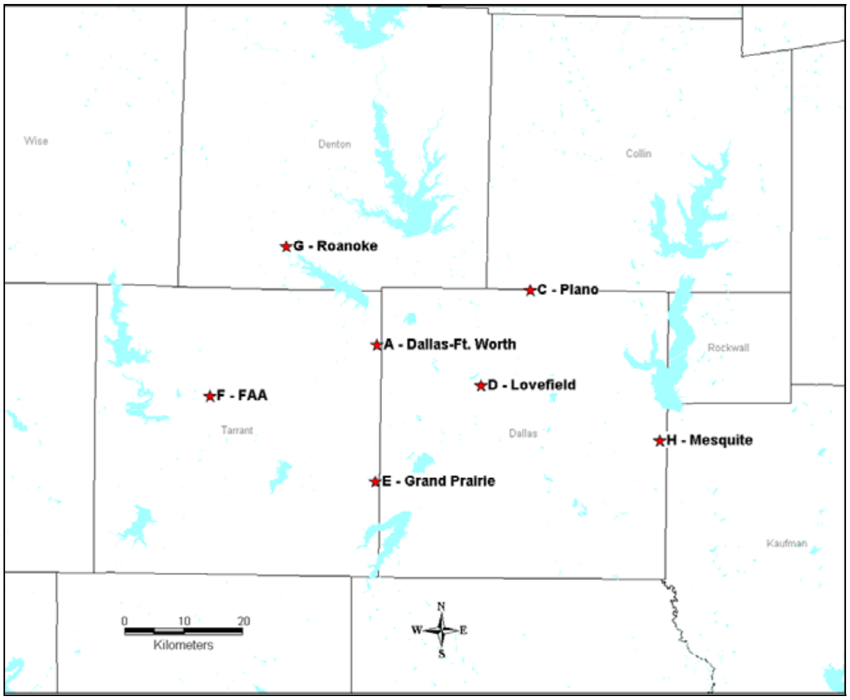

Figure 1. Locations of the Dallas-Ft. Worth LDAR II sites (stars). The central processor and sensor are located at A (Dallas-Ft. Worth International Airport). Local lakes and county boundaries are also shown.

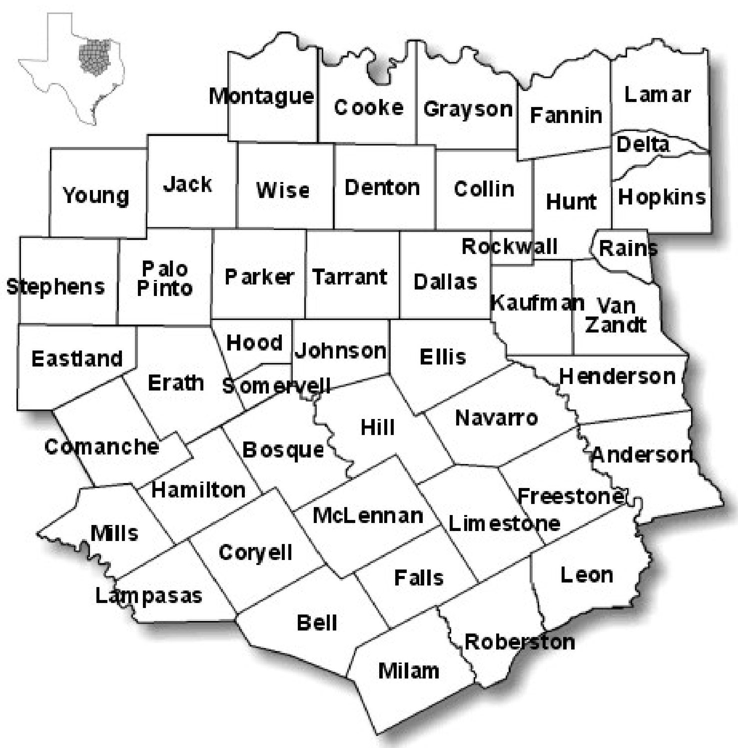

Figure 2. A detailed map of the area and counties encompassed by the Ft. Worth NWS CWA.

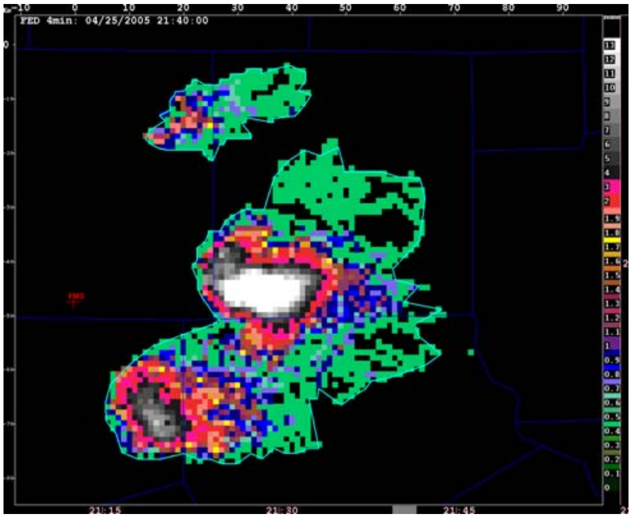

Figure 3. An example of Flash Extent Density (FED) on 25 April 2005 at 2140 UTC as three distinct supercells track east across the Dallas-Ft. Worth area. The color-bar on the right displays the FED intensity level in units of: flashes min^{-1} km^{-2}. The cross represents the location of the FWS WSR-88D in southern Tarrant Co. The cyan lines surrounding the FED are the 0.25 FED threshold TITAN-identified lightning cells.

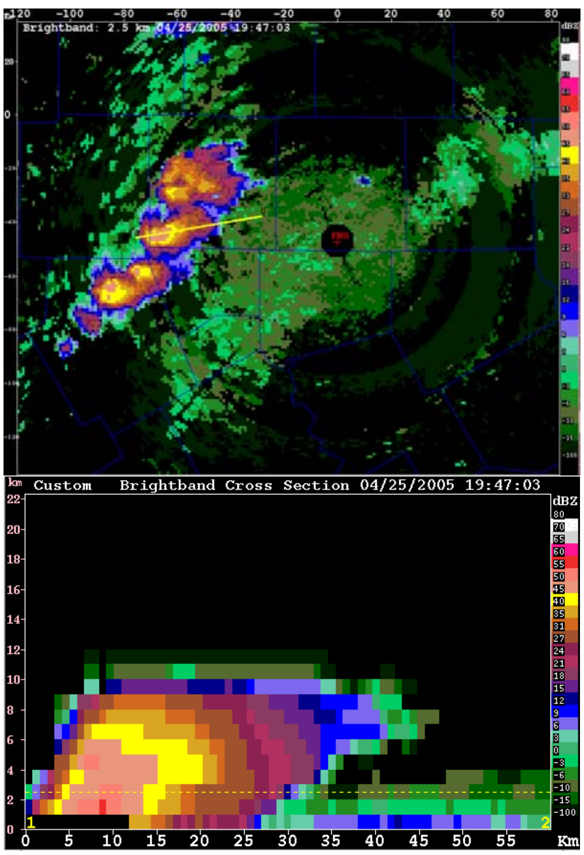

Figure 4. Top: 2.5 km CAPPI of WSR-88D reflectivity (dBZ) at 194703 UTC of the 25 April 2005 supercells during their initial development at 194703 UTC. Area of the CAPPI is about 200 km x 200 km; reflectivity color scale is denoted on the right. The yellow line indicates the location of the vertical cross-section shown in the bottom plot. Although 55 dBZ is present between 1 and 2 km, the vertical development of reflectivity is not yet sufficient for lightning production.

Date	Cell ID	35 dBZ Cell Initiation (UTC)	VHF Source Initiation (UTC)	0.25 FED Cell Initiation (UTC)	VHF Source Lag (min)	0.25 FED Cell Lag (min)
5-Apr	Dallas Co.	2210	2242	2252	32	42
25-Apr	Northern	1929	1950	1956	21	27
25-Apr	Central	1929	1950	2006	21	37
25-Apr	Southern	1923	1950	2026	27	63
25-May	Isolated	1920	1922	1924	2	4
25-May	Tail End	1809	1810	1812	1	3
14-Jun	E.Isolated	0526	0526	0528	0	2
1-Jul	W. Merge	1410	1500	1508	50	58
11-Jul	Dallas	2116	2120	2124	4	8
11-Jul	N Tarrant	1914	1916	1920	2	6
11-Jul	NW Tarrant	1931	1942	1944	11	13
Average					15.5	23.9

Table 1. A detailed analysis of the eleven thunderstorms that initiated within range of the LDAR II. The first column depicts the date of the event and the second column specifies the thunderstorm ID. The middle three columns provide the initiation times (in UTC) of the respective TITAN 35 dBZ cell, VHF sources and the TITAN 0.25 FED cell. The lag times between the 35 dBZ cell and the initial VHF source and 0.25 FED cell are given in the last two columns. The average lag time to the first VHF source is 15.5 min, while the average lag time to the TITAN 0.25 FED cell is 23.9 min.

3. TITAN-DERIVED STORM ATTRIBUTES

TITAN is a robust software application that calculates many attributes as an individual cell is followed in a Lagrangian fashion. Three TITAN-derived storm attributes for both reflectivity and lightning cells are tracked for this study, including: maximum dBZ or FED, storm area and storm normalized area growth rate. The maximum dBZ or FED value is simply the largest value within the boundary of the identified storm cell. The storm area is the area of the composite reflectivity or FED above a particular threshold value in km². Lastly, the normalized area growth rate (NAGR) is a weighted history of the identified cell's area, taking into account the last five sets of data. Thus, the past 25 to 30 minutes of radar information and 16 minutes of LDAR II data are considered. The specific NAGR weights used for this study are 1.0, 0.95, 0.90, 0.85 and 0.5 respectively.

4. LAG CORRELATIONS BETWEEN LIGHTNING AND RAINFALL

The nationwide availability of National Lightning Detection Network (NLDN) data since 1989 (Cummins et al., 1998) and the localized use of electric field mills has led to numerous studies that have correlated cloud-to-ground (CG) lightning to associated rainfall and radar reflectivity. Typically, peak CG flash rates precede the maxima in rainfall by 10 to 15 minutes (Piepgrass et al., 1982; Williams et al., 1989). Non-inductive charging (NIC) mechanisms, which involve the interaction and collision of riming graupel/hail and ice particles within a thunderstorm, create elevated areas or layers of charge in the mixed phase region, typically found above -10ºC (Takahashi, 1978; Saunders, 1993). The elevated charge regions, caused by lofting of particles in intense updrafts, favors the initiation of lightning in a thunderstorm as in-cloud (IC) flashes. 26% of thunderstorms in the NWS Southern Region show CG lightning lagging IC lightning by more than 23 minutes. The delay is even more pronounced in the High Plains, where 50% of thunderstorms see CG lightning lag IC lightning by more than 31 minutes on average (MacGorman, personal communication). CG flashes typically do not occur until elevated charge regions descend to lower levels in the storm (Lang and Rutledge, 2002; Fehr et al., 2004). The physical relationship between CG and IC flashes provides confidence that the IC-to-rainfall lag correlations will have increased temporal viability than the CG-to-rainfall lag correlations found in earlier studies. Therefore, total lightning provides added value in a nowcasting environment due to its independent, yet physical connection to the prediction of thunderstorm coverage and intensity in the 0-1 hour timeframe, which is of specific interest for the development of automated forecast algorithms applicable to the ANC.

5. ANALYSIS OF FORECAST POTENTIAL

5.1 *Initial Observations*

Observations of the thunderstorms studied in the Dallas-Ft. Worth area show that warm-precipitation (i.e. coalescence) processes often dominate the initial stages of development, especially in isolated cells. For example, the 25 April 2005 event in Figure 4 shows high reflectivity values in the lower levels of the three supercells, but little presence of significant hydrometeors in the mixed phase region (at and above 5.5 km on this day) during the initial 45 minutes of growth. Table 1 illustrates that the lag times between the occurrence of 35 dBZ TITAN cells and total lightning was somewhat larger for the 25 April event when compared to most other thunderstorms that initiated within the LDAR II domain, but total lightning never provided a lead-time in regards to the initiation of a 35 dBZ threshold TITAN thunderstorm cell. These results confine the focus of total lightning data analysis toward improving the short-term growth and dissipation forecasts of individual convective cells required in operational nowcasting.

5.2 *Normalized Area Growth Rate As A Forecast Tool*

The purpose of the ANC's growth/decay component is to predict whether a TITAN 35 dBZ threshold storm cell will grow, maintain its current area, or dissipate 60 minutes from the forecast time. The most effective TITAN-derived reflectivity thunderstorm cell attribute for this task is the history-weighted NAGR. The use of thunderstorm cell trends to create a 60-minute forecast is inherently flawed, but is currently the best available nowcasting technique until computing power increases to support 0-60 minute data assimilation and numerical weather prediction. The similarities between reflectivity- and FED-derived cells allow for similar NAGR analyses to be conducted on the total lightning data. The reflectivity and FED NAGRs can be used complementarily to provide more consistency in the growth/decay forecast. The fuzzy logic framework of the ANC thrives when more data sets are brought in to provide crosschecks and redundancy in the automated forecast.

To evaluate and compare the forecast potential of the TITAN-derived reflectivity and FED cells, the data are re-sampled to 5-minute time periods. Results are shown in Figure 5 that displays the linear correlation coefficients (r) when using the NAGR to forecast the 35 dBZ cell area in 5-minute intervals from 0-70 minutes. The linear correlation coefficients are relatively low due to the wide variance that exists in both the NAGRs and cell area attributes, but using $r \geq 0.3$ is a strong indicator that a physical relationship is still present between the two. The lag correlations show that the TITAN-derived radar reflectivity NAGR is a better forecast tool in the 0-30 minute range. However, the TITAN-derived FED NAGR performs as well or better than the reflectivity cells in the 40+ minute timeframe. The 0.25 and 1.0 FED threshold cells build to $r \geq 0.3$ by 40 and 45 minutes, respectively. This is comparable to the 35 dBZ cells which exhibit skill until 40 minutes, but the FED cells outperform the 45 dBZ NAGRs which never exhibit any skill of $r \geq 0.3$ (Fig. 6).

The lag correlation analysis of the FED and reflectivity cells supports the physical relationship of total lightning activity and rainfall discussed earlier in Section 4. The growth of the total lightning cell corresponds to the flux of supercooled water droplets, ice crystals and graupel/hail through the mixed phase region from thunderstorm updrafts > 6-7 m s^{-1} (MacGorman and Rust, 1998; p. 219). The hydrometeors responsible for electrification descend from the mixed phase region when the updraft can no long suspend them or downdraft becomes dominant. At this point, the reflectivity seen at 2.5 km increases as ambient wind shear distributes the hydrometeors in a wider swath, thus increasing the 35 dBZ threshold cell area.

5.3 *Maximum dBZ or FED As A Forecast Tool*

The second TITAN-derived thunderstorm cell attribute utilized by the ANC to forecast growth/decay is the maximum dBZ value. The current threshold value used in the Ft. Worth ANC is 49 dBZ. A TITAN identified cell with maximum reflectivity <49 dBZ is forecast to decay and a cell with maximum reflectivity >49 dBZ is forecast to grow. This is incorporated into the ANC to ensure that intense convection is not fully dissipated in the 60-minute forecast.

As with the other attributes, the TITAN-derived reflectivity and FED cells are compared by re-sampling the data into 5-minute time periods. Lag correlations are shown in Figure 7. It displays the linear correlation coefficient when using either the maximum dBZ or FED value to forecast the 35 dBZ cell area in 5-minute intervals from 0-70 minutes. The results are very similar to those discussed in Section 5.2. Initially, the maximum dBZ is a better forecast tool but drops off rapidly after 25 minutes. The maximum FED correlation drops off less rapidly and therefore becomes a superior forecast tool after about 25 minutes. This further supports the earlier findings that TITAN-derived total lightning attributes provide better forecasts in the 40-60 minute timeframe.

5.4 *Thunderstorm Intensity Forecasts*

The current growth/decay component of the Ft. Worth ANC accounts for the growth, maintenance or decay of thunderstorm cell area, but it does not factor in the evolution of thunderstorm intensity. The linear correlation coefficient between the 35 dBZ cell area and maximum reflectivity is 0.6, so the two do not always work synergistically. As in the previous results, lag correlation analysis has been conducted to evaluate the ability of the TITAN-derived reflectivity and FED cell NAGRs to predict the future maximum reflectivity within the 35 dBZ threshold cells. The TITAN attributes are re-sampled to 5-minute time periods and the linear correlation coefficients are calculated in 5-minute intervals from 0-60 minutes.

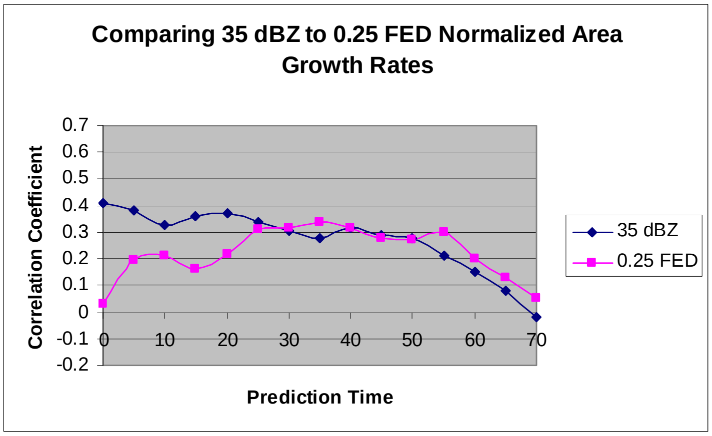

Figure 5. The lag correlations in 5-min intervals comparing the TITAN 35 dBZ cell NAGR (blue) to the TITAN 0.25 FED cell NAGR (pink) as predictors for the 35 dBZ cell area. The lag correlations are calculated for each of the 15 thunderstorms in the dataset and then averaged together at each 5-min iteration.

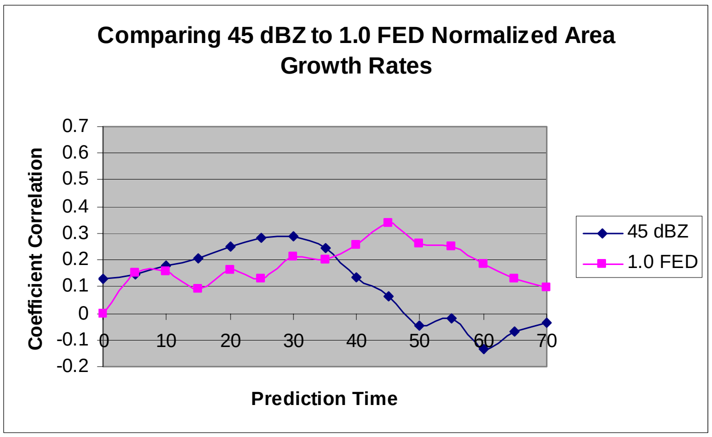

Figure 6. Same as Figure 5, except comparing the TITAN 45 dBZ NAGR (blue) to the TITAN 1.0 FED NAGR (pink).

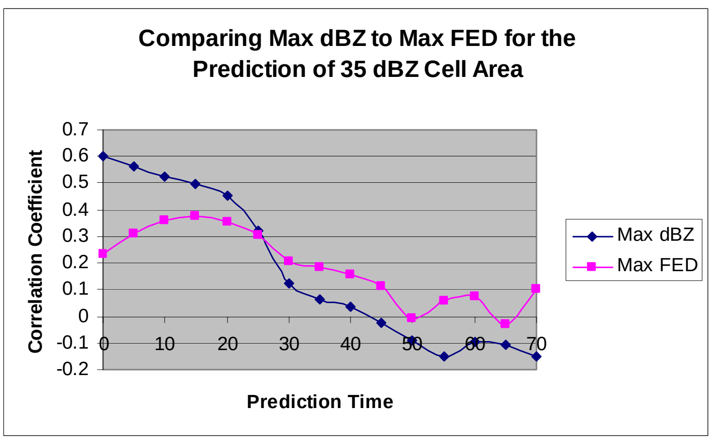

Figure 7. Same as Figure 5, except comparing TITAN maximum reflectivity (dBZ; blue) to the TITAN maximum FED (pink).

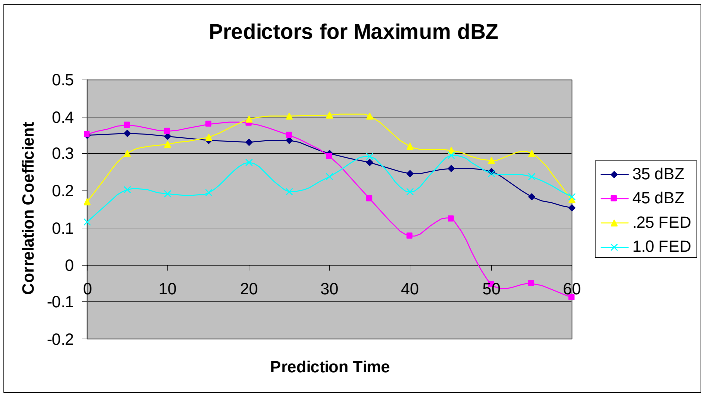

Figure 8. The lag correlations for 5-min intervals comparing the TITAN 35 dBZ cell NAGR (blue), TITAN 45 dBZ cell NAGR (pink), TITAN 0.25 FED cell NAGR (yellow) and TITAN 1.0 FED cell NAGR (cyan) as predictors for the maximum reflectivity (dBZ). The lag correlations are calculated for each of the 15 thunderstorms in the dataset and then averaged together at each 5-min interval.

Figure 8 illustrates the results of the lag correlation analysis between the four separate NAGRs and future thunderstorm intensity. The reflectivity cells perform the best with r ~ 0.35 for the first ten to twenty minutes. However, the FED cells perform the best at the 60-minute forecast time. The correlation coefficients (r ~ 0.15-0.20) of the FED cells at the 60-minute forecast time are similar to those seen with the forecast of thunderstorm cell area. In addition, the 35 dBZ and 0.25 FED cells outperform their 45 dBZ and 1.0 FED counterparts. This indicates that identifying larger thunderstorm cells, as a result of lower thresholds, is beneficial for both the reflectivity and total lightning data when conducting attribute analysis for nowcasting.

6. THUNDERSTORM OBSERVATIONS

6.1 *Splitting Cells*

The complementary use of radar and total lightning data can be applied to thunderstorm feature identification when used in the operational setting. On 25 April 2005, the northernmost supercell was tracking east-northeast across central Tarrant County into northwest Dallas County. At 203737 UTC, the composite reflectivity shows no evidence of a left split in the storm (Fig. 9). However, the FED data from 2036 UTC shows a new maximum developing in the northern area of the reflectivity core, indicative of a new updraft in the supercell (Fig. 10). Nearly 7 minutes after the identification of the two distinct FED cores, the composite reflectivity provides the first indication of the left split in the supercell at 204242 UTC (Fig. 11). The reflectivity cross-section in Fig. 12 supports the FED data showing two separate elevated convective cores at 10 km and 23 km. The higher temporal resolution and greater sensitivity of total lightning data to the microphysical processes within a thunderstorm prove advantageous in operational situations such as this.

6.2 *Cell Mergers*

Another area of interest to forecasters is the interaction of lightning between thunderstorm cells. A thunderstorm's anvil lightning activity is sensitive to the vertical wind shear and the advection of charge-carrying hydrometeors. The interaction of lightning strikes between cells often appears to be an antecedent for the merger of thunderstorms. On 25 April 2005 at 2128 UTC three distinct supercells were evident across the Dallas-Ft. Worth area (Fig. 13). The southernmost supercell in Johnson County had lightning activity extending through its anvil northeastward into the central supercell entering Dallas County. However, the supercell farthest north in northeastern Tarrant County has no lightning interaction with the others farther south. Figure 14 shows that at 2206 UTC the supercells that had lightning interactions earlier ended up with similar motions to the southeast, while the northern supercell drifted east and weakened to the point that lightning activity ceased. This example suggests that radar reflectivity and total lightning can be used in combination to identify deviant shear and motion vectors in areas void of quality vertical wind information.

7. RADAR AND LIGHTNING LIMITATIONS

It is important to note the limitations that exist when using radar reflectivity and total lightning information in a complementary fashion. The most obvious disadvantage that exists with radar data is the 5-7 minute frequency of the volume scans. The WSR-88D also suffers from “cone of silence” issues for thunderstorms close to the radar site. In addition, radar echo tops have poor height resolution at long ranges such that the echo tops become erratic as thunderstorms pass between different volume scan elevation levels. Since monitoring VHF radiation is continuous and omni-directional, these problems are absent with the LDAR II. Development is underway in the NWS Southern region offices with lightning mapping arrays to develop a “lightning top” product. The 90th percentile VHF source height in grid boxes will be used as an approximation for the thunderstorm echo top and provided as a graphical product. This will provide forecasters with another source of information when the WSR-88D echo top accuracy is in question.

LDAR II and total lightning detection in general have their limitations as well. As discussed in Section 5.1, total lightning is only of value when NIC mechanisms are present. Often times, warm rain processes are initially dominant in storm development across the southern United States. The latency of lightning initiation in thunderstorms makes LDAR II data of more use after storm development, such as in the forecast of cell dissipation. The effective range of LDAR II for identification of VHF sources is only 150 km before Earth curvature affects detection of sources in the lower troposphere. For cell identification and attribute analysis, the LDAR II is only reliable out to 100-120 km. This allows for total lightning coverage only in the immediate vicinity of the Dallas-Ft. Worth area and neglects other locations in the CWA, such as Waco, TX. The inherent flaws of the WSR-88D and LDAR II are minimized when used complementarily to highlight their individual advantages.

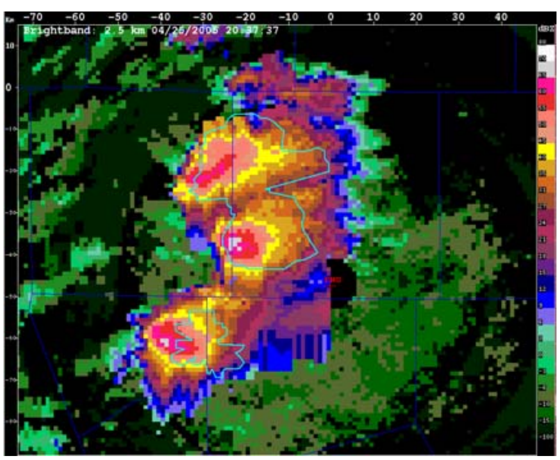

Figure 9. A 2.5 km CAPPI on 25 April 2005 at 203737 UTC in a format similar to Fig. 4. The supercell of interest is the reflectivity core farthest north, just entering Dallas Co. The boundaries of the 0.25 FED lightning cells are overlaid in cyan and the county boundaries are overlaid in blue.

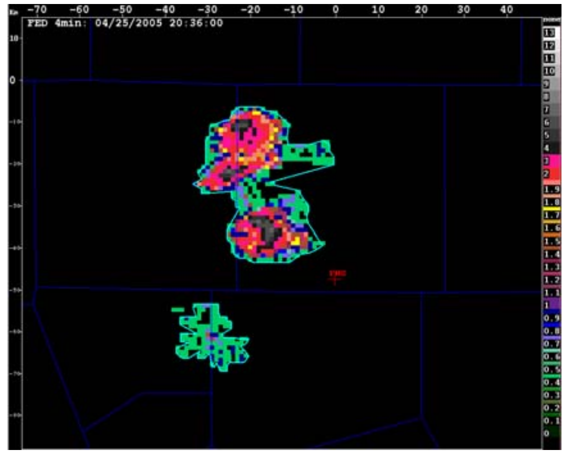

Figure 10. The FED on 25 April 2005 at 2036 UTC in a format similar to Fig. 3. Two distinct maxima (>5 flashes min^{-1} km^2) in the total lightning activity can be seen in the supercell of interest along the Tarrant and Dallas Co. line.

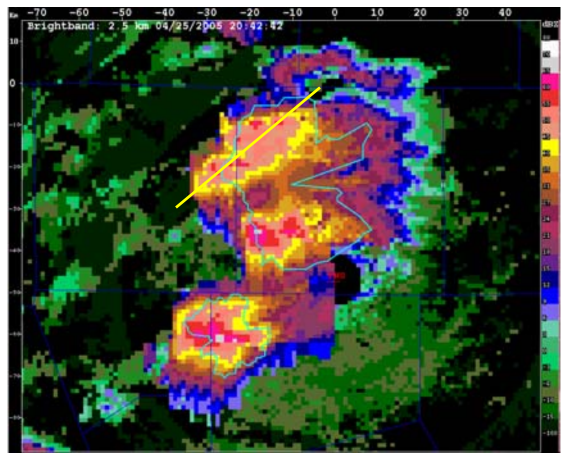

Figure 11. Same as Figure 9 except at 204242 UTC. This is the first evidence in the radar data of the left split in the supercell of interest visible in northwestern Dallas Co. The yellow line represents the cross-section taken in Fig. 12.

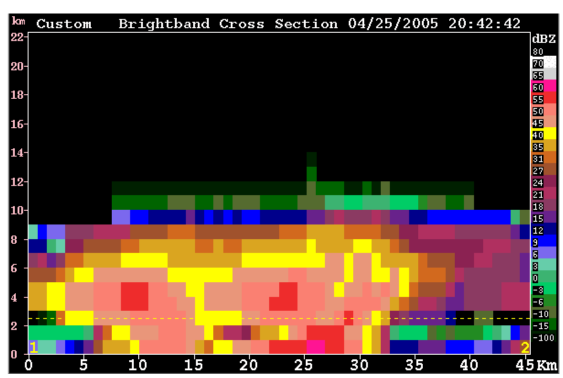

Figure 12. Reflectivity (dBZ) cross-section from southwest-to-northeast through the supercell of interest at 204242 UTC. Two distinct maxima are seen aloft (~4-5 km) as the supercell splits.

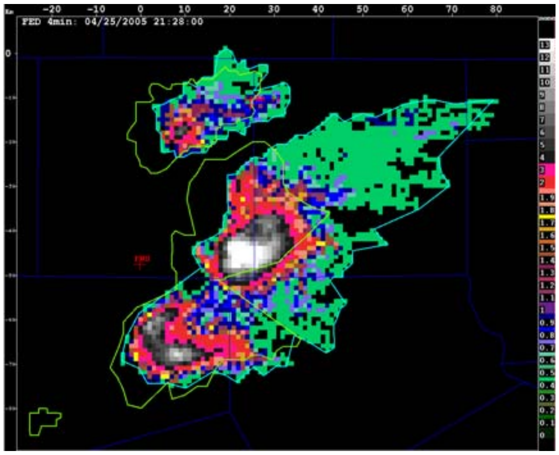

Figure 13. The FED on 25 April 2005 at 2136 UTC. The 35 dBZ cells and 0.25 FED cells are overlaid in yellow and cyan respectively.

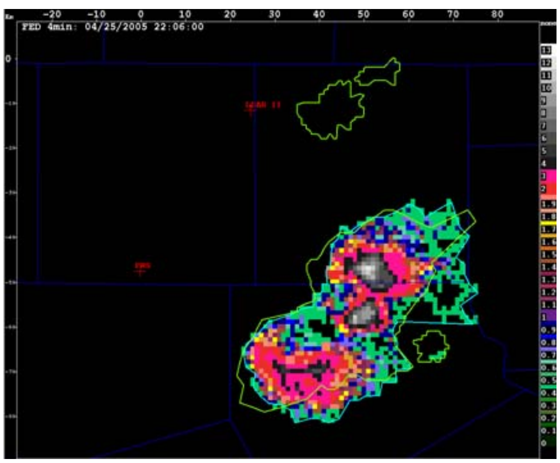

Figure 14. Same as Figure 13 except at 2206 UTC.

8. SUMMARY AND FUTURE WORK

The complementary use of WSR-88D radar reflectivity and total lightning data is becoming commonplace across the NWS Southern region, with seven time-of-arrival lightning mapping array systems now operational. Total lightning information is also in demand for automated nowcasting software packages, such as the NCAR ANC. TITAN-derived radar reflectivity attributes are more successful when forecasting in the 0-30 minute timeframe. Whereas, TITAN-derived total lightning attributes perform better during the 30-60 minute timeframe. An automated nowcasting system exhibits increased skill when integrating multiple datasets. For 60-minute forecasts, reflectivity attributes may not perform as well but they are available earlier in the cycle due to the delay of total lightning activity (at least for storms in the Dallas-Ft. Worth area). The TITAN-derived NAGR also shows skill at forecasting the future intensity of a storm, which may benefit the ANC area growth/decay forecasts.

The promising performance of the total lightning cell attributes confirms that they will complement radar reflectivity for use in the ANC. Membership functions are currently being created for incorporation into the fuzzy logic of the ANC growth/decay component. Skill score analysis will be conducted to analyze the improvements made to the growth and decay forecasts of the ANC. Further research must be done to evaluate the cell attribute performance of other total lightning representations, such as VHF source density and effective range source density. The total lightning data representation method that best complements radar reflectivity will likely become the standard for future integration into operational forecasting.

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