**1.7 THE IMPORTANCE OF TOTAL LIGHTNING IN THE FUTURE OF WEATHER NOWCASTING**

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## 1. INTRODUCTION

Regional lightning detection networks such as the Lightning Detection and Ranging (LDAR) system, the Lightning Mapping Array (LMA) (Rison et al., 1999) and the Surveillance et Alerte Foudre par Interferometrie Radiometrique (SAFIR) system represent the state-of-the-art in lightning detection. These networks detect over 95% of total (cloud and cloud-to-ground) lightning in two or three dimensions with location accuracies of less than 1 km. Major metropolitan areas and surrounding suburbs can easily be covered by one of these regional networks due to their effective range of over 150 km. As of the fall of 2003, LDAR and LMA networks already exist at the NASA Kennedy Space Center (KSC) in Florida; Dallas-Fort Worth (DFW), Texas; Huntsville, Alabama; Norman, Oklahoma; White Sands, New Mexico; Socorro, New Mexico and Tucson, Arizona. A SAFIR network has also been installed at DFW. As the number of total lightning research networks grows in the United States, it is increasingly important to show how this data can be used to help the meteorological and aviation industry.

DFW LDAR II total lightning data from 13 October 2001 will be used to demonstrate the advantages of having a regional total lightning detection network. DFW LDAR II data from other cases will be used to expand upon nowcasting applications shown by the 13 October 2001 case. These advantages include (1) a better representation of the cloud-to-ground (CG) lightning hazard region, (2) higher temporal resolution than radar for thunderstorm growth and decay observations, (3) potential increased lead time for severe weather warnings and (4) safer and more efficient airspace management due to the volumetric representation of lightning activity.

## 2. DATA

The DFW LDAR II network is made up of 7 sensors with 20 to 30 km baselines (Fig. 1). These sensors detect pulses of radiation produced by the electrical breakdown processes of lightning in 5 MHz VHF bands that currently have center frequencies ranging from 61 to 64 MHz. These pulses of radiation are used to reconstruct the path of individual cloud and CG lightning flashes in 3 dimensions. The DFW LDAR II network can map lightning flashes in 3 dimensions within approximately 150 km of the center of the network, degrading in performance with increasing range. Lightning flash detection efficiency is expected to be greater than 95% within the interior of the network (a range of 30 km from DFW International Airport – sensor A) and greater than 90% out to a range of 120 km from DFW International Airport. Expected 3-dimensional location accuracy for individual pulses of radiation is between 100 and 200 m within the network interior and better than 2 km to a range of 150 km from the center of the network.

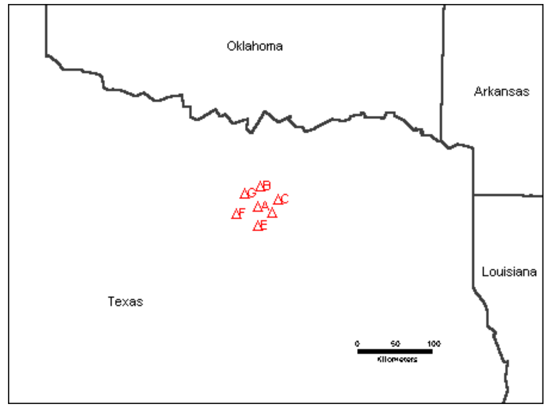


*Figure 1. DFW LDAR II sensor sites. Each site is represented by a triangle, with its site identifier to the upper right. State boundaries and names are also shown.*

The U.S. National Lightning Detection Network (NLDN) detects CG lightning with a flash detection efficiency of approximately 90% and a median location accuracy of 500 m (Cummins et al., 1998). The radar data used in this study consist of Fort Worth WSR-88D base reflectivity images.

## 3. CG LIGHTNING HAZARD

Assessing the CG lightning threat region is critical for many applications that include, but are not limited to: (1) grounds crew safety at airports, (2) outdoor events attended by large numbers of people, such as sporting events, (3) mission critical operations, including space shuttle launches, (4) operations involving explosives or highly flammable material and (5) golf courses. The majority of current CG lightning safety applications use a single point sensor that detects CG and cloud lightning within 50 nm of a point of interest or NLDN data, sometimes in combination with electric field mills (EFMs). The NLDN and single point sensor data are used to monitor thunderstorms that are producing CG lightning at distant to close ranges from a point of interest (i.e. an airport). In order to assess the immediate threat of CG lightning at a point of interest, EFMs may be used to monitor the build-up of the

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electric field on the ground produced by the clouds overhead.

Unfortunately these methods for assessing the CG lightning threat do not completely identify the risk within spatial scales on the order of the urban zone. One reason for this is that the CG lightning threat is not completely identified by the NLDN because the NLDN requires the occurrence of CG lightning in order to identify the high-risk area. It can not identify areas where the threat remains high and CG lightning is not occurring. A second reason is that EFMs have a very limited effective range of a couple of kilometers. For areas with spatial scales on the size of the urban zone, it becomes impractical to cover the region with large quantities of EFMs.

CG lightning produced within stratiform rain regions that are attached to active thunderstorms are an important cause of lightning related injuries and fatalities (Holle et al., 1993). These stratiform regions usually contain longer cloud lightning flashes that help produce isolated CG lightning discharges. A single, long cloud flash can produce isolated CG flashes that are sometimes separated by over 70 km (Fig. 2). Thus, total lightning networks can help address the problem of identifying the CG lightning hazard within urban zones because they map the horizontal extent of both cloud and CG flashes.

Figure 3 shows the spatial extent of lightning activity in the DFW area as represented by LDAR II and the NLDN. The LDAR II sources (red dots) show cloud lightning that is propagating tens of kilometers beyond the boundaries outlined by the NLDN flashes (black dots) between 0103 and 0108 UTC 13 October 2001. A comparison with Figure 4 shows that the NLDN flashes are mainly clustered within the main convective areas (>40 dBZ) and the LDAR II sources are propagating through attached stratiform rain regions. The combination of these two lightning datasets helps depict the high CG lightning risk areas represented by the regions covered by NLDN flashes and the lower, but still important CG lightning risk areas covered by LDAR II sources only.

Mesoscale convective systems (MCSs) often generate large areas of stratiform precipitation that are attached to and sometimes trail the main convective line of thunderstorms. These large thunderstorm complexes are known as leading line, trailing stratiform MCSs (Houze et al., 1989). Such a MCS passed through the DFW LDAR II network on 15 June 2001.

Figure 5 gives a dramatic example of the CG lightning risk within the trailing stratiform region of the 15 June MCS. A comparison with Figure 6 shows that the NLDN flashes are mainly clustered along the leading convective line that is >50 km southeast of the center of the DFW LDAR II network (sensor A). However, the LDAR II sources indicate that cloud lightning is propagating over 100 km to the northwest of the leading convective line, through the trailing stratiform region. The apparently random pattern of isolated CG flashes (sometimes located over 100 km from the leading convective line) produced by these trailing stratiform

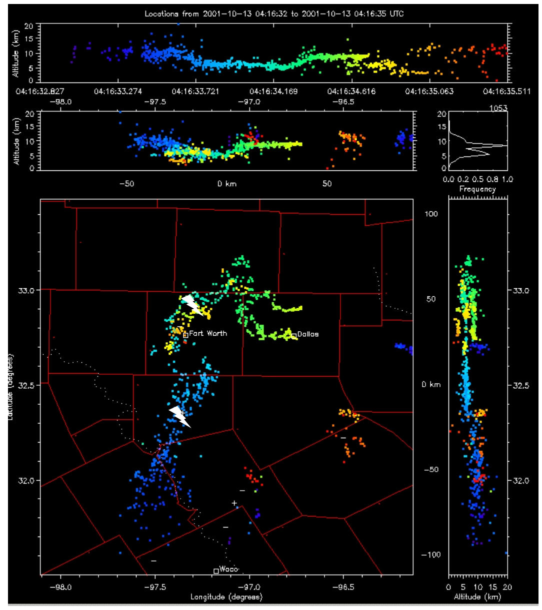


*Figure 2. A spider lightning flash detected by the DFW LDAR II network on 13 October 2001 between 0416:33-36 UTC. The top panel is an altitude (y) versus time (x) plot. The lower left is a plan view showing latitude (y) versus longitude (x). The lower right is a latitude (y) versus altitude (x) cross-section. The panel just above the plan view is an altitude (y) versus longitude (x) cross-section and the panel just to its right is an altitude (y) versus source frequency (x) plot. LDAR II sources are shown by dots and NLDN CG lightning stroke locations are indicated by the white lightning symbols.*

cloud flashes demonstrates the unpredictable nature of CG lightning in stratiform regions. Figure 5 shows that the whole DFW area is covered by trailing stratiform cloud lightning and therefore is at risk for isolated CG lightning discharges.

LDAR II and radar reflectivity observations from

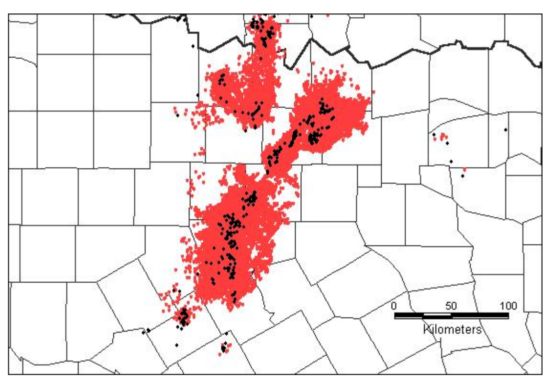


*Figure 3. DFW LDAR II lightning sources (red) and NLDN CG lightning flashes (black) detected between 0103 and 0108 UTC 13 October 2001.*

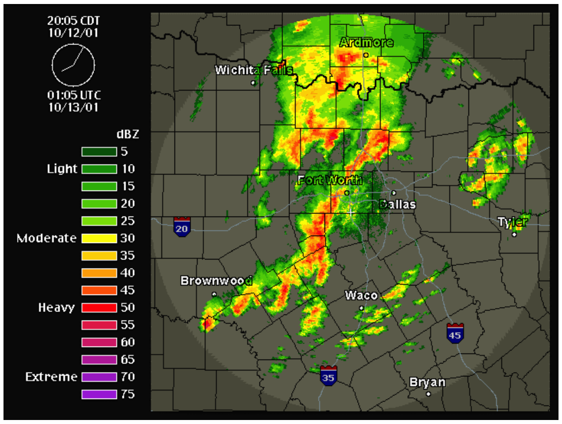


*Figure 4. Fort Worth WSR-88D base reflectivity image from 0105 UTC 13 October 2001. The color key for reflectivity values is located on the left. (Image saved from The Weather Underground, 2001, www.wunderground.com).*

four MCSs that passed through the DFW area have shown that trailing stratiform regions do not necessarily have cloud lightning propagating throughout their entire area of coverage (not shown). Therefore radar data alone can not define the isolated CG lightning threat through identification of the boundaries of the trailing stratiform region. It is critical to be able to map the horizontal extent of cloud lightning through the trailing stratiform region in order to properly define the isolated CG lightning threat.

Observations from the New Mexico Tech (NMT) LMA have helped define another important application involving the mapping of total lightning flashes. Rison et al. (2003) discuss numerous observations of the mapping of "bolts from the blue" within NMT LMA data. These flashes can sometimes extend tens of kilometers beyond the cloud boundary of thunderstorms and always go to ground. Rison et al. (2003) found that

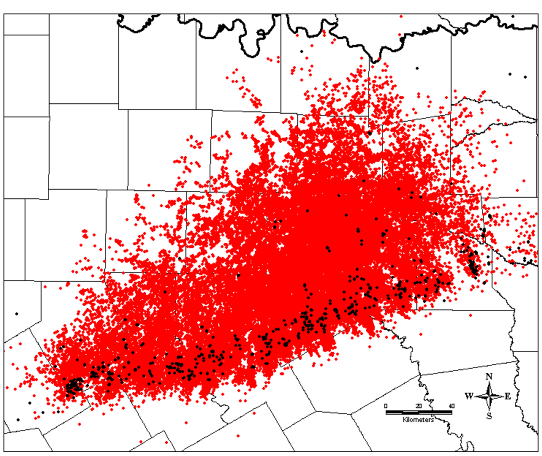

*Figure 5. Same as Figure 3, except for lightning detected between 0312:30 and 0317:30 UTC 15 June 2001.*

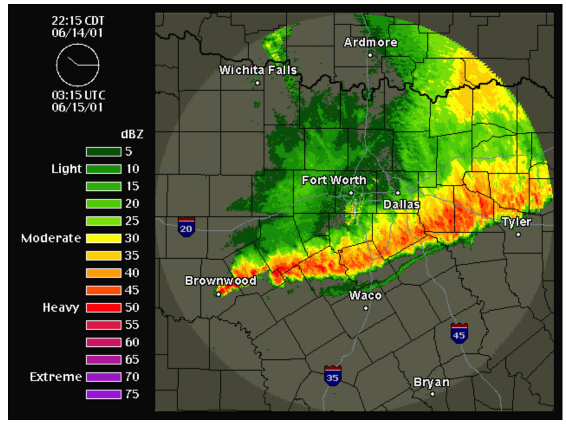


*Figure 6. Same as Figure 4, except for 0315 UTC 15 June 2001.*

these flashes are quite common within storms observed with the NMT LMA and can represent the majority of CG flashes produced throughout the lifetime of a storm. A storm observed by the NMT LMA on 2 August 1999 produced 24 CG flashes throughout its lifetime, 18 of which were considered "bolts from the blue." These observations imply that using radar reflectivity data in combination with the mapping of total lightning flashes will identify storms that are producing dangerous flashes at some distance from the radar echo.

## 4. THUNDERSTORM GROWTH, DECAY AND ORGANIZATION

A major benefit provided by regional total lightning networks is that they produce a continuous data stream in real time. Lightning data are updated on time scales shorter than the typical WSR-88D volume scan of 5 to 6 minutes. These shorter time scales can help in the early identification of thunderstorm growth and decay trends.

Since cloud lightning flash rates depend upon the amount of charge separation in the cloud and therefore updraft strength, they are useful indicators of thunderstorm growth and decay. Figure 7 shows the 2-minute cloud lightning flash rates from an isolated thunderstorm that developed in the DFW area. Thunderstorm growth is clearly shown by the rapid jump in 2-minute cloud flash rates from 12 to 81 between 0045 and 0049 UTC. The rates stay between 70 and 80 cloud flashes per 2-minute interval until 0059 UTC. After 0059 thunderstorm decay is clearly visible within the cloud rates as they dropped from 74 to 18 between 0059 and 0105 UTC.

Altitude information provided by three-dimensional total lightning networks can also be a useful indicator of thunderstorm growth and decay. On 25 May 2002 the complete lifecycle of a thunderstorm was detected by the DFW LDAR II network (Fig. 8). The time versus altitude plot shows the growth and decay of this thunderstorm. The maximum altitude of the main body of lightning flashes (ignoring isolated sources at

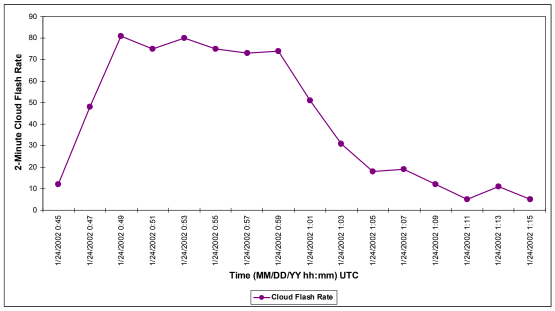


*Figure 7. Cloud flash rate of an isolated thunderstorm detected by the DFW LDAR II network between 0045 and 0117 UTC 24 January 2002. Time is on the x-axis and 2-minute cloud flash rates are on the y-axis.*

extremely high altitudes) within this storm increases from 12 to 15-16 km between ~0409 and ~0418 UTC. This increase in altitude corresponds to the thunderstorm's growth phase. The maximum altitude remains between 15 and 16 km during the storm's maturity phase. Then the maximum altitude decreases from 15-16 to 12 km between ~0537 and ~0600 UTC. This decrease in altitude corresponds to the thunderstorm's decay phase.

Observations from the DFW LDAR II network have shown that the length of cloud lightning flashes is a useful indicator of thunderstorm maturity and organization. In a moderate-to-high shear environment, thunderstorms produce anvils that can extend over 50 km downwind of the convective region during their mature phase. In a process that is similar to long cloud flash propagation in MCSs (see Section 3), cloud flashes initiate within the main body of the convective cell and propagate long distances through the storm's attached anvil. Thus, high total and extensive flash rates can occur if a number of large supercells are mature and within range of a regional total lightning network.

As discussed in Section 3, when thunderstorms merge together and start to develop a shared, attached stratiform rain region, longer cloud flash lengths develop. These longer flashes usually propagate from the main convective areas through stratiform precipitation areas. Therefore, the development of longer cloud flashes is also a useful indicator of MCS development.

Figure 9 shows a time series of total lightning rates and the rates of flashes over 25 km in length (extensive) from 0000 to 0200 UTC 13 October 2001. Thunderstorms on this day developed in a highly sheared environment. Between 0000 and 0045 UTC most of the thunderstorms within range of the DFW LDAR II network were supercells. As the total number of thunderstorm cells increased, the 2-minute total lightning flash rate rose from 213 to 719 between 0000 and 0045 UTC. Despite the lack of MCS organization at this time, 2-minute extensive flash rates still reached values up to 9. The frequency of these longer flashes

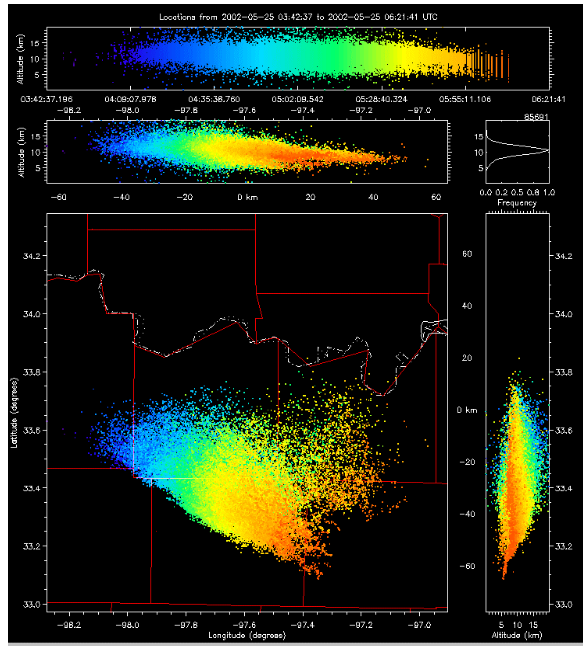


*Figure 8. Same as Figure 2, except for an isolated thunderstorm detected by the DFW LDAR II network between 0345 and 0615 UTC 25 May 2002.*

indicate that substantial anvils have developed and are attached to mature supercells.

Between 0045 and 0115 UTC the isolated supercells began merging together to form a leading line, trailing stratiform MCS. This can be seen by a continued increase in total lightning flash rates and a pronounced jump in the extensive flash rate (Fig. 9). Extensive flash rates had two pronounced peaks during this time period of 18 and 22 at 0058 and 0110 UTC, respectively. This transition period from isolated cells to

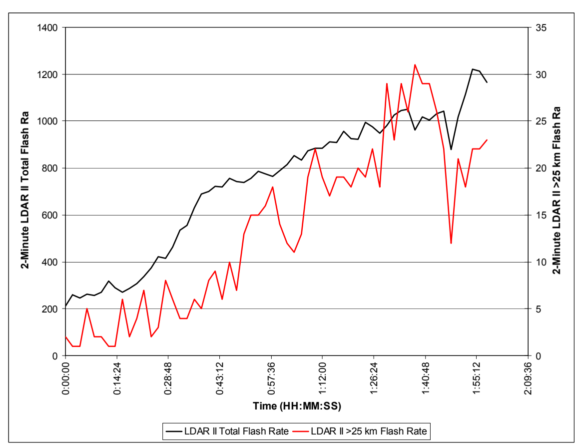


*Figure 9. Time series of 2-minute flash rates for all flashes (black) and flashes over 25 km in length (red) from 0000 to 0200 UTC 13 October 2001. Time is on the x-axis, all lightning flash rates are on the left y-axis and lightning flash rates for flashes over 25 km are on the right y-axis.*

an MCS would be more pronounced in an environment with weaker shear. In a more weakly sheared environment than the 13 October case, the extensive flash rate would be extremely low during the isolated cell phase and then jump to relatively high values during the MCS phase. This phenomena has been observed with the Tucson LDAR II network (not shown).

As the MCS continues to develop, the total lightning flash rate begins to level off at an extremely high value of ~1000 between 0130 and 0145 UTC (Fig. 9). During this time period the extensive flash rate makes another substantial jump and stays generally between 25 and 30. These 2-minute extensive flash rates correspond to a cloud flash of at least 25 km in length occurring every 4 seconds! The high total and extensive lightning flash rates that occur after 0115 UTC help indicate that an intense MCS is developing with a large, attached stratiform rain region. This would be important nowcasting information for the urban zone.

## 5. SEVERE WEATHER SIGNATURES

A number of total lightning signatures observed by LDAR and LMA have been linked to severe weather. These signatures do not occur every time there is severe weather, but when they are found, severe weather is usually present.

Lightning-free regions (lightning holes) have been identified within LMA and LDAR lightning source data since 1998 (Krehbiel et al., 2000). These features are found within the convective core of thunderstorm cells and are surrounded by a large number of lightning flashes on all sides. To date, lightning holes have been observed by the NMT LMA during field programs in the central United States, the Huntsville, AL LMA (Goodman 2003, personal communication) and the DFW LDAR II network. Figure 10 shows an example of lightning holes observed by the DFW LDAR II network within multiple supercells on 6 April 2003. The westernmost supercell shows a distinct lightning hole on the western side of the convective core lightning activity (bright pink areas). The supercell in the center shows a distinct lightning hole on the southern side of the convective core lightning activity. These holes are likely created by extremely strong updrafts that eject the charged particles outside of the updraft core. This is similar to the bounded weak echo region (BWER) concept, where extremely strong updrafts eject all of the precipitation particles outside of the updraft core. Large hail and tornadoes are usually present when lightning holes appear. The supercells in Figure 10 were producing hail larger than baseballs during the time period shown. Lightning holes are usually 5 to 10 km in diameter and may last for several to tens of minutes. They are easier to identify during time intervals that are less than 5 minutes. Time intervals of 5 minutes or greater cause the original hole to be covered over by subsequent lightning due to storm motion. Continuous cycles of lightning hole growth, decay and replacement were observed within the 6 April supercells for over 30 minutes.

Lightning source density notches (lightning notch)

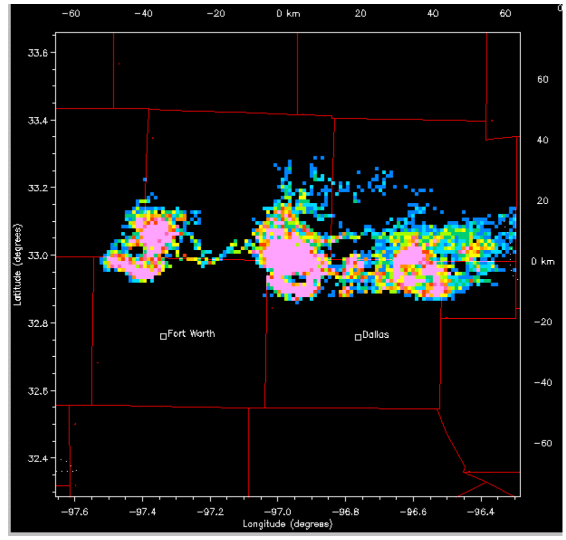


*Figure 10. DFW LDAR II source density plot from 0304 to 0307 UTC 6 April 2003. Bright pink colors represent ≥ 20 sources per ~1 km$^2$ grid box.*

have been observed within DFW LDAR II, KSC LDAR and Huntsville, AL LMA data (Goodman 2003, personal communication). These features tend to show up in supercells and some other severe thunderstorms. Figure 11 shows an example of a lightning notch within a supercell observed by the DFW LDAR II network on 11 October 2001. The lightning notch appears as a lightning free region on the southwest side of the convective core lightning activity. These features tend to show up on the upwind side of strong upper-level winds within strongly sheared environments. The exact cause of these lightning notches is unknown. Two possible explanations have been that the notch is caused by (1) a strong rear inflow jet or (2) a strongly sheared lightning hole. In either case this feature signals severe weather. A strong rear inflow jet would cause strong to severe straight-line winds at the surface and a highly sheared lightning hole would be associated with extremely strong updrafts and the severe weather that accompanies them.

Total lightning networks also sometimes show features that can also be found using radar data. Total lightning networks have an advantage when identifying these features because of their continuous data stream giving increased lead time compared to radar volume scans taking 5 to 6 minutes to update.

Bow echoes are an example of a severe weather signature that can be identified using both radar and total lightning data. Figures 12-14 show a sequence of DFW LDAR II source density images that highlight LDAR and LMA's ability to identify bow echoes. Each of these images was created using only 2 minutes of data. With this update cycle, the evolution of the storm can be monitored 5 times per 10-minute interval using total lightning data versus 2 times per 10-minute interval using WSR-88D reflectivity data. The total lightning

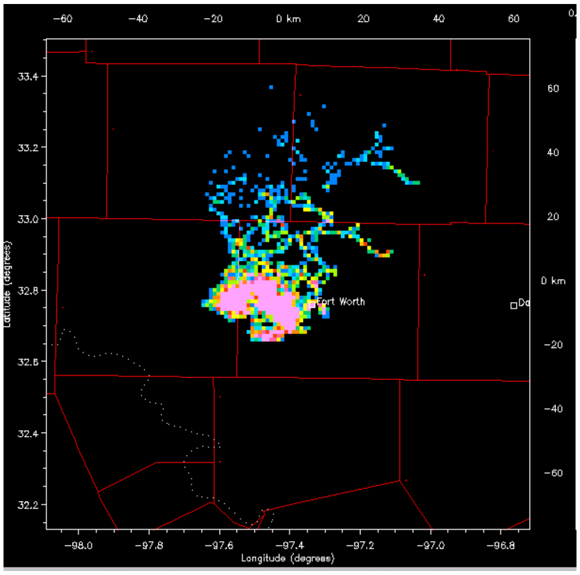


*Figure 11. Same as Figure 10, except for 0030 to 0032 UTC 11 October 2001.*

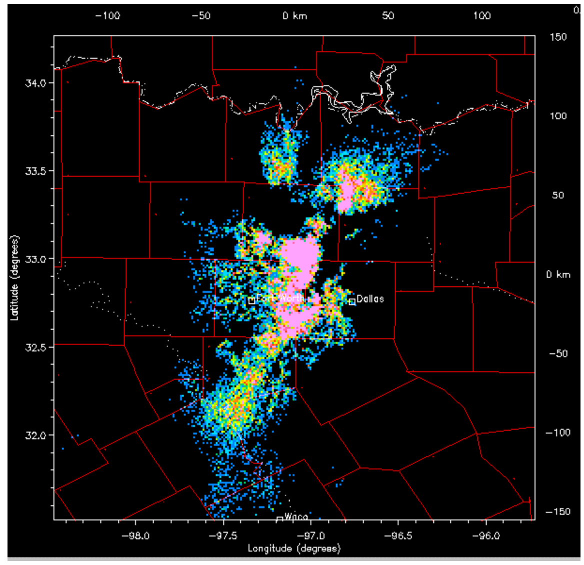


*Figure 12. Same as Figure 10, except for 0150 to 0152 UTC 13 October 2001. Bright pink colors represent ≥ 10 sources per ~1 km$^2$ grid box.*

density image from 0150 to 0152 UTC 13 October shows a developing line of thunderstorms oriented north-northeast to south-southwest between Dallas and Fort Worth (near center of image) (Fig. 12). By 0206 UTC, the line of storms appears to be splitting just south of the DFW area (Fig. 13). The main line of storms approaching Dallas on the southern end and north of the DFW area on the northern end (solid bright pink line) has already started to develop into a bow echo. Strong rear inflow from the west-southwest was helping to create this feature. By 0232 UTC, the bow echo is very pronounced just north-northeast of Dallas (Fig. 14). The line of thunderstorms (bright pink sources) has wrapped around the strong west-southwest rear inflow such that the northern portion of the bow echo is oriented in a southwest to northeast manner.

## 6. AIR TRAFFIC MANAGEMENT

Regional volumetric total lightning data within the urban zone and/or near major international airports can potentially be a great aid in safer and more efficient air traffic management. In general, aircraft are routed around the convective cores (>40 dBZ) of thunderstorm cells. This is due to the turbulence created by updrafts strong enough to produce radar reflectivities over 40 dBZ. WSR-88D and Terminal Doppler Weather Radar (TDWR) usually help define the major updraft areas around international airports through indirect measurements of vertical velocity provided by high reflectivities and convergence zones. The high-density cores of lightning activity could help further define these areas because of the updraft speeds necessary to produce large enough charge generation and separation for lightning initiation. However, the altitude of lightning activity away from the main convective cores may be just as important.

Observations from the DFW LDAR II network have shown that cloud lightning has preferred paths of propagation through anvils and stratiform rain regions that are attached to active thunderstorm cells. These preferred lightning paths often slope downward in altitude with increasing distance from the main convective cores. The bow echo detected by the DFW LDAR II network on 13 October 2001 shows these preferred lightning pathways. In Figure 15 total lightning

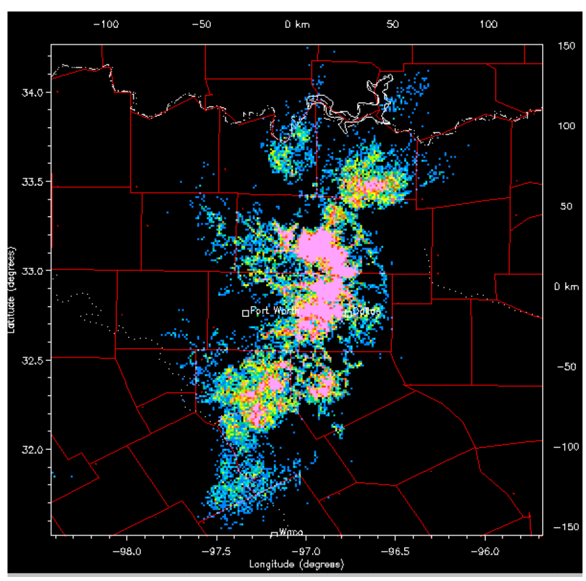


*Figure 13. Same as Figure 12, except for 0206 to 0208 UTC 13 October 2001.*

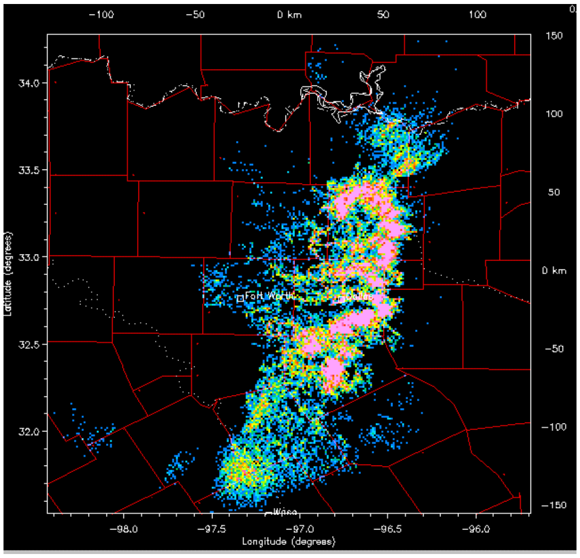


*Figure 14. Same as Figure 12, except for 0232 to 0234 UTC 13 October 2001.*

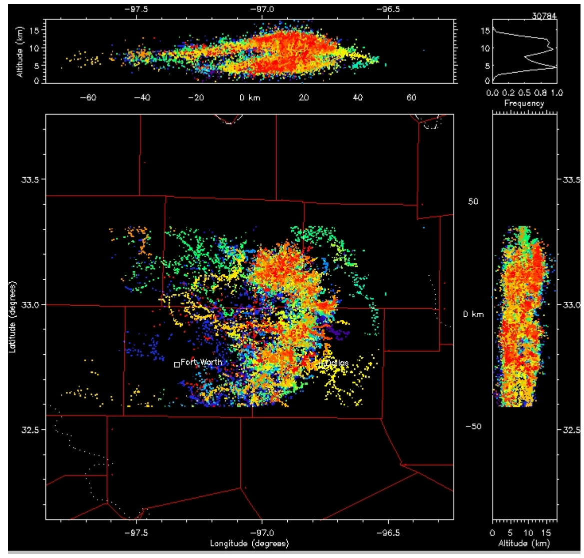


*Figure 15. Same as Figure 2, except without the upper panel and for 0205 to 0207 UTC 13 October 2001.*

sources were trimmed to only show those associated with the bow echo between 0205 and 0207 UTC. In the plan view, the higher source densities outline the convective area of the bow echo approaching Dallas (Fig. 16). The longitude versus altitude panel (top) shows that lightning within the convective region of the bow echo was distributed between altitudes of 2 and 15 km, but the peak altitude decreased significantly toward the west in the trailing stratiform region (see Fig. 16). Cloud lightning initiating in the main convective line is propagating through this trailing stratiform region for distances up to 60 km. Figure 15 also shows that cloud lightning is propagating eastward from the convective line through a leading anvil (not shown in Figure 16). The anvil lightning extends as far as 25 km east of the convective line and descends in altitude from ~12 to ~7 km.

Total lightning altitude information could be used by air traffic managers to avoid routing aircraft through regions of preferred lightning propagation. Figures 17-19 demonstrate the potential usefulness of such information for increasing safety and making more efficient use of airspace. Figure 17 shows the Fort Worth WSR-88D base reflectivity image from 2152 UTC 27 May 2002. Two clusters of convective cells are located south of Fort Worth, one to the southeast and one to the southwest. Both of these convective cells were attached to a large stratiform rain region covering the DFW area that extended as far north as the Oklahoma border.

Total lightning altitude information must be represented in ways such that air traffic controllers can easily interpret the data. Figure 18 shows how the total lightning altitude data could be used for en-route aircraft flying at cruising altitude. All total lightning sources are plotted as light blue dots and those lightning sources at or above 10 km (near cruising altitude for commercial aircraft) are plotted in red. Lightning sources produced within the convective cores south of Fort Worth extend over 10 km in altitude. However, those lightning sources associated with cloud flashes that are propagating northward, through the attached stratiform region, are descending to altitudes below 10 km. This information would show the air traffic controller that aircraft at cruising altitude could safely avoid lightning activity in large portions of the stratiform region where total lightning was not occurring or was occurring at altitudes below 10 km.

Total lightning altitude information for this case could be represented in a different manner for air traffic controllers responsible for departing or approaching aircraft. The Center Weather Service Unit (CWSU) at DFW is a joint National Weather Service (NWS) and Federal Aviation Administration (FAA) facility that is

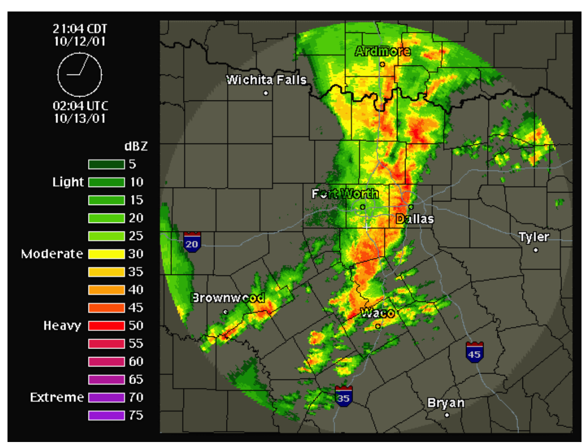


*Figure 16. Same as Figure 4, except for 0204 UTC 13 October 2001.*

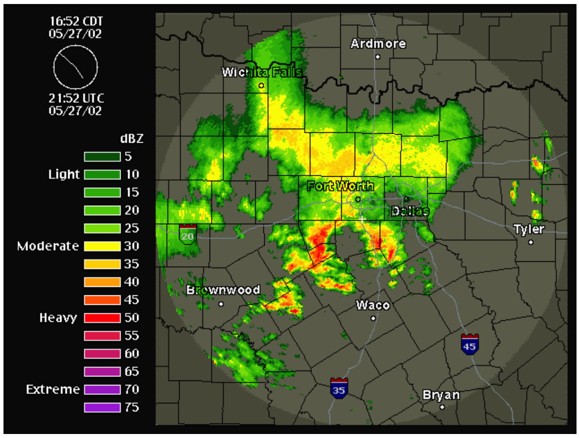


*Figure 17. Same as Figure 4, except for 2152 UTC 27 May 2002.*

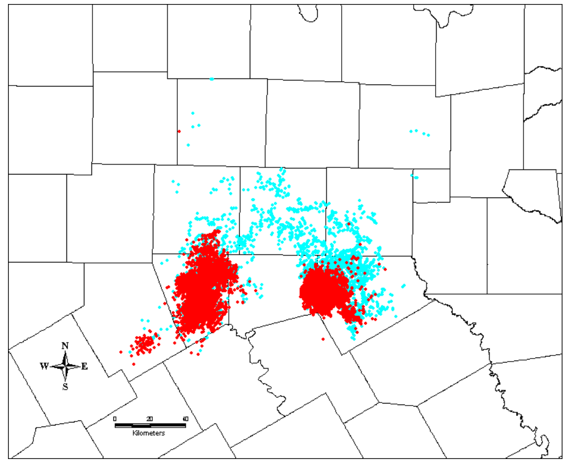


*Figure 18. DFW LDAR II lightning sources detected between 2150 and 2155 UTC 27 May 2002. Light blue dots represent all total lightning sources and red dots represent only those sources at or above 10 km altitude.*

responsible for approaching or departing aircraft at altitudes between 2.44 and 6.0 km altitude. Figure 19 shows the same total lightning source data with an emphasis on the altitude layer between 2.44 and 6.0 km. In this case the light blue dots still represent all total lightning sources, but the red dots represent only those lightning sources located between 2.44 and 6.0 km in altitude. It becomes readily apparent that cloud lightning that was propagating north, through the stratiform region, is sloping downward. The stratiform lightning region that did not contain lightning at cruising altitudes did contain lightning between 2.44 and 6.0 km. Therefore, the CWSU at DFW would potentially avoid sending aircraft into this region for lightning safety and other possible associated hazardous weather.

## 7. Conclusions

Regional total lightning detection networks such as the LDAR, LMA and SAFIR systems represent the state-of-the-art in lightning detection. These networks detect over 95% of all cloud and CG lightning in two or three dimensions with location accuracies of less than 1 km. Major metropolitan areas and surrounding suburbs can easily be covered by one of these regional networks due to their effective range of over 150 km from the center of the network. As of the fall of 2003, seven LDAR or LMA networks and one SAFIR network already exist in the United States. As the number of total lightning research networks continues to grow in the United States and abroad, it is increasingly important to develop useful applications for the meteorological and aviation community.

Regional total lightning networks provide rich two- or three-dimensional datasets in a continuous data stream. The ability to map out the true extent of both cloud and CG lightning within stratiform rain regions, anvils and clear air allows a complete representation of the lightning risk area. This will improve both ground and air safety. The ability to monitor thunderstorm characteristics on time scales shorter than WSR-88D scans may have important implications for increasing lead time of important weather phenomena. These phenomena include (1) first classification of a radar cell as a thunderstorm, (2) nowcasting thunderstorm growth and decay and (3) nowcasting severe weather such as tornadoes, large hail and strong straight-line winds.

This paper has summarized some of the potential total lightning applications that exist. The implementation and evolution of such applications could have a substantial impact on nowcasting in the urban zone and its surrounding areas. The NWS, FAA and total lightning communities should continue to work together to take advantage of the benefits such regional networks can provide.

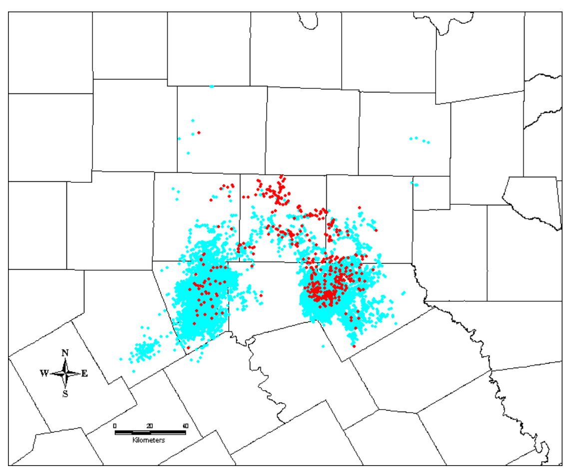


*Figure 19. Same as Figure 18, except red dots represent DFW LDAR II lightning sources located between 2.44 and 6.0 km altitude.*

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