Submitted to EOS, May 1999
Revised September 1999

Lightning Mapping Observations in Central Oklahoma

Paul R. Krehbiel, Ronald J. Thomas, William Rison, Timothy Hamlin, Jeremiah Harlin, and Michael Davis

Langmuir Laboratory for Atmospheric Research, Geophysical Research Center, New Mexico Institute of Mining and Technology, Socorro, New Mexico

Great Plains storms are well known for their ability to produce severe weather. They are also prodigious producers of lightning. Just how prodigious has been vividly illustrated by recent observations in central Oklahoma with a new GPS-based lightning mapping system. The observations are useful not only for studying storm electrification but also provide a valuable indicator of storm structure and intensity.

Lightning can be mapped in three spatial dimensions by measuring the arrival times of impulsive VHF radiation events as a lightning discharge progresses through a storm. The availability of accurate, low-cost GPS receivers has made it relatively easy to obtain measurements of sufficient timing accuracy to produce high quality pictures of the total lightning activity over a large geographical area. Figure 1a shows an example of such observations from a line of thunderstorms that moved over central Oklahoma on the night of June 10-11, 1998. Ten mapping stations were deployed over a county-wide area northwest of Oklahoma City and detected lightning from the storm system as far south as the Oklahoma-Texas border. The figure shows one minute of activity in the storm; major lightning discharges occurred about once per second at different locations along the 200-300 km extent of the storm, out to the maximum range of the mapping system.

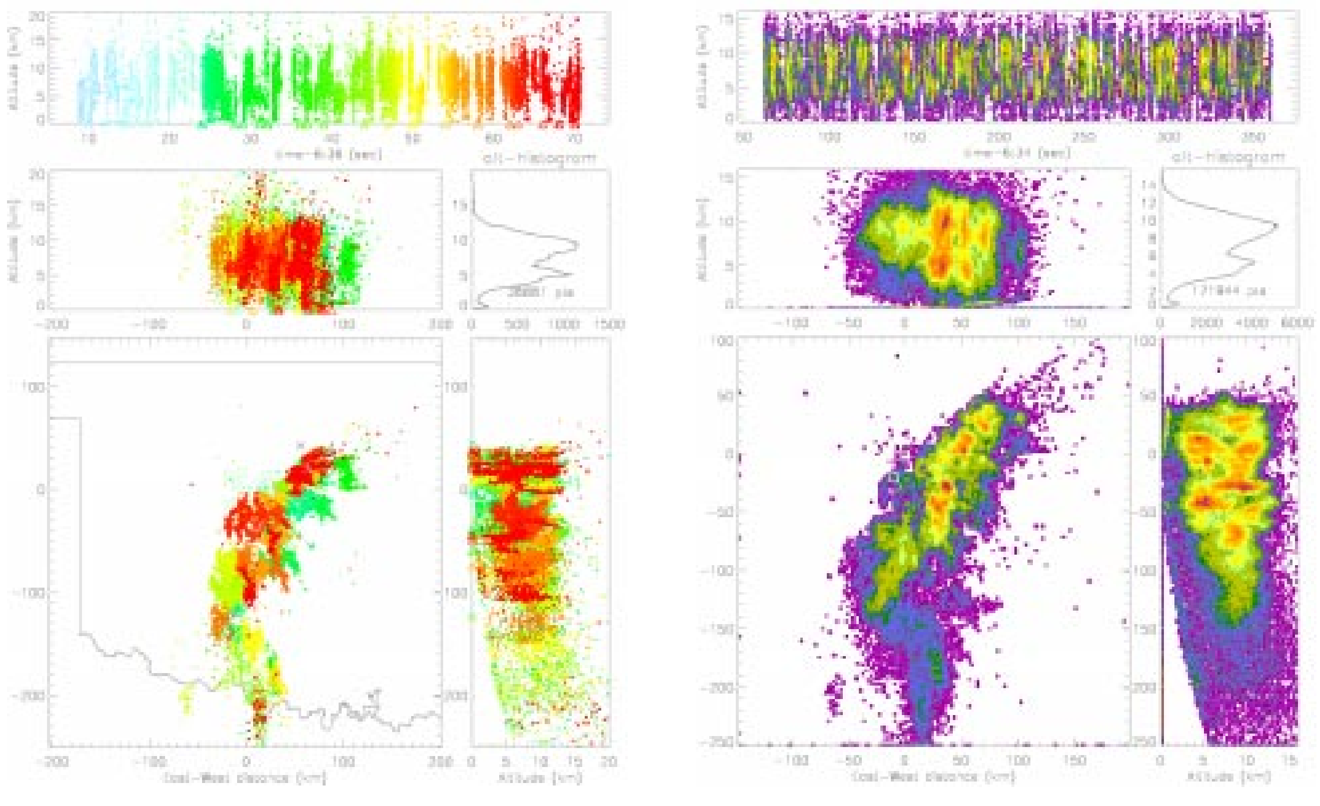

Figure 1. Maps of the total lightning activity in a line of thunderstorms over central Oklahoma on the evening of June 10-11, 1998. a) One minute of observations showing individual radiation events from lightning discharges in the storm (left); b) five minutes of observations showing the density of radiation events (right). The observations were from a county-wide network of ten measurement stations (□) located northwest of Oklahoma City, which detected lightning in the storm as far south as the Oklahoma-Texas border. The different panels show plan views, east-west and north-south vertical projections, and height-time plots of the lightning activity. Groups of sources below 7 to 8 km altitude (msl) were cloud-to-ground discharges; those above about 6 km altitude were intracloud discharges. The density plots show the location of the main convective cells of the storm.

Figure 1b shows a slightly expanded view of five minutes of observations from the storm. Instead of overlaying individual radiation sources on top of one another, as in Figure 1a, the figure now shows the density of the radiation sources. The lightning activity was most concentrated in several locations that corresponded to the main convective cells of the storm. Animations of the observations show the motion of both the individual cells and of the storm as a whole.

System Operation

The lightning mapping system has been developed at New Mexico Tech under an Academic Research Infrastructure grant from the National Science Foundation, and is patterned after the Lightning Detection and Ranging (LDAR) system developed at the NASA Kennedy Space Center [Maier et al., 1995]. The system operates by detecting radiation from lightning discharges in an unused VHF television channel, in this case Channel 3 (60-66 MHz). Rather than telemeter high-bandwidth data to a central site to measure the time-of-arrival values, as in the LDAR system, the new system takes advantage of GPS technology to measure the arrival times independently at each remote location. In particular, the arrival times are determined with 50 ns time resolution by phase-locking a 20 MHz digitizer to the 1 pulse per second output of a GPS receiver at each station [Rison et al., 1999]. The time of the peak radiation event is recorded in every 100 microsecond window that the signal exceeds a noise threshold.

The data in this article are from the initial operation of the system in Oklahoma during June, 1998. The results were obtained by post-processing data recorded locally at each measurement site. The observations were analyzed using an automated procedure which identifies sets of arrival times that potentially correspond to each other and processes the arrival times to determine the source location and goodness of fit value. The statistics of the measurement errors indicate overall timing uncertainties of 40-50 ns rms, corresponding to 50 to 100 m best-case location errors over the network. The location uncertainties increase with distance from the array, becoming radial at large distances, where the locations are primarily two-dimensional. The signal propagation is line-of-sight, so that distant sources below the local horizon are not detected by the network. This causes the minimum source altitude to increase with range, as seen in Figure 1.

The time-of-arrival technique constitutes a highly accurate space-time filter that enables correlated events to be extracted from the complex data stream and uncorrelated events to be rejected. The result is that one is able to sort out simultaneous activity both from a given lightning discharge and from multiple discharges in different locations. This ability is crucial in large storm systems, where the lightning activity is widespread and often nearly continuous. It was not unusual in Oklahoma for the system to be triggered during 90% of the 100-microsecond data windows during active storms (9000 times per second). 500 to 1000 events per second were typically located during such activity.

A Horizontally Extensive Discharge

Figure 2 shows observations of a horizontally extensive lightning discharge from the storm of Figure 1. The discharge occurred over the southern edge of the measurement network and had an overall extent of 75 km in the east-west direction. It discharged three charge levels in the storm; from other studies, the middle level (5-6 km msl) corresponded to the main negative charge region of the storm, and the upper level to the upper positive charge [e.g., Shao and Krehbiel, 1996]. The lightning began as an intracloud discharge between the main negative and upper positive charges. During the first part of the discharge the upper level channel propagated more than 50 km to the west and decreased in altitude (blue to green sources), indicating that the upper positive charge region similarly decreased in altitude. Subsequent breakdown in the main negative charge region continued the discharge to the north (red sources), where it produced a negative-polarity stroke to ground. The time and location of the ground stroke is indicated by data from the National Lightning Detection Network (NLDN) [Cummins et al., 1998] and is denoted by the small triangle near $x = +15$ km, $y = -10$ km. In the process of going to ground the breakdown appeared to discharge a region of lower positive charge, indicated by a third level of (red) radiation sources between 3 and 4 km altitude. A considerably simpler cloud-to-ground discharge occurred in a separate part of the storm to the south, for which the NLDN located two strokes to ground.

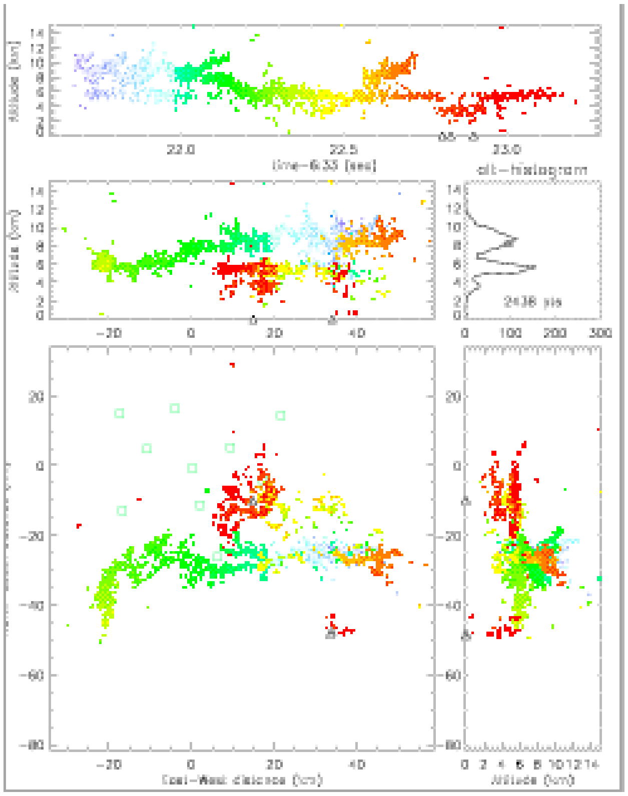

Figure 2. Observations of a horizontally extensive (75 km) intracloud and cloud-to-ground flash from the storm of Figure 1. The network of measurement stations is denoted by the small squares (□) and the location of cloud-to-ground strokes by the small triangles (△). More than 2400 radiation events were located at three levels in the storm during the 1.5 second discharge.

Supercell Lightning

Figure 3 shows one minute of lightning in a large 'supercell' storm, one of several that occurred over central Oklahoma on the afternoon of June 8, 1998. The storm was a single entity about 60 km in diameter that produced large hail and torrential rain, but no tornadic activity. In contrast with the observations of Figure 1, where the lightning consisted of temporally isolated events having a relatively well-defined structure, lightning in the supercell was essentially continuous and had an amorphous structure. The cumulative effect of the lightning was to fill a saucer-shaped volume over the 60 km diameter of the storm, up to a height of about 12 km msl. A relatively small number of cloud-to-ground discharges of both negative ($\triangle$) and positive ($\times$) polarity occurred beneath the lowest part of the storm.

A significant feature of the supercell lightning activity was the presence of lightning-free regions or 'holes' in plan views of the storm. The hole seen in Figure 3 was about 5 km in diameter and was almost certainly associated with a very strong (60-100 mph) updraft in the storm. Several holes were observed to occur at different locations and different times in the storm, indicating a time-varying updraft structure. The hole locations changed on a time scale of a few minutes. Evidence that the holes were associated with updrafts is seen in another feature of the observations, namely the occurrence of lightning radiation at high altitude (15-16 km) immediately above the hole in Figure 3. High altitude lightning was seen in a number of convectively vigorous storms from the Oklahoma study, often more intense and localized than in the Figure 3 data. The discharges occur independently of other lightning in the storm and are observed to rise up above the level of the other lightning over a time interval of a few minutes, to an altitude between 15 and 20 km msl. This indicates that the discharges are within (or possibly above) overshooting convective tops that briefly penetrate the base of the stratosphere. The high-level discharges represent an entirely new regime of lightning activity that could provide a valuable indicator of strong convective surges in storms.

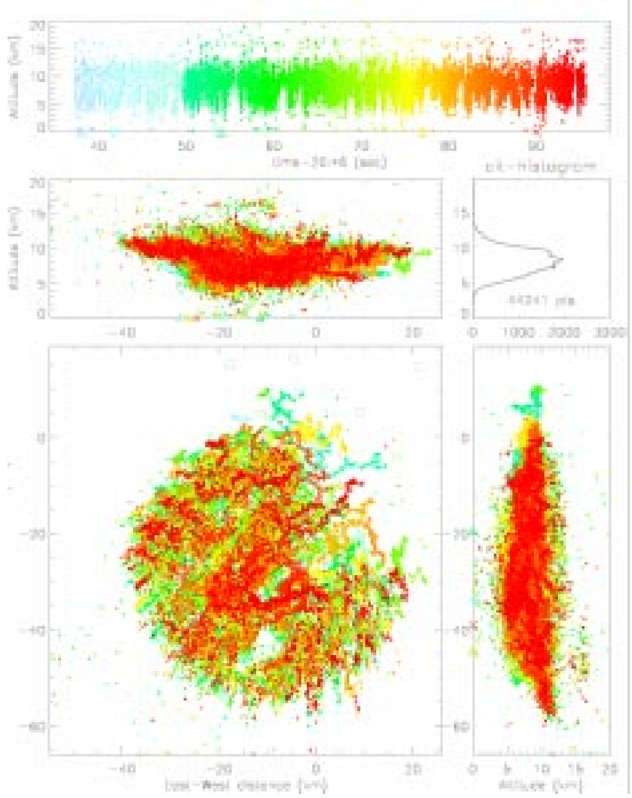

Figure 3. Observations of lightning in a large supercell storm, showing the volume-filling nature of the activity. The lightning 'hole' in the southern part of the storm is believed to be the location of a very strong updraft. This is supported by the occurrence of high-altitude lightning at 15-16 km altitude above the hole, believed to be in an overshooting convective top produced by the updraft.

Lightning in a Tornadic Storm

Figure 4 shows lightning in the early stages of a tornadic storm that went on to produce two F1 and two F2 tornadoes over northern Oklahoma City on the evening of June 13, 1998. The figure shows thirty seconds of lightning activity an hour earlier in the storm, a few minutes prior to touchdown of an initial F0 tornado. The location of the tornado

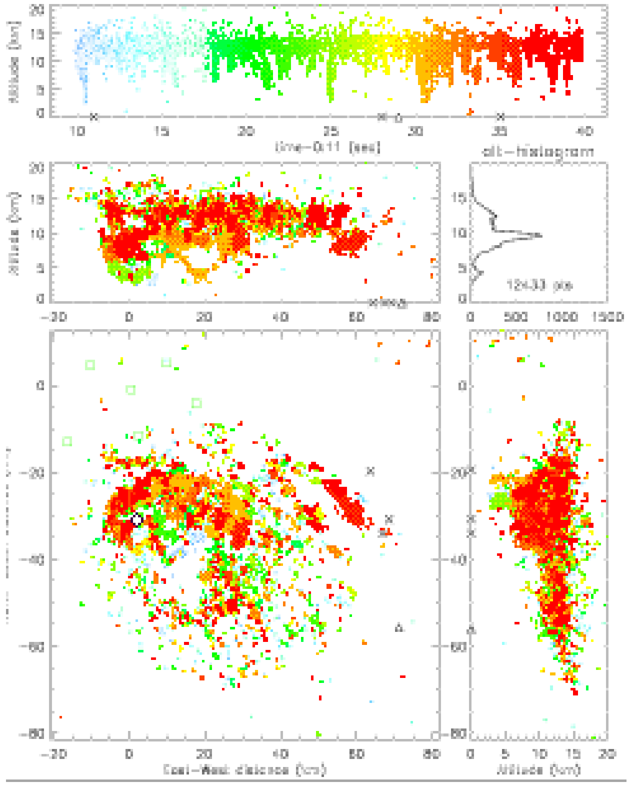

Figure 4. Observations of lightning at the beginning of a tornado-producing storm. The black diamond near $x = 0$ km, $y = -30$ km, indicates the location of the first, small F0 tornado from the storm. The lightning activity exhibited a hook-like structure on the west side of the storm and a lightning-free region immediately above the tornado track, similar to the hook echoes and weak-echo regions observed by meteorological radars.

is indicated by the black diamond in the figure. Amazingly, the lightning exhibited a counter-clockwise 'hook'-like structure on the west side of the storm in the vicinity of the tornado, similar to the hook echoes observed by meteorological radar in tornadic storms. The hook enclosed a lightning-free region about 5 km in diameter. As before, the lightning-free region almost certainly corresponded to the storm updraft. This is consistent with the fact that hook radar echoes surround a weak echo region known to be the location of the main updraft in tornadic storms. The tornado touched down five minutes later, immediately below where the updraft had been. The storm moved eastward at about 50 km hr^{-1}, which would have placed the tornado in the low-altitude lightning region (3-4 km) on the west side of the storm. The lightning in this region was probably associated with the low-altitude wall cloud that is a characteristic feature of tornadic storms. Overall, the lightning consisted of more or less continuous, minor discharges at high altitude in the storm (11-14 km), punctuated by discrete, more energetic discharges at lower altitude. A few positive cloud-to-ground discharges were occurring below the anvil extending eastward ahead of the storm. The nature of the overall lightning activity is not at all understood.

Final Comments

Although it is well known even to the casual observer that Great Plains storms are very active electrically, the mapping observations have shown in detail just how active the storms are. The total lightning activity is much greater than indicated solely by cloud-to-ground strike locations, and can be a useful indicator of the nature and severity of storms. However, very little is understood about the lightning activity and electrification processes in large storms. We plan to operate the mapping system in a multi-investigator program in northeastern Colorado and northwestern Kansas during the summer of 2000 to learn more about lightning in large storms. This program, called the Severe Thunderstorm Electrification and Precipitation Study (STEPS), is proposed to study the large hailstorms and supercell storms that occur in this region of the U.S. Another network of mapping stations will be operated by NASA scientists in northern Alabama to study storms in the southern U.S. and to determine the value of space-borne optical lightning detection by satellites. Low-earth orbit optical lightning detectors have already provided fascinating observations of the distribution of lightning over the surface of the earth [Christian and Latham, 1998]. Satellite observations of individual lightning discharges have been shown to be well-correlated with ground-based measurements from the lightning mapping system [Thomas et al., 1999].

Current work with the mapping system is directed at processing the observations in real time, both for research studies and for potential operational applications. The real-time observations are obtained by communicating the time-of-arrival measurements to a central location via wireless links or the Internet for processing and display. For further information on the lightning mapping observations see http://ibis.nmt.edu/nmt_lms.

Acknowledgments

This work has been supported by the National Science Foundation under ARI Grant ATM-9601652. Initial development of the lightning mapping system was supported by the U.S. Air Force Office of Scientific Research under grant F49620-96-1-0304.

References

Christian, H.J., and J. Latham, Satellite measurements of global lightning, *Q. J. Roy. Meteorol. Soc., 124*, 1771-1773, 1998.

Cummins, K.L., M.J. Murphy, E.A. Bardo, W.L. Hiscox, R.B. Pyle, and A.E. Pifer, A combined TOA/MDF technology upgrade of the U.S. National Lightning Detection Network, *J. Geophys. Res., 103*, 9035-9044, 1998.

Maier, L., C. Lennon, T. Britt, and S. Schaefer, LDAR system performance and analysis, in *Proc. Intn'l. Conf. Cloud Phys.*, Amer. Meteorol. Soc., Boston, Mass., Dallas, Texas, Jan. 1995.

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

Shao, X.M., and P.R. Krehbiel, The spatial and temporal development of intracloud lightning, *J. Geophys. Res., 101*, 26,641-26,668, 1996.

Thomas, R.J., P.R. Krehbiel, W. Rison, T. Hamlin, D.J. Boccippio, S.J. and Goodman, H.J. Christian, Comparison of ground-based 3-dimensional lightning mapping observations with satellite-based LIS observations in Oklahoma, submitted to *Geophys. Res. Lett.*, May, 1999.