The Relationship Between Radar Reflectivity and Lightning Activity at Initial Stages of Convective Storms

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ABSTRACT

Radar and lightning data sets were collected during the Severe Thunderstorm Electrification and Precipitation Study (STEPS) stationed on the High Plains. This study documents the results of data analysis of 14 storms, 2 with no lightning detected, for which data were collected as part of this study. Previous studies are typically limited in terms of the number of storms studied, or by the lightning data collection systems used. It was found that in all 12 storms with lightning, the initial activity was intracloud lightning. In order for lightning to occur, radar echoes of at least 40 dBZ had to exist at altitudes greater than 7 km MSL. Storms that produced only intracloud lightning differed from those that went on to produce cloud-to-ground strikes in that there were differences in the altitude lightning originated at, and the reflectivity it occurred in. Thunderstorms that displayed positive cloud-to-ground strikes could be distinguished between those with negative cloud-to-ground strikes by the reflectivities present at the time of the initial intracloud strike, and by the time between the first 25 dBZ echo and first intracloud strike. The one case in which a storm switched from negative to positive polarity, differed from a regular negative cloud-to-ground lightning storm in that the initial intracloud strike originated at an altitude less than 8 km. These results show that a combined knowledge of storm intensity and the initial lighting activity may enable lightning forecasts, and aid to improve thunderstorm forecasts.

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INTRODUCTION

Lightning is an impressive meteorological phenomenon, both in terms of its physical manifestation and its destructive power. There are over 2000 thunderstorms globally at one time, producing at least 100 lightning strikes to earth per second. Between 1959 and 1990, lightning was responsible for $35 million in damage, 93 deaths, and more than 250 injuries in the United States, becoming the second leading cause of weather-related fatalities (NLSI, 2001). Currently, no lightning forecasting system is commonly available, other than predicting by observing the trend on real-time lightning displays. An understanding of the association between storm intensity and the initial lighting activity may enable lightning forecasts, as well as having the potential to improve thunderstorm forecasts.

For many years, scientists have studied the electrical processes of thunderstorms in order to determine the mechanisms that cause cloud-to-ground (CG) strikes. These mechanisms have been the topic of much debate; but in recent years, the theory that ice particle interactions cause electrification seems to have prevailed. In order for lightning to occur, large ice particles (graupel or small hail) must collide with small ice particles above the freezing level, resulting in a net negative charge for the large particle and a net positive charge for the small particle. However, the storms updraft and gravity separates the large particles from the small ones. The gravitational separation results in a charge separation, with negative charge lower and positive charge higher. In order for collisions to occur, large graupel particles need to interact with smaller ice particles. Updrafts provide the vertical velocity needed.

Reflectivities above the freezing level are likely to be associated with graupel particles at these higher altitudes. Dye et al. 1986 stated that this was because the significant numbers of ice particles are not nucleated until about –15 degrees Celsius, adiabatic liquid content reaches a maximum near this altitude, and the maximum in the ice crystal diffusional growth rate occurs near this temperature. Dye et al. 1986 also suggested that if this is the case then the onset of electrification will occur at different radar reflectivities (reflectivity being the measure of the radar echo intensity as discussed in Stephens, 1994) in different geographic regions due to the various concentrations and distributions of ice particle sizes and concentrations within clouds.

Many past electrification studies were not able to observe lightning and radar reflectivity inside convective storms due to instrumentation limitations. Such limitations include not being able to see the altitude at which lightning occurs and not having the lightning mapping capability in conjunction with research radars that detect the microphysical properties of clouds. The 2000 Severe Thunderstorm Electrification and Precipitation Study (STEPS), conducted in eastern Colorado and western Kansas in May-July 2000, collected several comprehensive radar and lightning data sets using the New Mexico Institute of Mining and Technology’s Lightning Mapping Array (LMA) and the National Center for Atmospheric Research’s S-band polarimetric (S-Pol) radar. This makes it easier to investigate the relationships of lightning to storm structure and evolution, and enhance the understanding of electrification and lightning in severe storms on the High Plains (STEPS, 2000). More information on the STEPS field project can be found at http://www.mmm.ucar.edu/pdas/steps-science.html.

Previous lightning research has been done on small isolated thunderstorms that form over the mountains of southwestern United States, and above sea breeze convergence zones in southeastern coastal areas (Krehbiel, 1986). The area of eastern Colorado and western Kansas is unique because CG lightning flashes often lower the positive charge to ground instead of the more usual occurrence of negative charge to ground being lowered. The occurrence of positive (+) CG strikes are closely linked to the occurrence of tornadoes, while a change of polarity has
been found in severe storms. Little documentation currently exists on initial lightning activity, this being the first lightning that a storm produces. The purpose of this paper is to document several cases collected during STEPS to determine a relationship between initial lightning strikes and radar reflectivity. Questions such as whether the initial lightning activity was intracloud (IC) or CG, the altitude at which it originated, what reflectivity at which initial lightning activity occurred, how long it was after the first 25 dBZ radar echo, and how much lightning activity there was in the thunderstorm can be answered. Radar, the National Lightning Detection Network (NLDN), and the LMA, make it possible to investigate these questions in greater depth.

This paper is a study of 14 storms. It discusses the instrumentation used to determine initial lightning, and compares storms with no lightning activity to those storms that did display lightning. It also compares thunderstorms with only IC to those with both IC and CG lightning, and thunderstorms that produced –CG lightning to those that produced +CG lightning. A summary of results is given and suggestions for future work are made. The individual storms are discussed in more depth in an appendix.

**INSTRUMENTATION**

Primary instrumentation in STEPS included the S-Pol radar, Colorado State University’s CHILL Radar, the Goodland Doppler radar, the NLDN, an armored T-28 aircraft for storm penetrations, two mobile balloon sounding systems to characterize the storm environment, six mobile mesonets for the observation of weather beneath storms, the LMA to map the three-dimensional distribution of lightning, and the National Severe Storms Laboratory mobile balloon unit for electric field, temperature, and wind profiles within storms.

For this research, the NLDN, radar data, and the LMA were used to make CG lightning polarity, location, and reflectivity observations. Below is a brief description of these instruments.

**National Lightning Detection Network (NLDN)**

The NLDN consists of 108 ground-based remote sensing stations that monitor CG lightning activity across the United States using triangulation techniques. Within seconds of a lightning strike, the NLDN detects both +CG and negative (–)CG lightning, locates where each flash strikes the ground, and estimates its peak current. Using signal processing and global positioning systems with time synchronization, the NLDN is able to detect 95% of all CG strikes (NLDN, 2000). For the purposes of this research, the NLDN data were overlaid on Goodland Doppler radar data and were used to detect storms that exhibited CG lightning, and to determine whether or not the storm would be suitable for further analysis.

**Lightning Mapping Array (LMA)**

The LMA, which was first tested in 1998, maps the location of lightning in three dimensions. It allows one to study the initiation and development of lightning flashes and determine the initial CG lightning and IC flash rates for storms. The system operates by detecting radiation from lightning discharges in an unused VHF television channel (Krehbiel, 1999).

Figure 1 shows the locations of the LMA stations relative to the Doppler network. The three radars lie at the vertices of the blue-yellow triangle. The LMA, as seen in red, consists of 15 time-of-arrival stations for locating the lightning. Ten of the stations are electric field sensors and field change instruments for measuring the overall charge structure of storms. The field
sensors sample continuously at a 10 to 50 Hz rate, while the field change data sample at a 5 or 10 kHz rate. The other five stations are fast electric field change recording stations for detecting and locating CG and IC strikes.

The electric field data are time-tagged for accurate time synchronization between stations to allow the data to be located (STEPS, 2000). These data are then plotted every ten minutes on a display. For this study, the LMA was used to detect the initial strike, determine if it was CG or IC lightning, and to record the altitude at which it originated. Because many strikes can occur over 10 minutes, the data over the 10-minute interval were plotted on the Goodland radar scan. All strikes occurring during a radar scan were displayed. The only time strikes were not displayed was for 8 seconds between the beginning and end of a radar sequence. This made it easier to tell if a storm was producing lightning, and then recorded for plotting on the time-height diagram for analysis.

**Radar**

Radar data from the field project were taken from Goodland Doppler radar and the S-Pol research radar. Parameters such as velocity, reflectivity, and differential properties are derived from these instruments, providing a picture of what is going on inside a storm and the electrification of that storm. A time-height diagram was produced once a storm was chosen for analysis.

A time-height diagram has height as the vertical axis and time as the horizontal axis and has a contour plot of radar reflectivity drawn in this height/time space. The construction of a time-height diagram can be seen below in Figure 2. Radar scans are performed at several elevation angles, with the lowest angle corresponding to the lowest altitude and the highest angle with the greater altitude. A radar sequence involves a complete horizontal rotation of the radar for each of the vertical elevation angles. To produce a time-height diagram, the lowest and highest altitudes of each reflectivity are plotted. This is done for each radar sequence until the storm dissipates. Once all the data points are plotted, the points are connected to form a contour map of radar reflectivity in height/time space. The appendix shows all the time-height diagrams for the 14 storms studied. Once the initial lightning activity was extracted from the LMA, it could be plotted on the time-height diagram and relationships between radar reflectivity and initial lightning activity could be shown.
Figure 2: Producing time-height diagrams

OBSERVATIONS AND DISCUSSIONS

Detailed storm descriptions and time-height diagrams are given as an appendix. Below in Table 1 is a summary of all 14 cases labeled with an arbitrary letter. The date and time of each storm is given. The maximum reflectivity the storm reached is also shown. Below the maximum reflectivity are the maximum heights of each of the other reflectivities. The next column shows the first lightning as well as the time it occurred after the first 25 dBZ radar echo. The reflectivity that the lightning originated at is also given. Below the reflectivity is the altitude of each of the other reflectivities during the initial strike. The lightning that the storm went on to produce is also shown. If the storm produced CG lightning, the polarity and the time it occurred is listed.
Table 1: Summary of Storms

<table>
<thead>
<tr>
<th>Day</th>
<th>Time (UTC)</th>
<th>Maximum Reflectivity</th>
<th>1st Lightning IC/CG</th>
<th>Time after 1st 25 dBZ</th>
<th>Height Originated (km)</th>
<th>Initial Activity Reflectivity</th>
<th>Lightning Activity</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Lightning</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>July 12</td>
<td>2229-2312</td>
<td>50 dBZ</td>
<td>25 dBZ – 12.9 km</td>
<td>35 dBZ – 11.7 km</td>
<td>40 dBZ – 6.2 km</td>
<td>45 dBZ – 6.1 km</td>
<td>50 dBZ – 4.5 km</td>
<td>--- Isolated</td>
</tr>
<tr>
<td>June 11</td>
<td>2040-2110</td>
<td>55 dBZ</td>
<td>25 dBZ – 6.74 km</td>
<td>30 dBZ – 4.1 km</td>
<td>35 dBZ – 4 km</td>
<td>---</td>
<td></td>
<td>Weak in intensity and short lived</td>
</tr>
<tr>
<td>Only IC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>June 11</td>
<td>2032-2140*</td>
<td>50 dBZ</td>
<td>IC @ 21:01:08</td>
<td>33 min</td>
<td>7.150</td>
<td>25 dBZ – 8.5 km</td>
<td>IC</td>
<td>To the north of a system that produced +CG lightning</td>
</tr>
<tr>
<td>June 11</td>
<td>2010-2230*</td>
<td>55 dBZ</td>
<td>IC @ 21:19:52</td>
<td>10 min</td>
<td>8.003</td>
<td>40 dBZ – 12.1 km</td>
<td>IC</td>
<td>Split during the last stages, the lower half went on to produce – CG lightning</td>
</tr>
<tr>
<td>June 23</td>
<td>2022-2100*</td>
<td>50 dBZ</td>
<td>IC @ 20:38:28</td>
<td>16 min</td>
<td>7.824</td>
<td>35 dBZ – 10.8 km</td>
<td>IC</td>
<td>Isolated storm south of –CG system</td>
</tr>
<tr>
<td>June 23</td>
<td>2039-2155*</td>
<td>60 dBZ</td>
<td>IC @ 20:46:55</td>
<td>7 min</td>
<td>8.861</td>
<td>45 dBZ – 11.3 km</td>
<td>IC</td>
<td>Isolated</td>
</tr>
<tr>
<td>June 23</td>
<td>2041-2154</td>
<td>55 dBZ</td>
<td>IC @ 20:59:16</td>
<td>18 min</td>
<td>9.755</td>
<td>25-40 dBZ – 10.1 km</td>
<td>IC</td>
<td>Isolated at first, then merges with another storm where it produces +CG</td>
</tr>
<tr>
<td>July 12</td>
<td>2224-2302**</td>
<td>55 dBZ</td>
<td>IC @ 22:32:09</td>
<td>8 min</td>
<td>7.393</td>
<td>45-50 dBZ – 10.3 km</td>
<td>IC</td>
<td>Isolated</td>
</tr>
<tr>
<td>July 12</td>
<td>2253-2328**</td>
<td>55 dBZ</td>
<td>IC @ 22:57:57</td>
<td>5 min</td>
<td>8.380</td>
<td>25 dBZ – 9.9 km</td>
<td>IC</td>
<td>Isolated</td>
</tr>
<tr>
<td>Day</td>
<td>Time (UTC)</td>
<td>Maximum Reflectivity</td>
<td>1st Lighting IC/CG</td>
<td>Time after 1st 25 dBZ</td>
<td>Height Originated (km)</td>
<td>Initial Activity Reflectivity</td>
<td>Lightning Activity</td>
<td>Comments</td>
</tr>
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</tr>
<tr>
<td>June 11</td>
<td>2030-2225*</td>
<td>60 dBZ</td>
<td>IC @ 21:12:01</td>
<td>42 min</td>
<td>8.743</td>
<td>35 dBZ</td>
<td>IC, +CG 1st CG @ 2139</td>
<td>Joined the system to the west and intensified</td>
</tr>
<tr>
<td>June 23</td>
<td>1935-2230*</td>
<td>60 dBZ</td>
<td>IC @ 20:02:01</td>
<td>27 min</td>
<td>6.450</td>
<td>45 dBZ</td>
<td>IC, -CG 1st CG @ 2106</td>
<td>Switched polarity later on to +CG</td>
</tr>
<tr>
<td>June 23</td>
<td>2026-2135</td>
<td>60 dBZ</td>
<td>IC @ 20:36:27</td>
<td>10 min</td>
<td>10.080</td>
<td>40-45 dBZ</td>
<td>IC, -CG 1st CG @ 2052</td>
<td>Storm to the east of system, merges around 2100</td>
</tr>
<tr>
<td>June 23</td>
<td>2039.7***</td>
<td>60 dBZ</td>
<td>IC @ 20:49:38</td>
<td>10 min</td>
<td>6.821</td>
<td>45 dBZ</td>
<td>IC, +CG 1st CG @ 2150</td>
<td>Merges with another storm</td>
</tr>
<tr>
<td>July 12</td>
<td>2034-2158</td>
<td>60 dBZ</td>
<td>IC @ 20:39:46</td>
<td>5 min</td>
<td>8.236</td>
<td>35 dBZ</td>
<td>IC, -CG 1st CG @ 2052</td>
<td>Very strong updrafts</td>
</tr>
</tbody>
</table>

**Storms without lightning activity vs. storms with lightning**

Two storms without lightning and 12 storms with lightning were analyzed. The two that did not produce any lightning were storms A and B. Storm A intensified to 50 dBZ, however, the heights of the strongest reflectivities remained under 7 km. The reflectivity for storm B reached only 35 dBZ. In comparing the storms with no lightning activity to those that did, it seems that storms typically have the height of the 40 dBZ contour above an altitude of 7 km in order to produce lightning. For the field area, the 0 degree Celsius isotherm was typically at an altitude of 4-5 km, the −10 degree Celsius isotherm usually occurred at 5-6 km and the −15 degree Celsius isotherm occurred at 6-7 km. The cloud base was usually around 10-15 degrees, which roughly corresponded to 3 km.

The storms studied during the field project uphold Dye’s theory as stated in the introduction that ice collisions contribute to electrification. In each of the 12 storms that had lightning activity, there was no particular time in the storm evolution that initial lightning occurred. Some happened right before the storm reached maximum height, some right at the maximum height, and others right after.
Previous research showed that in Florida, the first lightning occurred when the storm reached an intensity of 35 dBZ (Dye et. al., 1989). They did not however state the height that this reflectivity must surpass. For one storm in Montana, the reflectivity of 45 dBZ exceeded an altitude of 6 km. Although more than one storm in those areas should be studied to determine if this is the case for all storms, the area of northeastern Colorado and western Kansas is different. It seems that here a storm should typically reach greater intensity and form at higher altitudes. If this is the case, then Dye et. al.’s hypothesis that the onset of electrification will occur at different radar reflectivities in different geographic regions due to the various concentrations and distributions of ice particle sizes and concentrations within clouds seems correct (Dye et. al., 1986).

**Thunderstorms with only IC lightning vs. thunderstorms with CG strikes**

Seven storms with only IC activity and 5 storms with both IC and CG lightning were analyzed. Interstorm comparisons were made by looking at the altitude of the initial strike, the height of the 40 dBZ contour, and the reflectivity at which lightning originated.

The altitude that the initial IC strike originated at, and the height of the 40 dBZ radar contour at the time of this initial strike, differed for the two types of thunderstorms. Those that only produced IC lightning had the initial strike originate at altitudes of 7-10 km. The IC lightning in storm G originated at 9.755 km at a time where the height of the 50 dBZ reflectivity was greater than 7 km. The range of 7-10 km was also the height of the 40 dBZ radar contour. For thunderstorms that went on to produce CG strikes, the altitude range was broader and included lower altitudes. These were between 6-10 km. The height of the 40 dBZ radar contour, however, was at a higher altitude. This was around 8.5-10 km.

The differences between reflectivity of origin, whether it originated in low or high reflectivity, also seems to characterize if a thunderstorm will go on to produce CG lightning. Thunderstorms that produced CG lightning did not originate in reflectivities of less than 30 dBZ. Storms J and N both originated in a reflectivity of greater than 30 dBZ. In both of these storms the height of the 25 dBZ radar echo was greater than 12 km. The height of the 35 dBZ contour was also greater than 9.5 km. Storm N did not reach 45 dBZ. Both storms did however have the initial IC lightning originate at an altitude between 8-9 km. Lightning that originated in high reflectivity, greater than 40 dBZ, occurred in storms K, L, and M. In these storms, the height of the 25 dBZ was less than 12 km during the initial IC strike. For storms L and K, the 45 dBZ contour was greater than 8 km.

For thunderstorms with only IC lightning, the heights of reflectivities during the first initial strike were also different depending on whether the lightning originated in high or lower reflectivities. Storms C and I had lightning that originated in 25 dBZ. For lightning that originated in 25-30 dBZ, the height of the 35 dBZ radar contour was less than 9.5 km. The height for the 40 dBZ radar contour was also less than 8 km. Storm D, F, G, and H had lightning that originated in high reflectivity, greater than the 40 dBZ contour, the height of the 50 dBZ contour was less than 8 km.

**Thunderstorms with +CG lightning vs. –CG lightning**

A total of 3 –CG lightning thunderstorms (K, L, N) and 2 +CG lightning thunderstorms (J, M) were studied. Case K switched polarity from negative to positive.

Thunderstorms that produced –CG lightning had less time between the first 25 dBZ radar echo and the first CG strike. This time was around 15-30 minutes. The time between the initial
IC strike and the first CG strike was also less. This time was between 5-20 minutes. The maximum intensity during the time of the first IC strike was 45 dBZ. Rison et. al. 1996 studied one storm in Florida where they found that a CG strike occurred five minutes after the initial IC strike. It did originate in high reflectivity. Although this was only one storm, it is consistent with the three cases observed here. The reflectivity of 50 dBZ was present at the time of the first IC strike for thunderstorms K and L. Storm N did not reach 50 dBZ during the initial IC lightning.

Storms with +CG lightning took longer for both the IC and the first CG lightning to initiate where both times were greater than one hour. Positive CG lightning is known to occur with severe weather and both cases here support this observation. At the time of the initial IC strike, the reflectivity present was lower than for a –CG lightning storm.

The case that switched polarity was different than regular –CG cases. In case K, the time interval from the first IC strike to the first CG strike to be less than 5 minutes. The other two –CG lightning cases were greater than 5 minutes. Case K was also different in that all the radar reflectivities below 45 dBZ occurred at lower altitudes. The 50 dBZ reflectivity was lower in the storm than the other –CG lightning storms. More cases of storms that switch in polarity will have to be studied to see if this is representative.

SUMMARY AND CONCLUSION

Relationships between radar reflectivity and initial lightning activity of both IC and CG lightning have been determined for the 14 cases studied here. Figure 3 (below) is a summary of the results. It shows these relationships and determines if a storm studied here produced lightning. If it did produce lightning, it shows the breakdown between those that went on to produce CG strikes. Whether the lightning was positive or negative or switch in polarity can also be determined. More cases should be studied in order to obtain representative results. The results shown here seem consistent with the theory stated in Dye et. al.’s, 1986 that collisions between ice particles contribute to storm electrification.

Since radar and lightning data were collected in STEPS, lightning and improved tornado forecasts may be achievable in the near future. Lightning activity is important and should be investigated thoroughly in order to prevent the damages and fatalities associated with it. Time constraints prevented deeper analysis of these storms, or similar analyses of more storms seen during the field project. Research in this area should continue in order to gain understanding of storms on the High Plains.
Figure 3: Summary of results

ACKNOWLEDGEMENTS

This work would not be possible without the help of numerous people. Special thanks to all my mentors for their help in my research and aiding in revisions and comments. Also thanks to Jay Miller for his hard work in preparing and editing programs so that I would be able to interpret the data.
APPENDIX

Storm Descriptions
June 11, 2000

An asymmetric mesoscale convective system (MCS), a large organized convective weather system that lasts for several hours and is comprised of a number of individual thunderstorms, approached the area from the west. The system produced numerous –CG and +CG lightning ¾ inch hail at 2143 UTC was reported. A well defined gust front produced gustnadoes and had peak outflows up to 50 knots. The system studied was one of three MCS that developed along a north-south line. Figure 3 shows the development on June 11 with the researched storms circled and labeled. Following is a brief description of each storm.

Figure 4: NIDS images on June 11 at 2030, 2100, and 2130 UTC

2030-2225* (J)
This storm reached a maximum reflectivity of 60 dBZ. It produced both IC and +CG lightning with initial activity shortly after development. The first CG strike was one hour and 10 minutes after the first 25 dBZ echo. At 2134 UTC, the storm had joined the MCS and had reached 60 dBZ.

2032-2140 (C)
This storm reached a maximum reflectivity of 50 dBZ and produced only IC lightning. The storm was to the north of another storm that went on to produce +CG lightning. Many weak storms formed around the area but died off rather quickly. The radar echo of 40 dBZ reflectivity stayed under 9 km in this storm. Lightning occurred late in the storm as the 50 dBZ echo appears. It originated high in the storm in 25 dBZ.

2040-2110 (B)
With a maximum reflectivity of only 35 dBZ, this storm was very short lived. It did not produce any lightning activity. Reflectivity echoes stayed under 7 km. This storm was to the south of storms D and C.
Maximum reflectivity of this storm was 55 dBZ. It intensified quickly with 40 dBZ reaching to 10 km. Initial lightning activity occurred during this time. The storm began to split at around 2205. The left side of the storm went on to produce –CG lightning

June 23, 2000

Storms developed in a multicellular line from southwest of Burlington, Colorado to near Goodland, Kansas. Pea to dime size hail was reported with some of these storms. The storms were –CG lightning producers and at 2120, lightning turned positive. Figure 4 shows the development on June 23 with the researched storms circled and labeled. Following is a brief description of each storm.

Figure 5: NIDS images on June 23 2030, 2100, and 2130 UTC

This storm produced both IC and –CG lightning. The first IC lightning was very late in the storm, 33 minutes after the first 25 dBZ radar echo. The thunderstorm formed with the line and although the first strike was negative, it later switched in polarity.

An isolated storm to the south of the multicellular line. It begins to dissipate at 2100 as the line strengthens and produces –CG lightning. The storm reached a maximum reflectivity of 50 dBZ. It did not intensify rapidly and initial IC stroke occurred in a low reflectivity of 35 dBZ.

This is an isolated storm to the east of the line. The storm reaches a maximum reflectivity of 60 dBZ. It strengthened rapidly to 50 dBZ where an IC strike occurred. It produced many –CG lightning strikes later on. Stronger echoes (of 55 to 60 dBZ) stayed under 4 km. Around 2100, the storm merged into the line.

This storm had a maximum reflectivity of 55 dBZ. IC lightning occurred at high altitude in 45 dBZ, seven minutes after development. Radar top echoes could not seen from the radar scan. The storm intensified rapidly with 60 dBZ occurring at over 7 km in altitude.
**2039-??*** (M)**

With a maximum reflectivity of 60 dBZ, this storm produced +CG lightning about an hour after the first IC strike was detected. This storm merged with another storm (G) but remains the stronger of the two.

**2041-2154 (G)**

This storm started out as an isolated cell but was overpowered by another storm after which it produced +CG lightning. Maximum reflectivity was 55 dBZ and all reflectivities with the exception of 55 dBZ reached high levels in the storm. Initial lightning activity occurred at an altitude of 9.7 km.

*July 12, 2000*

Isolated storms developed. Several intense, quasi-stationary storms (stationary or moving very little) were responsible for hail, flooding rains, and a couple of tornadoes. Most had +CG lightning activity. Figure 5 shows the development on July 12 with the researched storms circled and labeled. Following is a brief description of each storm.

![Radar images on July 12 at 2130, 2200, and 2300 UTC](image)

**2034-2158 (N)**

This particular storm had strong updrafts during initial lightning activity. Initial IC lightning occurred just before the storm reached peak intensity. The storm reached maximum reflectivity of 60 dBZ and produced –CG lightning 18 minutes after the first 25 dBZ echo.

**2224-2302** (H)

Maximum reflectivity in this storm was 55 dBZ. At 2250 this storm begins to die while cells begin to build behind it. The storm intensified quickly and reflectivities of 50 dBZ and below reached high altitudes. Lightning originated in 45 dBZ right after the storm had reached its maximum intensity. Storms to the northwest were dominated by –CG lightning, but the most northern storm remains a densely +CG lightning thunderstorm with the most production between 2300-0000.

**2229-2312** (A)

This isolated storm intensified and dissipated quickly. It barely reached 50 dBZ and did not produce any lightning. The 40 dBZ reflectivity stayed below 6 km in altitude.
Maximum reflectivity in this isolated storm was 55 dBZ. It did not intensify rapidly and initial lightning activity occurred at low reflectivity at the early stage of the storm. This storm only produced IC lightning.

*Not the exact ending point. Due to time constraints and for purposes of this paper, some time-height diagrams were not taken to the exact ending of the storm but to a point where the storm begins to dissipate or is well part of another system.

**The time-height diagram was done on RHI scans. The program that displays the radar images is off by 1.1 km. All analysis of this storm was done to account for the 1.1 km difference in altitude, however, the diagrams do not account for this. Thus, 1.1 km should be added to each point.

***Time height diagram not included.

**Time-Height Diagrams**

Following are the time height diagrams for the storms studied. They are labeled as seen in Table 1.
REFERENCES
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