APPLICATION OF LIGHTNING IN PREDICTING HIGH IMPACT WEATHER

Charlie Liu, Chris Sloop and Stan Heckman
Earth Networks, Inc
12410 Milestone Center Drive, Germantown, Maryland 20874 USA
Phone: +1 301.250.4315 Email: cliu@EarthNetworks.com

ABSTRACT

Recent research has indicated a strong correlation between total lighting data (both in-cloud and cloud-to-ground) and severe weather such as hail and high wind storms. The lightning activities preceding severe storms have certain characteristics in lightning flashes, such as high in-cloud (IC) flash rates in the storm formation stage. The greater volume of strong updrafts during a severe thunderstorm results in more charging overall, leading to greater numbers of ICs and positive cloud-to-ground (CG) flash rates. The detection of total lightning data, especially IC lightning, enables improvements in the lead time of severe weather prediction and alerting.

Earth Networks Total Lightning Network (ENTLN) provides the capability of detecting total lightning data efficiently on a continental scale which has enabled development derivatives such as: A real-time lightning cell tracking program to identify and track the properties, speed and direction of storm cells with associated lightning flash rate and proprietary advanced alerts. Applications of these lightning derivatives are used in numerous countries outside of the US and are of particular value in areas where radar and weather infrastructures are lacking or are in need of improvement. As high impact weather events increase on a global scale, the need for real-time information and alerting is critical. This presentation will provide an overview of the technologies and present case studies to show the relationships between the lightning activities and the severe weather.

INTRODUCTION

The lifecycle of a thunderstorm convection cell can be described by the classical tripole model, in which the main negative charge is located in the center of the cell, the main positive charge is in the cloud-top ice crystals, and a smaller positive charge is in the lower section of the cell, below the negative charge (Williams 1989). The initial electrification of the central and top parts may give rise to cloud flashes with intense enough charging producing ground lightning (Williams et al. 1989). Severe thunderstorms, which may generate high wind, hail and tornadoes have certain characteristics in the lightning flashes, such as high IC flash rates in the storm formation stage. Severe storms may have either exceptionally low negative CG flash rates, or have exceptionally high positive CG flash rates; the greater volume of strong updrafts during a severe thunderstorm results in more charging overall, leading to greater numbers of ICs and positive CGs (Lang and et al. 2000 and 2001). Past studies have shown that the CG flash rate has no correlation with tornadogenesis and that using CG lightning flash patterns exclusively to detect tornado formation is not practical (Perez et al. 1997).

A study focused on severe thunderstorms in Florida using the lightning detection and ranging network (LDAR) total lightning data confirmed a distinguishing feature of severe storms, i.e., the systematic total lightning and abrupt increase in total lightning rate precursor to severe weather of all kinds – wind, hail and tornados (Williams et al. 1999). A pure CG lightning detection system, due to the lack of IC detection capability, is not adequate for predicting severe storm development. The convection-cell structure of a thunderstorm is often visible in a weather radar image, and it can also be identified in lightning flash clusters when the rates are high enough. But the lightning cells based on CG flashes can only show the mature stage of a convection cell (Tuomi et al. 2005), and they can’t be used for early severe storm warning.

The Huntsville, Alabama, National Weather Service office utilizes total lightning information from the North Alabama Lightning Mapping Array (NALMA) to diagnose convective trends; this lightning data has led to greater confidence and lead time in issuing severe thunderstorm and tornado warnings (Darden et al. 2010). In one study, the IC lightning precursor provided a valuable short-term warning for microburst hazard at ground level (Williams et al. 1989). The lightning cells identified from the total lightning data would be able to track the whole lifecycle of a storm. A study based on data from the Lightning Detection Network in Europe (LINET) achieved an important step in tracking lightning cells using total lightning data (Betz et al. 2008).

The Earth Networks Total Lightning Network (ENTLN) is a total lightning detection network—its wideband sensors detect both IC and CG flash signals. The deployment of this high density sensor network and the improvement in the detection efficiency on the server side, especially in IC flash detection, made it practical to track and predict severe weather in real-time. Studies have shown that the severe weather often occurs tens of minutes after the total lightning rate reaches the peak, so tracking the rise of total lightning flash rate provides severe weather prediction lead time. By using the ENTLN total lightning data, a real-time lightning cell tracking system and subsequent dangerous thunderstorm alert system have been developed. This study will provide some statistical characteristics of lightning in severe storms by comparing the lightning data with severe weather reports and hail index data from NEXRAD radar data. The concept of alert issuing and some examples are also presented.

EARTH NETWORKS TOTAL LIGHTNING NETWORK (ENTLN)

ENTLN lightning detection sensor is a wideband sensor with detection frequency ranging from 1HZ to 12MHZ, which enables the sensor to detect both CG strokes and IC pulses. The sensor records whole waveforms of each flash and sends them back, in compressed data packets, to the central server. Instead of using only the peak pulses, the whole waveforms are used in locating the flashes and differentiating between IC pulses and CG strokes. ENTLN is a time of arrival (TOA) system.

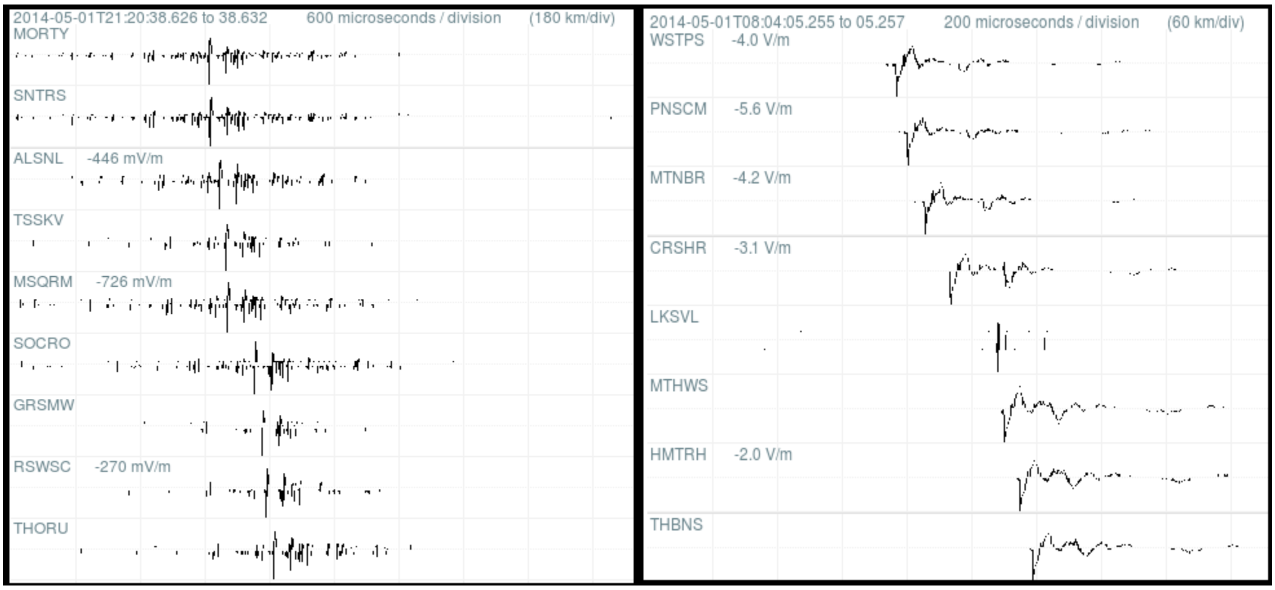

Figure 1. The graph on the left shows the waveforms from an IC pulse, across multiple sensors in ENTLN. The graph on the right shows the waveforms from a return stroke (CG).

The waveform arrival time and signal amplitude can be used to determine the peak current of the stroke and its exact location including latitude, longitude and altitude. Pulses and strokes are then clustered into a flash if they are within 700 milliseconds and 10 kilometers. A flash that contains at least one return stroke is classified as a CG flash, otherwise it is classified as an IC flash. In the lightning cell tracking and alert generation, only flashes are used.

Figure 2 shows the detection efficiency by comparing lightning imaging sensor (LIS) on board of TRMM satellite. South of latitude 35, we measure what fractions of flashes that are seen by the LIS sensor are also seen by ENTLN. North of latitude 35 LIS cannot see, so we measure the density of our receiver sites, and we assume that our detection efficiency will be the same as our mean detection efficiency at places south of 35 with a similar density of sensors. The statistics are adjusted based on the detection efficiency. To study the relationship between severe weather and lightning data, the lightning cells are first located by clustering the lightning flashes.

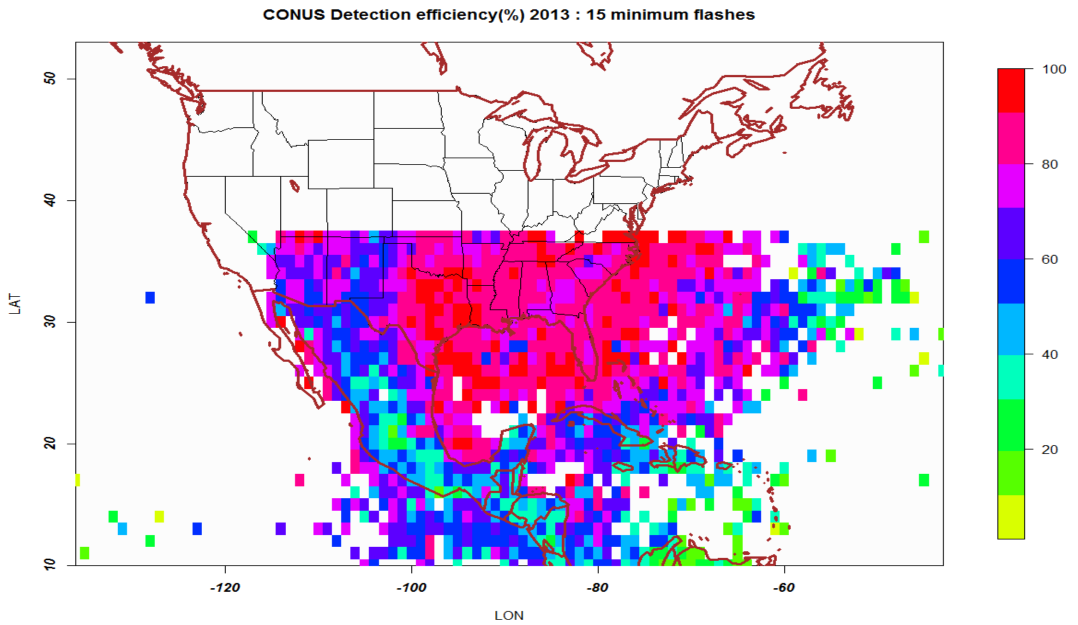

Figure 2. ENTLN detection efficiency comparing to LIS

LIGHTNING CELL TRACKING AND DANGROUS THUNDERSTORM ALERT

A lightning cell is a cluster of flashes with a boundary as a polygon determined by the flash density value for a given period. The polygon is calculated every minute with a six-minute data window. The cell tracks and directions can be determined by correlating the cell polygons over a period of time. By counting the flashes in the cell, it is possible to estimate the lightning flash rate (flashes/min). The cell speed and area are also calculated.

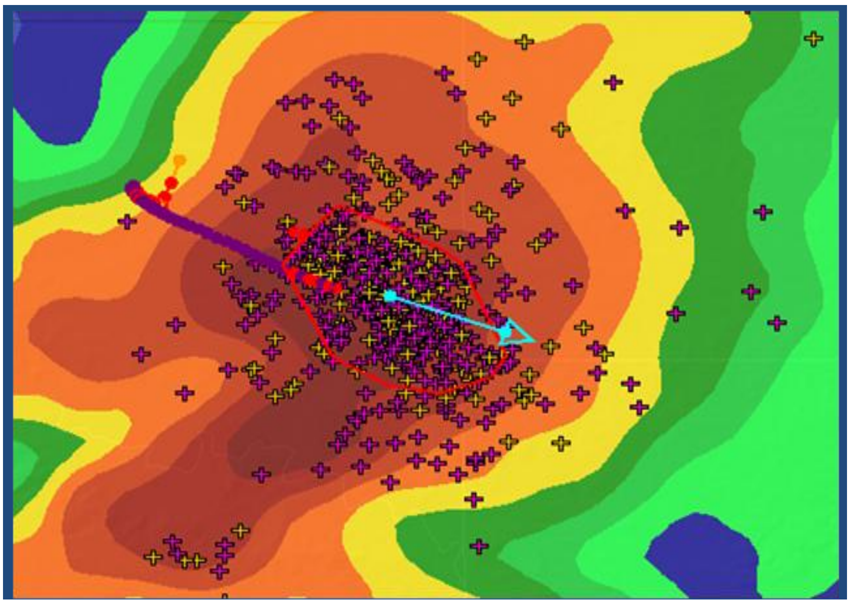

Figure 3. Defining a lightning cell. The curve behind the polygon indicates the path of the cell, and the arrow shows the moving direction of the cell.

The flash data is streamed from a lightning manager service to the cell tracker as soon as a flash is located. The cell tracker keeps flashes in a moving time window of six minutes. Two gridding processes are executed every minute, using a snapshot of the flash data in that time window. The first gridding is on a coarse grid to quickly locate areas of interest and the second gridding is operated on a much finer grid using density functions to find the closed contours.

To simplify the calculation, a convex polygon, which is the cell polygon at the time, is generated from each of the closed contours. In most cases, the cell polygon is similar to the previous minute polygon, so the correlation between the two polygons is straightforward. But in the case of sharp rise of the flash rate, or cell split or merger, the correlation of subsequent cells is not obvious. Special care is taken to link the cell polygons and produce a reasonable path of the moving cells. When a storm cell regroups after weakening, based on the trajectory of the cell and the time-distance of two polygons, a continuous cell path may be maintained.

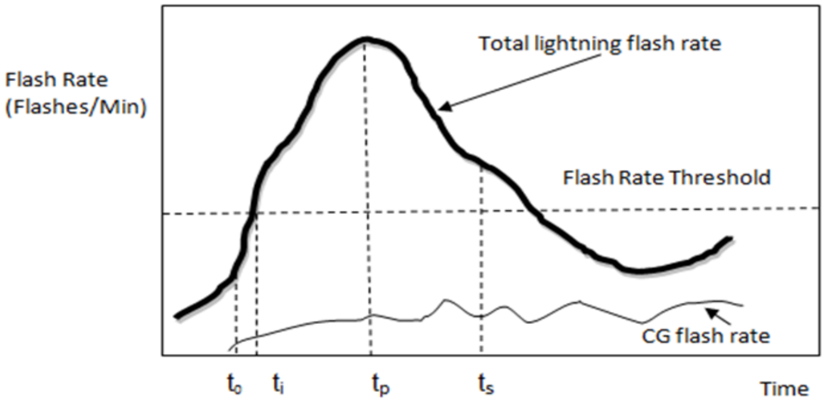

Figure 4: Total lightning rate graph with t_0 = jump time; t_p = peak total lightning rate time; t_s = time of severe weather; t_i = issuing time of Dangerous Thunderstorm Alert (DTA); $t_s - t_i$ = lead time

Once a lightning cell is located and tracked, the total flash rates, including IC and CG, are calculated. By monitoring the flash rates and the rate changes, the severe storm cells or the ones to potentially become severe, can be identified. Figure 4 shows the schematic cell history, the total lightning rate has a sudden jump at t_0 and the severe weather follows at t_s after the rate peaks at t_p.

In a microburst, the pattern may show up once, while in a super cell thunderstorm the pattern can repeat many times during the lifetime of the cell. When a cell is identified and the total lightning rate jumps passing the threshold, a dangerous thunderstorm alert (DTA) can be issued at t_i. The threshold of total lightning rate may vary in different regions or different type of storms. Combining the information from the cells, such as the speed, direction and size of the cell, a warning area ahead of the storm cell can be determined. The cell may reenergize and repeat the process again and trigger more alerts. Some cells may disappear quickly and some may keep going for hours. The

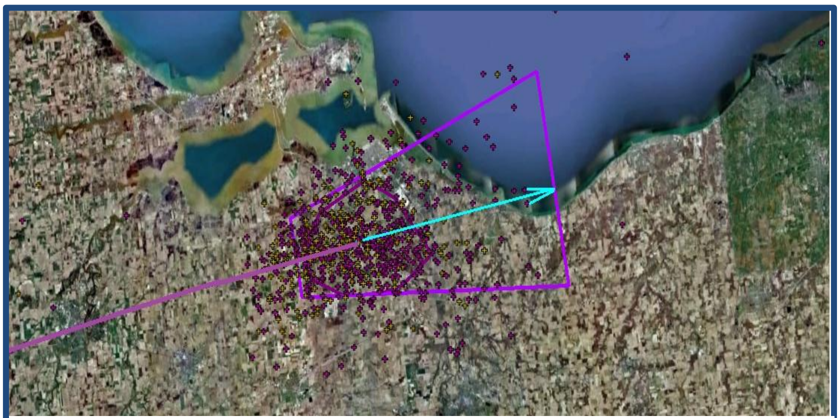

Figure 5: An alert polygon can be created for the area 45 minutes ahead of the moving cell.

alert polygon covers the distance that a cell will travel in 45 minutes with the speed demonstrated at the moment when the alert is generated. The alert polygon is updated every 15 minutes to reflect the updated path of the cell. The density of our 8,000 station surface weather network is sufficient to provide wind gust and rain rate data in real-time along the storm cell path; the real-time weather data provides additional information for the dangerous thunderstorm alerts.

One concern in previous studies (Darden et al. 2010) is the issue when artificial trends in lightning data are strictly related to efficiency or range issues. For such reason, flash data instead of stroke/pulse data are used in the cell tracking; the latter may be affected more by the detection efficiency. The thresholds can be adjusted based on the known detection efficiency for different regions.

LIGHTNING CHARACTERISTICS IN STORMS

The study area covers the middle part of the United States that lies west of the Mississippi River and east of the Rocky Mountains. Frontal thunderstorms over the Great Plains frequently trigger high wind and, occasionally, tornadoes. The frequency of hailstorms is greatest in an area centered in the southwestern corner of the Nebraska Panhandle and in adjacent parts of Wyoming and Colorado. Hail storms are common during late spring and early summer. ENTLN has a relatively uniform lightning detection efficiency distribution in this region.

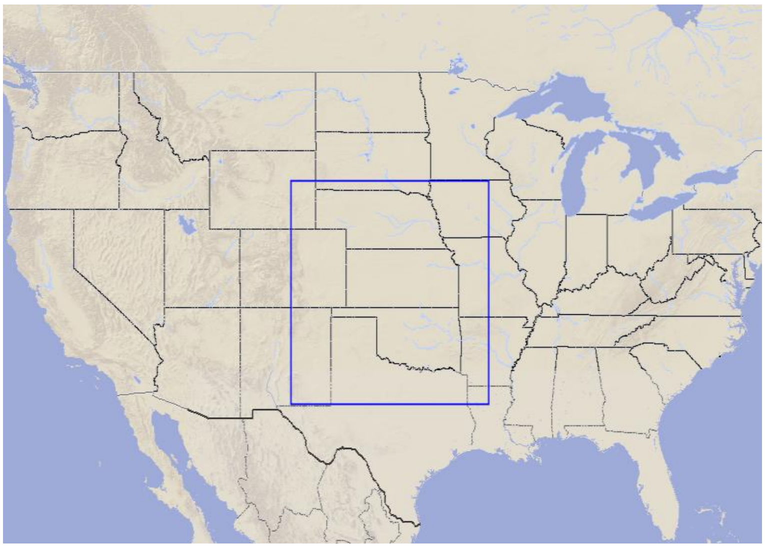

Figure 6 Study region: middle of United States

The local storm reports (LSR) from SPC were used to identify the types of storms, in which the lightning properties such as total flash rates, IC/CG flash ratio, and peak current are examined. For each severe weather report of the tornado, high wind and hail, the properties of the lightning cells within 25 Km and 30 minutes before and after the storm report time are studied. When the Hail

Index detected from the NEXRAD radar data, the properties of the lightning cells that overlap with the hail index locations are also examined.

If there is a severe storm report along the path of a lightning cell, the storm associated with the lightning cell is considered a severe storm. Since there could be many lightning cells associated with a large storm, multiple lightning cells can be studied. For the study period (May 1 to July 31, 2013, table 1 shows some statistics of the storms and lightning data.

Table 1: Storm reports and lightning data from May1 to July 31, 2013 in the study region

Storm Type	Number of LSR	Number of Lightning Cells with LSR
Tornado	191	687
Hail	2087	4052
High Wind	1407	3396

Consistent with the previous studies, the lightning cells that generated tornados have highest total lightning flash rates [Liu 2011]. Hail and high winds have higher flash rates than normal storms but lower lightning flash rates than tornados (Figure 7).

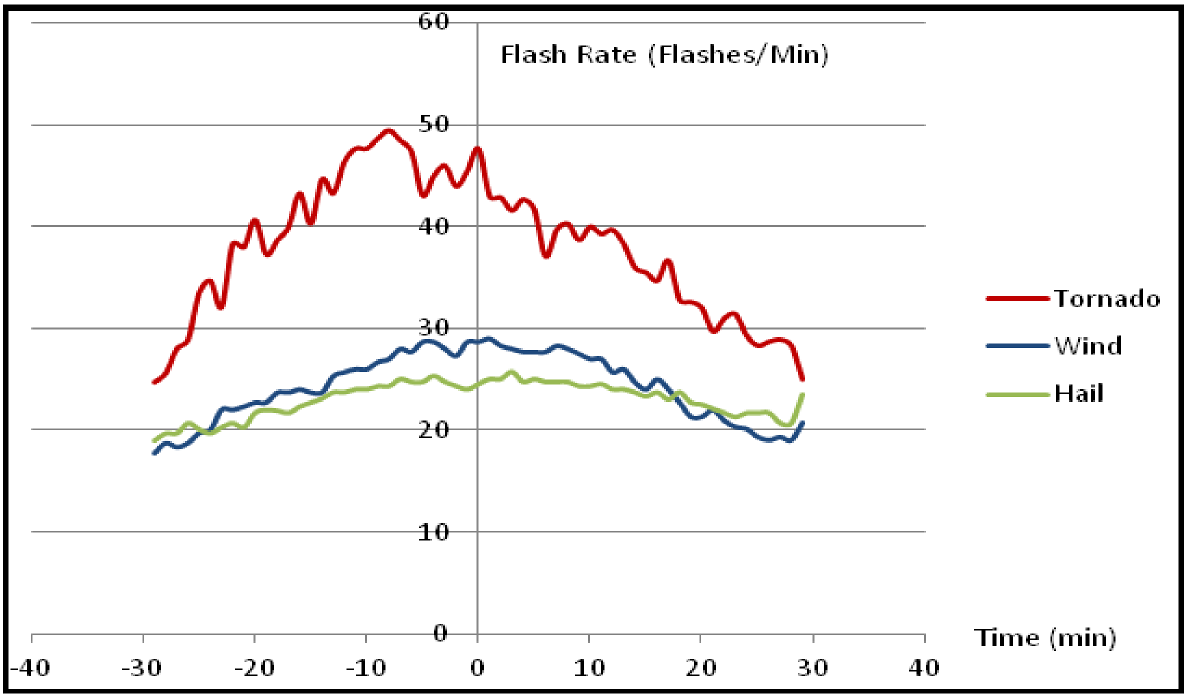

Figure 7. Total lightning rate in tornado, hail and high wind

Figure 8 shows that all the severe storms have higher IC/CG flash ratio than ordinary storms, which typically have IC/CG ratio as 4 or 5. The extremely high and fluctuating IC/CG ratio before tornado touchdowns indicates the higher number of IC flashes in the strong updrafts. The sudden jump of the IC lightning with extreme high IC flash rates is characteristic for many of the tornadic storms. There seems no clear trend in the peak currents of the flashes in the severe storms, though the peak currents for tornados tend to fluctuate more than other storms, it may due to the small number of tornadic events in the study comparing to other storms.

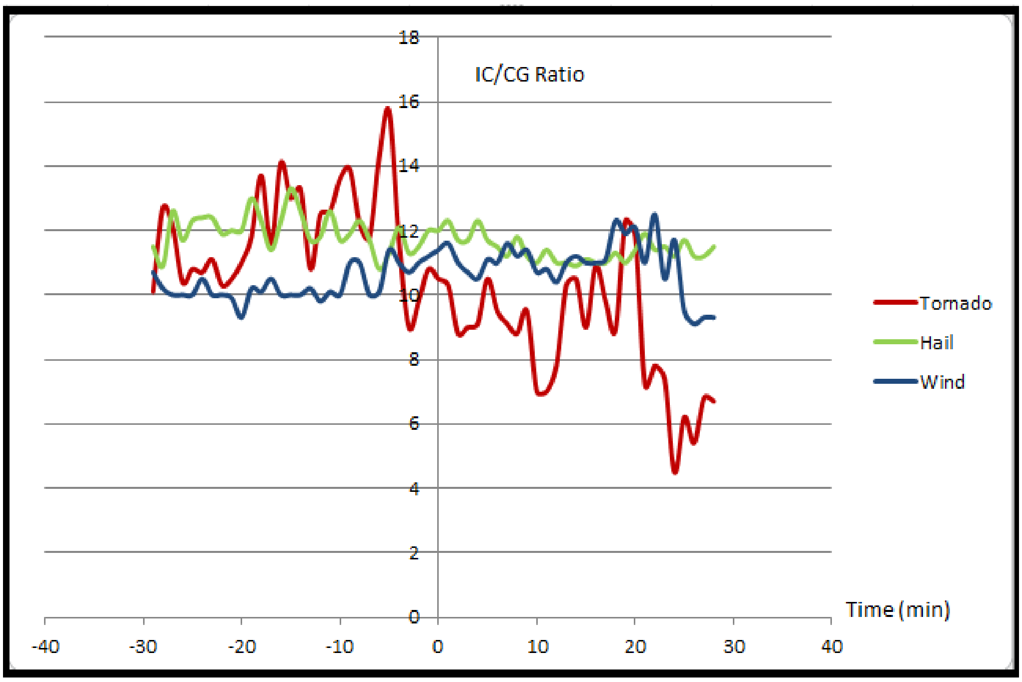

Figure 8: IC/CG ratio in tornado, hail and high wind

LIGHTNING DATA AND HAIL INDEX

There are several methods for the detection of hail and estimation of hail size using single-polarization radar. The NEXRAD hail detection algorithm is widely used and has proved to be quite reliable. Hail Index is a derivative product from NEXRAD hail detection algorithm and provides an indication of whether the thunderstorm structure of each storm identified is conducive to the production of hail. Hail Index provides the time, location, max hail size, probability of hail and probability for severe hail. As indicated by survey (Holleman, 2000, 2001), the probability of hail is more reliable than the hail size estimation.

The Hail Index data used in this study was from the individual NEXRAD radar sites in the study region. By comparing the location and time of the hail index with the lightning data, it is shown that almost all the Hail Indices were detected inside the lightning cells or near lighting cells.

Figure 9 shows the median total lightning rate in the cells with various sizes of Hail Index detected from radar. The relationship between the max potential hail size detected by radar and the median total lightning rate seems random, there is no clear correlation.

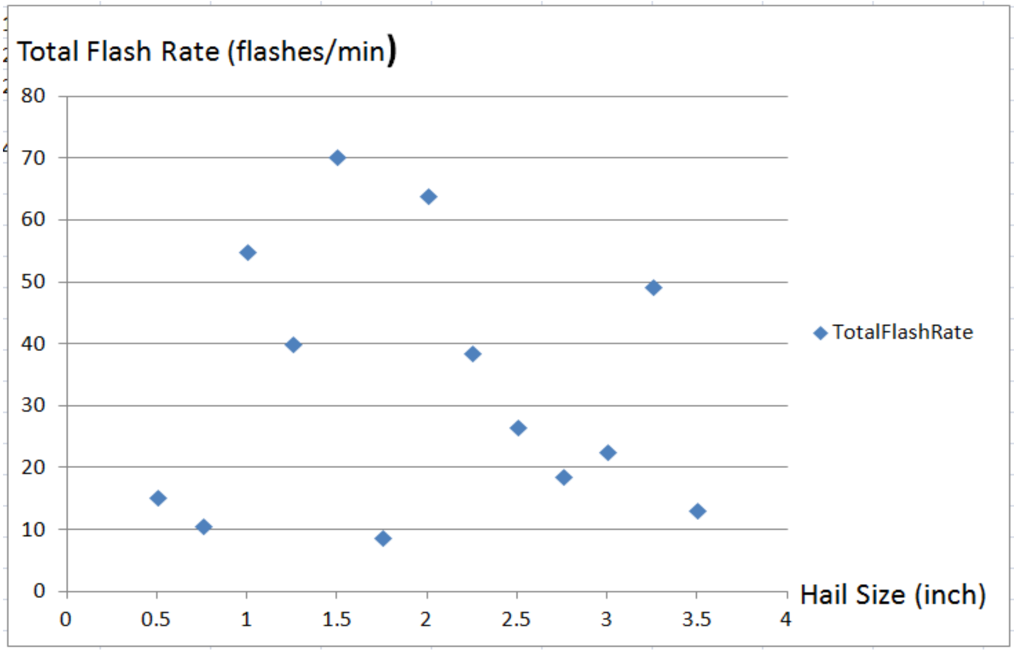

Figure 9: Total lightning rate vs. max hail size in NEXRAD Hail Index

On the other hand, when comparing the Severe Probability in the Hail Index and the total lightning flash rate in the corresponding cells, one can find there is a certain trend. Figure 10 shows the median flash rates in cells that have certain Severe Probability in Hail Index, it appears that the cells with higher severe probability in hail index also have higher lightning flash rate.

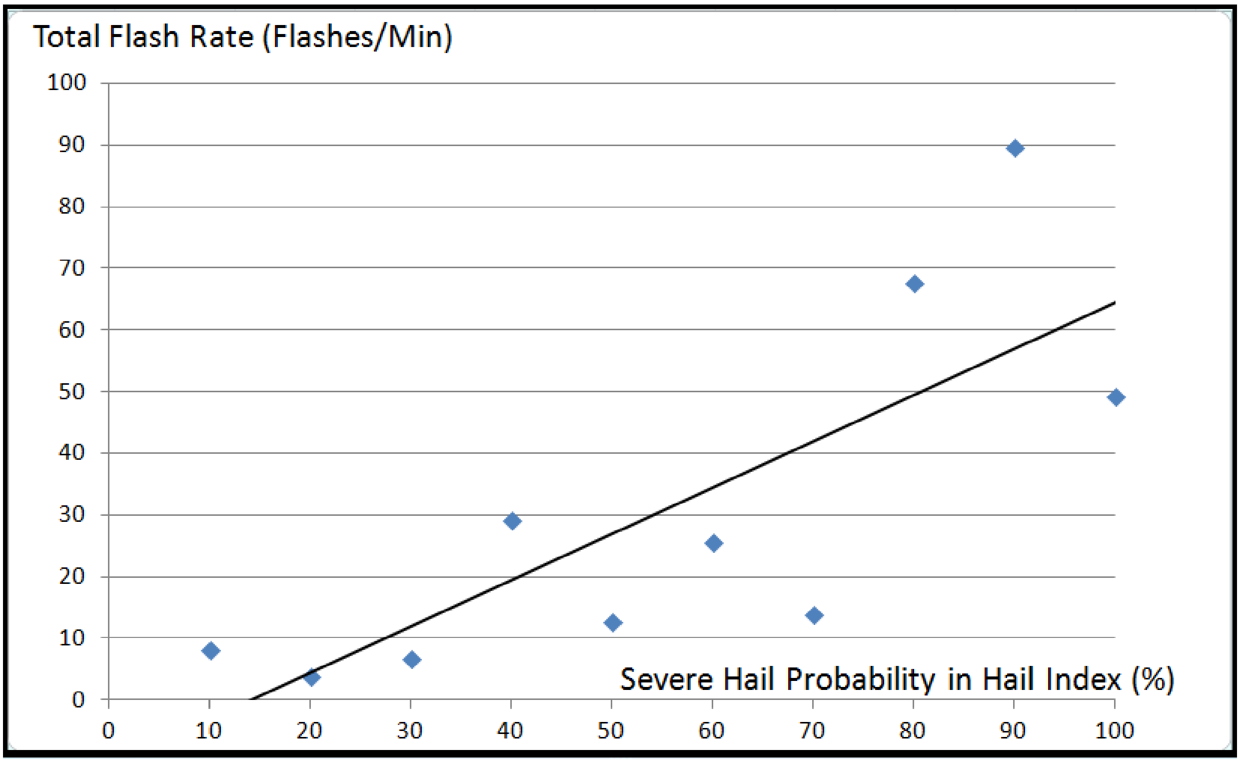

Figure 10. Severe Probability in Hail Index vs. the Total Lightning Flash Rate in the Lightning Cells

To find the chance that a lightning cell with certain flash rate can produce hail, first, the maximum lightning flash rate for a single track of lightning cells is calculated, then the existence of the Hail Index detected by the NEXRAD in the lightning cells is recorded. So the percentage of lightning cells with different lightning flash rates that may produce hail can be calculated. Figure 11 shows that the higher the flash rate of a lightning cell, the higher chance the hail may be produced from the storms. For example, in average 90% of the cells with flash rate 50 flashes/min may produce hail that can be detected by NEXRAD as Hail Index. Since the Hail Index is an indicator from radar that there is a possibility of producing hail in the storm, the high lightning rate can be used as a proxy of hail potentials in storm cells. This graph may change for other regions and seasons.

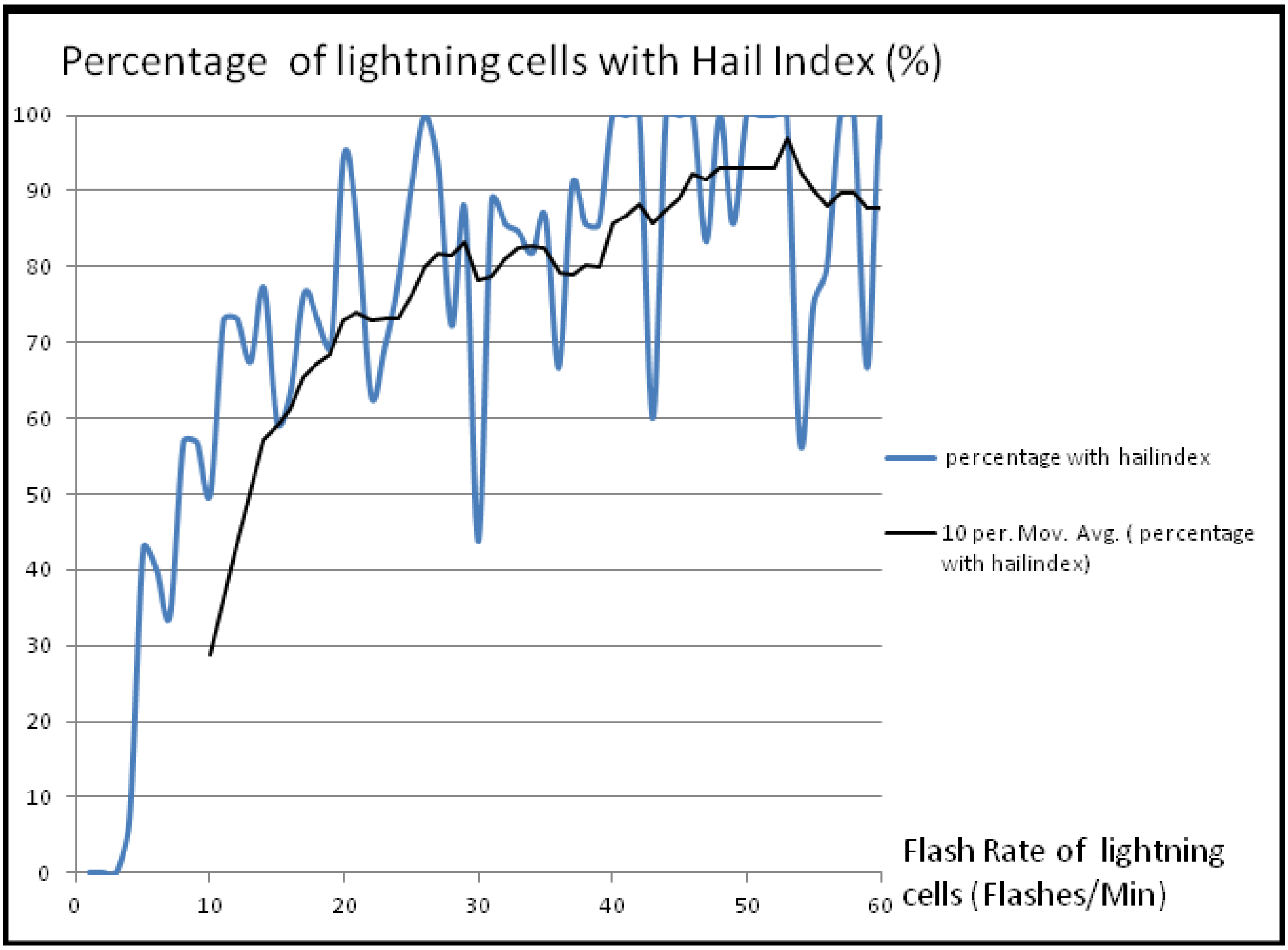

Figure 11. Percentage of Hail Index in cells with certain total lightning flash rate

CASE STUDY AND ANALYSIS

The cells and alerts from numerous storms have been reviewed by our meteorologists through the live cell tracking and alert system on a daily basis. We have been closely monitoring the accuracy and lead time of the alerts and comparing them with National Weather Service (NWS) severe weather warnings. For most of the storms from various locations across the U.S., there is a clear pattern in the distribution of the total lightning flash rates during the lifetime of the cells. Based on the cell data, it is possible to provide 10 to 40 minutes or even greater lead time for issuing

Dangerous Thunderstorm Alerts (DTAs). One case included in the study is the severe thunderstorm outbreaks across the study region in May 19 and 20, 2013. The thunderstorms triggered multiple tornados and widespread severe hail storms. One of the tornados was an EF5 tornado that struck Moore, Oklahoma, and adjacent areas on the afternoon of May 20, 2013; with peak winds estimated at 210 mph (340 km/h), killing 24 people and injuring 377 others. The tornado was part of a larger weather system that had produced several other tornadoes across the Great Plains over the previous two days (including five that struck Central Oklahoma on May 19).

The lightning rate graph in Figure 12 clearly shows the pattern described in the previous section—before the storm intensifies, the total lightning flash rate jumps, reaches the peak and then decreases. This pattern can repeat many times in the lifetime of a super cell thunderstorm. In this particular storm, the highest total lightning rate (88 flashes/min) precedes the strongest tornado activity, producing EF-5 damage in this case. The storm also generated high rates of cloud lightning, with as high as 13 times more IC than CG lightning. The IC/CG ratio reaches 12 before the touchdown.

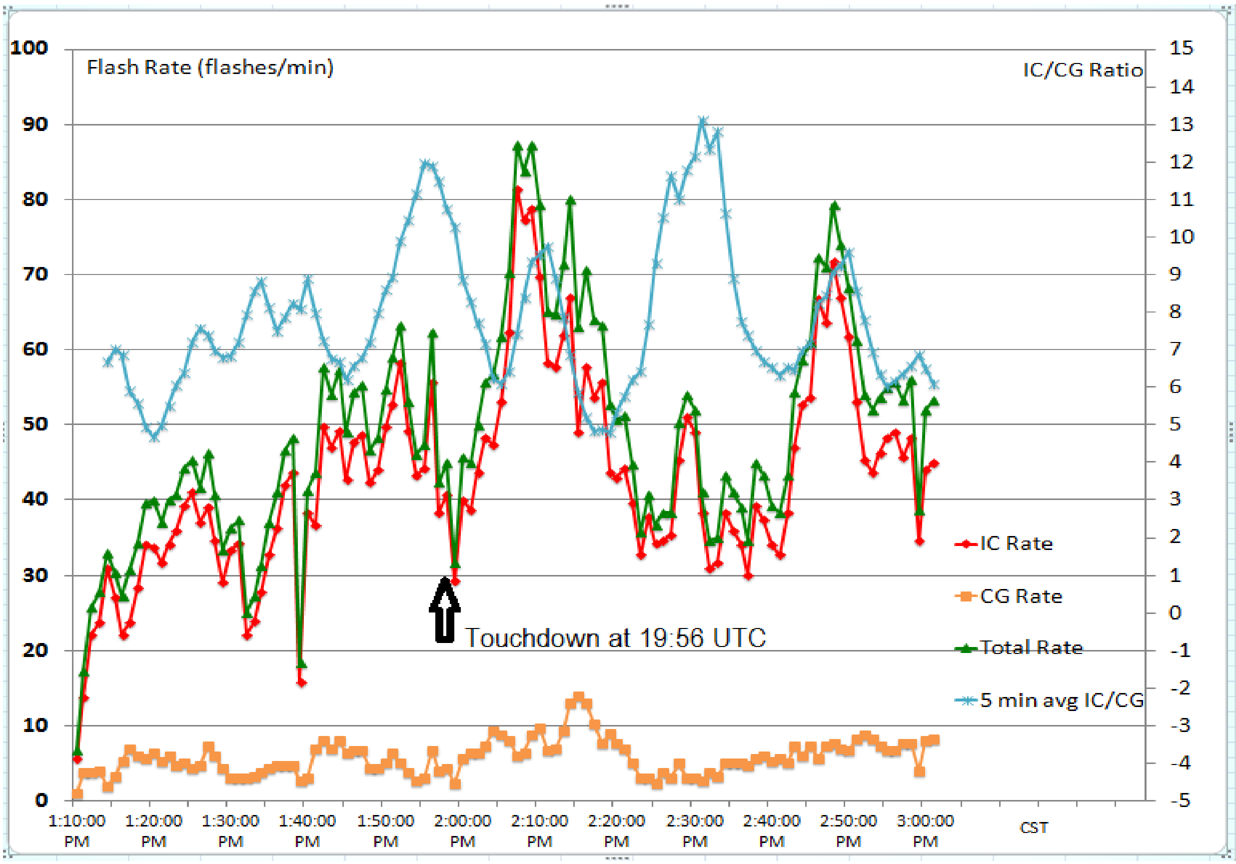

Figure 12: Lightning Rate and IC/CG ratio during the Moore Tornado 2013

When examining the radar data during the storms, the Hail Indices from NEXRAD were present almost in all the lightning cells with high total lightning rate (>25flashes/min) (Figure 13). The

Moore Tornado touched down at 19:56 UTC, the first DTA was issued at 19:12 UTC with 44 minutes of lead time.

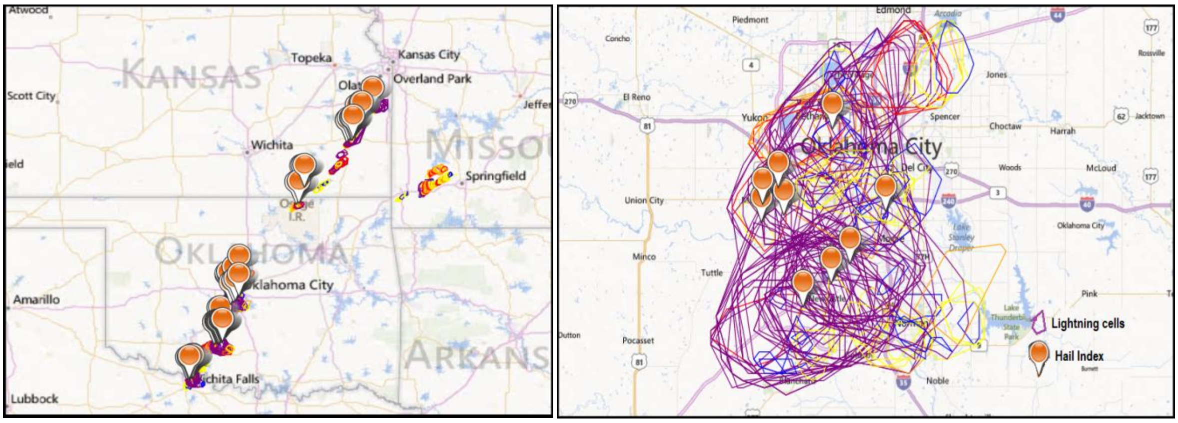

Figure 13. Hail Index detected from NEXRAD in the lightning cells (a) Hail Indices in the line of storms in 2 hour (1800 to 2000UTC, May 20, 2013). (b) Zoomed-in view of the Hail Indices in the Moore Tornado Lightning cells

CONCLUSIONS

This study provided further evidence about the relationship between the lightning data and severe weather; The IC flash rate and the rate jumps can provide early indicators of severe thunderstorms capable of producing hail, high wind or tornadoes. Most severe convective storms can generate high IC flash rate and high IC/CG flash-rate ratios. The higher the total lightning rate, the higher chance the hail can be produced from the convective storms. By tracking the lightning cells in a storm and monitoring the total lightning flash rates, it is possible to issue Dangerous Thunderstorm Alerts (DTA) with a lead time of up to 30 minutes before ground-level severe weather develops. ENTLN is a total lightning detection network that can detect both CG and IC flashes efficiently, and can be used to provide advance warning of severe weather. The cell tracking and DTAs can be used as an automated severe storm prediction tool, which can be used to augment radar, computer model data and observations to issue reliable severe weather warnings.

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