

The Application of Total Lightning Detection and Cell Tracking for Severe Weather Prediction

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Abstract

Intracloud (IC) lightning is better correlated to storm severity than cloud-to-ground (CG) lightning. The detection of both IC and CG flashes, or total lightning, enables improvements in the lead time of severe weather prediction and alerting. The WeatherBug Total Lightning Network (WTLN), created specifically for the detection of both IC and CG lightning strokes, covers the contiguous United States, Alaska, Hawaii and the Caribbean with a high density of sensors. Other areas are covered by a global low-density network for CG detection only.

The properties of lightning cells preceding numerous severe storms in various locations of the contiguous United States have been studied and certain predictive patterns in the lightning cells have been identified. The time evolution of the lightning flash rate and the IC/CG ratio of individual cells are used to identify thunderstorms likely to produce damaging hail, high wind, or tornadoes with significant lead times before they occur. Studies have shown that early detections in the sudden rise of the rate of IC discharges and subsequent peak of total flash rate can serve as an indicator for severe storm conditions. Using WTLN lightning data, a real-time lightning cell tracking and the WeatherBug Dangerous Thunderstorm Alert (WDTA) program has been developed. The results of several storm studies will be presented.

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 lightning, 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 WeatherBug Total Lightning Network (WTLN) 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 minutes after the total lightning rate reaches the peak and tracking the rise of total lightning flash rate provides severe weather prediction lead time. By using the WTLN total lightning data, a real-time lightning cell tracking system and subsequent dangerous thunderstorm alert system have been developed. This study will provide insight into the WTLN development and show features such as the IC and CG waveforms and the IC detection efficiency. The concept of alert issuing and some examples are also presented.

WeatherBug Total Lightning Network (WTLN)

The WeatherBug Lightning Detection Network (WTLN) is the fruit from a decade of research and development efforts. By combining advanced lightning detection technologies with modern electronics, a WeatherBug Lightning Sensor (WLS) can acquire detailed signals emitted from both IC and CG flashes and continuously sends information to a central server. A WLS is composed of an antenna, a global positioning system (GPS) receiver, a GPS-based timing circuit, a digital signal processor (DSP), and onboard storage and internet communication equipment.

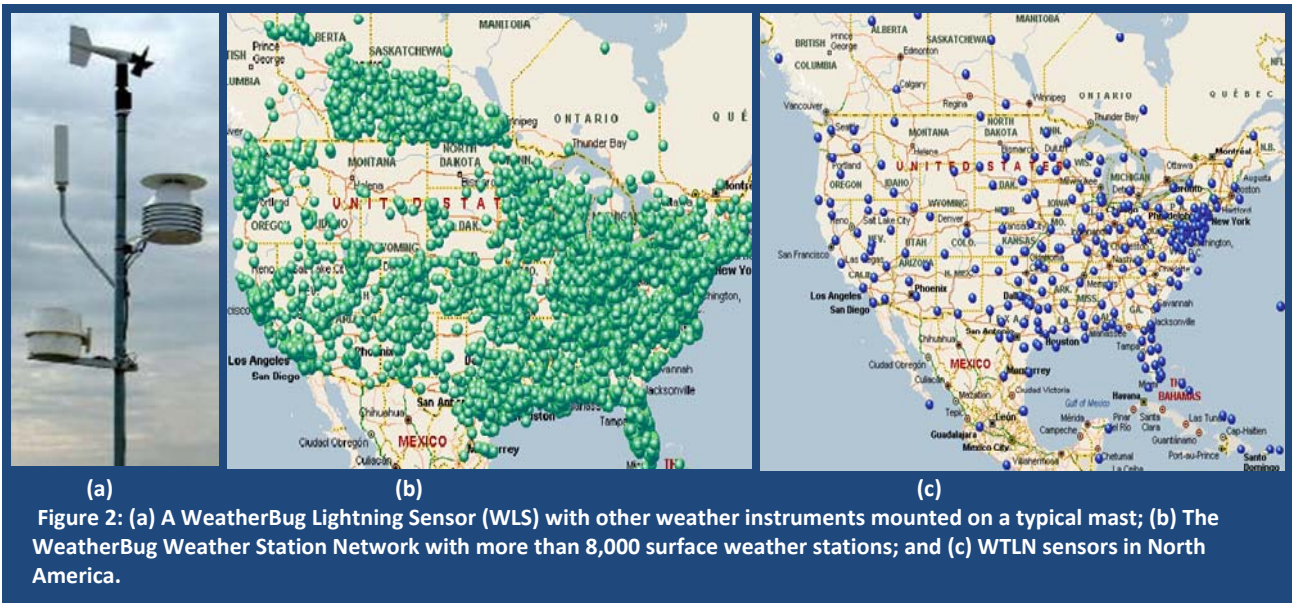
The WLS is unique compared to other existing sensor technologies. The sensor is a wideband system with detection frequency ranging from 1HZ to 12MHZ. The wide frequency range enables the sensor to not only detect strong CG strokes, but to also detect weak IC pulses. The sensor records whole waveforms 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 and CG strokes. The rich signal information enhances the detection efficiency and location accuracy of the system. Sophisticated digital signal processing technologies are employed on the server side to ensure high-quality detections and to eliminate false locations.



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

When lightning occurs, electromagnetic energy is emitted in all directions. Every WTLN sensor that detected the waveforms records and sends the waveforms to the central lightning detection server via the Internet. The precise arrival times are calculated by correlating the waveforms from all the sensors that detected the strokes of a flash. The waveform arrival time and signal amplitude can be used to determine the peak current of the stroke and its exact

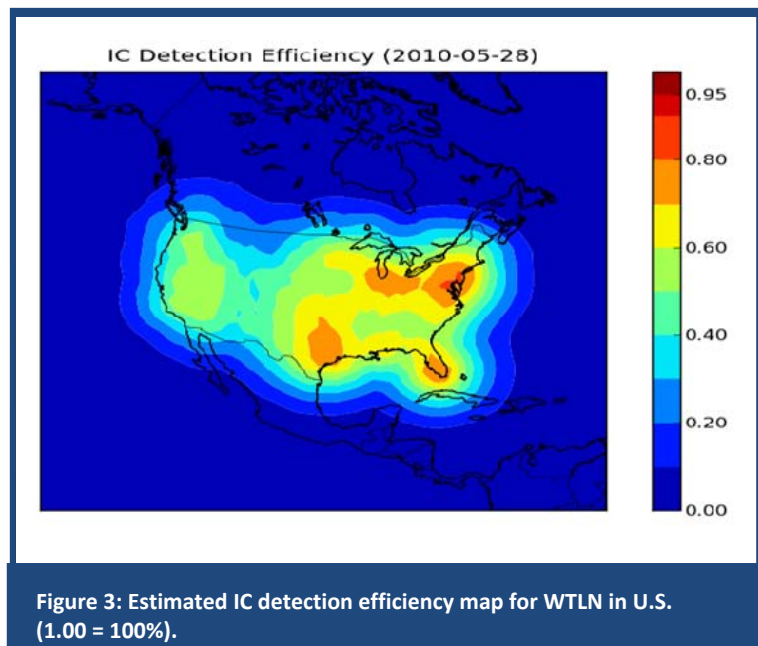
location including latitude, longitude and altitude. Strokes are then clustered into a flash if they are within 700 milliseconds and 10 kilometers. A flash that contains at least one return stroke is classified as a CG flash, otherwise it is classified as an IC flash. In the lightning cell tracking and alert generation, only flashes are used.



With over 8,000 WeatherBug proprietary surface weather stations and 1,200 cameras primarily based at neighborhood schools and public safety facilities across the U.S., WeatherBug maintains the largest exclusive surface weather network in the world. The weather station and lightning sensor at site locations are plugged into a data logger which sends independent weather and lightning data via the Internet to central servers.

Taking advantage of the locations of the surface weather stations in our existing weather network, WeatherBug quickly deployed a high density network of lightning sensors in the U.S. A high density network covers the contiguous United States, Alaska, Hawaii and the Caribbean basin. WTLN continues to grow as hundreds of new sensors are typically added annually. A global lightning network for long-range CG lightning detection utilizing low frequency data is also deployed but is not used in this study.

Significant effort has been put in improving IC detection efficiency both in the sensor deployment and server-side optimization. WTLN has a relatively good IC detection efficiency (up to 95%) in the U.S. Midwest and East, where most of storms occur. The efficiency in other areas is improving with continuing sensor deployment.



Lightning Cell Tracking and Dangerous 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.

The flash data is streamed from a lightning manager service to the cell tracker as soon as a flash is located. The cell

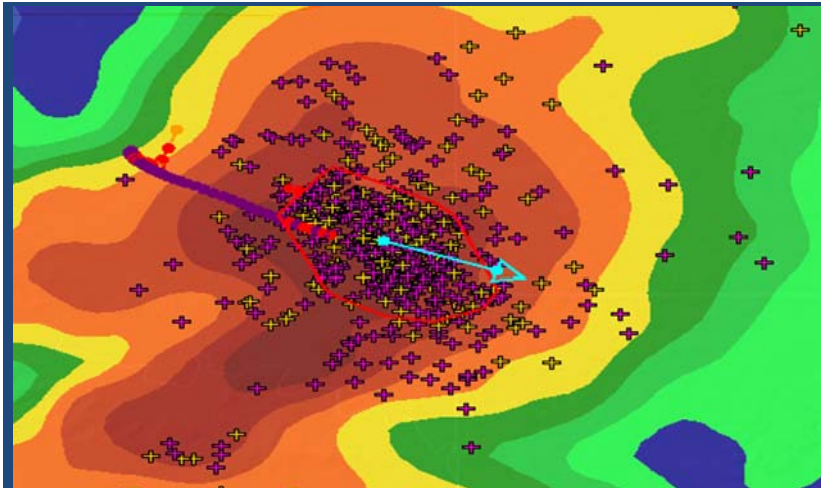


Figure 4: Defining a lightning cell. The curve behind the polygon indicates the path of the cell, and the arrow shows the moving direction of the cell.

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.

Once a lightning cell is located and tracked, the total flash rates, including IC and CG, are calculated. By monitoring the

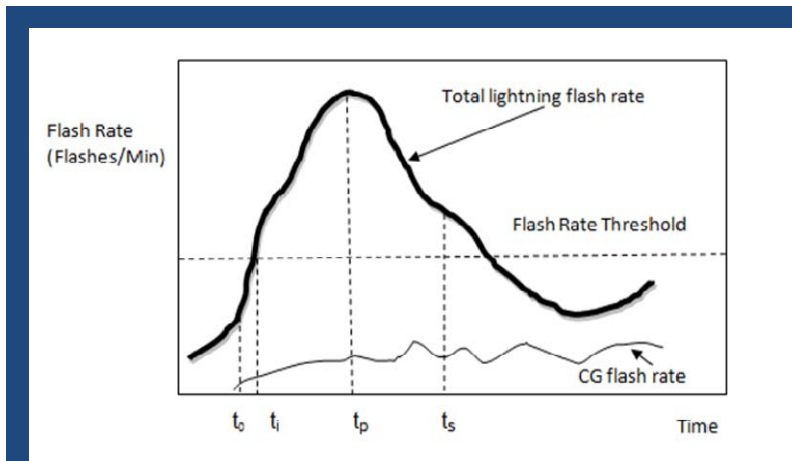


Figure 5: Total lightning rate graph with t_0 = jump time; t_p = peak total lightning rate time; t_s = time of severe weather; t_i = issuing time of Dangerous Thunderstorm Alert (DTA); $t_s - t_i$ represents the lead time of the alert.

flash rates and the rate changes, the severe storm cells or the ones to potentially become severe, can be identified. Figure 5 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. To simplify the study, a threshold of 25 flashes/min was chosen. Combining the information from the cells, such as the moving speed and 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. Some storms may contain mostly CG flashes, although they are not usually severe in terms of high wind, hail or tornadoes. CG strokes can cause serious property damages and be threats to people.

The 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.



Figure 6: An alert polygon can be created for the area 45 minutes ahead of the moving cell.

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 data are used in the cell tracking; the latter may be affected more by the detection efficiency. The thresholds can be adjusted when the detection efficiency becomes known for different regions. Further study will be conducted in this area.

Case Studies 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 30 minutes or even greater lead time for issuing dangerous thunderstorm alerts (DTAs). Three typical cases are presented here: (1) a long tornado with a 240km track; (2) a fast-moving hail storm; (3) a slow-moving tornado with heavy rain.

1. Louisiana to Mississippi Tornado, April 24, 2010

Based on the NWS LSR storm survey, this was one of the deadliest U.S. tornadoes in 2010 and the first EF-4 of the year. On April 24, 2010, a tornado touched down in eastern Louisiana and tracked north eastward into Mississippi with a 240 km path and a maximum width of 2.8 km. This track length is one of the longest tornado tracks on record. Yazoo and Holmes counties, in Mississippi, were particularly hard hit when the tornado reached its maximum strength with estimated winds of 274 km/hr.

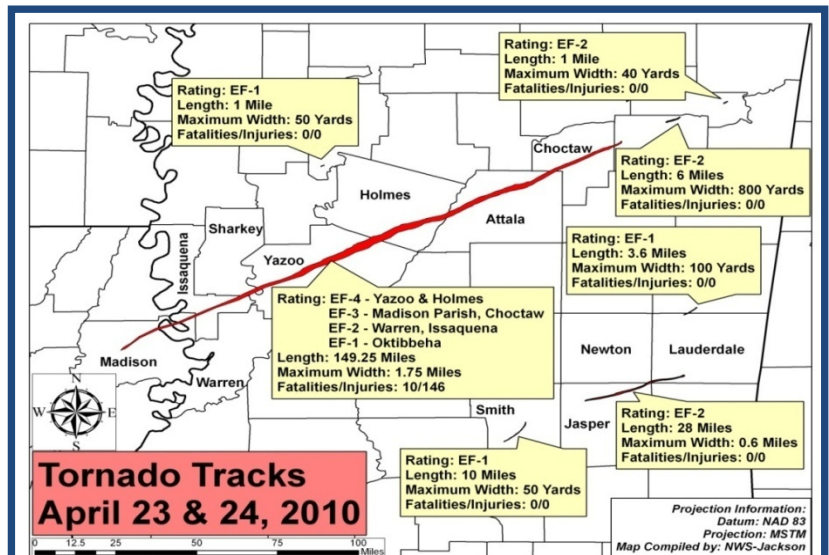


Figure 7: Survey of tornado tracks in Louisiana and Mississippi on April 24, 2010 (courtesy of NWS-Jackson).

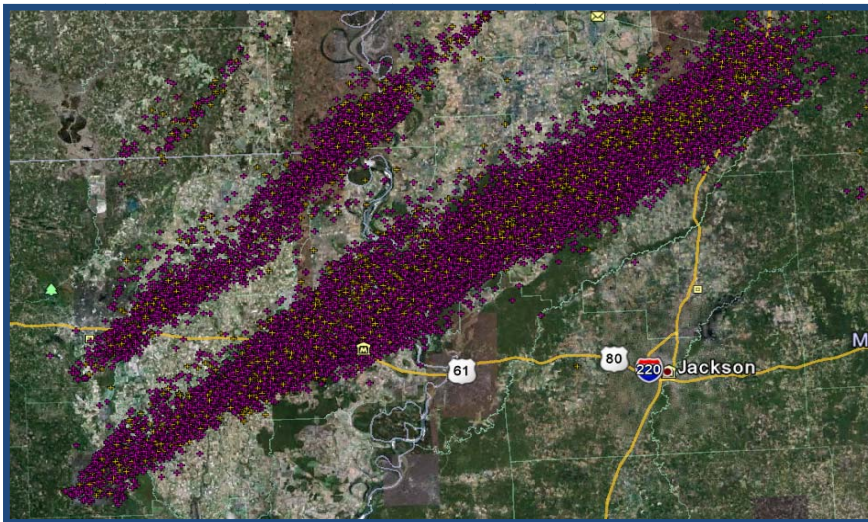


Figure 8: Lightning flashes detected by WTLN (April 24, 2010 1600 UTC – 1840 UTC). Purple dots represent IC flashes and yellow dots represent CG flashes.

Across the two states at least 10 people were killed and 146 injured. This storm produced a large number of flashes (139,152 flashes in about four hours, with the majority being IC). Figure 8 shows the flashes along a portion of the tornado track. This storm produced a large number of flashes (139,152 flashes in about four hours, and a majority of them were ICs); Figure 8 shows the flashes along a portion of the tornado track.

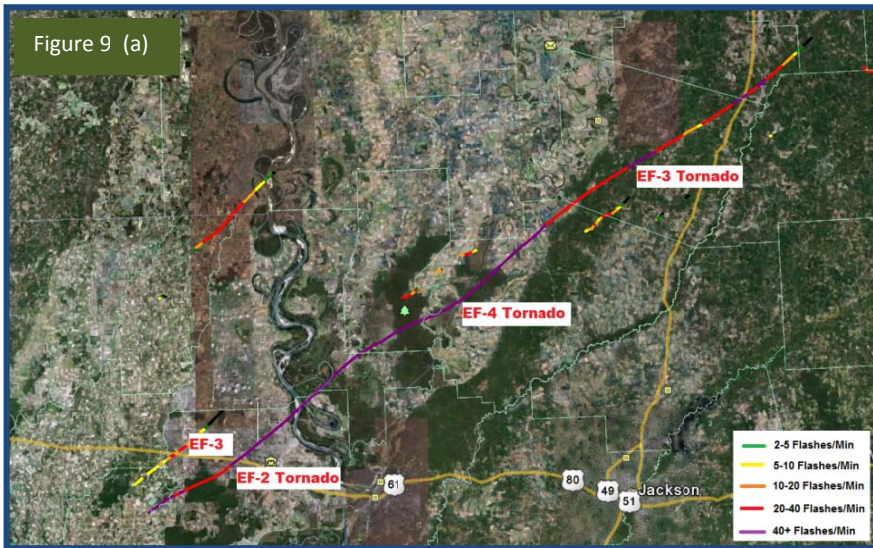


Figure 9 (a)

Figure 9(a) shows that a single lightning cell track formed and lasted during the tornado's lifetime. Figure 9(b) shows the area covered by the lightning cell, which is very close to the tornado's tracks from the storm report in Figure 7. Based on the cell tracker, the first DTA from the previous adjacent lightning cell was issued at 10:07 a.m. CDT. Without the previous cell, the first alert from this cell would be at 10:35 a.m. CDT, a 35-minute lead time before the tornado touchdown.

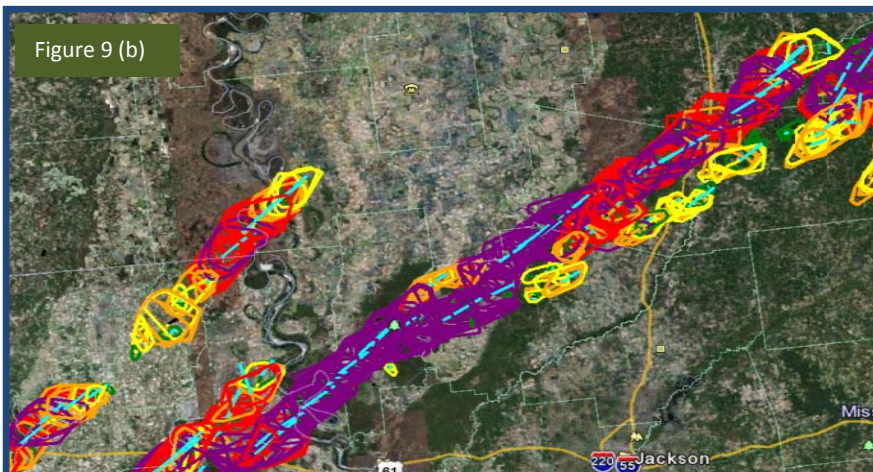
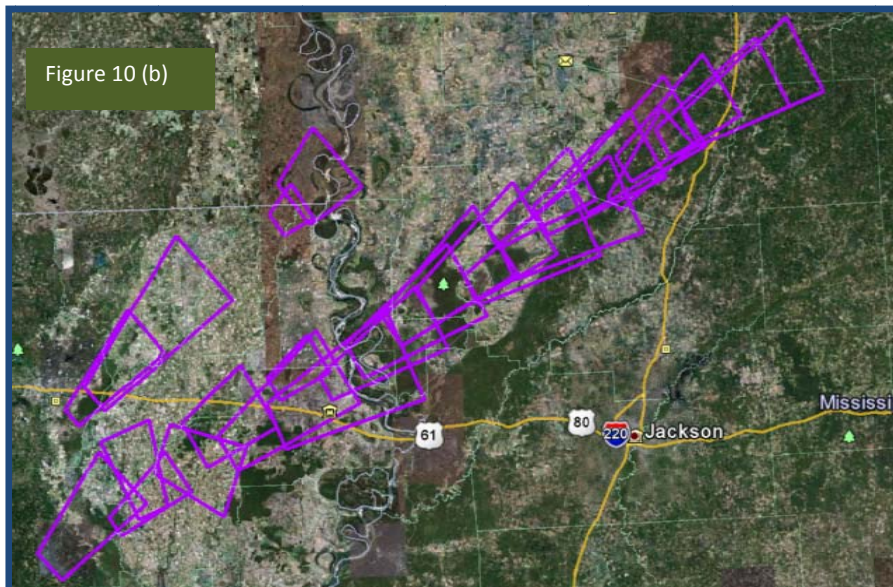
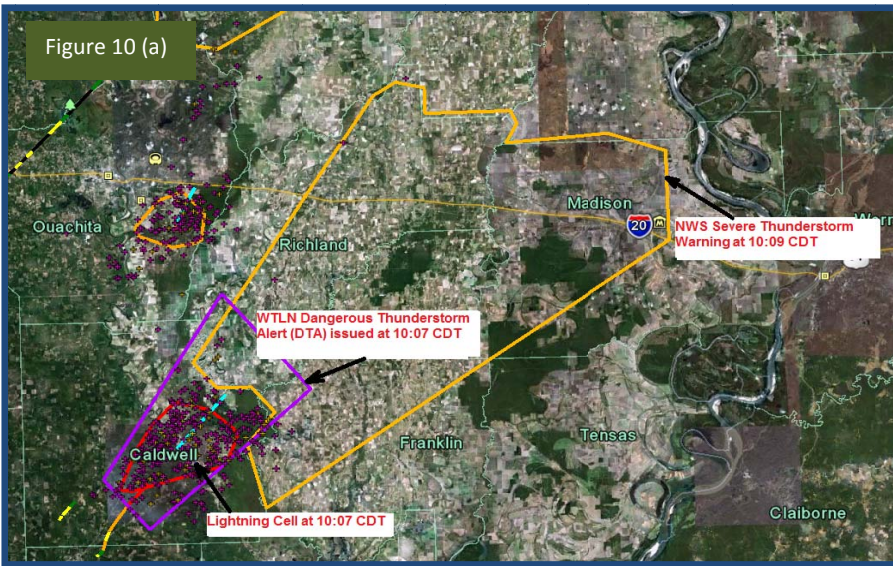


Figure 9 (b)

Figure(s) 9: (a) Lightning cell tracks detected from WTLN for the tornado and (b) area covered by the lightning cells.



Figure(s) 10: (a) First alert polygon at April 24, 2010 1507 UTC and (b) subsequent alert along the path of the tornado.

Since the storm generated high flash rates continuously, the subsequent alert polygons covered the entire tornado track (Figure 10).

The lightning rate graph in Figure 11 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 (89 flashes/min) precedes the strongest tornado activity, producing EF-4 damage in this case.

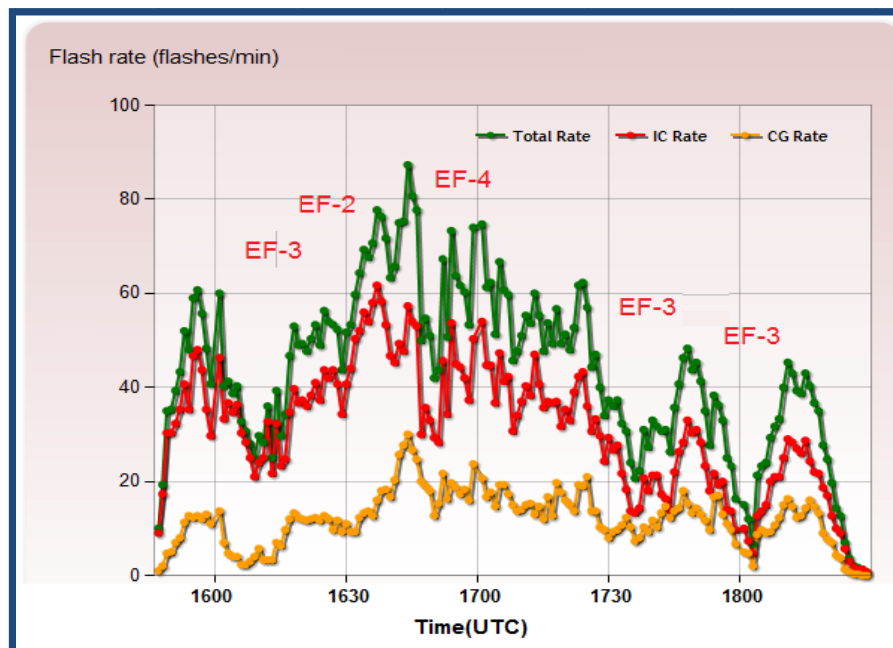


Figure 11: Lightning rates during the tornado, April 24, 2010.

2. Mississippi Hail Storm, May 2, 2010

Figure 12 shows a single two-hour long lightning cell in which the total lightning flash rate increases gradually with some early abrupt jumps followed by a gradual rate decrease. Multiple reports of golf-ball size hail were issued along the track of the cell, with most of the hail occurring during the descent after 71 flash/min flash rate peak. The first WeatherBug Dangerous Thunderstorm Alert (WDTA) from tracking this cell was issued at 2127 UTC, which is about 30 minutes before the first hail was reported.

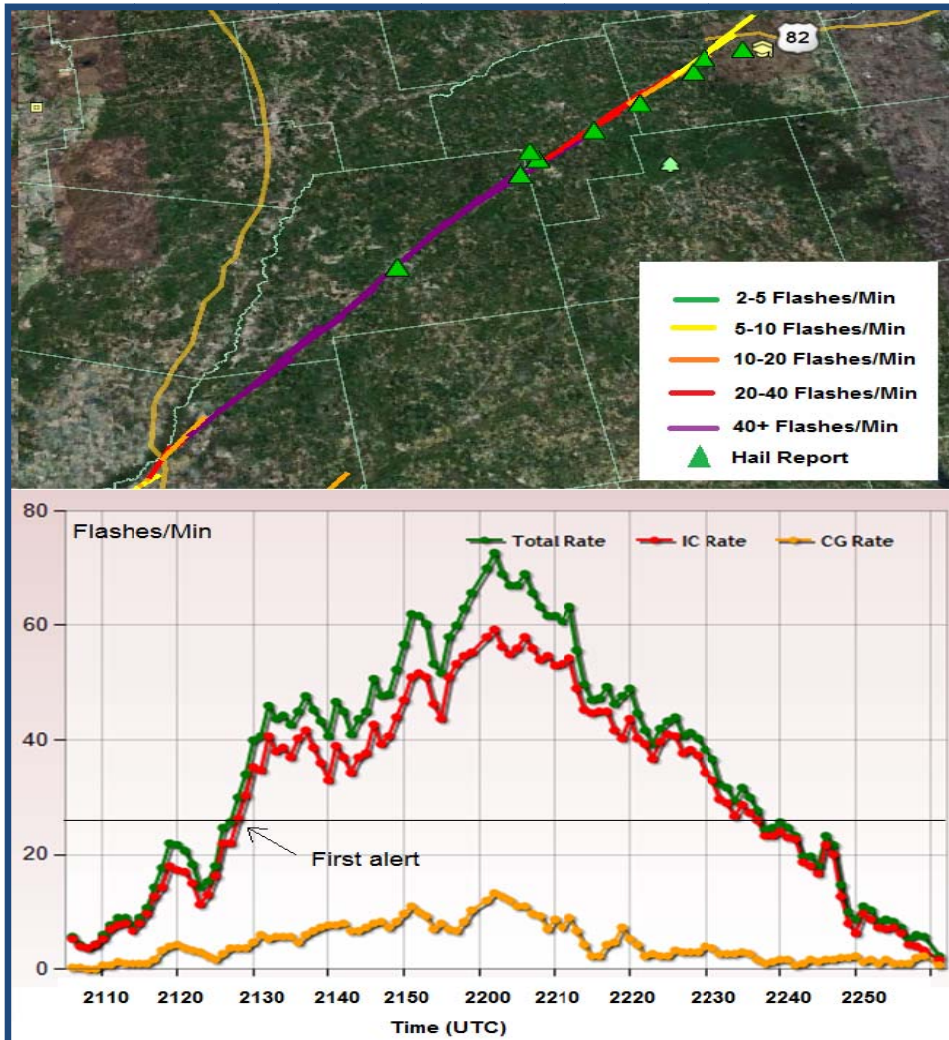


Figure 12: May 2, 2010 Mississippi Storm. The top graph shows the lightning cell track moving southwest to northeast; the green triangles are actual locations of reported hail. The bottom graph shows the lightning flash rates (Flashes/Min) during the storm.

3. South Dakota Tornado, July 6, 2010

This slow-moving storm near Brule, South Dakota, produced multiple-reported tornado touchdowns. Multiple quarter-size hail and wind damage reports were also received. From the storm timelines reported by NWS, the tornado touchdowns occurred when the total lightning flash rates dipped into the valley. The highest total lightning flash rate is 66 flashes/min and the highest IC rate is 51 flashes/min. The CG rates stayed relatively low and flat during the storm. The first WeatherBug Dangerous Thunderstorm Alert (WDTA) from tracking this cell was issued at 2035 UTC, 46 minutes before the first touchdown was noted. Flash rates in most of the storms with tornadoes tend to fluctuate more dramatically than in storms with only hails or winds. Further study to identify the signatures of the different storms from the total lightning rate distribution is needed.

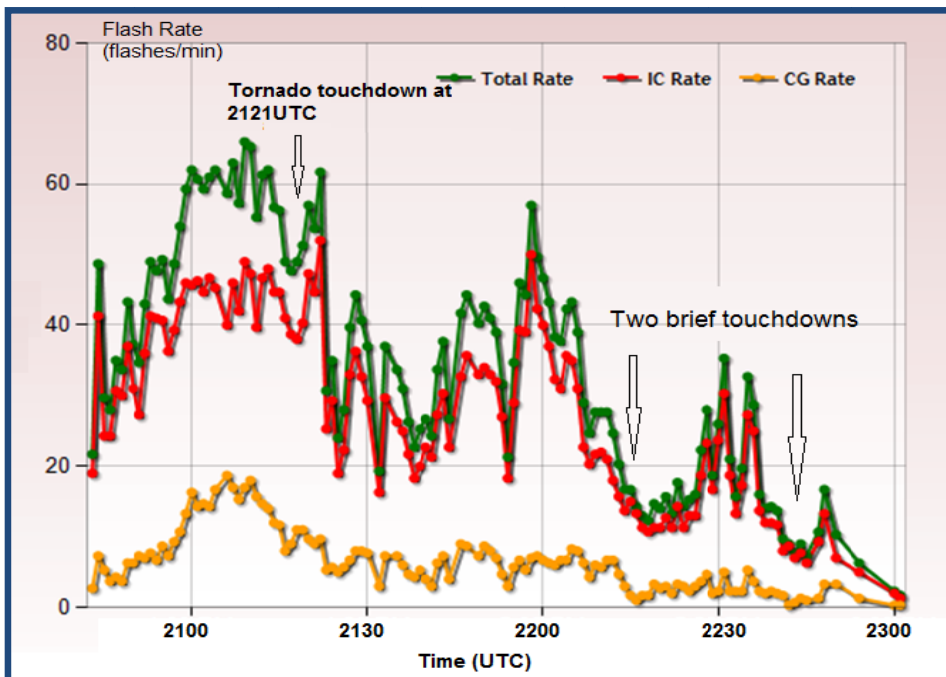


Figure 13: Flash rate from July 6, 2010 storm, Brule, South Dakota.

Conclusions

This study provided further facts about the relationship between the total lightning rate and severe weather; CG flash rate in a storm does not have a clear correlation with the severe weather activities, but 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. By tracking the lightning cells in a storm and monitoring the total lightning flash rates, it is possible to issue WeatherBug Dangerous Thunderstorm Alerts (WDTAs) with a lead time of up to 30 minutes before ground-level severe weather develops. WTLN 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 WeatherBug Dangerous Thunderstorm Alerts (WDTAs) 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. Further study is needed to determine the appropriate WeatherBug Dangerous Thunderstorm Alert (WDTA) threshold for various storm characteristics and relative geographic differences in WTLN detection efficiency. Further study is also needed to correlate the WeatherBug Dangerous Thunderstorm Alert (WDTA) to NWS severe thunderstorm warning to evaluate lead time and accuracy.

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