

POSITIVE LIGHTNING ACTIVITY DURING AN INTENSE DERECHO

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ABSTRACT: A derecho is an extratropical mesoscale convective system (MCS) that produces damaging winds from a series of downbursts. On 4 July 1999, a severe derecho caused extensive damage to forested regions along the United States/Canada border, west of Lake Superior. There were 665,000 acres of forest destroyed in the Boundary Waters Canoe Area Wilderness (BWCAW) in Minnesota and Quetico Provincial Park in Canada, with approximately 12.5 million trees blown down. This storm resulted in additional severe weather (hail, wind and tornados) before and after the occurrence of the derecho, with continuous cloud-to-ground (CG) lightning occurring for more than 34 hours during its path across North America. At the time of the derecho the percentage of positive cloud-to-ground (+CG) lightning measured by the Canadian Lightning Detection Network (CLDN) was greater than 70% for more than three hours, with peak values reaching 97% positive CG lightning. Such high ratios of +CG are rare, and may be useful indicators for short-term forecasts of severe weather (Price and Murphy, 2002).

INTRODUCTION

A derecho is an extratropical mesoscale convective system (MCS) that produces damaging winds from a series of downbursts. These damaging downbursts occur with bow echoes observed in conventional radar imagery. A derecho must have a damage path of at least 450 km in length, with at least three reports of hurricane force winds, each separated by at least 75 km, and with no more than three hours between successive wind damage events (*Fujita and Wokimoto, 1981; Johns and Hurt, 1987*).

Bow echoes are typically 20-120 km long bow-shaped systems of convective cells that are noted for producing long swaths of damaging winds. They tend to propagate in the direction of the mean low-level flow. The shape of the bow is formed by the presence of an elevated rear inflow jet (RIJ), which accelerates the mid section of the bow forward. The RIJ forms due to density differences that occur at the boundary of cold dry air, and warm moist air meeting along a cold front. A vertical cross section in the core of the bow echo reveals a strong, vertical updraft at the leading edge of the system. The updraft turns rapidly rearward at mid levels feeding into a stratiform precipitation region. A strong elevated RIJ flows horizontally toward the updraft core before descending rapidly to the surface at the boundary of the cold and warm air (*Weisman, 1993*).

The edges of the bow echo are often associated with line-end or bookend vortices that can strengthen the RIJ and result in extremely intense damaging surface winds. Since the RIJ is bringing in dry cold air toward the updraft, it appears on radar images as a weak V-shaped echo, or rear-inflow notch (RIN), pointing toward the strong gust front (Figure 1). The RIJ in Figure 1 accelerated this storm from 100 km/h to about 150 km/h, resulting in potential low-level wind speeds approaching 200 km/h in the region of extensive blowdown (*Parke and Larson, 2000*).

The intensity of a derecho depends on a number of environmental factors: a) the density difference between the cold, dry outflow air and the warm, very humid air being displaced by the outflow; b) the intensity of the warm updraft which results in a local area of low pressure at the base of the updraft, accelerating the cold, dense RIJ forward and downward into the low-pressure layer; c) the amount of horizontal vorticity generated by the inflowing warm air (due to friction with the ground) that can further accelerate the RIJ downward and forward; d) precipitation and evaporation from the stratiform region of the storm can further cool and increase the density of the outflow air behind the front; and e) large scale cyclonic circulation north of the bow echo and anticyclonic circulation south of the bow echo can focus the rear jet and hence influence the intensity of the derecho (*COMET, 1999*).

METEOROLOGICAL CONDITIONS

Periodically from late June through early September, a warm area of high pressure in the troposphere located in the western North Atlantic Ocean called the "Bermuda High," is displaced westward to lie over the

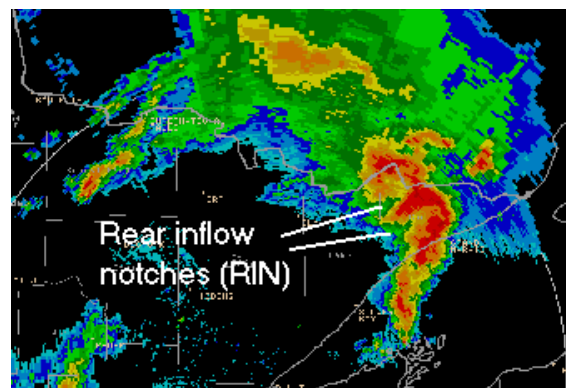


Figure 1. Radar reflectivity PPI-scan (Plan Position Indication) at the time of the derecho (1817 UTC 4 July 1999) showing a bow echo with well defined rear inflow notches (RIN).

southern or southeastern United States. The airmass associated with this area of high pressure warms adiabatically as it subsides. The result is a "capping inversion", which is usually able to effectively suppress the development of deep convective storms. The northern periphery of this region is often characterized by warm and moist advection in the low-levels, mid-level cold advection, and high-level divergence. This region is often referred to as the "ring of fire" since lifting and destabilization can be enhanced by the presence of transient low pressure troughs in the mid-troposphere, often sufficient to overcome the capping inversion along its edge, resulting in the release of buoyant energy, and the development of organized deep convective storms.

At 00 UTC 4 July 1999, the westward displaced Bermuda High, characterized by 700 mb temperatures from 10-16°C, was situated over the Ohio Valley with a high pressure ridge extending northward across the western Great Lakes. A strong low-pressure trough in the mid-troposphere extended from Saskatchewan southwestward into Washington and Oregon and was moving eastward. The polar frontal boundary, which was approximately co-located with the southern edge of the stronger upper wind flow would be the focus for the development of deep convective storms. At 300 mb, a strong upper-level jet stream remained along the southern edge of this cold air, extending into northern Ontario, with maximum wind speeds around 70 ms⁻¹. At 850 mb a southwesterly low-level jet stream extending from the western Gulf of Mexico into southern Minnesota advected large amounts of warm air and tropical moisture to the northern edge of the capping inversion. An additional source of moisture was evapo-transpiration from the forest canopy and undergrowth. The two months prior to the day of the derecho had above normal temperatures and near record rainfall, saturating the ground and stimulating rapid growth of vegetation. The combined effects of the low-level warm advection and evapo-transpiration resulted in surface dew point temperatures from 25-26°C and 850 mb dew points between 19-20°C by 1200 UTC (early morning local time). The approaching cold air aloft caused a dramatic destabilization of the atmosphere at the time when the bow echo started to form.

Severe bow echoes are most often observed in environments with moderate-to-strong low-level vertical wind shear, and very high convective available potential energy (CAPE) (Johns, 1993). At 1200 UTC 4 July 1999 (prior to the derecho), nearby rawinsonde analyses from Aberdeen SD (KABR), Chanhassen MN (KMPX), and International Falls MN (KINL) indicated that the most unstable CAPE ranged from moderately unstable (760 Jkg⁻¹) at KINL, situated somewhat north of the surface front, to very unstable (3660 Jkg⁻¹) at KABR in the warm sector. However, the data indicated that the airmass in the region was strongly capped. The rawinsonde data were characterized by very strong low-level (0-2 km above ground) storm relative flow, but weaker mid-level (4-6 km above ground) storm relative flow. These results indicated that the large-scale environment had many characteristics in common with that normally associated with the occurrence of warm season derechos (Evans and Doswell, 2001).

This storm was quite extraordinary for a number of reasons. As is shown in Figure 2, the storm had a very long lifetime. The approximate location of the center of the storm is shown based on GOES-8 satellite imagery, together with lightning data obtained from the Canadian Lightning Detection Network (CLDN). Locations are shown every 3 hours, and times are shown when the CG flash frequency was higher than 15 flashes per 5-minute period (3 flashes/minute). Based on Fig. 2 the storm was active (>15 CG per 5-minutes) for more than 34 hours! After traveling over the Atlantic this storm re-entered the United States just north of Myrtle Beach, South Carolina on 6 July 1999, with additional severe weather damage. Severe wind damage from this storm covered a total distance of more than 11,000 km from Nebraska through Ontario and Quebec, onto New England, and finally through Georgia, Alabama and Mississippi. The storm maintained itself for more than 2 days, resulting in extensive damage at all times it was found over land.

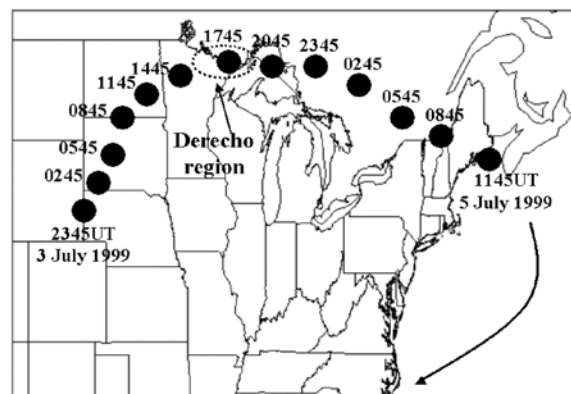


Figure 2. Location of the storm center from 2345 UTC on 3 July until 1145 UTC on 5 July 1999 at 3-hour intervals. The region of the severe blowdown (derecho) is indicated by the dotted area. The arrow represents the path traveled by the storm while over the Atlantic.

LIGHTNING ANOMALIES

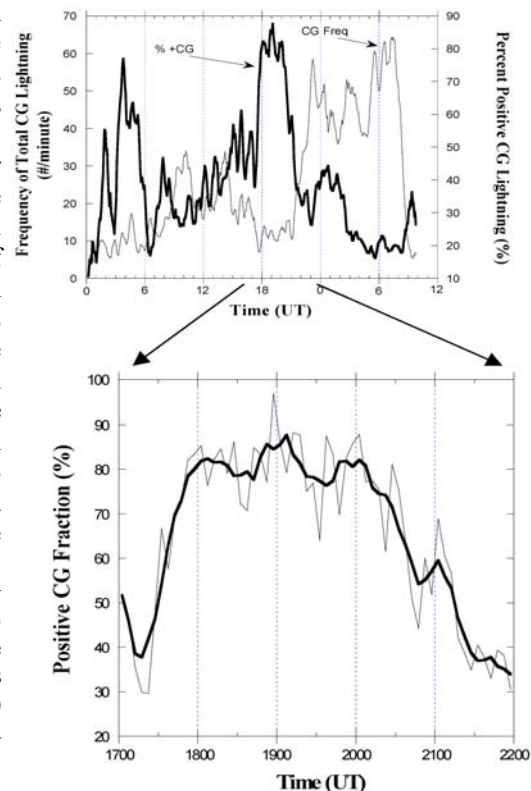
The lightning data used in this study are part of the Canadian Lightning Detection Network (CLDN) (Burrows *et al.*, 2002). The CLDN has been archiving lightning data since 1998, and covers all of Canada and the northern portions of the United States. As mentioned above, the times shown in Figure 2 represent the continuous period (0000 UTC 4 July – 1200 UTC 5 July) when CG lightning frequencies were greater than 3 flashes per minute. As shown in Figure 3a the total CG lightning frequencies never dropped below this value for 34 hours. The area of the storm did change with time, covering larger areas when it passed over Canada and

New England, and hence the greater lightning frequencies. Near the end of this storm there was more than one CG flash every second. It should be noted that intracloud flashes (IC) are not detected by the CLDN very efficiently. Hence the true flash frequency of all lightning was likely a factor of 3-4 greater. Furthermore, there may be some ambiguity between IC flashes and positive flashes with peak currents less than 10 kA. We did not adjust for this since forecasters receive the lightning data with no corrections made. However, removing the weak positive flashes from the data set made no significant changes to our results.

The lightning activity from this storm was separated subjectively from other storms occurring at the same time using satellite, radar and lightning data. Individual storms can normally be well isolated spatially from other storms occurring at the same time.

Of special interest in Figure 3 is the fraction or percentage of lightning that has positive polarity. Positive CG lightning (+CG) is normally quite rare, with measurements around the globe showing only about 5-10% of summer CG lightning being positive in polarity. The reason for this is that the negative charge center in thunderstorms is usually a lot closer to the ground than the positive charge center, resulting in more frequent -CG discharges to ground than +CG discharges. In the US and Canada the summer time climatological fraction of positive CG lightning is less than 10% (Orville *et al.*, 2002). For this reason it is interesting to note the large percentage of positive lightning, and the rapid change in storm characteristics, that occurred during the lifetime of this storm.

Figure 3. a) Time series showing 34 hours of lightning activity associated with this storm (00 UT 4 July – 12 UT 5 July, 1999) showing the total CG frequency (flashes/minute), and the percentage of positive CG flashes; b) a zoom of the time series during the period of the derecho (17 UT-22 UT 4 July, 1999) showing 80% positive CG lightning for more than 2 hours, and a peak 5-minute value of 97%. (5-minute values: thin curve; 25 minute running mean: bold line)



The most striking anomaly in Figure 3a occurs between 1800-2100 UTC on 4 July (Figure 3b). This is the period of the derecho and extreme wind damage along the US/Canada border. There were also numerous reports of hail and wind damage across Minnesota. During part of this 3-hour period the storm was located over Lake Superior, which reduced the potential for severe damage or injury. There are also other +CG anomalies around 0200-0500 UTC on the 4th, and 0000-0200 UTC and 0900 UTC on the 5th. All these periods are associated with severe weather reports in South Dakota, Ontario, Quebec and New England (tornadoes, large hail or wind damage).

In Figure 3b, the 5-minute +CG fraction is given during the most intense portion of this storm, namely the derecho and blowdown of 12.5 million trees over a distance of 220 km (dotted area in Figure 2). During the passage of the storm in this region the positive fraction of CG remained above 70% for more than 3 hours, above 80% for approximately 2 hours, with a peak 5-minute value of 97%! As mentioned above, it is fortunate that the storm spent a number of hours over Lake Superior, preventing potential damage to property and injury to people in the surrounding areas. It is also interesting that during this most intense portion of this derecho, the total CG lightning frequency was much lower than during the period before and after (Fig. 3a), with a minimum of approximately 6 flashes/minute at 1745 UTC just prior to the onset of the derecho. A decrease in total lightning activity shortly before the occurrence of severe weather has been previously documented (Perez *et al.*, 1997). It should be noted that the mean magnitude of both negative (-16 kA) and positive (+24 kA) peak currents did not change dramatically during the lifetime of this storm, and showed no correlation with the severe weather reports.

It is not known what causes the percentage of +CG to change so dramatically during the lifetime of a single storm. A number of theories have been suggested (Williams, 2001). The most realistic appears to be the positive charging of large precipitation particles in the strong updraft when the cloud liquid content is sufficiently large (Takahashi, 1978). This positive charging near the 0°C isotherm would be able to explain the enhanced positive lightning during the severe weather conditions. It could also explain the rapid transition of the storm from a low (high) percentage of +CG to a high (low) fraction over a short period of time. This hypothesis is strengthened by the fact that the large majority of the positive lightning occurred within the convective cores of these storms (based on radar) and not in the usual stratiform region of MCSs. In addition, it

is also possible that intracloud lightning could be short-circuiting the lower negative charge center, and therefore increasing the positive fraction by decreasing the negative CG flashes. This appears to be the case during the derecho phase of the storm since the actual number of positive flashes remained fairly constant through this period. Hence the fraction of positive flashes can change due to increases in +CG lightning or decreases in -CG lightning.

It has been previously noted that severe weather is related to high +CG fraction (Seimon, 1993; MacGorman and Burgess, 1994). This study further supports this idea, and perhaps strengthens the case for using lightning data for detecting and perhaps nowcasting severe weather events (Brannick and Doswell, 1992). As shown in Figure 3b the extreme positive lightning values increased to 80% before 1800 UTC, while the extensive wind damage continued throughout Ontario and Quebec for a number of hours.

CONCLUSION AND DISCUSSION

An extremely long-lived severe storm crossed the United States and Canada on 4 and 5 July 1999. This storm had continuous lightning activity over more than 34 hours, and resulted in large amounts of damage resulting from strong winds. Just before passing from the United States into Canada along the Minnesota/Ontario border, a bow echo developed and produced an intense derecho. The derecho passed through two nature reserves blowing down 12.5 million trees over a 215 km path. The storm resulted in additional blowdowns in Ontario and Quebec later in the storm lifetime.

The lightning activity associated with the storm showed large fluctuations in the percentage of positive cloud-to-ground lightning. During the derecho phase of the storm the positive lightning was greater than 70% for more than 3 hours, with a peak 5-minute value of 97%. At the same time the total CG lightning frequencies during this 3-hour period was relatively low compared with the periods before and after the derecho.

During the 34-hour period of the storm, there were other periods of high positive lightning activity, all associated with severe weather reports. It therefore appears that the fraction of positive lightning may be linked to the likelihood of severe weather, and may be used by forecasters as a tool for nowcasting severe weather.

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