2014
23rd International Lightning Detection Conference
18 - 19 March • Tucson, Arizona, USA
5th International Lightning Meteorology Conference
20 - 21 March • Tucson, Arizona, USA

Large Scale Outbreaks of Thundersnow and Self-Initiated Upward Lightning (SIUL) During Two Blizzards

Walter Walter A. Lyons and Thomas E. Nelson
FMA Research, Inc., Fort Collins, CO USA

Tom A. Warner, Alana Ballweber, Ryan Lueck
SD School of Mines and Technology, Rapid City, SD USA

Timothy J. Lang
NASA MSFC, Huntsville, AL USA

Steven A. Cummer
Duke University, Durham, NC USA

Marcelo Saba and Carina Schumann
INPE, Brazil

Kenneth L. Cummins
University of Arizona, Tucson, AZ USA

Nicolas Beavis and Steven A. Rutledge
Colorado State University, Fort Collins, CO USA

Timothy Samaras, Paul Samaras, Carl Young
Samaras Technologies, Bennett, CO USA

Abstract—**Upward lightning from tall objects can be either (1) triggered by preceding IC and/or CG flashes nearby, termed lightning-triggered upward lightning (LTUL), or (2) can be self-initiated upward lightning (SIUL). In the latter, upward leaders originate due to locally strong electric fields but without any preceding lightning. Observations have confirmed that the conditions producing sprites in summertime mesoscale convective systems also favor LTUL development, with both sometimes resulting from the same parent +CG. Though relatively infrequent, sprite-class +CGs also occur during continental winter cyclonic storms producing heavy snow and strong winds. Monitoring of two blizzards revealed one storm was devoid of energetic (sprite-class) lightning while a second produced considerable lightning, including some capable of inducing sprites. However, upward lightning from a variety of tall, and some not so tall (~100 m), structures occurred in both storms. These upward discharges were dominated by self-initiated upward lightning. It is believed that sufficiently intense electric fields were generated by elevated, embedded convective cells. The strong winds played a key role in "stripping away" the corona discharge shielding at the tops of tall objects allowing for leader initiation, as has been observed in Japanese winter snowstorms.**

Keywords—lightning; self-initiated upward lightning (SIUL); thundersnow; sprites; charge moment change

INTRODUCTION

A long term research goal has been the documentation of the range of meteorological regimes which produce energetic CG lightning capable of inducing mesospheric transient luminous events (TLEs) and, in particular, sprites [Lyons, 1996; Lyons, 2006; Cummer and Lyons, 2005; Lang et al., 2011a]. Sprites can occur in almost any type of convective storm in which sufficient charge is lowered to ground by CGs with enough total charge moment change (CMC) to trigger mesospheric electrical breakdown [Lyons, 2006]. Total CMC values larger than ~500 C km for +CGs (and perhaps twice that for the very rare –CG sprites [Lang et al., 2013]) can often induce a sprite. The sprite parent +CGs are most commonly found in the stratiform regions of large continental mesoscale convective systems (MCSs) [Lyons et al., 2009; Beavis et al., 2014; Lang et al., 2010]. Since 2007, the National Charge Moment Change Network (CMCN) [Cummer et al. 2013] has provided near real-time monitoring of the impulse CMC (iCMC), which is defined as the portion of the total CMC occurring in the first ~2 ms of the discharge, including the return stroke (RS) and the initial continuing current (CC). Experience has shown that +CGs can begin to trigger sprites with iCMC values of ~100 C km (about 10% probability), rising to >75% probability with an iCMC >+300 C km [Lyons et al., 2009]. Positive CGs with >300 C km iCMCs are termed "sprite-class," or sprite parent +CGs (SP+CGs) if there was an optically confirmed sprite.

A climatology of the density of >300 C km iCMC +CGs, broken down by season created by Beavis et al. [2014] shows their occurrence closely follows the seasonal migration of large MCSs in the U.S. (Fig. 1). During the winter months, sprite class +CGs are concentrated in the southeastern U.S. during outbreaks of convective storms associated with frontal systems [Beavis et al., 2014; Orville, 1990, 1993]. Yet, routine monitoring of the CMCN has documented sporadic occurrences of sprite-class iCMC +CGs in a variety of "cold air" precipitation systems in other parts of the nation. Sprite-class iCMCs occur in west coast winter cyclonic storms [Cummer and Lyons, 2008], a region with a high percentage of winter +CGs [Orville et al., 2011]. These are sometimes accompanied by reports of spectacular upward lightning discharges from tall structures and bridges [Warner et al., 2011; Lyons et al., 2012]. Holle and Watson [1996] documented two outbreaks of energetic lightning in the central U.S., both producing >50% +CGs during freezing rain north of a warm front associated with embedded convective cells of “moderate reflectivity.” On 11 February 2008, the CMCN recorded a cluster of sprite-class +iCMCs in southwestern Missouri, with freezing rain and sleet and surface temperatures as low as -5 to -10°C [Lang et al., 2011b; Lyons and Cummer, 2008; Lyons et al., 2012]. Intense overrunning was generating moderately strong (~40-45 dBZ) embedded convective cells which supplied the requisite charge. Other types of winter convective systems can generate documented SP+CGs. Sprites are routinely observed above powerful +CGs within intense snow squalls during arctic outbreaks over the Sea of Japan [Brook et al., 1982; Takeuti et al., 1976, 1978; Takahashi et al., 2003; Suzuki et al., 2006; Matsudo et al., 2007]. The same processes occur, though less frequently, during cold air advection over the Great Lakes [Moore and Orville, 1999; Schultz, 1999; Steiger et al., 2009]. Though sprite-class +CGs have been detected over the Great Lakes [Lyons et al., 2012], sprites have yet to be optically confirmed. The same can be said for sprite-class +iCMCs lightning over the Gulf Stream during arctic outbreaks, where sprites have also been predicted [Price et al., 2002; Beavis et al., 2014; Lyons et al., 2012].

Thundersnow events in large, mid-continental cyclonic storms have long been of interest, as there appears to be some correlation between winter lightning and intense snowfall rates [Lyons, 1989; Market and Becker, 2009; Crowe et al., 2006]. Thundersnow is relatively rare, estimated to account for only 0.1 to 0.01% of all NLND reports [Walt Peterson, 2012, personal communication]. A climatological study by Market et al. [2002] uncovered only 191 thundersnow events between 1961-1990. They generally occurred within a broad band through the central plains and the Great Lakes states, with relatively few in the southern plains or southeast. Market and Becker [2009] noted that of 1088 CGs in 24 thundersnow events, 80% were of negative polarity. This is in contrast to the general perception that thundersnow is often associated with +CGs. Yet the CMCN does occasionally record sprite-class +CGs within regions of heavy snowfall during cyclonic storms, as in North and South Dakota, on 28 February 2008 [Lyons and Cummer, 2008]. An existing network of SpriteNet cameras, normally used to monitor summer MCSs for sprites [Lu et al., 2013], has been on standby to optically confirm sprites above winter cyclonic storms, but this has yet to be successful. The storms discussed below were targeted in this hope. In the process, a totally unexpected finding emerged, i.e., the widespread occurrence of self-initiated upward lightning (SIUL) from tall structures in regions experiencing heavy snow and high winds.

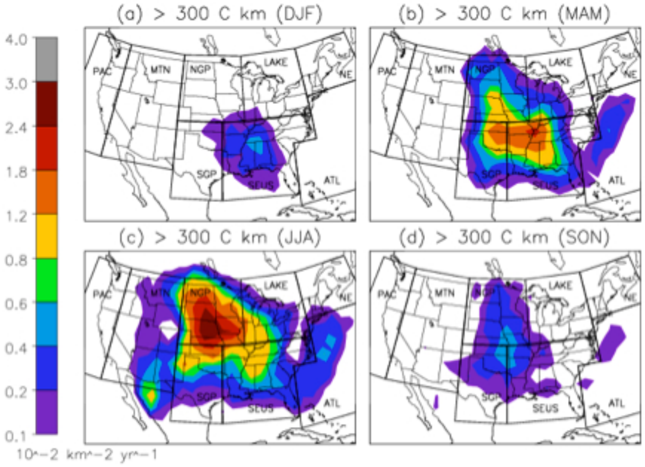


Figure. 1. The density of sprite-class +CGs (those with iCMCs >300 C km) over the continental United States broken out by season (Beavis et al., 2014).

Interest in upward lightning from tall objects is long standing [McEachron, 1939; Berger, 1967; Orville and Berger, 1973; Eriksson and Meal, 1984; Hussein et al., 1995; Rakov, 2003]. Since 2006, monitoring of upward lightning during Project UPLIGHTS from 10 towers located on a ridge in Rapid City, SD has documented numerous examples of lightning-triggered upward lightning (LTUL) [Warner, 2011; Warner et al., 2012a, 2012b, 2012c; Warner et al. 2013]. There are two modes of LTULs. Upward leaders from towers can be triggered by 1) the approach of horizontally propagating negative stepped leaders associated with intracloud lightning or a +CG, and/or 2) a +CG return stroke as it propagates through a previously formed leader network that passes near the towers. Lyons et al. [2014, this conference] provide detailed illustrations of these two modes of LTUL. As noted by Lueck [2013], during summer convective systems, LTULs are typically found within extensive MCS stratiform regions, often some distance from the convective core.

Stanley and Heavner [2003] reported SP+CGs were often followed by NLDN [Cummins et al., 1998; Cummins and Murphy, 2009] reports of -CGs from tall towers, some up to 50 km distant. These detections result from recoil leaders [Mazur, 2002] and reconnecting stepped leaders to towers following an initial upward positive leader formation. This hypothesis motivated an ongoing monitoring program for concurrent sprites and LTULs. For the Rapid City towers, at least one half dozen sprites induced by the sprite parent +CG that also triggered an LTUL have been documented to date [Lyons et al., 2011; Warner et al., 2011]. Both SP+CGs and LTULs favor the same meteorological regimes (large stratiform regions in summer MCSs) and lightning characteristics (energetic +CG discharges with vast horizontal networks of negative leaders travelling through the stratiform positive charge regions.)

It has been speculated that large +iCMC CGs sometimes found within heavy snow bands in mid-continental cyclonic storms are generating sprites [Lyons, 2006] and perhaps LTULs from tall objects as well [Lyons and Cummer, 2008; Lyons et al., 2012]. The studies presented below suggest that while this may indeed be possible, a more frequent upward lightning mode appears to be SIULs. These upward leaders arise from the tops of tall objects in the presence of intense electric fields without any preceding +CG or overhead IC leaders. Extensive discussions of this phenomenon can be found in Rakov [2003] and Wang et al. [2008]. SIULs appear to show a definite preference for cold season storms, often with low cloud ceilings and strong winds [Zhou et al., 2012; Diendorfer et al., 2009; Wang and Takagi, 2012].

MIDWEST BLIZZARD OF 1-2 FEBRUARY 2011

A major blizzard was forecasted to move through the central U.S. on 1-2 February 2011. SpriteNet cameras, the CMCN, and other resources were prepared to monitor for energetic lightning events in the storm, which materialized as predicted (Fig. 2). A ~200 kilometer wide band of heavy snow and intense winds stretched from central Oklahoma through northern Illinois and eastward into Ontario and New England. Snow totals in northern Illinois, likely enhanced by the warm waters of Lake Michigan, approached 20-30 inches (51-76 cm) in some areas (Fig. 3). Chicago proper experienced over 21 inches (54 cm) of snow, with wind gusts near 70 mph ($31\ m\ s^{-1}$) causing total traffic paralysis. Most interestingly, media broadcasts from the Chicago Loop around 0300 Z on 2 February included live reports of thundersnow, apparently resulting from discharges atop local skyscrapers. Given that low-level winds were off Lake Michigan, where the NLDN was indicating no lightning, this prompted a more detailed investigation of the lightning reports within the snow band.

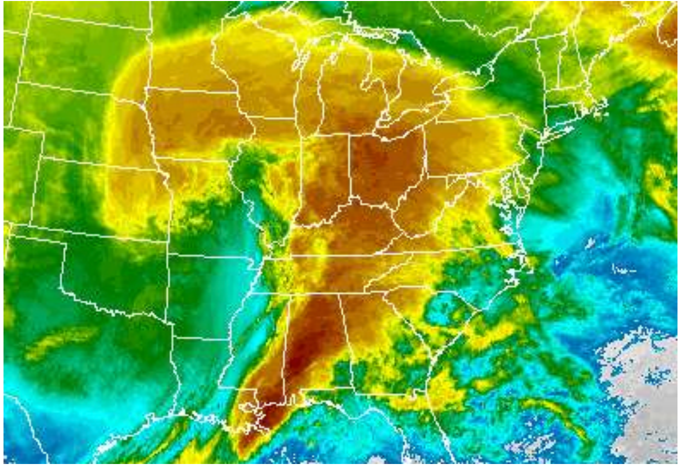


Fig. 2. GOES infrared satellite image at 2215 Z on 1 February 2011. An intense occluded low pressure center is located in east central Illinois. A dry wedge is intruding behind the cold front, with air overrunning the cold surface air in the southern edge of the comma cloud, resulting in elevated, embedded convective cells. Thundersnow was reported in northern Illinois at this time.

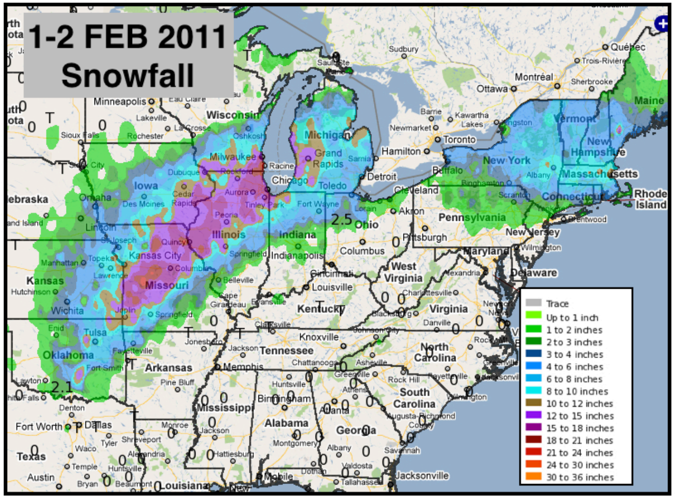


Fig. 3. Total snowfall for the 1-2 February 2011 storm (inches). Heaviest accumulations were in northern Illinois, where the maximum in thundersnow lightning occurred.

There was considerable warm sector lightning during this storm (generally south of the Ohio and east of the Mississippi Rivers). More notable was a persistent clustering of lightning within the heavy snowfall region. A total of 282 flashes were reported within the area of highest accumulations (thundersnow lightning). This is a rather large number compared to other storms [Rauber et al., 2013]. Thundersnow often occurs in the northwest and northern sector of occluded cyclones, with the maximum frequency found in a broad band from the Great Salt Lake region through the northern plains and Great Lakes states [Market et al., 2002]. Typically 80% of the NLDN reports in snowstorms are negative polarity. In this case, when the 1153 individual stroke events were examined, the total was 93% negative polarity, with 534 reported -ICs and 579 reports of -CGs. The NLDN reports in the Chicago Loop found a clustering of 43 events around two tall buildings, the Willis (Sears) Tower and Trump Tower (Fig. 4). This prompted a more in depth examination of the NLDN data by comparing their locations to the FCC's Antenna Structure Registration (ASR) tower database, as well as inspection of Google Earth imagery. In this analysis, a flash was defined as the grouping of NLDN events that occurred within 1 second

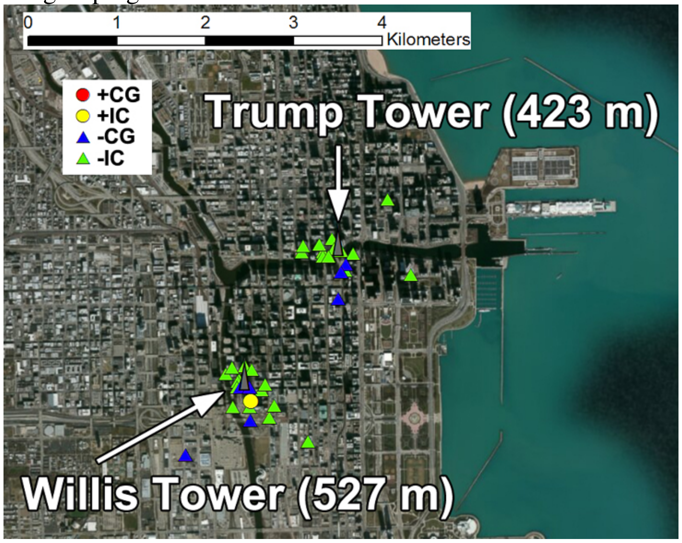


Fig. 4. A clustering of NLDN reports around two tall skyscrapers in the Chicago Loop during the height of the blizzard, 00-05 Z on 2 February 2011. A total of 11 suspected SIUL flashes were comprised of 43 events, mostly NLDN detected -CGs and –ICs resulting from impulsive processes within the upward branching discharge.

and within 50 km of any initial NLDN event in the heavy snowfall region. The spatial criterion was based on the observation that clearly identifiable, temporally isolated discharges can have extensive horizontal leaders emanating from tall towers that can progress up to 50 km from the initial NLDN-indicated event [Warner, 2011; Kuhlman and Manross, 2011] Schultz et al. [2011] reported SIULs during thundersnow events near Huntsville, AL included leaders tracked using a 3-D LMA to distances of 80 km.

If one event in a flash was within 1 km of a tall object, then all of the events for that flash, as well as the flash itself, were assigned a classification of Yes, indicating they were associated with a suspected upward flash from a tall object. Those flashes that had at least one event within 3 km of a tall object, but none within 1 km, were assigned the classification of Maybe, indicating that flash may have begun with an undetected upward flash from a tall object. Similarly, all of the events within a flash classified as Maybe were assigned a classification of Maybe. If a flash did not meet the previous criteria, it was assigned a classification of No, along with the associated events.

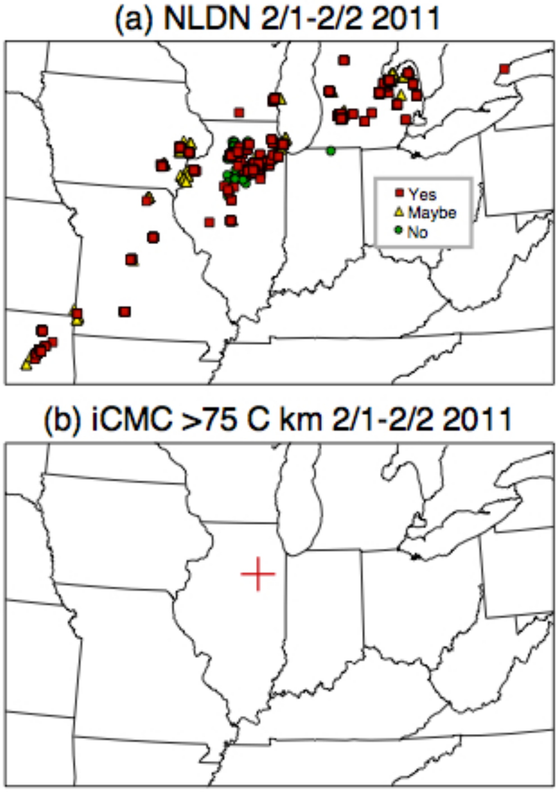


Fig. 5. (a) Distribution of all NLDN reports within the heavy snow band during the blizzard of 1-2 February 2011 over a 26-hour period. The events clearly associated with SIULs (Yes) are shown in red, with likely (Maybe) in yellow. Those CG and IC reports for which an elevated object could not be associated are termed No (green). Note the lack of lightning reported over the warm waters of the Great Lakes. (b) The only energetic lightning reported in the snow band during the entire storm was a 100 C km +CG in east central Illinois.

Based on these criteria, 72% of the flashes were classified as Yes, 21% as Maybe and 7% as No. Furthermore, 75% of the NLDN events were classified as Yes, 19% as Maybe and 6% as No. Fig. 5 a shows all the examined NLDN events, color-coded as to whether they were very likely (Yes), possibly (Maybe) or not apparently (No) associated with tall objects. And even the relatively few (6.4%) No events should be taken with a grain of salt. Inspection of currently available Google Earth imagery revealed a number of obvious tall structures, including transmission line towers, not included in the latest ASR update. Many of the participating structures, such as transmission lines and wind turbines, are less than 100 m tall. Even smaller towers, such as new cell phone towers or ham radio antennas not in the ASR database, may be difficult to spot in Google Earth imagery and were thus not identified.

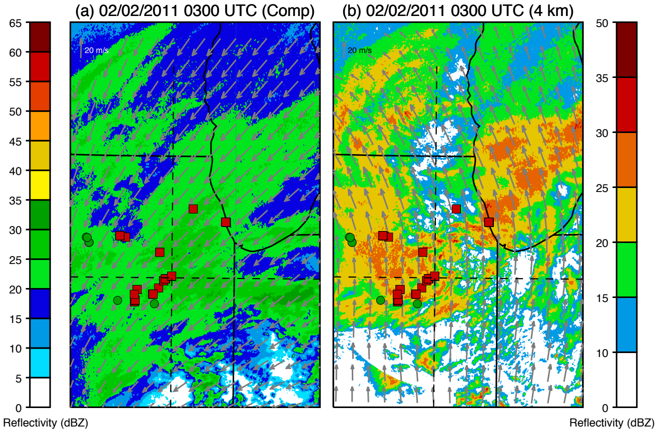


Fig. 6. (a) Composite NMQ reflectivity at 0300 Z, 2 February 2011. Shown are 0300 Z RUC 950 hPa horizontal vector winds (grey; degraded to 0.2° latitude/longitude resolution for clarity). NLDN events during 0255-0305 Z are indicated by symbols (red – SIUL; green – no tall object involved). (b) Same except that the display is a 4-km CAPPI with the RUC winds at the 600-hPa (~4-km) level. Note that a non-standard reflectivity color scale is used to accentuate the embedded convective cells. The dashed lines indicate the vertical cross–sections in Figure 7.

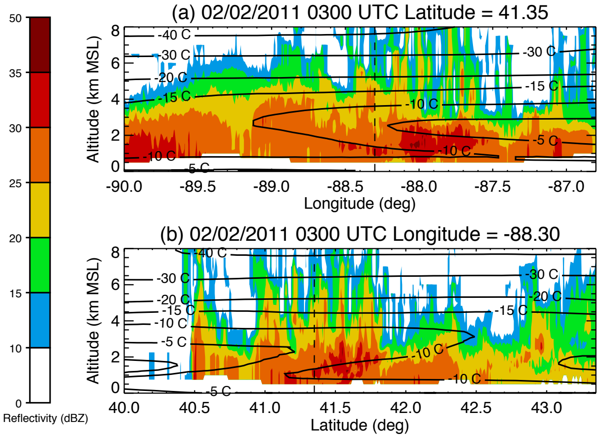


Fig. 7. (a) Vertical cross-section of 0300 Z NMQ radar reflectivity (shaded) and RUC temperatures (°C, black contours) along a constant latitude near a cluster of suspected SIULs. (b) Same as (a) but along a constant longitude. The vertical dashed black line in each subplot indicates the location of the other vertical cross-section. Note that a non-standard reflectivity color scale is used in the cross-sections to accentuate the embedded convective cells.

The CMCN detected only a single flash >75 C km, a 100 C km +CG, on the very eastern fringe of the snow band (Fig. 5b). Thus, this storm, while failing to produce energetic or sprite-class CGs, clearly presented favorable conditions for the initiation of upward positive leaders as SIULs. Note the absence of any NLDN reports over the warm waters of the Great Lakes, further suggesting the need for elevated objects to initiate lightning discharges during these conditions.

For each lightning event in the snow band, the wind speeds near the surface (10 m) at and 950 hPa (close to the median height of the taller towers) were retrieved from the Rapid Update Cycle (RUC) hourly analyses. The surface winds averaged a brisk 10 m s^{-1}, with the minimum being 4 m s^{-1} and the maximum 18 m s^{-1}. However, most participating tall structure and skyscraper heights were in the 200-400 m AGL range. The RUC analysis winds at the same event locations at 950 hPa, averaged 20 m s^{-1}, peaked at 28 m s^{-1}, and had a minimum of 10 m s^{-1}, all above the 8 m s^{-1} threshold proposed by Wang and Tagaki [2012] for SIULs from tall objects (without rotating turbine blades). The winds were strong wherever lightning was occurring, with no significant differences between the Yes, Maybe, and No lightning categories.

The national NMQ 3-D gridded NEXRAD radar database [Zhang et al., 2011], permitted a comprehensive analysis of both conventional base and composite reflectivities at the grid cell nearest each lightning event. The vast majority were associated with values <30 dBZ, with a mode of 28 dBZ. A widely used forecasting "rule of thumb" suggests lightning usually begins to appear in systems when reflectivities exceed 30-35 dBZ [Petersen et al., 1996]. Almost all the inspected events from Oklahoma to Michigan, whether or not a tower appeared to be involved, occurred with a reflectivity <30-35 dBZ, and apparently within stratiform precipitation, if based only upon visual inspection of conventional NEXRAD radar displays.

The above finding raised the question as to the source of the charge required to produce strong, near-surface electric fields. Using the NMQ gridded data, the 0300 Z composite reflectivity in the Chicago area was recreated, along with plots of the Yes (and several No) NLDN events for the 0255-0305 Z period (Fig. 6a). The color scale employed closely mimics that used for many operational radar reflectivity displays, and the precipitation appears essentially stratiform. Yet, this region was at the southern fringe of the cyclone's comma cloud and just north of the occluding frontal zone, suggesting a frontal surface aloft. A 4 km altitude CAPPI reflectivity presentation at the same time, using a non-conventional reflectivity color scale, clearly shows elevated embedded cellular convection above the frontal surface (Fig. 6b).

Using the contemporaneous RUC wind field analyses, horizontal wind vectors in the lower layer (950 hPa) show the intense northeasterly flow coming onshore from Lake Michigan (Fig. 6a). At 4 km, however, the flow is southerly, indicative of intense overrunning by warmer, unstable air above the frontal surface (Fig. 6b). The overrunning of unstable air above the frontal surface in northern Illinois is revealed in east-west (Fig. 7a) and north-south (Fig. 7b) vertical cross sections through the active lightning region at 0300 Z. These reveal coarsely resolved elevated cellular reflectivity structures, with reflectivities >30 dBZ above the frontal surface including regions where temperatures were near -10°C. The strongest vertical structures tended to be preferentially arranged north and east of the SIUL clusters. These findings mirror the results of extensive airborne and surface radar analyses of winter cyclonic storms reported by Rauber et al. [2013] and Rosenow et al. [2013]. They propose thundersnow can often be found in the southern portion of the occluded cyclone comma cloud in which dry air intrusion behind the surface cold front results in overrunning, destabilization, and the development of elevated, embedded convection.

Thus, while reflectivities at the actual strike locations were often modest, just upstream in the strong airflow there typically existed cellular-like convection with reflectivities >30 dBZ in suspected regions of mixed-phase hydrometeors. During the peak lightning activity in northern Illinois (0200-0500 Z, 2 February 2011), many of the NLDN events occurred within and up to 50 km downwind of pockets of somewhat higher reflectivity (30-45 dBZ). This is reminiscent of the findings of Market and Becker [2009], in which thundersnow lightning tended to appear some 15 km downwind of the region of maximum snowfall. A detailed study of this event will be available in a forthcoming paper [Warner et al., 2014].

NORTHERN PLAINS BLIZZARD OF 4-5 OCTOBER 2013

The forecast for an unseasonably early but major blizzard in western South Dakota on 4-5 October 2013 more than verified. Rain changed to snow early on 4 October, and by 1000 Z, heavy snow was falling throughout the Black Hills region and surrounding plains. The Rapid City National Weather Service office measured 23.1 in (59 cm) of snow at the airport, and much higher amounts (55 in/140 cm) were noted in surrounding areas. Wind gusts reached 55 mph (25 m s^{-1}) before instrumentation failed. Unofficial wind gusts to 68 mph (30 m s^{-1}) were reported during the 48-hour storm. Widespread tree damage, power failures, and the loss of 21,000 head of cattle resulted. GOES infrared imagery (Fig. 8) shows the rapidly developing, and already partially occluded, cyclone. Note the dry air incursion behind the cold front moving northeastward towards Rapid City. Embedded convective elements in the developing comma cloud shield can be noted in the GOES IR imagery. This resembles the conditions found during the 1-2 February 2011 storm.

One major difference between this and the 1-2 February cyclone was the level of electrical activity. During

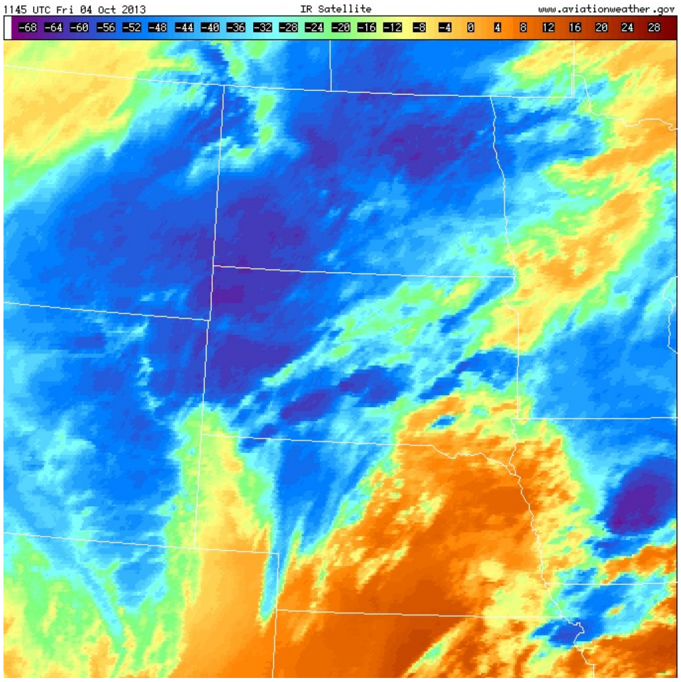


Fig. 8. GOES infrared imagery at 1145 Z 4 October 2013, showing a rapidly occluding cyclone, centered over central Nebraska, with a dry wedge intruding behind the surface cold front. Embedded convective cells can be seen near Rapid City within the southern fringes of the developing comma cloud.

the 48-hour period, some 125,000 NLDN CG and IC strokes were logged in South Dakota, Nebraska and surrounding areas While the majority of the lightning was concentrated in eastern Nebraska, which experienced a major late season tornado outbreak, there also was considerable lightning activity in the western portion of South Dakota associated with cold rain and heavy snow areas. Fig. 9 shows the distribution of 187 CGs with peak currents >150 kA on 4 October 2013. There were 25 -CGs and 12 +CGs with >200 kA peak currents, with maximum values of -382 kA and +558 kA.

Fig. 10 shows the distribution on 4 October 2013 of large iCMCs (>100 and >300 C km). While the majority were in the warm sector region of eastern Nebraska impacted by severe weather, six sprite-class +CGs and numerous slightly less energetic +CGs did occur within the heavy snow/cold rain region of western South Dakota. Though clouds and/or daylight prevented the SpriteNet camera at the Yucca Ridge Field Station (YRFS) in northeast Colorado from monitoring, it is likely that sprites and elves were being produced above the area impacted by the blizzard in this storm.

In addition to widespread natural downward lightning, between 1130 Z on 4 October 2013 and 0930 Z on 5 October 2013 (22 hours), numerous suspected upward lightning flashes were observed in western South Dakota during moderate to heavy snow and very strong winds. Analysis of NLDN stroke data, along with electric field meter records and interferometer data from Upward Lightning Triggering Study (UPLIGHTS) sensors near Rapid City [Warner et al., 2013] indicated that 4 of the 10 ridge top

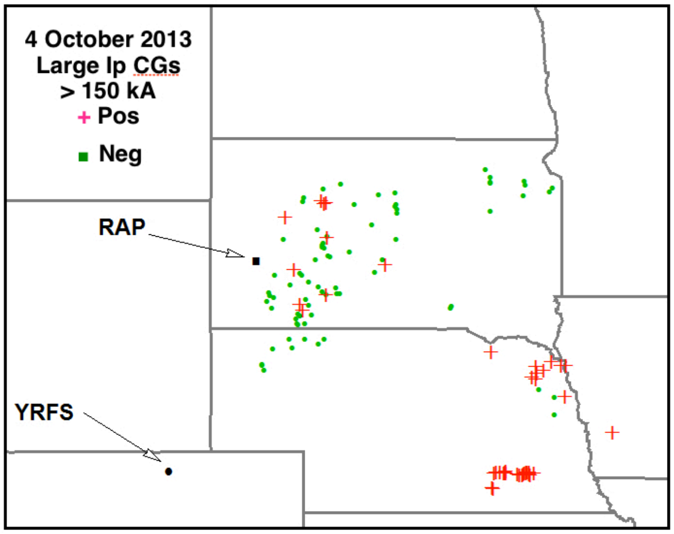


Fig. 9. Plot of NLDN strokes with peak currents greater than 150 kA on 4 October 2013. While high peak current positives were numerous within the eastern Nebraska warm sector tornadic storms, considerable activity of both polarities was noted in the region of heavy snow and cold rain in western SD.

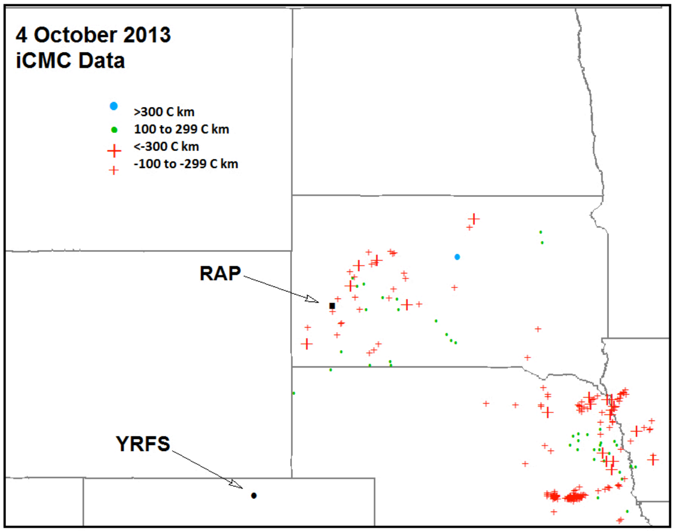
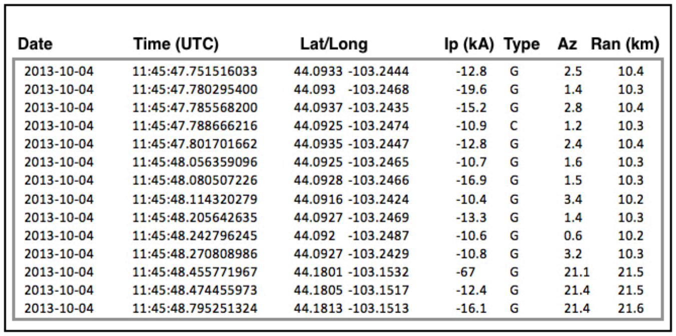


Fig. 10. Plot of CMCN strokes with iCMCs >100 C km on 4 October 2013. A number of sprite class (>+300 C km) strokes were present in the heavy snow region. If not for cloud cover or daylight, the SpriteNet camera at YRFS would likely have captured sprite imagery.



Date	Time (UTC)	Lat/Long	Ip (kA)	Type	Az	Ran (km)
2013-10-04	11:45:47.751516033	44.0933 -103.2444	-12.8	G	2.5	10.4
2013-10-04	11:45:47.780295400	44.093 -103.2468	-19.6	G	1.4	10.3
2013-10-04	11:45:47.785568200	44.0937 -103.2435	-15.2	G	2.8	10.4
2013-10-04	11:45:47.788666216	44.0925 -103.2474	-10.9	C	1.2	10.3
2013-10-04	11:45:47.801701662	44.0935 -103.2447	-12.8	G	2.4	10.4
2013-10-04	11:45:48.056359096	44.0925 -103.2465	-10.7	G	1.6	10.3
2013-10-04	11:45:48.080507226	44.0928 -103.2466	-16.9	G	1.5	10.3
2013-10-04	11:45:48.114320279	44.0916 -103.2424	-10.4	G	3.4	10.2
2013-10-04	11:45:48.205642635	44.0927 -103.2469	-13.3	G	1.4	10.3
2013-10-04	11:45:48.242796245	44.092 -103.2487	-10.6	G	0.6	10.2
2013-10-04	11:45:48.270808986	44.0927 -103.2429	-10.8	G	3.2	10.3
2013-10-04	11:45:48.455771967	44.1801 -103.1532	-67	G	21.1	21.5
2013-10-04	11:45:48.474455973	44.1805 -103.1517	-12.4	G	21.4	21.5
2013-10-04	11:45:48.795251324	44.1813 -103.1513	-16.1	G	21.4	21.6

Fig. 11. NLDN reports associated with one SIUL flash at 1145.47 Z during the 4 October 2013 Rapid City, SD blizzard.

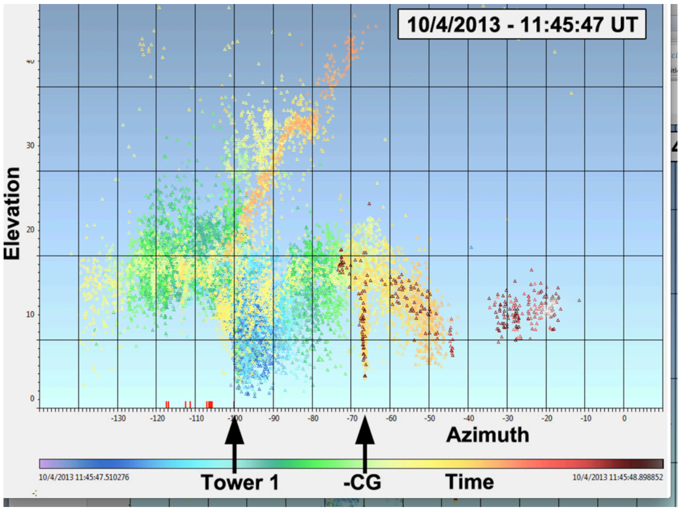


Fig. 12. Time color-coded display of interferometer sources showing the development of a massive SIUL discharge emerging from the top of Tower 1 at 1145.47 Z on 4 October 2013 during heavy snow and strong winds. In addition to producing 11 NLDN reports from recoil and reconnecting dart leaders, a 3-stroke –CG flash also came to ground northeast of the originating tower.

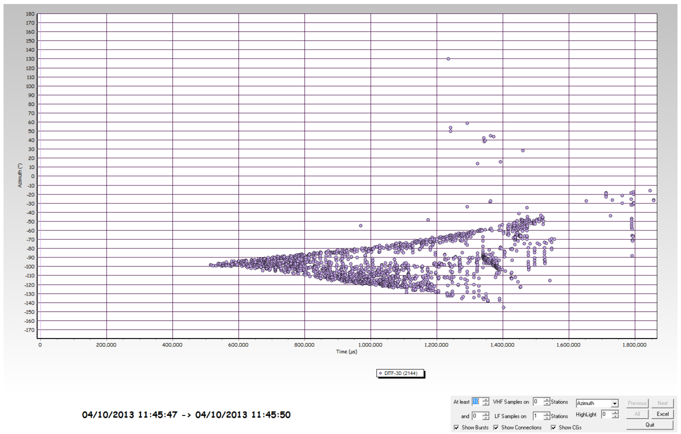


Fig. 13. Time versus azimuth display of interferometer sources for the SIUL at 1145.47 Z on 4 October 2013, showing the emergence of the upward positive leader and the expansion of the discharge towards the interferometer, located east-northeast of Tower 1.

communication towers experienced 25 self-initiated upward lightning flashes. These were comprised of 203 separate CG and IC events, all but two of which were negative. Of the 203 events, 125 were located within 500 meters of the 163 m tall Tower 1. In addition, a 500 m tall TV transmission tower near Faith, SD experienced 17 likely SIUL flashes, with five much shorter cell phone towers involved a total of 15 likely SIUL flashes.

Between 1133 and 1145 Z, Rapid City ridge top towers experienced five upward lightning flashes which were detected by a digital interferometer (before a regional power outage ended observations). This system provided azimuth and elevation data from the interferometer to the lightning-generated radiation sources. In all five cases, the lightning source points began at the tower top location and expanded upward and outward with time. There were no source points associated with preceding lightning activity prior to the development of the upward leader from the towers. This indicates that the upward leaders were self-initiated from the towers without being triggered by proceeding nearby flash activity (i.e., SIUL as opposed to LTUL).

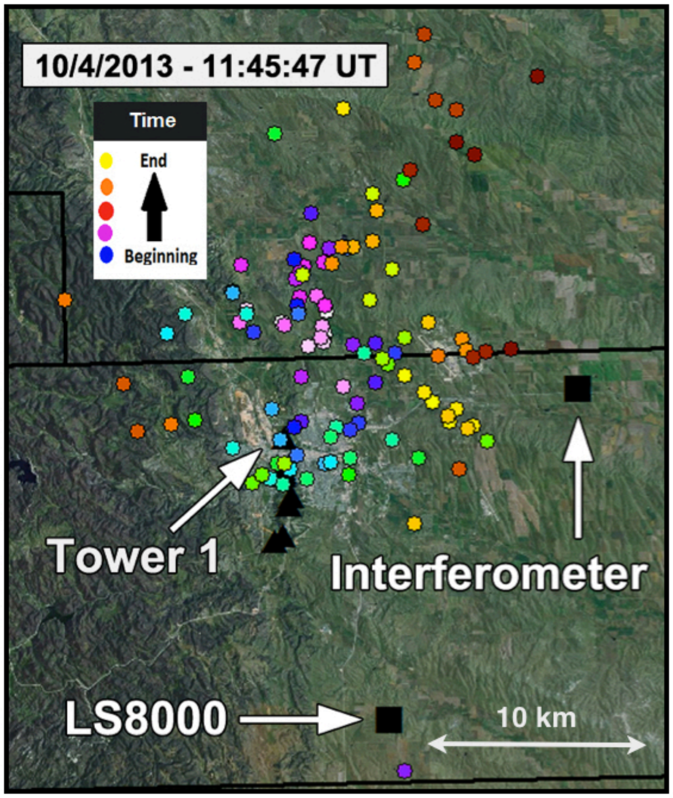


Fig. 14. Plot of plan position of those interferometer sources that could be located in 3-D using additional azimuths provided by the LS8000 receiver. The time color coded display indicates the discharge emerged from Tower 1 and gradually spread outward and northeastward, including a 3-stroke CG to ground well to the northeast of the originating UPL.

An electric field meter located 5 km west of the towers showed a non- to slowly-varying positive (foul weather) electric field (using the physics sign convention) of 0.5-3.5 kV m^{-1} prior to the flashes. In each case, the electric field experienced a negative excursion caused by the development of upward positive leaders (UPLs) from the towers. NLDN data reported numerous subsequent negative events (-CG and -IC) at the tower locations following the initial development of the UPLs.

Correlated interferometer data showed that fast recoil leaders developed on decayed branches of the UPLs and traveled back to the main channel or tower resulting in subsequent impulsive return connections/return strokes. All of these events were negative, consistent with upward positive leaders developing from the tower tops.

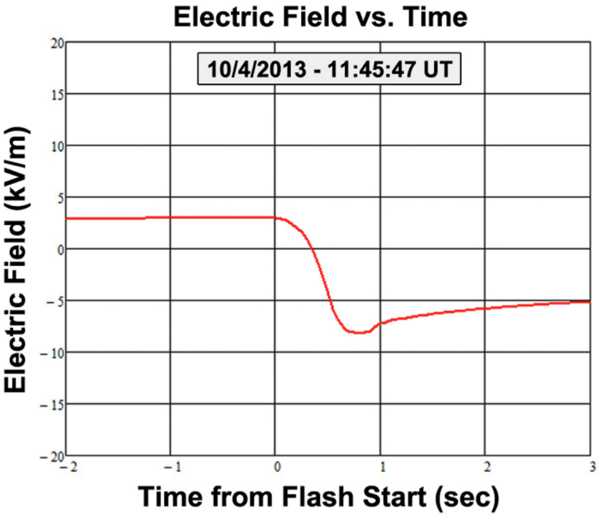


Fig. 15. Electric field prior to and during the SIUL at 1145.47 Z on 4 October 2013. Note the 3 kV m^{-1} foul weather field prior to the onset of the upward positive leader.

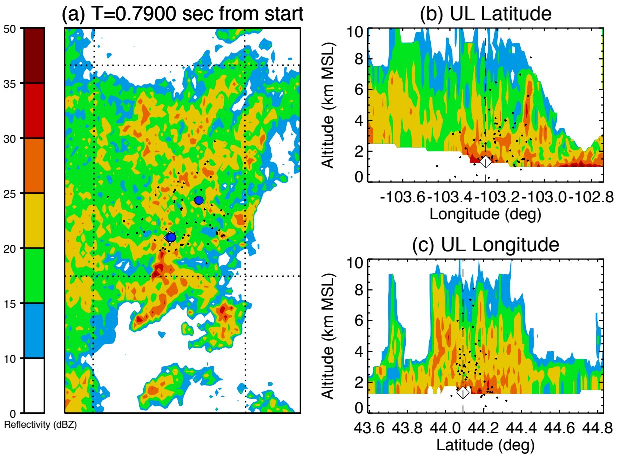


Fig. 16. CAPPI display at 5 km AGL of NEXRAD radar reflectivity at 1145 Z on 4 October 2013. This is near the -10°C level. Pockets of reflectivity >30-35 dBZ indicate small, embedded convective cells present above the more stratiform surface layer precipitation. Dual-polarization analysis indicated all precipitation was snow in the lowest layers. The white triangle is Tower 1, the initiation point of the SIUL, which in the plan view is covered by the numerous NLDN –CG reports (the southwest of the two –CG blue circles).

For reasons not clear, Tower 1 was involved in 21 of the 25 SIUL flashes reported from the ridge top towers over a 20-hour period. Fig. 11 displays the sequence of NLDN events beginning at 1145.47.751 Z on 4 October 2013. It appears to show a typical sequence of NLDN reports that follow upward positive leaders from tall objects, save for the last three, which will be discussed below. Fig. 12 displays the source data from the interferometer, located east-northeast of Tower 1, from the 1145.47 Z SIUL. The horizontal axis represents the azimuth from the instrument with zero degrees being true north and negative values rotating counterclockwise from north to -150° (south). The interferometer records source points at 4 μs temporal resolution and these source points are displayed using rainbow time coloring spanning warm to cold colors with time. The initial sources begin at 11:45:47.510200 Z as blue points located in the direction of Tower 1's tip and these expand primarily upward with time. A display of the azimuth vs. time of the interferometer sources (Fig. 13) shows the discharge initiating at Tower 1 and expanding closer to the interferometer. A comparison display (not shown) of the elevation of the sources vs. time shows the discharge gaining in height as it moves generally eastward.

Animation of these returns show three main branches emerge from the initial development. Multiple recoil leaders then develop toward the outer extent of the branches, some of which retrace the branch and channel path back to Tower 1 forming return strokes. The NLDN recorded 11 negative events coincident with these recoil leader/return stroke sequences.

The last three NLDN reports (Fig. 11) record an unusual feature of this particular SIUL. At 1145.48.447600 Z, development associated with a recoil leader on the right branch traveled back toward the tower. However, after traveling 10° to the left of its origin, this development began traveling downward while still 35° right of the tower. At 1145.48.455700 Z this activity reached the ground forming a return stroke recorded by the NLDN as a -67 kA CG 12 km northeast of Tower 1 (15.8 km, -66° from the interferometer). Two more NLDN events were recorded at this location at 1145.48.474455 Z and 1145.48.795251 Z. These correlated with source development that again formed near the outer extent of the right branch and which followed the newly formed path to ground established by the first event at 1145.48.455700 Z. In this case, the complex processes involved in a SIUL also resulted in a non-collocated 3 stroke CG flash (as opposed to an impulsive dart leader reconnection with the originating tall object).

Fig. 14 shows a 2-D plot of source points for this event SIUL recorded by the interferometer that have been correlated with corresponding azimuth values from a separate LS8000 instrument. This device provides a second azimuth allowing location of the source. While data capacity issues for the LS8000 greatly limited the number of location retrievals, it is clear that the source points did originate near Tower 1 and then expanded outward, especially to the east and north over time.

The electric field meter trace for the 1145.47 Z SIUL is presented in Fig. 15. The electric field was steady positive (foul weather) at 3 kV m^{-1} prior to the flash, indicating a negative charge layer aloft. Upon development of the upward positive leader, the electric field experienced a negative charge and reversed polarity. The same pattern was observed for all 5 SIUL cases captured by the interferometer.

Multiple aspects of this case are now under investigation. In particular, the sources of the charge in the nimbostratus clouds need to be further clarified. The

NEXRAD radar located east of Rapid City provided excellent coverage. Dual-polarimetric measurements at low altitudes indicated snow as the dominant hydrometeor throughout the entire region at 1145 Z. A 5 km CAPPI reflectivity display (Fig. 16) shows that above and near the towers small pockets of >30 - 35 dBZ were present aloft nearby and especially south of the ridge top towers. The radar does provide evidence of numerous small, embedded, elevated convective cells that span the -10 to -20 °C temperature layer favorable for non-inductive charging. It is likely that the overrunning of warmer air above the cold surface layer in the rapidly occluding comma cloud was providing the destabilization needed for embedded convection aloft.

DISCUSSION AND CONCLUSIONS

Two mid-continental occluding winter cyclonic storms were monitored in the hopes of detecting outbreaks of sprite-class +CGs (and even optically confirming sprites) associated with the cold sector thundersnow lightning. The lightning characteristics of the two storms were markedly different, though they both produced significant numbers of self-induced upward lightning (SIUL) from tall and, some not so tall, towers within the region of heaviest snow and strong winds.

The 1-2 February 2011 midwestern storm produced 282 lightning flashes (composed of 1153 events), of which fully 93% appeared likely or probably to have initated from elevated structures ranging from 500+ m skyscrapers to <100 m tall wind turbines and transmission line towers. The SIUL-releated reports were overwhelmingly (>96%) negative CGs and ICs. These likely resulted from the NLDN detecting not the initial upward positive leader but subsequent highly impulsive recoil and dart leader reconnections to the tall object. In some cases, branches of the expanding in-cloud channels were detected at tens of kilometers from the SIUL origination point. Only a single energetic CG (a positive flash with a +100 C km iCMC) was noted over the entire 26 hours. It would appear the charging mechanisms were sufficient to create strong enough fields to induce upward leaders from elevated structures, but little in the way of natural downward lightning. The question remains as to how much of the lightning recorded during this storm would have occurred in the absence of human built tall objects.

The 4-5 October 2013 northern high plains blizzard, which occurred under generally warmer atmospheric conditions, was a prolific lightning producer, not only in the warm sector (which experienced tornadic storms), but also within the region of heavy snow and strong winds in the northwestern quadrant of the occluding cyclone. Initial analyses of the NLDN data have uncovered at least 57 SIUL flashes comprised of 367 events (almost all negative CGs and ICs). Of these, 25 flashes originated from the well-studied towers located on a ridge in Rapid City, SD. The first five of the events were characterized using a nearby interferometer (before a regional power outage) and an electric field meter located 5 km from Tower 1. Analysis of one SIUL (at 1145.47 Z), which was typical of the five, confirmed the lightning clearly initiated as an upward positive leader from the tower top. The discharge then moved upward and outward with complex branching behavior and generating 14 additional NLDN detections. Of these, the last 3 three were new return stroke connections to the ground many kilometers distant from the tower.

A common element in these two SIUL outbreaks, aside from heavy snow, was the strong winds. It appears that enhanced electric fields at the top of the participating structures, along the presumably lower altitude of the charge centers within the precipitating nimbostratus clouds, were sufficient to allow the initiation of upward positive leaders without a prior triggering lightning discharge. The notable winds in these blizzards may have played a key role by "stripping" away much of the corona discharge shielding from the grounded tall structures, as appears to be the case with the tower and wind turbine observations of SIULs in Japan winter snowstorms [Wang and Tagaki, 2012]. We note that a number of SIUL events were associated with towers on flat terrain with physical heights <100 m.

In both storms, during the SIULs, low altitude radar reflectivity displays generally gave the impression of a primarily stratiform precipitation system, with reflectivities rarely larger than the 30-35 dBZ value generally considered a minimum for lightning development [Peterson et al., 1996]. Radar data must be carefully analyzed, particularly at the -10 to -20°C region, where non-inductive charging is likely to be occurring. This in order to detect the embedded convective cells aloft which provide sufficiently strong convective updrafts for charge generation.

ACKNOWLEDGMENT

We appreciate the ongoing support of Vaisala, Inc., in supplying the NLDN data stream which is essential to the real-time operation of the National Charge Moment Change Network (CMCN). Partial support was provided by the DARPA NIMBUS program to Duke/FMA Research, and National Science Foundation grant AGS-1010657 to Colorado State University and grant AGS-1048103 to South Dakota School of Mines and Technology.

REFERENCES

Beavis, N. K., T. J. Lang, S. A. Rutledge, W. A. Lyons, and S. A. Cummer (2014), Regional, seasonal, and diurnal variations of cloud-to-ground lightning with large impulse charge moment changes, Mon. Wea. Rev., *submitted.*

Berger, K. (1967), Novel observations on lightning discharges: Results of research on Mount San Salvatore, *J. Franklin Inst., 283*, 478– 525.

Brook, M., M. Nakano, P. Krehbiel, and T. Takeuti (1982), The electrical structure of the Hokuriku winter thunderstorms, *J. Geophys. Res., 87*, 1207-1215.

Crowe, C., P. Market, B. Pettigrew, C. Melick, and J. Podzimek (2006), An investigation of thundersnow and deep snow accumulation, *Geophys. Res. Lett., 33,* L24812, doi:10.1029/2006GL028214.

Cummer, S. A., and W. A. Lyons (2005), Implications of lightning charge moment changes for sprite initiation, *J. Geophys. Res., 110,* A04304, doi:10.1029/2004JA010812,2005.

Cummer, S. A., W. A. Lyons, and M. A. Stanley (2013), Three years of lightning impulse charge moment change measurements in the United States, *J. Geophys. Res., 118*, 5176-5189, doi:10.1002/jgrd.50442.

Cummins, K.L., M.J. Murphy, E.A. Bardo, W.L. Hiscox, R.B. Pyle, and A.E. Pifer (1998), A combined TOA/MDF technology upgrade of the U.S. National Lightning Detection Network, *J. Geophys. Res., 103,* 9,035 – 9.044.

Cummins, K.L., and M.J. Murphy (2009), An overview of lightning location systems: History, techniques, and data uses, with an in-depth look at the U.S. NLDN, *IEEE Trans. Electromagn. Compat., 51(3),* 499–518.

Diendorfer, G., H. Pichler, and M. Mair (2009), Some parameters of negative upward-initiated lightning to the Gaisberg Tower (2000-2007), *IEEE Trans. Electromagn. Compat., 51(3),* 443–452.

Eriksson, A. J., and D. V. Meal (1984), The incidence of direct lightning strikes to structures and overhead lines, In, *Lightning and Power Systems*, London: IEE Conf. Pub. No. 236, 67-71.

Holle, R. L., and A. I. Watson (1996), Lightning during two central U.S. winter precipitation events, *Wea. and Forecast., 11,* 599-614.

Hussein, A.M., W. Janischewskyj, J.-S. Chang, V. Shiostak, W. A. Chisholm, P. Dzurevych, and Z.-I. Kawasaki (1995), Simultaneous measurements of lightning parameters for strokes to the Toronto Canadian National Tower, *J. Geophys. Res, 100*, No. D5, 8853-8861.

Kuhlman, K. M., and K. L. Manross (2011), Lightning and polarimetric signatures of two electrified winter storms in central Oklahoma, paper presented at, *5th Conf. of Meteorological Applications of Lightning Data,* Am. Meteorol. Soc., Seattle, WA, 7 pp, https://ams.confex.com/ams/91Annual/webprogram/Paper185790.html

Lang, T. J., W. A. Lyons, S. A. Rutledge, J. D. Meyer, D. R. MacGorman, and S. A. Cummer (2010), Transient luminous events above two mesoscale convective systems: Storm structure and evolution, *J. Geophys. Res., 115*, A00E22, doi:10.1029/2009JA014500.

Lang, T. J., J. Li, W. A. Lyons, S. A. Cummer, S. A. Rutledge, and D. R. MacGorman (2011a), Transient luminous events above two mesoscale convective systems: Charge moment change analysis, *J. Geophys. Res., 116*, A10306, doi:10.1029/2011JA016758.

Lang, T. J., W. A. Lyons, S. A. Cummer, S. A. Rutledge, and T. E. Nelson (2011b), Toward a climatology of precipitating systems that produce lightning with large impulse charge moment changes, paper presented at *5th Conf. on the Meteorol. Applications of Lightning Data*, Am. Meteorol. Soc., Seattle, WA, Paper 4.3, https://ams.confex.com/ams/91Annual/webprogram/Paper184639.html

Lang, T. J., S. A. Cummer, S. A. Rutledge, and W. A. Lyons (2013), The meteorology of negative cloud-to-ground lightning strokes with large charge moment changes: Implications for negative sprites, *J. Geophys. Res. Atmos., 118*, doi:10.1002/jgrd.50595.

Lu, G., S. A. Cummer, J. Li, L. Zigoneanu, W. A. Lyons, M. A. Stanley, W. Rison, P. R. Krehbiel, H. E. Edens, R. J. Thomas, W. H. Beasley, S.A. Wiess, R. J. Blakeslee, E. C. Bruning, D. T. MacGorman, T. C. Meyer, K. Palivec, T. Ashcraft and T. Samaras (2013), Coordinated observations of sprites and in-cloud lightning flash structure, *J. Geophys. Res. Atmos., 118*, doi:10.1002/jgrd.50459.

Lueck, R. (2013), Dual-polarization radar observations of upward lightning producing storms, paper AE13A-0330, presented at AGU Fall Meeting, San Francisco, CA.

Lyons, W. A. (1989), Wintertime lightning, *LDIS Technical News and Notes, No. 89-1*, R*SCAN Corporation, Minneapolis, MN. Available from corresponding author.

Lyons, W. A. (1996), Sprite observations above the U.S. High Plains in relation to their parent thunderstorm systems, *J. Geophys. Res., 101*, 29,641–29,652.

Lyons, W. A. (2006), The meteorology of transient luminous events-An introduction and overview, *NATO Advanced Study Institute on Sprites, Elves and Intense Lightning Discharges*, edited by M. Fullekrug et al., pp. 19–56, Springer, Dordrecht, The Netherlands.

Lyons, W. A., and S. A. Cummer (2008), Stratospheric Lightning: Forecasting and Nowcasting Tools, Final Report, SBIR Phase II, Missile Defense Agency, Contract HQ0006-06-C-7313, FMA Research, Inc., Fort Collins, CO, 298 pp.

Lyons, W. A., S. A. Cummer, S. A. Rutledge, T. J. Lang, T. Meyer, T. A. Warner, and T.A. Samaras (2011), TLEs and their parent lightning discharges, paper presented at *14th Intl. Conf. on Atmospheric Electricity*, August 7-12, Rio De Janeiro, Brazil, 4 pp.

Lyons, W. A., M. Stanley, J. D. Meyer, T. E. Nelson, S. A. Rutledge, T. J. Lang, and S. A. Cummer (2009), The meteorological and electrical structure of TLE-producing convective storms. In *Lightning: Principles, Instruments and Applications*, H.D. Betz et al. (eds.), 389-417 pp., Springer Science+Business Media B.V., DOI: 10.1007/978-1-4020-9079-0_17.

Lyons, W. A., T. A. Warner, S. A. Cummer, S. A. Rutledge, T. J. Lang, T. C. Meyer, G. Lu, T. E. Nelson, and T. Samaras, 2012: Different strokes: Researching the unusual lightning discharges associated with sprites and jets and atypical meteorological regimes, paper presented at the *22nd Intl. Lightning Detection Conf.*, Broomfield, CO, Vaisala, Inc., www.vaisala.com/en/events/ildcilmc/ Pages/ILDC-2012-archive.aspx

Lyons, W.A., T.E. Nelson, T.A. Warner, A. Ballweber, R. Lueck, T.J. Lang, M.S.S. Saba, C. Schumann, S.A. Cummer, L. Zigoneanu, K.L. Cummins, M. Quick, W. Rison, P. Krehbiel, N. Beavis, S.A. Rutledge, J. Myers, T.A. Samaras, P. Samaras, and C. Young (2014), Meteorological aspects of two modes of lightning triggered upward lightning (LTUL) events in sprite-producing MCSs, paper presented at the *23nd Intl. Lightning Detection Conf.*, Tucson, AZ, Vaisala, Inc.

Market, P. S., and A. E. Becker (2009), A study of lightning flashes attending periods of banded snowfall, *Geophys. Res. Lett., 36*, L01809, doi:10.1029/2008GL036317.

Market, P. S., C. E. Halcomb, and R.L. Ebert (2002), A climatology of thundersnow events over the contiguous United States, *Wea. Forecasting,17*,1290-1295..doi.org/10.1175/15200434(2002)017 <1290:ACOTEO>2.0.CO;2

Matsudo, Y., T. Suzuki, M. Hayakawa, K. Yamashita, Y. Ando, K. Michimoto, and V. Korepanov (2007), Characteristics of Japanese winter sprites and their parents' lightning as estimated by VHF lightning and ELF transients, *J. Atmos. Solar-Terrest. Phys., 59*, 1431-1446.

Mazur, V. (2002), Physical processes during development of lightning flashes. *C.R. Phys.*, 3, 1393-1409, doi:10.1016/S1631-0705(02)01412-3.

McEachron, K. B. (1939), Lightning to the Empire State Building, *J. Franklin Inst., 227*, 149-217., doi: 10.1016/S0016-0032(39)90397-2.

Moore, P. K., and R. E. Orville (1990), Lightning characteritics in lake-effect thunderstorms. *Mon. Wea. Rev., 118*, 1767-1782.

Orville, R. E. (1990), Winter lightning along the East Coast. *Geophys. Res. Lett., 17(6),* 713-715.

Orville, R. E (1993), Cloud-to-ground lightning in the Blizzard of '93, *Geophys. Res. Lett, 290*, 1367-1370.

Orville, R. E., and K. Berger (1973), An unusual lightning flash initiated by an upward-propating leader, *J. Geophys. Res., 78(21),* 45204525.

Orville, R. E., G. R. Huffines, W. R. Burrows, and K. L. Cummins (2011), The North American Lightning Detection Network (NALDN) – Analysis of flash data: 2001-2009, *Mon. Wea. Rev., 139*, 1305- 1322. Doi: 10:1175/2010MWR3452.1

Petersen, W. A., S. A. Rutledge, and R. E. Orville (1996), Cloud-to-ground lightning observations from TOGA COARE: Selected results and lightning location algorithms, *Mon. Wea. Rev., 124*, 602–620.

Price, C., W. Burrows, and P. King (2002), The likelihood of winter sprites over the Gulf Stream, *Geophys. Res. Lett., 29*, doi:10.1029/2002GL015571.

Rakov, V. (2003), A review of the interaction of lightning with tall objects, in *Recent Devel. Geophysics, 5(2003),* 57-761 ISNB: 81-271-0026-9.

Rauber, R., J. Wegman, D. Plummer, A. Rosenow, M. Peterson, G. McFarquhar, B. Jewett, D. Leon, P. Market, K. Knupp, J. Keeler, and S. Battaglia (2013), Stability and charging characteristics of the comma head region of continental winter cyclones, *J. Atmos. Sci.,* doi:10.1175/JAS-D-13-0253.1, in press.

Rosenow, A. R., D. M. Plummer, R. M. Rauber, G. M. McFarquhar, B. F. Jewett, D. Leon, and J. M. Keeler (2013), Vertical motions within generating cells and elevated convection in the comma head of winter cyclones, *J. Atmos. Sci.*, in review.

Schultz, C. J., E. C. Bruning, L. D. Carey, W. A. Petersen, and S. Heckman (2011), Total lightning within electrified snowfall using LMA, NLDN and WTLN measurements, *Eos Trans. AGU*, Fall Meet. Suppl.

Schultz, D.M. (1999), Lake-effect snowstorms in northern Utah and western New York with and without lightning, *Wea. Forecasting*, *14,* 1023-1031.

Suzuki, T., M. Hayakawa, Y. Matsudo, and K. Michimoto (2006), How do winter thundercloud systems generate sprite-inducing lightning in the Hokuriku area of Japan? *Geophys. Res. Lett., 33*, L10806, doi:10.1029/2005GL025433, 2006.

Stanley, M. A., and M. J. Heavner (2003), Tall structure lightning induced by sprite-producing discharges, paper presented at *11th Intl. Conf. on Atmospheric Electricity,* Guntersville, AL, NASA Marshall Space Flight Center, 4 pp.

Steiger, S. M., R. Hamilton, J. Keeler, and R. E. Orville (2009), Lake-effect thunderstorms in the Lower Great Lakes, *J. Appl. Meteor. Climatol.*, *48*, 889– 902.

Takahashi, Y., R. Miyasato, T. Adachi, K. Adachi, M. Sera, U. Uchida and H. Fukunishi (2003), Activities of sprites and elves in the winter season, Japan, *J. Atmos. Sol. Terr. Phys., 65, 551-560.*

Takeuti, T., M. Nakano, and Y. Yamamoto (1976), Remarkable characteristics of cloud-to-ground discharges observed in winter thunderstorms in Hokuriku area, Japan, *J. Meteor. Soc. Jap., 54*, 436-440.

Takeuti, T., M. Nakano, M. Brook, D. J. Raymond, and P. Krehbiel (1978), The ananomalous winter thunderstorms of the Hokuriku coast, *J. Geophys. Res., 83*, 23385-2394.

Wang, D., N. Takagi, T. Watanabe, H. Sakurano, and M. Hashimoto (2008), Observed characteristics of upward leaders that are initiated from a windmill and its lightning protection tower, *Geophys. Res. Lett., 15*, L02803, doi:10.1029/2007GL032136, 2008.

Wang, D., and N. Takagi (2012), Characteristics of winter lightning that occurred on a windmill and its lightning protection tower in Japan, *IEEJ Transactions on Power and Energy, 132(6),* doi:10.1541/icejpes 132.568

Warner, T. A. (2011), Observations of simultaneous upward lightning leaders from multiple tall structures, *Atmos. Res.*, doi: 10.1016/j.atmosres.2011.07.004.

Warner, T. A., S. A. Cummer, W. A. Lyons, T. J. Lang and R. E. Orville (2011), Coordinated video and RF measurements of positive CGs inducing both sprites and upward tower discharges, paper presented *at 5th Conf. on Meteorological Applications of Lightning Data*, Am. Meteor. Soc., Seattle, WA.

Warner, T. A., K. L. Cummins, and R. E. Orville (2012a), Upward lightning observations from towers in Rapid City, South Dakota and comparison with National Lightning Detection Network data, 2004–2010. *J. Geophys. Res.: Atmos.*, *117*, D19109, doi:10.1029/2012JD018346.

Warner, T. A., M. M. F. Saba and R. E. Orville (2012b), Characteristics of upward leaders from tall towers, paper presented at *4th Intl. Lightning Meteorology Conf.,* Boulder, CO, 10 pp., www.vaisala.com/en/events/ildcilmc/Pages/ILDC-2012-archive.aspx

Warner, T. A., M. M. F. Saba, S. Ridge, M. Bunkers, W. A. Lyons and R. E. Orville (2012c), Lightning-triggered upward lightning from towers in Rapid City, South Dakota, paper presented at *4th Intl. Lightning Meteorology Conf.,* Vaisala, Boulder, CO, 10 pp., www.vaisala.com/en/events/ildcilmc/Pages/ILDC-2012-archive.aspx.

Warner, T. A., J. H. Helsdon Jr., M. J. Bunkers, M. M. F. Saba, and R. E. Orville (2013), UPLIGHTS – Upward Lightning Triggering Study, *Bull. Amer. Meteor. Soc.*, 94(5), 631-635.

Warner, T.A., T.J. Lang, and W.A. Lyons (2014), Synoptic scale outbreak of self-initiated upward lightning (SIUL) from tall structures during the central U.S. blizzard of 1-2 February 2011, *J. Geophys. Res.* (submitted)

Zhang, J., et al. (2011), National Mosaic and Multi-Sensor QPE (NMQ) System: Description, results, and future plans, *Bull. Am. Meteorol. Soc., 92*, 1,321–1,338.

Zhou, H., G. Diendorfer, R. Thottappillil, H. Pichler, and M. Mair (2012), Measured current and close electric field changes associated with the initiation of upward lightning from a tall tower, *J. Geophys. Res., 117*, D08102, doi:10.1029/ 2011JD017269.