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Meteorological Aspects of Two Modes of Lightning-Triggered Upward Lightning (LTUL) Events in Sprite-Producing MCS

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***Abstract*—Upward lightning from tall objects can be either self-initiated (SIUL), that is, leaders originating due to locally strong electric fields but without any preceding lightning, or triggered by prior lightning discharges in the general vicinity, termed lightning-triggered upward lightning (LTUL). The LTULs can be triggered by (1) nearby +CG return strokes propagating through previous leader networks near the tall object, or (2) the overhead proximity of horizontally propagating negative stepped leaders from either IC or +CGs. Examples of both modes of LTULs are presented. The meteorological environments in which LTULs occur in the U.S. high plains show a strong similarity to the convective regimes (trailing MCS stratiform regions) and the parent lightning which trigger sprites.**

Keywords*—lightning; lightning-triggered upward lightning; self-initiated upward lighting; sprites; charge moment change.

INTRODUCTION

The discovery of transient luminous events (TLEs) and in particular sprites lead to the realization that there exists a class of especially energetic lightning discharges that had received relatively little attention from researchers [Lyons, 1996]. Ongoing meteorological investigations of sprite-generating storms, especially in the central U.S. [Lyons et al., 2006], revealed that many convective regimes can poentially generate an occasional sprite-class parent cloud-to-ground lightning stroke (SP+CG). These are almost always positive CGs possessing large impulse charge moment changes (iCMC), defined as the product of the charge lowered to ground and the height from which the charge is drawn, over the first ~2 ms of the stroke [Cummer and Lyons, 2005]. The National Charge Moment Change Network (CMCN), in operation since 2007 [Cummer et al., 2013], routinely monitors iCMCs in near-real time over the U.S. Highly energetic (large iCMC) CGs can produce sprites at values as low as ~100 C km rising to a >75% probablity of a sprite from a +CG >300 C km [Lyons and Cummer, 2008], with larger values required for the rare negative CG sprite [Lang et al., 2013]. SP+CGs events are most commonly produced within large mesoscale convective systems (MCSs) with significant stratiform precipation regions [Lyons, 2006; Lyons et al., 2009; Lang et al., 2011, 2012]. The climatology of sprite-class + iCMCs (>300 C km)) shows a strong resemblance to the annual patterns of large MCSs (Fig. 1), with occurrences in the northern plains peaking during the summer months [Beavis et al., 2014]. Initially based upon anecdotal reports from high plains storm chasers, it has been realized that spectacular displays of upward lightning

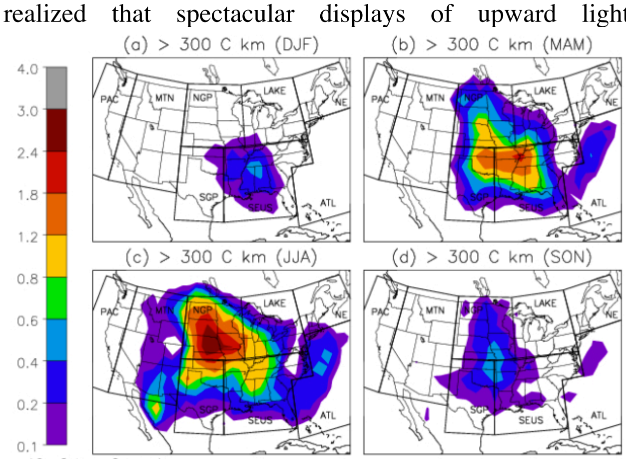

Figure. 1. The density of sprite-class +CGs (those with iCMCs >300 C km) over the continental United States by season (Beavis et al., 2014).

(object-induced lightning), such as from tall broadcast transmission towers, were also common within MCS stratiform regions. It was proposed [Stanley and Heavner, 2003] that sprite class +CGs sometimes appeared to induce upward lightning discharges from tall towers, even over distances of tens of kilometers. These upward positive leaders, though themselves generally not detected by the NLDN [Cummins et al. 1998; Cummins and Murphy, 2009] were frequently followed by recoil leaders and dart leader downward reconnections, typically reported as -CG or -IC events. This process has now been termed lightning triggered upward lightning (LTUL), implying the requirement for a preceding CG lightning discharge (within several tens of km) or, alternately, the passage close overhead of negative leaders above, though sometimes below, cloud base [Warner, 2011; Warner et al., 2012a, 2012b, 2012c]. A comprehensive discussion of object-originated upward lightning from tall structures is provided by Rakov [2003].

To further explore the relationship between SP+CGs and LTULs, a collaborative effort began in 2006 to optically monitor for sprites above the 10 hill top towers in Rapid City, SD, that frequently launch LTULs [Warner et al., 2013]. That tall structures are often involved in upward lightning has long been appreciated [McEachron, 1939; Berger, 1967]. It was not clear, however, that the same CG could be responsible for both an LTUL event and for inducing mesospheric electrical breakdown (a sprite). As documented in Warner et al. [2011] and Lyons et al. [2011], at least a half dozen cases of SP+CGs also serving as the parent for LTULs occurred within leading line/trailing stratiform (TT/LS) MCS stratiform regions.

The 10 Rapid City towers, with physical heights of 91 to 191 m, are located atop hills [Warner et al., 2013] thus enhancing their effective height [Rakov, 2003] several times over. For towers on flat terrain, the general "rules of thumb" are that structures of 100 m or less are generally struck by natural downward lightning, and only rarely launch upward positive leaders, whereas by the time physical (or effective) heights reach ~500 m, almost all lightning events are upward discharges [Rakov, 2003; Eriksson and Meal, 1984]. The rapid expansion of wind energy globally, with over 45,000 utility wind turbines in the U.S. alone, has brought attention to the fact that wind turbines, which are generally not much taller

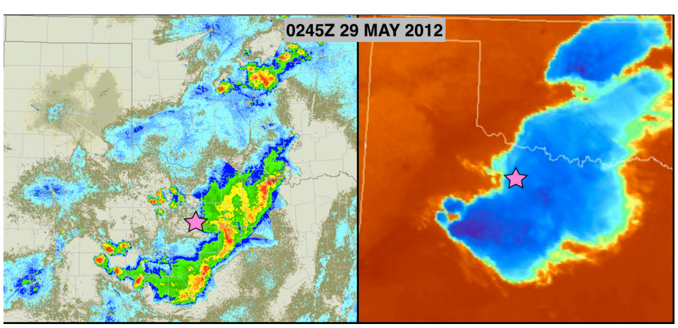

Figure. 2. NEXRAD regional reflectivity and GOES infrared images at 0245 Z 29 May 2012. Pink star shows location of +CG and subsequent LTUL events from a wind turbine. Note the location is at the far trailing end of the MCS.

than 100-120 m physical height and are often located on relatively flat terrain, are struck with significant frequency [Wilson et al., 2013; Wang et al., 2008]. Wang and Tagaki [2012] suggest that strong winds (>8 m s^{-1}) appear to facilitate initiation of upward leaders from structures of ~100 m height. They suggested that space charge buildup near tower tops due to corona discharges in the presence of intense ambient electric fields could inhibit upward leader initiation. Removal of this space charge by strong thunderstorm winds (and/or by the rotation of turbine blades) appears to enhance the likelihood of upward leader initiation.

During the summer of 2013, a high-density lightning mapping array (LMA) was operated in north central Kansas providing coverage over a large wind farm [Cummins et al., 2014; Rison et al., 2014, this conference]. This location was also situated in a region of high probability of sprite-class CGs (Fig. 1) and was within range of SpriteNet cameras capable of optically confirming sprites above the LMA [Lu et al., 2013]. This opportunity allowed for further exploration of the meteorological regimes which produce lightning favorable for

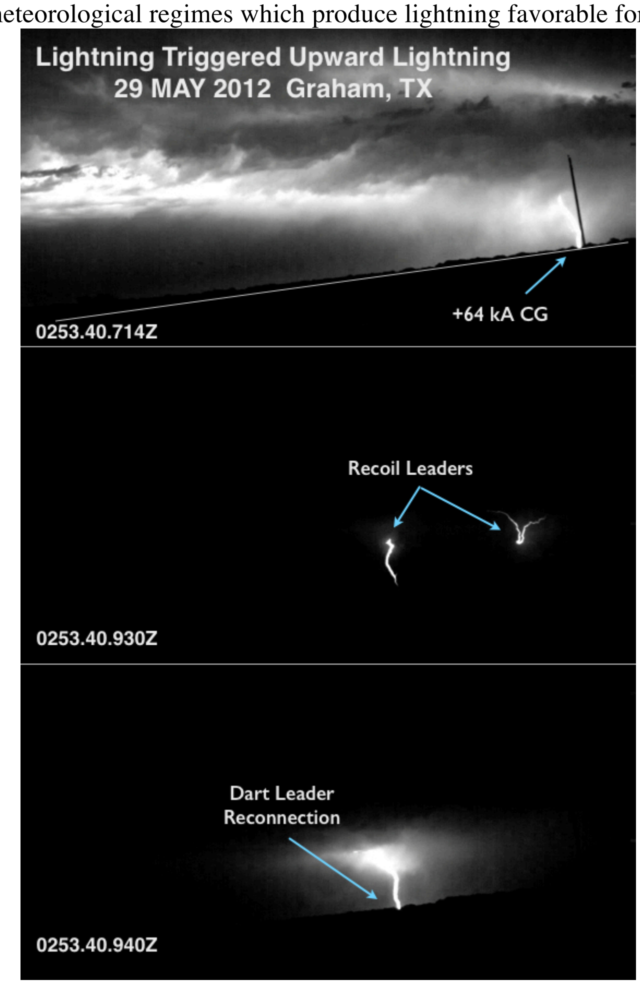

Figure 3. Phantom high-speed camera (5000 ips) capture of 64 kA +CG near Graham, TX on 29 May 2012. The initial return stroke was followed by a continuing current and IC leaders spreading northwestward towards a wind farm. After 50 ms, an upward positive leader from a wind turbine 10 km distant was followed by a series of 33 dart leaders reconnecting to the turbine. Note: the camera axis was tilted, with the horizon delineated in the top image.

LTUL events, as well as triggering sprites. It also allowed investigating lightning interactions with ~100 m tall structures on relatively flat terrain previously thought not to be prime candidates for initiating upward positive leaders.

SUMMER 2012 FIELD CAMPAIGN

During the summers of 2012 and 2013, as part of the Duke University/FMA Research PhOCAL program (Physical Origins of Coupling to the upper Atmosphere from Lightning), operations were designed to use a combination of fixed-base and mobile standard and high-speed cameras to record TLEs while simultaneously capturing their SP+CGs, preferably within an LMA, facilitating a more complete characterization of the lightning which induces mesopheric sprites.

During 2012, a Phantom 7.3 camera was deployed in a van through portions of Texas and Oklahoma covered by several LMAs, with the task of capturing sprite-class CGs, and secondarily, monitoring upward discharges from tall structures. On 29 May 2012 (all dates UTC), a prototypical leading line/trailing stratiform (LL/TS) MCS moved eastward through north central Texas (Fig. 2). Though not especially intense, this system was characteristic of those which produce sprites [Lyons, 2006; Lang et al., 2011, 2012]. Indeed, a SpriteNet camera in Lubbock, TX detected four sprites between 0239 and 0416 Z above the MCS trailing stratiform region. The mobile Phantom camera was deployed southwest of Graham, TX (at 32.8780 N; 98.7208 W), within the western portion of the MCS stratiform, an area of light rain and infrequent +CGs. The field of view was oriented towards a wind farm about 40 km to the northeast. At 0253.40.711 Z, a 64 kA +CG was reported by the NLDN. The entire lightning sequence was captured at 5000 ips by the Phantom (Fig. 3). Several recoil leaders [Mazur, 2002] were visible below cloud base accompanying the initial downward stepped leader for the 10 ms before the return stroke (RS). A continuing current lasted 75 ms. The estimated iCMC was 80 C km, with a complete charge moment change (CMC) estimated at 200-400 C km. Though quite energetic, this stroke's metrics were a bit smaller than the minumum usually found to produce a sprite [Lyons et al., 2009]. We note a sprite had been recorded from a 77 kA +CG at 0239 Z. Thus, some of lightning in the trailing stratiform region was clearly close to or exceeded sprite-class intensity. After the RS, there was marked in-cloud brightening as an apparent network of leaders moved northwestward, passing above a number of wind turbines (Fig. 4). At 51 ms after the RS, an upward positive leader was launched from a wind turbine about 10 km to the northwest of the +CG location. The LTUL luminosity exhibited a typical initial stage continuing current which was not detected by the NLDN. Recoil leaders were associated with both the channels linked to the +CG RS and the LTUL upward positive leader. At 189 ms after the RS, there began a series of 33 apparent downward dart leader reconnections, of which 19 (typically the brighter ones) were detected by the NLDN, all as negative CGs, with an average peak current of 11 kA (range: 4 to 22 kA). The intervals between dart leaders were erratic, lasting between 2 and 75 ms. In the video, all dart leaders appeared to involve a single turbine. Fig. 4 shows 11 NLDN reported subsequent dart leader reconnections which were catagorized as -CGs located within 300 m of the turbine, with

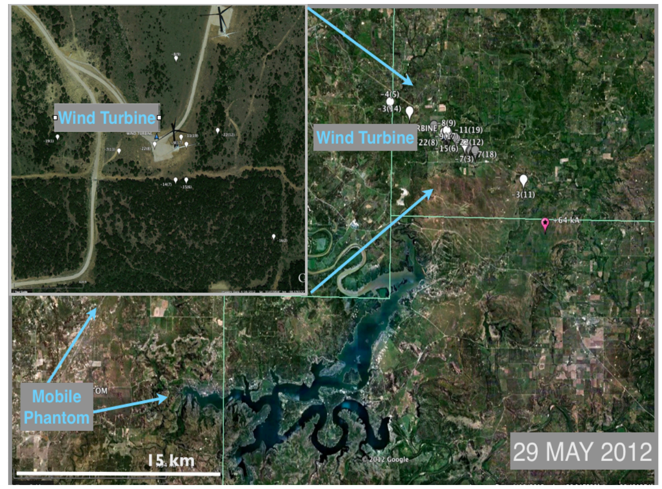

Figure 4. The Lightning-Triggered Upward Lightning (LTUL) event of 0253 Z, 29 May 2012, near Graham, TX. A single 64 kA +CG resulted in a 680 ms sequence which included an upward positive leader from a wind tubine located 10 km away, followed by a complex series of recoil and 33 downward dart leaders, 19 of which were detected as –CGs by the NLDN. More than half of the –CGs were located by the NLDN within 300 m of the turbine.

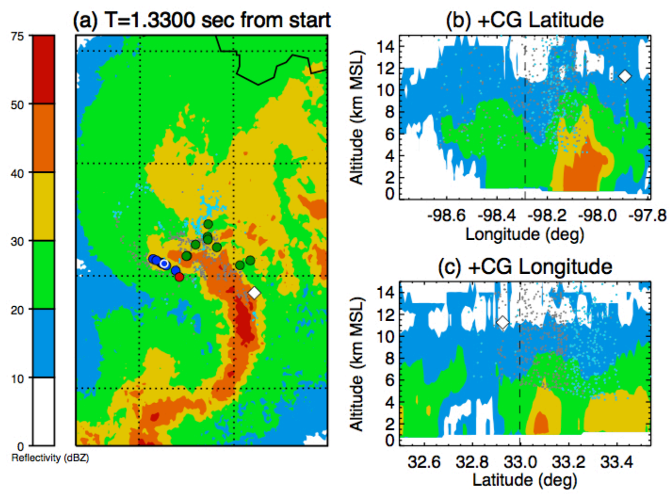

Figure 5. Reflectivity and LMA VHF sources for the 50+ km discharge resulting in a 64 kA +CG (red dot) near Graham, TX at 0253.40.711 Z on 29 May 2012 (Fig. 3). The lightning initiated (white triangle) in the leading edge of the MCS convective core and travelled northwest. At 51 ms after the +CG, the Phantom recorded the initiation of an upward positive leader from a wind turbine (white circle), followed by a complex display of recoil leaders and 33 stepped leaders reconnecting to the turbine. Gray dots are VHF sources, except blue when the LTUL was in progress. Green circles (-ICs). Blue circles (-CGs).

the remaining spread out in a band connecting the turbine and the RS strike point. The entire discharge lasted 680 ms. This turbine was estimated to be no taller than 120 m (base to blade tip) and was located on relatively flat terrain. It is not known if the blades were rotating or tethered at the time.

As reported by Warner et al. [2012a, 2012b, 2012c], within MCS convective systems in western South Dakota, a large fraction of the LTULs are preceeded by +CGs, some up to 50 km distant. About half of the LTUL upward positive leader events are followed by complex recoil and dart leader reconnections to the tower which can result in several NLDN reports per flash. The number of subsequent NLDN detections associated with tall objects reported here (19) was the largest number reported at the time from a single flash.

Fig. 5 shows the plan view of the composite NEXRAD radar reflectivity compiled using the 3-D NMQ national mosaic [Zhang et al., 2011]. In addition, east-west and north-south vertical cross sections thought the location of the LTUL are shown on the right side. The location was approxmately 175 km from the centroid of the Southwest Oklahoma LMA, and thus VHF sources were only availble above the line of sight horizon, approximately 3.5 km AGL. While vertical location errors are significant, the XY positions map out the channel reasonably well. The lightning initiated near the convective core of the leading line, and moved northwest, passing over the wind turbine. A series of –CGs and the +64 kA +CG occured before the onset of the LTUL sequence. Though horizontally extensive, this discharge was less energetic than a typical SP+CG, but still produced a network of negative leaders sufficient to initiate an LTUL.

LTULS IN THE KANSAS LMA

On 29-30 May 2013, conditions in the central plains were ideal for the development of deep convection, which organized into several LL/TS MCSs by late afternoon, and which then persisted through much of the night. Approximately 35 sprites were recorded from SpriteNet cameras in Colorado and New Mexico above the several MCSs during the night. By 0900 Z, a large LL/TS MCS was located in central Kansas.

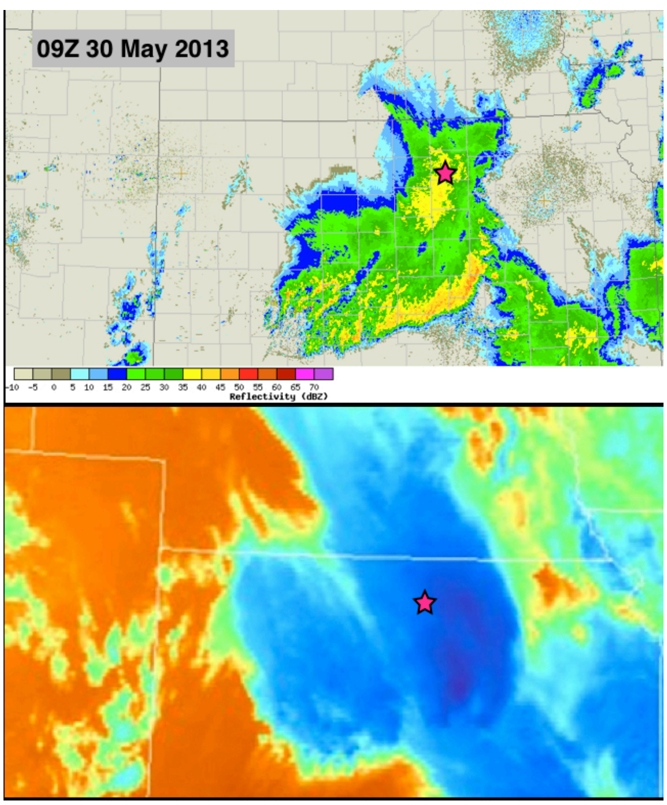

Figure 6. NEXRAD regional reflectivity (top) and GOES infrared satellite (bottom) imagery at 0900 Z on 30 May 2013. The star marks the location of the 91 kA +CG that triggered at least 4 upward positive leaders from 120 m tall wind turbines.

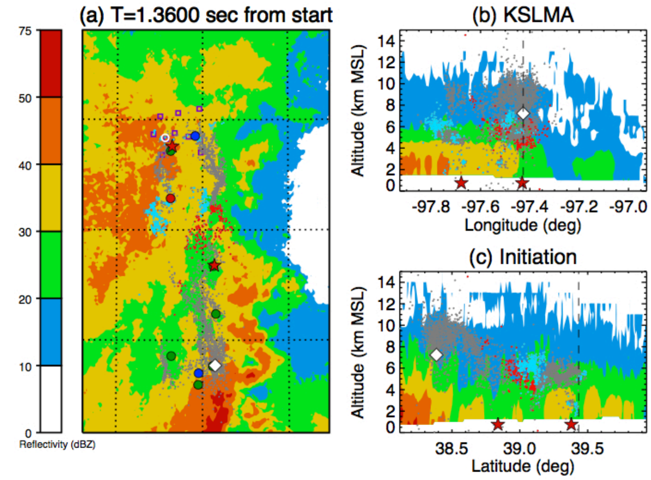

Figure 7. Plan and vertical reflectivity cross sections of a massive, 200 km long discharge originating at ~6 km AGL (white triangle) within the northern end of the MCS convective core. After first moving upward into a 10 km positive charge layer, it propagated downward and northward before making a U-turn over the wind farm and LMA receivers (open purple boxes). It spawned two SP+CGs (pink stars), the second of which also triggered the LTUL events shown in Fig. 8. The white circle represents the turbines experiencing LTULs. Grey dots are LMA VHF sources with red dots indicating those during periods of sprite luminosity and blue dots are those during the LTULs. Half degree latitude and longitude lines are shown. Green circles are –CGs, blue are –ICs.

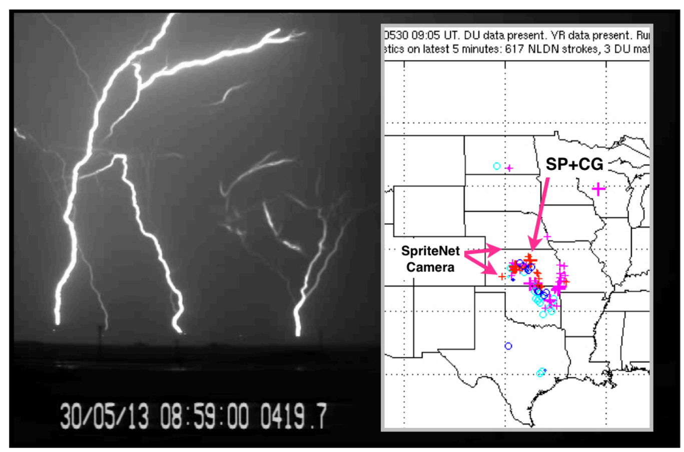

Figure 8. Four LTUL upward positive leaders luanched by wind turbines, triggerd by 91 kA +CG (not in field of view) at 0859.00 Z 30 May 2013.

It has long been noted that discharges associated with SP+CGs can be horizontally extensive and long lasting, at times approaching 300 km in total length and 5 seconds duration [Lang et al., 2012, 2013; Lyons et al., 2009]. At 0858.59.540 Z, a negative leader initiated near the northern end of the convective line at about 6 km AGL and propagated upward into an elevated positive charge layer around 10 km AGL (Fig. 7). It then began moving northwards at 10 km altitude for about 25 km after which it began a gradual descent into the 4-5 km AGL positive charge layer within the MCS trailing stratiform region. It then continued for another 100 km. As it reached east of the wind farm, it executed a U-turn, first westward and then southbound, passing over and then 50 km south of the wind farm, for a total length of ~200 km over a duration of 1340 ms (for an average propagation speed ~1.5 x10^5 m s^{-1}).

At 122 ms after flash initation, an 87 kA +CG, with a 250 C km iCMC, occurred in the stratiform region, though still well south of the wind farm. It triggered a sprite captured by the SpriteNet camera at Bennett, CO. The ongoing discharge continued moving north, made the U-turn, and began heading south of the wind farm (Fig. 7). Some 801 ms after initiation (at 0859.00.341 Z), a second 91 kA +CG, with about a 60 ms continuing current and a robust 280 C km +iCMC, triggering another sprite, with illumination beginning within 10 ms of the SP+CG. As shown in Fig. 8, using a standard speed camera, four (at least) wind turbines, located approximately 4 km northwest of the +CG attach point, launched upward positive leaders. Due to the temporal limitations of the standard speed video, plus initial satuation of the image, it is not possible to determine exactly when the upward leaders initated, but some 30 ms after the +CG appears plausible. The upward leader luminosity continued for approximately 220 ms. The LTUL events, triggered by a SP+CG, began after and continued longer than the sprite illumination, a behavior noted in prior Rapid City UPLIGHTS events [Warner et al., 2011; Lyons et al., 2011]. Thus, the processes involved with the triggered upward positive leaders and subsequent recoil and dart leaders appear unlikely to be significantly influencing sprite initiation per se. What sprites and LTULs do have in common, however, is the massive parent discharge. In particular, we note the vast network of horizontal leaders that aid in the lowering of huge amounts of charge to the ground requisite for a sprite through the +CG continuing current, while also sending horizontally propagating negative leaders great distances through elevated positive charge layers. Such horizontal leaders, whether associated with only strong intracloud development or following a +CG through previously formed leader networks can pass over tall obects and can enhance the local electric field sufficiently to initiate upward leaders [Warner et al., 2012a, 2012b, 2012c]. There were also two additional –CGs detected by the NLDN after the events in Fig. 8, likely from dart leader reconnections during an LTUL to a turbine further east that were not recorded by cameras. Rison et al. [2014] provide further discussions of these events.

While a prior +CG in the general vicinity appears the more common mode for LTUL generation in high plains storms, the passage overhead a tall object by an IC, without any associated prior CG, can also trigger an LTUL. Fig. 9 shows the NEXRAD regional radar reflectivity and GOES infrared imagery at about 2345 Z on 29 May 2013, during the earlier wave of convective activity impacting the wind farm. A linear LL/TS MCS had already passed the wind farm, which was thus located in the trailing stratiform region. This MCS had been producing a large number of sprite-class +CGs in northern Kansas and southern Nebraska (Fig. 10). There were also a number of energetic negative CGs within the convective core 50-100 km to the south of the wind farm. At 2320.07.098 Z, an upward positive leader emerged from a wind turbine, with luminosty continuing for 318 ms. There was, however, no prior triggering +CG. Rather the LMA noted an extensive IC discharge which originated within the convective core some 50 km to the south of the turbine. This flash started at 2320.06.650 Z, and as with the case discussed above, initiated with a upward negative leader at ~6 km AGL which then ascended into an upper positive layer around ~10 km.

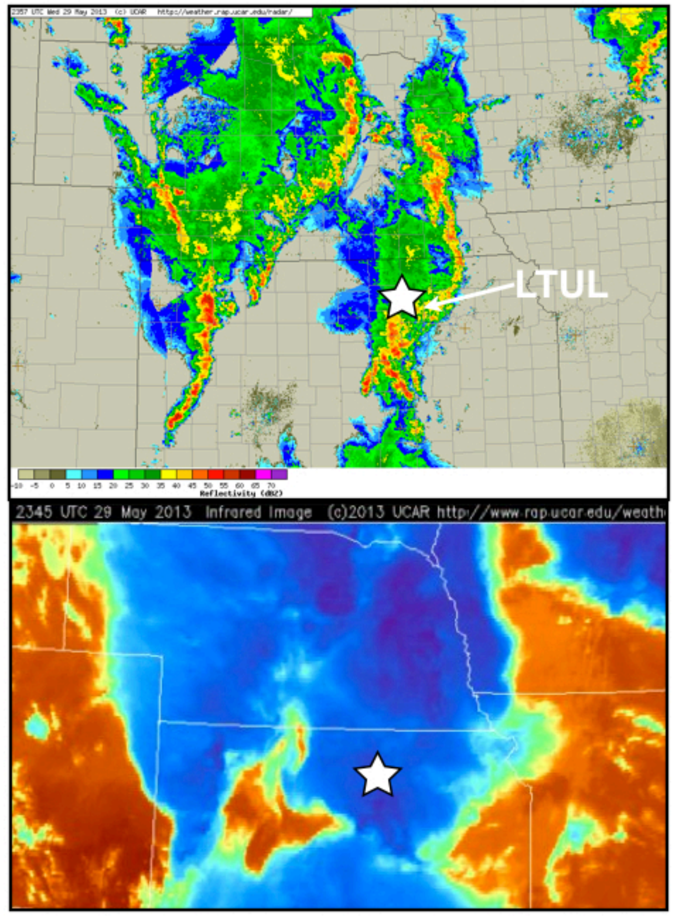

Figure 9. NEXRAD reflectivity (top) and GOES infrared images (bottom) at ~2345 Z, 29 May 2013. The star indicates the location of the LTUL from a wind turbine induced by the passage overhead of an extensive IC channel. The event occurred within the trailing stratiform of a large MCS.

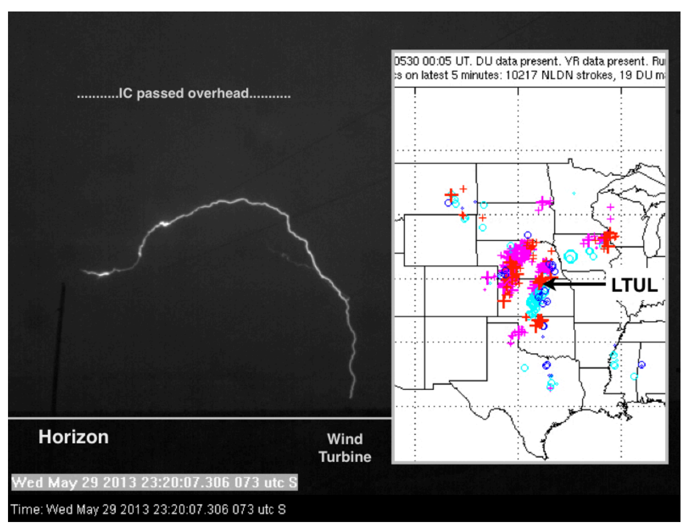

Figure 10. The upward positive leader from a wind turbine triggered by the passage overhead of a negative IC leader, without any prior CG in the general vicinity. The northern portion of the MCS was generating a large number of high iCMC (sprite-class) +CGs, but none were associated with this event.

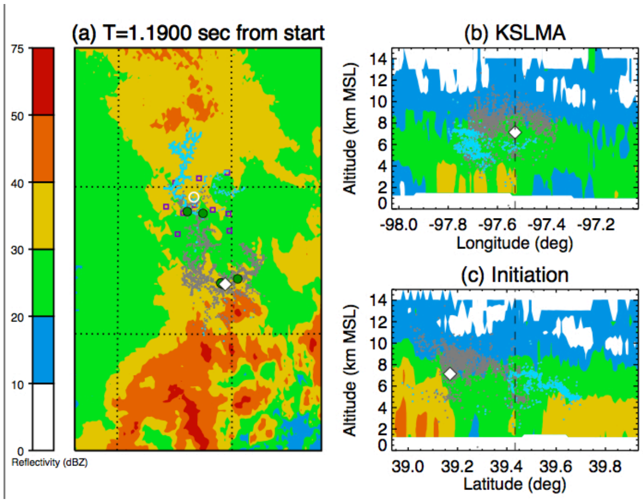

Figure 11. Plan and vertical reflectivity cross sections of a 50 km long discharge at 2320 Z 29 May 2013 which originated (white triangle) at 6 km AGL above the northern end of the convective core of the MCS. It first ascended to 10 km into a positive charge layer aloft. It then propagated downward and northward before passing over the wind farm and LMA receivers (open purple boxes). The passage overhead near a turbine triggered the LTUL shown in Fig. 10. The white circle represents the impacted turbine. Gray dots are LMA VHF sources, while blue dots are those during the LTUL. Green circles are –ICs. The dashed lines are half degree latitutde and longitude markers.

The flash initially radiated channels in several directions but with a main channel moving north towards the wind farm while descending into a positive stratiform layer at ~ 4-5 km AGL (Fig. 11). When this channel reached the wind farm, a negative leader descended from 8 km to about 4 km AGL into a region of positive charge at 2320.07.070 Z, detected by the NLDN as a -98 kA IC. This presumably created an enhanced local electric field near the surface. A clear brightening in the sky above the turbine was detected shortly thereafter by the Phantom camera as the in-cloud leader passed nearby, with the upward leader initiating 12 ms later at 2320.07.098 Z. The channel luminosity lasted until 2320.07.416 Z (318 ms).

There were numerous recoil events and one apparent dart leader reconnection to the wind turbine which was not, however, reported by the NLDN as a -CG. Though not especially highly branched, the upward discharge produced over 200 apparent recoil leaders, beginning 50 ms after upward positive leader initiation and continuing for 186 ms.

As has often been noted during the Rapid City LTUL episodes and elsewhere [Warner et al., 2012c; Orville and Berger, 1973], the upward leader can often transition to horizontal propagation below cloud base as seen in Fig. 10. It has been proposed that this behavior may result from a negative charge screening layer at and just below the cloud base [Coleman et al., 2003] which creates a negative potential well which ducts the upward positive leader into the horizontal.

DISCUSSION AND CONCLUSIONS

There are two modes of lightning-triggered upward lightning (LTUL) from tall structures. The first, and most common, involves an (almost always) positive CG strike, sometimes at a distance approaching 50 km, associated with extensive in-cloud leader networks, prior to the initiation of the upward positive leader. The second mode involves a leader passage overhead or nearby the tall object, which locally intensifies the electric field at the object top sufficiently to launch a leader. These findings are based upon analyses of 80+ LTUL events from moderately tall towers (91 -191 m) on hilltops around Rapid City, SD, during the passage of MCS stratiform regions during summer [Warner, 2011; Warner et al., 2012a, 2012b, 2012c]. Since a LMA was unavailable for those studies, the role of extensive networks of negative in-cloud leaders passing nearby the impacted towers could not be evaluated, though it is believed this was likely, as brightening within the clouds was commonly observed before upward leader initiation.

In the cases presented here, the availability of high resolution 3-D LMA source mapping clearly shows that horizontally extensive discharges likely play a prominent role in triggering upward positive leaders from tall objects whether or not there is a prior +CG involved.

In the case of an obvious prior +CG, which was also documented to have a large iCMC, there was in addition a confirmed sprite. This replicates the prior findings in the UPLIGHTS program in Rapid City that the meteorological regimes and lightning characteristics that can induce LTULs are also often favorable for potential SP+CGs [Lyons et al., 2011; Lueck, 2013].

Not all SP+CGs will necessarily trigger LTULs. For instance, tall objects are required in the areas experiencing locally enhanced near-surface electric fields. Also, LTULs can be triggered by highly energetic but not quite sprite-class +CGs. But it is clear that the meteorological conditions favorable for sprites and LTULs significantly overlap in central U.S. summer convective storms. Thus, a forecast of a mesoscale convective system capable of producing sprites is also equivalent to predicting an increased likelihood that tall objects may be involved in upward lightning. As noted by Beavis et al. [2014], mid-continental summer convective systems producing sprite-class lightning are often organized and long lasting. Therefore, forecasts of "outbreaks" of upward lightning events from tall structures during the passage of large MCS stratiform regions should show useful skill levels. This should be noted by the wind energy industry as it may suggest potential means to mitigate the any negative impact of such events.

While the initial upward positive leader does not appear to be routinely detected by the NLDN, in a significant fraction of LTULs (perhaps more than half?), subsequent processes including recoil leaders and especially reconnecting dart leaders, generate NLDN reports, typically as modest peak current –CGs and –ICs. In the first case (Graham, TX) presented here, 19 NLDN –CGs were reported following the triggering +CG. These are strokes that would not have occurred had the turbine not been present at that location. Given the many tens of thousands of broadcast transmission towers, cell phone towers, wind turbines and transmission line towers, additional care may be needed in the forensic applications of NLDN data for strokes occurring near tall, and perhaps not so tall (~100 m), structures [Byerley et al., 1999].

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