Cloud-to-Ground Lightning Production in Strongly Forced, Low-Instability Convective Lines

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Abstract

On 9 November 1998, a convective line initiated over Oklahoma along a cold front in a moderately unstable environment. The line moved east into an area of low to zero instability during 10 and 11 November 1998, yet continued producing damaging surface wind gusts. After moving into weaker instability, the strongly forced, low-instability convective line quit producing cloud-to-ground (CG) lightning as detected by the National Lightning Detection Network (NLDN). This paper seeks to explain the evolution of CG lightning in this case, the maintenance of the convective line in a low-instability environment, and the production of damaging surface winds. On 9 March 2002, a similar case occurred. Lightning production in this case is documented, and other similarities between this and the 9-11 November 1998 case are noted.

1. Introduction

Mesoscale convective systems (MCSs) occasionally occur in which many severe wind reports are received, yet very little cloud-to-ground (CG) lightning is detected by the National Lightning Detection Network (NLDN). Such MCSs often occur during the winter season in low instability environments with strong dynamics, and take the form of strongly forced, low-instability convective lines. These convective lines pose a dilemma for forecasters: severe thunderstorm watches and warnings do not seem appropriate because CG lightning is absent, but advisories for strong wind do not seem appropriate either because this wind does not occur on the synoptic scale.

On 9 November 1998, a cyclone formed over the southern Plains, and began to rapidly deepen on 10 November. At 21 UTC 9 November, a convective line formed along the cyclone's cold front in the Texas and Oklahoma panhandles. As this line moved across the United States it quit producing observed CG lightning, yet produced widespread wind damage from north Texas to eastern Ohio (Fig. 1). The purpose of this paper is to understand the production of CG lightning in strong forced, low-instability convective lines. Section 2 will discuss the evolution of the 9-11 November 1998 case, including lightning production, maintenance of the convective line in a low CAPE environment, and how winds meeting severe criteria, defined as ≥ 25.7 m s^{-1} (50 knots), reached the surface. Section 3 examines lightning production in the similar case of 9-10 March 2002. Section 4 concludes this paper.

2. 10-11 November 1998

In this section, the 10-11 November 1998 case is examined chronologically, beginning 00 UTC 10 November and ending 00 UTC 11 November. Section 2a covers the time during which frequent CG lightning was observed with the convective line. By 12 UTC 10 November, the line made a transition to producing nearly no observable CG lightning, and at the same time began producing more widespread damaging winds. Section 2b will discuss environmental conditions that allowed the line to make this transition. Finally, section 2c will describe how the convective line dissipated.

a. Frequent CG Lightning Phase

At 00 UTC 10 November, a large-amplitude 500-mb trough moved out of the Rockies, with strong diffluence developing over much of the Plains (Fig. 2a). An axis of 45 m s^{-1} flow was rounding the base of the 500-mb trough. A 992-mb low was centered over central Kansas (Fig. 3a). The ascending branch of the frontal circulation associated with the cyclone's cold front aided in the development of the convective line (Fig. 4c) (Connors 1999), which was located from the low center southwest into north-central Texas (Fig. 4a).

According to MacGorman and Rust (1998, 218-220), vigorous updrafts must be present in the mixed-phase region of the cloud, defined as that portion of the cloud between –10˚C and –40˚C, for sufficient charge separation to occur for the production of CG lightning. To test the requirements for lightning production, the –10˚C and –40ºC isotherms were located on observed soundings. Vertical distribution of convective available potential energy (CAPE) was examined, and updraft potential in the convective line's mixed-phase region was inferred based on vertical distribution of stability.

The convective line was producing frequent CG lightning early in its lifetime as detected by the NLDN (Fig. 4b). The 00 UTC 10 November KOUN sounding supported this observation (Fig. 4d): the –10˚C isotherm was located at approximately 550 mb, while the equilibrium level (EL) pressure was 189 mb and temperature was –64ºC. Cloud top temperatures estimated from satellite observations ranged from –60ºC to -70ºC along the convective line, indicating that parcels were reaching the altitudes indicated by the KOUN sounding. CAPE was 1623 J kg^{-1} with an LI of -6ºC. These observations indicate the presence of instability and the likelihood of deep storm updrafts in the preline environment. Strong upward vertical motion was likely present in the mixed-phase region of the convective line's updrafts, indicating a high chance for CG lightning consistent with NLDN observations.

In summary, the convective line was in a region of moderate instability at the time of initiation. In this environment, maintenance of the convective line was not difficult. Deep, strong updrafts through the depth of the troposphere, evidenced by the degree of instability, were supportive of high lightning frequency.

b. No CG Lightning Phase

Between 00 and 12 UTC 10 November 1998, the cyclone moved from central Kansas to north-central Iowa. At 12 UTC 10 November, a 500-mb closed low was located over western Iowa, northeast Nebraska, and southeast South Dakota (Fig. 2b). Strong diffluence aloft was noted downstream of the low, and a 45 m s^{-1} jetstreak had rounded the base of the trough and was moving across Missouri, western Illinois, and entering southwest Wisconsin (Fig. 2b). A 971-mb surface low was located in north-central Iowa (Fig. 3b). The convective line was located from central Illinois south through eastern Arkansas and into Louisiana at 12 UTC (Fig. 5a). Around 12 UTC, CG lightning rates in the northern portion of the convective line decreased to near zero (Fig. 5b), marking a dramatic shift in the convective line's evolution.

Moving eastward, the convective line encountered an increasingly hostile environment for CG lightning production. Although well ahead of the line, the 12 UTC 10 November ILN sounding (Wilmington, Ohio) was the best available sounding to represent the preline environment (Fig. 5d). This sounding had an LI of –2ºC and CAPE of 180 J kg^{-1}, with all the CAPE located at temperatures warmer than –15˚C. Thus, vertical motions within the mixed-phase region of the cloud sufficient to separate charge, ultimately leading to CG lightning, were less likely to occur. Despite its lack of CG lightning, the convection maintained itself and produced damaging winds.

A few speculations are presented which may have contributed to the maintenance of the convective line. Inflow of moist air to the east was likely important to the line's maintenance. RUC-derived soundings were examined to evaluate the moisture profile ahead of the convective line. The low levels moistened by 09 UTC, and by 18 UTC RUC-derived soundings indicate a moist adiabatic, nearly saturated atmosphere up to the tropopause. The 21 UTC KCAK sounding (Akron, Ohio) was chosen as a derived sounding representative of the preline environment (Fig. 6). Above about 820 mb, the preline environment was saturated and nearly moist adiabatic. Parcels displaced upward in this environment would experience little resistance to continued vertical motion. Given the strong ongoing convective line and associated frontal circulation, this upward displacement would have easily occurred.

Around 12 UTC 10 November as the convective line was moving into Indiana, widespread damaging surface winds were reported despite the lack of CG lightning (Fig. 1). Because of the strong surface cyclone, sustained surface winds of 15.4 to 20.6 m s^{-1} (30 to 40 knots) were occurring in a large area ahead of and behind the convective line (Fig. 3b). Given the already strong winds, not much would have been required to push convective winds past severe criteria on this day, with high momentum air from aloft likely responsible for the production of damaging surface winds.

Cross sections including vertical velocity (ω) from RUC model output support descent of high momentum air at the time widespread damaging winds were occurring in the absence of lightning (Fig. 5c). A broad area of sinking motion reached the surface immediately behind the convective line. Likely contributing to this descent include synoptic-scale sinking behind the cyclone fostered by strong cold advection, mesoscale descent associated with the downward branch of the frontal circulation, and storm-scale descent within individual convective elements. In addition, the moist postline environment promoted moist adiabatic descent. Such moist-adiabatic descent would have been important in two respects. First, conditional instability ($\partial\theta_{es}/\partial z < 0$) was present behind the line, so moist descent would have been unstable. Second, moist adiabatic conditions reduced the horizontal scale and increased the magnitude of descent immediately behind the convective line (Fig. 5c). Evidence for a moist adiabatic environment behind the convective line includes moist surface air (Fig. 2b) and the development of a parallel stratiform precipitation region (defined by Parker 2000) around the convective line.

Vertical wind profiles behind the convective line indicate that not much descent would have been required to bring down air of sufficient momentum to exceed severe criteria. Postline 12 UTC 10 November observed soundings were examined for the lowest level at which 25.7 m s^{-1} (50 knot) flow occurred. As damaging winds began to reach the surface, 25.7 m s^{-1} winds could be found at 1030 m AGL (830 mb--Davenport, Iowa), 800 m AGL (870 mb--Springfield, Missouri), and 735 m AGL (905 mb--Little Rock, Arkansas). The low altitude at which 25.7 m s^{-1} wind was found suggests that descent of sufficient momentum to produce severe wind gusts could have occurred easily.

c. Dissipation Phase

Between 12 UTC 10 November and 00 UTC 11 November, widespread damaging wind occurred with the convective line across Indiana and Ohio. At 00 UTC 11 November, a broad 500-mb trough was centered over the western Great Lakes, with a closed low centered over western Lake Superior and a large area of 50-70 m s^{-1} flow within the trough base (Fig. 2c). The occluding surface low had moved to the Canadian border, with a tight pressure gradient and resultant strong winds across the north-central United States (Fig. 3c). By this time, the convective line had dissipated into a rainband extending from southeast Ontario to northern Georgia (Fig. 7a), and was no longer producing damaging wind reports or lightning (Fig. 7b).

Soundings taken at 00 UTC 11 November were unfavorable for CG lightning. The soundings from KBUF (Buffalo, New York) and KPIT (Pittsburgh, Pennsylvania—Fig. 7d) at this time show zero CAPE and LIs greater than zero. The –10˚C isotherm in each sounding is near 500 mb. With the lack of instability above the –10˚C isotherm, strong updrafts were unlikely in the mixed-phase region. Enough charge separation likely did not occur for the production of CG lightning, consistent with NLDN observations.

As speculated above, the nearly moist adiabatic atmosphere ahead of the convective line was likely necessary for its maintenance. Comparing RUC-derived 00 UTC 11 November soundings for KPIT and KBUF with earlier RUC-derived soundings, the preline lower atmosphere was further from saturation at 00 UTC 11 November than at 12 UTC. In the absence of CAPE, deep convection would have been very difficult with a non-moist adiabatic preline environment.

As the convective line weakened, its associated frontal circulation also diminished, as shown in RUC model output (Fig. 7c). A weakening in the downward branch of this circulation would have decreased descent of high momentum air, reducing the potential for damaging surface winds.

3. 9-10 March 2002

On 9-10 March 2002, a 500-mb trough was located over the north-central United States, with a deepening surface cyclone moving from the central Plains to the northern Great Lakes. A strong baroclinic zone associated with this low served as a focus for the development of a strongly forced, low-instability convective line, which produced widespread severe wind reports from Kansas and Oklahoma to Iowa (Fig. 8). This line weakened substantially, with almost no severe reports across Illinois and Indiana, then redeveloped in the stable environment to the east and produced widespread damaging wind in Ohio, West Virginia, and western Pennsylvania (Fig. 8). CG lightning production was examined in this case, and the similarities to the 9-11 November 1998 case are discussed.

Conditions for the production of CG lightning changed dramatically over 9-10 March 2002. As with 9-11 November 1998, soundings were analyzed to ascertain thermodynamic preline characteristics. The 00 UTC 9 March 2002 TOP sounding (Topeka, Kansas), just east of initiation, showed 793 J kg^{-1} of CAPE and an LI of –4.3ºC (Fig. 9a). Nearly all CAPE was located between the –10ºC and –40ºC isotherms, indicating the likelihood of strong convective updrafts in the mixed-phase region of the convective line. NLDN data from the early period of the line's evolution shows a high frequency of detected CG lightning (Fig. 10a).

CG lightning with the convective line was no longer detected by the NLDN as the line moved into central Indiana around 15 UTC (Fig. 10b). Preline 12 UTC 9 March soundings show a substantial change in thermodynamic parameters, which explains the lack of detected CG lightning. The KILX (Lincoln, Illinois) sounding (Fig 9b) showed CAPE of 1 J kg^{-1} and an LI of +3.3ºC, and the BNA sounding showed no CAPE with an LI of +4.6ºC. No instability was present in the mixed-phase region of the convective line, not allowing sufficient charge separation for CG lightning. This is consistent with NLDN observations of no detected CG lightning. Around 21 UTC 9 March, the convective line became very intense and produced widespread wind damage across central and eastern Ohio (Fig. 8), yet almost no CG lightning was detected by the NLDN during this time (Fig. 10c).

Around 02 UTC 10 March, the NLDN again began detecting high frequencies of CG lightning with the convective line (Fig. 10d). Thermodynamic changes in the preline environment by 00 UTC 10 March began to favor renewed CG lightning production. The KIAD sounding (Sterling, Virginia) was representative of the preline environment (Fig. 9d). It showed CAPE of 465 J kg^{-1} and an LI of –2ºC. CAPE was present up to the –30ºC isotherm, indicating the potential for well-developed updrafts in the mixed-phase region of the convective line once it moved into the higher-CAPE area. Charge separation and CG lightning should have been able to occur, and NLDN data shows a high frequency of CG lightning (Fig. 10d).

Three similarities were found between the 9-11 November 1998 and 9-10 March 2002 cases regarding the maintenance of the strongly forced, low-instability convective line and the production of damaging winds. First, preline soundings from KILX (12 UTC 9 March—Fig. 9b) and KIAD (00 UTC 10 March—Fig. 9c) show a nearly moist adiabatic preline atmosphere, with saturation up to 500 mb (KILX) and 750 mb (KIAD). Second, these soundings showed 30 m s^{-1} of flow at 730 m AGL (ILX) and 900 m AGL (IAD), indicating that high-momentum air could have easily descended to the surface. An increase in 850-mb flow of 10 m s^{-1} (20 knots) occurred as the convective line was beginning to produce more widespread damaging winds in Ohio around 21 UTC 9 March. Third, the RUC model output showed a frontal circulation along the convective line, the downward branch of which seems to have transported high-momentum air from aloft.

4. Conclusions

Two strongly forced, low-instability convective lines (9-11 November 1998 and 9-10 March 2002) are examined to understand the factors that control the production of CG lightning in these systems. When CG lightning is frequent, CAPE implies vertical motions of several m s^{-1} in the mixed-phase region of the cloud, between –10ºC and –40ºC, where the charge separation process is thought to occur (MacGorman and Rust 1998, 218-220). When CG lightning is absent, little or no instability is found in the cloud's mixed-phase region. Thus, the vertical distribution of CAPE in the mixed-phase region, rather than the mere presence of CAPE in a sounding, is important for determining the occurrence of CG lightning from synoptic data.

Synoptic flow was very strong in both cases, so not much was required for severe wind to reach the surface. Descent of momentum from aloft is thought responsible for the damaging surface winds in both events. This descent originated on the synoptic scale behind the associated cyclone, on the mesoscale from the downward branch of the associated frontal circulation, and from storm-scale downdrafts. Consequently, even environments with low or zero instability, if strongly forced, are capable of producing severe weather, even in the absence of CG lightning.

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