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Analysis of Cloud and Cloud-to-Ground Lightning in Winter Precipitation

Brian P. Pettegrew[1], Patrick S. Market[1], Ronald L. Holle[2], and Nicholas W. S. Demetriades[2]

[1]Department of Soil, Environmental and Atmospheric Sciences
University of Missouri-Columbia
Columbia, Missouri

[2]Vaisala, Inc.
Tucson, Arizona

1. INTRODUCTION

Lightning characteristics in weather events across the continental United States has been studied extensively in the last decade using Vaisala's National Lightning Detection Network (NLDN: Orville 1991, 1994, Zajac and Rutledge 2001, Carey and Rutledge 2003) and the North America Lightning Detection Network (NALDN: Orville et al. 2002). Most of these studies, however, either focus on the climatological aspect of lightning characteristics over a number of years or by specific weather type (Carey and Rutledge 2003). Orville (1994) identified a latitudinal dependence on the polarity of lightning showing that the percent of positive flashes increases with increasing latitude. He also indicated diurnal tendencies in flash rate, but attributed them to dissipating mesoscale convective systems over the central plains.

Recent research in thundersnow has aroused new interest in lightning characteristics in a specific weather event. Previous studies of this phenomenon include Holle et al. (1998) who examined surface observations at or below freezing in the presence of thunder and lightning. Market et al. (2002) extended this work by creating a 30-year climatology of thundersnow, and dividing it spatially and temporally over the U.S. during the winter season, which is defined as October through April.

Vaisala, Inc. performed upgrades to the NLDN (Cummins et al. 2006) to adjust the threshold frequency in order to minimize the number of false positive cloud-to-ground strokes and flashes and identify them instead as cloud flashes. A collaboration between Vaisala, Inc. and the University of Missouri was started in order to use the cloud lightning data in order to analyze not only the feasibility of the product but also to analyze the storm characteristics of convective snowfall via lightning data.

Previous research on lightning in winter precipitation has been done primarily on the mountainous coasts of Japan (Taniguchi et al. 1982, Brook et al. 1982, Michimoto 1993) while few studies of lightning with winter precipitation have been done over the central U.S. (e.g., Trapp et al. 2001; Holle and Watson 1996). Part of the difficulty with *in situ* studies in this region has been the flat terrain and strong winds creating blizzard conditions, with cloud particles and precipitation particles blowing at significant speeds (MacGorman and Rust 1998). The current work seeks to gain an understanding of the thundersnow environment using lightning data along with assessing the value of cloud lightning detection in the NLDN in storms involving winter precipitation.

2. DATA AND METHODOLOGY

Lightning stroke data was taken from local archives of Vaisala's NLDN data feed. According to Cummins et al. (1998), the NLDN has a median location reporting error of about 500 m. Biagi et al. (2007) reports a detection efficiency of ~71% for cloud-to-ground (CG) strokes and >90% for CG flashes. The detection efficiency of the cloud lightning in the NLDN varies between 10 and 20%. In previous studies (Orville et al. 2002), low amplitude (<10 kA) positive CG flashes were eliminated from datasets and deemed cloud flashes. Omitting low amplitude positive CG events is not necessary for this study since the upgrade of the NLDN to identify cloud flashes by implementing a 15 kA cutoff on low amplitude positive CG lightning (Cummins et al. 2006). It should be noted that the latitude and longitude data represented in the NLDN for CG strokes indicates the point where the lightning strikes the ground and not where it originates in the cloud. The detection of cloud flashes is more complicated since there is no contact with ground.

Fourteen cases were analyzed for the winter season (October through April). These cases were all significant storms producing heavy precipitation both in the warm sector of the cyclone and in the subfreezing air, where winter precipitation fell.

Corresponding author: Brian Pettegrew, University of Missouri-Columbia, 302 ABNR Building, Columbia, MO 65211. E-mail: bpp4y8@mizzou.edu

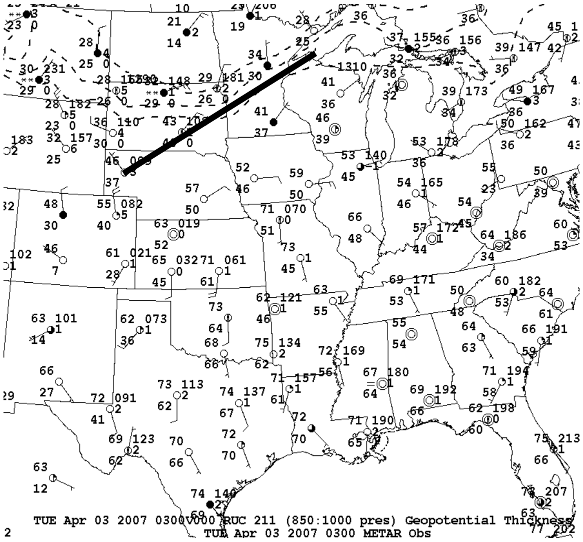

Figure 1. Map encompassing central U.S. representing domain from which lightning data was queried along with surface METAR observations. Dashed lines are 850-1000-mb thickness from 1290 gpm to 1310 gpm. Line represents rain-to-snow transition line.

For each of the cases, lightning data was queried for a region encompassing the central U.S. (longitude 110 W to longitude 79 W in Figure 1) and separated into cloud and CG events. Using surface METAR reports and 40-km Rapid Update Cycle (RUC2) analyses of 850-1000-mb thickness, a rain-snow transition line was determined. The standard rain-to-snow transition line in this partial thickness regime is 1290 geopotential meters (gpm).

However, mixed-phase precipitation such as sleet, ice pellets, and freezing rain can occur at thicknesses greater than 1290 gpm. For this reason, thickness was plotted up to 1310 gpm at a 10 gpm interval and plotted with surface METAR reports at matching times every 4 hours. From this approach, a line is fixed with two endpoints, each having a longitude and latitude point, indicating a transition line representative of the 4-hour period. The slope of the line was calculated given the coordinates for these endpoints. We employed a simple linear equation of the classic form:

$$y = mx + b$$

Where m is the slope, x is a point in the x direction, which is represented by a change in the longitude between the western endpoint and the longitude of any given lightning event detected, and b is the y-intercept given by the latitude on the western endpoint of the line. Solving for y gives the latitude of the line at any given longitude of a detected lightning event, thus by comparing the latitude of the line to the latitude of the detected lightning, those that occur in cold air as opposed to warm air can be separated.

24-hr lightning trends were determined in each case based on both the total lightning from the storm and from lightning determined to be associated with frozen precipitation. A percent occurrence of each type of lightning (e.g. negative CG, positive CG, and cloud) was also calculated in each case along with a cloud to CG ratio. This will help not only to gain knowledge of lightning characteristics in storms with frozen precipitation but also serve as a determination of the value of cloud lightning detection by Vaisala's NLDN. A seasonal trend was developed for the entirety of the season, both with the total dataset and the winter dataset. This was further broken down into the individual lightning types. Additionally, the average distance between cloud flashes and CG strokes was determined. Ideal groupings consisted of one CG stroke and one cloud flash at the same time, but of course, this is not the case in some of these cases, particularly those that exhibited some stronger tendency to lightning activity.

Each individual case and case subset was further analyzed for its physical characteristics via model initial soundings from the RUC. A model initial time was taken of the most active lightning from each 4-hr subset along with a latitude and longitude location of the most active lightning associated with frozen precipitation. The RUC model displays data points in the vertical every 50 mb from 50 mb down to the surface. Employing Brown's (1993) feature preserving techniques for composite soundings, the most unstable lifted parcel level (MULPL), the top of the inversion layer, the height (pressure and height in meters) of the -10°C isotherm, and the height (pressure and height in meters) of the -20°C isotherm were determined for compositing. The mean of these sounding features and the significant levels (i.e. 850, 700, 500, 300, 250, etc…) were determined. From these data, a sounding profile was produced using the RAOB 5.7 sounding analysis software. There was a total of 45 northeast (NE) soundings to composite while there were only 19 northwest (NW) cases. The NE cases were further subdivided into three 4-hour segments, the four hours prior to the most active lightning (N=7), the four hours during the most active lightning (N=12), and the four hours after the most active lightning occurred (N=8). Caution is given to results given the small dataset.

3. RESULTS AND DISCUSSION

The values for the fourteen individual storms were combined by matching the lightning data for each 4-hr segment to the times of the day. Thus, all lightning occurring between 0000 UTC and 0400 UTC for a given storm was matched with lightning from the other storms for the same period. By doing this, an overall 24-hr trend for the entire season may be formed. The fourteen-storm total lightning event count was 3,185,829 with 35.0%

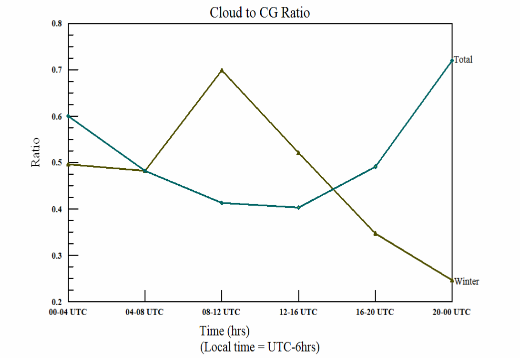

Figure 2 24-hr trend in cloud to cloud-to-ground ratio of the storm total dataset and the lightning associated with winter precipitation for the winter season of 2006-2007. Time in UTC.

detected as cloud flashes and 65.0% detected as CG strokes. Of all of the observed CG strokes, 95.1% were observed as negative CG strokes with only 4.9% observed as positive CG strokes. Out of the total dataset, positive CG strokes made up 3.2% on average. These events were observed at an event rate of 76.6 min^{-1}. Only 1.4%, or 44,280 events, of these storms' total count occurred in regions containing winter precipitation, of which 31.3% were identified as cloud flashes and 68.7% were observed CG strokes. Of the observed CG strokes, 92.0% were observed as negative CG strokes with 8.0% being observed as positive CG strokes. In the entire dataset of lightning in winter precipitation, positive CG strokes accounted for 5.5% of the total.

The percentage of positive lightning events was well under the average (~11%) found by Orville (1994). Further, the percentage of positive lightning in winter precipitation is contrary to Hobbs (1974) and MacGorman and Rust (1998) who state that since ice particles typically attain a positive charge in a winter cloud, a lightning event in a winter cloud might lower positive charge to the surface. Other work by Holle and Watson (1996) found a convective winter storm that lowered up to 59% positive lightning events associated with winter precipitation. However, Orville and Huffines (2001) found that the monthly mean percentage of positive lightning from 1989-1998 peaked at about 17% in December and gradually decreased into the spring, meaning that, in that decade, greater than 80% of all observed lightning was negative. This appears to be the case for these events, as the majority of charges lowered to ground were low amplitude negative CG strokes. This does not account for cloud flashes however. These are explained later in this section regarding cloud to CG ratios.

The percentage of lightning that made up the dataset of lightning activity associated with winter precipitation fluctuated within the divided 4-hr subsets. While the average percentage for the entire season was about 1.4%, the highest percentage, 2.2%, occurred during the hours of 0000 UTC to 0400 UTC. This coincided with the peak time for lightning activity in winter precipitation. This percentage decreased during the daytime to a minimum of 0.8% from1200 UTC and 1600 UTC and from 2000 UTC and 0000 UTC.

The average cloud-to-CG ratio for all lightning in these storms is 0.53. The ratio fluctuates ranging from its highest at 0.60 during peak lightning activity (0000 UTC to 0400 UTC) to 0.40 during the minimum in lightning activity (1200 UTC to 2000 UTC; Fig.2). The average cloud-to-CG ratio for those lightning events associated with winter precipitation is 0.46. The minimum is 0.25 occurring from 2000 UTC to 0000 UTC when lightning activity begins to increase. The cloud flash activity continues to decrease until after 0000 UTC when it begins to increase again maximizes at 0400 UTC along with the CG lightning. The maximum ratio, of 0.70 occurs from 0800 UTC to 1200 UTC. This is seen with the decrease of the occurrence of CG lightning and continuously observed cloud lightning. It should be noted that the cloud to CG ratio was observed using stroke data and not flash data.

Further, analysis was performed to quantify the observed distance between observed cloud flashes and CG strokes occurring at the same time in the same storm. On average, cloud flashes and CG strokes occurred within 0.74 km from each other. This varied from as close as 0.25 km to as far as 1.75 km.

When the data are matched up with the individual times of day, a more coherent trend appears for wintertime cyclone events. Figure 3a shows the 24-hr lightning trends for the combined storm dataset, along with the 24-hr lightning trend in winter precipitation shown in Figure 3b. The storm total lightning trend for this winter season shows a decrease in occurrence of all lightning types from 0400 UTC to 0800 UTC with a flat line trend until it begins to increase by 2000 UTC until it reaches its peak near 0400 UTC. Orville (1994) identified overall diurnal trends in the high plains for yearly climatologies of the overall network, partly due to the increase in mesoscale convective system (MCS) activity during the summer months. The 24-hr trend for positive lightning in this instance is fairly steady with minimal change. However, this may not be the case for winter events associated with frozen precipitation. The 24-hr trend of lightning associated with winter precipitation shows a much more defined diurnal trend with at 0400 UTC. Instead of a steady average, the lightning events associated with winter precipitation are lowest in the afternoon towards 1800 UTC. It is apparent that this is the case with all observed or

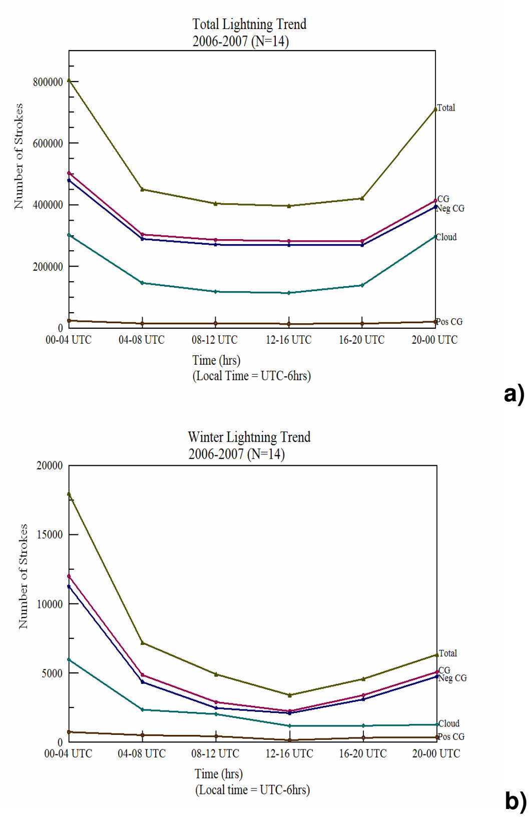

Figure 3 24-hr lightning trend for both *a*) the storm total dataset and *b*) the lightning associated with winter precipitation for the winter season of 2006-2007. Time in UTC.

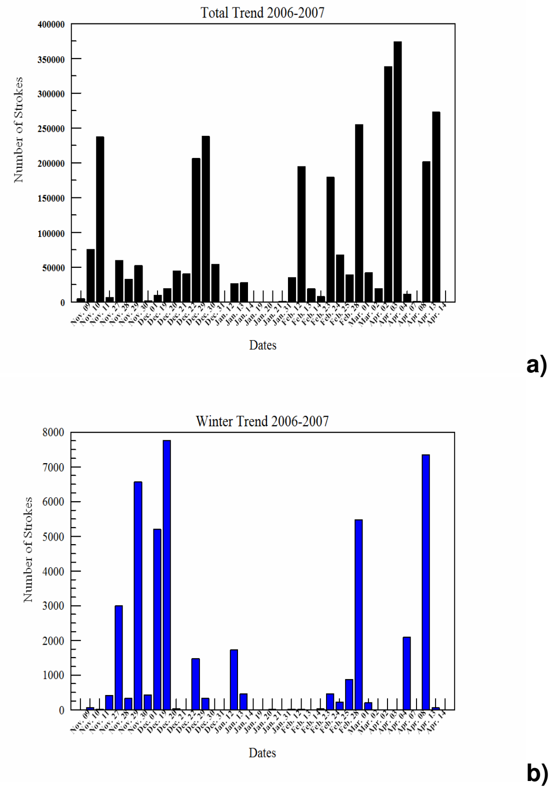

Figure 4 Seasonal lightning trend for both *a*) the total storm dataset and *b*) the lightning associated with winter precipitation for the winter season 2006-2007. Dates are labeled monthly.

identified types of lightning detected by the NLDN. Few positive strokes are observed.

While little emphasis can be placed on the seasonal trend of lightning occurrence given only one year of data, a trend line was formed to gain knowledge of how the season between 2006 and 2007 performed against known trends for winter convection. The overall observed lightning a tendency to increase (Fig. 4a) through the course of the winter season (October through April). Accordingly, this also shows that lightning activity peaks first during the month of December, particularly towards the end of the month and the beginning of January. While dropping in the middle of winter, lightning totals again peak during the beginning of March and into April. This is attributed to more active spring weather associated with less winter precipitation.

The trend in lightning associated with winter precipitation, however, is much different with the trend line remaining fairly stable with a slight decrease through the season (Fig. 4b). This does not follow the findings of Market et al. (2002) in which occurrence of thundersnow actually tends to increase through the season. However, the occurrence of thundersnow may also not gage the actual numbers of observed lightning events associated with winter precipitation well. An initial maximum occurs late in November into early December with the low point occurring in late January and February. The event cycle then peaks again towards the spring months of March and April. This tendency does in fact follow Market et al. (2002) with the peaks in thundersnow occurring early and late in the defined winter season.

Further, the trend can be analyzed spatially by determining the average lightning location for winter lightning for each day of occurrence. October is the only month for this particular winter season that is not included since the first thundersnow event for the winter season did not occur until 09-10 November. Additionally, there is no correlation between the amount of lightning found in winter precipitation and the intensity of the storm itself. One would assume that in a more intense system (i.e. greater pressure and/or height falls) more lightning might occur. Iskenderian (1988) showed that, in the context of precipitation maxima, the deepening of cyclones does not always correlate with the max precipitation. Figure 5 shows the average location for winter lightning over the central U.S.

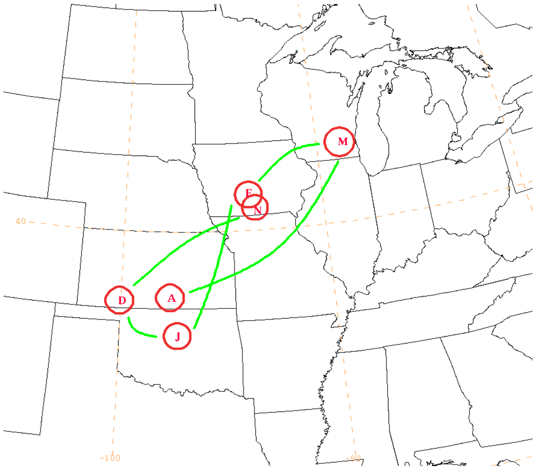

Figure 5 Map indicating monthly average location for winter lightning in the central U.S. Each red circle represents the latitude-longitude location of the average with the letter representing the month of the average. Green track connects average locations in order.

4. COMPOSITE SOUNDINGS

The composite soundings are composed of RUC initial sounding features from the average (in some cases sole) location of most active lightning in winter precipitation. The location(s) was analyzed for its geographic orientation with respect to the location of the center of the surface low similar to Market et al. (2002, 2006). A majority of the cases were designated northeast (NE) of the cyclone center. In total, there were 45 NE cases. Some subsets were divided and composites created separately for their timing significance, although it significantly decreases the number of samples. There were only 19 northwest (NW) cases occurring in a total 5 of the events. These composite soundings were analyzed using RAOB 5.7 software.

The NE composite sounding (Fig. 6) was the warmer of the two composite soundings. The top of the inversion layer was located just below 800 mb representing the necessary warm nose in this instance to produce frozen precipitation. In this particular composite, the temperature at the top of the inversion is 2.7℃. The profile between the top of the inversion down to 950 mb represents a stable dry adiabatic layer. Above the inversion, the temperature profile is moist-neutral up to approximately 500 mb. The tropopause level is at about 250 mb. Veering in the wind pattern in the lowest 200 mb indicates warm air advection below the inversion. Winds become fairly linear with little directional shear above the inversion. This is supported by the curvature of the hodograph inset in Figure 6. There is also little speed sheer in the vertical with winds near the surface at about 20 knots (10.3 m s^{-1}) increasing to 40 knots (20.6 m s^{-1}) by 550 mb and an 80 knot (41.1 m s^{-1}) jet above 300 mb. In terms of instability parameters, there is no potential instability or CAPE when lifting from the most unstable parcel originating at 704 mb. However, this composite had a Lifted Index (LI) of 1.7, which is statistically significant according to Market et al. (2006), and a calculated downdraft CAPE (DCAPE) of 470 J/kg.

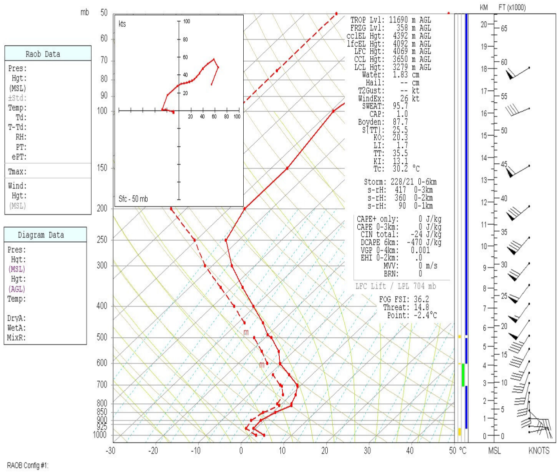

Figure 6 Full northeast composite (N=45) composed from RUC initial soundings at the latitude and longitude of most active lightning in winter precipitation.

Using Brown's (1993) feature preserving compositing method, the height and pressure level of the -10℃ isotherm was found and inserted into the composite data for reference to a lightning favoring profile. The -10℃ isotherm was located at 601 mb, or 4175 m (4.2 km). This average height is well above the 1.8 km recommended by Michimoto (1993). This was also well within the moist-neutral layer between 800 and 600 mb and above the most unstable lifted parcel level (MULPL) of 704 mb. A parcel lifted from below the -10℃ isotherm has been correlated to instability profiles most often associated with those of convective winter precipitation events. Following MacGorman and Rust (1998), the best region of mixed-phase particles, which include graupel and supercooled water droplets, occurs typically between -10℃ and -20℃. For this reason, the pressure level and height of the -20℃ isotherm were preserved also. On average, the pressure height of this isotherm was at 490 mb, or 5745 m (5.745 km), which is well above the moist-neutral layer.

The northwest (NW) composite is, conceptually, the colder of the two composite profiles between NE and NW. The entire column resides below 0℃, indicative of a snowfall event. This is a more common occurrence on the NW side of a cyclone where the cold air begins to fall into place behind the typically associated cold front. The sounding profile for NW cases (Fig. 7) looks mostly familiar to the subset composite from 0400 UTC to 0800 UTC of the NE cases (not shown). It

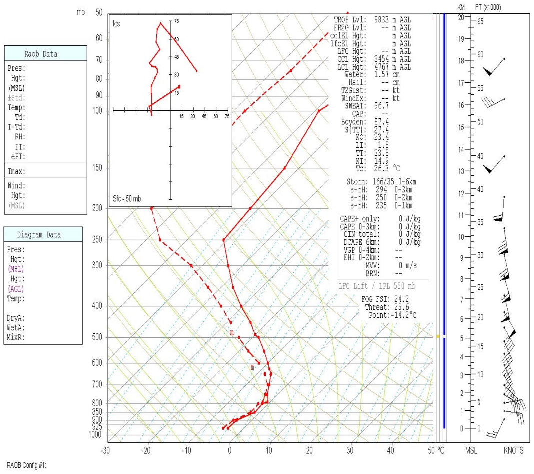

Figure 7 Northwest composite (N=19) composed from RUC initial soundings at the latitude and longitude of most active lightning in winter precipitation.

should be pointed out that the profiles for the NW cases were sampled from locations of surface pressures below 1000 mb. The model surface begins at 950 mb, which may explain the lack of a pseudoadiabatic layer. Using the feature preserving compositing, a slight warm nose (still below 0℃) indicative of the top of an inversion layer exists at 800 mb. The MULPL is more elevated in this event than the NE composites, at 550 mb. Again, no potential instability is found in the profile. This sounding is more saturated than the NE composites and is so up to 700 mb where the profile dries more proficiently. Near the surface, the profile rises isothermally between 800 and 900 mb. Below 900 mb, the profile cools more swiftly indicating a stable atmosphere, probably in the vicinity of a frontal boundary. Above the inversion, the sounding shows a moist-neutral profile up to 500 mb with which it stabilizes. There is considerably less wind shear for the NW composite than that of the NE composite. Wind speeds near the surface are at 23 knots from 210°. Wind speeds at 950 mb are similar between the NW and NE composites. Unlike the NE composites, the wind backs in the lowest 300 mb (up to 600 mb) where the profile is becoming less saturated. Above this level, this wind begins to veer slightly indicative of warming aloft and cooling near the surface. The -10℃ isotherm is located at 623 mb or 3900 m (3.9 km). This is nearer to the surface than the NE composite, located 4.2 km above the surface. This is more closely associated to the NE composite taken between 0000 UTC and 0400 UTC, the time of most active lightning for NE cases (not shown). As a whole, the NW composite appears more conducive to lightning generation based on the thermal profile alone when compared to events that were observed on the NE side of the cyclone. In terms of the -20℃ isotherm, similar circumstances are found, where the height and pressure level are more closely correlated to the NE composite from 0000 and 0400 UTC. In terms of stability parameters, the Total Totals index (TT) for the NW cases was slightly lower than the NE cases at 33.8℃ and a slightly higher K-Index (KI) at 14.9. The LI for NW cases were 1.8.

In summary, the NE and NW composite soundings bear some similarities and contradictions. The similarities involve mostly the elevated moist-neutral atmosphere above the frontal inversion along with no potential instability and similar stability parameters. However, while the TT is higher in the NE cases, the KI is higher in the NW cases indicative of a more unstable atmosphere with respect to heavy precipitation. When broken down into the individual 4-hour subsets, the NE cases begin to show some similarity to the NW cases, including the profile for the period of greatest lightning activity, 0000 UTC to 0400 UTC. Among these similarities are the heights of the -10℃ isotherm, being located roughly 3.8 to 3.9 km above ground level. Similarity also exists with the -20℃ isotherm. Case studies of two different cases were performed comparing and contrasting elevated convective events with warm precipitation and observed thundersnow.

5. CASE STUDIES

Two case studies were performed to identify the synoptic and mesoscale situation of elevated convection. These studies were performed to compare lightning trends, synoptic and mesoscale situations, and soundings. The soundings and trends are then compared back to the determined composites lightning trends.

The first case involved the occurrence of elevated convection with only warm precipitation on 12 and 13 October 2007. Using RUC initial analysis, it could be determined that while this case followed the conceptual model for mesoscale convective system (MCS) development, there were also synoptic and mesoscale similarities to winter time elevated convective events. When comparing sounding profiles (not shown) of peak lightning to the composites, there were observed similarities, but the primary difference was the lack of a defined frontal inversion with regions of drier air in the lower levels. Also, the heights of the -10℃ and -20℃ isotherms were significantly higher (Fig. 8) while most unstable lifted parcel levels were not.

The second case was a winter time convective snow event in the Midwest U.S. Three peak times were observed for the out of season thundersnow event that occurred on 02 December 2007 across Illinois, Wisconsin and Michigan. The peak times occurred at 0100, 0800, and 1800 UTC. The soundings at these times more closely resembled the composite soundings with a defined frontal

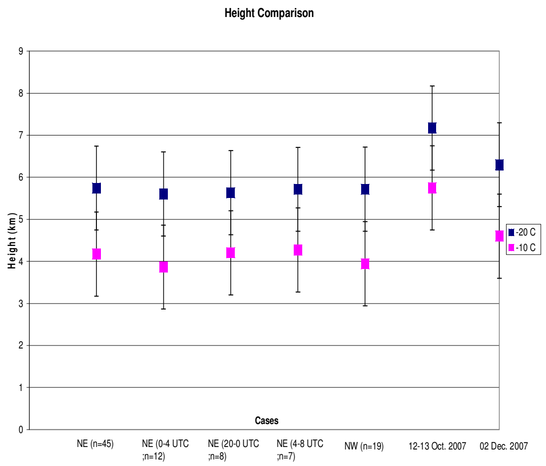

Figure 8 Analysis of -10°C and -20°C isotherms for 2006-2007 winter composites along with case study comparisons.

inversion and mixed phase regions of a similar height (Fig. 8). In fact, the heights of the isotherms in this case were more reminiscent of the heights found in the northeast composites. The synoptic and mesoscale features found in the thundersnow event resembled those of the warm season event. In both cases, a low was defined with perturbations present around 500 mb. They both also exhibited maximum Theta-E values at 700 mb with lightning tending to occur near thermal gradients, just inside the region of best warm advection. This is confirmed in the soundings with the veering in the lower levels representing warm air advection. For the winter event, this could be representative of the warm conveyor belt and the trough of warm air aloft producing additional instability.

Of further interest in both events was the location of the lightning in relation to the gradient of moisture at 850 mb. In both cases and at all the analyzed times of these events, the preferred location for lightning occurred just on the moist side of the gradient where RH values rapidly changed from greater than 90% to less than 70%. For the winter convection, this coincides with the presence of a dry slot formed with the occurrence of an extratropical cyclone, but is not he case with the MCS development. The distance from moist to dry air has not yet been quantified. Further analysis revealed similarities in cold cloud-top-temperature peaks occurring in the region of lightning occurrence. GOES-12 IR imagery was looked at and enhanced for cloud-top-temperatures for each peak time and location of lightning for both cases. For the warm season case, it was expected that the tops reached a higher level, and thus, the cloud top temperatures would be colder. Indeed they were with the initial lightning peak at onset of convection under a cold cloud top colder than -60°C. During the height of convection, 24 hrs later, the cloud top temperature reached temperatures colder than -70°C. The cold season case did not reach temperatures this cold given the nature of the convection, but at the peak reached colder than -50°C.

6. SUMMARY

Fourteen storms were analyzed for the winter season of 2006-2007 for lightning characteristics. Each storm exhibited a different lightning trend throughout its lifetime, but when matched together, it suggested a more coherent trend in total lightning in a 24-hr period for a wintertime cyclone than had been inferred earlier (e.g., Market et al. 2002). Moreover, lightning associated with winter precipitation made up only 1.4% of the total lightning and showed a distinct diurnal trend peaking between 0000 UTC and 0400 UTC. Of the winter lightning total, 31% were detected as cloud flashes and 69% as CG strokes. This diurnal peak occurred several times on an individual storm basis.

Previous research (Reap and MacGorman 1989) has only identified diurnal patterns in lightning associated with the development and decay of MCS activity in late summer and with early cold season elevated thunderstorms, not containing winter precipitation. It can be inferred, however, that when looking at convective snow, similar conditions may exist providing a peak in lightning activity both at dusk and at dawn.

From these lightning analysis, model initial soundings were compiled from latitude/longitude locations of observed lightning to form a composite sounding representative of lightning occurrence. Composite soundings consisted of lightning both northeast and northwest of the parent cyclone. Similarities between the two were drawn, particularly in the type and magnitude of instability present. The heights of the -10° C isotherms, above which indicates the typical region of best mixed-phase precipitation, were similar in elevation. This similarity held true in the thundersnow case study while the elevations were significantly higher in the warm precipitation case. However, synoptic and mesoscale similarities did arise between the two separate events.

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