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Proximity soundings of thundersnow in the central United States

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[1] Proximity balloon soundings for snow events with lightning and thunder during the period 1961 through 1990 reveal a less statically stable environment than similar nonthundering snow events. When thundersnow is present, a less stable environment (and in some cases subsequent upright convection) is found aloft in all of the thundering cases examined here; all of the events feature their most unstable parcel originating above a frontal inversion. In fact, only events in the cold air north of an extratropical cyclone are included in this study. Events with a lake effect or orographic enhancement are eliminated from the sample. The basic composite derived by averaging temperatures at an established interval reveals a nearly saturated lower atmosphere, below 0°C throughout its depth, with the frontal inversion present and its most unstable parcel occurring just above the top of the inversion. The feature-preserving composite approach of R. A. Brown (1993) better defines the frontal inversion bottom and top as well as the level and temperature of the most unstable parcel; these are the features in need of preservation, and a less statically stable environment emerges by doing so. Other salient features include the most unstable parcel originating some 30–50 mbar above the top of the frontal inversion and significant drying ~100 mbar above the level of the most unstable parcel. The bulk sounding characteristics also favor the existence of lightning. The composite temperature at the level of the most unstable parcel is −8.7°C, which allows for enhanced amounts of supercooled water to enter any updraft that may form. The temperature of the most unstable parcel at its origin is also warmer than the charge reversal temperature; therefore convection of any appreciable depth will span that level. Moreover, the height of the composited −10°C level is 2959 m above ground level, which previous investigators have shown is sufficiently high to favor lightning production. Yet no convective available potential energy (CAPE) appears with either composite approach, which concurs with previous studies. While several of the composite members feature CAPE for elevated layers, the majority do not, suggesting that other processes (e.g., the release of symmetric instability), which are difficult to assess from a single sounding, tend to be at work.

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1. Introduction

[2] The occurrence of snow with lightning and thunder has been a topic of research interest for some time, although relatively little work has been performed in the United States. In particular, the work of *Holle et al.* [1998] and *Market et al.* [2002] provided basic fields that indicate geographical preference for the occurrence of winter thunderstorms and thundersnow, respectively. Also, *Schultz* [1999] revealed insights into those convective snow events that occur near large midlatitude lakes (i.e., Lake Ontario and Great Salt Lake), including the finding that most of the sounding profiles with those events were completely devoid of convective available potential energy (CAPE). Case studies have also been offered, which address individual thundersnow occurrences [*Halcomb and Market*, 2003; *Stuart*, 2001; *Trapp et al.*, 2001]. However, there has been no detailed examination of thundersnow proximity soundings in the absence of external forcings (e.g., lake effect or mountain influence), as with *Schultz* [1999]. One early analysis exists [*Curran and Pearson*, 1971] but was brief and did not address completely the stability of these events nor any of the known criteria for lightning production. Moreover, *Curran and Pearson* [1971] included any and

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Table 1. Soundings That Comprise the Thundersnow Case Set

Date	Time, UTC	Sounding Station ID	Snow Total, cm	Case Type
18 Feb. 1961	1200	OVN	1	NWC
19 Feb. 1962	0000	GRB	5	NEC
8 March 1962	1200	OVN	10	NEC
17 March 1965	1200	GRB	18	NEC
23 March 1966	0000	OVN	9	NWC
3 Dec. 1967	0000	PIA	T	NWC
19 March 1971	0000	GRB	7	NEC
3 April 1980	1200	OVN	0	NWC
18 Feb. 1984	1200	LBF	14	NWC
15 Dec. 1987	0000	UMN	15	NWC
15 Dec. 1987	1200	PIA	13	NWC

all proximity soundings for surface observations nationwide, without filtering for geographical location, synoptic setting, etc.

[3] It is well known that the three ingredients needed to generate deep moist convection in the warm season are moisture, lift, and instability [*Johns and Doswell*, 1992]. Applying this approach to the thundersnow environment, it is clear that the atmosphere must be ascending and moisture rich; the presence of instability is not always clear. Moreover, the height of the −10°C isotherm is known to influence lightning production [*Michimoto*, 1993] as is its location above the level of unstable parcel origin [*Bright et al.*, 2005] if present at all. Thus the purpose of this research is to determine the typical vertical profile of temperature and moisture (and thus static stability) present when the snow-producing environment features lightning. Sounding profiles help to determine if, in addition to moisture and lift, instability is present. In this fashion, we build on the composite foundation laid by *Curran and Pearson* [1971] in examining proximity soundings of snowstorms featuring lightning. With this paper, the mean proximity sounding profiles, their stability, and their conduciveness to lightning production during cases of snow with thunder and lightning associated with an extratropical cyclone are established.

[4] To do so, we follow this format: In section 2, we shall discuss our approach to the data set and the manner in which cases were selected for further analysis. Section 3 is devoted to the aggregate results from proximity soundings. In section 4, we offer some concluding remarks.

2. Methodology

[5] Two sets of soundings were compared in this study. The first set, which encompassed those balloons flown at or near to the time and location of an active thundersnow cloud, was selected for the obvious reason. The second collection of nonthundering cases was chosen because of their lack of lightning activity, but otherwise for their synoptic-scale similarity (presence of a transient area of low pressure in the sea level pressure analysis that possesses two or more closed isobars at a 4-mbar contour and similar 24-hour snow totals) to the thundering cases. Although the potential problems with the representativeness of any particular sounding profile have been well documented [*Brooks et al.*, 1994], the limited data set in this particular instance demanded a looser standard on what is considered a proximity sounding. On a more positive note, the same approach as that of *Curran and Pearson* [1971] was employed, with whose conclusions several comparisons are made. Last, although all of the thundering soundings come from the 1961–1990 period and all of the nonthundering soundings were flown during 2001–2005, the data were obtained from the National Center for Atmospheric Research, so we presume a consistent quality in the data while acknowledging that equipment and quality control measures have surely evolved over the years.

2.1. Thundering Cases

[6] Following the approach of *Market et al.* [2002], synoptic 3-hourly weather observations from 1961 to 1990 were scanned for reports of snow with thunder. Selected events occurred in the central United States, between the Rocky and Appalachian Mountain ranges and in the absence of lake influences. Only events associated with an extratropical cyclone (ETC) were examined for this study. For this study, we define an ETC as a transient area of low pressure having at least two closed isobars (4-mbar contour interval) in the sea level pressure field; the mean central pressure of the low for the eleven events studied was 1000 mbar, with only two ETCs clearly occluded at the time of those thundersnow events. Specifically, events that occurred to the northwest and northeast of the ETC center were selected. This criterion also follows *Market et al.* [2002], who found those locations within an ETC to be favored for thundersnow occurrence. This selection process placed the focus on cold-season, elevated convection that exists largely in the absence of surface influences.

[7] All other events that may have occurred elsewhere in the cyclone, or that featured orographic influence or lake enhancement were disregarded. Cases of thunder with snow only were kept in the study; if other forms of winter precipitation occurred, then the case was eliminated. This approach was used to ensure a relatively uniform thermodynamic profile in each event (e.g., the deep warm layers that can accompany freezing rain and ice pellet events are avoided) and resulted in a collection of eleven (Table 1) proximity soundings from thundersnow cases.

2.2. Nonthundering Cases

[8] Cases with snow but no thunder were selected for the period 2001–2005 (Table 2). This more recent era allowed the use of National Lightning Detection Network (NLDN) data to help confirm the presence of lightning. Locations were chosen for their availability of both surface and upper air data. These locations frequently had human observers present at the surface weather station to help verify the presence (or in this case, absence) of lightning at the time of the balloon flights beyond the cloud-to-ground flashes detected by the NLDN. Additionally, events were selected where snow was falling at the time of the balloon flight. Moreover, a collection of cases was sought (Table 2) that had a range of snowfall totals similar in nature to those in the thundering cases (Table 1). Last, a similar number of cases northeast and northwest of the cyclone center was sought to keep the comparison to thundering cases as uniform as possible.

2.3. Proximity Soundings

[9] Of the many potential thundersnow events, only a small subset occurred at or near the time and place of an

Table 2. Soundings That Comprise the Nonthundersnow Case Set

Date	Time, UTC	Sounding Station ID	Snow Total, cm	Case Type
14 Jan. 2001	1200	GRB	8	NEC
30 Jan. 2001	0000	OVN	8	NWC
1 Feb. 2002	1200	GRB	8	NWC
2 April 2002	1200	GRB	5	NEC
16 Jan. 2003	1200	SGF	8	NWC
15 Feb. 2003	1200	OVN	20	NWC
24 Feb. 2003	0000	SGF	20	NEC
3 Feb. 2004	0000	GRB	8	NEC
15 March 2004	1200	OVN	5	NEC
6 Jan. 2005	1200	GRB	13	NWC
22 Jan. 2005	1200	GRB	13	NWC
14 Feb. 2005	1200	GRB	5	NWC

actual balloon sounding. This work is patterned after *Curran and Pearson* [1971]; a reanalysis of their sounding profile is reproduced in Figure 1. We note briefly the presence of elevated potential instability (PI) in their mean composite sounding. PI is a condition of the atmosphere wherein a layer that is lifted will saturate and achieve a lapse rate in excess of the moist adiabatic lapse rate. The *Curran and Pearson* [1971] sounding may also be characterized as conditionally unstable, wherein a parcel displaced from a single layer will be stable for dry displacements, but unstable for moist ones. Indeed, when the most unstable parcel is lifted, it benefits from a CAPE of 55 J kg^{-1}.

[10] The *Curran and Pearson* [1971] approach yielded eleven proximity soundings in thundersnow events, a process that is defined presently. Three of the events occurred at the exact time and location of a sounding. Four of the events occurred at the exact time of a sounding but were not at the exact location where the sounding occurred; the location of thundersnow was within 90 nautical miles (nmi; 166.7 km) of the sounding station. The remaining four cases occurred within 90 nmi of the sounding station and the thundersnow report occurred in a window of zero to three hours after the rawinsonde was released.

[11] Nonthundering cases were selected when (1) neither the NLDN nor the surface observation indicated lightning activity in the area, (2) snow was falling at the time of the colocated radiosonde balloon flight, (3) the balloon ascent occurred in the early half of the snow storm, and (4) these criteria occurred in the synoptically favored northeast or northwest quadrants (as described above).

2.4. Approach

[12] Observed soundings for thundersnow cases ($N = 11$; Table 1) were analyzed for instability and compared to a set of snow cases of similar size and snowfall totals but with no thundersnow ($N = 12$; Table 2). These years represent a period for which data from the NLDN were available to help confirm the likely absence of lightning (cloud-to-ground). The Mann-Whitney nonparametric statistical approach was used to test for differences between the thundersnow and nonthundersnow case sets, similar to the approach of *Schultz* [1999] for lake effect events with and without lightning. Mean soundings in thundersnow events were prepared. Simple means were calculated; the feature-preserving approach of *Brown* [1993] was also employed. These profiles were then compared to the nonthundersnow events in terms of their potential stability profiles.

3. Analysis

[13] Horizontal composite analyses of thundersnow cases have failed to reveal much difference between the snow-

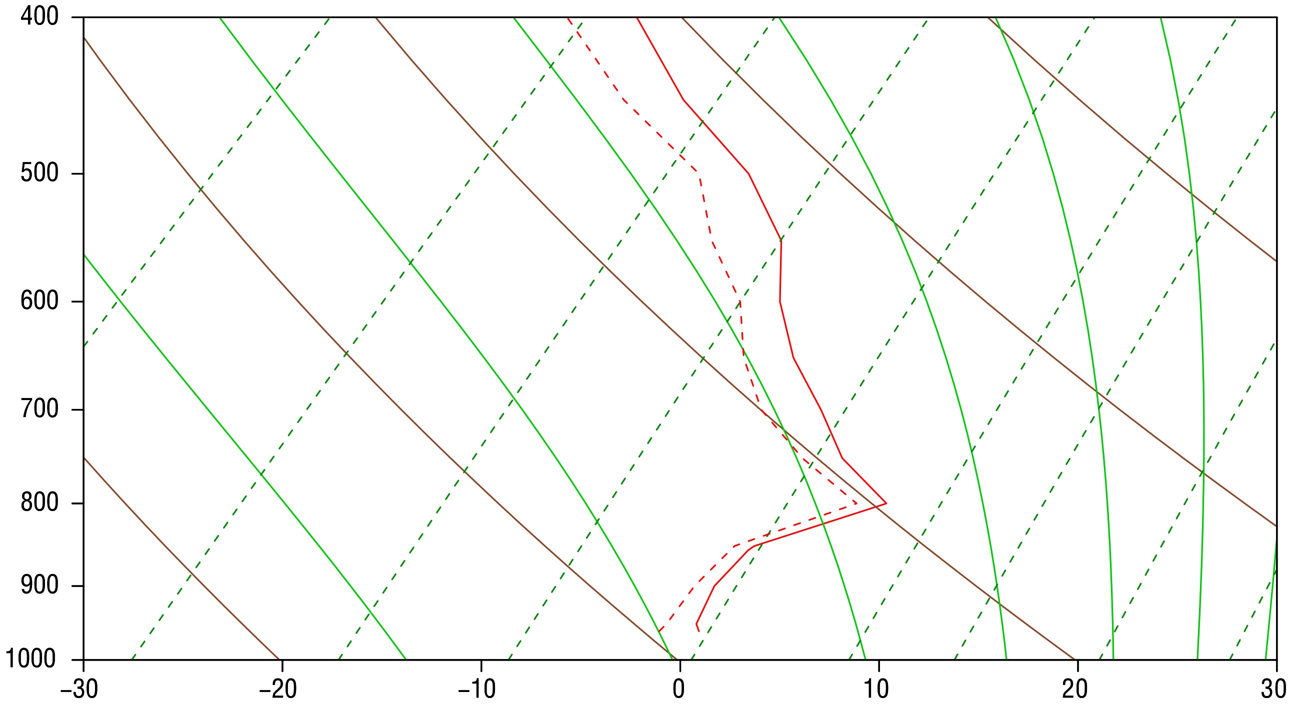

Figure 1. Reanalyzed skew-*T* log *p* diagram of sounding data taken from *Curran and Pearson* [1971] (red solid curve, temperature; red dashed curve, dew point).

storm that produces lightning and thunder and the snowstorm that does not. Both environments are dynamic, with significant forcing for ascent and ample moisture for cloud and precipitation production. However, recent cases have shown that the thundersnow environment is often one prone to lower static stability. In addition, there are several bulk parameters conducive to lightning generation that can be evaluated with sounding data. As such, analyses of the vertical atmospheric profiles of environments with and without thundersnow to assess their stability as well as their ability to produce lightning are presented.

3.1. Mean Profiles

[14] The mean profiles used raw data from sounding balloon flights, and show mean temperature, mean dew point, mean wind speeds, and median wind direction throughout the atmosphere. The proximity sounding for northeast cases (NEC; Figure 2a) was created from a relatively small data set: only four cases. Neither CAPE nor PI was present in this sounding. However, a moist-neutral lapse rate was present from 500 mbar to 400 mbar. This layer was shallower, and found higher than in the soundings northwest of the cyclone center (NWC; Figure 2b). Another difference from the NWC profile was the consistent veering in the wind profile throughout the troposphere. Backing of the wind with height was not found in this NEC profile, suggesting a more homogeneous, less complex atmospheric structure for these cases as opposed to the NWC cases. Last, the NEC composite was notably the cooler, drier of the two, especially in the lowest 200 mbar. These signatures suggest an event forced by larger-scale mechanisms, north of a surface warm front, above the warm frontal inversion, and embedded in the warm conveyor belt [*Carlson*, 1991] or perhaps even the low-level jet.

[15] The northwest proximity sounding (Figure 2b) was created from seven cases. Unlike earlier work (Figure 1), neither CAPE nor PI was present in this mean sounding. However, the actual lapse rate was moist-neutral from 700 mbar to 550 mbar. Winds veered from the surface up to 600 mbar, indicating warm advection. From 600 mbar to 400 mbar the winds backed with height, suggesting cold advection, while from 400 mbar to 200 mbar the winds veered with height again, suggesting another warm advection layer. *Lupo et al.* [1992] have shown this kind of thermal advection profile for developing cyclones. Indeed, the more complex wind structure suggests additional mesoscale forcing processes for vertical motion. Specifically, the easterly warm advection flow between 800 and 600 mbar strongly suggests the presence of the trough of warm air aloft (or "trowal"), its requisite airstream [e.g., *Martin*, 1999], and attendant forcing for ascent. Such a concentration of warm advection in the midtroposphere (with cold advection inferred farther above) enhances the prospects for elevated instability and its release. Large-scale differences between NWC and NEC cases have been detailed by *Market et al.* [2004].

[16] Taken as an aggregate, these thundersnow soundings may be viewed in one of two ways. Figure 3 presents soundings using all 11 thundersnow cases that were derived simply from the means of temperature and dew point temperature at each level as well as the feature-preserving approach of *Brown* [1993]; both were compared to the simple mean profile of the nonthundering cases ($N = 12$). Not surprisingly, the simple mean profile from the thundersnow cases looks very much like the samples in Figure 2, with temperatures uniformly below freezing throughout the depth of the profile. However, this mean sounding was uniformly warmer, more moist, and less stable than the nonthundering composite sounding. Both soundings reveal deep warm advection, at least up to the top of the inversion. Moreover, the mean temperature in the lowest few hundred millibars of the NEC (Figure 2a) and NWC (Figure 2b) cases as well as the aggregated view (Figure 3) suggest balloon flights in proximity not only to thundersnow but also to the precipitation transition zone. As such, we speculate that the probability increases for supercooled water to be entrained into any updraft(s) that may exist and encourage graupel production, which is favorable for lightning production.

[17] The *Brown* [1993] compositing method was also used, with the features to be preserved being the (1) bottom and (2) top of the frontal inversion as well as (3) the first level above the inversion top. These levels were chosen as they were recurring features in many of the individual thundersnow soundings; of particular interest was the most unstable parcel in the sounding originating not from the top of the frontal inversion, but from a level a short distance above the inversion top; this is unlike the most unstable level of *Curran and Pearson* [1971], which can be seen as the inversion top in Figure 1. When the mean temperature and pressure at these three levels were calculated and inserted, the third and final sounding emerged in Figure 3. Although the base of the inversion is cooled relative to its simple mean cousin, a less stable environment is achieved, a point with which we deal presently.

3.2. Stability Analysis

[18] Comparison of the potential stability profiles for the NWC cases ($N = 7$) to the NEC cases ($N = 4$) from section 3.1 (Table 1) revealed soundings for the NWC cases that had more pronounced, deeper layers of potential instability (Figure 4a). Of the four NEC cases, only one exhibited PI in the midtroposphere. The others exhibited layers that were, at best, potentially neutral. By contrast, five of the seven NWC cases had decreases in equivalent potential temperature (θ_e) with height in the midtroposphere; four of those are significant. Yet no statistically significant differences were found between the NEC and NWC case values for the standard instability quantities (K Index, Total Totals, etc). These indices were tested, as they are well known, and have been shown to be useful in the analysis of such events [e.g., *Medlin*, 1993].

[19] However, Mann-Whitney tests of the same indices between the aggregate thundersnow cases and those from the nonthundersnow set revealed more interesting results. Of significance was the higher pressure of the level from which the most unstable parcel was lifted (MULPL) in the thundersnow cases (mean of 671 mbar) versus the nonthundersnow events (mean of 632 mbar) at a confidence interval of $p = 0.01$. The MULPL is determined by using the temperature and dew point values at each pressure level and finding the one with the greatest CAPE. As these soundings tend to exhibit no CAPE, we use instead the lowest lifted index (the difference between the observed temperature at

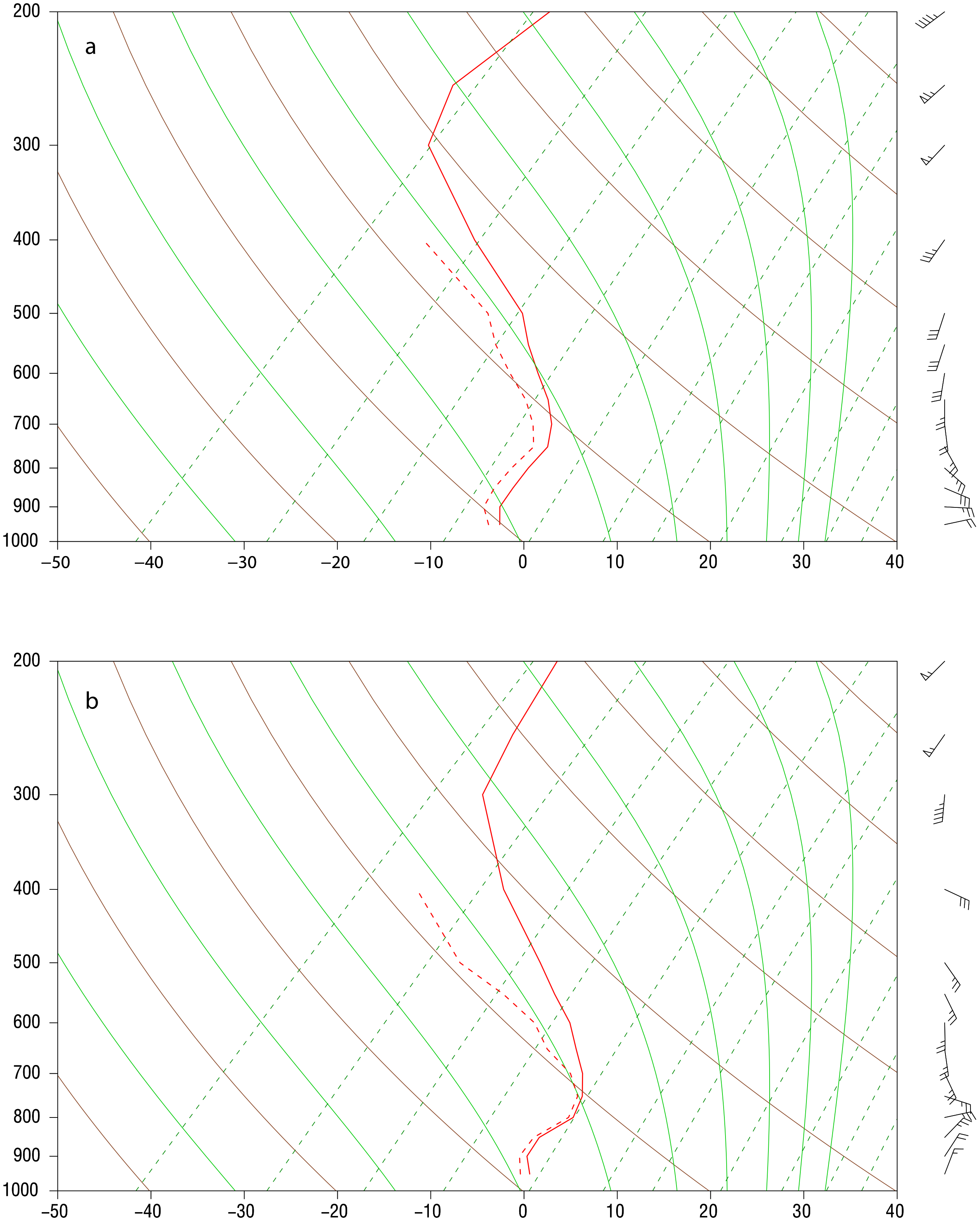

Figure 2. Standard skew-*T* log *p* diagram of the mean profiles of temperature (red solid curve) and dew point (red dashed curve) from proximity soundings (a) northeast ($N = 4$) and (b) northwest ($N = 8$) of a cyclone center. Winds at right are plotted in knots; mean speed is plotted on the median wind direction shaft. Background contours include dry adiabats (solid curves, concave upward), moist adiabats (solid curves, concave downward), and mixing ratios (dashed curves, sloping up and to the right).

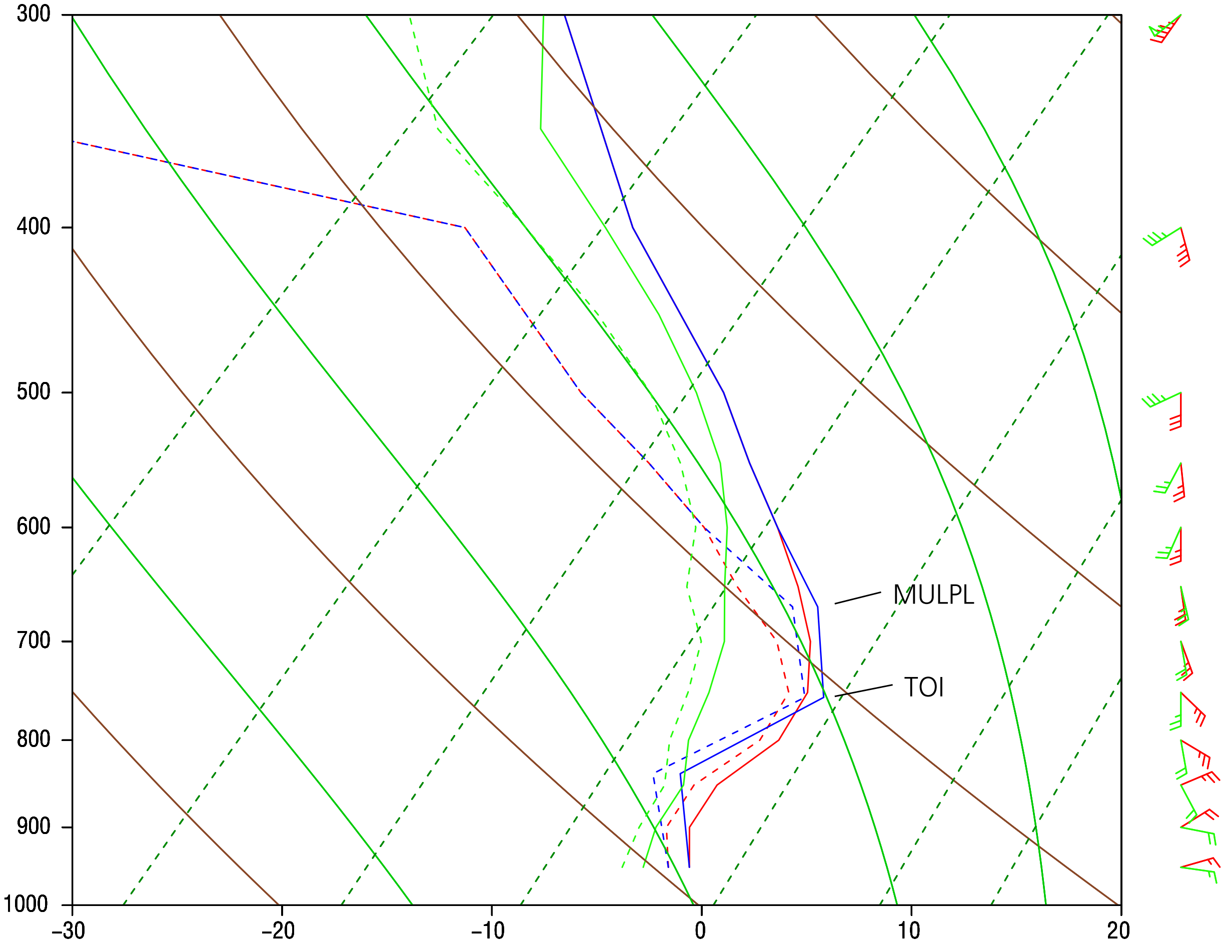

Figure 3. Skew-T log p diagram of composite temperature (solid curves) and dew point (dashed curves) soundings based upon simple averages (red), averages for features to be preserved (blue), and simple averages for nonthundering cases (green). Winds at right are plotted in knots for thundering cases (red) and nonthundering cases (green); mean speed is plotted on the median wind direction shaft. The arrows labeled "TOI" and "MULPL" refer to the top of the inversion and the level of the most unstable parcel, respectively, in the feature-preserving composite method.

500 mbar and that of a parcel lifted adiabatically to the same level) and the value as a proxy. Additionally, the 700–500-mbar lapse rate was also greater in the thundersnow cases (mean of 6.5 K km^{-1}; s.d. 1.3 K km^{-1}) than in the nonthundersnow cases (mean of 5.5 K km^{-1}; s.d. 0.7 K km^{-1}) studied (p = 0.03). Using the same test, the most unstable lifted index (MULI) differences between thundersnow (mean of 1.3; s.d. 3.4) and nonthundersnow (mean of 3.8; s.d. 3.3) cases failed narrowly the accepted benchmark for statistical significance (p = 0.06). It is noteworthy, however, that four of the eleven cases of thundersnow had MULI $\leq$ 0, whereas the 12 cases of nonthundersnow had none.

[20] The difference between stability regimes is best visualized by comparing their θ_e-p plots (Figure 4b). With the thundersnow cases, the atmosphere tended to be warmer, with more pronounced layers of PI. Indeed, lapse rates of θ_e tend to be negative in thundersnow cases (mean of -1.5 K; s.d. 3.1 K) over shallow depths (mean of 55 mb; s.d. 29 mbar); nonthundering cases tended to be stable (mean of +1.0 K; s.d. 1.9 K) over similar depths (mean of 77 mb; s.d. 47 mbar). This conclusion is reached by finding the least stable layer in each sounding profile and assessing its depth and attendant lapse rate. A Mann-Whitney test of the two lapse rate samples allows us to reject the hypothesis that they are identical at a confidence interval of $p = 0.02$. Of the nonthundersnow cases examined, only three of the twelve have any PI below 500 mbar, and two of those three were nearly potentially neutral. These results were not altered dramatically when nonthundersnow cases are compared only to NWC cases. Not only did the NWC cases comprise seven of the eleven total thundersnow cases, but also they were borne of a less stable environment than either the NEC thundersnow events or the nonthundersnow case set. In summary, NWC cases tend to inhabit an environment more prone to upright convection than nonthundersnow cases; the environment that harbors NEC cases is one of greater stability to upright convection and not easily distinguishable from the nonthundersnow cases.

[21] Returning briefly to the *Brown* [1993] composite approach for the thundering cases (Figure 3), it is noteworthy that while the Brown approach yielded a slightly less stable atmosphere (an MULI of +2.1 as opposed to that based upon the simple mean MULI of +3.2), still no CAPE

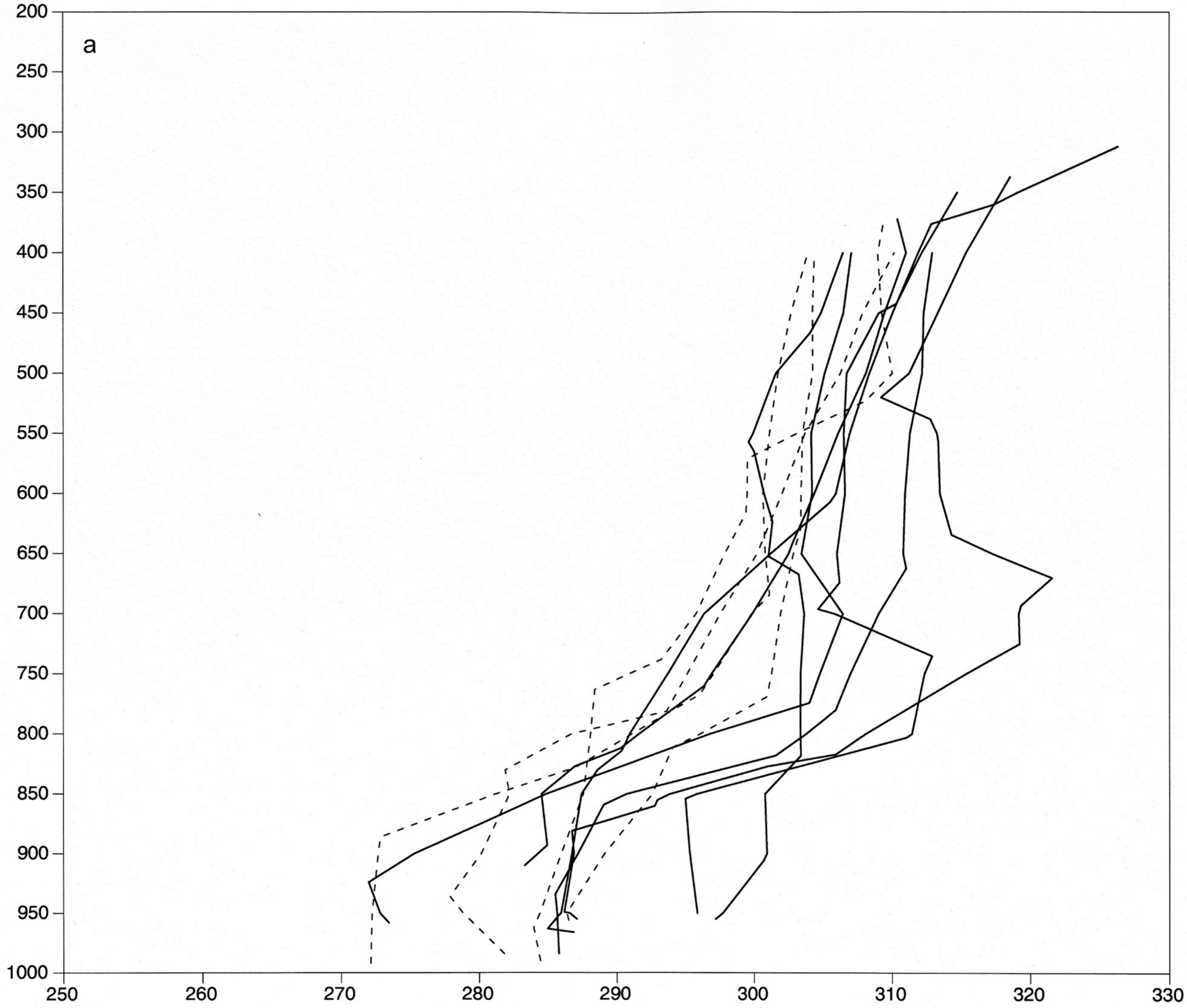

Figure 4. Plots of θ_e-p for (a) thundersnow soundings northwest of the low center (solid curves) and northeast of the low center (dashed curves) and (b) the aggregate thundersnow cases (solid curves) along with the soundings from the nonthundersnow case set (dashed curves).

was realized. This stands in stark contrast to the work of *Curran and Pearson* [1971] (Figure 1), wherein the most unstable parcel yielded a CAPE of 55 J kg^{-1}. Recognizing that layers bearing snow (thundering and not so) are often saturated, and that the mean temperature of the level where the most unstable parcel originates possesses a standard deviation of ±5.1°C, a test was conducted through a slight alteration to the feature-preserving profile generated with the Brown approach. Specifically, the level of the most unstable parcel was warmed by just 1°C above what the *Brown* [1993] approach yielded, and that same level was also saturated (dew point temperature increased by 2.2°C). The result is shown in Figure 5. With the virtual temperature correction, this profile possessed 54 J kg^{-1} of CAPE for the most unstable parcel, more in line with the *Curran and Pearson* [1971] study. The subtle change in this experiment and its outcome serve as a reminder that the typical thundersnow environment tends to be one of weak static stability. In fact, of the three soundings that were flown at the same location and time of a thundersnow report at the surface, only one presented CAPE in the sounding profile.

[22] Indeed, the majority of these thundersnow soundings fail to produce CAPE in their thermodynamic profile, an idea borne out in previous studies [e.g., *Colman*, 1990]. In fact, of the eleven cases of thundersnow examined, only four revealed CAPE of any kind. Thus the depiction in Figure 5 must be viewed as an idealized portrait, a conclusion that is strongly supported by our daily experience.

[23] By the same token, it is also noted that, of the twelve nonthundering cases of snowfall, none featured any CAPE in their thermodynamic profile. Therefore a middle grouping of thundersnow events that occur in the absence of CAPE is found. This is not a new conclusion, but a condition, often of slantwise ascent, that has been studied by many authors in the last decade or so [*Moore and Lambert*, 1993; *Nicosia and Grumm*, 1999; *Halcomb and Market*, 2003; *Moore et al.*, 2005]. Although our emphasis in this work is on sounding analyses, we employ briefly a

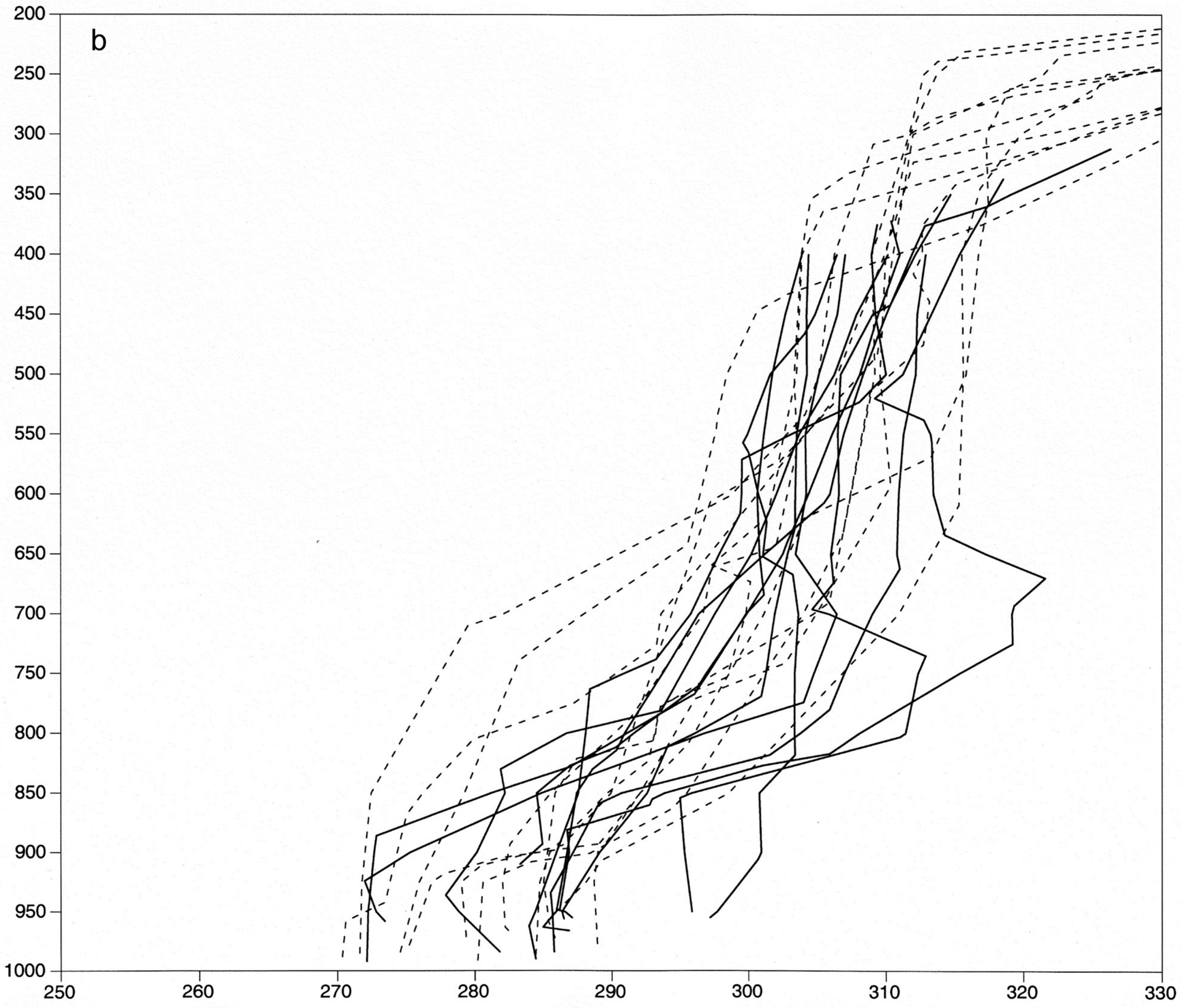

Figure 4. (continued)

cross-section approach to the data in order to determine more clearly the presence or absence of symmetric instability in those thundersnow cases without CAPE.

[24] As a means to bolster the conclusions from the proximity soundings alone, cross sections were thus constructed for each event in both case sets. For the older, thundering case set, radiosonde data were objectively analyzed every 50 mbar to a 150-km horizontal grid for the dates and times in Table 1 using the *Barnes* [1973] technique. For the more modern, nonthundering case set, the initial fields from the Rapid Update Cycle operational numerical weather prediction model were used for the dates and times in Table 2, with the thinned, 80-km grid employed, when available, to produce the best possible comparison to the thundering case set. In each case, cross sections of geostrophic absolute momentum, θ_e and equivalent potential vorticity were constructed following *Moore and Lambert* [1993] as embellished by *Schultz and Schumacher* [1999] in order to diagnose the existence of potential symmetric instability (PSI). In the thundering case set, the seven that exhibited PI in the sounding were also potentially unstable in the cross section; two more were neutral for slantwise displacements, and two were absolutely stable. Cross-section analyses of the nonthundering case set revealed three cases of PSI, nine cases of absolute stability, and no cases of PI. Nevertheless, only two of the thundering cases studied here approached a PSI state.

[25] Yet it is well known that there are thundersnow events that do result from the release of symmetric instability and subsequent slantwise ascent [e.g., *Moore et al.*, 2005]. This paper does not dispute that finding, but does corroborate the idea that thundersnow events are borne of a less statically stable environment than nonthundering snow systems and establishes that the existence of CAPE (and resultant upright convection) in a sounding profile is easily within the statistical variability of the tests employed here.

3.3. Lightning

[26] The creation of lightning in any cloud is a matter of complex microphysics [e.g., *MacGorman and Rust*, 1998; *Black and Hallett*, 1998], yet some bulk properties have

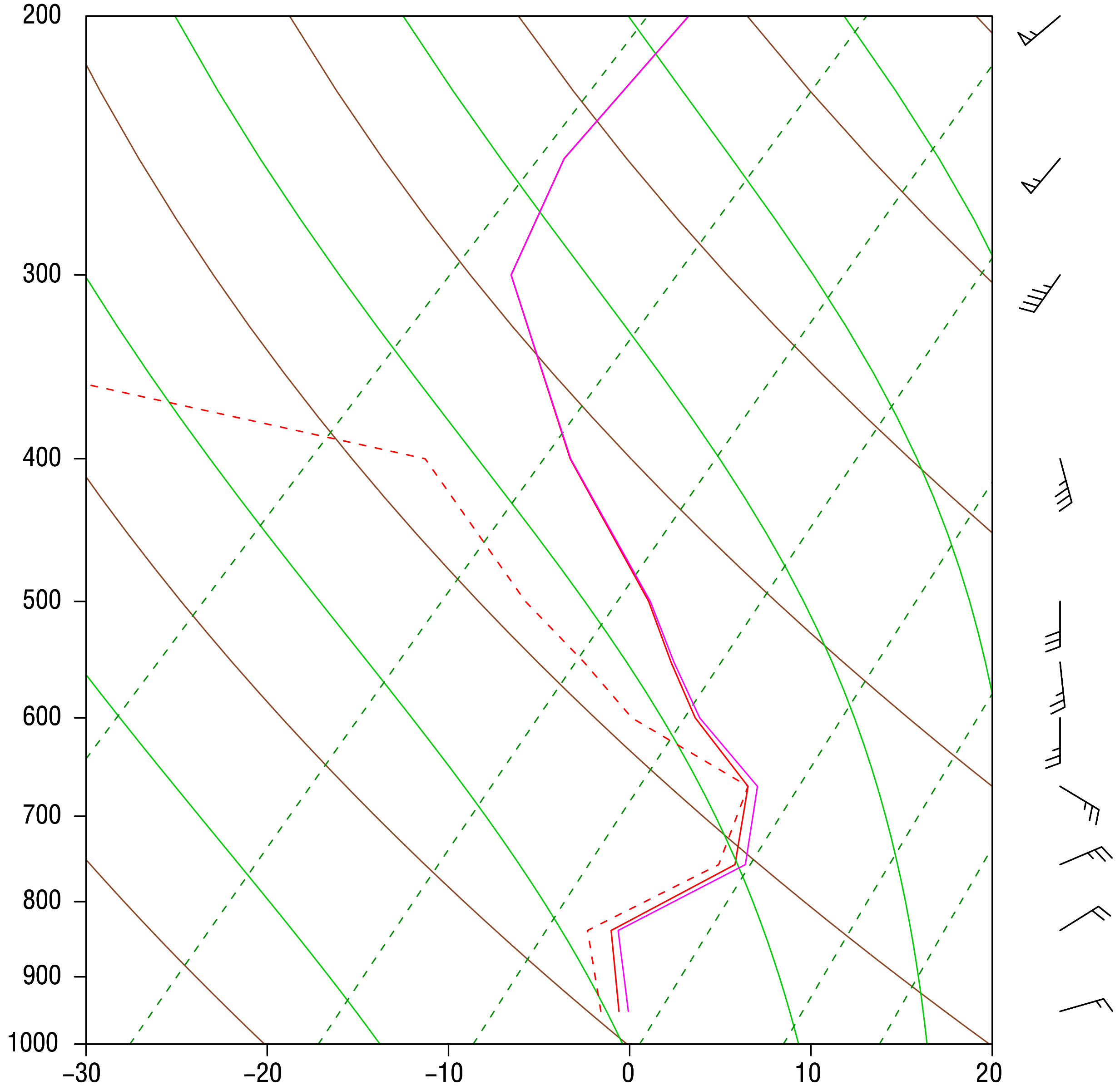

Figure 5. Skew-*T* log *p* diagram using the *Brown* [1993] composite approach for temperature (red solid curve), dew point (red dashed curve), and virtual temperature (magenta solid curve) soundings as in Figure 3 (blue curves in Figure 3), but with the level of the most unstable parcel (670 mbar) being saturated and warmed by 1°C. Winds at right are plotted for thundering cases as in Figure 3.

been determined to be critical for the creation of lightning in the snow-bearing cloud. Chief among them comes from a study by *Michimoto* [1993], who found that lightning activity tends to diminish when the height of the −10°C isotherm drops below 1.8 km above ground level (agl) and that no lightning occurs when the −10°C level is less than 1.4 km agl. All of the thundersnow cases in this study met that criterion, with a mean height of the −10°C level of 2.9 km (±0.6 km) agl. Yet nine of the twelve nonthundering soundings featured the −10°C level above 1.8 km also.

[27] Another criterion that has been advanced recently is the level of the most unstable parcel in a sounding relative to the height of the −10°C level [*Bright et al.*, 2005; *Van Den Broeke et al.*, 2005]. In this study, six of the eleven thundering cases featured the most unstable parcel originating from a level beneath the −10°C isotherm (and thus a temperature warmer than −10°C also). Only two of the nonthundering cases were structured this way, yet neither of those cases was even close to the condition of gravitational instability.

[28] Deeper inspection of the idealized composite sounding (Figure 5) also shows that the equilibrium level of the most unstable parcel was well above the −20°C level. This criterion has been shown by *Takahashi et al.* [1999] to emphasize the most active level for particle charging, a point used by *Bright et al.* [2005] in their bulk prediction scheme for lightning. While the CAPE is of a level below what *Van Den Broeke et al.* [2005] have recommended, this

modified sounding does possess in principle the requisite ingredients for cloud-to-ground lightning production.

4. Conclusions

[29] A comparison of a set of thundersnow proximity soundings to a set of soundings of nonthundering snowfall with similar synoptic settings and snowfall totals reveals the former set to be of a less stable environment and more prone to lightning production. This study corroborates the essential structure of the thundersnow proximity sounding composites of *Curran and Pearson* [1971], although what is shown in the present study evinces elevated instability based at a higher level. Moreover, this study compares for the first time a set of thundersnow cases that exist in the absence of lake effects or orographic enhancements to a set of nonthundering cases.

[30] What emerges is a composite sounding profile that is cold enough to support snow throughout, with a nearly moist neutral environment above a frontal inversion, and which features its most unstable level some 30 to 50 mbar above the top of the inversion layer (Figure 3); significant drying then occurs within 100 mbar of the MULPL. This also leads to a layer that is significantly less stable in the thundersnow cases. Slight modification of the composite results reveals a CAPE for the MULPL (Figure 5) that is more in line with the findings of *Curran and Pearson* [1971]. In either event, the sounding with thundersnow is not only more physically conducive to lightning than a synoptically similar, nonthundering environment, but the differences between them are distinct and can be assessed easily.

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