A Case Study of Severe Winter Convection in the Midwest

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ABSTRACT

Between 2100 UTC 11 February 2003 and 0200 UTC 12 February 2003, a line of thunderstorms passed swiftly through parts of eastern Iowa and into north-central Illinois. Although this storm somewhat resembled a warm season, line-type mesoscale convective system, it was unique in that the thunderstorm winds exceeded the severe criterion (50 kt; 25.7 m s^{-1}) during a snowburst. While the parent snowband deposited only 4 cm of snow, it did so in a short period and created a treacherous driving situation because of the ensuing near-whiteout conditions caused by strong winds that reached the National Weather Service severe criteria, as the line moved across central Illinois. Such storms in the cold season rarely occur and are largely undocumented; the present work seeks to fill this void in the existing literature.

While this system superficially resembled a more traditional warm season squall line, deeper inspection revealed a precipitation band that failed to conform to that paradigm. Radar analysis failed to resolve any of the necessary warm season signatures, as maximum reflectivities of only 40–45 dB*Z* reached no higher than 3.7 km above ground level. The result was low-topped convection in a highly sheared environment. Moreover, winds in excess of 50 kt (25.7 m s^{-1}) occurred earlier in the day without thunderstorm activity, upstream of the eventual severe thundersnow location. Perhaps of greatest importance is the fact that the winds in excess of the severe criterion were more the result of boundary layer mixing, and largely *coincident with* the parent convective line. This event was a case of forced convection, dynamically linked to its parent cold front via persistent frontogenesis and the convective instability associated with it; winds sufficient for a severe thunderstorm warning, while influenced by convection, resulted from high momentum mixing downward through a dry-adiabatic layer.

1. Introduction

On the evening of 11 February 2003, a line of severe thunderstorms moved swiftly through southeast Iowa (IA) and northwest and central Illinois (IL) with winds in excess of 50 kt (25.7 m s^{-1}) and brief heavy *snowfall.* On radar, the line appeared similar in form to a small squall line. The convective line developed ahead of a strong synoptic-scale cold front as it pushed through the area. The National Weather Service in Lincoln, Illinois (ILX), issued severe thunderstorm warnings for several counties in central Illinois due to the strong winds, which also aided in creating near whiteout conditions during the brief heavy snowfall. The first severe thunderstorm warning was issued at 0002 UTC 12 February 2003 for Marshall County, Illinois; within an hour, the front and convection had passed leaving wind damage, a covering of snow, and an unusual phenomenon referred to as snowrollers [an artifact of snow moisture, winds, and topography that result in cylindrical snow formations; Tam (1982)] in the Peoria, Illinois (PIA), area.

Surface weather observations at PIA substantiated the passage of the cold front (Table 1) but failed to capture the true severity of this system. Along with

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TABLE 1. Automated surface observations from PIA, DVN, and HON, on 11 and 12 Feb 2003, following METAR code: time (UTC), sky follows METAR abbreviations, ceiling (CIG; ft), visibility (VIS; statute miles), current weather (WX) follows METAR coding, temperatures (T; °F) and dewpoint temperatures (Td; °F), wind direction (DIR; °), wind speed and gusts (speed; kt), and the altimeter setting (ALTI; in.). Entries with an asterisk also featured lightning in remarks, as determined by the Automated Lightning Detection and Ranging (ALDAR) system equipped on ASOS; those with an "M" are missing.

	Date	Time	Sky	CIG	VIS	WX	T	Td	DIR	Speed	ALTI
PIA	11 Feb	2054	BKN	8500	10		33	21	240	19G24	29.79
	11 Feb	2154	OVC	6000	10		34	23	240	19G24	29.76
	11 Feb	2254	FEW	7000	10		36	23	250	17G25	29.75
	11 Feb	2354	BKN	6000	10		38	25	250	19G30	29.74
	12 Feb	0036	BKN	3000	2.5	−SN	32	28	310	21G34	29.83
	12 Feb	0044	BKN	3000	9	−SN	32	26	310	17G29	29.84
	12 Feb	0054	OVC	3900	9		32	25	310	15G25	29.86
	12 Feb	0154	CLR		10		25	14	310	11G20	29.93
DVN	11 Feb	1954	BKN	7000	10		34	29	240	24G30	29.70
	11 Feb	2054	BKN	5500	8		37	21	240	23G35	29.66
	11 Feb	2154			5		38	22	250	25G35	29.64
	11 Feb	2242			1.25	−SN	36	27	300	36G43	M
	11 Feb	2245			0.25	+SN	32	27	310	35G43	29.70
*	11 Feb	2254			0.5	SN	31	26	300	26G43	29.71
*	11 Feb	2257			2	−SN	31	26	310	21G32	29.71
*	11 Feb	2304			6		31	23	310	29G41	29.72
	11 Feb	2354	CLR		10		23	15	310	19G30	29.82
	12 Feb	0054	CLR		10		19	6	320	26G35	29.90
HON	11 Feb	1455	FEW	4700	10		31	25	250	16	29.67
	11 Feb	1555	CLR		8	BLSN	34	27	280	25G36	29.66
	11 Feb	1633	SCT	2800	0.5	BLSN	M	M	340	40G54	M
	11 Feb	1636	BKN	2800	0.25	BLSN	M	M	340	35G54	M
	11 Feb	1642	BKN	4400	0.75	BLSN	M	M	350	25G43	M
	11 Feb	1655	OVC	5000	5	BLSN	25	21	350	30G34	29.76
	11 Feb	1734	OVC	7500	5	BLSN	M	M	340	28G35	M
	11 Feb	1755	BKN	2500	5	BLSN	22	14	340	23G33	29.88

damage reports of downed trees and utility poles (see the National Oceanic and Atmospheric Administration publication *Storm Data*), spotter and observer reports of measured/estimated wind gusts included

1) 2345 UTC 11 February 2003, Galesburg, IL; 53-kt (27.2 m s^{-1}) wind gust;
2) 0032 UTC 12 February 2003, Roanoke, IL; 54-kt (27.8 m s^{-1}) wind gust; and
3) 0041 UTC 12 February 2003, Tremont, IL; 51-kt (26.2 m s^{-1}) wind gust.

Unique cases such as this one, which do not clearly fall into common operational paradigms, present somewhat of a challenge to forecasters regarding how best to communicate the weather hazard. At the National Weather Service, two responses that would be considered for such an event include a severe thunderstorm warning (SVR) and a high-wind warning (HWW). Typically, the SVR is issued for thunderstorms likely to produce hail of 0.75-in. diameter or greater and/or surface wind gusts of 58 miles per hour (mph; 25.7 m s^{-1}) or greater. HWWs are usually issued for expected surface wind gusts of 58 mph (25.7 m s^{-1}) or higher (in most parts of the country) due to synoptic-scale pressure gradients, terrain-forced winds such as mountain waves, or mesoscale winds associated with a wake low behind a squall line. We will explore the nature of the best response in section 7 of this paper.

Therefore, the case studied here is one of a convective line with few of the accepted characteristics of a typical squall line in the warm season. Additionally, winds occurred during thunderstorm activity sufficient to require the issuance of a severe thunderstorm warning, even though the origin of those strong winds was due only in part to the convective circulation. To better understand the event, this paper takes the following form: Section 2 reviews the related literature; section 3 looks briefly at the data and methods used in this study; in section 4 we provide a synoptic overview for the time period when the system was near its peak; section 5 supports the synoptic analysis with mesoscale analyses from the Rapid Update Cycle (RUC) model and soundings from both the time of the event and from 12 h prior to it; section 6 is devoted to observed radar and lightning aspects of this convective system, including a discussion on how this line of thunderstorms compares

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with squall lines typically observed with severe weather in the Midwest; and in section 7, we offer a brief summary of the results and some concluding remarks on the operational significance of this event.

2. Background

The event studied here was atypical of thundersnow cases, in that the event in question was not a case of elevated convection. While most thundersnow events in the Midwest occur in the presence of an extratropical cyclone (Market et al. 2002) resulting from some type of elevated instability, this event appeared to maintain a quality more related to warm season and warm sector severe weather rooted in the planetary boundary layer, of the like associated with squall lines. Previous snow event studies involving wintertime convection, such as Kocin et al. (1985) and Schneider (1990), have been completed with the aid of mesoscale models. Yet, these events were part of large synoptic-scale systems more typical of a cold season extratropical cyclone scenario described by established climatologies (Holle et al. 1998; Market et al. 2002).

Previous studies of such convective snowstorms are sparse in the existing literature. Kocin et al. (1985) performed a model evaluation of a convective snowburst event along the Atlantic seaboard, where the primary objective of the analysis was to demonstrate the practicality of using a mesoscale modeling system to forecast such phenomena; it also served to document dynamic processes associated with such events. Similar to the case of 11 February 2003, their 8 March 1984 system displayed excessive snow rates with near-blizzard conditions. However, the snowburst studied by Kocin et al. (1985) was due to the formation of a secondary surface low downstream of the primary surface low pressure center associated with strong dynamical forcing aloft. The authors also found the presence of a low-level jet (a similarity to the case studied here, as we will see shortly) associated with warm air advection. Schneider (1990) documented meteorological conditions associated with large-amplitude gravity wave disturbances. In particular, he studied the cyclone from 13 to 14 December 1987 in which an elongated band of snow fell from the Texas Panhandle up into Michigan due to a large-amplitude gravity wave, which also caused cloud-to-ground lightning, heavy snowfall, and blizzard conditions. Synoptic conditions included a deepening synoptic trough along with an associated 300-hPa jet streak and strong vorticity advection over an intensifying extratropical cyclone.

More recent work has focused on shallow, cold season convection, although not specifically on systems generating snowfall. Van den Broeke et al. (2005) examined two convective lines that formed along a surface cold front, similar to the event described here. Cloud-to-ground lightning production was linked to the existence and location of vertical instability in the lower, warmer part of the convective cloud; the specific criteria for which are discussed later within the context of this case. Damaging winds were also associated with the convective systems examined by van den Broeke et al. (2005), although on a more widespread basis (sufficient to be classified as a derecho; see Corfidi et al. 2006) than what is seen with the present case. Instead, it was the whiteout conditions (albeit brief), brought on by the combination of wind meeting the criterion for a severe thunderstorm (coincident with lightning) and falling snow, that makes this case important.

3. Data

Surface and upper-air observations form the foundation of this paper, with special emphasis on radiosonde observations at 1200 UTC 11 February 2003 and 0000 UTC 12 February 2003. For synoptic analysis, these upper-air data were fit to a 150-km grid via objective analysis using the Barnes (1973) objective analysis approach. To understand the storm-scale structure, additional observed data employed were the Weather Surveillance Radar-1988 Doppler (WSR-88D) level II data from the radars at ILX and Davenport, Iowa (DVN). Lightning flash information were taken from Vaisala's National Lightning Detection Network; this network had a median location accuracy of 500 m and a detection efficiency of 85%–90% in the region of study (Cummins et al., 1998).

Rapid Update Cycle initial field analyses were used for some synoptic, meso-α, and meso-β diagnostic variables. The RUC is well established in the operational community as a means of high-resolution analysis and short-term forecasting (Benjamin et al. 2004a,b). Analysis from the RUC came from only one run at one time, but different scales were employed for different purposes. The 80-km RUC initial field was used specifically for diagnostic variables using geostrophic assumptions in the synoptic analysis as suggested by Barnes et al. (1996), the chief example being the **Q**-vector diagnostic. A finer-scale 20-km RUC initial field grid was used for mesoscale diagnostic variables that forego the geostrophic assumption and make use of the total wind (i.e., frontogenesis).

4. Analysis

The synoptic and mesoscale environment for 0000 UTC 12 February 2003 revealed a dynamic pattern that was both similar and dissimilar to line-type convection. An observational analysis of the synoptic and meso-

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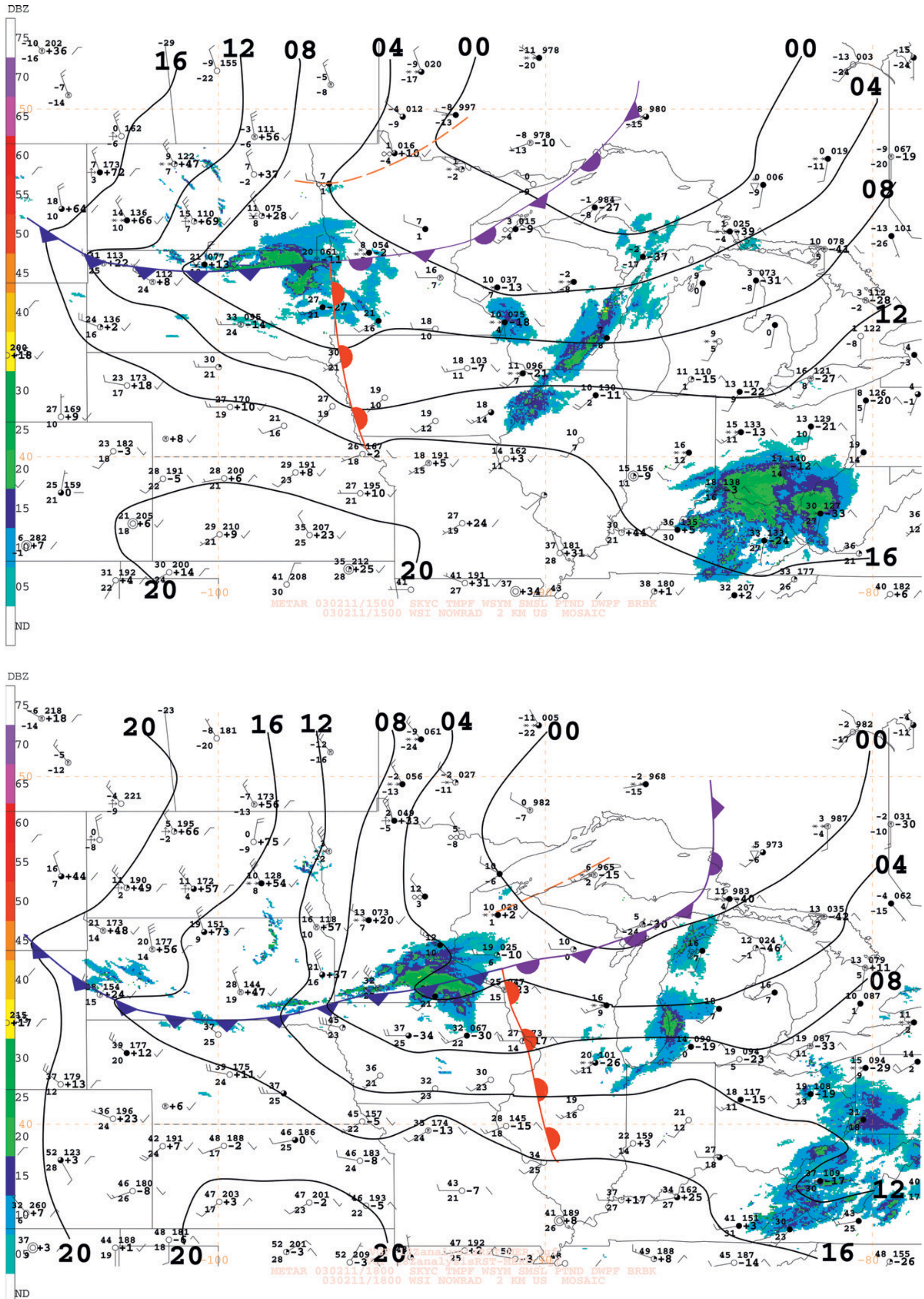
(a)



(b)

FIG. 1. Composites of reflectivity, and observed data (standard plotted station models) with subjective analysis of sea level pressure (black solid contours; every 4 hPa), valid at (a) 1500, (b) 1800, and (c) 2100 UTC 11 Feb 2003, and at (d) 0000 UTC 12 Feb 2003.

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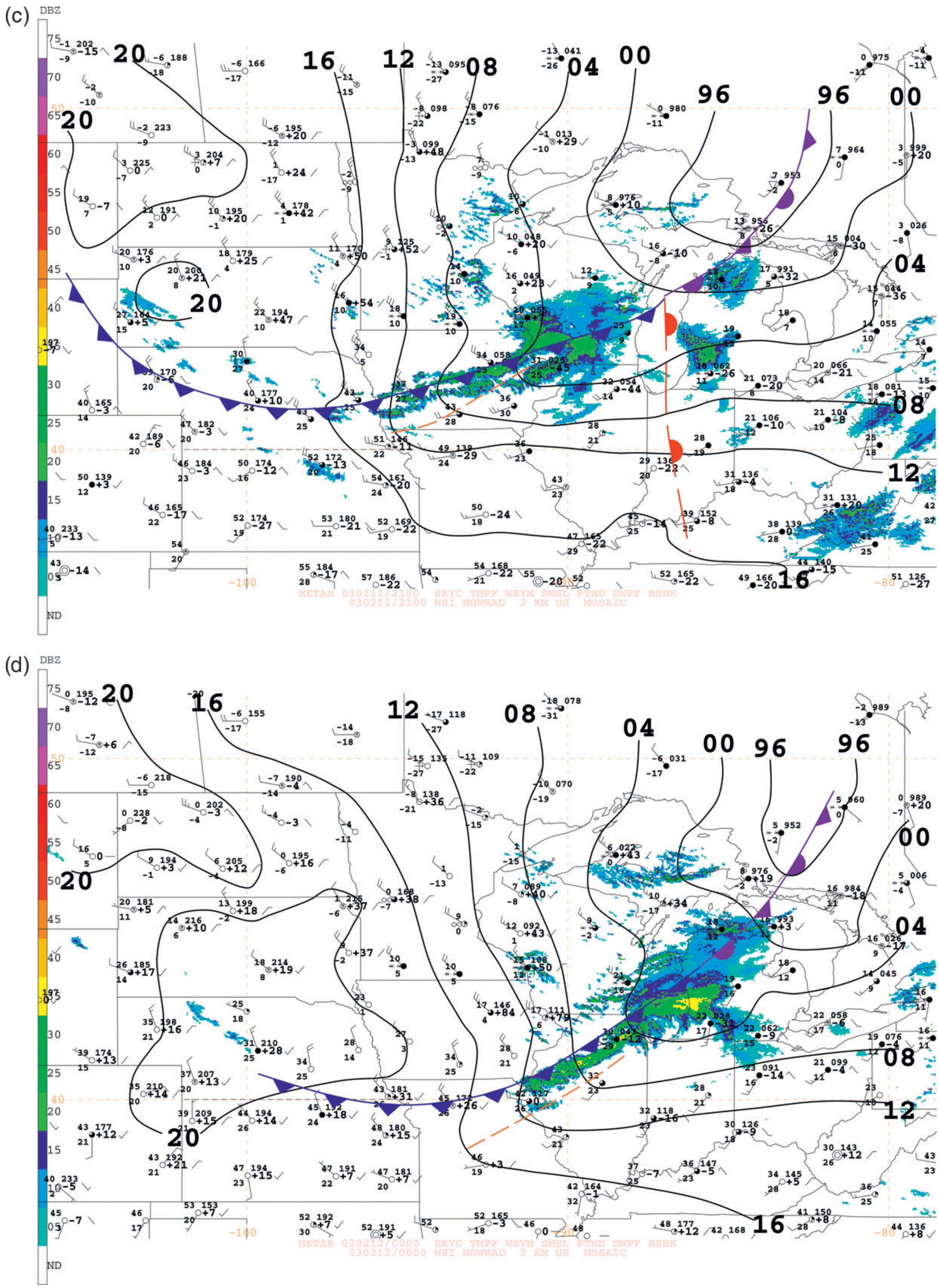

FIG. 1. (*Continued*)

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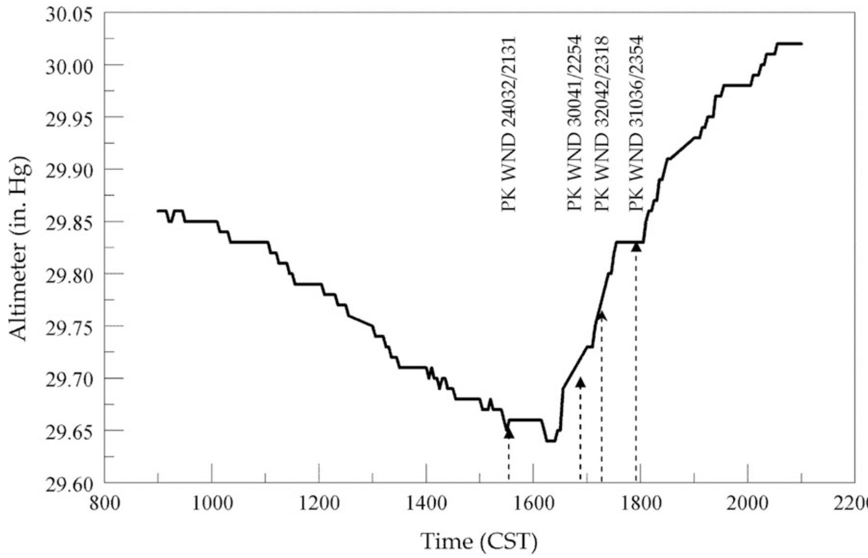

FIG. 2. Twelve hours (0900–2100 CST) of 5-min altimeter setting values (in.) from the Automated Surface Observing System (ASOS) at the airport in Moline, IL. Pertinent remarks from the encoded aviation routine weather report (METAR) are annotated onto the plot.

scale environments provided insight into this case of wintertime, line-type convection, including the presence of strong mass gradients at the surface and aloft that preconditioned the convective environment to be one with already strong wind speeds.

a. Synoptic-scale analysis

Aligned along and beneath the upper trough axis, the cold front was depicted in the surface analyses (Figs. 1a–d) progressing from South Dakota at 1500 UTC 11 February 2003 (Fig. 1a) to northern Missouri and Illinois by 0000 UTC 12 February 2003 (Fig. 1d). It is noteworthy that the bulk of the precipitation associated with the cold frontal zone was upstream of the surface cold frontal boundary during the morning hours (Figs. 1a and 1b), but that the area transitioned to being immediately prefrontal during the afternoon hours and especially at the time of the thundersnow event (Figs. 1c and 1d). We also note a significant pressure gradient ahead of the cold front in the warm sector as well as in the cold air behind it, throughout the day and especially over central Illinois at 0000 UTC 12 February 2003 (Fig. 1d), which supported winds of 30 kt and higher as we shall see presently.

Indeed, surface observations at DVN (Table 1) revealed the impact of this front well. At DVN, the temperature had fallen 1.1°C between 2154 and 2242 UTC on 11 February while the dewpoint had risen from −5.6° to −2.8°C in the same time period. This latter behavior resulted from sublimation of falling snow as well as moisture advection ahead of the frontal boundary. The altimeter had fallen 0.02 in. during the hour prior. Heavy snow was falling by 2245 UTC, just after frontal passage, with sustained northwest winds at 35 kt (18 m s^{-1}) and gusts to 43 kt (22 m s^{-1}). Several conditions were indicative of an intense cold front. First was the 33-min snow shower that began at 2216 UTC and ended at 2259 UTC. Second, the sky cleared (below 12 000 ft) by 2354 UTC while the dewpoint dropped to 15°F (−9.4°C). Finally, a moderate veer of 60° in wind direction in less than an hour was tempered by the persistence of blustery conditions behind the front. The temperature change was gradual at first, but then accelerated at sunset. A similar pattern was observed at Peoria, Illinois (Table 1).

Observations from earlier in the day at Huron, South Dakota (HON), also showed the passage of the cold front (Table 1). In addition to the usual cold frontal signatures, HON exhibited wind gusts in excess of the severe criterion but in the absence of lightning or even falling precipitation. Additionally, the strongest wind gusts at all three stations came after the pressure had ebbed and begun to rise; a similar signature was found in the 6-min observations from Moline, Illinois (Fig. 2), with wind gusts of 42 kt at 2318 UTC. This latter point matches well with the pressure gradient observed in the area near that time (Fig. 1d). Yet, no subsequent pressure fall was recorded as would be expected if a mesohigh had formed in association with a typical squall line. We shall explore the origins of such strong surface winds in the ensuing sections.

At 0000 UTC 12 February 2003, a 300-hPa polar jet

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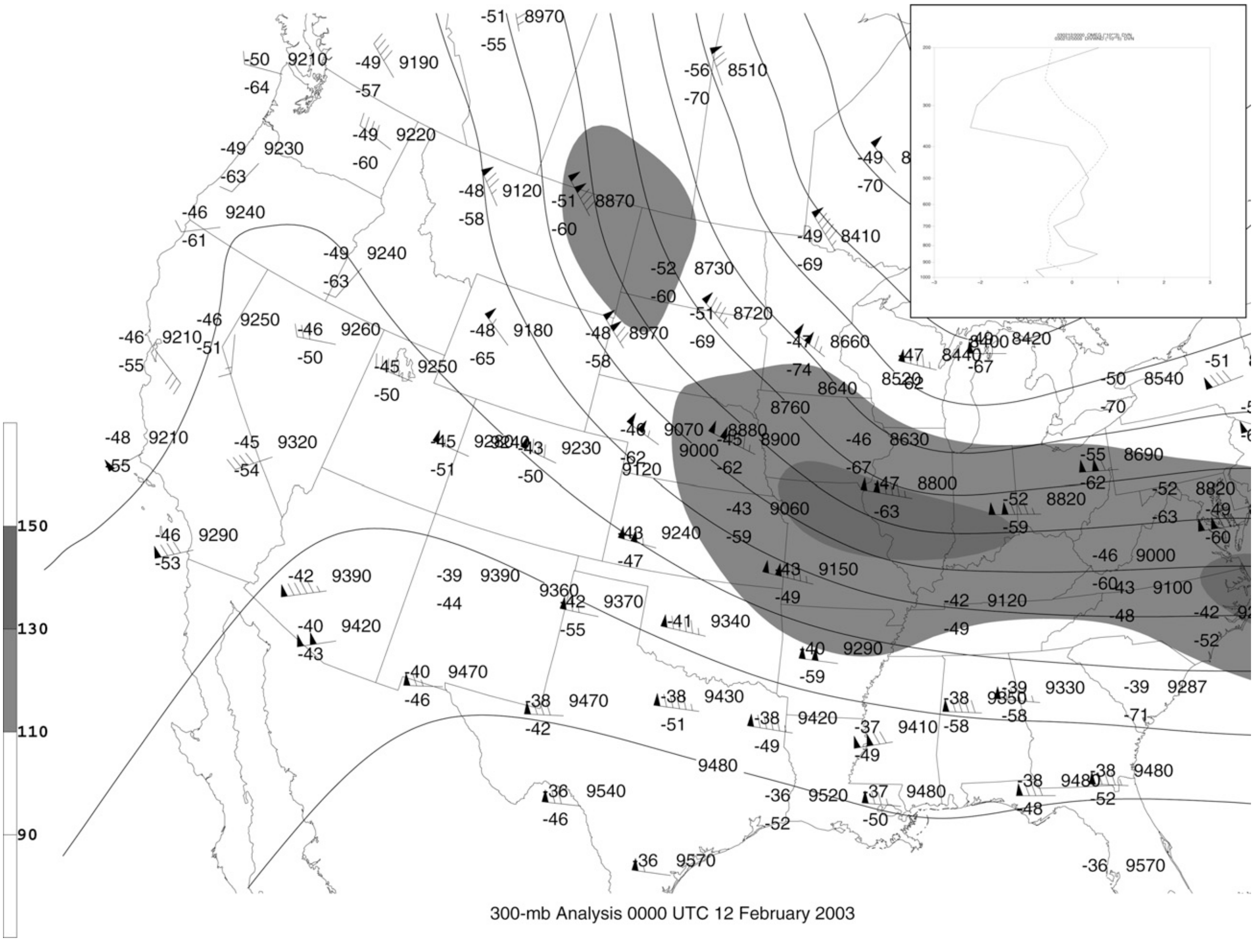

FIG. 3. Observed data [standard station models; temperatures and dewpoints (°C); wind barbs and flags (kt); height (gpm)] and objective analyses (contours) of the observed data valid at 0000 UTC 12 Feb 2003 for 300 hPa over the continental United States. Geopotential height is contoured (every 120 gpm; black, solid), with isotachs shaded (every 20 kt, starting at 110 kt); grayscale shading is indicated by grayscale bar left of image. Figure inset depicts the divergence (solid) and vertical motion (dashed) at 0000 UTC 12 Feb 2003 at DVN; horizontal scale represents variations in both divergence ($\times 10^{-5}$ s^{-1}) and vertical motion (μb s^{-1}).

(Fig. 3) flowed southward out of central Canada with a core centered over the Ohio Valley and wind speeds of up to 135 kt (69 m s^{-1}). Southern Iowa and central Illinois resided near the core of this jet streak but toward the left entrance region, the latter area typically associated with upper-level convergence (Moore and Van Knowe 1992), which was diagnosed there (Fig. 3, inset). While this is atypical for the ideal occurrence of severe weather, where strong mass convergence below and strong mass divergence aloft are preferred, other investigators have documented similar atypical arrangements (Rose et al. 2002). Nevertheless, the dominance of lower- to midtropospheric forcing for ascent was verified in this case (Fig. 3, inset).

A low-amplitude shortwave trough axis at 500 hPa (Fig. 4) from just west of Hudson Bay, southwest through Wisconsin, and into Kansas revealed a significant slope into the cold air, consistent with a strong cold front. The roughly circular absolute vorticity maximum (20×10^{-5} s^{-1}) in the base of the short-wave trough over Lake Superior suggested quasigeostrophic forcing for ascent downstream across eastern Iowa and northern Illinois, poleward of the 300-hPa jet (Fig. 3). The **Q** vectors from the 80-km RUC initial fields (Fig. 5) indicated a significant area of **Q**-vector convergence over central Illinois at 0000 UTC, further supporting evidence for midtropospheric forcing for ascent.

Analysis of the 850-hPa data (Fig. 6) indicated a trough axis running parallel to the surface frontal boundary, extending from the Great Lakes into Iowa and Missouri. Along the trough axis, dewpoint depressions remained relatively low with ILX reporting a dewpoint depression of 6°C, indicating a moist environment. Other stations along the trough in Iowa, Wiscon-

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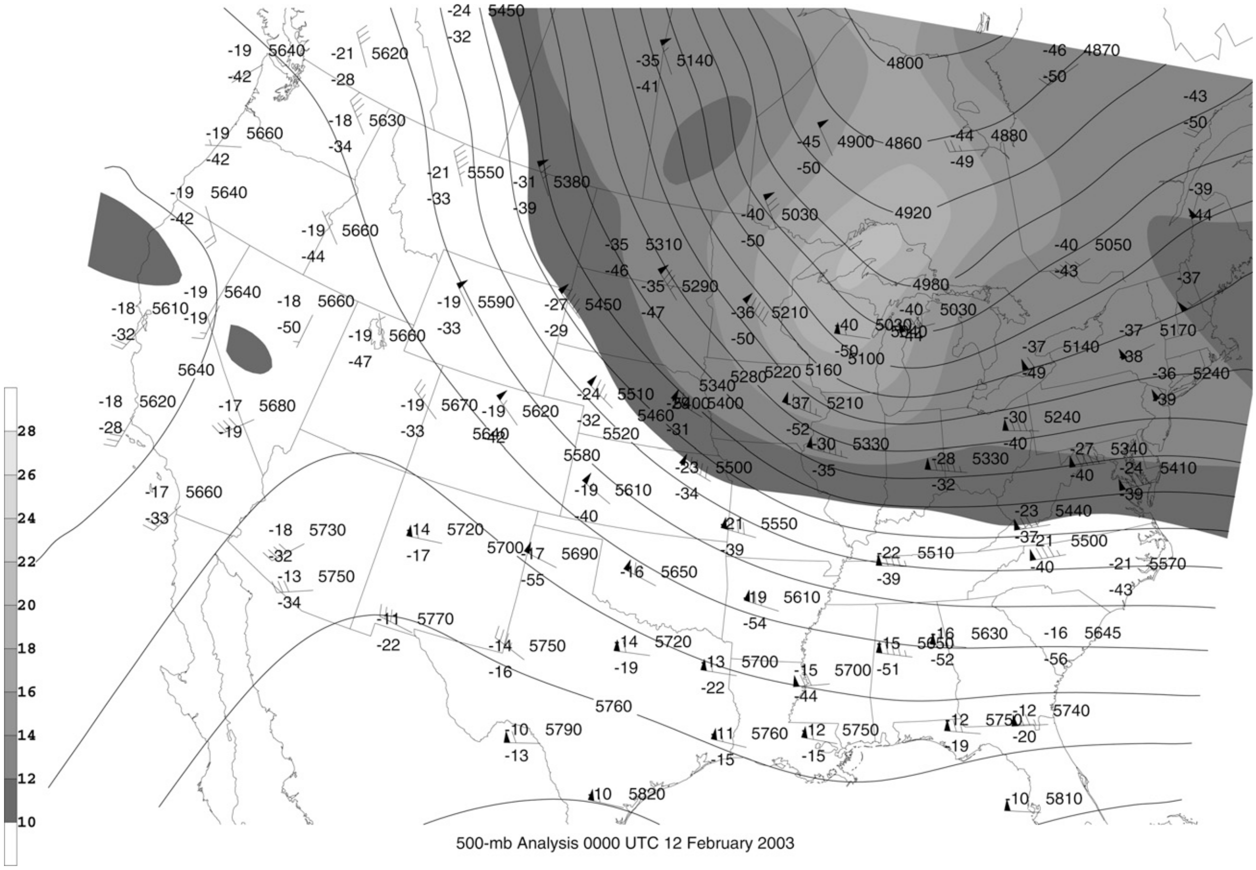

FIG. 4. Observed data (standard station models) and objective analyses (contours) of observed data valid at 0000 UTC 12 Feb 2003 for 500 hPa over the continental United States. Geopotential height (every 60 gpm; black, solid) and absolute vorticity (every 2×10^{-5} s^{-1}; shaded over 10×10^{-5} s^{-1}); grayscale shading is indicated by the grayscale bar left of image.

sin, and Michigan maintained dewpoint depressions of less than 5°C, revealing a more moist pretrough environment. Temperatures behind the 850-hPa trough dropped drastically, suggesting a front at this level. Thus, there is evidence that prefrontal moisture and a frontal lifting mechanism were present at this level. Of particular interest here are the wind speeds, which were also faster at ILX (57 kt) and DVN (66 kt) at this level than at any other station.

b. Mesoscale analysis

Initial fields from the 20-km RUC were used to examine the mesoscale environment prior to and at the time of this event. Plots of low-level (925 hPa) frontogenesis and vertical motion as well as the convective available potential energy (CAPE) based upon a parcel with the mean characteristics of the lowest 50-hPa layer revealed an environment with the necessary ingredients for convection, albeit shallow. At 2100 UTC 11 February 2003 (Fig. 7a), 925-hPa frontogenesis was found along and behind the location of the surface cold front. Significant areas had frontogenesis values >5.0 K (100 km)$^{-1}$ (3 h)$^{-1}$, and there was a significant region along the frontal zone where ω values were less than -10 and even -15 μb s^{-1}. In addition, CAPE values (nonexistent in the region as recently as 1800 UTC) blossomed and were maximized in area and magnitude, exceeding 50 J kg^{-1} over a large area coincident with the area where ω values ≤ -10 μb s^{-1}. This arrangement agrees well with the bulk of the precipitation being immediately along and ahead of the surface frontal zone at this time (Fig. 1c).

Hourly analyses showed much the same pattern, although the CAPE values showed a gradual decrease in area and magnitude, with only a small area of values >10 J kg^{-1} in evidence by 0000 UTC 12 February 2003 (Fig. 7b). However, the 925-hPa frontogenesis had increased substantially, with a closed contour of values in excess of 10.0 K (100 km)$^{-1}$ (3 h)$^{-1}$ over extreme southeastern Iowa. Vertical motion values of -20 μb s^{-1} were collocated with the small area of CAPE (Fig. 7b) and the region ahead of the cold front where

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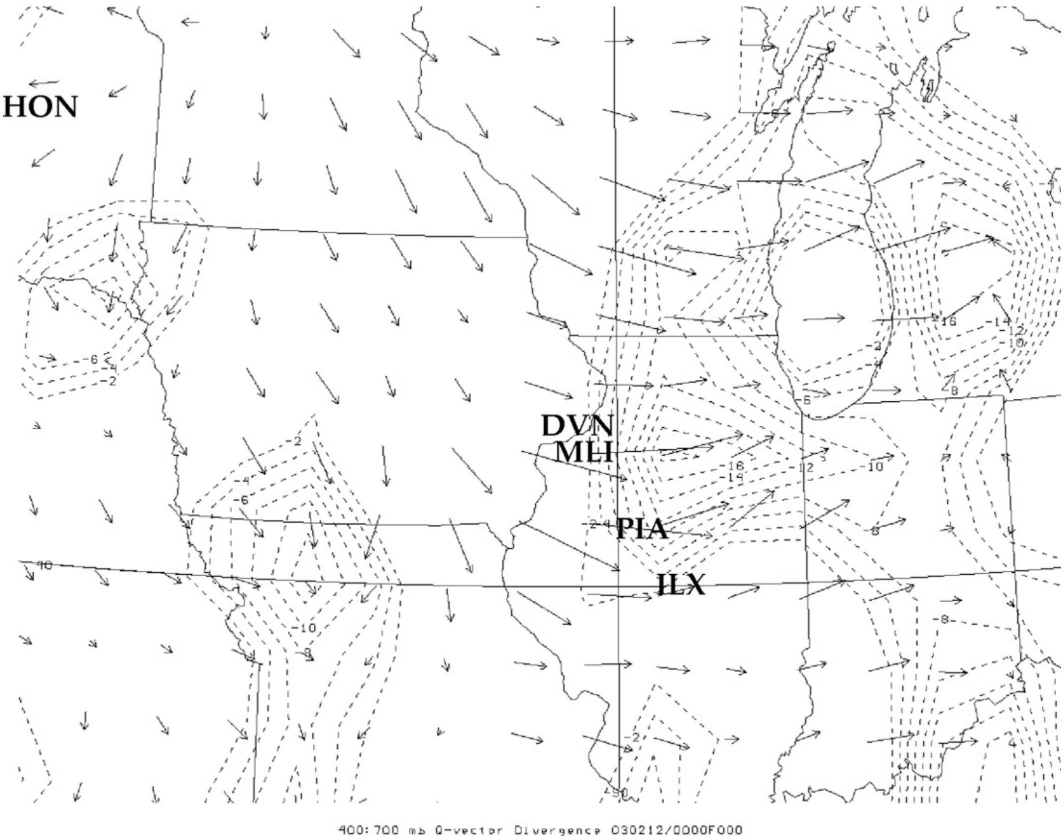

FIG. 5. The **Q** vectors and **Q**-vector divergence in the 400–700-hPa layer from the thinned 80-km RUC initial fields valid at 0000 UTC 12 Feb 2003. The **Q** vectors are in black vector form while negative values of the **Q**-vector divergence are contoured (every 2×10^{-14} s^{-3} hPa^{-1}; black, dashed). Observations from several stations discussed in the text (HON, DVN, MLI, PIA, and ILX) are also identified and located in this figure.

precipitation was occurring (Fig. 1d) and whiteout conditions were being experienced. Together, the analyses in Fig. 7 depict a dynamically forced region of ascent immediately along and ahead of the surface cold front capable of raising near-surface parcels to their lifting condensation level (LCL) and realizing modest amounts of CAPE.

Cross-section analysis revealed a zone of frontogenesis (Fig. 8) that sloped upward and northward, running roughly parallel to the 280-K θ_e contour. Above and to the south of the frontogenesis maximum was a narrow upward vertical velocity maximum (<-30.0 μb s^{-1}), which was complemented by the rather broad, sloping area of descent behind the surface frontal zone. These analyses demonstrate that a significant direct thermal circulation was likely because of the strong frontogenetic forcing. In addition to the convective instability diagnosed along the surface frontal zone, these RUC grids also depicted relatively deep (~100 hPa) dry-adiabatic layers along and just ahead of the surface frontal zone (Fig. 9), thus providing little inhibition for parcels to be lifted to their LCL. While the synoptic setting has already been shown to be capable of supporting sustained surface winds >25 kt (12.8 m s^{-1}) and >50 kt (25.7 m s^{-1}) at 850 hPa, these mesoscale analyses establish the lower troposphere as a region conducive to vertical mixing.

5. Sounding analysis

a. Lincoln, Illinois

We begin by examining the soundings from ILX, both of which flew on the day in question in the warm air ahead of the advancing cold front. ILX received a 5.3-cm (2.1 in.) snowfall early on 11 February 2003 and the 1200 UTC sounding (Fig. 10) flew near the end of the overnight snowfall under mostly cloudy sky conditions. Very cold temperatures existed in the lowest 100 hPa. The wind profile revealed significant veering in the lowest 100 hPa, with a weakly sheared unidirectional flow throughout much of the troposphere above the boundary layer.

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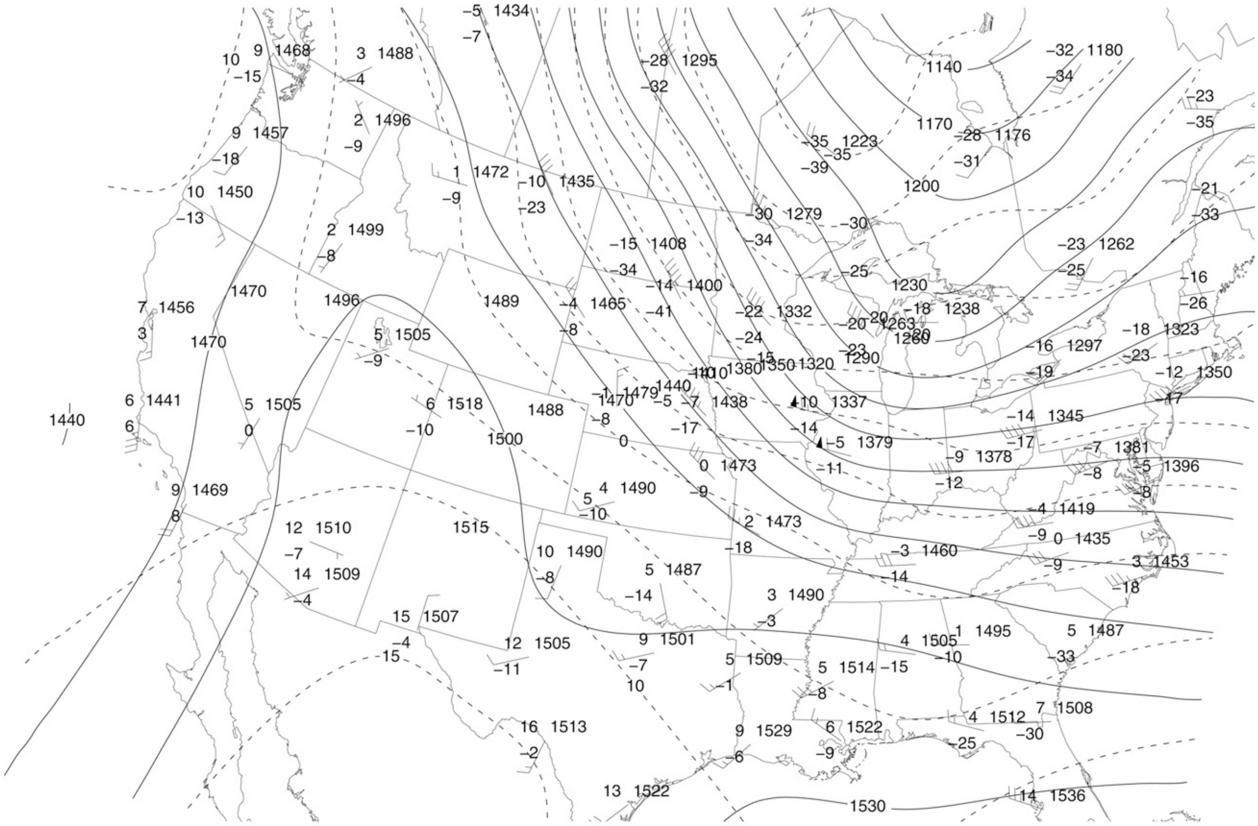

850–mb Analysis 0000 UTC 12 February 2003

FIG. 6. Observed data (standard station models) and objective analyses (contours) of observed data valid at 0000 UTC 12 Feb 2003 for 850 hPa over the continental United States. Geopotential height (every 60 gpm; black, solid) and temperature (every 5°C; black, dashed) are both contoured.

Analysis of the subsequent sounding at 0000 UTC 12 February 2003 revealed a much warmer, moister environment in the lowest 200 hPa (Fig. 10). This sounding flew in the warm air 100 km in advance of the surface frontal zone (note the weaker but persistent warm advection signature in the lower troposphere). However, surface temperatures were damped by the early evening flight time as well as the persistent snow field still on the ground at that time. Standard analysis of CAPE for a mean parcel from the lowest 100 hPa yielded a null value. The CAPE based upon the most unstable parcel lifted from 862 hPa produced a meager 3 J kg^{-1}, although it is noteworthy that the atmospheric profile was nearly dry adiabatic from that level up to ~625 hPa.

b. Davenport, Iowa

As with the morning sounding at ILX, the flight from DVN at 1200 UTC 11 February 2003 was also well ahead of the advancing cold front and also exhibited very cold air near the surface (Fig. 11). The wind profile at the time had a similar unidirectional shear signature to that at ILX (Fig. 10). Also in parallel with the ILX flights, the DVN sounding at 0000 UTC 12 February 2003 exhibited significant 12-h warming in the lowest 200-hPa layer along with 12-h moistening in the lowest 100 hPa (Fig. 11). In contrast to the ILX evolution (Fig. 10), the DVN atmosphere also exhibited cooling and significant drying in the midtroposphere (700–500-hPa layer), which encouraged the creation of potential instability.

We also note that the DVN sounding at 0000 UTC 12 February 2003 (Fig. 11) was launched as the precipitation band approached. As a result, surface temperatures were changing rapidly, and the unadjusted sounding suggested a superadiabatic surface layer. The 0000 UTC DVN sounding shown here (Fig. 11) requires adjustment of the surface ambient and dewpoint temperatures, determined by extrapolating the lapse rate in the 925–975-hPa layer down to the surface (980 hPa). These corrections yielded a nearly dry-adiabatic surface layer beneath the frontal inversion based at 892 hPa. Above the inversion, the atmosphere was conditionally

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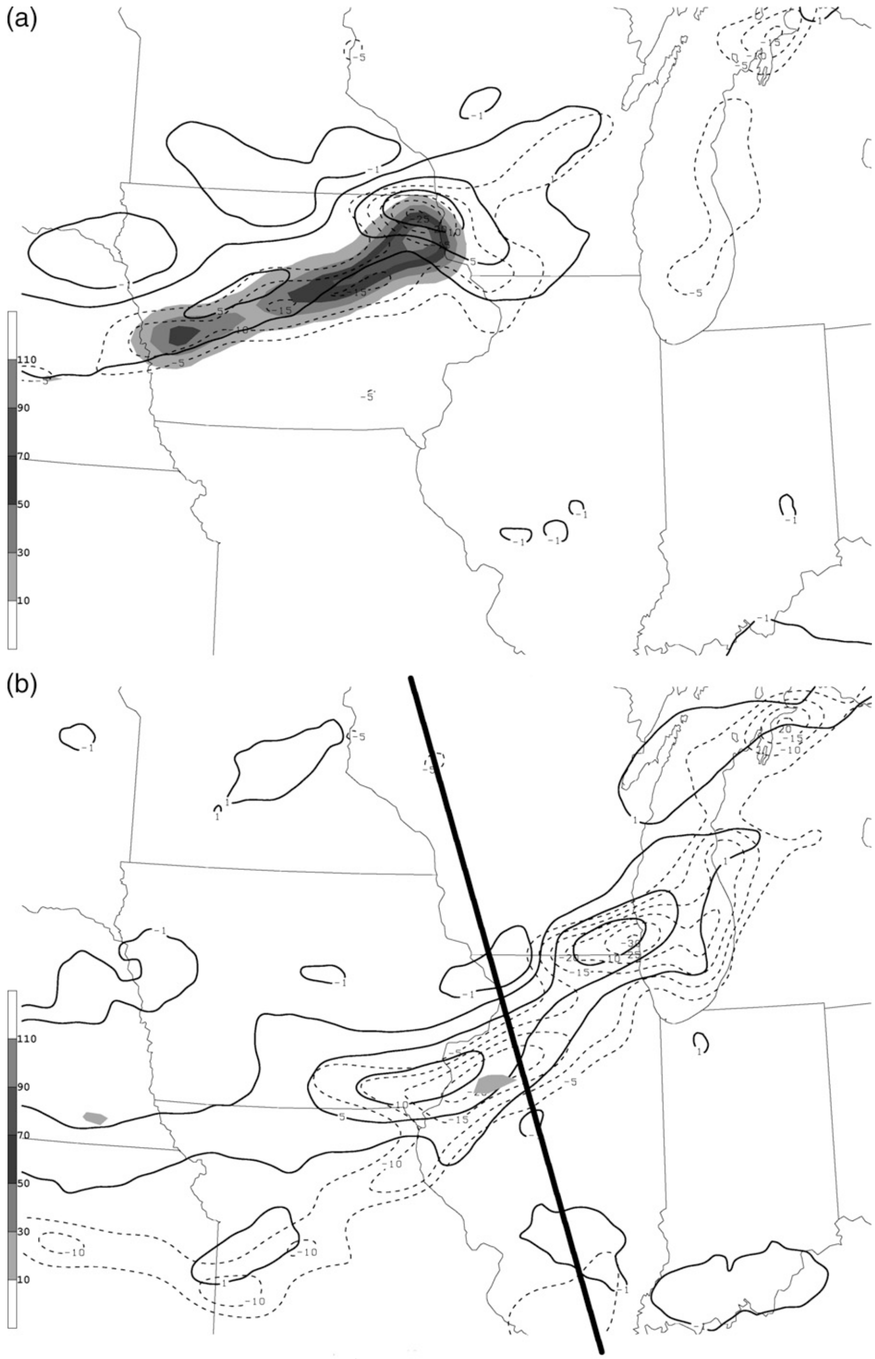

FIG. 7. The 20-km RUC analysis at 925 hPa of Petterssen frontogenesis [every 5 K (100 km)$^{-1}$ (3 h)$^{-1}$; black, solid], ω vertical velocity (every 5 μb s^{-1}; black, dashed), and CAPE for the mean parcel in the lowest 50 hPa (shaded every 20 J kg^{-1} above 10 J kg^{-1}; grayscale shading is indicated by the grayscale bar left of image) for (a) 2100 UTC 11 Feb 2003 and (b) 0000 UTC 12 Feb 2003. Dark solid line in (b) represents the cross-section line used in Fig. 8.

unstable in a layer from 850 to 687 hPa. Correspondingly, the most unstable parcel originates from the 826-hPa level, but yielded a minor CAPE value of only 3 J kg^{-1}.

The preceding analysis depicts a strongly forced, low-instability situation of the kind described by van den Broeke et al. (2005). Additionally, experiments with an adjusted DVN sounding from 0000 UTC 12 February

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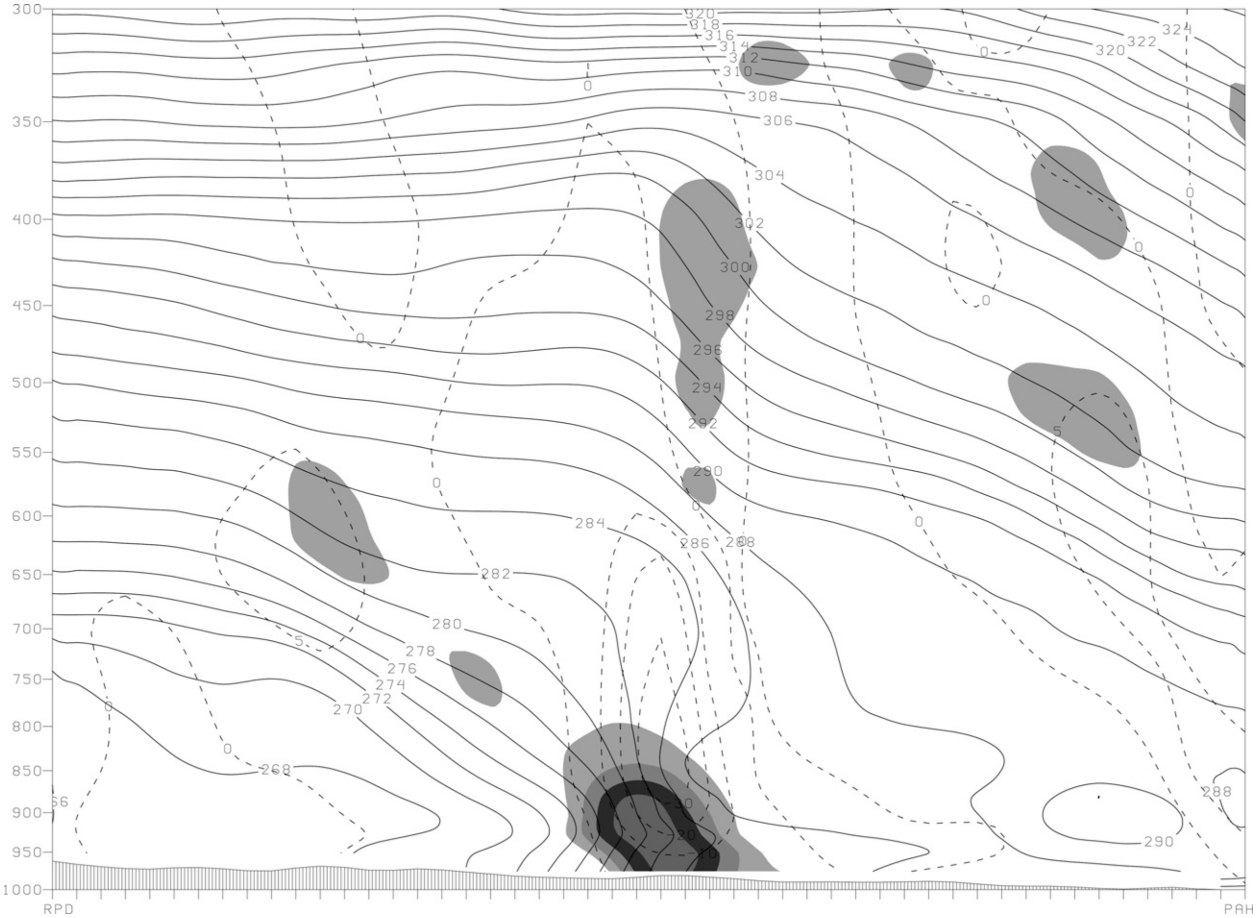

FIG. 8. Cross-section analysis from 20-km RUC initial fields valid at 0000 UTC 12 Feb 2003 showing equivalent potential temperature (every 2 K; solid black), ω vertical velocity (5, 0, -10, -20, and -30 μb s^{-1}; dashed), and Petterssen frontogenesis [1, 3, 5, and 7 K (100 km)$^{-1}$ (3 h)$^{-1}$; shaded], along a line from Rice Lake, WI (RPD), to Paducah, KY (PAH), which is shown in boldface in Fig. 7b.

2003 failed to yield significant CAPE. Figure 12 depicts one such adjusted DVN sounding from 0000 UTC 12 February 2003, where the surface temperature and dewpoint reflect those from DVN at 2200 UTC 11 February 2003 (1–2 h prior to the radiosonde launch). Also, the boundary layer has been adjusted to a well-mixed, dry-adiabatic condition in the lowest 50 hPa, and temperatures have been warmed by 1°C above the inversion level to 700 hPa (to offset the demonstrated cooling between the morning and evening balloon ascents), with subsequent superadiabatic layers removed. These changes are made in order to approximate warm air immediately ahead of the surface frontal zone. This idealized sounding produced only 169 J kg^{-1} of CAPE (for a parcel from the lowest 50 hPa). Yet, the resulting sounding possessed CAPE in excess of 100 J kg^{-1}, a lifting condensation level with a temperature warmer than -10°C, and a relatively low equilibrium level (592 hPa) colder than -20°C. These conditions are all

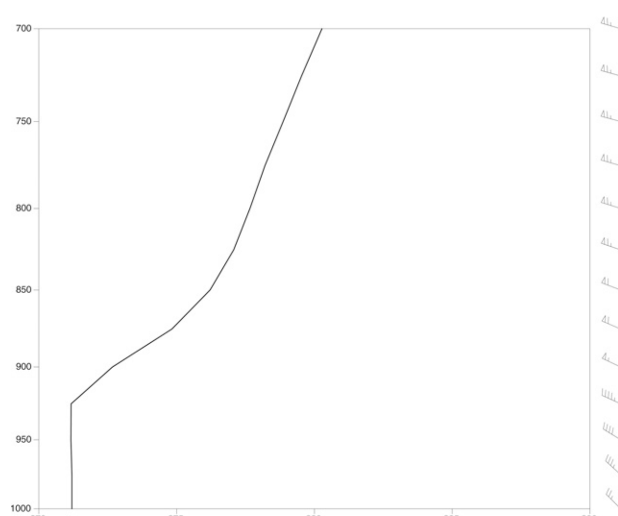

FIG. 9. Virtual potential temperature profile of the lower troposphere from the RUC 20-km initial field at 0000 UTC 12 Feb 2003 for DVN, with wind barbs on right (kt).

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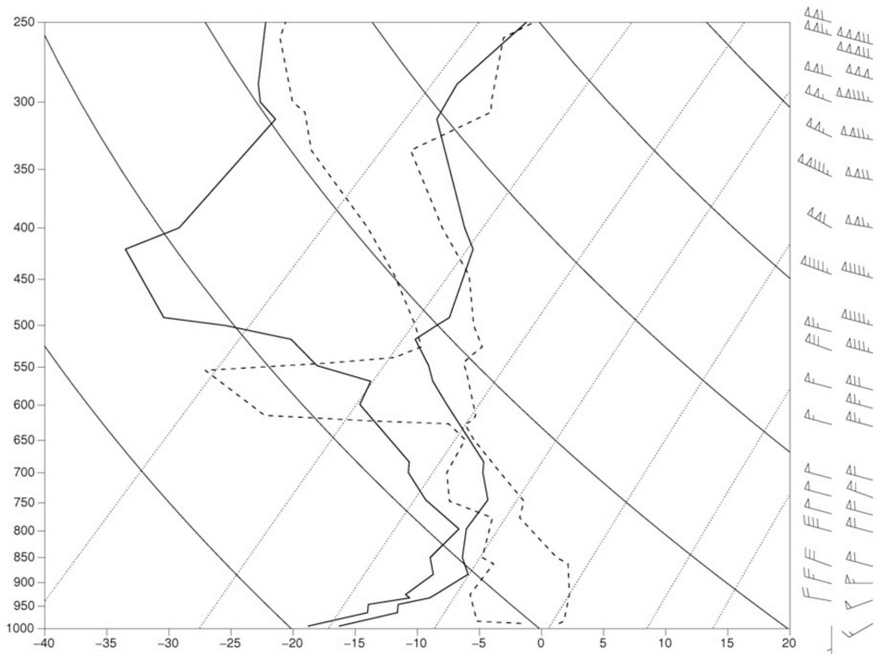

FIG. 10. Skew T–log$p$ plots of observed sounding data for ILX at 1200 UTC 11 Feb 2003 [temperature and dewpoint temperature (°C); both solid] and 0000 UTC 12 Feb 2003 [temperature and dewpoint temperature (°C); both dashed]. On the right, winds (kt) are plotted for the 1200 UTC 11 Feb 2003 sounding (immediately right of plot) and the 0000 UTC 12 Feb 2003 sounding (at far right).

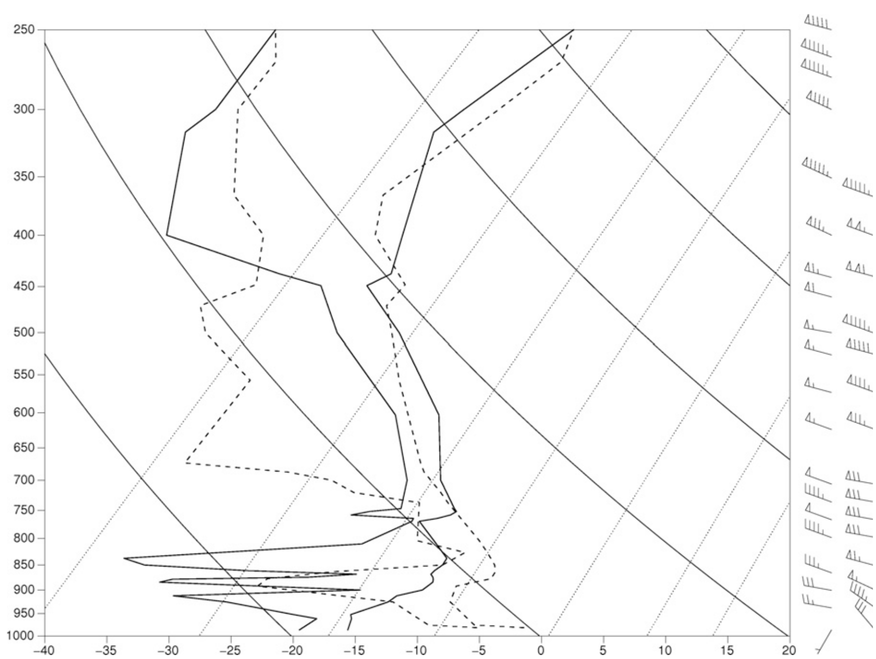

FIG. 11. Skew T–log$p$ plots of observed sounding data for DVN at 1200 UTC 11 Feb 2003 [temperature and dewpoint temperature (°C); both solid] and 0000 UTC 12 Feb 2003 [temperature and dewpoint temperature (°C); both dashed]. On the right, winds (kt) are plotted for the 1200 UTC 11 Feb 2003 sounding (immediately right of plot) and the 0000 UTC 12 Feb 2003 sounding (at far right).

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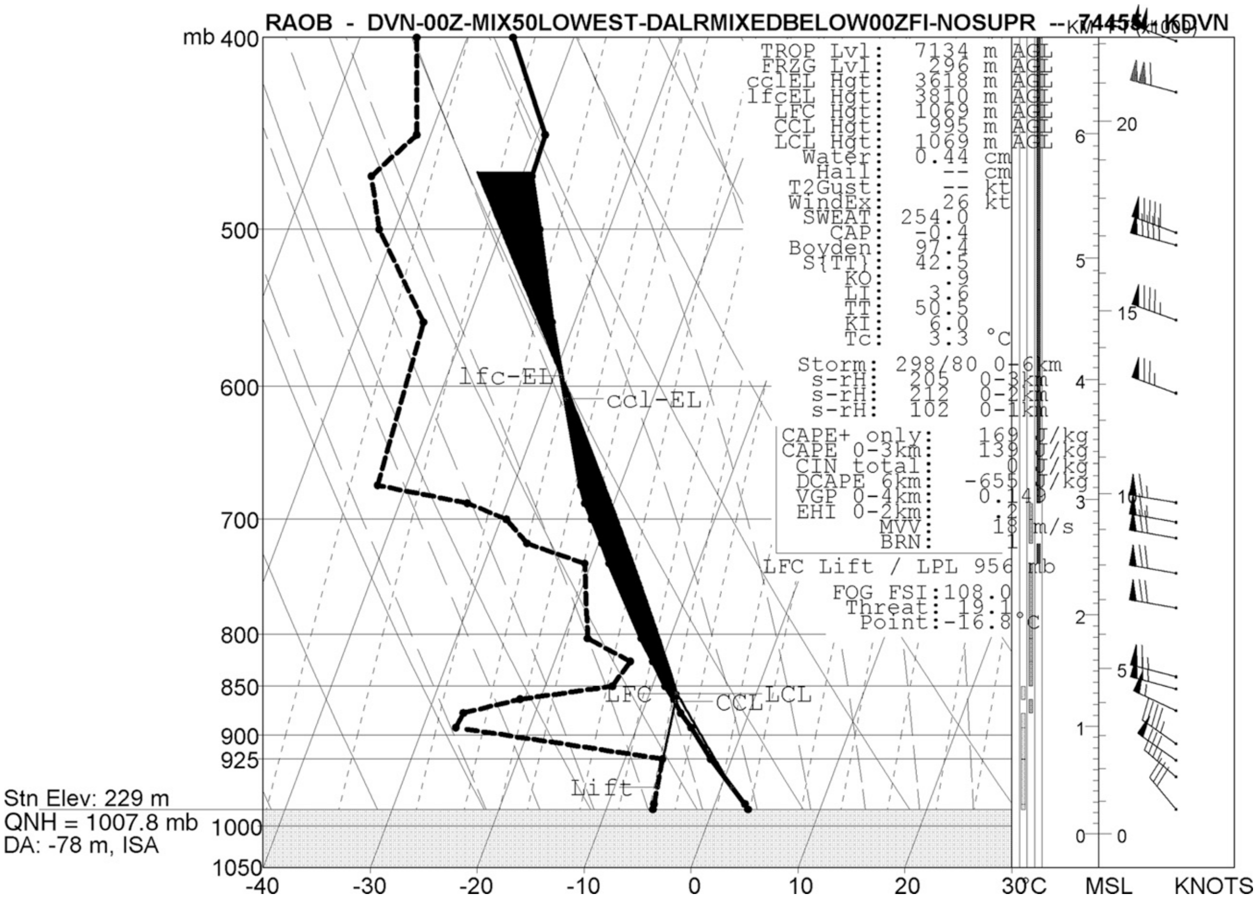

FIG. 12. Modified DVN sounding for 0000 UTC 12 Feb 2003. Changes include surface temperature (°C) and dewpoint (°C) from the 2200 UTC 11 Feb 2003 DVN ASOS, as well as a well-mixed, dry-adiabatic environment in the lowest 50 hPa. Temperatures between the 0000 UTC sounding inversion top (826 hPa) and 700 hPa have been warmed by 1°C. Superadiabatic layers have been removed.

thought necessary for the creation of lightning (van den Broeke et al. 2005). Moreover, winds were free to mix down in the lowest 50 hPa (and perhaps from as high as 892 hPa), a layer that contained winds in excess of 50 kt.

6. Storm-scale analysis

a. Radar analysis

WSR-88D data in Iowa and Illinois were examined to evaluate the characteristics of this line and contrast it with its warm season counterparts, the more common rain and severe weather producing squall lines. The strongest radar reflectivities in this case were located along a line parallel to the fast-moving surface cold front (Fig. 13a). Throughout the lifetime of the event, maximum reflectivities averaged between 40 and 45 d*BZ*. Storm tops never exceeded 3.7 km, and the highest reflectivities were limited to the lower portions of the strongest cells. Little change in radar characteristics was noted overall (Fig. 13b), except that maximum reflectivities were more widespread in areal coverage as the line reached extreme eastern Iowa into northern and central Illinois during the late afternoon and early evening.

The convective line in this case showed none of the characteristics of traditional severe-weather-producing squall lines based on an analysis of radar reflectivity and velocity data. There was no rear-inflow jet, stratiform precipitation region, or front-to-rear flow as described by Smull and Houze (1987) and Houze et al. (1989). Nor did this line evolve through the stages of squall-line evolution as described by Rasmussen and Rutledge (1993). What we see instead is a convective line along the cold frontal zone that most closely resembled the parallel stratiform mesoscale convective system (MCS) archetype of Parker and Johnson (2000). Yet, during the period when severe weather was occurring (and several hours before and after), the system studied here did not assume the life cycle suggested by Parker and Johnson (2000), where an expanding area of

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stratiform precipitation would exist on the left flank of the line. Not only did the stratiform region not develop, but there was no tendency for cell decay on the left flank or new cell generation on the right as would be expected with the parallel stratiform MCS archetype. Moreover, the convective line was found to tilt slightly down shear (Fig. 13c), a condition corroborated by the velocity cross section (Fig. 13d), and which persisted through the decay of this line, likely due to a lack of sufficient CAPE ahead of the front and the convective line, and the strong ambient vertical wind shear (e.g., Weisman 1993). Thus, the severe winds were not the result of squall-line convection but rather of the vertical mixing associated with the mesoscale and synoptic-scale systems.

b. *Lightning analysis*

While the analysis of lightning data does not shed light on the origin of the severe thunderstorm winds, it does show clearly the temporal and spatial extents of the thunderstorm activity. Moreover, the ensuing analysis is unique in that it represents relatively rare documentation of lightning behavior in a continental winter precipitation thunderstorm event. Indeed, storms producing snow and lightning of the nature of this event are rare, and our purpose here is to document the lightning characteristics of this snow and severe-wind-producing squall line. Finally, the operational utility of this analysis will be established in the cross sections to be discussed presently, showing the means by which forecasters might better anticipate lightning in such an event.

A total of 101 cloud-to-ground (CG) flashes were detected in the region by Vaisala's National Lightning Detection Network (NLDN) during an 8-h period between 1900 UTC 11 February 2003 and 0300 UTC 12 February 2003 (Fig. 14). Grouped into 2-h bins, the lightning data showed well the progression of the convective line toward the southeast. Analysis of these NLDN data showed that only 4 of the 101 flashes were of positive polarity, the mean peak current being −17.4 kA, with a standard deviation of ±18.5 kA. The negative CG flashes had a median multiplicity (the number of CG return strokes detected within a particular flash) of 2 and a range of 1–14 in this event sample. The positive flashes had low multiplicity values of 1 (two cases) and 2 (two cases), and a maximum peak current value of +32 kA. The 26 flashes that occurred in the area of severe wind reports between 2300 UTC 11 February 2003 and 0100 UTC 12 February 2003 were all negative CG flashes.

That these lightning flashes predominantly lowered a negative charge to ground stands in contrast to the larger body of work on winter lightning (e.g., Takeuti et al. 1978; Brook et al. 1982), most of which had been conducted in Japan. The historical research focus on western Japan has yielded a robust body of work (see Rakov and Uman 2003 for a thorough review) with an emphasis on surface-influenced events that are akin to those that form downstream of the North American Great Lakes. Also, our results differed from the findings of Holle and Watson (1996), who studied two central United States storms that exhibited lightning with winter precipitation and found lightning behavior similar to that on the east coast of Asia, where the dominant polarity detected is positive.

Yet, these results do tend to corroborate the hypothesis of Taniguchi et al. (1982) and Brook et al. (1982) that shear in the cloud layer may have some control over the polarity of a given lightning flash. A look at the nearby soundings (Figs. 10 and 11) suggests a fairly uniform speed and directional shear profile throughout the cloud layer, allowing for a more erect convective column, which is thought to be more conducive to negative flashes. Moreover, the cross-section analysis of the radar data from the Lincoln, Illinois, WSR-88D (Figs. 13c and 13d) supports this view as well. With RUC temperatures superimposed onto the cross section, we can visualize the region where temperatures exceeded −10°C, from which unstable parcels originated and rose to their LCL at ~1100 m (also warmer than −10°C; see Figs. 10 and 12). Reflectivity values of 20 dBZ extended above the −20°C level at ~2800 m (Fig. 13c), consistent with the modified sounding for DVN (Fig. 12) suggesting an equilibrium level above the −20°C level.

7. Summary

On the evening of 11 February 2003, a line of severe thunderstorms moved across northern and central Illinois bringing high winds and blinding snowfall at rates of up to several inches per hour. Spawned along the leading edge of a cold front, the resulting line of low-topped convection had its roots in the boundary layer. A 20-km RUC analysis supported the formation of convection along the cold front through a dry-adiabatic layer within the PBL, with a layer of potential instability above, which is largely consistent with observations taken at the time of the event. The bulk of the severe weather came just after sunset as the convective line moved southward.

The thermodynamic profile, while conducive to lightning production, was also cold enough to support snowfall, thus culminating in a severe thunderstorm with snow. In support of the spotter observations, a number

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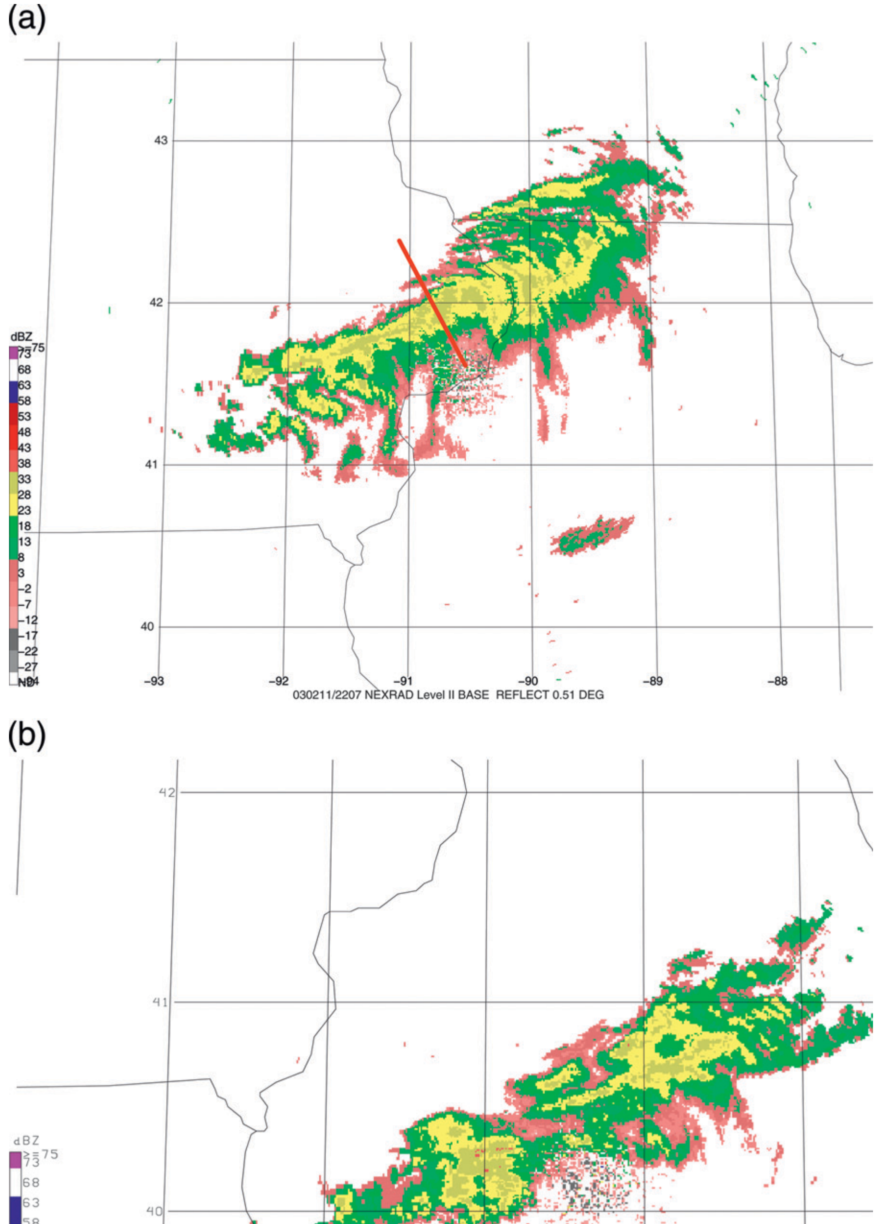

FIG. 13. Plots of WSR-88D radar base reflectivity for (a) the 0.51° tilt from DVN at 2207 UTC 11 Feb 2003, (b) the 0.4° tilt from ILX at 0045 UTC 12 Feb 2003, (c) a cross-section plot of reflectivity (dB*Z*; see color bar on left) for the DVN radar at 2207 UTC 11 Feb 2003 along the line depicted in (a), and d) a cross-section plot of base velocity (m s^{-1}; see color bar on left) for the DVN radar at 2207 UTC 11 Feb 2003 also along the line depicted in (a). Included in (c) are temperatures (every 10°C; dashed) from the RUC initial fields valid at 2200 UTC 11 Feb 2003. Boldfaced arrows in (d) approximate flow along a radial.

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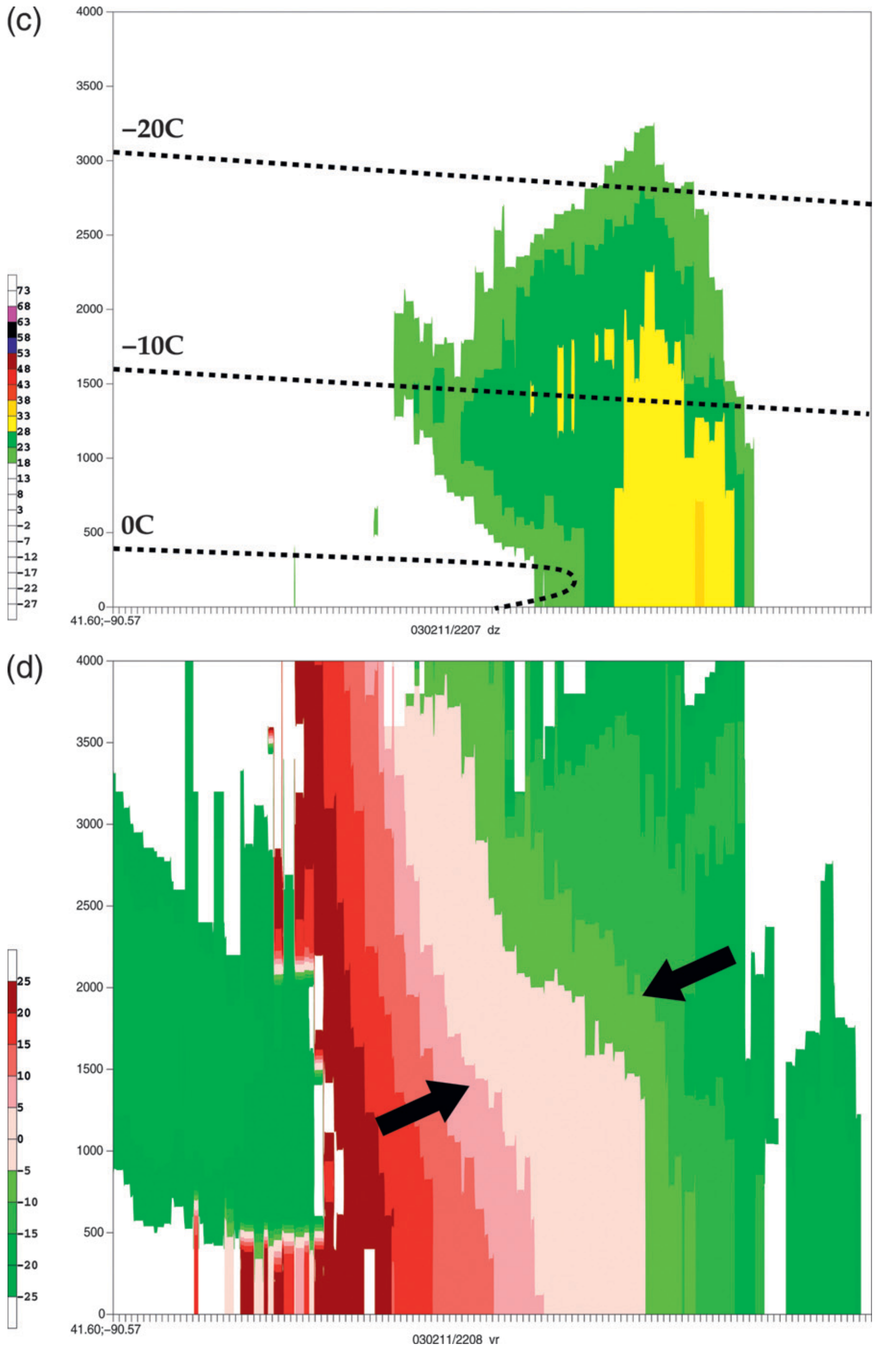

FIG. 13. (*Continued*)

of cloud-to-ground flashes, mostly negative, were recorded by the NLDN. This behavior contrasts with much of the established literature on lightning flashes with winter precipitation. Moreover, the typical thermodynamic signatures common to winter lightning in the Midwest (Market et al. 2006) were largely absent in this case. The convection in this case was not elevated, but had its origins in the boundary layer.

Although not a significant severe weather event in terms of injuries or damage, the manifestation of thundersnow in this fashion is quite unusual. The unique environment of a strong background pressure gradient and winds, significant low-level frontogenesis in the presence of modest near-surface CAPE, and a dry-adiabatic near-surface layer allowed for shallow convection and the subsequent mixing of winds to the sur-

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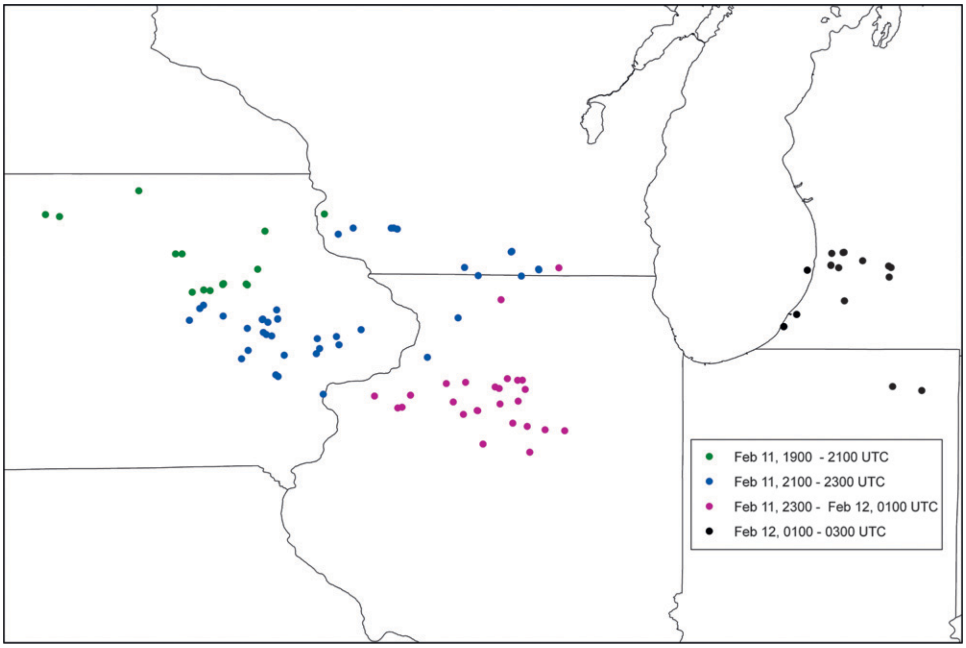

FIG. 14. A CG lightning flash summary plotted from 1900 UTC 11 Feb through 0300 UTC 12 Feb 2003 using flash data from the NLDN.

face in excess of the severe criterion. As such, our analysis has also demonstrated that a severe thunderstorm warning was the best response to an event of this nature.

Since the character of this event was unique compared to squall lines more commonly associated with those producing severe convective winds, but also did not quite fit the mesoscale or synoptic-scale paradigms, the forecaster had to judge which vehicle (SVR or HWW) would illicit the most appropriate response to the hazard. In this case, the forecaster selected the SVR. There is much logic to this choice. The fast-moving nature of the line, the rapid onset and decrease of severe winds, and the spatial scale affected most closely resembles the impact from a severe warm season squall line rather than either a high wind event due to the synoptic-scale pressure gradient or a mesoscale wake low event. Since the convective line in this case was producing lightning, albeit in limited amounts, these were indeed thunderstorms. The main difference from the warm season counterpart would have been the snow and blowing snow creating near-zero visibilities and travel impacts, and this could easily have been mentioned in the text of the SVR.

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REFERENCES

Barnes, S. L., 1973: Mesoscale objective map analysis using weighted time-series observations. NOAA Tech. Memo. ERL NSSL-62, National Severe Storms Laboratory, Norman, OK, 60 pp.

——, F. Caracena, and A. Marroquin, 1996: Extracting synoptic-scale diagnostic information from mesoscale models: The Eta Model, gravity waves, and quasigeostrophic diagnostics. *Bull. Amer. Meteor. Soc.,* **77,** 519–528.

Benjamin, S. G., G. A. Grell, J. M. Brown, T. G. Smirnova, and R. Bleck, 2004a: Mesoscale weather prediction with the RUC hybrid isentropic–terrain-following coordinate model. *Mon. Wea. Rev.,* **132,** 473–494.

——, and Coauthors, 2004b: An hourly assimilation–forecast cycle: The RUC. *Mon. Wea. Rev.,* **132,** 495–518.

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

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Corfidi, S. F., S. J. Corfidi, D. A. Imy, and A. L. Logan, 2006: A preliminary study of severe wind-producing MCSs in environments of limited moisture. *Wea. Forecasting,* **21,** 715–734.

Cummins, K. L., M. J. Murphy, E. A. Bardo, W. L. Hiscox, R. B. Pyle, and A. E. Pifer, 1998: A combined TOA/MDF technology upgrade of the U.S. National Lightning Detection Network. *J. Geophys. Res.,* **103,** 9035–9044.

Holle, R. L., and A. I. Watson, 1996: Lightning during two central U. S. winter precipitation events. *Wea. Forecasting,* **11,** 599–614.

——, J. V. Cortinas Jr., and C. C. Robbins, 1998: Winter thunderstorms in the United States. Preprints, *16th Conf. on Weather Analysis and Forecasting,* Phoenix, AZ, Amer. Meteor. Soc., 298–300.

Houze, R. A., Jr., S. A. Rutledge, M. I. Biggerstaff, and B. F. Smull, 1989: Interpretation of Doppler weather radar displays of midlatitude mesoscale convective systems. *Bull. Amer. Meteor. Soc.,* **70,** 608–619.

Kocin, P. J., L. W. Uccellini, J. W. Zack, and M. L. Kaplan, 1985: A mesoscale numerical forecast of an intensive convective snowburst along the East Coast. *Bull. Amer. Meteor. Soc.,* **66,** 1412–1424.

Market, P. S., C. E. Halcomb, and R. L. Ebert, 2002: A climatology of thundersnow events over the contiguous United States. *Wea. Forecasting,* **17,** 1290–1295.

——, and Coauthors, 2006: Proximity soundings of thundersnow in the central United States. *J. Geophys. Res.,* **111,** D19208, doi:10.1029/2006JD007061.

Moore, J. T., and G. E. VanKnowe, 1992: The effect on jet-streak curvature on kinematic fields. *Mon. Wea. Rev.,* **120,** 2429–2441.

Parker, M. D., and R. H. Johnson, 2000: Organizational modes of midlatitude mesoscale convective systems. *Mon. Wea. Rev.,* **128,** 3413–3436.

Rakov, V. A., and M. A. Uman, 2003: *Lightning: Physics and Effects.* Cambridge University Press, 687 pp.

Rasmussen, E. N., and S. A. Rutledge, 1993: Evolution of quasi-two-dimensional squall lines. Part I: Kinematic and reflectivity structure. *J. Atmos. Sci.,* **50,** 2584–2606.

Rose, S. R., P. V. Hobbs, J. D. Locatelli, and M. T. Stoelinga, 2002: Use of a mesoscale model to forecast severe weather associated with a cold front aloft. *Wea. Forecasting,* **17,** 755–773.

Schneider, R. S., 1990: Large-amplitude mesoscale wave disturbances within the intense Midwest extratropical cyclone of 15 December 1987. *Wea. Forecasting,* **5,** 533–558.

Smull, B. F., and R. A. Houze Jr., 1987: Rear inflow in squall lines with trailing stratiform precipitation. *Mon. Wea. Rev.,* **115,** 2869–2889.

Takeuti, T., M. Nakano, M. Brook, D. J. Raymond, and P. Krehbiel, 1978: The anomalous winter thunderstorms of the Hokuriku coast. *J. Geophys. Res.,* **83,** 2385–2394.

Tam, F., 1982: Snowrollers. *Weatherwise,* **35,** 276–277.

Taniguchi, T., C. Magona, and T. Endoh, 1982: Charge distribution in active winter clouds. *Res. Lett. Atmos. Electricity,* **2,** 35–38.

van den Broeke, M. S., D. M. Schultz, R. H. Johns, J. S. Evans, and J. E. Hales, 2005: Cloud-to- ground lightning production in strongly forced, low-instability convective lines associated with damaging wind. *Wea. Forecasting,* **20,** 517–530.

Weisman, M. L., 1993: The genesis of severe, long-lived bow echoes. *J. Atmos. Sci.,* **50,** 645–670.

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