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Strong Tornadoes in a Hybrid Cold-Core Environment:
The Northwestern Minnesota Case of 6 June 2008

Chauncy J. Schultz
National Weather Service, Grand Forks, North Dakota

1. Introduction

Six tornadoes occurred near the Park Rapids (KPKD) area of northwestern Minnesota during the mid-morning hours of 6 June 2008 (Fig. 1). Two of the tornadoes were strong, causing EF2 and EF3 damage. The tornadoes were associated with a closed, cold-core upper-level low. As noted by Davies and Guyer (2004), these synoptic situations are normally associated with convective available potential energy (CAPE) less than 1000 J kg^{-1} and weaker vertical shear than most significant tornado events. This makes their prediction especially challenging. The 6 June 2008 tornadoes were particularly difficult to anticipate due to their low-topped nature and distance from the WSR-88D located near Mayville, North Dakota (KMVX; Fig. 2). The lowest (0.5°) elevation slice near the location of the tornadoes is approximately 100 nautical miles from the radar and an estimated 11,500 feet above ground level (AGL). This distance along with the small size of the parent supercells made detection of low-level mesocyclones difficult.

The purpose of this study is to investigate the synoptic and mesoscale environment present during the climatologically atypical time at which the tornadoes occurred in this case. In addition, the project will analyze the radar data from KMVX in order to see what – if any – indication there may have been of the tornadoes with the low-topped storms.

Corresponding author address: Chauncy Schultz, National Weather Service, North Platte, NE, 5250 E. Lee Bird Drive, North Platte, NE 69101

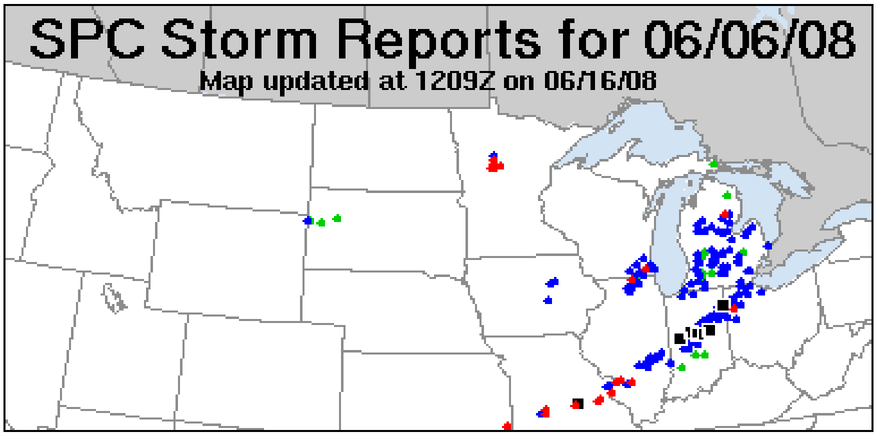

Fig. 1. Preliminary Storm Prediction Center storm reports for 6 June 2008. Tornado reports are in red, hail reports are green, and severe wind is in blue and black.

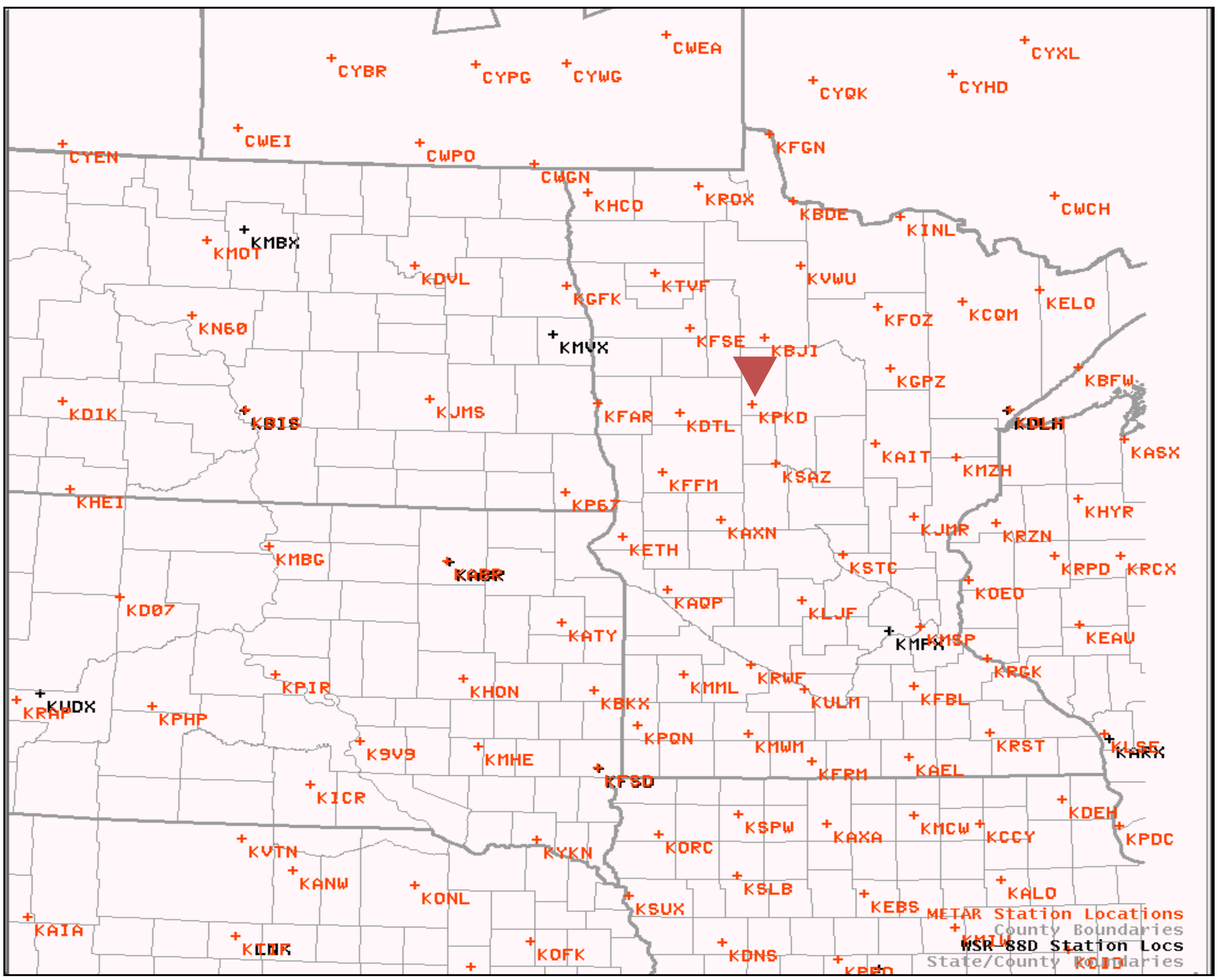

Fig. 2. Regional map showing the location of KMVX and other WSR-88Ds (in black) and KPKD and other Automated Surface Observing Stations (ASOSs; in red). Location of the EF3 tornado at 1437 UTC is denoted by a red inverted triangle.

2. Tornado Reports

The first tornado of the June 6 2008 event formed in Wadena County, 1.6 km (1 mile) east of Menahga, Minnesota. The tornado tracked northeast for 22.5 km (14 miles), crossed into Hubbard County by 1420 UTC, and dissipated 4.8 km (3 miles) northeast of KPKD by 1434 UTC. The tornado injured one person, destroyed eight large turkey barns, and damaged several homes along with hundreds of acres of forest. The tornado was rated an EF2 with peak winds of 58 m s^{-1} (130 mph). The second strong tornado of the event began at 1437 UTC 6.3 km (3.9 miles) west-northwest of Dorset, Minnesota. This tornado moved northeast across Pickerel Lake to 1.6 km northwest of Emmaville, Minnesota by 1447 UTC (19.3 km or 12.0 miles north-northeast of KPKD). The tornado had a path length of 11.3 km (7 miles). Two homes were completely destroyed and several were damaged at Pickerel Lake (Fig. 3). The tornado was rated an EF3 with peak winds of 72 m s^{-1} (160 mph). The track of the two strong tornadoes is shown in Fig. 4.

Fig. 3. View of damage at Pickerel Lake, Minnesota.

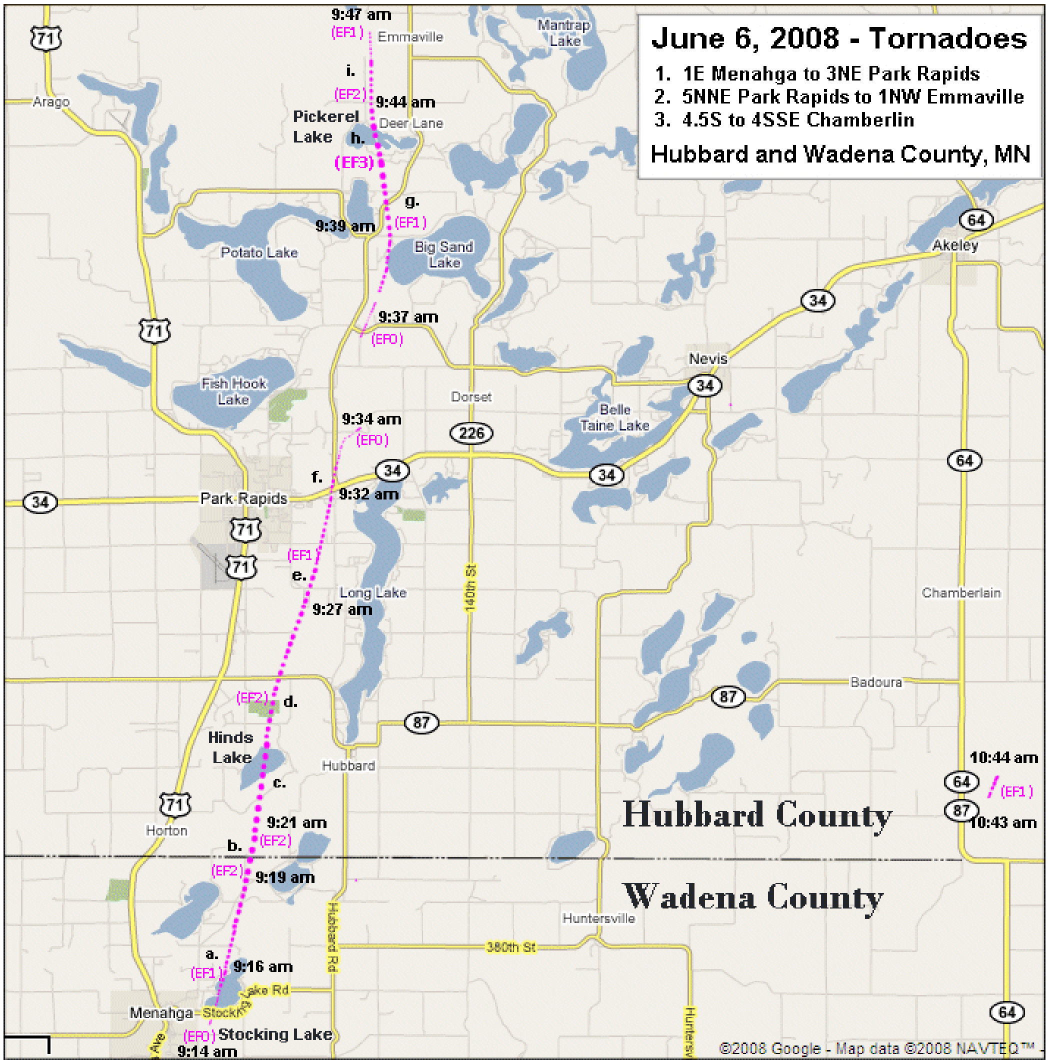

Fig. 4. Map of significant tornadoes in Hubbard and far northern Wadena Counties, Minnesota (all times are Central Daylight Time; UTC – 6 hours).

Three other tornadoes were reported in Hubbard County with ratings of EF0 and EF1. The same supercell responsible for the strong tornadoes produced two additional tornadoes between 1442 and 1503 UTC, one of which was ongoing at the time of the EF3 damage at Pickerel Lake. A third tornado, associated with a separate supercell, took place in southeastern Hubbard County near 1543 UTC. Total damage from the tornadoes was just over 5.7 million dollars.

2. Tornadoes in Close Proximity to Closed, Cold-Core Upper-Level Lows

Several studies have focused on tornado events that have occurred near closed-core upper-level lows, especially at 500 hPa (e.g., Davies 1993, 2006; Davies and Guyer 2004). Bell and Bosart (1989) defined a closed-core 500-hPa low as at least one closed 30-m contour with temperatures of -10° C or lower at that level. Davies and Guyer (2004) found that tornadoes associated with closed, cold-core upper-level lows occur most often in the spring and fall along surface boundary intersections. Although these events feature relatively small values of CAPE, the instability is usually maximized very near the surface. The concentration of instability in the low levels means that the 100-hPa layer often used in the mean-layer CAPE (MLCAPE) calculation may be too deep to accurately reflect the potential. Guyer and Davies (2006) suggest that with these events the most prudent parcel theory uses a surface-based CAPE (SBCAPE) calculation, or a 50-hPa mean-layer parcel, if MLCAPE is to be used**.** The Guyer and Davies (2006) study found the best discriminators between null cold-core systems and those that produced significant tornadoes to be 0-3-km SBCAPE, 0-1-km vorticity generation parameter (VGP), and 0-1-km energy helicity index (EHI). Again, in these situations the calculations of indices like VGP and EHI are best done using a surface-based parcel.

3. Synoptic Pattern on 6 June 2008

The 1200 UTC 6 June 2008 500-hPa observations indicated a closed low over south-central North Dakota with temperatures as low as -14° C (Fig. 5). This low was part of a larger negatively tilted trough that was lifting northward over the Northern Plains. Twelve-hour height falls of 120 m and a seasonably strong jet streak of 18 to 28 m s^{-1} (35 to 55 knots) were present over northwestern Minnesota at 500 hPa. The left exit region of a 50 m s^{-1} (100 knot) jet streak was present over the region at 250 hPa (Fig. 6). The 700-hPa and 850-hPa isobaric surfaces also displayed closed lows in southeastern North Dakota at 1200 UTC (Figs. 7a and 7b).

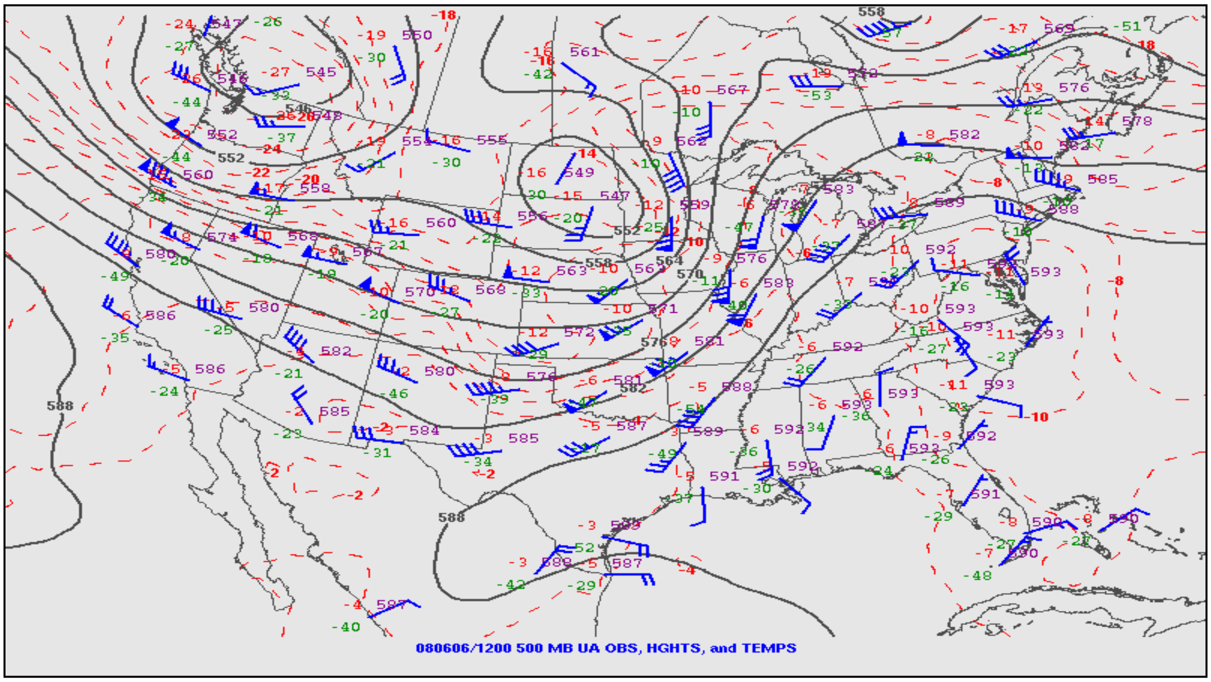

Fig. 5. 500-hPa observations (conventional form) at 1200 UTC 6 June 2008 with isotherms [dashed red contours, contour interval (CI) = 2° C] and height contours (solid grey contours, CI = 60 m).

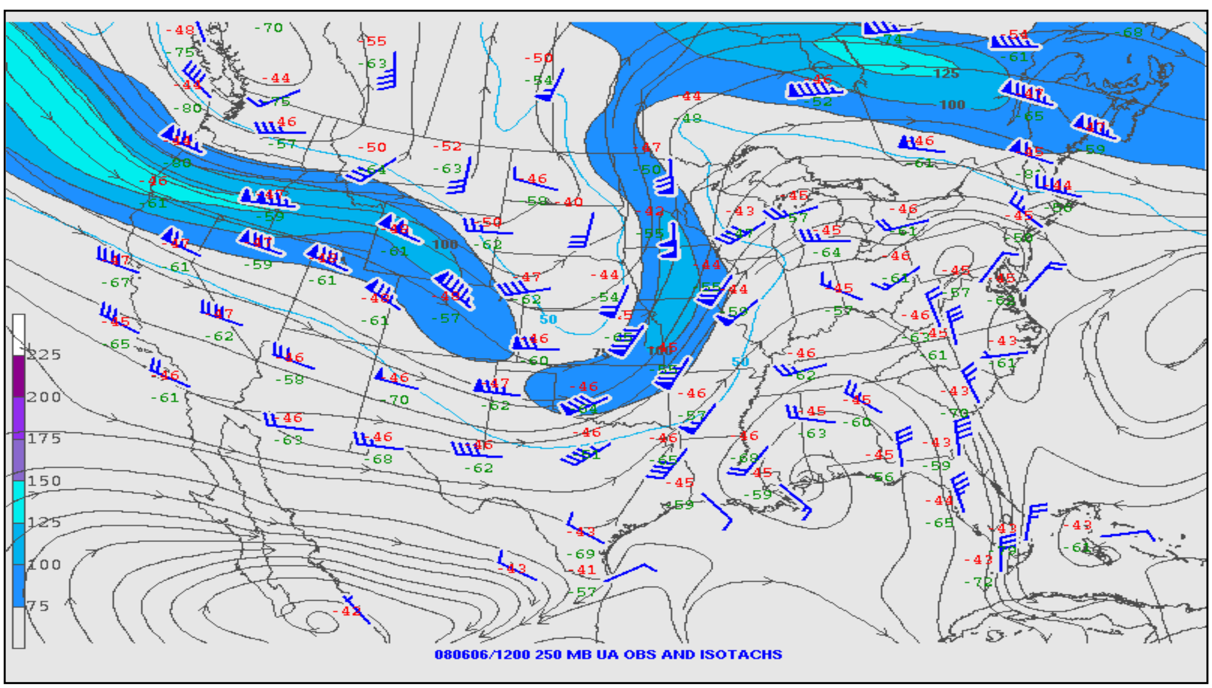

Fig. 6. 250-hPa observations (conventional form) at 1200 UTC 6 June 2008 with streamlines and isotachs (colored, CI = 25 kt).

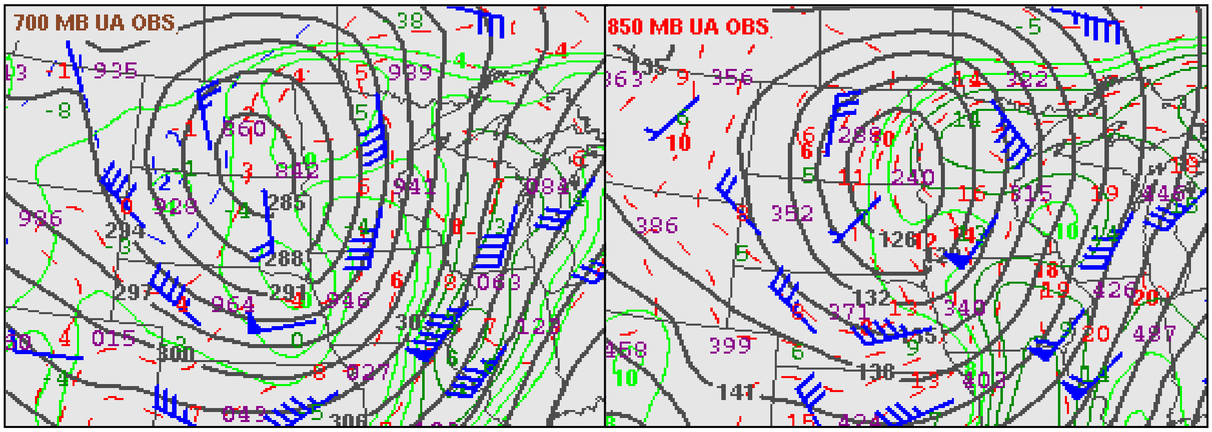

Fig. 7. Observations (conventional form) at 1200 UTC 6 June 2008 for a) 700 hPa with isotherms (dashed red contours, CI = 2° C), isodrosotherms (solid green contours, CI = 2° C), and heights (solid grey contours, CI = 30 m), and b) same as "a," but at 850 hPa.

The Rapid Update Cycle (RUC; Benjamin et al. 2002) 00-hour analyses (Bothwell et al. 2002) indicated that the closed 500-hPa low moved into southeastern North Dakota, to a point approximately 240 km (150 miles) west-southwest of where the tornadoes occurred, between 1200 and 1500 UTC. Meanwhile, a seasonably intense surface low pressure system (~983 hPa) moved from northeastern South Dakota into southeastern North Dakota (Figs. 8 and 9). A surface warm front extending from the low moved northward into west-central Minnesota, approaching Hubbard and Wadena Counties by 1400 UTC. The surface low appeared to undergo occlusion by 1800 UTC. Observations prior to occlusion indicated moderate moisture content in the warm sector of the cyclone with 850-hPa dewpoints of 10 to 12° C and surface dewpoints of 15 to 18° C (60 to 64° F).

In many ways, the synoptic pattern on 6 June 2008 closely resembled that described by Davies (2006) as being favorable for tornadoes near closed, cold-core upper-level lows. The significant tornadoes occurred roughly east-northeast of the closed 500-hPa low, along the surface warm front. Davies (2006) also stated that a thermal ridge would likely increase low-level lapse rates in the local area where the "peak" of the thermal ridge axis meets the edge of the surface moisture axis, since it would enhance the potential for rapid ascent of parcels in the lower troposphere. In this case, the warm sector contains a broad area of temperatures from 18 to 21° C (65 to 70° F), but the passage of the warm front, resultant increase in temperatures, and rapid destabilization influenced the environment in much the same manner as a significant thermal ridge. The surface theta-e ridge and theta-e advection did, in fact, concentrate itself immediately south of the tornadic supercell by 1500 UTC (Fig. 10). Davies (2006) also found that surface dewpoints associated with these events were usually only 10 to 12° C (50 to 54° F) and that mid-level winds were relatively weak close to the 500-hPa lows, contributing to relatively small deep-layer shear vectors. In contrast, the 6 June 2008 case displayed markedly higher low-level moisture levels, and strong wind fields throughout the troposphere. The stronger wind fields and resultant longer-than-typical wind shear vectors (which will be discussed further in Section 4) may have been one contributing factor to the strength of the tornadoes.

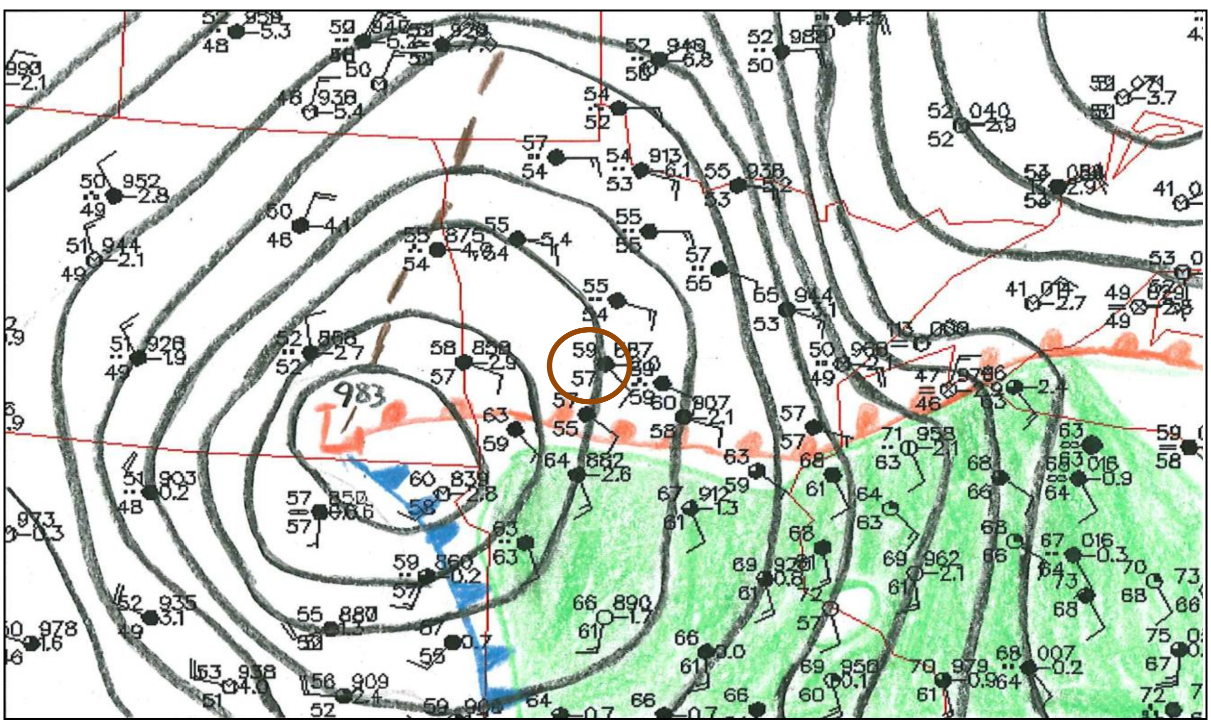

Fig. 8. Surface map at 1200 UTC 6 June 2008 with conventional surface observations and frontal analysis, isobars (solid black contours, CI = 2 hPa) and surface dewpoints greater than or equal to 15° C (60° F; green shaded area). Red circle highlights the KPKD observation.

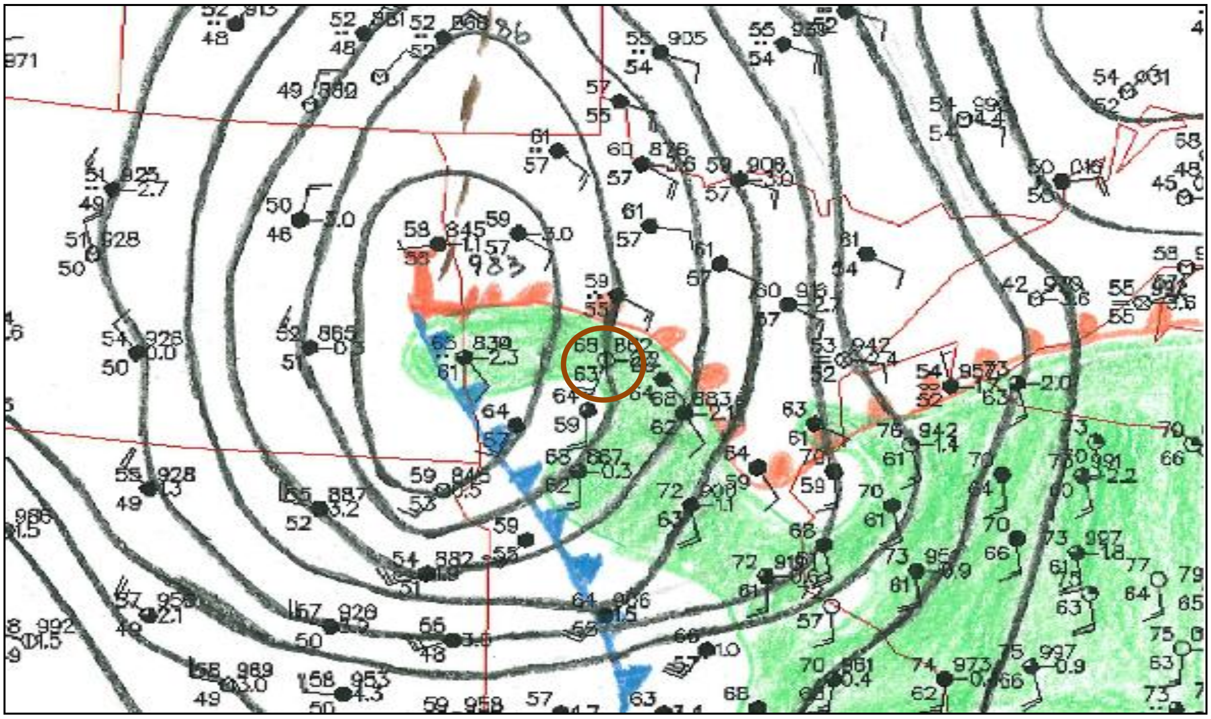

Fig. 9. Same as Fig. 8, except for 1500 UTC 6 June 2008.

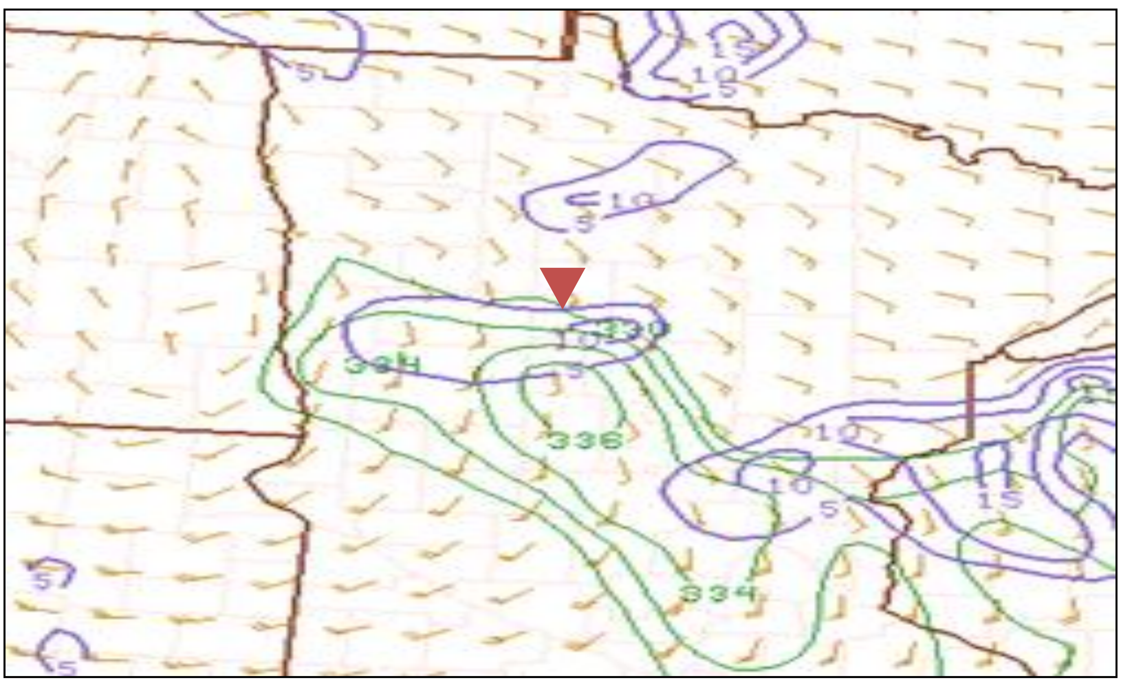

Fig. 10. RUC 00-hour analysis of surface theta-e (solid green contours, K, CI = 2 K), surface theta-e advection (solid blue contours, K h^{-1}, CI = 5 K), and surface wind fields (conventional form) at 1500 UTC 6 June 2008. Location of the EF3 tornado at 1437 UTC is denoted by a red inverted triangle.

4. Near-Storm Environment (NSE)

Radar imagery suggests that convective elements antecedent to the supercell had already developed south of Alexandria, Minnesota (KAXN) by 1200 UTC. This activity developed in the vicinity of the left exit region of the upper jet segment. Visible satellite imagery at 1200 UTC indicated a narrow "clear slot" in southwestern Minnesota. However, by 1400 UTC only small breaks in the clouds were observed either ahead or in the wake of the surface warm front (Fig. 11). This differs from other closed, cold-core upper-level low cases, which often have a much more substantial "clear slot" and thermal ridge (Davies 2008).

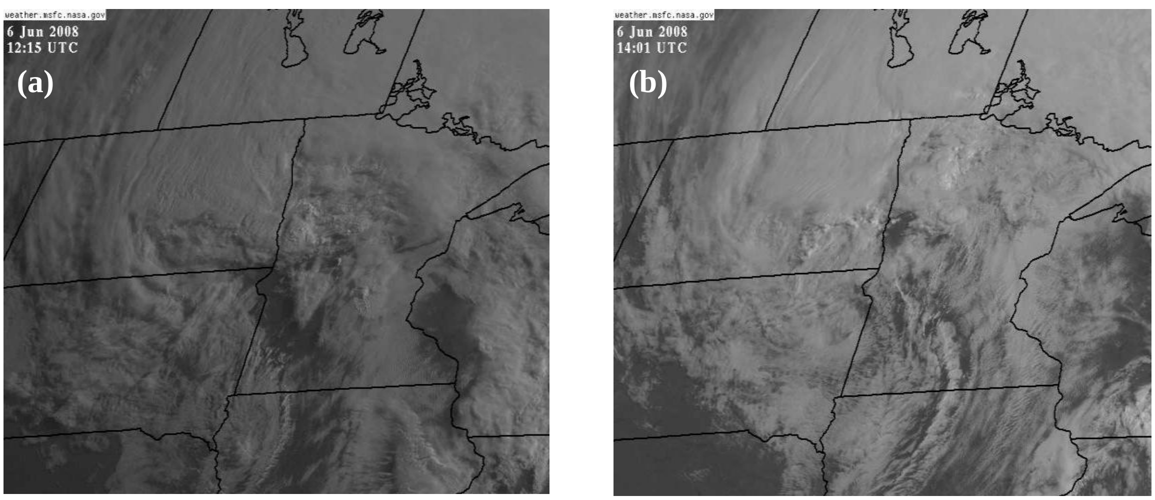

Fig. 11. *Geostationary Operational Environmental Satellite-12* (*GOES-12*) visible satellite imagery at a) 1215 UTC 6 June 2008 and b) 1401 UTC 6 June 2008.

Relatively substantial warming and moistening took place in the vicinity of the surface warm front between 1200 and 1500 UTC. The moist axis, where surface dewpoints were in excess of 60° F, was quite noticeable, though narrow. It was also focused into the vicinity of KPKD and the inflow region of the supercell, where surface winds were on the order of 10 to 13 m s^{-1} (20 to 25 knots), between 1400 and 1500 UTC.

Thompson et al. (2003) found that RUC soundings serve as a representative proximity sounding for supercell environments. RUC soundings at KPKD were utilized to analyze the evolution of the NSE. The soundings suggested that seasonably cold temperatures aloft yielded substantial near-surface instability with only slight warming. Unfortunately, lack of more significant temporal and spatial surface observations makes it difficult to ascertain whether or not the supercell occurred explicitly on either the "warm" or "cool" side of the frontal segment. It is apparent, however, that the significant tornado-producing storm was in close proximity to the boundary. Markowski et al. (1998) discussed the enhanced potential for tornadoes in close proximity to boundaries. Substantial changes in SBCAPE are noted at KPKD between 1400 and 1500 UTC 6 June 2008 due to the passage of the surface warm front. It was during that time that the significant tornadoes took place.

The hourly profiles, adjusted slightly for the surface observations at KPKD and using the virtual temperature correction (Doswell and Rasmussen 1994), resulted in over 700 J kg^{-1} of SBCAPE by 1400 UTC (Fig. 12a). An increase in temperature of 4° F to 68° F, in association with the warm frontal passage, yielded over 1700 J kg^{-1} of SBCAPE by 1500 UTC (Fig. 12b). Much of the instability was near the surface with 0-3 km SBCAPE over 300 J kg^{-1}. Moreover, the surface-based lifted condensation level (LCL) and level of free convection (LFC) were exceptionally low, between 200 and 400 m. There was little if any separation between the LCL and the LFC. This further suggested the potential for rapid updraft acceleration near the surface. The 6 June 2008 statistics were at least as favorable as the median numbers from the Guyer and Davies (2006) climatology; if the 1500 UTC observations best-represent the profile, then the case stood out slightly from a thermodynamic standpoint. Plan-view RUC data valid at 1400 UTC suggest KPKD was on the northern fringe of a narrow but substantial axis of SBCAPE

(Fig. 13). However, the surface dewpoints in the analysis were slightly lower than reality, so the plan-view data did not capture the degree of buoyancy as well as the modified soundings, which also had the virtual temperature correction applied.

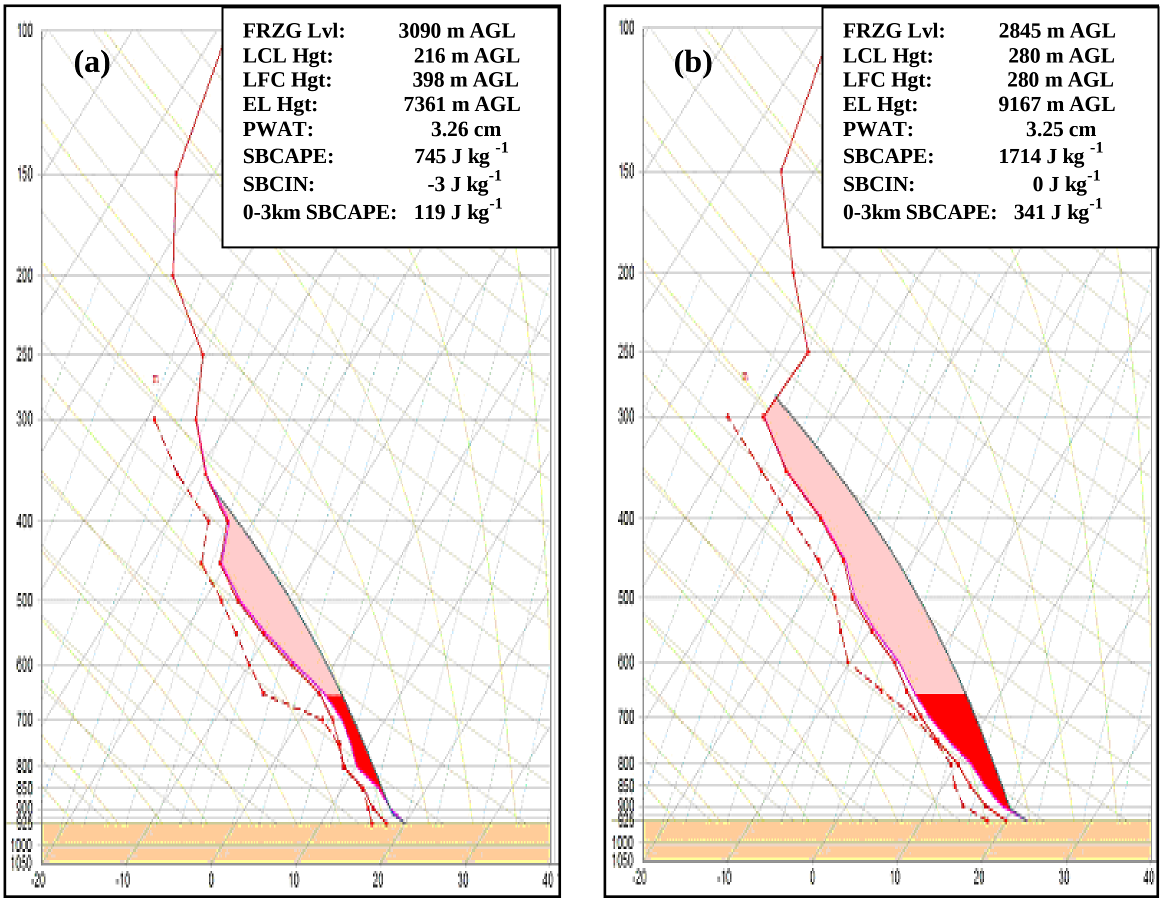

Fig. 12. Skew T–log P diagrams of RUC 0-h analyses at KPKD for a) 1400 UTC 6 June 2008 and b) 1500 UTC 6 June 2008. Solid red line is the environmental temperature profile, red dashed line is the environmental dewpoint, and solid pink line is the virtual temperature profile. SBCAPE is shaded red. Dark red shaded area represents the 0-3 km SBCAPE. Temperatures and dewpoints are in °C and pressure is in hPa.

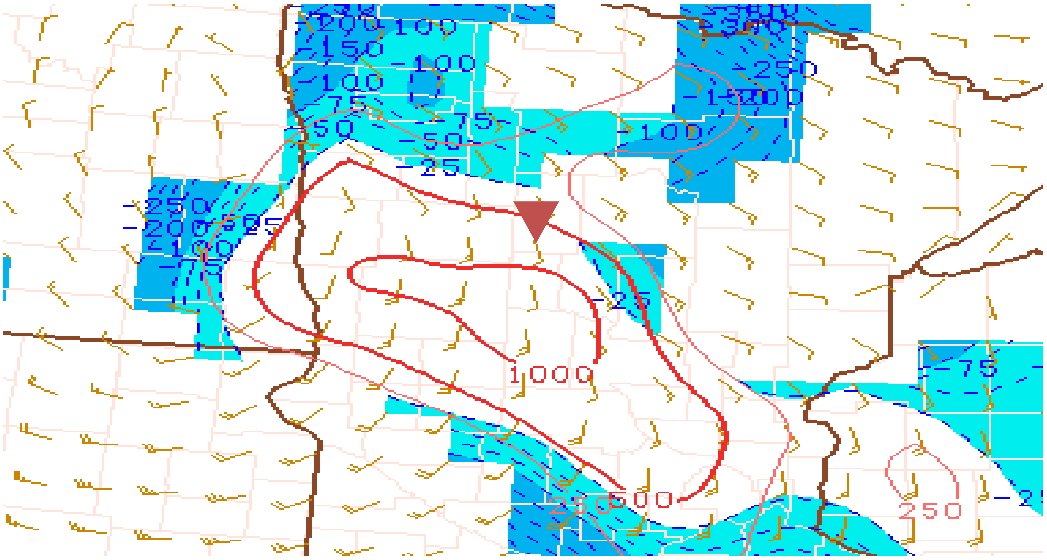

Fig. 13. Same as Fig. 10 but for SBCAPE (red contour, CI = 500 J kg^{-1}) and SBCIN (blue dashed contour and shaded area, CI = 50 J kg^{-1}).

The strong and veering wind fields in the vicinity of the warm front contributed to substantial wind shear through a deep layer, with 0–6-km bulk wind shear on the order of 50 knots. The hodographs taken from the RUC soundings were strongly curved in the lowest 2 km, which favors cyclonic rotation in supercells (Rotunno and Klemp 1982).

The bulk 0–1-km wind shear magnitude at KPKD was over 30 knots. The directional shear in this layer was on the order of 50°. In addition, the 0–1-km storm-relative helicity (SRH) ascertained from the RUC analysis was over 300 m^2 s^{-2} (Fig. 14). From a kinematic standpoint, this case stands out from others. A unique combination of strong low-level buoyancy, and shear profiles similar to those observed with more typical tornadic supercells, may have contributed to the strength and long path length of the EF3 tornado. This combination of environmental characteristics was captured by the 0-1 km EHI at KPKD, which was over 2 (not shown).

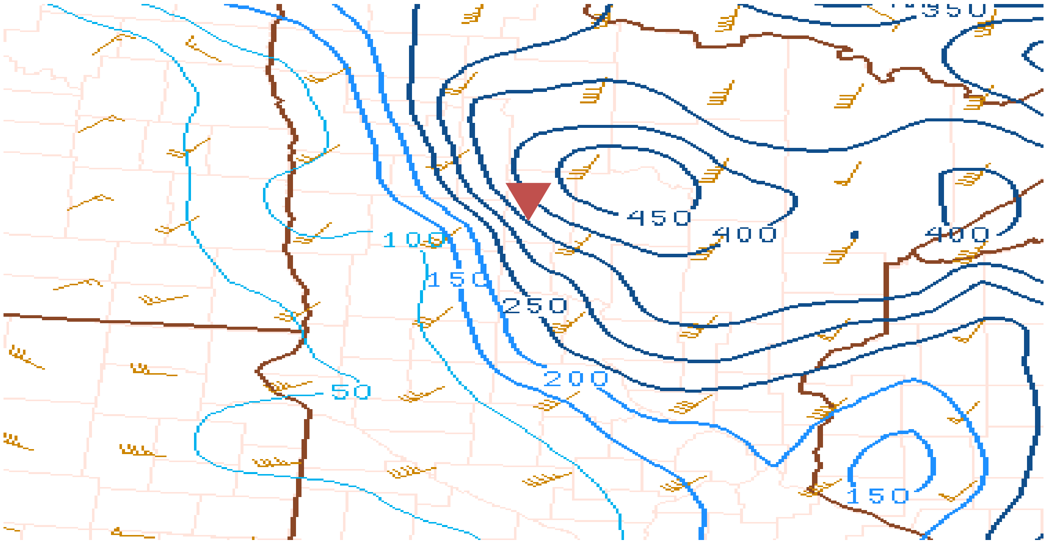

Fig. 14. Same as Fig. 10 but for 0-1 km storm-relative helicity (contour, CI = 50 m^2 s^{-2}) and storm motion vectors (conventional form).

It is important to consider the near-storm environment that was present after the last tornado in this event, since additional, but non-tornadic, storms occurred through early afternoon. The 1800 UTC RUC analysis sounding taken at Thief River Falls, Minnesota (KTVF), will be used to better understand the reason the storms did not produce additional tornadoes. The 1800 UTC surface observations at KTVF were similar to those found ahead of the warm frontal boundary all morning as it lifted northward, including at KPKD (i.e., temperatures between 63 and 68° F and dewpoints from 59 to 64° F). The RUC analysis sounding (Fig. 15) accurately portrayed the surface conditions. It is apparent based on this sounding that a shallow surface-based inversion existed and that relatively smaller values of 0-3 km and total SBCAPE (~200 and 900 J kg^{-1}, respectively) were present compared to the tornadic sounding taken earlier at KPKD. Another sounding taken at 1800 UTC from Bemidji, Minnesota (KBJI; some 120 km southeast of KTVF) reveals a similar stable near-surface layer (not shown). In addition, the 0–1-km bulk wind shear decreased to 20 knots and the 0–1-km SRH diminished to near 125 m^2 s^{-2}.

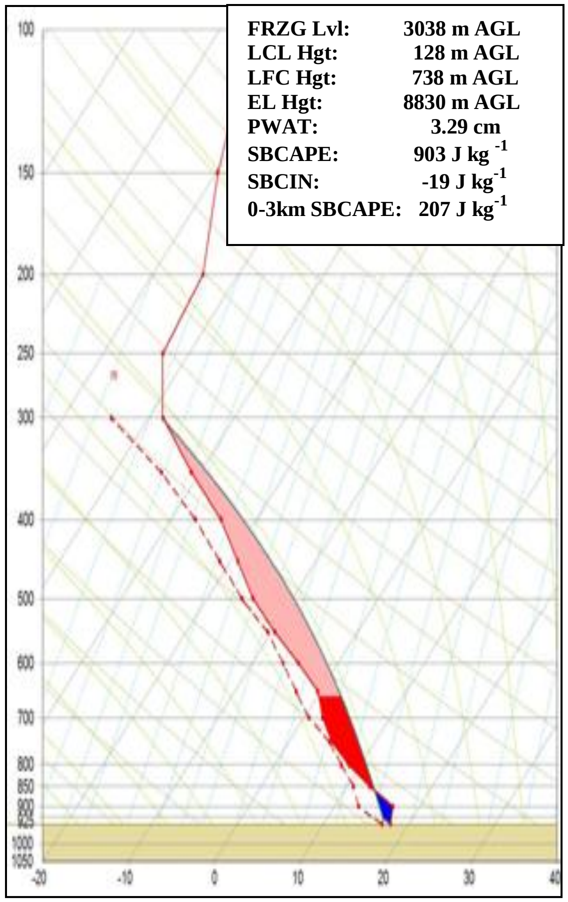

Fig. 15. As in Fig. 12, but for Thief River Falls, MN, at 1800 UTC 6 June 2008. Blue shaded area represents SBCIN (J kg $^{-1}$).

Soundings taken post-1800 UTC at KTVF and KBJI revealed a further decrease in tornado-likelihood, unlike the time-series of soundings taken earlier at KPKD. It appears that the overlap of favorable kinematic and thermodynamic properties in this case was short both temporally and spatially. The change in overall environment may have been induced at least in part by adjustments in the mass fields (such as winds and temperatures aloft) in response to the occlusion that the parent cyclone underwent.

5. Radar Observations

Due to the distance from the radar and resultant beam width and elevation, no manual or algorithm-defined tornadic vortex signatures (TVSs) were present in this case. The low-altitude storms did not exhibit much, if any, gate-to-gate shear, even at the 0.5° KMVX elevation angle. Maximum inbound and outbound storm-relative motion was only near 10 m s^{-1} (20 knots). However, the KMVX WSR-88D did sample the reflectivity structure associated with the low-topped supercells present in this event. The reflectivity values with the storms increased significantly as early as 1300 UTC, nearly 80 km (50 miles) southwest of KPKD. Although the strength of the storms oscillated somewhat through 1400 UTC, the maximum reflectivity maintained itself just over 50 dBZ at the 0.5° elevation angle (around 11,500 feet AGL). The reflectivity dropped below 30 dBZ at 1.3°, or just over 20,000 feet AGL. The most notable change in character occurred near the time of the first tornado at 1414 UTC, when two distinct reflectivity cores develop in the convection (Fig. 16). The two mini-supercells tracked north-northeast before weakening around 1500 UTC. Although distinct reflectivity gradients existed on the inflow side of the cells, no notable appendages or hooks appeared.

The most intense reflectivity signatures were associated with the easternmost supercell, which moved near the communities of Hubbard and Dorset. This cell maintained its dominant reflectivity core the longest, with maximum values near 60 dBZ. This storm did not produce a tornado. Interestingly, the EF3 tornado damage occurred only after the reflectivity structure of the western supercell had begun to wane. Radar imagery suggests maximum 0.5° reflectivity of 40 dBZ was present at 1442 UTC, two minutes prior to the damage at Pickerel Lake (Fig. 17).

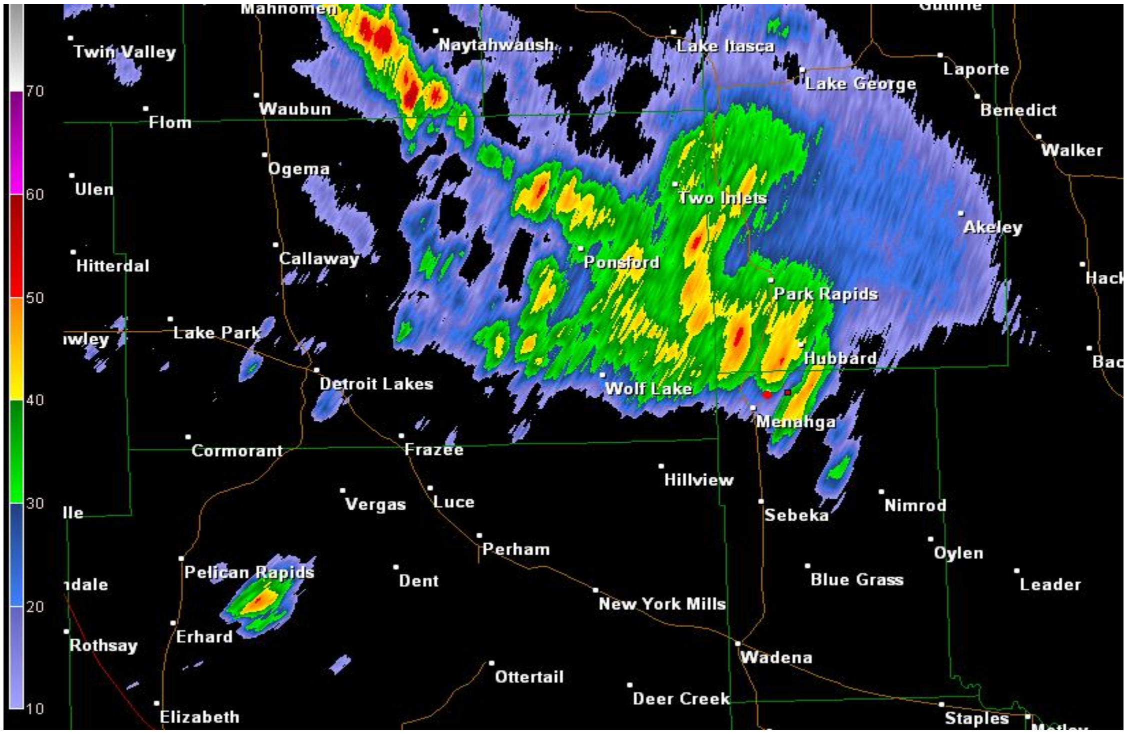

Fig. 16. KMVX 0.5° elevation reflectivity (dBZ) at 1414 UTC 6 June 2008. Tornado paths are represented by red dots.

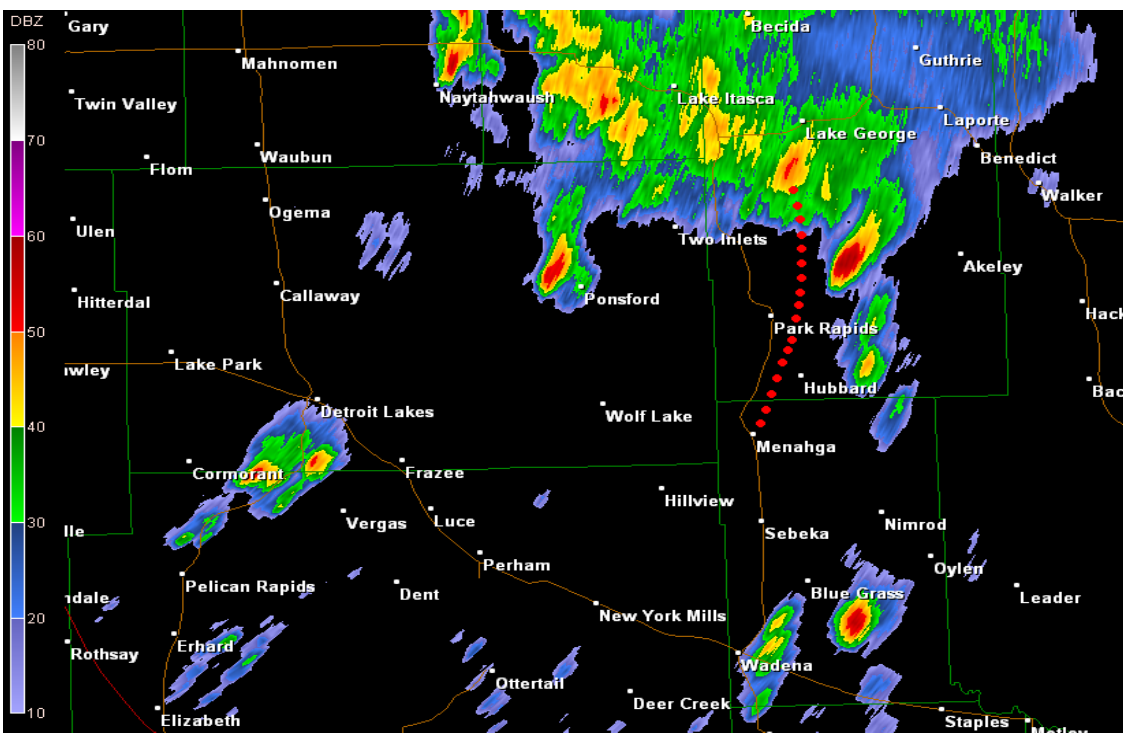

Fig. 17. Same as for Fig. 16 but for 1442 UTC 6 June 2008.

The storms' proximity to the nearest WSR-88D limited the value of the reflectivity and velocity data; identifying possible tornadic activity was difficult at best using these traditional data. One question, then, is what other radar tools are available to help in these situations. Spectrum width provides a measure of the variability of velocity estimates within a sample volume. Values are greater in areas of turbulent flow, such as in the case of mesocyclones. Herald and Drozd (2001) found spectrum width values greater than 8 m s^{-1} (16 knots) to be potential indicators of tornadic circulations, when used in concert with other radar imagery. Buller and Mentzer (1998) examined a case where spectrum width correctly identified the location of a weak tornado, and pointed out that continuity in spectrum width values is crucial when using them as a warning tool, given their potentially noisy signal.

The spectrum width from KMVX indicated a brief, rapid increase in value to 13 m s^{-1} (26 knots) northeast of Parkers Prairie, Minnesota, in southeastern Otter Tail County (~80 km or 50 miles southwest of KPKD) at 1314 UTC. Although collocated with a rapid increase in reflectivity, the high spectrum width value only lasted for one volume scan. Between 1318 and 1328 UTC, the spectrum width was 6 m s^{-1} (12 knots) or less. However, from 1328 through 1501 UTC, the mini-supercell had spectrum width greater than or equal to 9 m s^{-1} (18 knots) associated with the main reflectivity core. At times, the maximum spectrum width exceeded 10 m s^{-1} (20 knots). In fact, the maximum spectrum width value associated with the cell's life cycle (12 m s^{-1} or 23 knots) was noted at 1437 UTC, just south of Emmaville and prior to the EF3 tornado damage (Fig.18). At the same time, the eastern mini-supercell displayed spectrum width of 8 m s^{-1} or less with its primary reflectivity core.

Although the eastern storm did yield spectrum width greater than 8 m s^{-1} at times during its life cycle, the spikes were not as consistent in time or with respect to the reflectivity core.

Moreover, the maxima occurred in close proximity to range-folded data, which lowered confidence in its value. The spectrum width in this case may have indicated the tornado potential, despite the storm's low-topped nature and distance from the radar. Additional research should seek to quantify the potential use of spectrum width in these cases.

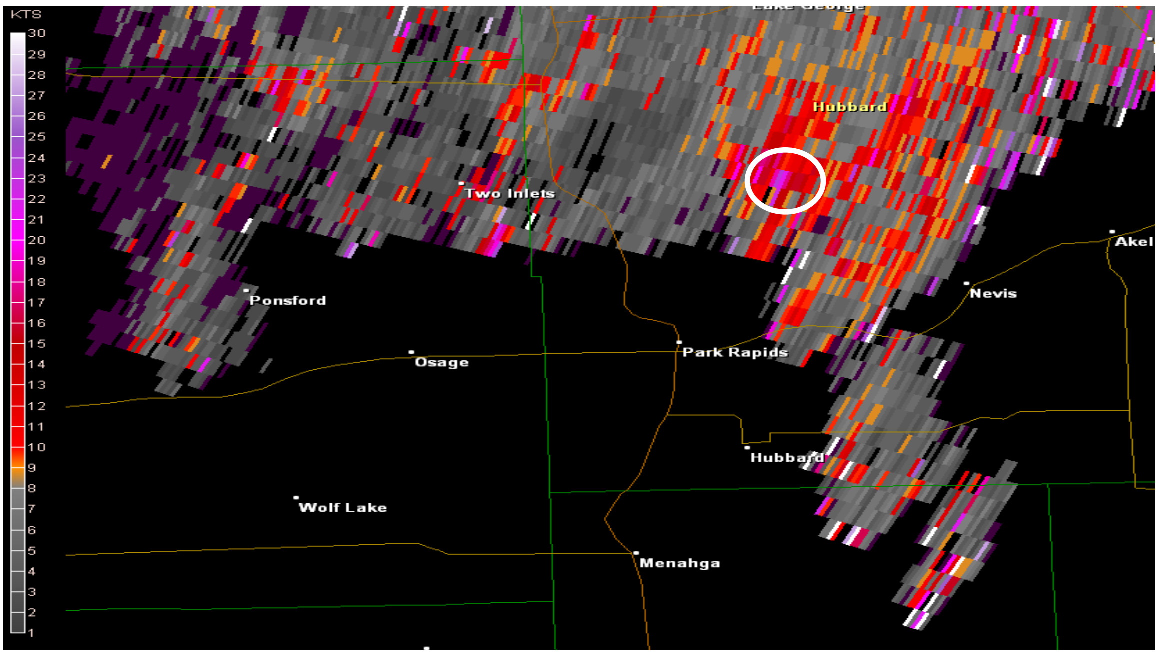

Fig. 18. KMVX 0.5° spectrum width (kt) at 1437 UTC 06 June 2008. White circle highlights spectrum width maxima associated with the tornadic supercell.

6. Summary and Conclusions

The northwestern Minnesota tornadoes of 6 June 2008 occurred in close proximity to a closed, cold-core upper-level low. In many ways, the environment was similar to other events of this nature: with spatially narrow but strong low-level SBCAPE downstream of the 500-hPa low and tornadogenesis near the intersection of surface boundaries. However, this case appeared to be a hybrid, since the tornadoes occurred far enough removed from the upper-level low to be influenced by strong low- and deep-layer wind shear, which was atypically strong compared to similar events. Low-level moisture was also higher than often observed with other cold-core cases. The strength and longevity of the EF3 tornado in this case likely owed its origins to the enhanced wind shear and strong low-level buoyancy.

The utility of radar data was very limited in this case; spotters provided the most important signals for warning decisions. However, the collocation of high spectrum width values greater than 8 m s^{-1} with distinct reflectivity cores of the mini-supercells identified a probable tornado potential. A non-tornadic storm in a similar environment as the EF3-producing supercell had stronger reflectivity signatures, but smaller and less temporally continuous spectrum width values. This could confirm some utility of spectrum width in identifying tornado potential in low-topped tornado events.

This case serves as a reminder that forecasters should be aware of the potential for tornadoes in the vicinity of closed, cold-core upper-level lows. The tornado potential is not relegated to climatologically favorable late afternoon and evening hours in these cases, nor is it necessarily reduced when a substantial "clear slot" is not apparent. Careful monitoring of the NSE and its evolution temporally and spatially can be helpful in identifying tornado potential in these situations.

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