3.1

OBSERVATIONS OF LOW LEVEL THERMODYNAMIC AND WIND SHEAR PROFILES ON SIGNIFICANT TORNADO DAYS

Daniel J. Miller*
NOAA/National Weather Service/WFO Duluth, MN

1. Introduction

Research since the mid to late 1990s, has contributed to a more robust understanding of meteorological environments supportive of tornadic supercell thunderstorms (e.g., Rasmussen and Blanchard 1998; Evans and Doswell, 2002). Considerable effort has been given to identifying environments on tornado "outbreak" days, when it is common for several long-lived supercells to produce cyclic tornadoes that are often long tracked and intense (e.g., Thompson and Edwards 2000). Research from field experiments and post analysis of many significant tornado (i.e. ≥F2 on the Fujita scale) events indicates that two atmospheric conditions in particular have emerged as being critically important in environments supportive of significant tornadoes. Those two conditions are strong low-level wind shear and moderate to high values of low-level absolute moisture and relative humidity (Markowski and Straka 2000; Markowski et al. 2002; Nordin et al. 2003). This has also been supported by numerical modeling simulations (e.g., Wicker, 1996). All of this suggests, rather strongly, that much of the tornado process, or at least processes related to supercell tornadogenesis and maintenance, seems to happen at the lowest levels of the atmosphere, generally ≤ 1 km AGL.

On several significant tornado days, a curious combination of low level wind shear and thermodynamic profiles has been observed. (For the remainder of this manuscript, "low-level" is assumed to mean within the lowest 1 km AGL.) An example of the thermodynamic profile is presented in Fig. 1, and an example of the wind shear profile is presented in Fig. 2. The observed low-level thermodynamic profile as viewed via a skew-T/log-P diagram (Fig. 1), is characterized by a layer where the mixing ratio decreases with height through roughly the lowest 1 km AGL, a moderate to steep temperature lapse rate, and a surface mixing ratio of at least 15 g/kg.

The observed low-level shear profile visualized via a hodograph (Fig. 2) reveals the presence of large bulk shear vectors both between the surface and 400-500 meters AGL, and the surface and 1 km AGL. In addition, the hodograph trace possesses a kink a few hundred meters AGL, which results in the hodograph taking on a distinctive "sickle" shape.

Careful scrutiny of these profiles, especially when combined with some radar and visual observations of severe storms, pose several important and perhaps troublesome questions regarding some commonly applied operational severe storm forecasting methodologies.

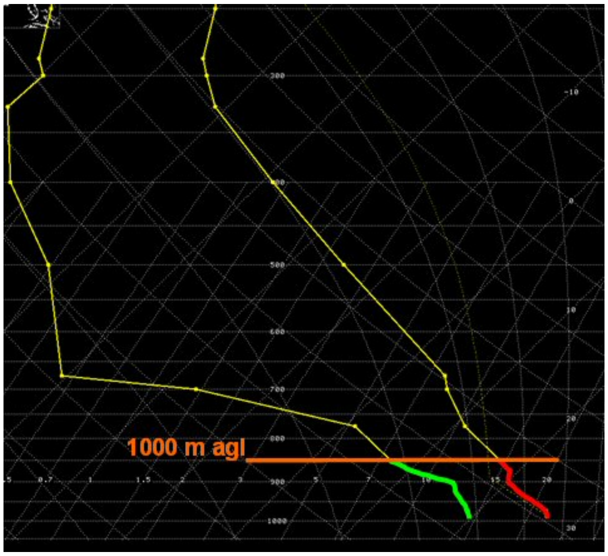

Figure 1. Example skew-T/log-P diagram. The height of 1 km AGL is denoted by the orange line, with the temperature profile (in red) and dewpoint temperature profile (in green) from the surface to 1km AGL also annotated.

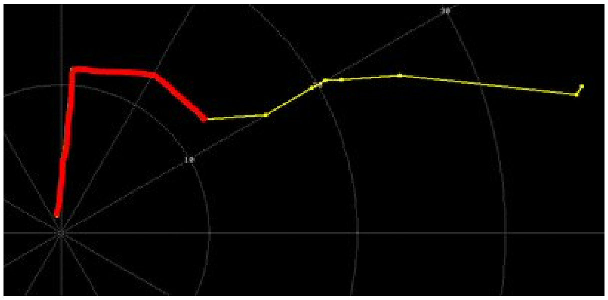

Figure 2. Example hodograph. The hodograph trace in the lowest 1 km AGL is annotated in red. In this example, the kink in the hodograph trace that results in the overall hodograph acquiring a "sickle" shape is approximately 400 m AGL. Hodograph rings are in ms^{-1}.

---

* *Corresponding author address:* Dan Miller, National Weather Service, 5027 Miller Trunk Highway, Duluth, MN 55811 email: dan.j.miller@noaa.gov

The purpose of this paper is two-fold: 1) to document the existence and details of the low-level thermodynamic and wind shear profiles observed in combination on many significant tornado days and 2) to draw attention to several important questions motivated by the existence of these profiles, both within the operational and research communities. With respect to the latter, few conclusions will be drawn, but rather several questions and associated opportunities for further research will be proposed.

2. Dataset of Observed Cases

In this preliminary investigation, fourteen significant tornado days have been identified where soundings and hodographs possessing low-level wind shear and thermodynamic profiles have been observed that are similar to the examples provided in Figs. 1 and 2. A summary of those events is provided in Table 1. Of the fourteen cases, all soundings and hodographs were observed at 0000 UTC, with the exception of 21 February 2005 in the California central valley, which was from 2100 UTC.

Date	Area Affected
5 April 1974	Ohio Valley Region
3 April 1982	Texas/Oklahoma/Arkansas
1 June 1985	**Ohio/Pennsylvania**
1 August 1987	Alberta, Canada
27 April 1991	Kansas/Oklahoma
17 June 1992	Minnesota
20 April 1996	Illinois
30 March 1998	Minnesota
4 May 1999	**Oklahoma**
19 June 2001	Wisconsin
9 May 2003	Oklahoma
30 May 2004	Kansas/Oklahoma
21 February 2005	**California Central Valley**
3 April 2006	Tennessee/SE Missouri

Table 1. Summary of the fourteen dates in the dataset, and the area(s) affected. The dates in **bold** denote events where soundings and hodographs are examined closely in section 3, and illustrated in Figs. 3, 4, and 5. All dates are in UTC time.

Several mean values of various convective and shear parameters for the cases identified in Table 1 are shown in Table 2. Examination of the values in Table 2 reveals that the soundings and hodographs in the dataset produce a combination of values that are generally in excellent agreement with the most recent research findings regarding significant tornado environments. The soundings possess significant instability, and minimal capping, while the near-surface airmass is very humid and contains significant absolute moisture content. Thus, lifting condensation levels (LCL) and the level of free convection (LFC) are both relatively low. In addition, the hodographs reveal the presence of large low-level bulk shear vectors, both from the surface to the height AGL of the kink in the hodograph trace, and from the surface to 1 km AGL. The bottom row in Table 2 reveals that on average, the shear vector magnitude from the surface to the height of the kink in the hodograph is 71% of the magnitude of the surface to 1 km AGL bulk shear vector.

Mean Parameters of the 14 Cases in Table 1	
Surface temperature	77F (25C)
Surface dewpoint	68F (20C)
Surface T/Td spread	7.6F (5C)
Surface relative humidity	68%
CAPE	3445 j/kg
CIN	42 j/kg
LCL height (AGL)	900 m (2792 ft.)
LFC height (AGL)	1628 m (5048 ft.)
Height of hodograph kink (AGL)	418 m (1297 ft.)
Shear vector mag (sfc-kink)	19 kt (9.8 ms^{-1})
Shear vector mag (sfc-1 km AGL)	28 kt (14.4 ms^{-1})
Shear vector magnitude ratio	0.71

Table 2. Mean values of several convective and shear parameters for the fourteen cases identified in Table 1.

Although no formal data set of null cases has yet been collected, considerable anecdotal observations reveal that similar low-level profiles of shear ***or*** thermodynamics are observed with a fair amount of frequency. However, significant tornado episodes appear to be associated when both are present. Therefore, it appears to be the ***superposition*** of these profiles in the lowest 1 km AGL that is of importance to significant tornado events.

3. Examination of Observed Profiles

Three pairs of observed soundings and hodographs from the database will be presented in this section, and examined with close scrutiny. Those cases are 1) 3 May 1999, 2) 31 May 1985 and 3) 21 February 2005.

The observed sounding and hodograph from 0000 UTC 4 May 1999 from Norman, OK is quite representative of many of the soundings and hodographs in the database, and is provided with annotation of several key features in Fig. 3. From the surface to 350 m AGL, the hodograph trace reveals

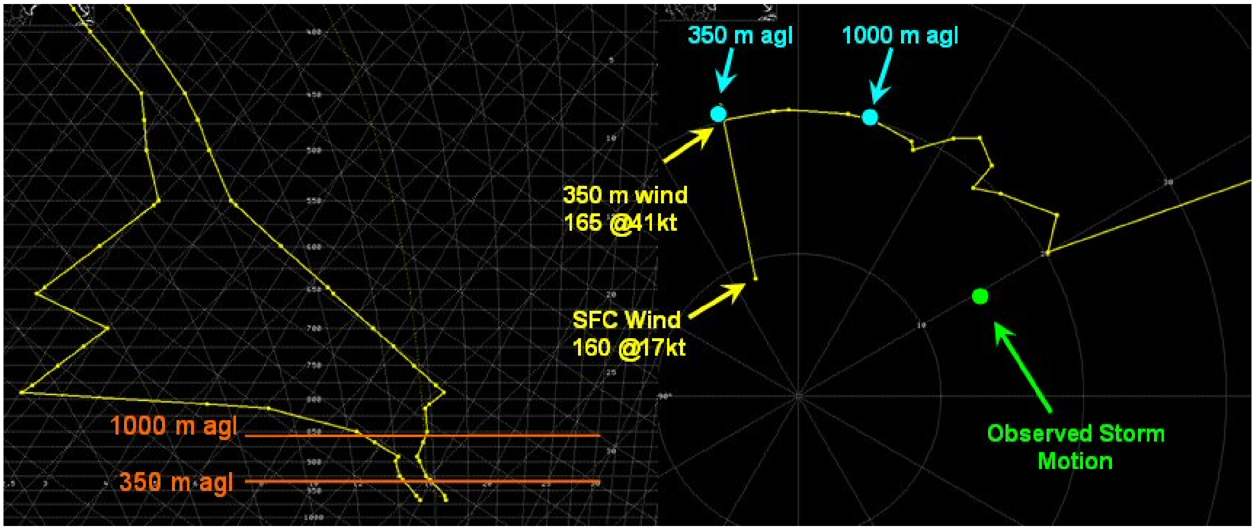

Figure 3. Observed sounding (left) and hodograph (right) from Norman, OK (OUN) at 0000 UTC 4 May 1999. Critical heights and associated observed wind speed/direction on the hodograph trace in meters AGL are annotated, along with observed storm motion. Heights AGL corresponding to the annotated critical levels on the hodograph are in orange at left on the skew-T/log-P diagram.

the presence of very strong shear, with wind direction nearly constant between 160 and 165 degrees, but a rapid increase in speed from 8.7 ms^{-1} (17 kt) at the surface to 21 ms^{-1} (41 kt) at 350 m AGL. Between 350 m AGL and 1 km AGL, wind speed remains fairly constant, near 21 ms^{-1} (41 kt), but substantial directional change is noted, with wind direction from 165 degrees at 350 m AGL, veering to 195 degrees at 1 km AGL. The notable and rather sudden transition from primarily speed, to primarily directional shear in a ground-relative sense results in the distinctive kink in the hodograph trace at 350 m AGL. Corresponding heights of 350 m and 1 km AGL are annotated in orange on the skew-T/log-P diagram to the left, and reveal the presence of an exceptionally moist and humid near-surface airmass. The dewpoint trace also reveals a decrease in mixing ratio with height through the lowest 1 km. Of particular note is that this thermodynamic profile was observed near the time of maximum diurnal heating when the moisture profile in theory should trend toward a constant mixing ratio in the boundary layer. The presence of this mixing ratio profile at this time of day suggests that there is continual replenishment of moisture in the lowest few hundred meters AGL from evapotranspiration, advection, convergence, or some combination thereof. This particular combination of temperature and dewpoint profile also reveals the presence of very low lifting condensation levels (LCL) for a surface parcel.

Fig. 4 shows the observed sounding and hodograph from 0000 UTC 1 June 1985 from Pittsburgh, PA. Annotations on the hodograph and skew-T/log-P diagram are the same as in Fig. 3. The low-level wind shear profile is very similar to that of the 0000 UTC hodograph from 4 May 1999 in Norman, OK, except that the flow through the depth of the troposphere is more veered, resulting in a displacement of the trace to the upper right quadrant of the hodograph. However, when storm motion is considered, the storm-relative flow and shear are quite similar (Markowski and Richardson, 2006). The wind direction is nearly constant through the lowest 400 m AGL (from 195 degrees at the surface, to 200 degrees at 400 m AGL), but speeds rapidly increase from 7.7 ms^{-1} (15 kt) at the surface to 16.4 ms^{-1} (32 kt) at 400 m AGL. The increase in wind speed through the 400 m AGL to 1 km AGL is small (from 16.4 ms^{-1} [32 kt] at 400 m AGL to 20.5 ms^{-1} [40 kt] at 1 km AGL), but stronger than the 4 May 1999 Norman, OK wind profile. However, as in the 4 May 1999 Norman, OK hodograph, wind direction veers by almost 40 degrees (from 200 to 240) in the 400 m AGL to 1 km AGL layer. As in the Norman, OK hodograph, a kink in the trace is evident at 400 m AGL also produces a distinct sickle shape. The low-level thermodynamic profile again reveals an exceptionally moist and humid airmass, with very low LCL heights for surface parcels. Similarly, a decrease in mixing ratio through the lowest 1 km AGL is evident, near the time of maximum surface heating.

The final example sounding and hodograph is from 2100 UTC 21 February 2005 at Sacramento, CA, and is shown in Fig. 5. Since Sacramento is not an upper air observation site, meticulous use of nearby observed soundings, 1-2 hour RUC model forecast soundings (Thompson et al. 2003), and surface observations were used to reconstruct the sounding

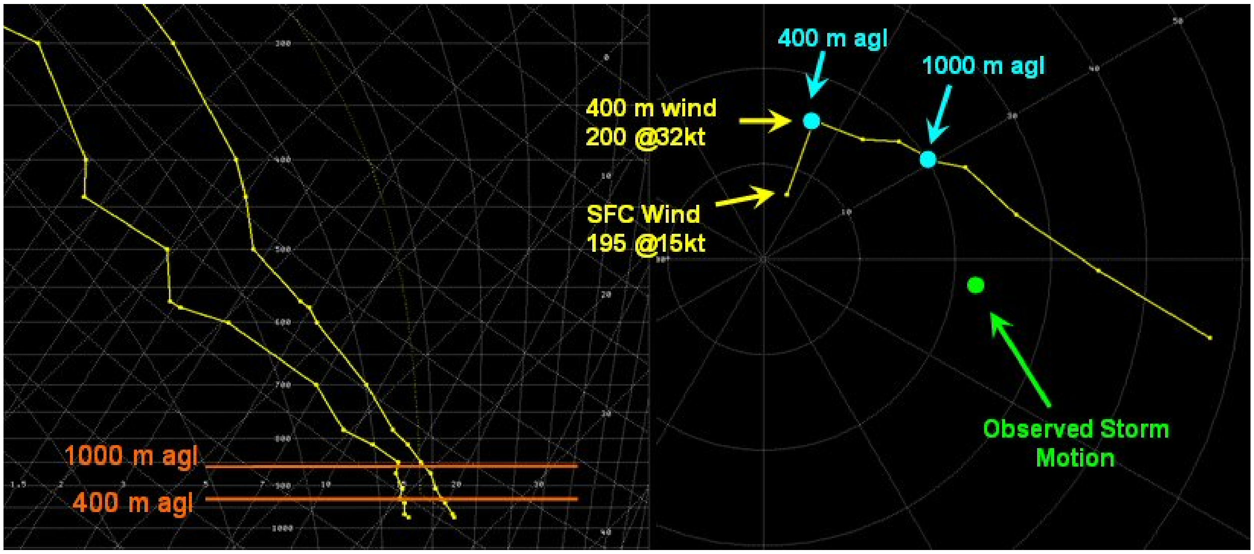

Figure 4. Same as Figure 3, except sounding (left) and hodograph (right) from Pittsburgh, PA (PIT) at 0000 UTC 1 June 1985.

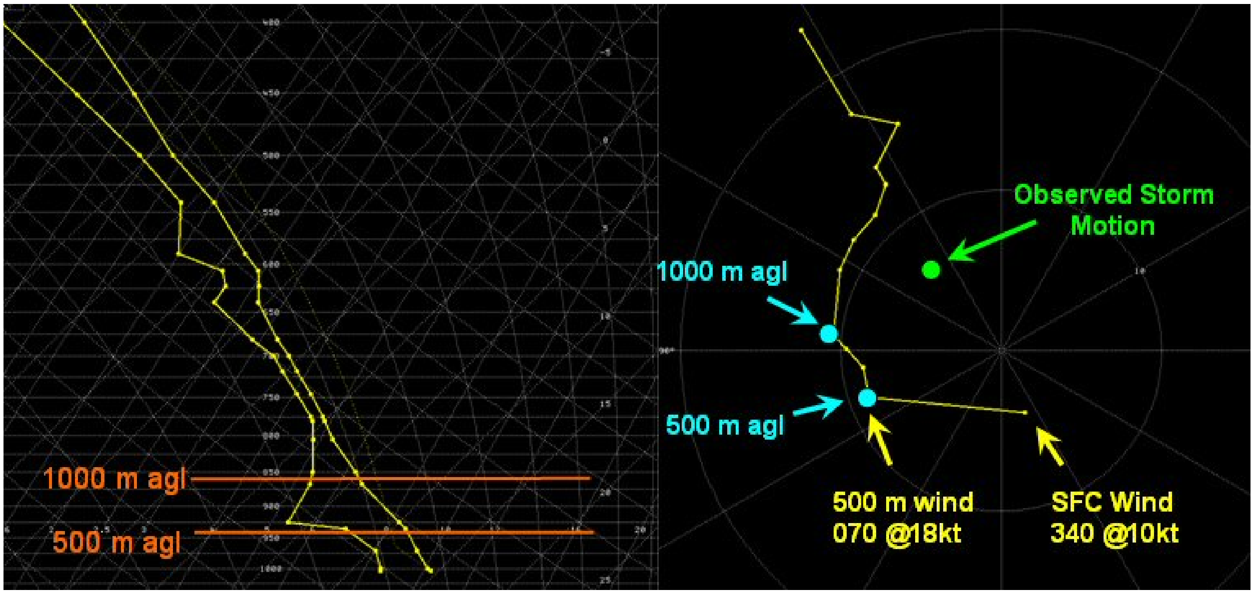

Figure 5. Same as figure 3, except observed sounding (left) and hodograph (right) from Sacramento, CA 2100 UTC 21 February 2005.

for this event. Winds from the KDAX WSR-88D VAD wind profile at 2100 UTC were used to construct the hodograph. The resulting sounding and hodograph were associated with a damage-producing tornado on the northwest side of Sacramento, and considering the time of year and geographic location, this event is considered significant. Examination of the low-level wind shear profile reveals significantly different properties than either the 4 May 1999 0000 UTC Norman, OK or the 1 June 1985 0000 UTC Pittsburgh, PA hodograph when viewed in a ground-relative sense. In addition to the rapid increase in wind speed from the surface to 500 m AGL, there is also significant veering with height in the same layer (from 340 degrees at the surface to 070 degrees at 500 m AGL.) Continued veering with height, along with a slow increase in wind speed is noted in the 500 m AGL to 1 km AGL layer, resulting in the overall hodograph trace still possessing a distinctive sickle shape, similar to the hodographs in Figs. 3 and 4, but displaced to the left part of the hodograph and rotated approximately 90 degrees counter-clockwise. However, when viewed in a storm-relative sense, the flow and shear profiles possess very similar characteristics as the first two examples. The low-level thermodynamic profile is also similar. Although the temperature is considerably cooler, and absolute moisture content is considerably lower, than the Norman, OK and Pittsburgh, PA examples, (as would be expected due to the geographic location and time of year), the low-level airmass is humid, and possesses very low lifted condensation levels for a surface parcel. In addition, a marked decrease in mixing ratio with height rate is once again present at a time close to that of maximum diurnal heating.

4. Important Questions for Investigation, Discussion and Operational Implications

In some ways, the presence of these low-level wind shear and thermodynamic profiles in observed data on significant tornado days is reassuring. Their presence seems to confirm that research over the past 10 years is on the right track. All soundings and hodographs in the dataset possess sufficient instability and deep layer shear for supercells, in combination with a highly sheared low-level airmass that also possesses significant absolute moisture content and high relative humidity*. Most importantly, it appears to be the superposition of this low-level shear and thermodynamic profile that is critically important on many significant tornado days.* However, a careful examination of the details of these profiles, especially when combined with radar and visual observation of supercell storms, motivates numerous important questions. The remainder of this paper will raise those questions in hope of motivating further research and storm-scale model simulations to attain a better understanding of their importance.

Since the cases identified in Table 1 are a collection of anecdotal observational evidence, perhaps the most obvious question posed by the information presented herein is:

Question 1) ***If a systematic search of the historical upper air database was performed, would a superposition of low-level shear and thermodynamic profiles presented here be present in a majority of significant tornado events?***

As a natural progression of question 1), and as was briefly mentioned in section 2:

Question 2) ***Would a systematic search of the historical upper air database also identify null cases, where the superposition of these profiles was present, but not associated with significant tornado events?***

Motivation for numerous other questions also exists based on the existence of these observed low-level shear and thermodynamic profiles, and these become even more important if the answer to question 1) is "yes," and the answer to question 2) is "no:"

Question 3) ***Is there a more effective way to examine low-level wind shear?*** Or perhaps stated differently: We have looked at layers increasingly lower in the atmosphere over the past 10 years, but despite that, are we looking low enough? In most currently applied operational forecasting methodologies for significant tornadoes, surface to 1 km AGL bulk shear vectors, helicity, or some combination thereof is examined. However, the *observed hodographs strongly suggest that there are very important characteristics to the shear that are present in a near-surface layer considerably more shallow than 1 km.* Proving that such features are important and relevant to significant tornado environments is beyond the scope of this paper, but given that the latest research has focused on the lowest levels of the atmosphere, it is prudent to assume that they do. With this in mind, it might be interesting to investigate 1) surface to 500 m AGL bulk shear and/or helicity; 2) a ratio of surface to 500 m AGL shear and/or helicity to surface to 1 km AGL shear and/or helicity and 3) the magnitude of the bulk shear vectors in the surface to 500 m AGL and surface to 1 km AGL layers to the total length of the hodograph through the same layer. It is easily conceivable that answers to any of those questions may improve our ability to isolate environments supportive of strong or violent tornadoes.

Question 4) ***What is the importance of surface heating in the contribution to instability on significant tornado days?*** The observed moisture profiles evident near diurnal max heating time in the soundings in Figs. 1, 3, 4 and 5 reveal that the lowest 1 km of the atmosphere is not well-mixed, despite a rather steep temperature lapse rate. Thus, processes resulting in a continual replenishment of moisture, such as advection, convergence and evapotranspiration are occurring in the lowest few hundred meters AGL. This moisture replenishment results in the very moist and humid near-surface airmass that is noted**. However, when viewed from a holistic sense, the end result is a very moist and humid near-surface airmass, that possesses very low LCL/LFC heights and is minimally capped and highly sheared.**

Question 5) ***Do we need to re-evaluate our use of the terms "elevated" and "surface-based" convection?*** Air flow motion evaluated via some time-lapse video of cloud condensation elements directly below the primary updraft base of some supercells, strongly suggests that in some instances, near-surface air parcels are *not* being ingested into the main updraft. But, storm strength evaluated via radar indicates these storms are tapping significant instability rooted within the boundary layer. Our current understanding of supercell updraft theory indicates that upward directed vertical pressure gradient forces should easily allow or force near-surface parcels to accelerate upward into the main updraft, especially in the presence of thermodynamic profiles as illustrated here. However, visual evidence suggests that sometimes this does not happen. Thus, these storms are not really “elevated,” but they are seemingly not truly “surface-based” either. So, what is an appropriate term to refer to storms that are apparently “boundary-layer” based but not “surface-based,” and more importantly, how do we address this issue operationally?

This leads to the final set of important questions, that deal with many currently calculated and applied “near-storm environment” parameters and indices. These are very difficult to answer, but are of paramount importance to short-term forecast and warning operations:

Question 6) ***What is our true skill in choosing the “correct” parcel to lift in the calculation of numerous popular near-storm environment parameters and indices?*** Assuming a surface parcel may not always result in the “real” value acting on the storm, and may, in part, explain the high false-alarm rate of energy-helicity index (EHI) and vorticity generation potential (VGP).

Question 7) ***How much do we really know about the so-called “near-storm” environment?*** Markowski et al, 1998 has already shown that storm-relative helicity (and implicitly wind and wind shear) can be highly variable on short temporal and small spatial scales. Do the radar and visual observations described indicate that thermodynamic profiles have similar variability?

Question 8) ***Can we improve on the utility of the two near-storm environment significant tornado forecast parameters that have shown the most promise, namely surface to 1 km EHI and surface to 3 km (VGP)?*** It seems plausible to suggest that improvement to these indices may be possible with refinements to examining near-ground shear (i.e. the layer below the kink in the observed hodographs), and more accurately choosing a “correct” parcel in the calculation.

The superposition of profiles presented here also strongly suggests that future research include examination of shear and thermodynamics in combination, rather than separately.

5. Acknowledgements

The author extends sincere gratitude to David Andra, Dr. Matthew Bunkers, Dr. Robert Conzemius, Jon Davies, Jeffry Evans, Michael Foster, Robert Johns, James LaDue, Les Lemon, Dr. Bruce Lee, Jeff Manion, Dr. Paul Markowski, Phillip Schumacher, Douglas Speheger, Richard Thompson, and Karen Trammell, all of whom either assisted in obtaining data, provided useful comments in review of this manuscript, or participated many thoughtful discussions with the author regarding this topic over the past several years.

6. References

Evans, J.S., and C.A. Doswell III, 2002: Investigating Derecho and Supercell Proximity Soundings. Preprints, 21st Conf. on Severe Local Storms, San Antonio. TX, Amer. Meteor. Soc., 635-638.

Markowski, P. M., and J. M. Straka, 2000: Some observations of rotating updrafts in low-buoyancy, highly-sheared environments. Mon. Wea. Rev., 128, 449-461.

Markowski, P. M., J. M. Straka, and E. N. Rasmussen, 2002: Direct surface thermodynamic observations within the rear-flank downdrafts of nontornadic and tornadic supercells. *Mon. Wea. Rev.*, **130**, 1692-1721.

Markowski, P. M., J. M. Straka, E. N. Rasmussen, and D. O. Blanchard, 1998: Variability of storm-relative helicity during VORTEX. *Mon. Wea. Rev.,* 126, 2942-2958.

Markowski, PM, and Y. Richardson, 2006: On the classification of vertical wind shear as directional shear versus speed shear. *Wea. Forecasting*, 21, 242-247.

Nordin, S. M., H. E. Brooks, and J. P. Craven, 2003: Significant Severe Thunderstorm Proximity Soundings, *Preprints*, 2nd Annual Student Conference, Long Beach, California, Amer. Meteor. Soc., (abstract only)

Rasmussen, E. N., and D. O. Blanchard, 1998: A baseline climatology of sounding-derived supercell and tornado forecast parameters. *Wea. Forecasting*, **13**, 1148-1164.

Thompson, R. L. and R. Edwards, 2000: An Overview of Environmental Conditions and Forecast Implications of the 3 May 1999 Tornado Outbreak. *Wea. Forecasting*, **15**, 682-699.

Thompson, R.L, R. Edwards, J.A. Hart, K.L. Elmore and P.M. Markowski, 2003: Close Proximity Soundings within Supercell Environments Obtained from the Rapid Update Cycle.

Wicker, L. J., 1996: The role of near surface wind shear on low-level mesocyclone generation and tornadoes. Preprints, 18th Conf. on Severe Local Storms, San Francisco, CA, Amer. Meteor. Soc., 115–119.