A Study of Various Thermodynamic and Wind Variables Associated with Tornadic Supercells Exhibiting Atypical Motion

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1. **Introduction**

Recent research into supercells has focused on narrowing the number of important storm processes that lead to these storms. For years it has been known that supercells generally deviate slightly to the left or right of the mean wind, but that in some rare cases, supercells move in a very atypical direction. For example, Corfidi (1998) examined the conditions present for the Jarrell, Texas tornado, which exhibited such an atypical motion, and found the environment to be extremely unstable with weak storm-relative helicity. He also found that the southwest movement of the Jarrell, TX storm was closely tied to the southwest movement of a strong convergence zone along a pre-existing boundary. This discrete propagation allowed the storm to move southwest despite mean cloud-layer winds indicating an east to northeast motion. An earlier study by Weaver (1979) found similar conditions for a tornadic supercell moving west, yet little has been studied concerning common parameter values among these events. The goal for this study will be to determine if any common characteristics exist among various parameters for these events.

In determining storm type and evolution, wind shear has been found to play a significant role. Studies by Klemp et al. (1981), Rotunno and Klemp (1982, 1985), and Klemp(1987) found that midlevel rotation or mesocyclones are created by the tilting and stretching of the horizontal vorticity found in the pre-storm vertical wind shear. This vertical vorticity produces a dynamically induced pressure deficit that is strongest in the midlevels of the atmosphere, effectively establishing a non-hydrostatic pressure gradient on the storm's flanks. These vertical pressure gradients force the updraft to move toward a particular flank, thus allowing it to become best correlated with the vertical vorticity on that flank (Weisman 1996). Davies-Jones (1984) found that when streamwise vorticity was ingested into the updraft of a storm, it was converted to vertical vorticity within the updraft. A later study by Davies-Jones et al. (1990) found that Storm-Relative Helicity (SRH) in the lowest two or three kilometers of the atmosphere is most relevant to the development of a midlevel mesocyclone. They went on further to state that differing values of SRH often can be associated with weak, strong, and violent mesocyclones. Weisman (1996), found that the 0-4 km or 0-6 km wind shear of the pre-storm environment is more beneficial to the operational forecaster in anticipating supercell rotation compared to SRH since an estimate of storm motion is not needed to make the calculation. Another similar study from Colquhoun and Riley (1996), found that the surface-600 mb shear magnitude to be best correlated with the intensity of a tornado.

Although ambient vertical shear and SRH have been found to be well correlated with midlevel rotation within supercells, recent tornadogenesis studies have pointed to the importance of midlevel winds and their role in redistributing precipitation away from the updraft. Brooks et al. (1994a,b) found that the midlevel storm-relative winds are important to the development of low-level mesocyclones, since their conceptual model indicates that the strength and lifetime of low-level mesocyclones is based on the balance between baroclinic generation of vorticity and storm outflow development. A later study by Rasmussen and Blanchard (1998) though showed that the same combination of parameters used by Brooks et al(1994a,b) demonstrated little skill in discriminating between tornadic and non-tornadic supercells or discriminating between tornadic supercells and ordinary thunderstorms. Thompson (1998) used Eta model initialized soundings to calculate a storm-relative wind in the midlevels (500 mb) and near surface (15 mb above the surface). This study did show some success at discriminating between tornadic and non-tornadic environments when Eta model storm-relative winds at 500 mb and the surface exceeded 15 knots. Rasmussen and Straka (1998) evaluated a data set of supercells and concluded that low precipitation (LP) supercells generally have anvil-level storm-relative wind speeds > 54 kts (~28 m/s), classic supercells have speeds between 35 and 54 kts (~18-28 m/s), and high precipitation (HP) supercells generally have speeds < 35 kts (~18m/s).

A very popular measure of instability defined by Moncrieff and Miller (1976) is Convective Available Potential Energy (CAPE). Rasmussen and Blanchard (1998) used CAPE as one of their investigated parameters and found it had some utility at forecasting tornadic environments. Combining shear parameters with CAPE, further enhanced forecasting skill. In addition, Rasmussen and Blanchard (1998) investigated Energy-Helicity Index (EHI), Vorticity Generation Potential (VGP), and Bulk Richardson Number (BRN). They found that EHI and VGP showed the highest skill at discriminating between tornadic and non-tornadic environments, while BRN showed significantly less skill.

Recently a study by Bunkers et al. (2000) described a method for forecasting supercell motion known as the Internal Dynamics (ID) method. The ID technique uses the 0-6 KM shear vector along with the mean wind to find a storm motion estimate. The advantage to this method is that it is Galilean invariant, meaning that the storm motion is the same, relative to the vertical wind shear, no matter where the vertical wind shear profile is positioned with respect to the origin of the hodograph. Because this technique has shown skill in predicting supercell motion compared to previous methods, this study will also test the Bunkers et al. (2000) scheme on storms exhibiting an atypical motion.

2. **Data and Methodology**

This study investigates soundings associated with cases where supercells exhibit a very atypical motion. Given that most tornadic supercells across the North American continent move with some easterly component to their motion, tornadic storms moving with some westerly component will be considered atypical. To accomplish this all F2 or stronger tornadoes between the years of 1950 and 2000 were investigated using *Storm Data* (National Climatic Data Center) and the compilation *Significant Tornadoes 1680-1991* (Grazulis, 1993). An event was included in this study only if the tornadic storm had an average storm motion between 30 degrees and 150 degrees. This yielded less than 30 cases over the 50-year period. Soundings were then gathered from the Radiosonde Data for North America, 1946-1994 (Forecast Systems Laboratory and National Climatic Data Center, 1995) and Radiosonde Data of North America, 1994-1997 (Forecast Systems Laboratory and National Climatic Data Center, 1999) as well as Radiosonde Data from the Forecast Systems Laboratory web page for data beyond 1997. In the interest of representativeness, events were discarded if they occurred beyond 150 km of the nearest sounding location. Further, events were discarded if soundings were found to be within a different air mass than the event, or if the soundings were convectively contaminated. Finally, a time constraint was put on the events in association with the proximity soundings used in this study. If events occurred beyond +/- 3 hours of the sounding time, the events were not included. These constraints produced a very small data set of only 15 cases over the 50-year period. As seen in Figure 1 and Table 1, it is also interesting to note that 14 out of the 15 cases occurred between the Rocky Mountains and the Mississippi River, with the lone outlier occurring in the lower Ohio Valley. Although the main focus of this study is not on the deviation of these events from the mean wind, storm motions averaged a deviation of 80 degrees from the 0-6 km mean wind, while only one event exhibited a storm motion within 40 degrees. This suggests that in most cases these events are a unique subset of highly deviant supercells. The average motion and path length for these tornadic storms are plotted in Figure 2.

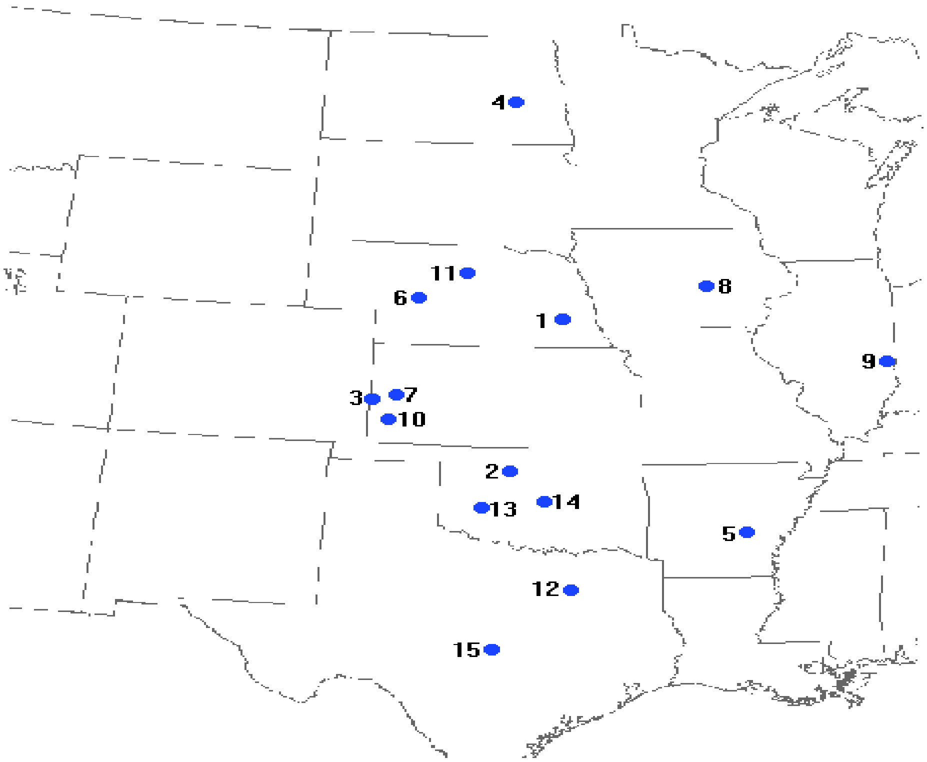

Fig. 1. Geographic plot of tornadic supercells in this study. Each event has been numbered for use in figures 5-8.

Event Number	Date	Location
1	30 August 1959	Lancaster County NE
2	16 April 1969	Alfalfa County OK
3	6 July 1966	Hamilton County KS
4	16 July 1957	Griggs County ND
5	24 July 1960	Arkansas County AR
6	18 June 1975	Logan County NE
7	22 June 1999	Wichita County KS
8	22 June 1964	Dallas County IA
9	3 May 1958	Edgar County IL
10	3 May 1987	Haskell County KS
11	8 May 1965	Rock County NE
12	10 May 1965	Navarro County TX
13	11 May 1982	Kiowa County OK
14	20 May 1977	Oklahoma County OK
15	27 May 1999	Williamson County TX

Table 1. Event dates and locations.

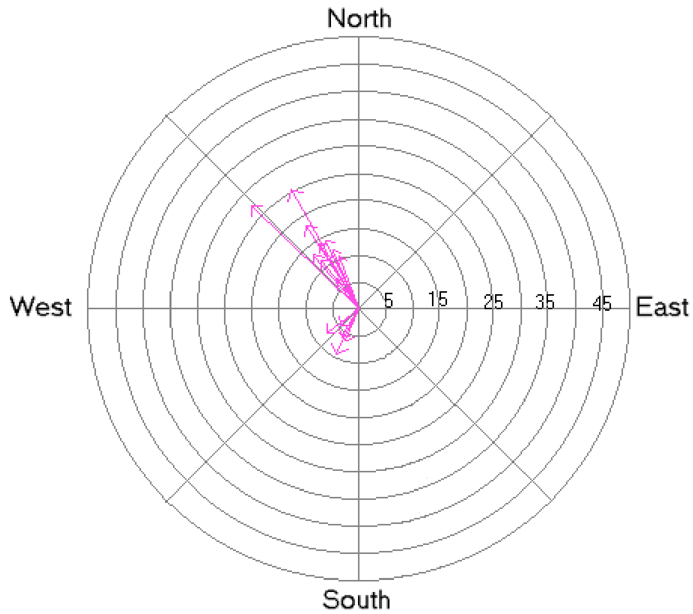

Fig. 2. Plot of storm motion and path length in miles.

In order to provide comparisons, the variables chosen were calculated in the same manner as in commonly referenced studies. CAPE was calculated by choosing the most unstable parcel in the boundary layer with the virtual temperature correction applied (Doswell and Rasmussen 1994). Due to the varying elevations found in the data set, the boundary layer was estimated as the lowest 100 mb above ground level (AGL). In most cases, this resulted in the surface parcel being the most unstable parcel, but a few cases had the parcel elevated by as much as 50 mb AGL.

Shear variables such as the 0-4 km mean shear and the 0-6 km shear were calculated in the same manner as Rasmussen and Blanchard (1998). SRH was calculated in a 0-3 km depth with actual storm motions used to calculate the variable. The actual storm motions were chosen instead of a forecast motion in order to eliminate any potential errors involved with a predicted storm motion. Combinations of CAPE and shear such as EHI (Hart and Korotky 1991; Davies 1993) or VGP (Rasmussen and Wilhelmson 1983) were also calculated in this study in the same manner as Rasmussen and Blanchard (1998).

Storm-relative wind speeds were calculated at 500 mb similar to Thompson (1998) while anvil-level storm-relative winds were calculated by averaging storm relative winds over a 1 km depth centered at the equilibrium level of the sounding. Finally, forecasted storm motions were calculated from the soundings using the ID method developed by Bunkers et al. (2000).

3. **Results**

a. Storm Motion Forecast

Bunkers et al. (2000) developed a storm motion forecast method called the ID method. Rasmussen and Blanchard (1998) used a similar Galilean invariant method, with comparable results. Given their conclusions, a test of the ID method against the events in this data set was accomplished. Although not shown here, several non-Galilean invariant methods (Maddox 1976, Davies and Johns 1993, and Davies 1998) were also calculated, but the results were extremely poor. When combining the results from all non-Galilean invariant methods, there was not one case where the storm motion forecast error was below 7 m/s. Bunkers et al. (2000), found that 75% of the events in their data set had an error rate of less than 5.4 m/s. Examination of Figure 3 for ID forecasted right-movers, reveals that only five of the events had an error rate less than 6.8 m/s, while Figure 4 reveals that no events were within 8 m/s of the actual motion for the ID forecasted left-mover motion. These poor results may be due to local variations in the vertical wind profile not found in the proximity sounding. Fronts, gravity waves, or outflow boundaries near the storms, could change the near-storm wind profile significantly enough to make the proximity soundings non-representative. Other factors, such as the interaction of the cold pool with the vertical wind shear in the lowest few kilometers, could cause many of these events to propagate in a manner that the ID method could not accurately predict. However, five of the events were forecast within a small error range (7 m/s), indicating that the ID method appears capable of reasonably forecasting some atypical propagation environments.

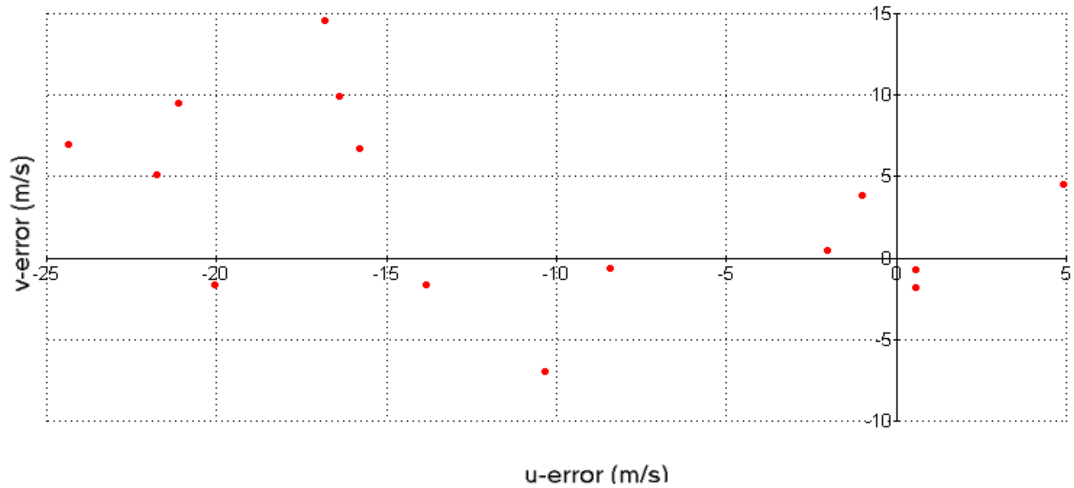

Fig. 3. Actual storm motion minus ID (Bunkers et al. 2000) right mover forecast motion.

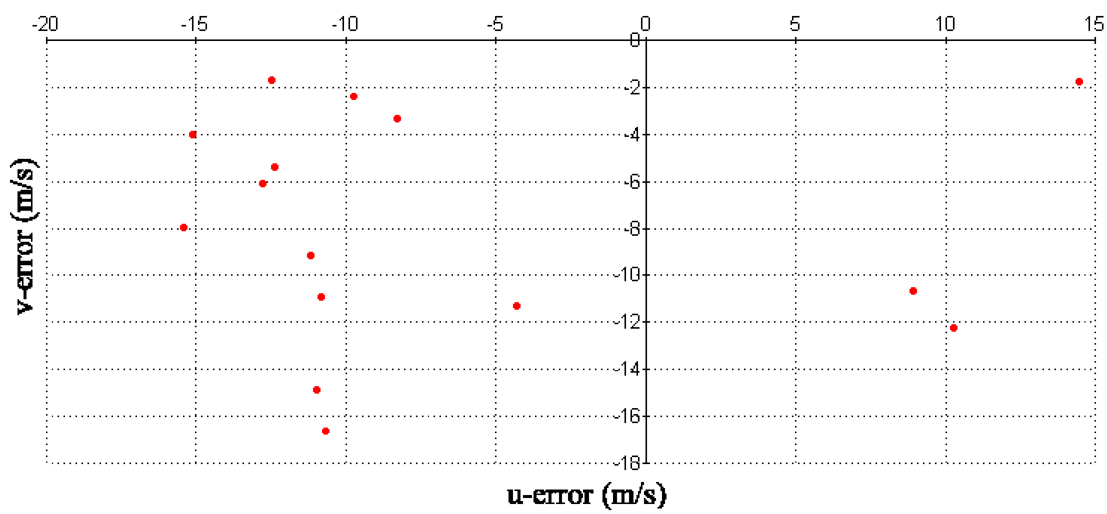

Fig. 4. Actual storm motion minus ID (Bunkers et al. 2000) left mover forecast motion.

b. CAPE

Corfidi (1998) found that in the Jarrell, Texas tornado, which was a tornadic storm exhibiting a highly non-standard motion, CAPE values exceeded 5500 J/kg across a very large area. An earlier study by Mentzer (1993), studying a back-building tornadic convective case, found CAPE values of approximately 6500 J/kg. Figure 5 reveals results similar to these studies with all but one case having a CAPE value around or exceeding 2000 J/kg. As some measure of this level of instability, a comparison of these values to the 25th (519 J/kg), 75th (1877 J/kg), and 90th (3028 J/kg) percentile values given by Rasmussen and Blanchard (1998) for tornadic supercells were made. For simplicity, if CAPE values at or below the 25th percentile value are considered weak, then none of the events had CAPE in the weak category. Further, all but one event had a CAPE value exceeding the 75th percentile value, with half the events exceeding the 90th percentile value. If CAPE values above the 75th percentile are considered high, while values above the 90th percentile are considered extreme, then high CAPE and occasionally extreme CAPE appear to be one of the ingredients existing when tornadic supercells move in an atypical manner.

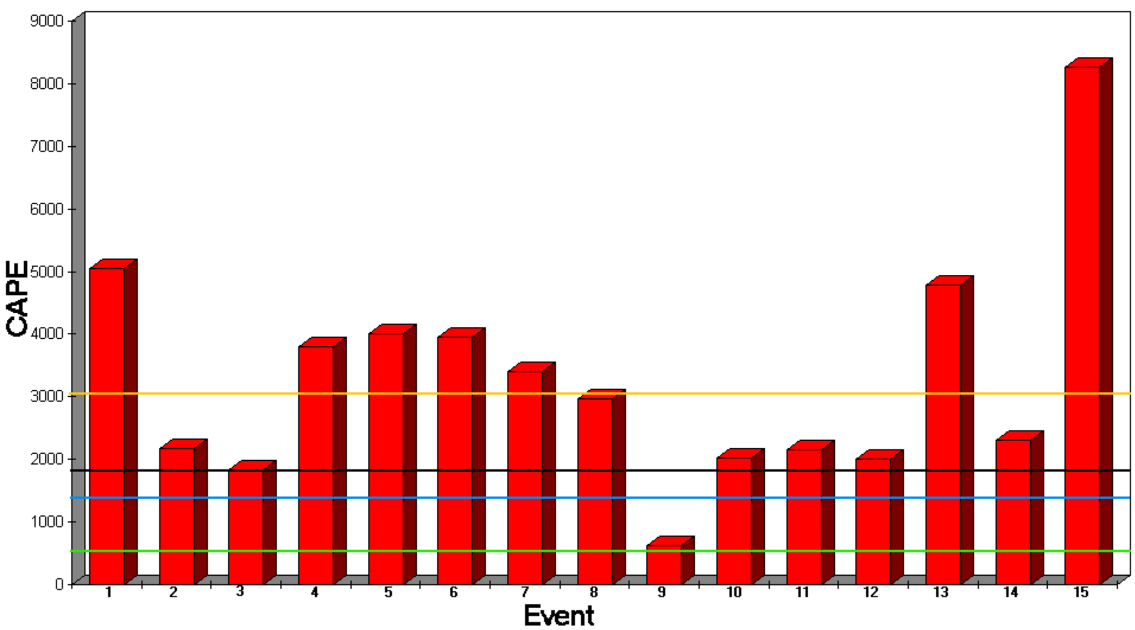

Fig. 5. Bar Graph of CAPE values for each event. The horizontal lines represent the 25th, median, 75th, and 90th percentile values found by Rasmussen and Blanchard (1998).

c. 0-4 km Mean Shear

Mean shear values for this data set, as seen in Figure 6, generally show most cases to be above 0.004 s^{-1} or around 16 m/s of cumulative shear over the lowest 4 km. A comparison of these values to the 25th (0.00560 s^{-1}), median (0.00802 s^{-1}), and 75th (0.00944 s^{-1}) percentile values found for tornadic supercells by Rasmussen and Blanchard (1998) were made. Out of the 15 cases, 11 were above the 25th percentile suggesting at least moderate levels of low-level shear are needed in most cases for these cells to become tornadic. However, all but one case was below the 75th percentile value and 87% of the cases were below the median value. This suggests that extreme levels of shear in the lowest 4 km tend to not be characteristic of environments where tornadic supercells would move in an atypical manner. The fact that a few events do exist above the median value and below the 25th percentile values does suggest that tornadic supercells exhibiting atypical motion can occasionally occur in environments with high shear as well as very weak shear, but usually occur with moderate levels of shear.

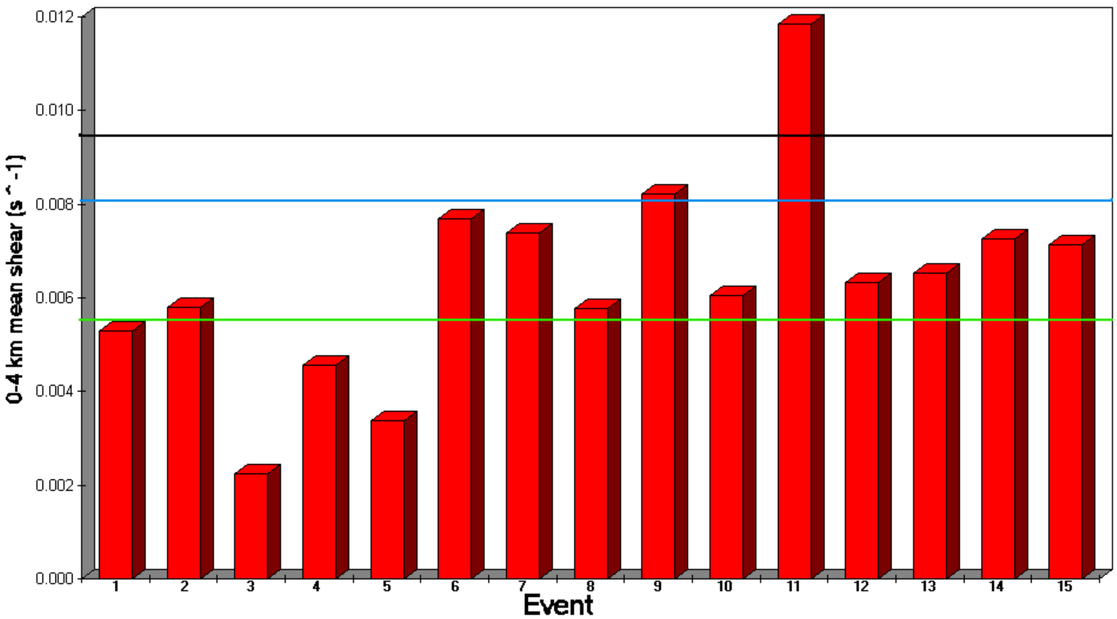

Fig. 6. Bar Graph of 0-4 km mean shear values for each event. The horizontal lines represent the 25th, median, and 75th percentile values found by Rasmussen and Blanchard (1998).

d. SRH

An examination of Figure 7 reveals extremely chaotic SRH values with a little over half of the events occurring with a negative SRH. When using just those cases discussed in section 3a, where observed storm motions where similar to forecast storm motions, the results are more clustered together. This approach yields only one case with a negative SRH (-6 $m^2 s^{-2}$) and only one case with a SRH over 100 $m^2 s^{-2}$, the value that Rasmussen and Blanchard (1998) gave as the 25th percentile value for tornadic supercells. Given these results, tornadic events exhibiting a non-standard motion appear to occur in environments with a SRH around zero, raising the question of the exact mechanism behind mesocyclone development and tornado-genesis in these types of storms. A study by Markowski, et al. (1998) found that values of SRH varied dramatically over very short distances during the VORTEX project. It is possible, then, that many of the events where forecast motions were not close to observed motions, the localized backing of surface winds may have caused SRH values to be higher than found in this study. These potential deficiencies highlight the importance of storm-scale or micro-scale features, in calculating SRH.

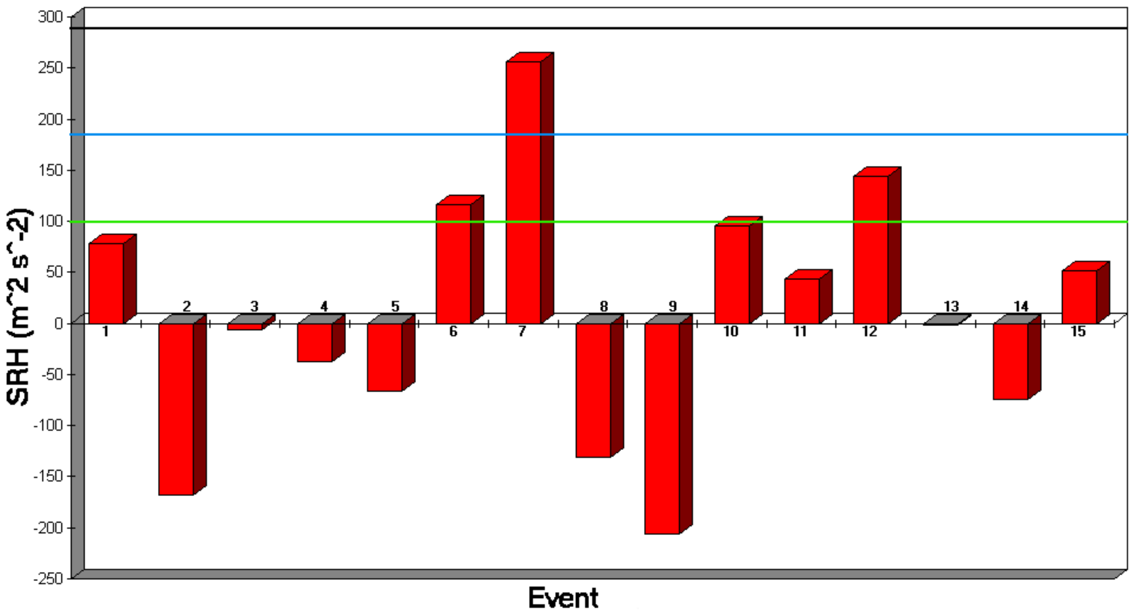

Fig. 7. Bar Graph of SRH values for each event. The horizontal lines represent the 25th, median, and 75th percentile values found by Rasmussen and Blanchard (1998).

e. 0-6 km Shear

The 0-6 km shear as shown in Figure 8, show a distinct lower threshold value for these tornadic events. All but three events had shear values greater than 13 m/s, and all but one had greater than 10 m/s of shear. These results compare favorably with Rasmussen and Blanchard (1998) with the mean values differing by only 1.4 m/s. This suggests that a lower limit between 10-15 m/s does exist, not only for normal propagating supercells, but also for those propagating in an atypical manner. Figure 4 also reveals a large number of cases with moderate to high shear values. This further suggests that many of the events not only propagated in a non-standard fashion, but also did against a fairly strong mean flow. Strong, deep-layer shear as seen in these events doesn't appear to prevent these cells from deviating in a non-standard fashion. This demonstrates the importance of sufficient deep-layer shear for development of mesocyclones in tornadic supercells, regardless of the motion.

f. Vorticity Generation Parameter (VGP)

The combination of CAPE and 0-4 km mean shear produce the VGP parameter (Rasmussen and Wilhelmson 1983). Rasmussen and Blanchard (1998) did indeed show some skill at discriminating between tornadic and non-tornadic events using VGP. Figure 9 has the VGP 0.27 line drawn as a reference for investigating this parameter, which was the mean value They found for tornadic supercells. All but three events had a VGP value greater than or equal to 0.27. Further, a third of the events had VGP values greater than the 75th percentile value of 0.390. The higher than average VGP values are most likely a result of the high CAPE discussed in section 3b.

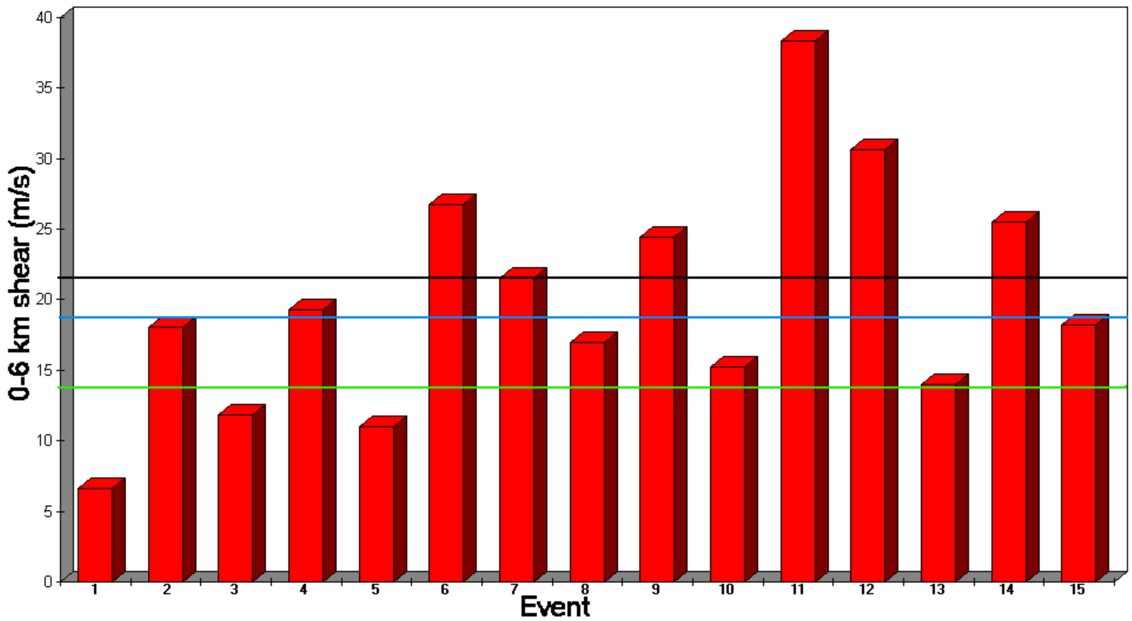

Fig. 8. Bar Graph of 0-6 km shear values for each event. The horizontal lines represent the 25th, median, and 75th percentile values found by Rasmussen and Blanchard (1998).

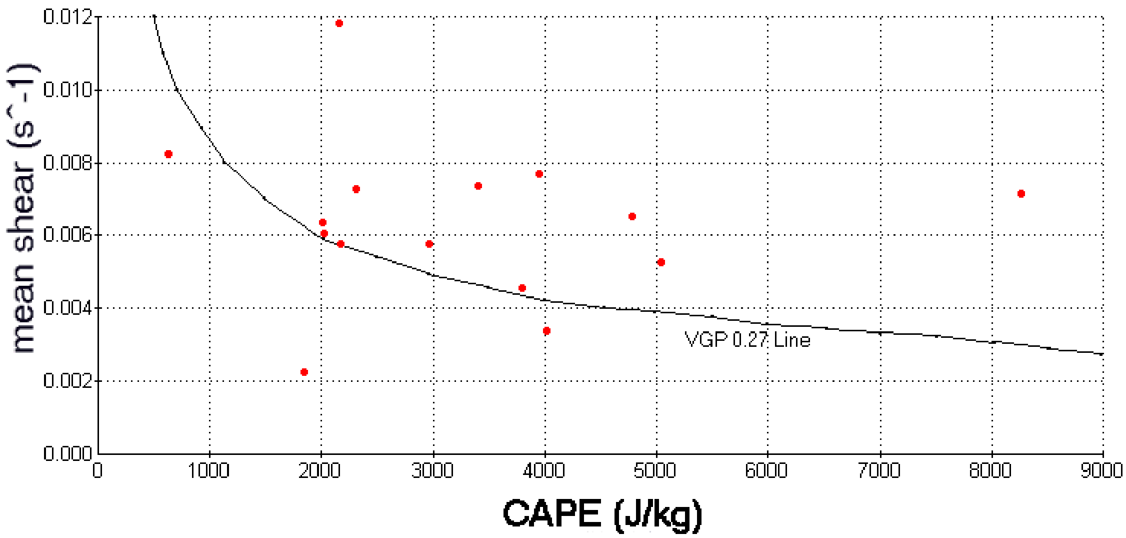

Fig. 9. Scatter diagram of CAPE vs. 0-4 km mean shear.

g. Energy-Helicity Index

EHI (Hart and Korotky 1991; Davies 1993) is a combination of CAPE and SRH (0-3 km depth in this case) and is displayed for the studied cases in Figure 10. The EHI 1.5 line, which Rasmussen and Blanchard (1998) found to distinguish between tornadic and non-tornadic events, has been drawn on Figure 10 as a reference. An examination of Figure 10 reveals only 5 out 15 cases are above the EHI 1.5 line. The likely reason for the poor results of EHI is the wide variation in SRH values discussed in Section 3c. When using the same methodology as Section 3d to remove those cases where forecast motions are not close to actual motions, all but one of these remaining cases had an EHI greater than 1.0, which Brooks et al (1994a,b) found as a baseline value for tornadoes. As with VGP, the EHI values greater than 1.0 are most likely a result of the high CAPE environments. However, these results are different than those from VGP in that the mean EHI value of these remaining events are close to mean values found in other studies such as Rasmussen and Blanchard (1998). This suggests that EHI values greater than 1.0 are not a unique characteristic of these events. Essentially, a high EHI value does not mean there is a higher chance for tornadic supercells to propagate in a non-standard fashion.

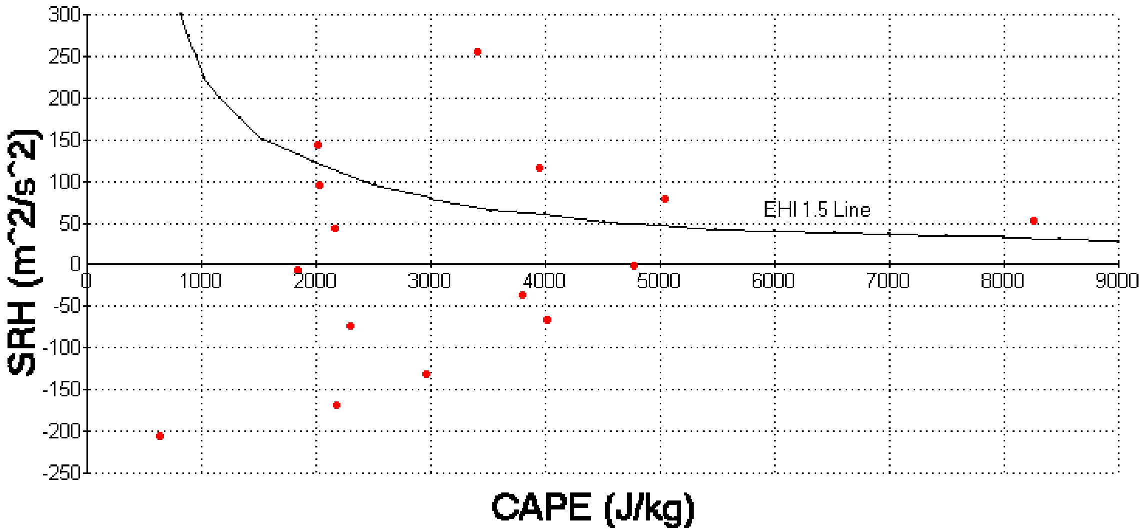

Fig. 10. Scatter diagram of CAPE vs. 0-3 km SRH.

h. Bulk-Richardson Number

If using 0-6 km shear as a proxy for the BRN shear similar to Rasmussen and Blanchard (1998), which is a function of the 0-6 km mean wind divided by the 0-0.5 km mean wind, one can use Figure 11 to reveal any trends similar to those of BRN. For clarity, an approximate constant BRN value of 50 was drawn on Figure 11. Values to the left and above the line represent values less than 50, while the opposite can be said for those values to the right and below the line. An examination of the plot reveals little correlation between BRN and these events. Weisman and Klemp (1982) found that BRN values < 50 favored supercells, while values > 50 favored multicellular convection. As seen in Figure 11, values are scattered above and below a BRN value of 50 indicating almost no trend in BRN. From this data, BRN appears to have no utility at forecasting tornadic potential in these events.

i. Storm-Relative Flow At Anvil-Level And 500 mb

The anvil-level flow has been found to play a critical role in determining storm type. In this paper, anvil-level flow was centered at the equilibrium level and averaged over a 1 km depth. Rasmussen and Straka (1998) found that HP supercells generally have anvil-level storm-relative wind speeds < 35 kts, classic supercells have storm-relative wind speeds between 35 kts and 54 kts, and LP supercells have speeds > 54 kts. Examination of Figure 12 reveals that only two cases reside below a 40 knot storm-relative wind speed and 10 of 15 events occur above 54 kts. The other parameter plotted in Figure 12 is the 500 mb storm-relative wind speed found by Thompson (1998) to be a good predictor of tornadic environments when values exceeded approximately 15 kts. Thompson (1998) did find some evidence of an upper limit around 37 kts, but stated that this limit could not be confirmed nor refuted due to the small number of cases above this value. Results here are similar to Thompson (1998) in that all but one value had a 500 mb storm-relative value exceeding 15 kts, but a little over half the values exceed the 37 kt threshold. The relevance of the large number of events exceeding the 37 kt threshold is not well understood.

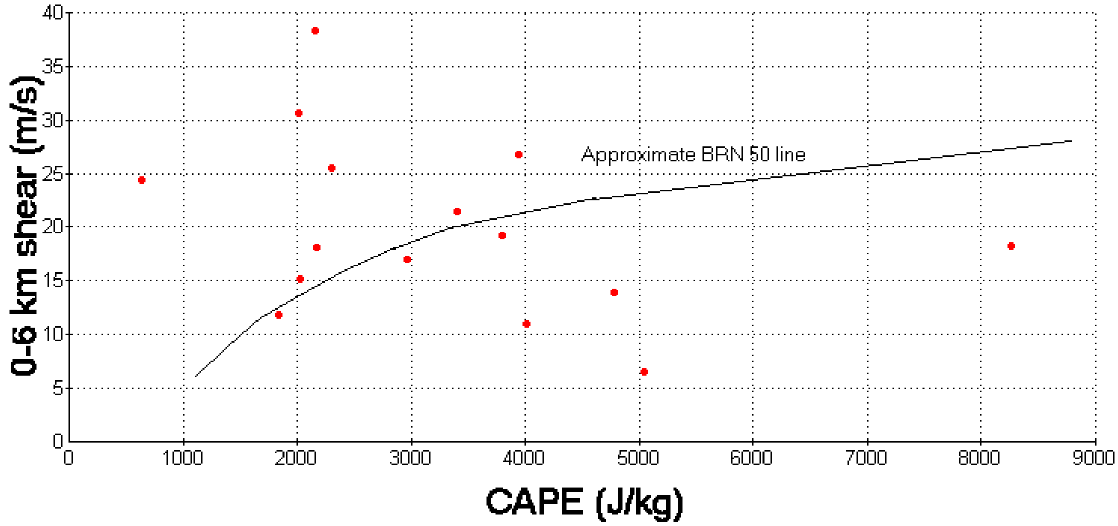

Fig. 11. Scatter diagram of CAPE vs 0-6 km shear.

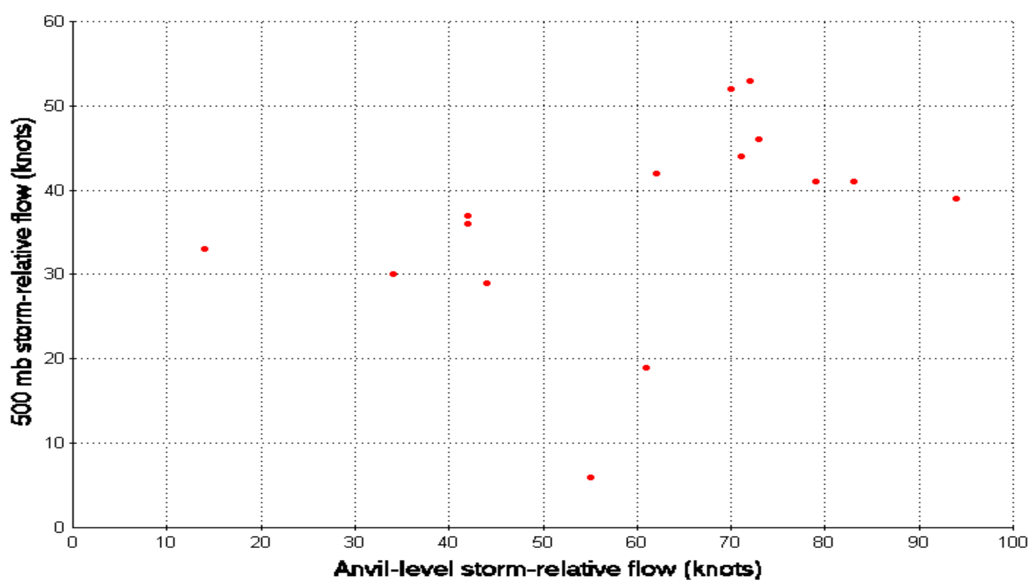

Fig. 12. Scatter diagram of 500 mb and anvil-level strom-relative wind speeds.

4. **Summary**

Soundings were studied for several tornadic events where average storm motions during the tornadic stage of the storm were between 030 and 150°. Of the 15 events analyzed, only 5 had an ID forecasted right-mover motion within 6.8 m/s of the actual storm motion and while the ID forecasted left-mover motion had none within 8 m/s . These poor results may be a result of localized influences in the vicinity of the storm that were not evident in the proximity sounding.

CAPE values for these events tend to be on the high end of the spectrum with no events found to have a generally weak CAPE and only one event found to have a moderate level of CAPE. High to extreme instability appears to be a common characteristic of the environment for these highly deviant supercells. However, the exact role that high to extreme instability plays in causing these supercells to move in an atypical manner, is not addressed in this study and will require additional research.

Shear related parameters were also investigated in an attempt to reveal any trends for these highly deviant supercells, as well as, determine similarities to other data sets using events with a more typical propagation. The 0-4 km mean shear was studied with the results indicating that at least moderate levels of shear are a common characteristic for the majority of these events. Some events occurred with weak shear values or high shear values, but it appears that most events occur with moderate levels of shear for these types of supercells. The 0-3 km SRH was also studied, but results were extremely variable with a little over half of the events occurring with negative SRH. It is speculated that much of the variability found in the SRH is the result of localized influences in the vicinity of the storm that were not evident in the proximity sounding. The 0-6 km shear was also examined with results very similar to other studies involving events with a more typical storm motion. Results indicated a baseline threshold value between 10-15 m/s and a mean value around 19 m/s. Further, many of the events also occurred in high levels of 0-6 km shear. These conclusions suggest that high levels of deep-layer shear are still supportive of highly deviant motions in supercells. It appears that sufficient deep-layer shear is vital in all tornadic events regardless of the storm motion.

Parameters combining shear and instability were analyzed for each event in this study. Results indicated that 12 out of 15 events occurred with VGP values equal to or greater than 0.27. Further, the mean value for these events was much higher than other studies looking at VGP values for tornadic events with a more standard movement. Similar to CAPE, a high VGP appears to be a common characteristic for these highly deviant supercells. EHI results for the entire data set were extremely variable due to the large spread found in SRH values. Results indicated that the BRN had no skill at forecasting the potential for supercells in these events.

Anvil-level storm-relative winds and 500 mb storm-relative winds were calculated for all events using actual storm motions. The data indicated that the majority of events favor an LP-like storm structure with around two-thirds of the events having an anvil-level storm-relative wind speed greater than 60 kts. It appears that a majority of these events are not a result of cold-pool dominated propagation as seen in HP storms. The exact mechanism for this highly deviant motion appears to be more directly tied to the orientation of the 0-6 km shear vector relative to the mean wind, rather than cold-pool dominated propagation. The 500 mb winds were also studied with results in agreement with the study done by Thompson (1998). The only difference found between the two studies was that all but two of these events had a storm-relative wind speed at 500 mb greater than 40 kts.

From this study it is evident that not just one, but several common characteristics exist in the environment where tornadic supercells move in an atypical manner. Table 2 is summary of these common sounding characteristics found in this study. Although boundary location and movement were not studied, both Weaver (1979) and Corfidi (1998) revealed a strong correlation between the west/southwest movement of strong convergence zones along pre-existing boundaries and the west/southwest movement of nearby tornadic supercells. Forecasting these rare events is undoubtedly difficult and the exact role that moving convergence zones has on storm motion was not addressed in this study. However, a quick comparison of values found in Table 2 to forecasted values may help a forecaster anticipate, or eliminate, the possibility of such events.

Parameter	Value/Range
CAPE	13 of 15 events > 2000 J/kg 7 of 15 events > 3000 J/kg
0-4 KM mean shear	11 of 15 events > 0.00560 s^{-1} 13 of 15 events < 0.00802 s^{-1}
0-6 KM shear	12 of 15 events > 13.6 m/s
VGP	12 of 15 events $\geq$ 0.27
Storm-Relative Flow at 500 mb	14 of 15 events > 15 kts
Storm-Relative Flow at Anvil-Level	13 of 15 events > 40 kts 10 of 15 events > 54 kts

Table 2. Common characteristics observed in event soundings.

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