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AN ANALYSIS OF A PROLIFIC TORNADO PRODUCING CYCLIC SUPERCELL THUNDERSTORM IN NUCKOLLS COUNTY NEBRASKA, MAY 24, 2004

John P. Monteverdi*, Elizabeth Polito, Matthew Gough,
Rebecca Bethke and Terrance Seddon
San Francisco State University, San Francisco, CA

1. INTRODUCTION

On 24 May 2004, a supercell thunderstorm (hereafter referred to as the "Thayer County storm") near Hastings, Nebraska and moved through Adams, Clay, Nuckolls and Thayer Counties, Nebraska and Republic County, Kansas, spawning 11 tornadoes in Nebraska alone (Fig. 1and Table 1).

Figure 1 Locations and tracks of 11 tornadoes associated with the Nuckolls County storm in Nebraska (source SPC, SeverePlot).

Figure 2 Tornado I (right, near Deshler) at 2115 UTC. View towards the southwest. (Photo: John Monteverdi).

Table 1. Nebraska tornado statistics, May 24, 2004. Letters refer to locations on Fig. 1 (Source: SPC)

Tornado Locations (Nuckolls and Thayer Counties)	**Time UTC**	**Path Length (km) /Width (m)**	**Mag**	**Lat**	**Lon**
A Nelson	2005	0/50	F0	40 13	98 06
B Nelson	2020	0/25	F0	40 12	98 03
C Nelson	2028	0/25	F0	40 16	98 07
D Oak	2035	0/15	F0	40 12	97 54
E Nora	2041	0/15	F0	40 11	97 59
F Ruskin	2052	0/15	F0	40 11	97 52
G Ruskin	2058	3/100	F1	40 04	97 52
H Deshler	2102	3/75	F0	40 04	97 49
I Deshler	2106	3 /450	F1	40 03	97 46
J Hardy	2116	0/25	F0	40 01	97 55
K Byron	2129	0/25	F0	40 00	97 41

The lead author witnessed more tornadoes than were recorded in SPC's final tally. For example, there were actually three tornadoes west of Hebron, Nebraska, shortly after 2115 UTC. One of the secondary, or satellite tornadoes, can be seen at the left of the main funnel, on Fig. 1. The Nuckolls County storm then moved into Kansas and produced another 5 tornadoes (Fig. 3).

Figure 3 Belleville, KS tornado at 2200 UTC. View towards the northwest. (Photo: Thom Trimble).

**Corresponding author address:*
Prof. John P. Monteverdi, Dept of Geosciences, San Francisco State University, 1600 Holloway Avenue, San Francisco, 94132; e-mail: montever@sfsu.edu

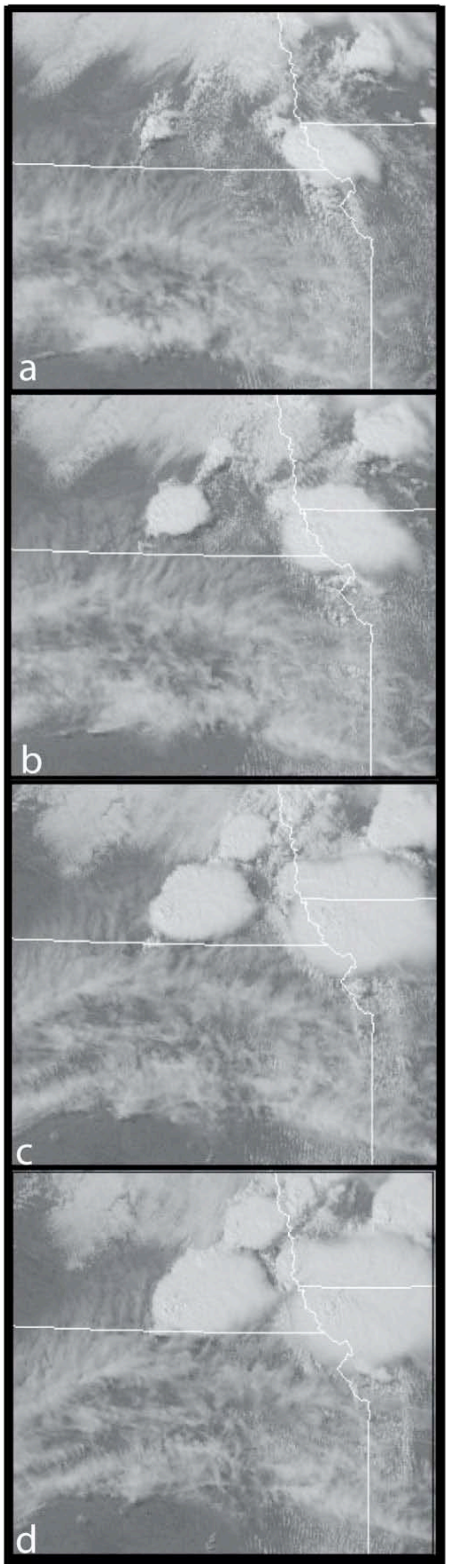

Figure 3 Visible satellite imagery at 1932, 2002, 2012 and 2032 UTC showing storm initiation near Hastings.

Analysis of the radar data shows that the Nuckolls County storm was a cyclic classic supercell. However, unlike other cyclic supercells, its long life cycle and repetitive tornado production were not related to interaction with subsynoptic scale boundaries, but to the favorable synoptic scale shear and buoyancy environment into which the storm moved.

The purpose of this paper is to present a brief examination of the synoptic and thermodynamic controls of this event. We also will show how the cyclic nature of the Nuckolls Couny storm's tornado production was consistent with the high values of low level shear found in the storm environment.

2. STORM EVOLUTION AND HISTORY

The Nuckolls County storm initiated near Hastings, Nebraska at around 1930 UTC. The storm quickly became severe and was responsible for many severe hail and wind reports in Adams County.

At the time of convective initiation, the area of south-central Nebraska lay in the northeast portions of a developing wave cyclone, centered in northwest Kansas (Fig 3). Backed surface flow (relative to winds in the mid-troposphere) ahead of a rapidly developing dry line bulge occurred northeast of this center. Storm initiation appeared to take place near the triple point intersection of cold front, quasi-stationary front and the dry line in the flow of air with high dew points into south central Nebraska.

Analyses of the radar information show that initially the storm moved northeastward with the mid-tropospheric flow (motion vector of ~220^{o}, 10 m s^{-1}) and split several times. Southwest of Edgar, Nebraska, the right moving storm became a supercell, developed strongly deviate motion (motion vector of ~330^{o}, 15 m s^{-1}). This deviate motion combined with strongly looped hodograph, created excessive values of storm relative helicity in the storm proximity (discussed below).

A bounded weak echo region (BWER) developed as the storm entered central Nuckolls County at around 2000 UTC and was prominent in each storm cycle. For example, at arount 2051 UTC , the 0.5^{o} base reflectivity from the Weather Surveillance Radar 88 Doppler (WSR-88D) at Hastings, Nebraska (KUEX) showed a well-developed hook echo (Fig. 4a) with a prominent velocity couplet (storm relative) (Fig. 4b). The 3.4^{o} base reflectivity (Fig 4c) depicted a circular echo free region over the inflow notch shown in Fig. 4a.

The first tornado with a long track (Fig. 5) formed on the extreme northeast (forward) portion of the lower level "horseshoe" lowered base, just ahead of the rear flank downdraft (RFD) cut (not shown) near Ruskin at around the time of the radar plots shown in Fig. 4. The tornado persisted for around 8 minutes until it dwindled through its "rope out" stage. At that time, the lead author was located near Ruskin, Nebraska, approximately 10 km away from the tornado to the southwest.

During the 3 hours the storm traversed Nuckolls and Thayer Counties in Nebraska and Republic County, Kansas, the radar evolution of the storm was complex. Several times the low level hook became disorganized to be replaced by a new mesocyclone-generated hook further southwest. During the second of these cycles, the first tornadoes developed near Nelson. (Fig. 6). In the 20 min following 2100 UTC, the storm's lowered base showed spectacular evolution, with as many as three tornadoes visible simultaneously (Fig. 2).

The storm continued to move southeastward over the next several hours. As it did so, it underwent at least two more cycles and produced tornadoes H, J and K (see Fig. 1 and Table 1).

In the storm's final cycle, reorganization essentially produced a new supercell on the southwest flank of the storm, This final phase was associated with five tornadoes in Republic County, Kansas.

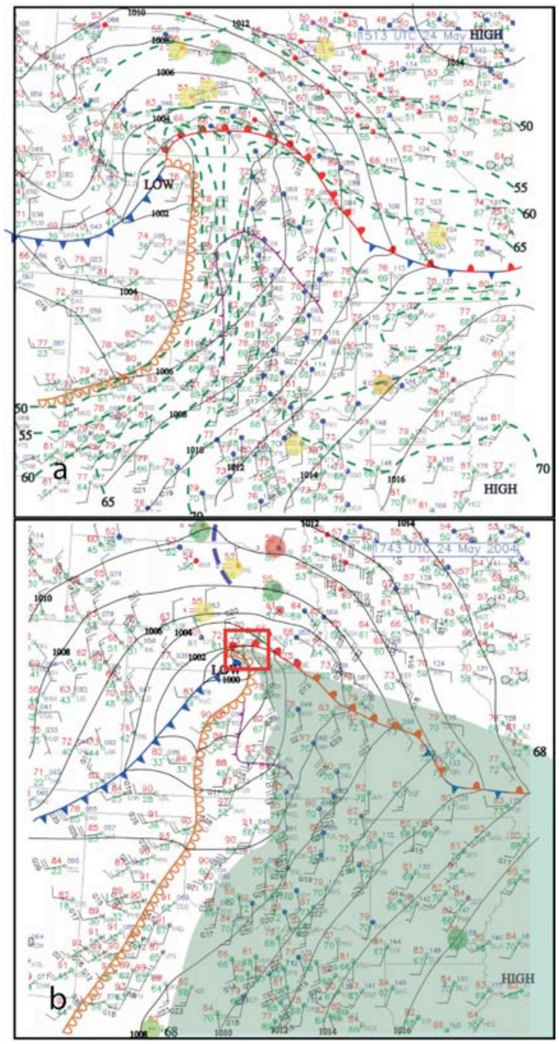

Figure 3 Subjective analysis of (a) 1513 and (b) 1743 UTC 24 May 2004 surface data. Storm initiation area shown as red box on b. Region with dew point temperatures 68F and greater shown on b.

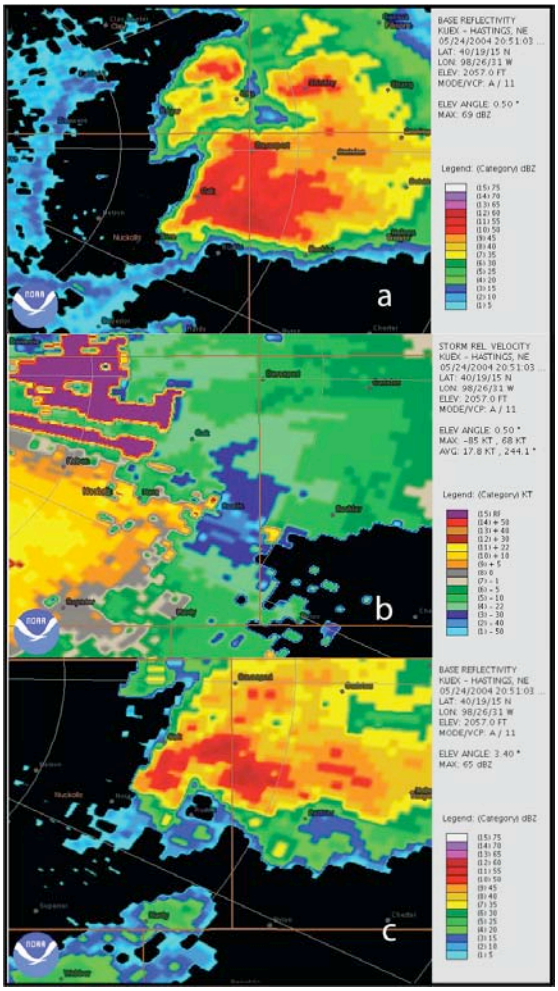

Figure 4 (a) Base reflectivity, 0.5° tilt,; (b) storm relative velocity, 0.5° tilt,; and (c) base reflectivity, 3.4° tilt, (2051 UTC) from KUEX, at approximate time of Ruskin tornado report (tornado G on Figs. 1 and 2 and also shown in Fig. 5)

Figure 5 The first long-track tornado (G on Fig. 1 and Table 1) associated with the Nuckolls County storm at 2058 UTC, near Ruskin, view to the southwest. (Photograph by Thom Trimble)

During its entire life cycle, the Nuckolls County storm was the southern-most storm in Nebraska and Kansas rooted in the rich surface moisture. At no point in its life cycle did the storm appear to interact with any preexisting surface boundaries, such as fronts or outflow features. Thus, it appears that the cyclic nature of the storm was entirely related to its interaction with the shear already present in the environment, as discussed below.

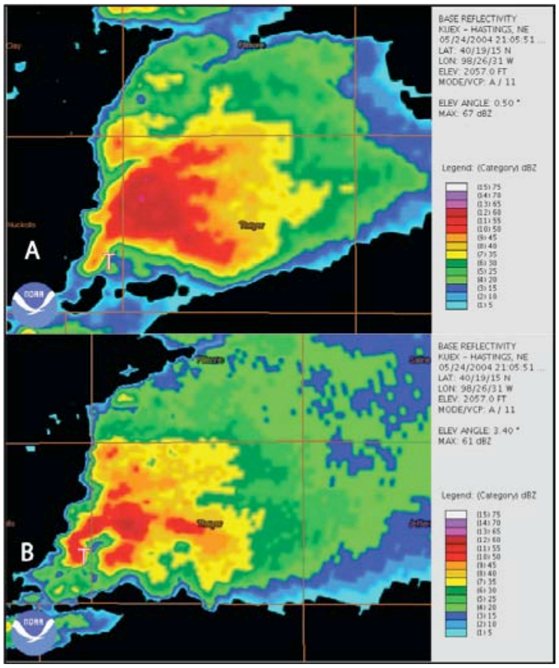

Figure 6 Base reflectivity (2105 UTC) from KUEX at 0.5^o and 3.4^o degree tilts, illustrating BWER, as explained in text. T shows the position of the long-track tornadoes near Hebron, seen in Fig. 2. The KUEX radar was intersecting the storm at a range of 56.7 km and at heights of 650 m (0.5^o tilt) and 3366 m (3.4^o degree tilt).

3. SYNOPTIC AND THERMODYNAMIC CONTROLS ON NUCKOLLS COUNTY STORM

3.1 Synoptic Scale Environment

Several key features in the synoptic-scale environment (in addition to those mentioned in Section 2 above) contributed both to the initiation of the Nuckolls County storm and to its evolution into a cyclic supercell. The synoptic-scale environment also created a low level shear environment so favorable for supercell tornadogenesis that the absence of boundaries in the near-storm environment did not deter the formation of tornadoes. Such boundaries have been identified as key players in many significant supercell tornado outbreaks (see, e.g., Markowski et al. 1998 and Rasmussen et al. 2000).

During the afternoon hours of 24 May 2004, a low amplitude shortwave trough (seen in the height fields in Figs. 7a and 7b) in the middle and upper troposphere moved from northwestern Kansas over south-central Nebraska the region. This trough was associated with substantial upward motion in the middle troposphere over noertheastern Nebraska but only weak to moderate upward vertical velocities existed over the storm initiation area near Hastings.

Pressure falls ahead of the trough (not shown) were associated with the development of a complex surface low pressure system (Fig 3a and 3b). The circulation around this center encouraged the progression of a dry line bulge into northwest Kansas and south-central Nebraska. North of this bulge, surface winds backed strongly (relative to the mid troposphere flow) (red box in Fig. 3b). As will be seen, this strongly backed surface flow in combination with the strong and rapid veering of the wind directions with height, helped create a low level shear environment that was extremely robust. In addition, the backed surface flow was associated with advection of high dew points into an area that was just north of the edge of the "lid", as evidenced by the 700 mb temperatures >10^{o}C extending from south-central Nebraska across Kansas on Fig. 7a.

A number of factors focused synoptic and sub-synoptic scale lift in the lower mid troposphere over southern Nebraska on May 24. First, differential cyclonic vorticity advection and warm advection were associated with quasigeostrophic forcing for mid-tropospheric layer lifting over the area. The quasigeostrophic effects can be diagnosed by the area of 700 mb cyclonic vorticity advection by the thermal wind inferred from Fig. 9c.

Second, solenoidal lifting along and just south of the synoptic-scale boundary (Fig. 3b), and roughly coincident with the greatest temperature gradient at 700 mb (Fig. 7c), possibly was an additional source of synoptic-scale lift. Finally, above 850mb, west-southwest winds had brought a warm, dry layer over the underlying very moist air mass at the surface. The resulting cap was very strong south of the Kansas border, and was roughly demarked by the 10^{o}C 700 mb isotherm (Figs. 3 and 7a).

The presence of strong winds in the mid and upper troposphere (not shown) also helped create a favorable deep layer (i.e., 0-6 km) shear environment for supercells over Nebraska. But, of special note, is the area of markedly backed strong southeasterly flow that extended from extreme southwest Nebraska eastward just north of the Kansas border (red box on Fig. 3b). This flow environment created low level shear values (e.g., 0-1 km) of high magnitudes, consistent with those experienced across outflow boundaries.

3.2 Thermodynamic and Shear Environment

The thermodynamic environment featured moderate to strong instability over central and southern Nebraska with surface based Convective Available Potential Energy (sbCAPE) of between 3500 and 4200 J/kg at 1800 UTC (Fig. 8). The greatest values were associated with the tongue of high dew points that had curled around the dry line bulge discussed above (Fig. 3). It is interesting to note that regions experiencing lowest values of Convective Inhibition Energy (CINH) were coincident with the surface dew point "tongue" (Fig.

3b). Thus, the values shown in Fig. 8 suggest that little or no inhibition existed for surface based convection in the area of high sbCAPE values in south-central Nebraska in the afternoon hours of 24 May.

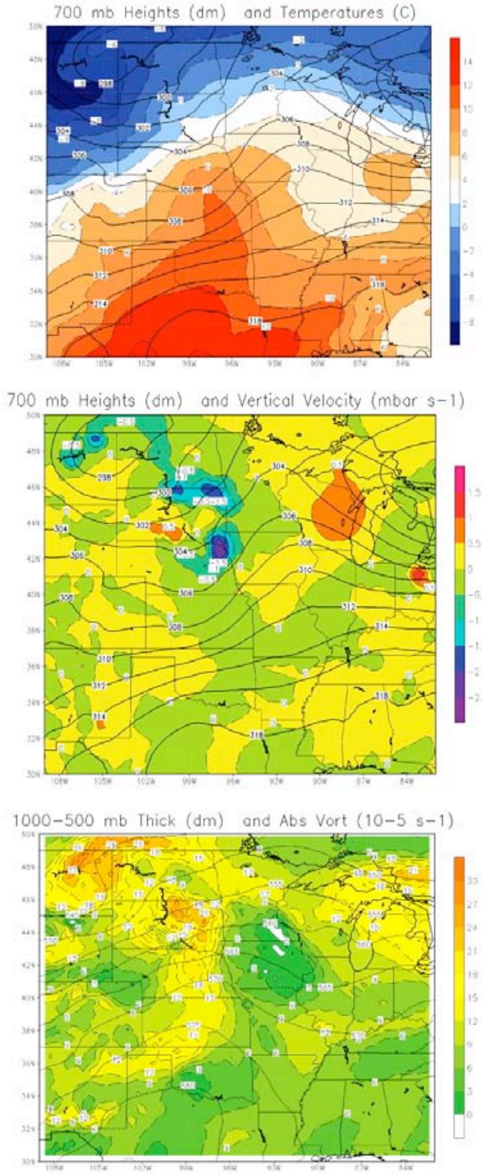

Figure 7 NCEP Reanalyses NAM data, showing key 700 mb features 1800 UTC, 24 May 2004. (a) 700 mb heights d(m) and temperatures (C); (b) 700 mb heights (dm) and vertical velocity (μbar s^{-1}); (c) 1000-500 mb thickness (dm) and 700 mb absolute vorticity (10^{-5} s^{-1}).

The KTOP (Topeka, KS) rawinsonde ascent was closest to the Nuckolls County storm at 1800 UTC on 24 May. This ascent was deep in the warm air south of the boundary, and showed the lid clearly (not shown) while the KOAX (Omaha, NE –not shown) sounding was just north of the synoptic scale boundary and away from the lid edge.

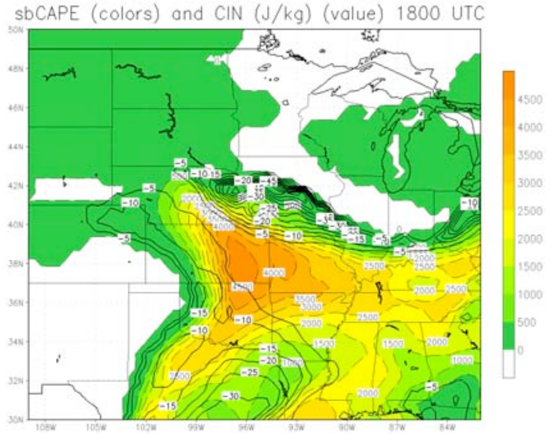

Figure 8 NCEP reanalysis of surface based CAPE (colors) and CINH (black contours) in J/kg at 1800 UTC 43 May 2004.

The greatest difference between the two soundings is the warmer temperatures in the 850-700 mb layer at KTOP. These were associated with the surge of the elevated mixed layer (EML) northeastward over Kansas during the day. The thermodynamic profile in the vicinity of the Nuckolls County storm would have been a merge of the two soundings, and without the lid. The authors have attempted to create a proximity sounding for Beatrice, Nebraska at 1800 UTC (Fig. 9) by merging the two soundings as described above, and including the wind profile from the surface to 5 km for the Fairbury, Nebraska, wind profiler, as discussed in the next section.

Another important point that should be made is that only in the region between the synoptic scale boundary (evident on Fig. 3) and the Kansas border was the dew point depression small enough to yield Lifting Condensation Levels (LCL) very close to the ground (<4000 feet) and also very close the parcel's Level of Free Convection (LFC). Recent studies have shown that tornadogenesis is favored in areas with small temperature and dew point spreads (Davies 2004).

To construct a proximity hodograph for the environment into which Nuckolls County storm moved, the authors used the winds extracted from the Fairbury, Nebraska wind profiler observation at 1600 UTC up to 5 km, and the winds from the 1800 UTC KTOP radiosonde observation.

The hodograph (Fig. 10) is striking. It contains a large anticyclonic loop from 0-3 km. Such a large loop is associated with dynamic pressure forces creating strongly deviant right moving supercells, often associated with mesocyclone tornadoes (Rotunno and Kemp 1985).

The motion of hypothetical splitting storms (given the wind profile shown in the hodograph) is also plotted on Fig. 10. According to the algorithm used to estimate the predicted storm motion (Bunkers et al. 2000), the left moving storm's motion vector should have been on the hodograph; the left movers would not be supercells and would be suppressed. These characteristics were verified by the radar animations examined by the authors (not shown) that showed that the left moving storms in southern Nebraska had brief life cycles and tended to be weak.

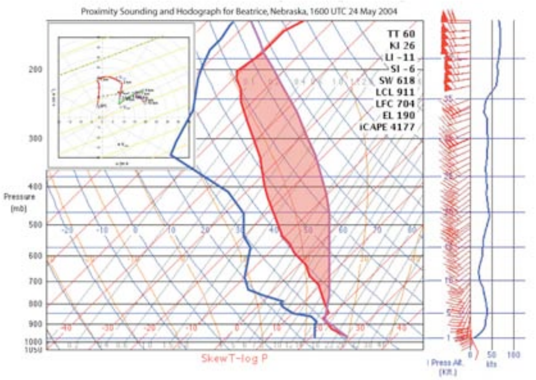

Figure 9 1800 UTC 24 May 2004 proximity sounding for Beatrice, Nebraska, obtained by combining (a) KTOP environmental (red) and dew point (blue) lapse rates (from bottom of lid to surface) and (b) KOAX environmental lapse rate (from top of lid) Inset is 1600 proximity hodograph, shown in Fig. 12. Mandatory and significant level wind information for KTOP and KOAX plotted at right.

A remarkable feature of the hodograph is the intense low level shear suggested by the anticyclonic loop, with a strong kink between 1 and 2 km. Such a kink was observed in the VAD-derived hodographs in Oklahoma on the day of the May 3, 1999 tornadic supercell outbreak (Thompson and Edwards 2000).

The calculated 0-1 km shear from Fig. 12 is 25.7 x 10^{-2} s^{-1}(Table 2). Such shear, if tilted into the vertical and stretched, would be converted into vertical vorticity with a magnitude comparable to that found with moderate and strong tornadoes (Rasmussen et al. 2000). Rasmussen et al. (2000) found such values along boundaries, and presented a case study example of a non-tornadic supercell becoming tornadic when it intercepted and "ingested" such boundaries.

In the present case, the low level shear values were so great that any supercell that formed in such an environment would rapidly process through the so-called supercell cascade to tornadogenesis. In addition, as long as such a storm continued to move through such a favorable buoyancy and shear environment it would continue to produce tornadoes cyclically.

The low level shear favorable for formation of mesocyclones and tornadogenesis is also dramatized by the 0-3 km Storm Relative Helicity (SREH) of 915 m^2 s^2 (Table 2). This value exceeds the values nominally considered favorable for the development of violent mesocyclones (Davies-Jones et al. 1990) and is obviously consistent with what was observed in the radar evolution of the storm.

Finally, the deep layer shear (0-6 km) of 5.6 x 10^{-3} s^{-1}, calculated from the hodograph shown in Fig. 11, was favorable for supercells (Weisman and Klemp 1986). The deep layer shear is a simultaneous control on both (a) the storm ventilation, ensuring that the precipitation core does not interfere with the updraft; and (b) the development of mid-level updraft rotation by providing adequate environmental deep layer shear which, when tilted into the vertical by the updraft, is favorable for the formation of mid-level mesocyclones. In the present case, the value of deep layer shear was of a magnitude that Weisman and Klemp (1986) classify as strong.

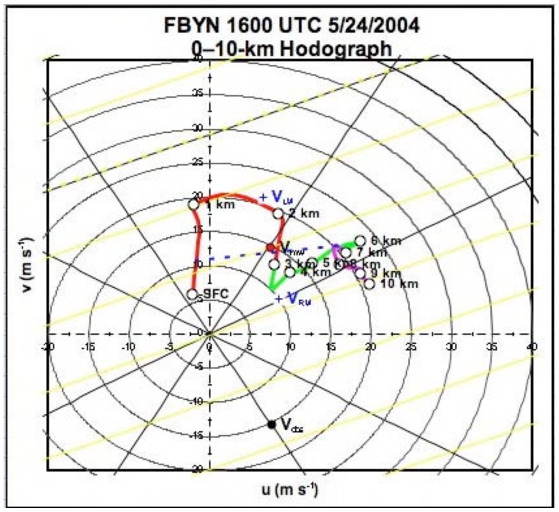

Figure 10 Proximity Hodograph for the Nuckolls County storm obtained from the 1600 UTC Fairbury (FBYN) profiler and the KTOP wind profile at 1800 UTC, as explained in the text.

A summary of the parameters discussed in this section is included in Table 1. The parameters are based upon an evaluation of the proximity soundings (Fig. 9), NCEP reanalysis sbCAPE and CINH (Fig. 8) and the proximity hodograph for the Beatrice area (Fig. 10).

Table 2 Parameters calculated on the basis of the proximity sounding and hodograph given in Figs. 11 and 12, respectively.

sbCAPE	4100 J/kg
0-6 km Shear	5.6 x 10^{-3} s^{-1}
0-3 km Storm Relative Helicity	915 m^2 s^{-2}
Actual Storm Motion	330/30 kts
0-1 km Shear	25.7 x 10^{-3} s^{-1}

4. SUMMARY

There were many unremarkable factors favoring both thunderstorm storm initiation and tornadic supercell mode that coincidentally came into play on May 24, 2004 in south-central Nebraska. These include favorable deep layer shear, adequate to rich low level moisture and a thermodynamic environment favorable for deep convection. All of these can be considered to be a consequence of the synoptic-scale environment.

Nevertheless, we believe that the Nuckolls County tornadic supercell represents a relatively unusual case. Recent submissions to the refereed literature rightfully focus on the role of storm-boundary interaction in the development of supercell tornadoes. However, this case, which essentially duplicated the environment found in Nebraska two days before (Monteverdi et al, 2006) appears to be an illustration of how a storm developing in a unique low level environment, one in which the "background" low level shear values are already favorable for supercell tornadogenesis, can become a repetitive tornado producer.

In this case, the 0-1 km shear values were of a magnitude usually found across outflow boundaries. In fact, the overall pattern setup on May 24 appears to have many similarities to that documented by Thompson and Edwards (2000) in Oklahoma on 3 May 1999. On that day there were also no obvious outflow or synoptic-scale boundaries (beyond a double dry line) present and it appeared that many storms proceeded to tornadogenesis merely by processing the low level shear already present in the environment.

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6. ACKNOWLEDGEMENTS

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