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RUC Soundings with Cool Season Tornadoes in "Small" CAPE Settings and the 6 November 2005 Evansville, Indiana Tornado

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1. Introduction

Several studies of tornadic supercell environments have shown that significant tornadoes (F2 and greater intensity) do occur with relatively "small" mixed-layer convective available potential energy (CAPE < 1000 J kg^{-1}). For example, in Johns et al. (1993), 36 of 242 significant tornado cases were in observed settings having less than 1000 J kg^{-1} of mixed-layer CAPE. Most of these "small" CAPE events occurred during the cool season from November through April. Recently, the nighttime tornado at Evansville, Indiana that killed 24 people on 6 November 2005 was a deadly cool season tornado in a relatively "small" CAPE environment (see Fig. 1).

Due to the differences in CAPE between many cool and warm season tornado environments, cool season tornado settings can at times appear less "ominous" than tornadic warm season settings where total CAPE is often 2 to 4 times larger. Because some cool season tornadoes are deadly (e.g., the 2005 Evansville event), it seems important from a forecasting perspective to examine tornado settings where CAPE is relatively "small" to find parameters and characteristics that are most useful in highlighting such environments.

Thompson et al. (2003) used Rapid Update Cycle (RUC) soundings to examine supercell and tornado environments. The 54 significant tornadoes in their database did not include significant tornadoes from relatively "small" CAPE environments (< 1000 J kg^{-1}). This informal study will examine parameters from RUC analysis profiles during 2001-2005 in severe weather environments with less than 1000 J kg^{-1} of mixed-layer CAPE, including 30 significant tornadoes. An examination of the setting for the deadly Evansville tornado event is also included.

2. Database and computations

An expansion of the RUC sounding database in Davies (2004) was used for this study. All profiles were located within 100 km and 60-90 minutes of random severe-warned and tornado-warned storms, within the storm inflow air mass. These were updated in the lowest levels using observed surface data. More detail is given in Davies (2004).

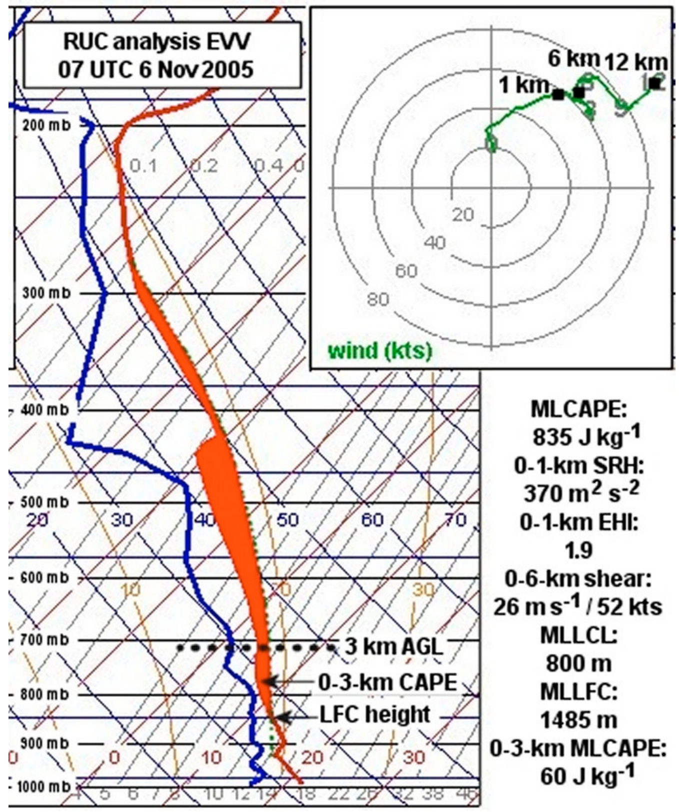

Fig. 1. *SkewT-logp diagram of RUC analysis sounding for Evansville, Indiana at 0700 UTC 6 Nov 2005. Red line is temperature, blue line is dewpoint, and red shading is mixed-layer CAPE. Significant features are labeled, and selected parameter values are shown. Inset depicts wind via hodograph trace in knots.*

Of 1531 RUC analysis profiles collected during 2001-2005, 1250 were associated with verified supercells. Of these, 1106 were not linked to tropical cyclones (e.g., Davies 2006, this volume) or mid-latitude cold core 500-mb lows (e.g., Guyer and Davies 2006, this volume), which are "small" CAPE settings that are somewhat unique and warrant separate study. Table 1 summarizes these profiles, categorized by

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Table 1. Summary of supercell profiles from RUC database 2001-2005 not associated with tropical systems or 500-mb cold core lows, by CAPE ranges (1106 of 1250 total supercells):

174 significant (F2-F4) tornadoes	
MLCAPE < 1000 J kg^{-1}:	30 (15 deadly events)
MLCAPE $\geq$ 1000 J kg^{-1}:	144 (32 deadly events)
378 weak (F0-F1) tornadoes	
MLCAPE < 1000 J kg^{-1}:	99 (2 deadly events)
MLCAPE $\geq$ 1000 J kg^{-1}:	279 (4 deadly events)
554 nontornadic	
MLCAPE < 1000 J kg^{-1}:	192
MLCAPE $\geq$ 1000 J kg^{-1}:	362

significant tornadic, weak tornadic, and nontornadic supercells, and by CAPE ranges.

Of the 1106 soundings, 321 had "small" CAPE (< 1000 J kg^{-1}), and 129 were associated with tornadoes, including 30 significant tornadoes according to the publication *Storm Data*. All but 3 of the "small" CAPE significant tornadoes occurred from November through April (the cool season), and a high percentage caused deaths (50%, 15 of 30).

Parameters known to be important regarding supercell tornado environments from prior empirical studies (e.g., Davies and Johns 1993; Rasmussen and Blanchard 1998; Rasmussen 2003; Thompson et al. 2003; Davies 2004, Craven and Brooks 2004) were computed for these "small" CAPE supercell cases. Tornadic events were compared with nontornadic events to isolate parameters that appeared to discriminate between the two groupings. The "small" CAPE supercell cases (< 1000 J kg^{-1}) were also compared with those in "moderate to large" CAPE settings ($\geq$ 1000 J kg^{-1}). All thermodynamic parameters were computed using lowest 100-mb mixed-layer (ML) lifted parcels and the virtual temperature correction.

3. Results

Table 2 shows median values of several parameters commonly used in supercell tornado forecasting, grouped similar to Table 1. Median values were used to reduce the influence of extreme outlying events. Looking only at the "small" CAPE cases (CAPE < 1000 J kg^{-1}), the following parameters appeared to show the largest difference in median values between the nontornadic and significant tornadic groups: 0-1-km SRH (storm-relative helicity), LFC (level of free convection), CIN (convective inhibition), and low-level CAPE (0-3-km). The 0-1-km energy-helicity index (EHI, e.g., Davies 1993; Rasmussen 2003), a composite CAPE-SRH parameter, also appeared to distinguish fairly well between nontornadic and tornadic "small" CAPE settings, although EHI values were definitely smaller than those in larger CAPE events. It is worth noting that none of the significant tornado environments associated with "small" CAPE in this study had mixed-layer CAPE values less than 250 J kg^{-1} (not shown).

In Table 2, note that median height of LCL (lifting condensation level, e.g., Thompson et al. 2003) was uniformly low for the "small" CAPE cases and not much of a distinguishing factor between categories. Cool season severe events typically have low LCL heights. However, median LFC height (*different* from LCL height) did suggest some useful discrimination (Davies 2004) between the "small" CAPE nontornadic and tornadic cases in Table 2. Because parameters such as 0-3 km CAPE and CIN are closely related to LFC height, they also suggested some similar distinguishing ability. The amount of CAPE below 3 km may in some ways be more consistently useful than LFC height because it is a positive *area* representing buoyancy close to the ground. In contrast, LFC is a single *point* in the vertical that can be very sensitive to

Table 2. Median parameter values for RUC database supercell cases not associated with tropical systems or 500-mb cold core lows, categorized by MLCAPE < 1000 J kg^{-1} and MLCAPE $\geq$ 1000 J kg^{-1}

RUC supercell cases	MLCAPE J kg^{-1}	0-1-km SRH $m^2 s^{-2}$	0-1-km EHI	0-6-km shear m s^{-1}	MLLCL m	MLLFC m	MLCIN J kg^{-1}	0-3-km MLCAPE J kg^{-1}
MLCAPE < 1000 J kg^{-1}:								
F2-F4 sig tor (30 cases)	676	357	1.4	25	772	1489	-20	69
F0-F1 wk tor (99 cases)	590	198	0.6	24	814	1636	-25	64
nontornadic (192 cases)	473	175	0.4	24	952	2516	-64	13
MLCAPE $\geq$ 1000 J kg^{-1}:								
F2-F4 sig tor (144 cases)	2494	206	2.9	25	1006	1556	-22	90
F0-F1 wk tor (279 cases)	2141	113	1.6	21	1246	1725	-20	70
nontornadic (362 cases)	2039	86	1.1	19	1254	2004	-34	49

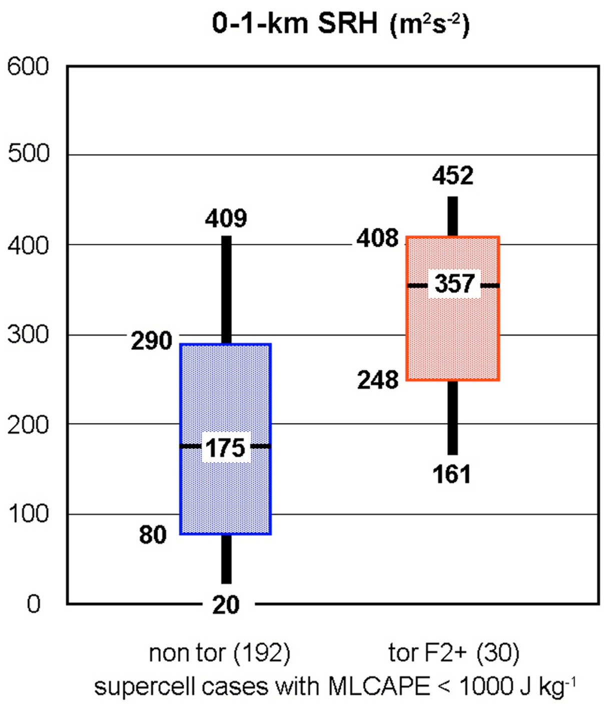

Fig. 2. Box and whisker diagram showing distribution of 0-1-km SRH for nontornadic and significant tornadic "small" CAPE supercells from Table 2. Boxes are 25th to 75th percentiles, and whiskers extend to 10th and 90th percentiles. Horizontal bars show median values.

lifted parcel choice and model sounding accuracy.

Figures 2 and 3 show the distribution of 0-1 km SRH and 0-3 km CAPE values for "small" CAPE cases via box and whisker diagrams, contrasting nontornadic and significant tornadic events (weak tornadoes were omitted to emphasize differences). These figures suggest that a *combination* of low-level wind profile and low-level thermodynamic environment is important in "small" CAPE tornado settings. Areas that have large low-level SRH *combined with* sizable low-level CAPE appear to offer better support for supercell tornadoes. Such environments would be strongly surface-based, offering little resistance to rising parcels within the same layer where strong low-level shear was located. This would likely facilitate the tilting of horizontal streamwise vorticity (Davies-Jones 1984; Davies-Jones et al. 1990).

Table 2 also shows median values of selected parameters for "moderate to large" CAPE environments ($\geq$ 1000 J kg^{-1}). Similar to the "small" CAPE cases, the significant tornadic storms in these larger CAPE environments also tended to have greater 0-1-km SRH, lower LFC heights, and more low-level CAPE. However, the differences in medians of these parameters weren't quite as great between nontornadic and significant tornadic categories as in the "small" CAPE cases. Notice, too, that the median value of EHI in Table 2 associated with significant tornadoes in "moderate to large" CAPE settings was at least twice that of significant tornadoes in "small" CAPE settings. This emphasizes that relevant parameter values and combinations vary greatly between seasonal situations, and that the idea of parameter "thresholds" is quite dubious. It behooves forecasters to concentrate on areas where parameter values are *maximized* in relation to areas of thunderstorm development, rather than using specific parameter "numbers" and "thresholds" when assessing environment conditions.

4. Evolution of the 6 November 2005 Evansville tornado environment

The deadly Evansville tornado early on 6 November 2005 occurred in an environment of relatively "small" CAPE, but with strong low-level SRH accompanied by sizable low-level CAPE. Figure 1 from earlier shows the Evansville RUC analysis sounding at 0700 UTC, roughly 1 hour before the long track tornado struck the south side of the city. Although mixed-layer CAPE was only around 835 J kg^{-1}, 0-1-km SRH based on observed storm motion was quite large (350-400 m^2 s^{-2}), and low-level CAPE was sizable (60 J kg^{-1}), with a relatively low LFC (1480 m). These characteristics fit well with the median values for "small" CAPE significant tornadoes in Table 2 from the prior section.

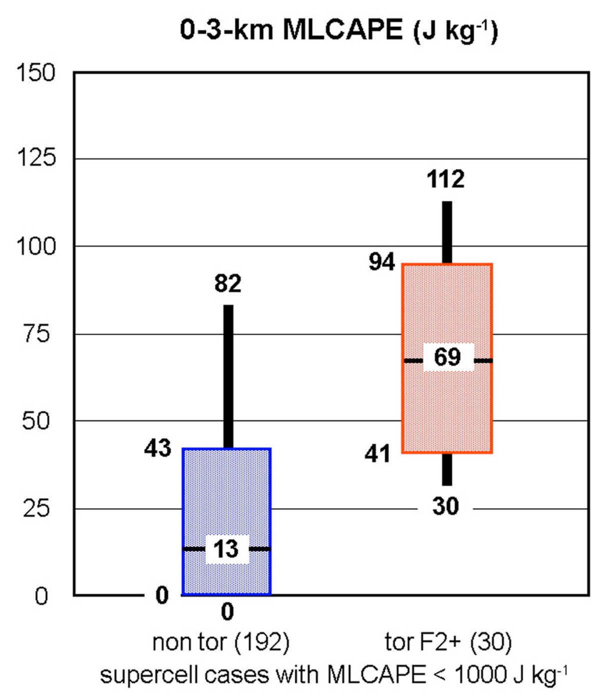

Fig. 3. As in Fig. 2, except 0-3-km mixed-layer CAPE.

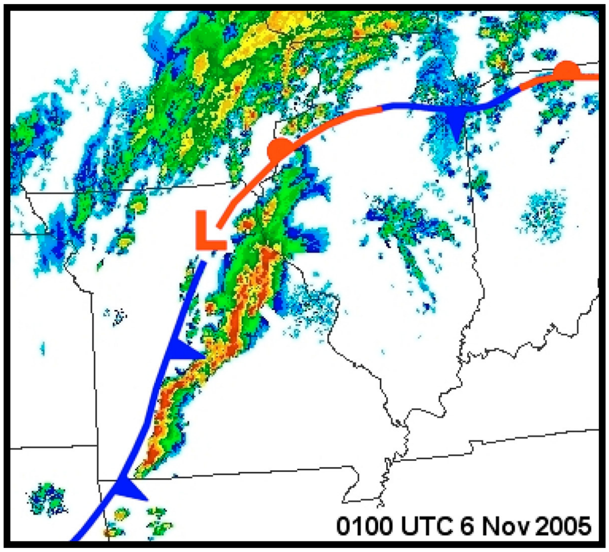

Fig. 4. *Mosaic of radar base reflectivity (0.5º elevation angle) and surface features (conventional) over the central Mississippi River Valley and surrounding area at 0100 UTC 6 November 2005.*

Mesoanalysis graphics from the Storm Prediction Center (SPC, Bothwell et al. 2002) documented the spatial evolution of these parameters through the evening of 5 November 2005 leading up to the Evansville tornado. At early to mid evening, a strong upper trough (not shown) was moving through the Midwest, generating a line of thunderstorms from west central Illinois to southwest Missouri in conjunction with a cold front (Fig. 4). Deep layer shear was strong across this entire area, greater than 25 m s^{-1} (50 kts, not shown), and very supportive of supercell storms. Figure 5 shows fields of total CAPE, 0-1-km SRH and 0-3-km CAPE at 0100 UTC 6 November 2005. Total CAPE greater than 1000 J kg^{-1} was present over a broad area from northern Indiana to Arkansas, and 0-1-km SRH (> 200-300 m^2 s^{-2}) was large over the same area ahead of the front. However, significant *low-level* CAPE (> 50 J kg^{-1}) was confined to southwest Missouri and northwest Arkansas. Tornadoes occurred with storms southeast of Springfield, Missouri after 0100 UTC where low-level CAPE was co-located with large SRH (Fig. 5). It is worth noting that tornado-warned storms northwest of St. Louis in the same time frame produced no tornadoes where low-level CAPE was absent.

As the evening progressed, although total CAPE lessened in value slightly, low-level SRH remained strong ahead of the front, and significant 0-3-km CAPE moved across southern Missouri and northern Arkansas on the SPC graphics (see Fig. 6 at 0400 UTC). This environment probably contributed to tornadoes that caused injuries in northern Arkansas and southern

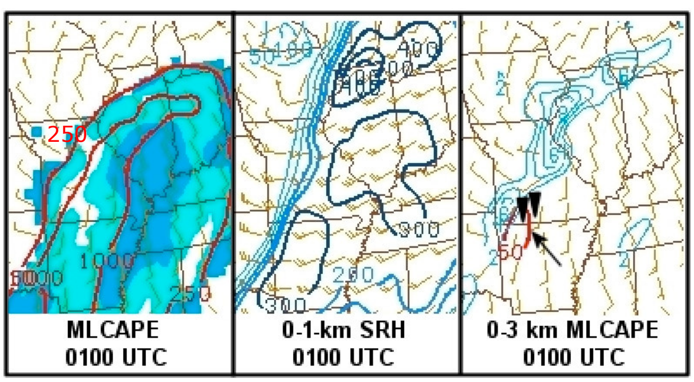

Fig. 5. *SPC mesoanalysis graphics of mixed-layer total CAPE (250 and 1000 J kg^{-1} red contours, blue shading depicting CIN), 0-1-km SRH (> 50 m^2 s^{-2}, blue contours), and 0-3-km mixed-layer CAPE (> 50 J kg^{-1}, red contour) at 0100 UTC 6 November 2005, centered on same general area as Fig. 4. F1 tornado reports between 0100 and 0200 UTC are indicated by inverted black triangles in last panel.*

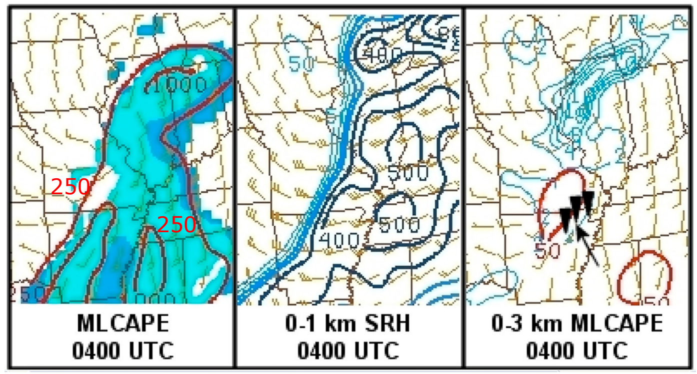

Fig. 6. *As in Fig. 5, except at 0400 UTC 6 November 2005. F2 tornado reports between 0400 and 0500 UTC are indicated in last panel.*

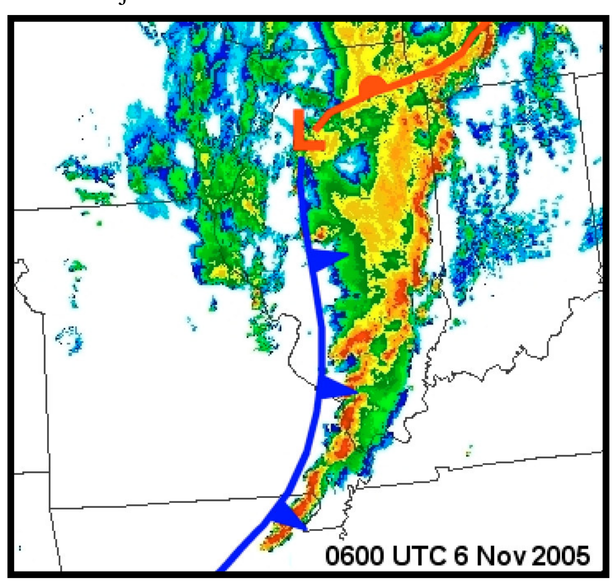

Fig. 7. *As in Fig. 4, except at 0600 UTC 6 November 2005.*

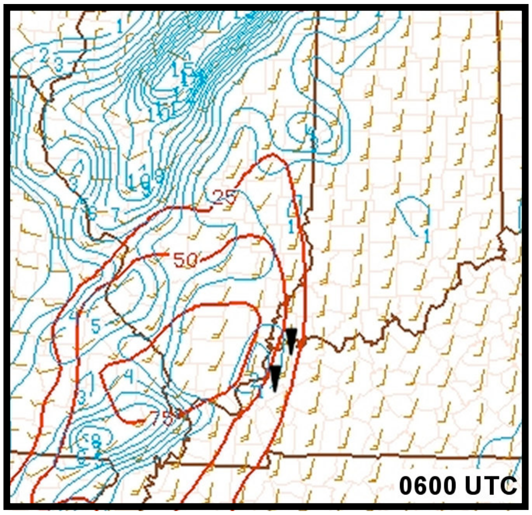

Fig. 8. *SPC mesoanalysis of mixed-layer 0-3-km CAPE (> 25 J kg^{-1}, red contours) at 0600 UTC 6 November 2005. F3 tornadoes 0700-0800 UTC are indicated by inverted black triangles.*

Missouri after 0400 UTC (Fig. 6).

By 0600 UTC, the line of storms (Fig. 7) had progressed to central and eastern Illinois through southeast Missouri. Total CAPE (< 1000 J kg^{-1}, not shown, but similar to Fig. 6) had *decreased* ahead of the surface front compared to 0100 UTC (Fig. 5), but significant 0-3-km CAPE (> 50 J kg^{-1}, Fig. 8) had moved eastward into southern Illinois and western Kentucky. In this same area, 0-1-km SRH (> 400 m^2 s^{-2}, not shown) had *increased*. Dovetailing with these analyses, LFC heights (Fig. 9) were quite low over an area along the Ohio River from Paducah, Kentucky to near Evansville, Indiana, where CAPE-SRH combinations via the 0-1-km EHI (Fig. 10) were maximized. Although total CAPE was relatively "small" (< 1000 J kg^{-1}) at 0600 UTC ahead of the

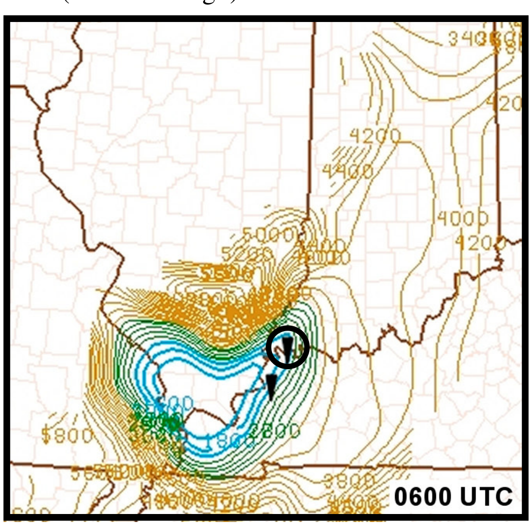

Fig. 9. *As in Fig. 8, except mixed-layer LFC height (blue lines < 2000 m). Evansville tornado is circled.*

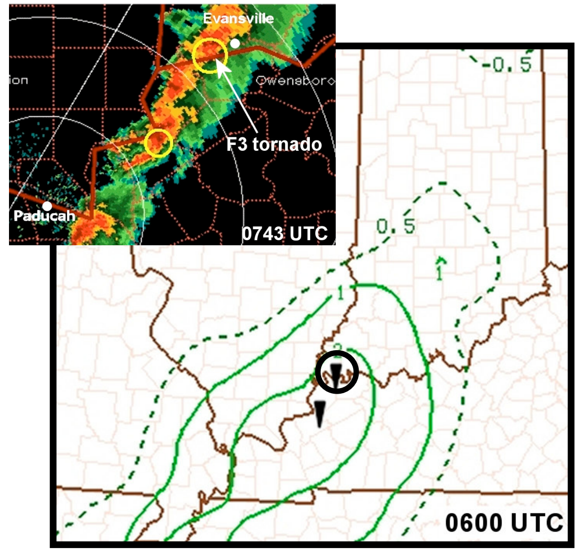

Fig. 10. *As in Fig. 9, except mixed-layer 0-1-km EHI. Radar inset (0.5^o base reflectivity) shows Evansville tornadic storm (arrow) at 0743 UTC.*

surface front, relevant parameters discussed in the prior section were co-located and favorable for supporting tornadoes over a well-defined area of the western Ohio River Valley.

Storms moving through southern Illinois at 0600 UTC area were oriented north to south in a broken squall line (Fig. 7), but individual cells in the line developed supercell characteristics in the strongly sheared, surface-based environment. By 0740 UTC, long track tornadoes from two different supercells (locations shown in Figs. 8-10, see also radar inset in Fig. 10) commenced over western Kentucky and southwest Indiana near the Ohio River, including the deadly Evansville tornado. Although total CAPE was "small" and had decreased through the evening ahead of the surface front, other parameters as discussed above suggested good environment support for supercell tornadoes in the Paducah-Evansville area 1-2 hours in advance of the deadly tornado.

Unfortunately, the "small" CAPE setting, with decreasing CAPE values by late evening, and the lack of timely tornado verification reports before 0600 UTC in southern Missouri and northern Arkansas, contributed to poor anticipation of the developing tornadic environment. Although timely local tornado warnings were issued in the Evansville area after 0730 UTC, only severe thunderstorm watches were in effect over the western Ohio River Valley in the hours prior to and during the deadly Evansville event.

5. Discussion and summary

This study confirms that cool season tornadoes in relatively "small" CAPE environments can be deadly, as 15 of 30 significant tornadoes associated with RUC profiles exhibiting mixed-layer CAPE less than 1000 J kg^{-1} caused deaths. The killer tornado at Evansville, Indiana on 6 November 2005 was a pointed example.

Examination of RUC profiles associated with "small" CAPE tornado cases in this study suggests that extra attention be paid to the juxtaposition of increased values of the following parameters in cool season severe weather situations:

- 0-1-km SRH
- 0-3-km mixed-layer CAPE

The co-location of these parameters may suggest enhanced potential for strong surface-based updrafts and low-level mesocyclone development in a strongly sheared near-ground environment. Such settings would offer little resistance to rising parcels within the same layer where strong SRH was located.

Trends of LFC height may be useful in locating areas where low-level CAPE is developing. Experience has shown that hourly LFC height estimations trending below 2600-3000 m AGL on plan view analyses will often anticipate the development of significant 0-3 km CAPE and more strongly surface-based environments. Both low-level CAPE and LFC height (Davies 2004) are *different* than LCL height, and can offer specific information for locating strongly surface-based environments relevant to tornadoes when LCL heights are uniformly low over large areas in the cool season.

This study also reaffirms that, when low-level CAPE is present, maximized areas of CAPE-SRH combinations (e.g., EHI) can be useful in locating tornado potential. However, relevant values of composite parameters such as EHI vary considerably between cool and warm season (see Table 2), rendering "thresholds" and specific number values to be dubious and misleading from a forecasting perspective (e.g., Brooks et al. 1994). Instead, the juxtaposition and evolution of areas of *maximized* parameter values are more operationally relevant, as shown in the Evansville case example.

Additional investigation of "small" CAPE tornado events is warranted. Studies such as McCaul and Weisman (2001) show that the proper vertical distribution of buoyancy, though relatively small in quantity, can contribute to strong mesocyclones when combined with appropriate shear. There may be ways to emphasize these characteristics in an operationally meaningful way for improving detection of some cool season tornado environments that involve deceptively "small" CAPE.

Further investigation is also suggested regarding choice of mixed-layer lifted parcel depth when computing CAPE-related parameters (see Davies 2006, and Guyer & Davies 2006, both this volume) in many cool season severe weather events. Although not pursued here, the large low-level relative humidity characteristics of many RUC soundings examined in this study suggests that lowest 100-mb mean lifted parcels commonly used (e.g., Craven et al. 2002) may average too deep a mixed layer to properly reflect CAPE characteristics in some cool season events. For example, the use of a lowest 50-mb mean lifted parcel (not shown) with the Evansville RUC profile in Fig. 1 boosted the total CAPE by 20% (to near 1000 J kg^{-1}), low-level CAPE by 25%, and the EHI value by more than a third. These may be more realistic values given the moist low-levels of this sounding.

In summary, cool season "small" CAPE environments often appear less "threatening" than warm season environments that have much larger amounts of total CAPE. Careful attention to parameters such as low-level SRH and low-level CAPE emphasized in this study can offer increased awareness of tornado potential in cool season settings where CAPE is deceptively small.

Acknowledgements

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