P1.3

Total CAPE, Low-level CAPE, and LFC in Significant Tornado Events with Relatively High LCL Heights

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1. Introduction

Lifting condensation level (LCL) height is used widely as a limiting parameter in supercell tornado forecasting. Studies such as Rasmussen and Blanchard (1998), Thompson et al. (2003), and Craven and Brooks (2004) have confirmed that most significant tornadoes are associated with environments having LCL heights less than 1300 m above ground. Markowski et al. (2002) also found that mean surface dewpoint depressions (related to LCL height) in the inflow of tornadic supercells were smaller than those associated with nontornadic supercells (5.7° C compared to 8.9° C). The accepted interpretation of these results is that higher LCL heights and larger surface dewpoint depressions (suggesting higher cloud bases) encourage rapid low-level cooling through evaporation in the sub-cloud layer when precipitation begins to occur. This "cold pooling" would likely interfere with developing surface circulations that could become tornadoes. Markowski et al. (2002) also suggested that surface dewpoint depressions in supercell inflow are related to rear flank downdraft properties that affect tornadogenesis.

Davies (2006a, hereafter D06) noted that some supercell tornadoes, particularly those in the elevated plains of the United States, tend to occur with LCL height environments that are *higher* (e.g., > 1300 m) than those found in the studies mentioned above. To explore tornadic supercells in such LCL environments, a database of Rapid Update Cycle (RUC; Benjamin et al. 2004) soundings was used to examine significant tornado cases associated with supercells and mixed-layer (ML) LCL heights that were relatively "high" (> 1300 m). This informal study will summarize the results and suggest parameters in high LCL settings that may be important when assessing environments with potential for supercell tornadoes. Two significant tornado events involving LCL heights that were relatively high will also be examined as brief case studies.

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Table 1. Summary of supercell profiles (1250 total) from RUC database 2001-2005
212 significant (F2-F4) tornadoes: 44 (21%) with LCL > 1300 m AGL
439 weak (F0-F1) tornadoes: 157 (36%) with LCL > 1300 m AGL
599 nontornadic: 223 (37%) with LCL > 1300 m AGL

2. Database and methodology

The database of RUC sounding profiles in Davies (2004, hereafter D04) and D06 was expanded to more than 1500 profiles from the years 2001 through 2005. All profiles were located within 100 km and 60-90 min prior to radar-warned storms in the storm inflow air mass (see D04 for more details). The resulting database was associated with storms chosen randomly from severe or tornado-warned events, with severe thunderstorm or tornado reports verified from the publication *Storm Data* and National Weather Service (NWS) office surveys posted online. Of 1531 profiles in the database, 1250 were associated with verified supercells. Table 1 is a summary of the supercell profiles, also noting those with higher LCL heights.

As in D04 and D06, observed surface temperature, dewpoint, and wind information at the same time and location were saved and used to modify profiles in the lowest 150 mb when they differed significantly from the raw model profile information (see D04 for details). This modification was done to make the lowest levels of model-derived soundings representative of *observed* surface conditions. All thermodynamic computations were performed using lowest 100-mb mixed-layer (ML) parcels and the virtual temperature correction (Doswell and Rasmussen 1994).

In this database, 212 profiles were associated with F2 and greater intensity tornadoes. From Table 1, 44 (21%) of these profiles were associated with LCL heights > 1300 m AGL (considered relatively "high", as in D06). The following section will look at this group of profiles more closely.

Table 2. Median parameter values associated with significant tornadoes in RUC database

F2-F4 tornado cases (212 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}
"high" LCL (> 1300 m) (44 cases)	3138	160	2.5	22	1523	1980	-31	68
"low" LCL (≤ 1300 m) (168 cases)	1624	234	2.2	24	832	1361	-16	94

3. Parameter results in "high" LCL tornado cases

Table 2 summarizes median values of several accepted parameters from supercell tornado environment research (e.g., Davies and Johns 1993; Rasmussen and Blanchard 1998; Rasmussen 2003; Thompson et al. 2003; D04, Craven and Brooks 2004) for the significant tornadoes in the RUC database. These are grouped by "low" LCL cases (≤ 1300 m) and "high" LCL cases (> 1300 m), similar to groupings in D06. Medians are used to eliminate the influence of isolated cases with extreme outlying values.

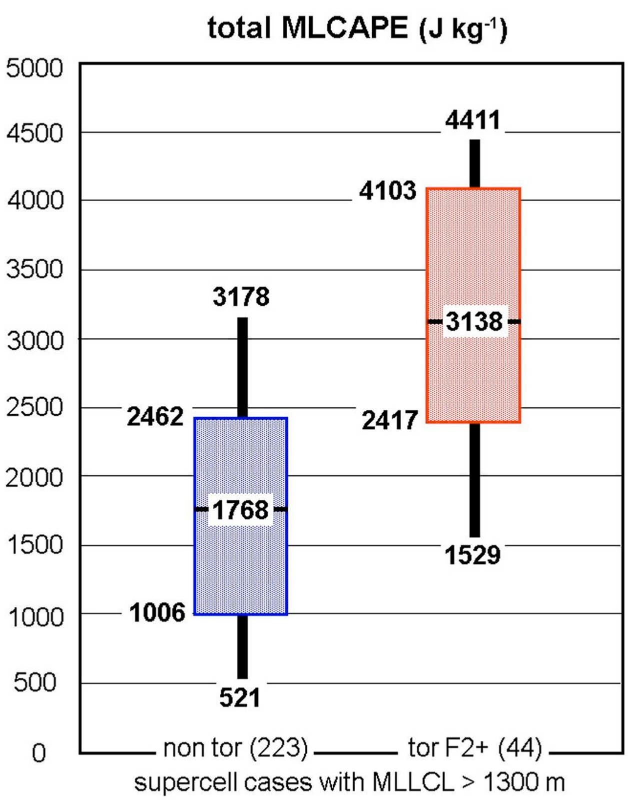

Fig. 1. Box and whisker diagram showing distribution of total mixed-layer CAPE for supercells with "high" LCL heights (> 1300 m) in RUC database that were nontornadic (223 cases) and significant tornadic (44 cases). Boxes are 25th to 75th percentiles; whiskers extend to 10th and 90th percentiles. Horizontal bars show median values.

Total convective available potential energy (CAPE), 0-1-km storm relative helicity (SRH), and 0-6-km shear are parameters used (in addition to LCL height) in the original formulation of the significant tornado parameter from Thompson et al. (2003). Median values of these parameters in Table 2 were within ranges most associated with significant tornadoes in that study, regardless of grouping by "low" or "high" LCL. It is notable that the median value of CAPE for the "high" LCL cases was nearly twice as large as for the "low" LCL cases.

Table 2 also shows median values of other thermodynamic parameters, such as 0-3-km CAPE (Rasmussen 2003; D06), and level of free convection height (LFC, e.g., D04). Note that CAPE below 3 km was relatively large (> 60 J kg^{-1}, similar to Rasmussen 2003) for both the "low" and "high" LCL cases, despite the difference in LCL height between groups. Median height of LFC was also relatively low (near 2000 m or below) for both groupings, as more CAPE in low-levels is generally associated with lower LFC heights.

Because Table 2 suggests that values of total CAPE and 0-3-km CAPE may be important in "high" LCL tornado cases, box and whisker diagrams in Fig. 1 and Fig. 2 show the distribution of these parameters. Nontornadic and significant tornadic supercell cases associated with "high" LCL heights in the RUC database are shown, with weak tornadoes omitted to emphasize differences. Note that the tornadic "high" LCL cases in Fig. 1 had considerably more total CAPE, with an offset of roughly 2 quartiles between categories. Also, the tornadic "high" LCL cases in Fig. 2 had more 0-3-km CAPE, with an offset of roughly one quartile between categories.

The results in Table 2 suggest that, in most significant tornado cases where LCL heights are relatively "high", sizable low-level SRH and deep layer shear are also present, the same as in significant tornado cases associated with "low" or more "typical" LCL heights. However, Figs. 1 and 2 suggest that an important difference may be large total CAPE in the environment, encouraging rapid updraft intensification, and the presence of buoyancy *in low levels*. Even with

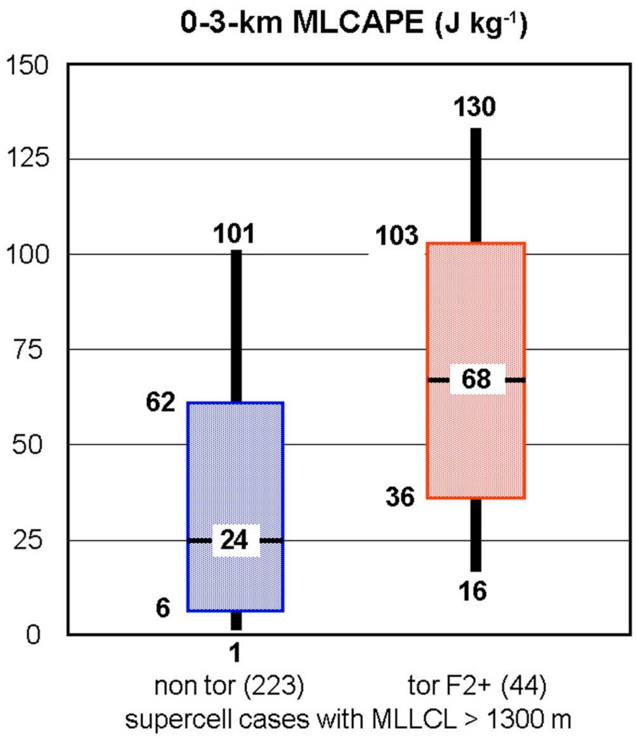

***Fig. 2.** As in Fig. 1, except 0-3-km mixed-layer CAPE.*

a relatively "high" LCL and cloud base, these factors suggest a strongly *surface-based* environment with significant low-level moisture depth and the lack of a strong inhibiting inversion. Such an environment would promote explosive storm growth in a sheared setting, possibly accelerating evolution of supercell storm features that could contribute to tornado development before significant cold pooling from evaporation below relatively "high" cloud bases.

The following cases (one near the Mississippi River, the other in the northern plains) will offer examples of these characteristics in supercell tornado forecast situations involving strongly sheared environments with relatively "high" LCL heights.

4. Case studies

All parameter fields shown in the following cases are from the Storm Prediction Center (SPC) mesoanalysis page (Bothwell et al. 2002), and use lowest 100-mb mixed-layer lifted parcels.

a. 13 April 2006 east central Iowa

Late on the afternoon of 13 April 2006, storms developed rapidly over central and eastern Iowa in strong low-level convergence ahead of a surface trough (Fig 3). This occurred beneath strong west-northwest flow aloft at 500 mb (not shown), resulting in a strongly sheared environment with 0-6-km shear values around 25 m s^{-1} (50 kts, not shown). Several supercells produced tornadoes, including a strong F2 tornado at Iowa City that injured 30 people, and another tornado that killed one person northwest of Muscatine.

Graphics from the SPC mesoanalysis page at 2300 UTC showed LCL heights (Fig. 4) to be relatively high (1600-2000 m) across east central Iowa, with spreads between surface temperature and dewpoint on the order of 11-15^{o} C (20-25^{o} F, Fig. 3). However, apart from LCL height, total CAPE was large (around 3000 J kg^{-1},

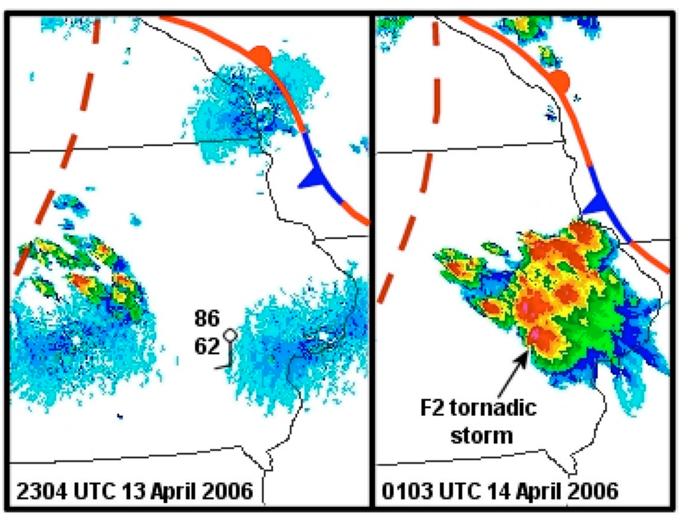

***Fig. 3.** Radar base reflectivity (lowest elevation angle) and surface features (conventional) over eastern Iowa and surrounding area at 2304 UTC 13 April 2004, and 0103 UTC 14 April 2004. Surface observation at Iowa City is shown, and supercell that produced the F2 Iowa City tornado is also indicated.*

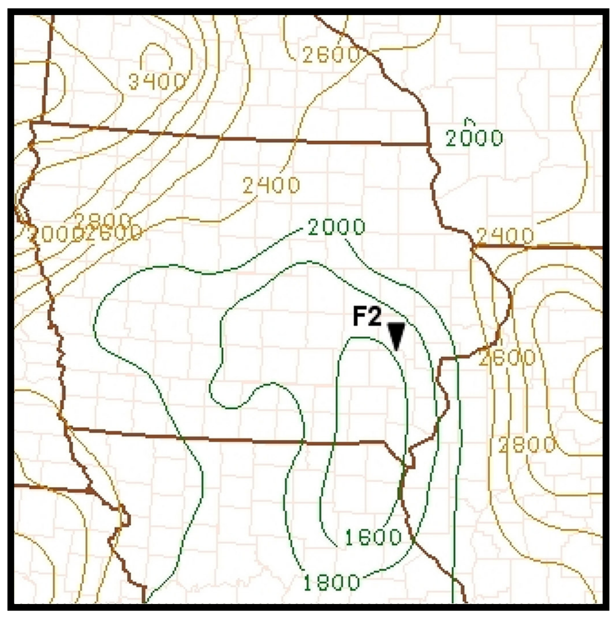

***Fig. 4.** SPC mesoanalysis of mixed-layer LCL height (200 m increments) at 2300 UTC 13 April 2004. Location of later tornado at Iowa City is also shown.*

not shown). When combined with sizable low-level SRH (150-250 $m^2\ s^{-2}$, not shown), this resulted in maximized values of the 0-1-km energy-helicity index (EHI, e.g., Davies 1993; Rasmussen 2003) over east and southeast Iowa (Fig. 5), suggesting support for supercell tornadoes. Also of note were sizable values of 0-3-km CAPE (50-75 J kg^{-1}, Fig. 6) from central to southeast Iowa at 2300 UTC. This resulted in LFC heights that were relatively "low" (2000-2200 m, not shown), even though LCL heights were "high".

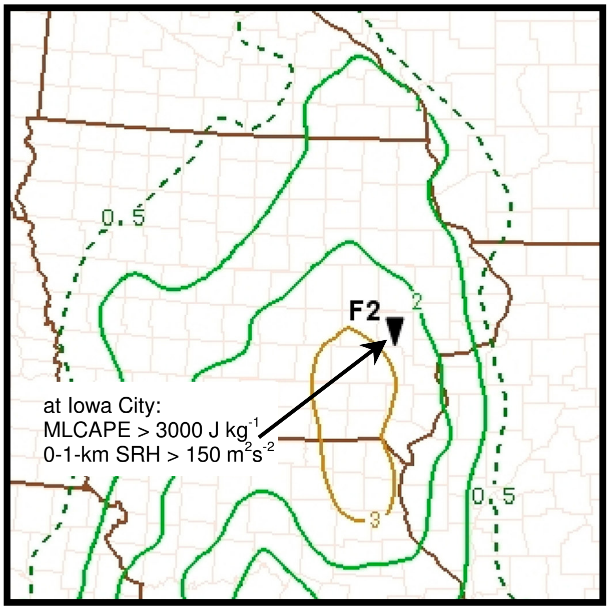

Fig. 5. *As in Fig. 4, except 0-1-km EHI, combining mixed-layer CAPE and 0-1-km SRH.*

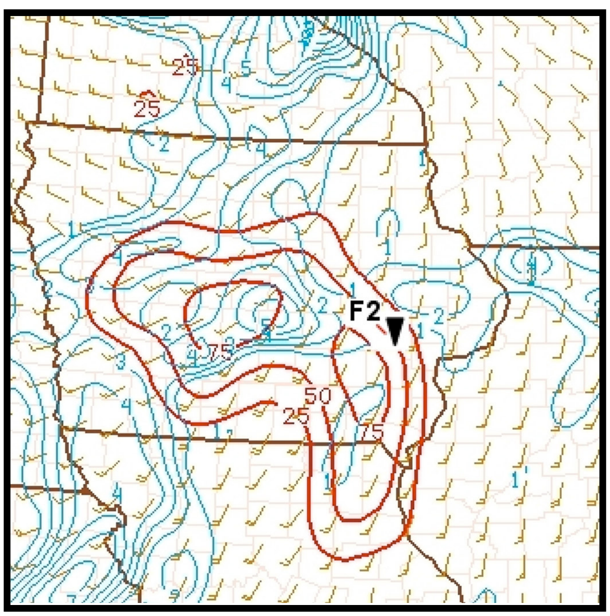

Fig. 6. *As in Fig. 4, except 0-3-km mixed-layer CAPE (> 25 J kg^{-1} in red), and surface vorticity (10^{-4} s^{-1} in blue). Wind flags show surface wind flow.*

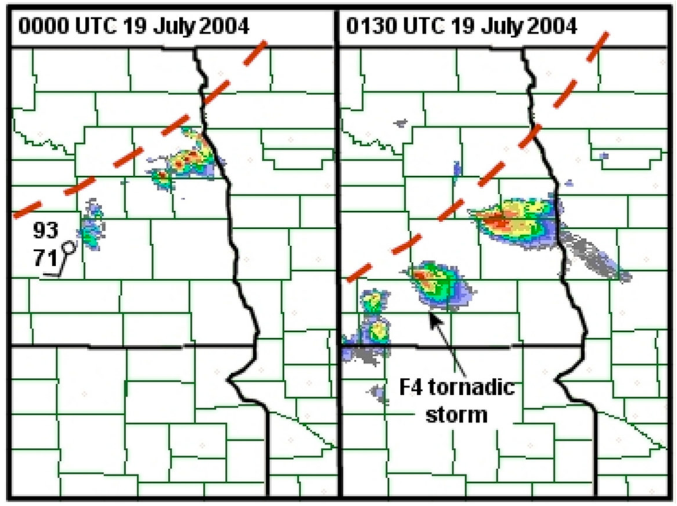

Fig. 7. *As in Fig. 3, except for 0000 UTC and 0130 UTC 19 July 2004 over eastern North Dakota and surrounding area. Surface observation at Jamestown is shown, and supercell that produced the F4 tornado southeast of Jamestown is also indicated.*

The Iowa City storm developed rapidly around 0000 UTC (14 April), producing its first tornado around 0115 UTC. The F2 tornado occurred around 0130 UTC. Other supercells also produced tornadoes, resulting in more than 10 tornadoes between 0000 UTC and 0300 UTC, and 1 death. Unfortunately, even with large CAPE and shear in the environment, the setting caught many forecasters unaware regarding the potential for tornadoes, possibly due to the deceptively high LCL heights. A severe thunderstorm watch remained in effect throughout the event.

b. 18 July 2004 eastern North Dakota

Two southward-moving supercell storms over eastern North Dakota on the evening of 18 July 2004 (Fig. 7) produced 8 tornadoes ahead of a slow moving surface trough under north-northwest flow at 500 mb (not shown). Resulting deep layer shear was strong, near 25 m s^{-1} (50 kts, not shown). The westernmost supercell in Fig. 7 was relatively high-based, yet produced the strongest tornado, rated F4 with intense damage.

At 0000 UTC (19 July), SPC mesoanalysis graphics showed LCL heights to be relatively high (Fig. 8), ranging from around 1300 m near the Red River to roughly 1800 m in the Jamestown area. However, total CAPE was large (> 3000 J kg^{-1}, not shown) over much of eastern North Dakota, and low-level SRH was on the order of 100-200 m^2 s^{-2} (not shown). This resulted in strong CAPE-SRH combinations, with 0-1-km EHI values maximized over east central and southeast North Dakota (Fig. 9).

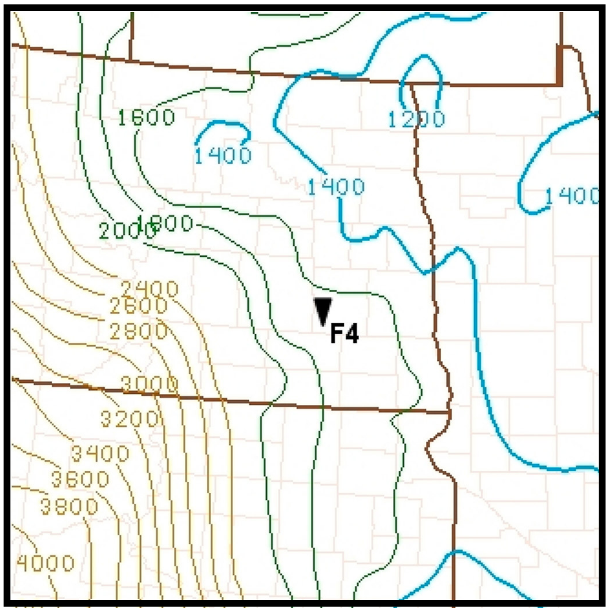

Fig. 8. *SPC mesoanalysis of LCL height as in Fig. 4, except at 0000 UTC 19 July 2004 over northern plains. Location of later F4 tornado near Jamestown is also shown.*

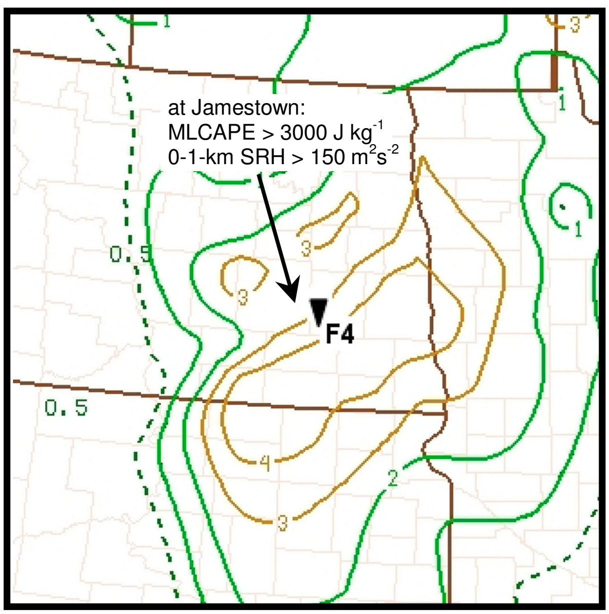

Fig. 9. *As in Fig. 8, except 0-1-km EHI, similar to Fig. 5.*

Although LCL heights were high, LFC heights were "low" in a relative sense, 2000-2400 m (Fig. 10) over east central North Dakota along the surface trough where supercells developed. As a result, 0-3-km CAPE was sizable, with values of 50-100 J kg^{-1} (not shown).

The supercell that produced the first tornadoes west of Grand Forks developed at late afternoon in an area where LCL heights were lowest (near 1300 m). However, the supercell that produced the F4 tornado at 0125 UTC east of Jamestown developed rapidly after 0000 UTC in an area where LCL heights were much higher (near 1800 m), and spreads between surface temperature and dewpoint were wide (12^o C; 22^o F, Fig. 7).

In both cases above involving strong or violent tornadoes, LCL heights were high (1600-1800 m), but strong CAPE-SRH combinations and deep layer shear were also present, as seen in the earlier RUC database results. Also notable was the presence of large total CAPE (near 3000 J kg^{-1}), significant 0-3-km CAPE (50-100 J kg^{-1}) and relatively low LFC heights, in spite of LCL heights that were well above "typical" ranges associated with supercell tornadoes.

5. Summary

Of the 44 significant tornado cases with "high" LCL heights examined in the RUC database for this study, all were in the range from 1300 m to 2000 m above ground. Similar to the study in D06, this confirms that significant tornadoes occasionally develop in environments with notably higher LCL heights than accepted ranges in several supercell tornado studies (e.g., Rasmussen and Blanchard 1998, Thompson et al. 2003, and Craven and Brooks 2004). The "high" LCL cases examined here also suggest that significant tornadoes do not occur when LCL heights are much above 2000 m.

Significant tornadoes in "high" LCL settings with this study were generally associated with established

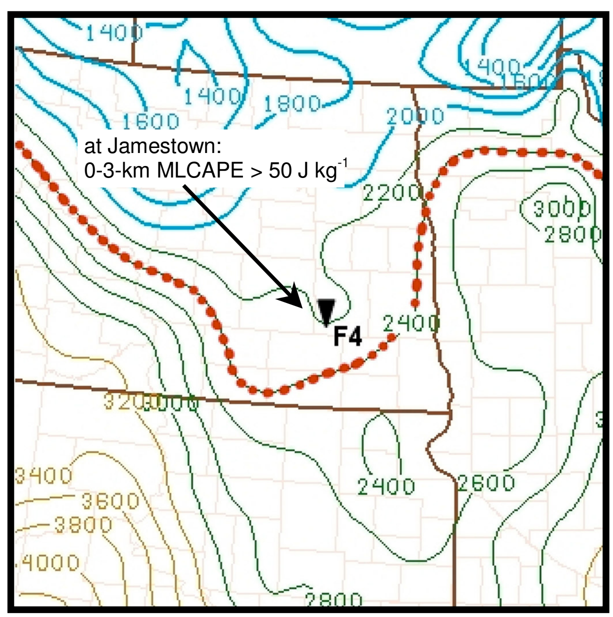

Fig. 10. *As in Fig. 8, except mixed-layer LFC height (200 m increments). The 2400 m contour is shown in red.*

supercell tornado environment characteristics such as sizable SRH, deep layer shear, and CAPE-shear combinations. Additional characteristics that appeared to offer discrimination between nontornadic and tornadic supercell environments in "high" LCL settings were _large total CAPE_ and the presence of _sizable 0-3-km CAPE_ (see Davies 2006b, this volume), a result of LFC heights that were relatively low. As suggested in section 3, large values of these particular parameters in a sheared environment may facilitate rapid surface-based supercell evolution before significant surface cold pools under high-based storms become a major factor. However, additional research is warranted with tornado cases in "high" LCL environments to further investigate why high LCL heights and cloud bases are not a negative factor in such events.

Similar to cases discussed in D06, the results in this study indicate that relatively "high" LCL heights be used with caution as a "limiting factor" in some supercell settings where other thermodynamic and kinematic factors appear very favorable for supercells and tornadoes. If large SRH and strong deep layer shear are present, large total CAPE (resulting in sizable CAPE-SRH combinations) *and* the presence of CAPE *in low levels* (below 3 km) may offer meaningful information to forecasters regarding tornado potential when LCL heights otherwise appear too "high" for significant supercell tornado development.

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