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Environmental Characteristics Associated with Nighttime Tornadoes

Jonathan M. Davies
Private Meteorologist, Trimble/Kansas City, Missouri

Anthony Fischer
Aviation Weather Center, Kansas City, Missouri

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ABSTRACT

Nighttime tornadoes are less common than tornadoes during daylight, but pose a disproportionate risk. Although there have been a number of studies about supercell and tornado environmental parameters, none have focused on characteristics specifically associated with tornado environments after dark. This study examines a large database of Rapid Update Cycle (RUC) analysis soundings associated with tornadic and nontornadic supercell storms, comparing nighttime and daytime environmental parameters. Results show that significant nighttime tornadoes generally occur with smaller instability but much larger storm-relative helicity (SRH) than during the day, mainly due to nocturnal intensification of the low-level jet ahead of synoptic-scale storm systems. At night, large convective inhibition (CIN) can be a limiting factor for tornadoes, although exceptions sometimes occur with very large warm sector SRH and deep shear.

Geographically, the elevated mixed layer (EML) that often spreads into the Plains from desert terrain to the southwest usually results in larger CIN associated with nighttime tornadoes than in the Gulf Coast states. This may be one reason that nighttime significant tornadoes in the Plains are less frequent and typically associated with larger CAPE than corresponding tornadoes farther east. Resulting stronger CAPE-shear combinations may help storm updrafts overcome larger low-level stability from the presence of the EML when significant tornadoes occur at night in the Plains. With the general absence of a topographically driven EML east of the Plains states and near the Gulf Coast, nighttime tornadoes are more common and tend to occur with smaller CAPE and CIN, particularly with strong wind fields and shear generated by dynamic early season systems.

1. Introduction

During the period 1985-2005, only 26% of all tornadoes in the United States occurred at night, but caused 43% of tornado fatalities (Ashley 2007). More recently, during 2007-2008, 99 of 207 U.S. tornado deaths (47%) were from nighttime tornadoes, including the 4 May 2007 Greensburg, Kansas event (11 deaths) and the 5-6 February 2008 event in the southeastern U.S.

Corresponding author address: Jonathan M. Davies, 9101 Alpha Ridge Rd., Trimble, MO 64492-7884
E-mail: davieswx@gmail.com

(37 nighttime deaths). Tornadoes after dark present an enhanced risk because people sleeping are less likely to receive warning, and tornadoes at night are more difficult to spot.

There are probably several ingredients and characteristics contributing to nighttime tornadoes that are different from daytime tornado events. Although a number of empirical studies of environmental parameters associated with supercell tornadoes have been done (e.g., Rasmussen and Blanchard 1998, hereafter RB98; Thompson et al. 2003, hereafter T03; Craven and Brooks 2004), none to date have looked at characteristics specifically associated with nighttime tornadoes. This study examines environmental parameters from a sizable database of Rapid Update Cycle model analysis soundings (RUC, Benjamin et al. 2004) associated with nighttime supercells, comparing these to characteristics associated with daytime supercells. The results shed light on environments that support nocturnal tornadoes. Geographical variations with nighttime tornado environments are also examined.

2. Database Methodology

In T03, RUC model soundings were found to be reasonable estimates for supercell environments. The 2001-2006 RUC database used here is an expansion of Davies (2004, hereafter D04), comprised of 40-km resolution soundings prior to 2002, and 20-km resolution soundings thereafter. Using the same methodology, soundings were selected to represent a geographically broad spectrum of both tornadic and nontornadic supercells in the eastern two thirds of the U.S. All soundings were located in warm sector inflow within 100 km of and 90 minutes prior to well-defined supercell events from radar and National Weather Service warnings. Surface observations were used to update the model soundings to improve accuracy in lowest levels. The reader is referred to D04 for detail about methodology and selection criteria.

The database has 1705 RUC analysis soundings during all months of the year, prior to the implementation of the Enhanced Fujita (EF) Scale (McDonald and Mehta 2006), and is similar to that constructed in T03, but larger in size. **Table 1** summarizes the categorization and grouping of cases into daytime and nighttime events. **Figure 1** shows the nighttime supercell case distribution per state categorized by nontornadic, weak tornadic (F0-F1), and significant tornadic storms (F2-F4; there were no F5 tornadoes during 2001-2006). Regarding significant tornadoes, there are 57 nighttime cases in the database, compared with 198 daytime cases. This is consistent with the fact that nighttime tornadoes are less common (Ashley 2007).

All thermodynamic parameters were computed using lowest 100-hPa (mb) *mixed layer* ("ML") lifted parcels as in T03 and suggested by Craven et al. (2002). The virtual temperature correction (Doswell and Rasmussen, 1994) was also applied. Storm motions for storm-relative wind parameters were estimated using the method given in Bunkers et al. (2000).

3. Parameter Results

Parameters examined in this study are pertinent to supercell and tornado environments based on previous studies, such as RB98, T03, and Rasmussen (2003, hereafter R03). The original significant tornado parameter components developed in T03 are included: MLCAPE (convective available potential energy), 0-1-km SRH (storm-relative helicity), 0-6-km bulk shear, and MLLCL (lifting condensation level). Additional parameters are MLCIN (convective inhibition), and 0-1-km EHI (energy-helicity index), a composite parameter. Box and whisker diagrams are used to display parameter value distributions in different categories that show 90th, 75th, 25th, and 10th percentiles along with the median value, as in RB98, R03, and T03.

On the most basic level, CAPE (instability or positive buoyancy) is required for thunderstorms. **Figure 2** shows MLCAPE distributions associated with daytime (**Fig. 2a**) and nighttime (**Fig. 2b**) supercell events, categorized as in **Fig. 1**. In the database, nighttime significant tornado events were associated with only one half to two thirds the MLCAPE found with daytime significant tornado events, which is a substantial difference. Considering only nighttime supercells (**Fig. 2b**), most significant tornadoes occurred in environments with MLCAPE values between 600 J kg^{-1} and 1800 J kg^{-1}, and tended to be associated with larger CAPE than nontornadic events.

Negative buoyancy and inhibition to rising near-surface air parcels is indicated by CIN (Colby 1984). Large amounts of CIN suggest a significant low-level stable layer that can reduce tornado potential (see D04), even when CAPE is present above. **Figure 3** shows distributions of MLCIN, and indicates that both daytime and nighttime significant tornadoes tended to occur with smaller CIN than nontornadic supercells, which is similar to results found in D04. Examining only nighttime supercells, MLCIN values with over half the nontornadic events (**Fig. 3b**) were very large (100-300 J kg^{-1}) compared to tornadic events. This suggests that many supercells with near-surface cooling after dark tend to be "elevated" (Colman, 1990), or at least not strongly surface-based, with the main storm inflow rooted above a stable near-surface layer. Values of MLCIN in **Fig. 3b** appear to discriminate well between nontornadic and significant tornadic supercells at night. However, there are sometimes exceptions when nighttime significant tornado events occur with unusually large low-level and deep layer wind shear in the warm sector, as illustrated by two specific cases in Fischer and Davies (2009) associated with very large CIN.

Figure 4 shows distributions of 0-1-km SRH, representative of horizontal streamwise vorticity that can be tilted into thunderstorm updrafts to produce rotation (Davies-Jones et al. 1990) for low-level mesocyclones and tornadoes. Significantly stronger 0-1-km SRH was found in each of the nighttime supercell categories (**Fig. 4b**) compared to the corresponding daytime categories (**Fig. 4a**). This reflects the typical intensification of the low-level jet after dark (e.g., Bonner 1968) ahead of synoptic-scale storm systems and the resulting effect on low-level shear. In particular, the range of SRH values associated with nighttime F2-F4 tornado events (250-300 m^2 s^{-2} and above) tended to be larger by roughly two quartiles when compared to corresponding daytime events. Although there was considerable overlap in SRH values between nighttime categories, this large difference in low-level shear suggests a strong distinction between nighttime and daytime significant tornado events. Large SRH may act to support and intensify low-level mesocyclones with supercells when smaller CAPE is present during nighttime tornado events.

The composite EHI parameter (Hart and Korotky 1991; Davies 1993) combines MLCAPE and 0-1-km SRH as a simple indicator to suggest potential for low-level mesocyclones. **Figure 5** shows distributions of 0-1-km EHI. The ranges for both daytime and nighttime significant tornadoes were quite similar, yet showed a sizable upward offset from EHI values associated with nontornadic supercells, matching results from R03 and T03. It is notable that, although nighttime significant tornadoes appeared to be associated with less MLCAPE and larger SRH than corresponding daytime events (see **Fig. 2** and **Fig. 4**), the magnitude of the resulting CAPE-SRH *combinations* was similar to those associated with daytime significant tornado environments.

Substantial shear through a deep layer enhances vertical pressure gradients to intensify supercell updrafts (Rotunno and Klemp 1982), which can affect tornado development. Distributions of 0-6-km bulk shear shown in **Fig. 6** exhibited little difference between daytime and nighttime supercell events regarding ranges and general trends. However, all nighttime significant tornadoes were associated with 20 m s^{-1} (roughly 40 kt) or more of 0-6-km bulk shear, with the majority above 25 m s^{-1} (50 kt).

Lower LCL heights (RB98) are related to larger low-level humidity and lower cloud bases, which can affect supercell downdraft characteristics and tornado potential (Markowski et al. 2002). Similar to past studies, **Fig. 7** shows that significant tornadoes were associated with lower MLLCL heights for both daytime and nighttime supercell events, although there was considerable range overlap between categories. Because of nocturnal low-level cooling, nighttime MLLCL values tended to be 100-400 m lower than daytime values. The majority of MLLCL heights associated with nighttime significant tornadoes were below 1000 m AGL.

4. Geographical Differences in Parameter Results

One plausible reason that nighttime tornadoes are less common in the Plains compared to the Gulf Coast (e.g., Grazulis 1993) may have to do with the elevated mixed layer (EML). This warm layer of air that develops over the dry, elevated terrain of the southwestern U.S. is often advected eastward above a moist boundary layer in the adjacent Plains states (Carlson et al. 1983; D04). Cooling after dark beneath the EML can result in widespread increase of CIN across large sections of the Plains. **Figure 8** shows median MLCIN values from this study's database, comparing nighttime nontornadic and significant tornadic supercells in five states along the Gulf Coast with those in five states in the Plains (**Fig. 1** highlights the two state groupings). Notice that the median values of MLCIN for the Plains cases in both categories were twice as large as those along the Gulf Coast. This appears to emphasize that nighttime supercells in the Plains often occur atop a deep stable layer associated with the EML.

Focusing strictly on nighttime significant tornadoes, **Table 2** shows median parameter values in the database from the Gulf Coast (20 cases) and the Plains (12 cases; all Texas cases occurred away from the Gulf Coast) using the same state groupings in **Fig. 8**. The most notable differences were with values of MLCAPE, MLCIN, and EHI. Median values of SRH were large and nearly the same for both geographical groupings (see **Fig. 9**). But the median MLCAPE for the Plains cases was nearly 2.5 times larger than in the Gulf Coast cases (see **Fig. 9**), which suggests that CAPE with nighttime significant tornado cases in the Plains tends to be much larger than with nighttime significant tornado cases near the Gulf Coast. Because of these CAPE differences, the median EHI in **Table 2** (see also **Fig. 10**) was twice as large in the Plains tornado cases. This suggests that larger CAPE-SRH combinations may be required for most nighttime significant tornadoes in the Plains states to help supercell updrafts overcome larger near-surface CIN typically found at night in the Plains.

RUC analysis soundings associated with deadly nighttime EF-3 tornadoes in Tennessee (**Fig. 11**, just north of the Gulf Coast states, 22 deaths on 5 February 2008) and Kansas (**Fig. 12**, 2 deaths on 23 May 2008) illustrate the differences in geographical environmental characteristics suggested by **Table 2**. Comparing these figures, notice the differing MLCAPE (< 1000 J kg^{-1} in Tennessee; > 3000 J kg^{-1} in Kansas) and 0-1-km EHI values (2.9 in Tennessee, a massive 10.3 in Kansas). However, 0-1-km SRH values were very large and quite similar in both environments (above 500 m^2 s^{-2}). Notice also that MLCIN with the Tennessee sounding (25 J kg^{-1}) was less than half that on the Kansas sounding (near 70 J kg^{-1}) due to the lack of an EML. In contrast, the EML was very apparent on the Kansas sounding with a marked inversion at about 800 hPa (mb).

To further illustrate typical differences between settings that support nighttime significant tornadoes in the southeastern U.S. and the Plains, synoptic and parameter features from the Storm Prediction Center mesoanalysis (SPC, Bothwell et al. 2002) associated with both deadly tornado episodes in 2008 mentioned above are shown in **Fig. 13** and **Fig. 14**. Tornado events in the southeastern U.S. are most common in late fall, winter, and early spring (e.g., Grazulis, 1993), and a result of synoptic systems which are often very "dynamic" with intense wind fields over a large area. This is seen in **Fig. 13a** and **Fig. 13b**, where winds at 500 hPa (mb) exceeded 30 m s^{-1} (around 60 kt) over a very large area, and winds at 850 hPa (mb) were as high as 35 m s^{-1} (around 70 kt). In contrast, nighttime tornadoes in the Plains occur mainly in the spring with synoptic systems that are also strong, but somewhat less intense regarding wind field magnitudes. This is seen in **Fig. 14a** where 500-hPa (mb) winds exceeded 30 m s^{-1} (60 kt) over a smaller area, and maximum winds at 850 hPa (mb) within the low-level jet (**Fig. 14b)** were around 25 m s^{-1} (50 kt). Also notice that MLCAPE was relatively small in the southeastern U.S. event (**Fig. 13c**, generally < 1000 J kg^{-1}), but much larger in the Plains event (**Fig. 14c**, values near 3000 J kg^{-1}). In addition, the range of largest 0-1-km SRH values (**Fig. 13d** and **Fig. 14d**,) was very impressive and quite similar (400-700 m^2 s^{-2}) in both cases. Like the database information in this study, this comparison suggests that nighttime significant tornadoes in the Plains tend to occur with larger CAPE than in the eastern and southeastern U.S., while SRH tends to be large in both locations. More intense wind fields associated with strong early season systems in the southeastern U.S. may also help to facilitate supercell updrafts and tornadoes when lesser instability is present.

Figure 15 is an additional comparison of these two events using 700-hPa (mb) temperatures as a rough way of detecting the presence of an EML. Notice in **Fig. 15a** that temperatures the southeast U.S. event were only 4-6^o C, while temperatures were twice as warm in the Plains event (**Fig. 15b**, near 12^o C). Although some of the differences were seasonal, the dramatically warmer temperatures aloft in the Plains case were also indicative of an EML layer that advected eastward from the desert Southwest. As discussed earlier in this section, larger CAPE may be required in the Plains to overcome this EML when tornadoes occur at night.

5. Summary and Discussion

This study suggests several important characteristics that contribute to nighttime tornado environments. In significant nighttime tornado events, 0-1-km SRH tends to be considerably larger than with daytime tornado events, typically greater than 250-300 m^2 s^{-2}. This is primarily due to the effects of the nocturnally enhanced low-level jet. With the larger low-level SRH, combinations of MLCAPE and SRH can support low-level mesocyclones that may produce tornadoes, even with cooler surface temperatures at night that result in less CAPE (often 1000-1500 J kg^{-1} or smaller). Large CIN and low-level stability tend to have a limiting influence on nighttime tornado development, particularly when MLCIN values approach 100 J kg^{-1} and larger. In most nighttime cases, CIN appears to discriminate well between significant tornadic and nontornadic events, though there are exceptions (see Fischer and Davies 2009). Although not a substantial discriminating factor between night and day tornadic events, deep layer shear is strong with nighttime significant tornadoes (usually 20-25 m s^{-1} or 40-50 kt and greater), which can help to intensify supercell mesocyclones. Also, MLLCL heights become lower and more supportive of tornadoes at night with surface cooling, when values below 1000 m AGL are most common with nighttime significant tornadoes.

There are also important geographical differences in characteristics that support nighttime tornadoes. In the southeastern U.S., nighttime significant tornadoes tend to occur with smaller MLCAPE combined with very large SRH. With the typical absence of a topographically driven EML, MLCIN is also smaller and warm sector environments tend to be more strongly surface-based. In contrast, nighttime tornado environments in the Plains typically feature much larger MLCAPE at night, as well as large SRH. Values of MLCIN also tend to be larger in the Plains states with nighttime tornado settings due to surface cooling and the aforementioned EML, so that larger MLCAPE may be required combined with already large SRH to promote mesocyclones of sufficient strength to generate tornadoes. On the other hand, strong wind fields and shear with early season systems in the southeastern U.S. may in a sense “balance” smaller CAPE, supporting nighttime tornadoes in environments with considerably less instability than found in nocturnal tornado events in the Plains during the spring.

When forecasters observe strong low-level jet intensification at dusk accompanied by large increases in SRH within the warm sector, they should be alert to the potential for nocturnal tornado development in areas where CAPE from near-surface parcels is available and thunderstorms are ongoing or expected to develop. Careful attention should be given to nighttime settings where SRH and shear are very strong, particularly when 0-1-km SRH values are “extreme” (approaching 450-500 $m^2\ s^{-2}$ or greater), and deep layer shear magnitudes are near or above 25-30 $m\ s^{-1}$ (50-60 kt). This is especially true in the Plains when CAPE within the warm sector is unusually large (e.g., 2000-3000 $J\ kg^{-1}$) during the first few hours after dark, resulting in mesocyclones that may be strong enough to overcome low-level stability associated with the EML and radiational cooling in the boundary layer. In areas farther east (particularly the southeastern U.S.), forecasters should be alert to the fact that, when SRH and deep shear are large or “extreme”, nighttime tornadoes are common with much smaller CAPE (sometimes less than 1000 $J\ kg^{-1}$), especially if CIN is relatively small (e.g., < 50-75 $J\ kg^{-1}$).

In closing, it is important to emphasize that significant nighttime tornadoes sometimes occur with unusually large warm sector CIN in the Plains. A companion paper by Fischer and Davies (2009) will investigate two such atypical nighttime tornado cases.

REFERENCES

Ashley, W. 2007: Spatial and temporal analysis of tornado fatalities in the United States: 1880-2005. *Wea. Forecasting*, **22,** 1214-1228.

Benjamin, S. G., and Coauthors, 2004: An hourly assimilation/forecast cycle: The RUC. *Mon. Wea. Rev.*, **132**, 495-518.

Bonner, W. D., 1968: Climotology of the low level jet. *Mon. Wea. Rev.*, **96**, 833-849.

Bothwell, P. D., J. A. Hart, and R. L. Thompson, 2002: An integrated three-dimensional objective analysis scheme in use at the Storm Prediction Center. Preprints, *21st Conf. on Severe Local Storms*, San Antonio, TX, Amer. Meteor. Soc., J117-J120.

Bunkers, M. J., B. A. Klimowski, J. W. Zeitler, R. L. Thompson, and M. L. Weisman, 2000: Predicting Supercell Motion Using a New Hodograph Technique. *Wea. Forecasting*, **15**, 61–79.

Carlson, T. N., S. G. Benjamin, G. S. Forbes, Y. F. Li , 1983: Elevated mixed layers in the regional severe storm environment: Conceptual model and case studies. *Mon. Wea. Rev.*, **111**, 1453–1474.

Craven, J. P., and H. E. Brooks, 2004: Baseline climatology of sounding-derived parameters associated with deep moist convection. *Nat. Wea. Dig.*, **28**, 13-24.

-------, R. E. Jewell, and H. E. Brooks, 2002: Comparison between observed convective cloud-base heights and lifting condensation level for two different lifting parcels. *Wea. Forecasting*, **17**, 885-890.

Colby, F. P., 1984: Convective inhibition as a predictor of convection during AVE-SESAME-2. *Mon. Wea. Rev.*, **112**, 2239-2252.

Colman, B. R., 1990: Thunderstorms above frontal surfaces in environments without positive CAPE. Part I: A climatology. *Mon. Wea. Rev.* **112**, 2239-2252.

Davies, J. M., 1993: Hourly helicity, instability, and EHI in forecasting supercell tornadoes. Preprints, *17th Conf. on Severe Local Storms*, St. Louis, MO, Amer. Meteor. Soc., 107-111.

-------, 2004: Estimations of CIN and LFC associated with tornadic and nontornadic supercells. *Wea. Forecasting*, **19**, 714-726.

Davies-Jones, R. P., D. Burgess, and M. Foster, 1990: Test of helicity as a tornado forecast parameter. Preprints, *16th Conf. on Severe Local Storms*, Kananaskis Park, AB, Canada, Amer. Meteor. Soc., 588-592.

Doswell, C. A. III, and E. N. Rasmussen, 1994: The effect of neglecting the virtual temperature correction on CAPE calculations. *Wea. Forecasting*, **9**, 625-629.

Fischer, A., and J. M. Davies, 2009: Significant nighttime tornadoes in the plains associated with relatively stable low-level conditions. *NWA Electronic Journal of Operational Meteorology*, 2009-EJ4.

Grazulis, T. P., 1993: *Significant Tornadoes 1680–1991*. St. Johnsbury, VT: The Tornado Project of Environmental Films.

Hart, J. A., and W. Korotky, 1991: The SHARP workstation v1.50 users guide. NOAA/National Weather Service, 30 pp. [Available from NWS Eastern Region Headquarters, 630 Johnson Ave., Bohemia, NY 11716.]

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

McDonald, J.R., and K.C. Mehta, 2006. A recommendation for an enhanced Fujita scale. Texas Tech Univ., Wind Science and Engineering Research Center. Available online at http://www.wind.ttu.edu/EFScale.pdf.

Rasmussen, E. N., 2003: Refined supercell and tornado forecast parameters. *Wea. Forecasting*, **18**, 530-535.

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

Rotunno, R. and J. B. Klemp, 1982: The influence of the shear-induced pressure gradient on thunderstorm motion. *Mon. Wea. Rev*., **110**, 136-151.

Thompson, R. L., R. Edwards, J. A. Hart, K. L. Elmore, and P. Markowski, 2003: Close proximity soundings within supercell environments obtained from the Rapid Update Cycle. *Wea. Forecasting*, **18**, 1243-1261.

TABLES AND FIGURES

Table 1. RUC analysis soundings in this study associated with supercells from 2001-2006.

	Nontornadic	F0-F1 tornadoes	F2-F4 tornadoes	Total
Daytime supercell cases	**646**	**496**	**198**	**1340**
Nighttime supercell cases	**242**	**66**	**57**	**365**

Table 2. Median values of parameters associated with nighttime significant tornadoes from this study in states along the Gulf Coast (Louisiana/Mississippi/Alabama/Georgia/Florida) and the Plains states (Texas/Oklahoma/Kansas/Nebraska/South Dakota).

	MLCAPE J kg^{-1}	**MLCIN** J kg^{-1}	**$SRH_{(0-1)}$** m^2 s^{-2}	**$EHI_{(0-1)}$**	**$shear_{(0-6)}$** kt	**MLLCL** m AGL
Gulf Coast (20 cases) (LA/MS/AL/GA/FL)	**1120**	**22**	**298**	**1.9**	**51**	**703**
Plains (12 cases) (TX/OK/KS/NE/SD)	**2654**	**50**	**296**	**4.2**	**56**	**996**

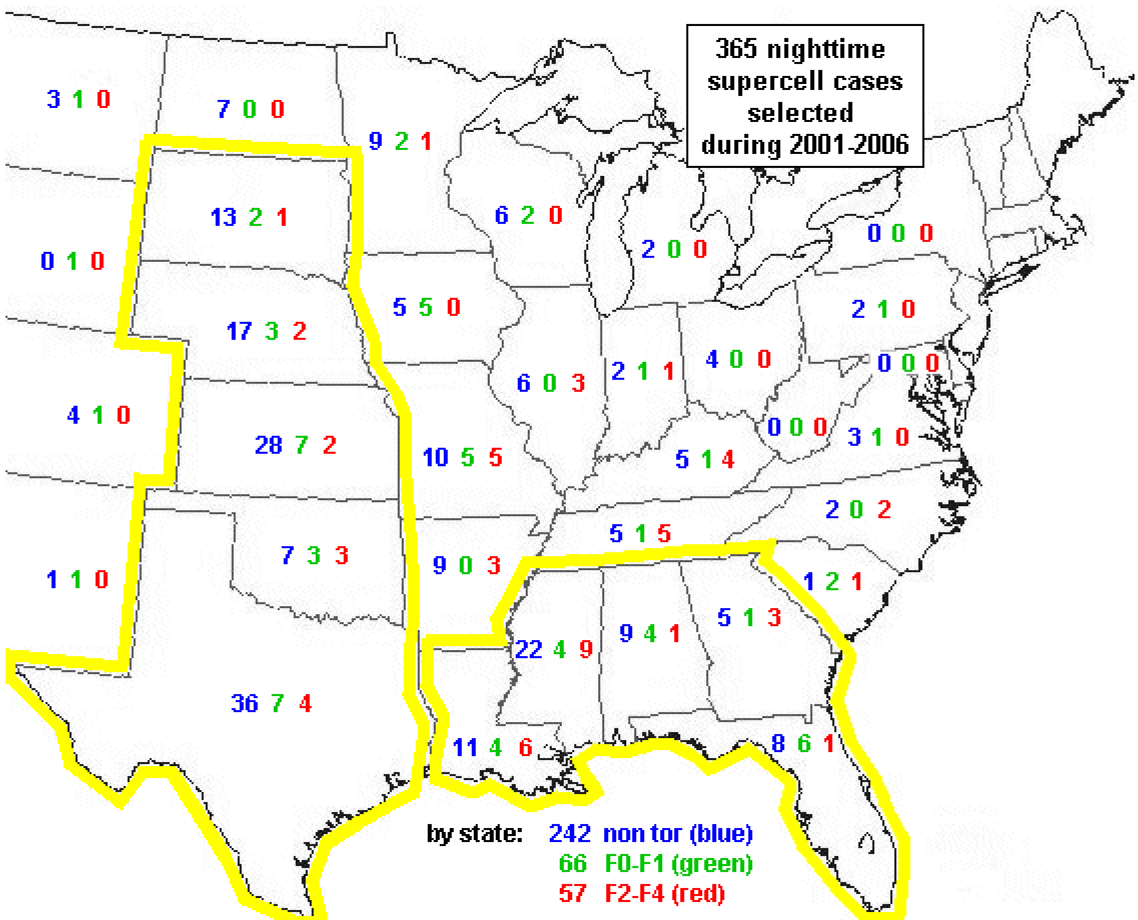


Figure 1. Map of eastern two thirds of the U.S. showing distribution of 365 nighttime supercells by state from the RUC database used in this study. Data are grouped as cases with no tornadoes ("non tor"; blue number at left), weak tornadoes ("F0-F1"; green number in middle), and significant tornadoes ("F2-F4"; red number at right). Two groupings of five states each are highlighted in yellow (South Dakota, Nebraska, Kansas, Oklahoma, and Texas as “Plains” states, and Louisiana, Mississippi, Alabama, Georgia, and Florida as “Gulf Coast” states), used later in the study to examine geographical differences in Table 2 and Figs. 8 through 10.

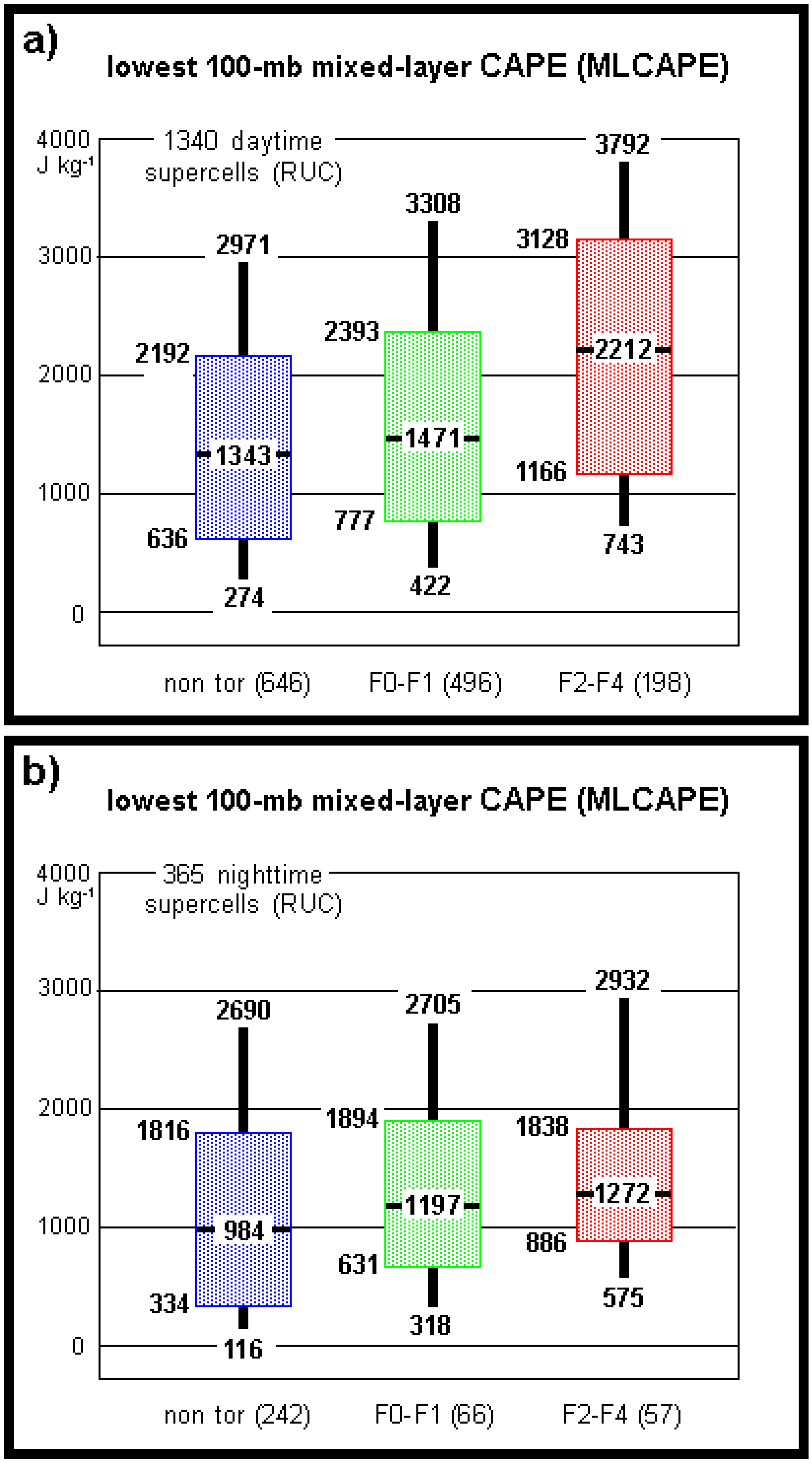


Figure 2. Box and whisker plots of MLCAPE (J kg^{-1}) using lowest 100-hPa (mb) mixed-layer lifted parcels for RUC analysis soundings in this study; **a)** shows distributions for daytime supercells, and **b)** nighttime supercells. Data are grouped as cases with no tornadoes ("non tor"; blue at left), weak tornadoes ("F0-F1"; green in middle), and significant tornadoes ("F2-F4"; red at right). Numbers in parentheses give total cases in each category. Boxes denote 25th to 75th percentiles, with horizontal bar showing median value. Whiskers extend to the 10th and 90th percentiles.

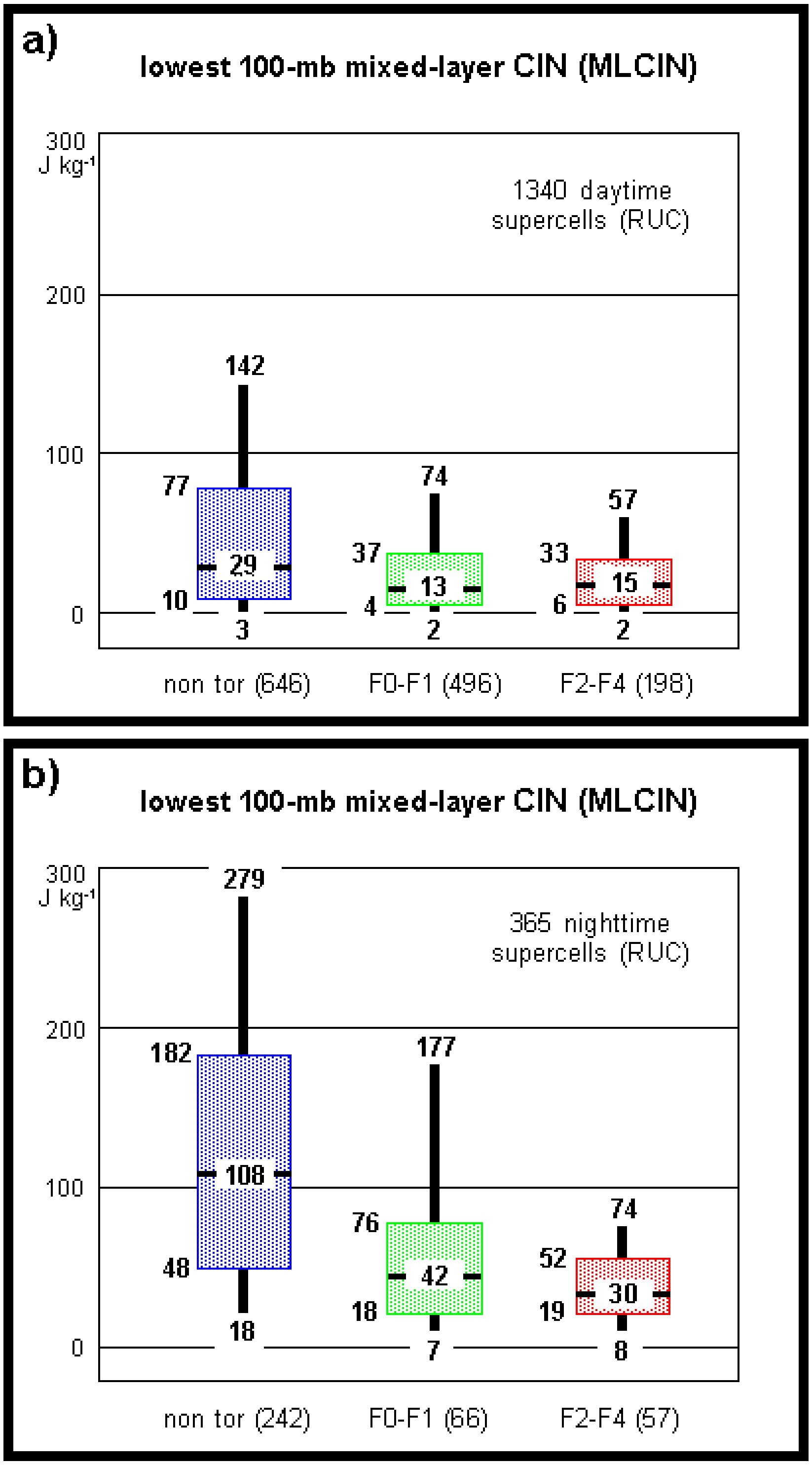


Figure 3. As in Fig. 2, except for MLCIN (J kg^{-1}), using lowest 100-hPa (mb) mixed-layer lifted parcels.

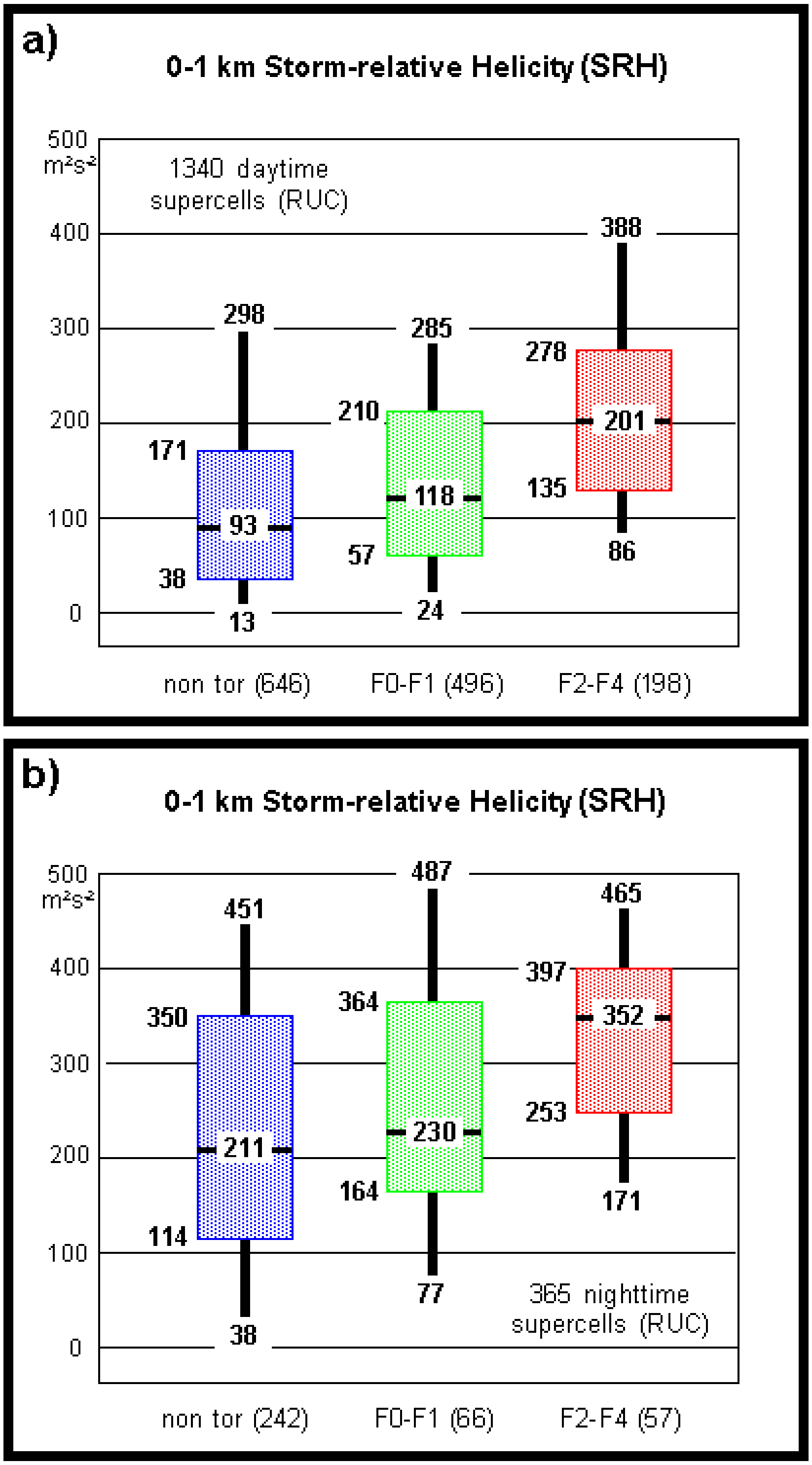


Figure 4. As in Fig. 2, except for 0-1-km AGL SRH ($m^2\ s^{-2}$).

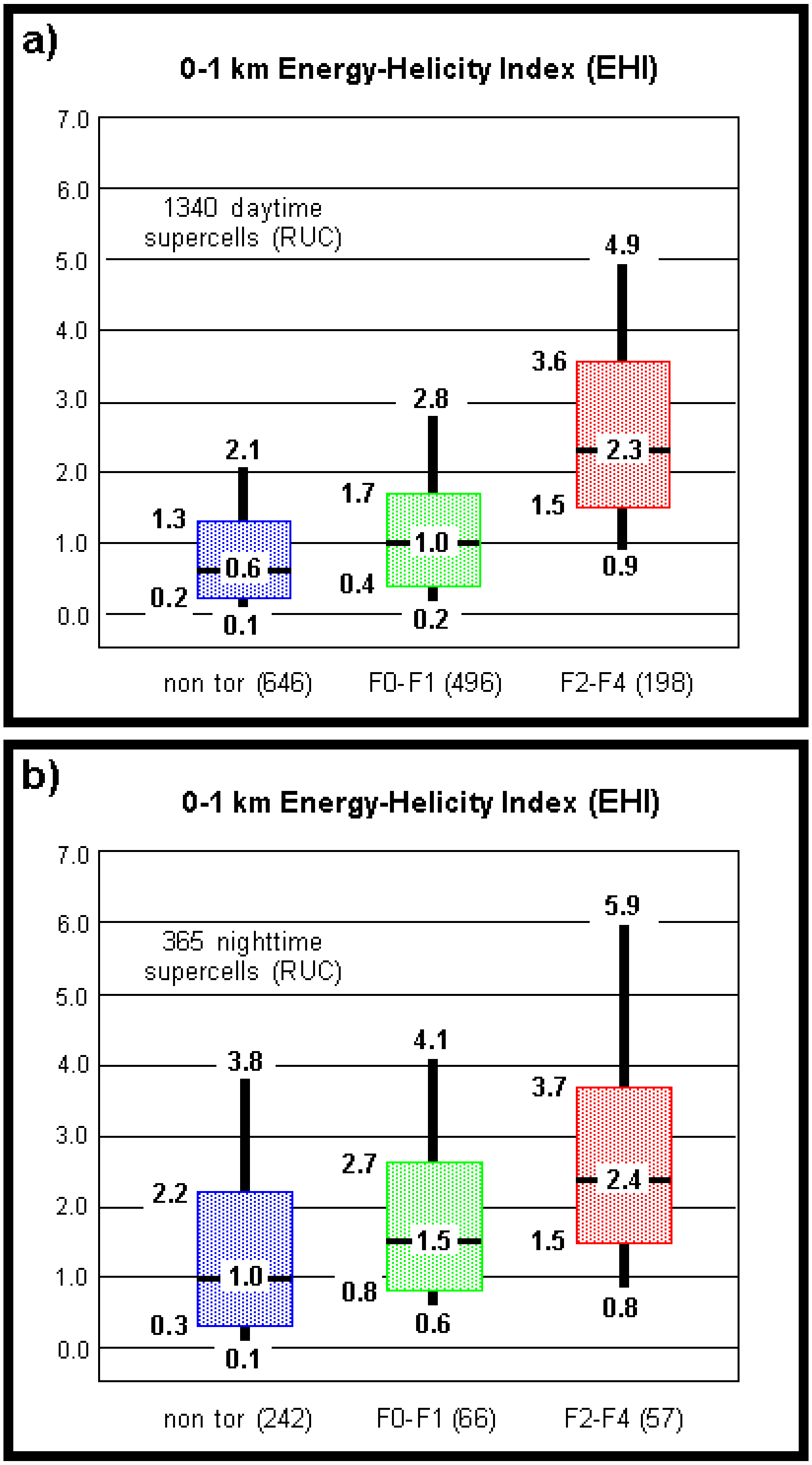


Figure 5. As in Fig. 2, except for 0-1-km EHI (dimensionless) combining MLCAPE and SRH.

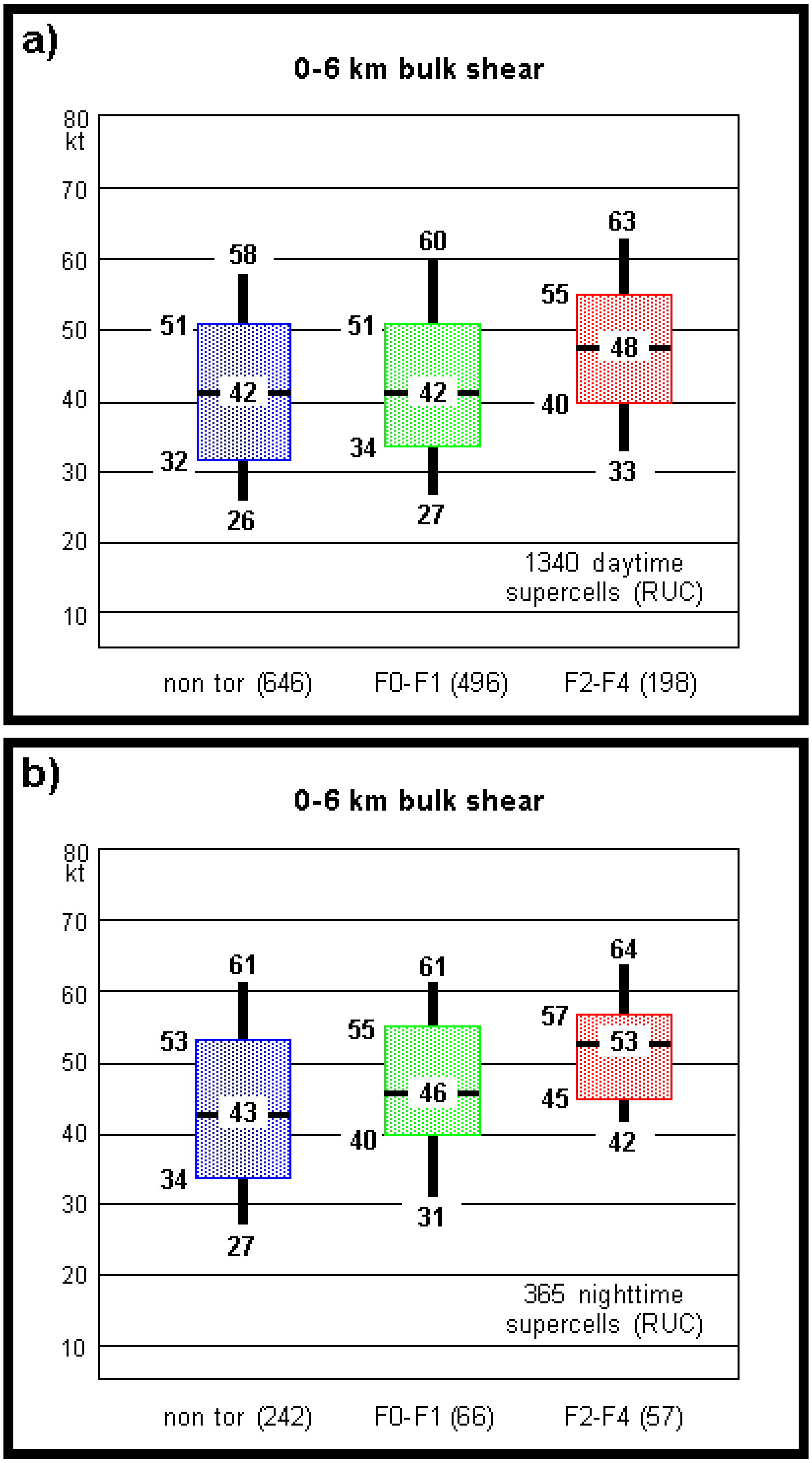
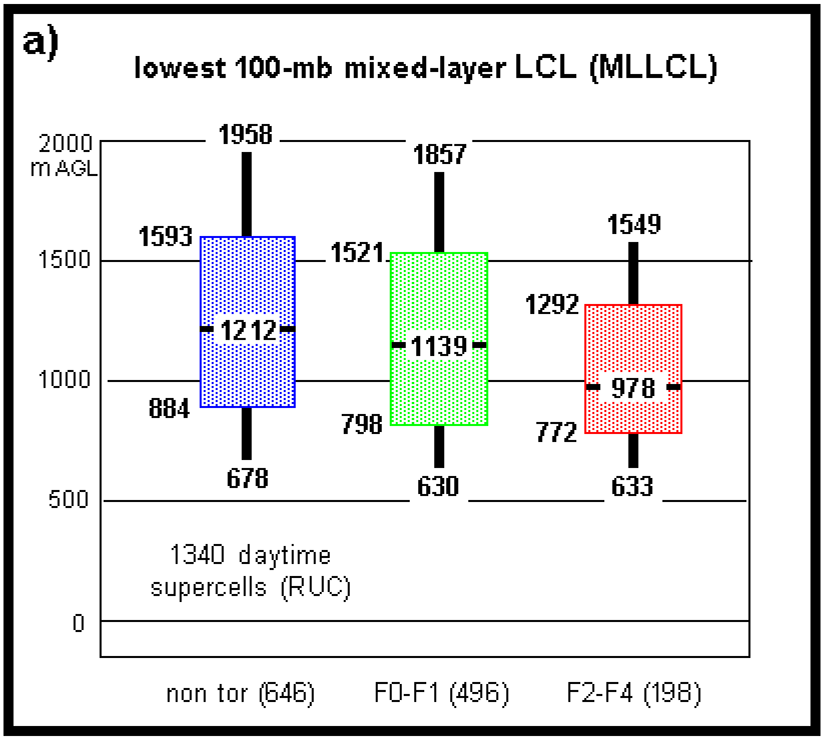


Figure 6. As in Fig. 2, except for 0-6-km AGL bulk shear (kt).



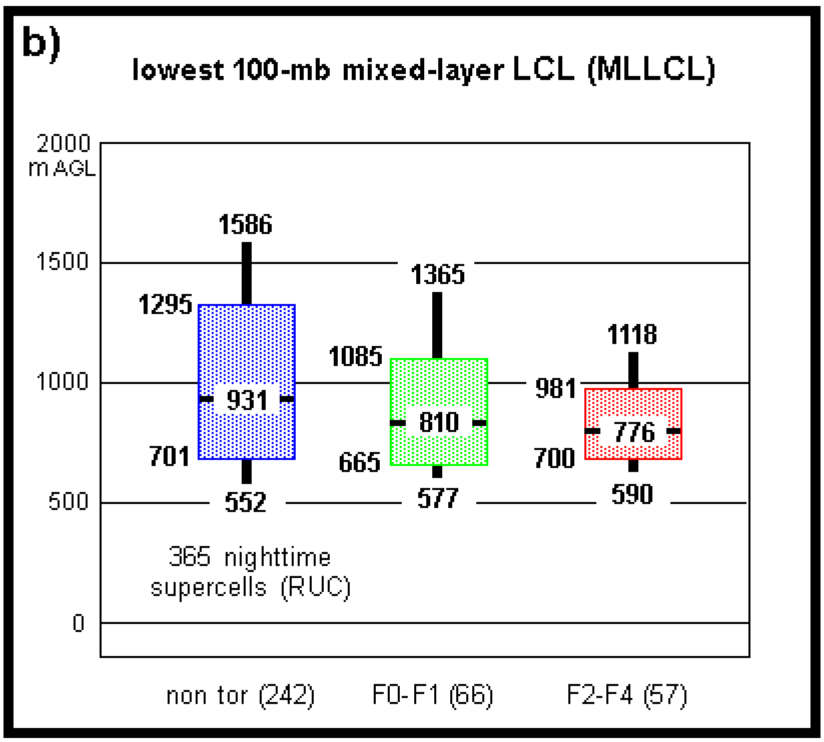


Figure 7. As in Fig. 2, except for MLLCL (m AGL) using lowest 100-hPa (mb) mixed-layer lifted parcels.

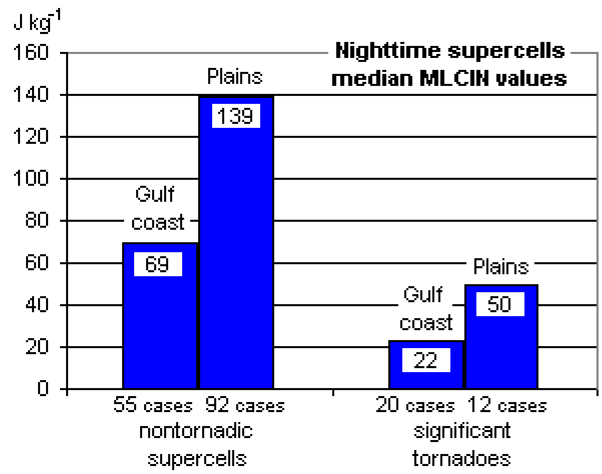


Figure 8. Bar graphs showing median values of MLCIN (blue, J kg^{-1}) for subsets of nontornadic nighttime supercells (left) and significant nighttime tornadoes (right) drawn from the database in this study. These are grouped as states along the Gulf Coast (Louisiana, Mississippi, Alabama, Georgia, and Florida, labeled "Gulf Coast") and the Plains (Texas, Oklahoma, Kansas, Nebraska, and South Dakota, labeled "Plains"). The number of cases is shown below the corresponding bar.

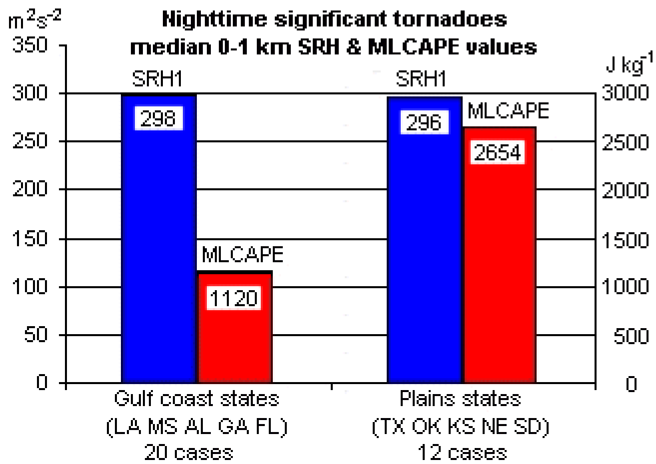


Figure 9. Bar graph showing median values of 0-1-km SRH (blue) and MLCAPE (red) for significant nighttime tornadoes along the Gulf Coast (left, same states as Fig. 8) and the Plains (right, same states as Fig. 8). Scale for SRH (m^2 s^{-2}) is displayed at left, and MLCAPE (J kg^{-1}) at right.

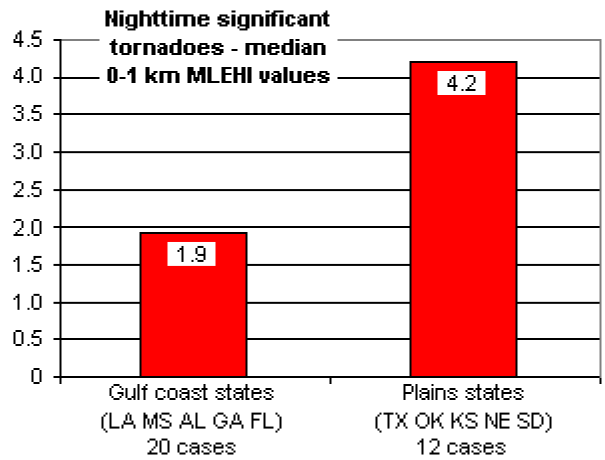


Figure 10. As in Fig. 8, except for 0-1-km EHI only (red), combining MLCAPE and SRH as shown in Fig. 9. Values for EHI are dimensionless.

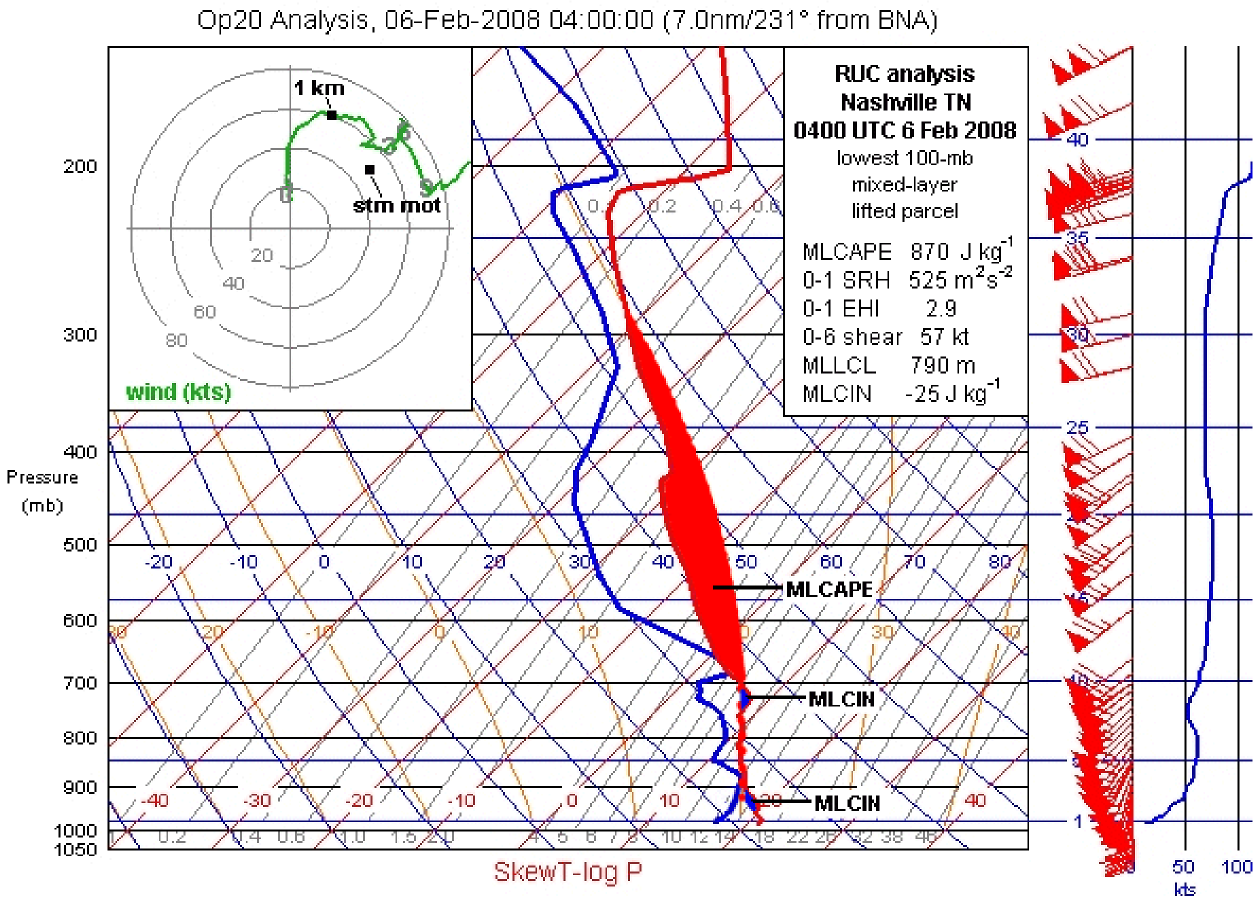


Figure 11. Skew*T*-log*p* diagram and hodograph (conventional) for RUC analysis sounding at Nashville, Tennessee at 0400 UTC 6 February 2008, associated with the inflow region of a nighttime tornadic supercell that killed 22 people from 0400-0430 UTC. Positive area (MLCAPE) using lowest 100-hPa (mb) mixed-layer lifted parcel is shaded red and negative area (MLCIN) is shaded blue. Values for parameters examined in this study are also shown, with MLCIN displayed as negative number. The virtual temperature correction was applied, but is not shown graphically.

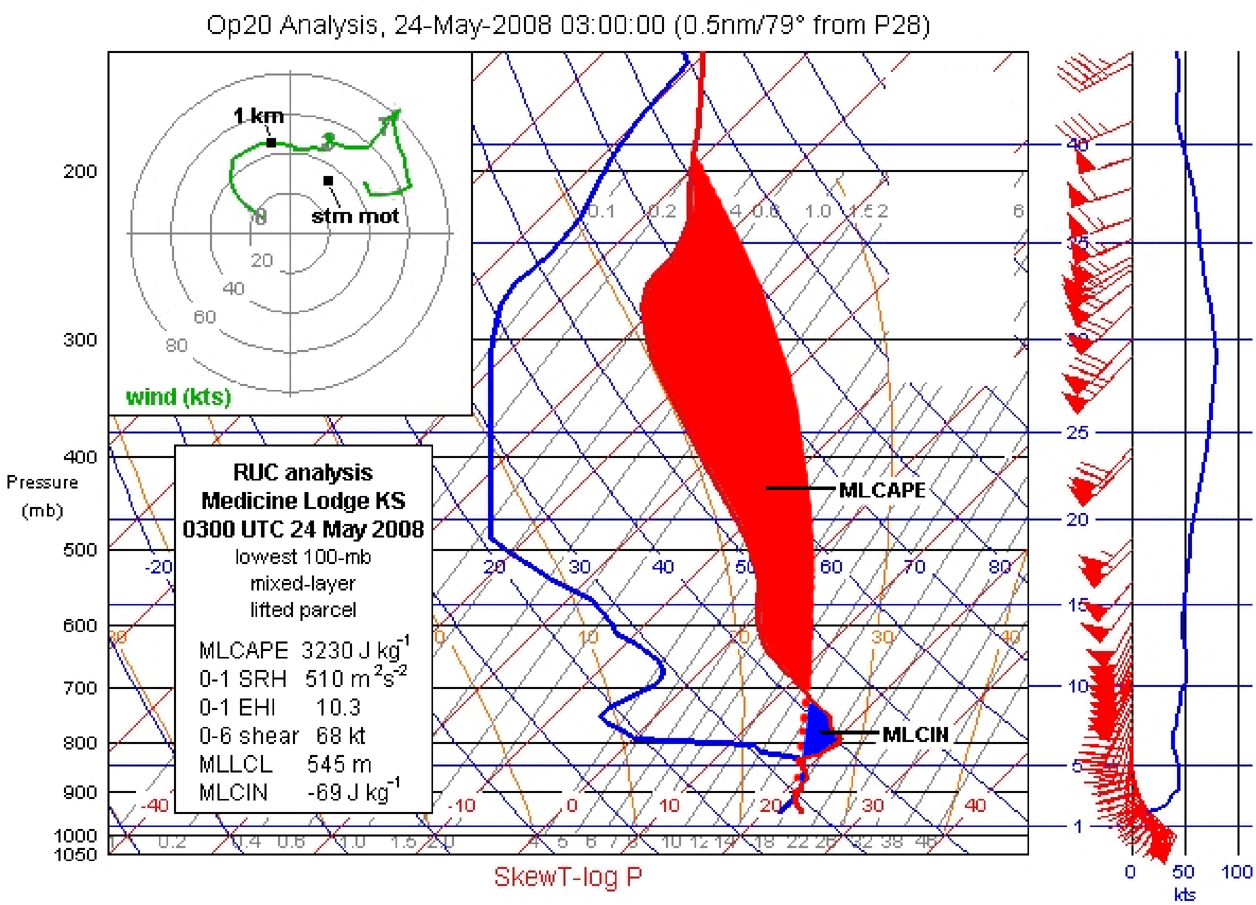


Figure 12. As in Fig. 11, except RUC analysis sounding at Medicine Lodge, Kansas modified for 0300 UTC 24 May 2008, associated with inflow region of nighttime tornadic supercell that killed two people around 0330 UTC.

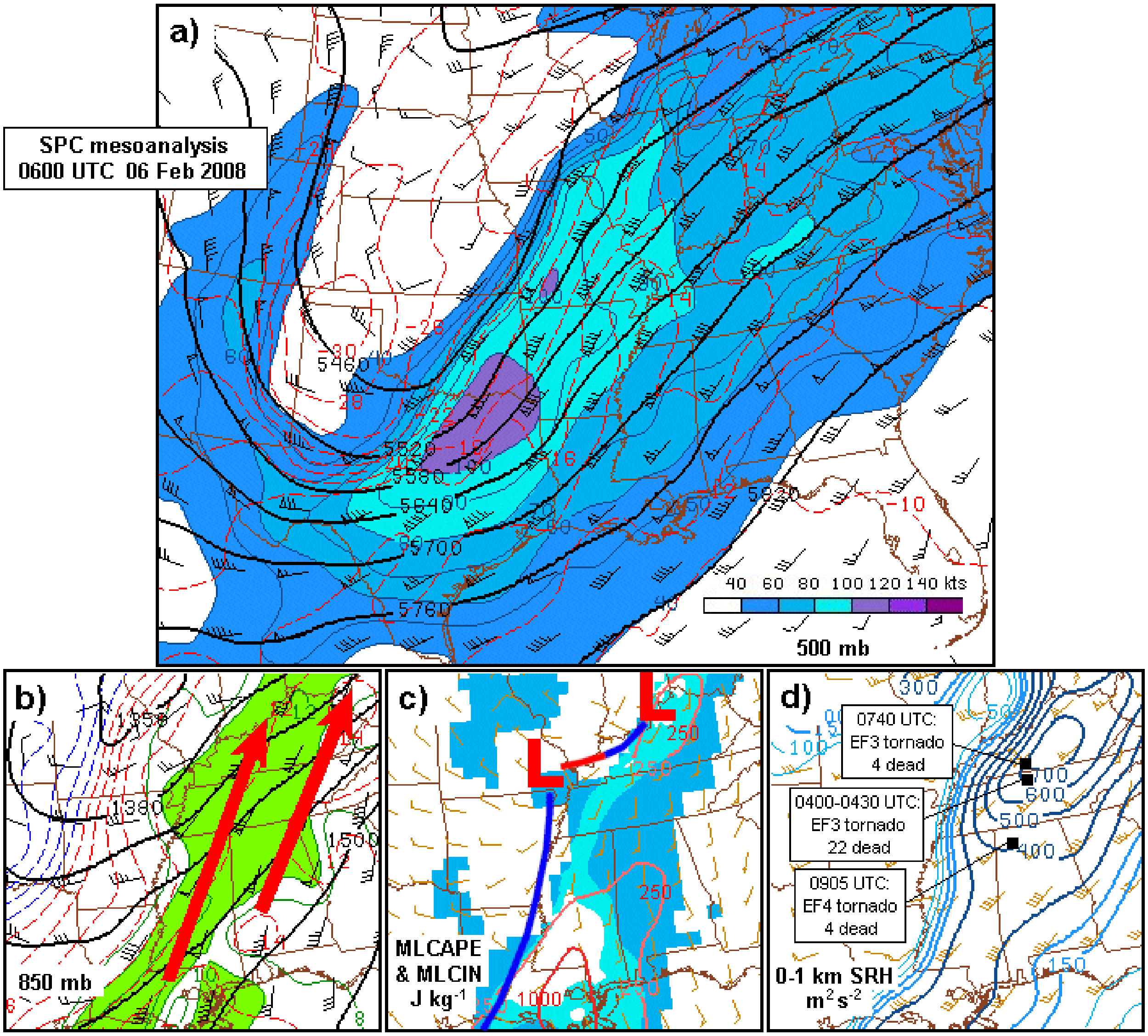


Figure 13. Plots from the SPC mesoanalysis of height contours (m MSL, heavy solid lines), wind (conventional barbs in kt), and temperature (^{o} C, dashed lines) for **a)** 500 hPa (mb) and **b)** 850 hPa (mb) at 0600 UTC 6 February 2008. Also shown are **c)** lowest 100-hPa (mb) MLCAPE and MLCIN (J kg^{-1}), and **d)** 0-1-km SRH (m^2 s^{-2}) for the same time. Isotachs in a) are shaded at 20 kt intervals according to blue/purple key. Green shading in b) shows dewpoint $\geq$ 10^{o} C, with red arrows indicating low-level jet axes. Surface lows, fronts (conventional colors), and wind barbs (kt) are shown in c), where light blue shading is MLCIN between 25 and 100 J kg^{-1}, and dark blue is MLCIN $\geq$ 100 J kg^{-1}. In d), wind barbs (kt) are supercell motion estimates, and locations and times of deadly nighttime tornadoes are shown.

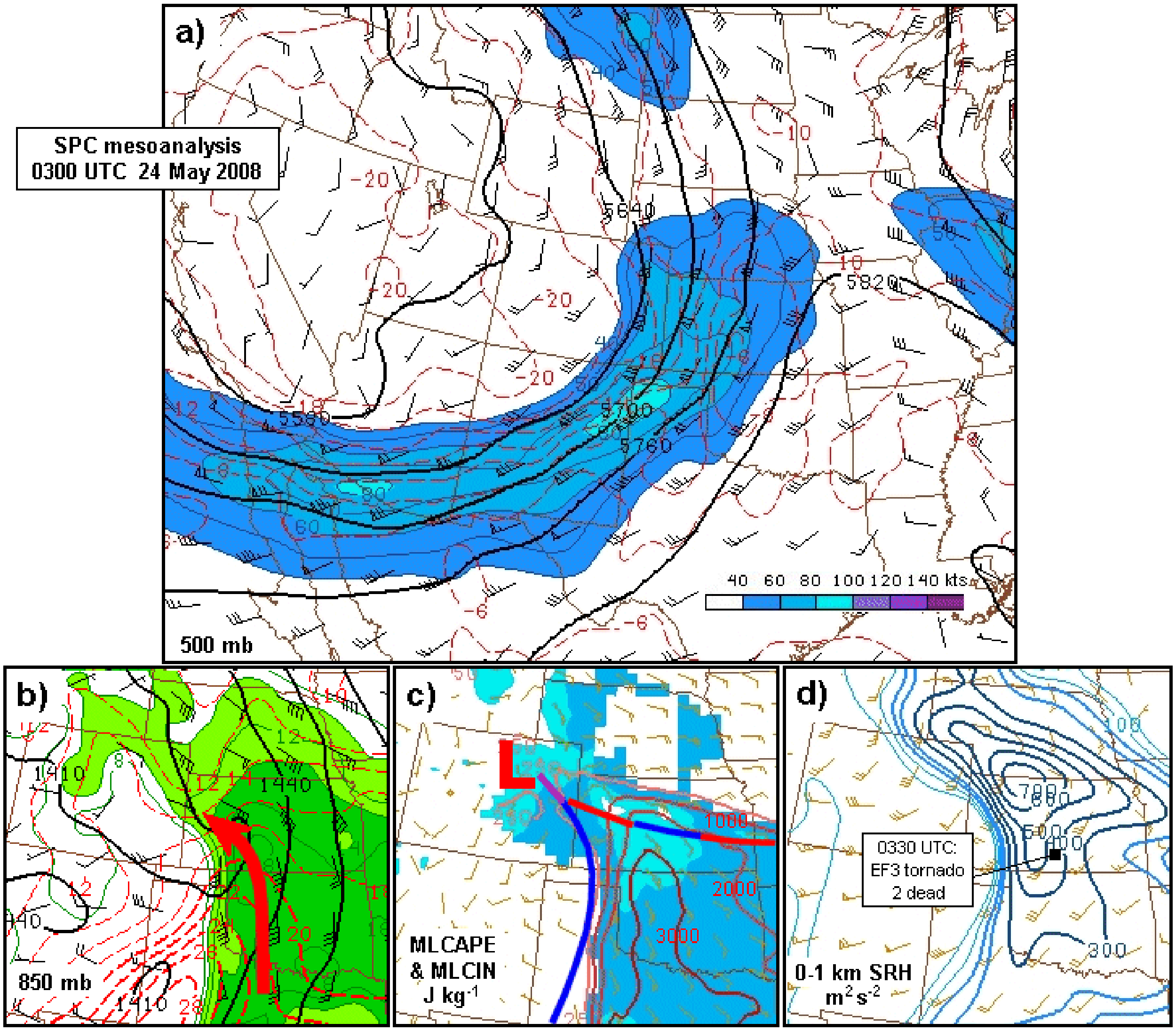


Figure 14. As in Fig. 13, except for 0300 UTC 24 May 2008.

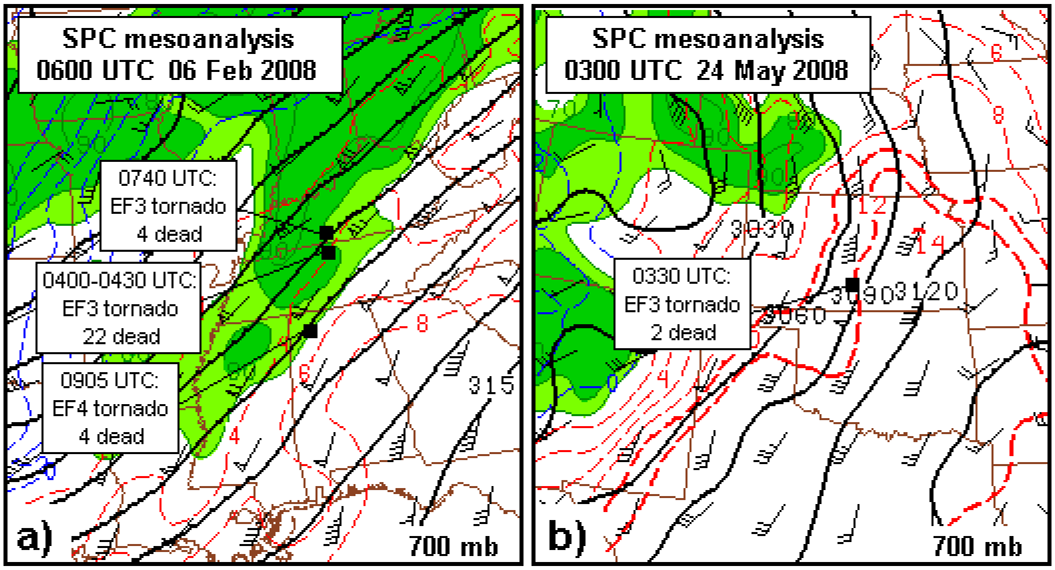


Figure 15. Plots from the SPC mesoanalysis showing 700-hPa (mb) height contours (m MSL, heavy solid lines), wind (barbs in kt), and temperature (^{o} C, dashed lines) on **a)** 6 February 2008 0600 UTC as in Fig. 13, and **b)** 24 May 2008 0300 UTC as in Fig. 14. Green shading shows relative humidity $\geq$ 70%. Isotherms are at 2^o C intervals. Locations and times of deadly nighttime tornadoes are also shown, as in Figs. 13d and 14d.