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Environmental Characteristics Associated with Nocturnal Significant-Tornado Events in the Central and Southern Great Plains

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ABSTRACT

Nocturnal significant-tornado events are investigated in association with a similar synoptic pattern in the spring, over the central and southern Great Plains, from 1999–2009. This pattern is characterized by a well-defined midlevel trough over the Intermountain West, with prevailing southwesterly winds at 500 hPa over the central United States. The underlying topography of the region contributes to the development or deepening of a lee cyclone over the High Plains with the rapid intensification of a low-level jet stream (LLJS) observed around 0000–0300 UTC. The LLJS development is as much as 3–6 h sooner and driven by different dynamical processes than that documented with the nocturnal boundary-layer wind maximum (NBLWM). In the 15 documented tornado cases, ratings of the nocturnal tornadoes exceed that of any antecedent, daytime occurrence. To determine which aspects of the local environment are critical to nocturnal tornado development within the context of the identified synoptic pattern, a similar sample of 18 nontornadic cases was compiled during the same time period. Rapid Update Cycle-2 (RUC-2) soundings representative of the warm sector environment revealed that the most important differences between the tornadic and nontornadic cases involved low-level thermodynamic profiles. Comparison of several thermodynamic parameters indicates that low-level static stability is a strong discriminator between the tornadic and nontornadic cases, with the tornadic cases characterized by larger mixing ratios, smaller convective inhibition, and a lower level of free convection.

1. Introduction

Climatological studies (e.g., Concannon et al. 2000; Brooks et al. 2003) clearly have defined a spatial maximum in tornado occurrence over the Great Plains, extending from western Texas into eastern Colorado, Nebraska, and Iowa. The location of this maximum is annually repeatable and largely dependent on the underlying geography of the region. To the south, the Gulf of Mexico provides a source of moist air in the low levels, whereas the high terrain of the western United States and northern Mexico serve as a genesis region for the development of an elevated mixed layer (EML; Carlson et al. 1983; Lanicci and Warner 1991a,b,c) that can contribute to the superposition of high lapse rates over near-surface moisture, yielding a vertical thermal stratification resembling a Type 1 or "loaded gun" sounding profile as defined by Miller (1972).

The characteristics of this Great Plains environment are largely responsible for the strong diurnal signal in tornado occurrence (Kelly et al. 1978), whereby convective inhibition (CIN; Colby 1984) associated with the EML often delays thunderstorm development and subsequent severe weather to near or just after the peak of diurnal heating. Thereafter, the relatively rapid development of CIN can occur as the boundary layer underlying the EML begins to cool and stabilize. This typically leads to the dissipation of ongoing, diurnally initiated storms, while limiting the potential for subsequent, surface-based thunderstorm initiation.

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The late afternoon to early evening peak in tornado frequency, coupled with low population density and the lack of forests (i.e., greater visibility) all contribute to a reduced vulnerability to fatalities over the central United States when compared to other parts of the country east of the Rocky Mountains (Ashley 2007). However, when nighttime tornadoes do occur in the Plains, they can create significant challenges for the integrated warning system (Doswell et al. 1999) and pose a threat to life and property. Recent examples include: 1) the 21 April 2001 Hoisington, KS tornado, which resulted in one fatality, 28 injuries, and $43 million in damages (NCDC 2001); and, 2) the 4 May 2007 tornado, which leveled the rural community of Greensburg, KS, causing 11 fatalities, 63 injuries, and $250 million in property damage (NCDC 2007).

The primary motivation for this work stems partly from these two events, which are associated with a specific, recurring synoptic pattern that can foster an increased probability for significant (F/EF2+), late evening and/or nighttime tornadoes in the central and southern Great Plains. As illustrated in Figs. 1 and 2, the synoptic pattern consists of a high-amplitude midlevel trough over the Intermountain West and a midlevel ridge centered over the southeastern United States. At the surface, lee cyclogenesis is underway over the High Plains, which contributes to the development of a LLJS during the evening hours. This occurrence is 3–6 h prior to the formation of the NBLWM observed under quiescent synoptic-scale conditions as documented by Blackadar (1957), Wexler (1961), Holton (1967), and Bonner (1968).

Our identification of this pattern and initial attempts to apply an anecdotally constructed conceptual model to operational forecasts dates back to 2002. Since then, a number of these nocturnal significant-tornado events have been anticipated successfully. However, the general tendency has been to under-forecast the number and damage level of tornadoes in several of the more prolific nocturnal events. In other cases, the pattern was identified and tornadoes were forecast, but none were observed.

To address these operational forecasting shortcomings, we manually identify a sample of significant tornado (sigtor, after Hales 1988) events, and a similarly sized sample of nontornadic (nontor) severe weather cases which fit the identified synoptic pattern during the principal spring severe weather season. We specify case selection criteria in the following section, including a more detailed description of the synoptic pattern. Representative RUC-2 sounding differences between the sigtor and nontor events are presented in section 3, and our findings are summarized in section 4.

2. Data and methods

Our knowledge of several nocturnal tornado events in the central and southern Great Plains which occurred in similar synoptic patterns (two examples are provided in Figs. 1 and 2) served as the basis for initial data collection for this exploratory study. Questions regarding which specific processes or aspects of this pattern are critical to enhancing the nocturnal tornado threat led to an expansion of the dataset. This was accomplished through the use of the NOAA/National Climatic Data Center (NCDC) "Storm Events" database (available online at http://www4.ncdc.noaa.gov/cgi-win/wwcgi.dll?wwEvent~Storms) and the NOAA/ National Weather Service (NWS)/Storm Prediction Center (SPC) upper-air map archive (available online at http://www.spc.noaa.gov/obswx/maps/).

a. Case-selection criteria

From 1999–2009, a total of 44 tornado events with F/EF2+ damage after local sunset (calculated online at http://www.esrl.noaa.gov/gmd/grad/solcalc/) during the spring severe weather season (March–June) in the central and southern Great Plains (Texas to Nebraska) were considered as potential cases. Automated upper-air analyses of the prospective events then were compared manually to the synoptic-scale pattern shown in Figs. 1 and 2. Manually determined matches were those which exhibited the primary midlevel trough west of the Rocky Mountains and an indication of lee cyclogenesis over the High Plains from the surface through 850 hPa at 0000 UTC on the day of the event.

Tornado events which began during the daylight were not excluded. However, our case selection was limited to those events where the most intense storms and tornado damage occurred after local sunset. Although some light persists after sunset under clear-sky conditions, this is not necessarily the case in near-storm

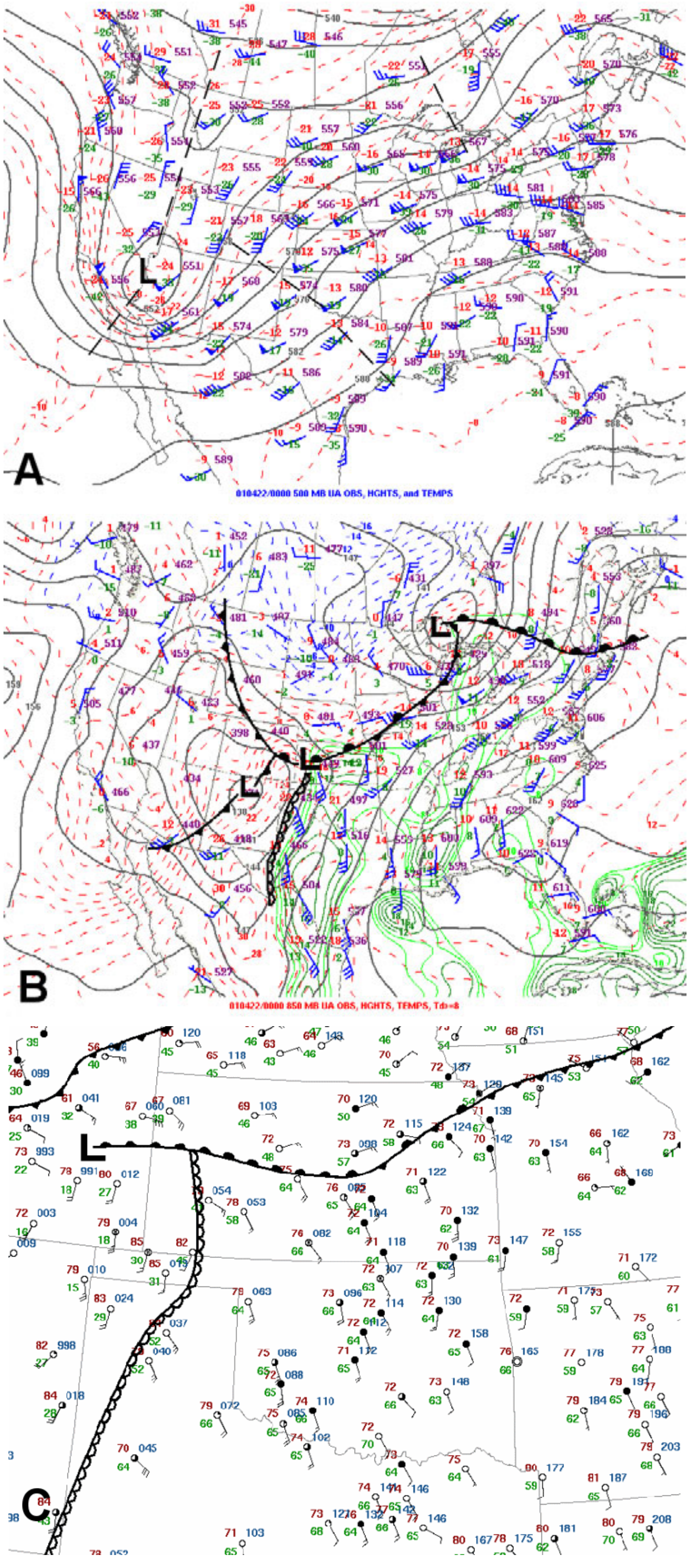


Figure 1: Automated Storm Prediction Center analyses of temperature (dashed, ºC), dewpoint temperature (solid green, ºC), and geopotential height (solid black, dam) valid at 0000 UTC 22 April 2001 for a) 500 hPa and b) 850 hPa. Surface station model plots (c) are shown for the same time, and each image is manually annotated with conventional frontal symbols. *Click images to enlarge.*

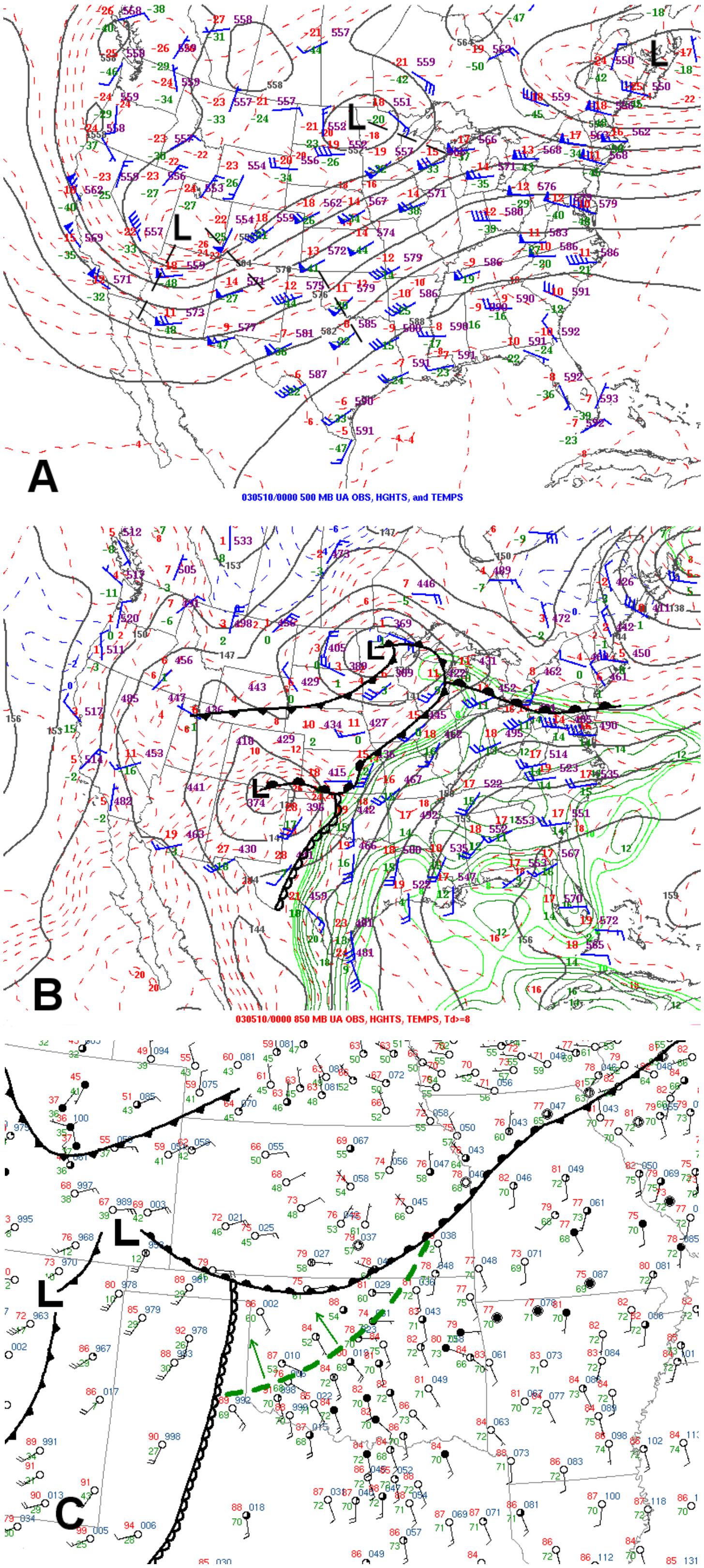


Figure 2: Same as Fig. 1, except for 0000 UTC 10 May 2003. The green dashed line and arrows in the surface analysis (c) denote a moisture gradient and direction of motion. *Click images to enlarge.*

environments (Ashley et al. 2008). Because the average report time for the beginning of the most damaging tornado for each case was 105 min after local sunset, we believe that the established criterion is a sufficient estimate of nocturnal sky conditions for each of the cases.

The period of analysis was restricted to 1998 onward, due to limited data availability in prior years. Following this series of constraints, a total of 15 significant, nocturnal tornado cases were identified (34 percent of all possible events), accounting for 27 individual significant tornadoes which were all associated with supercells. (Fig. 3 and Table 1).

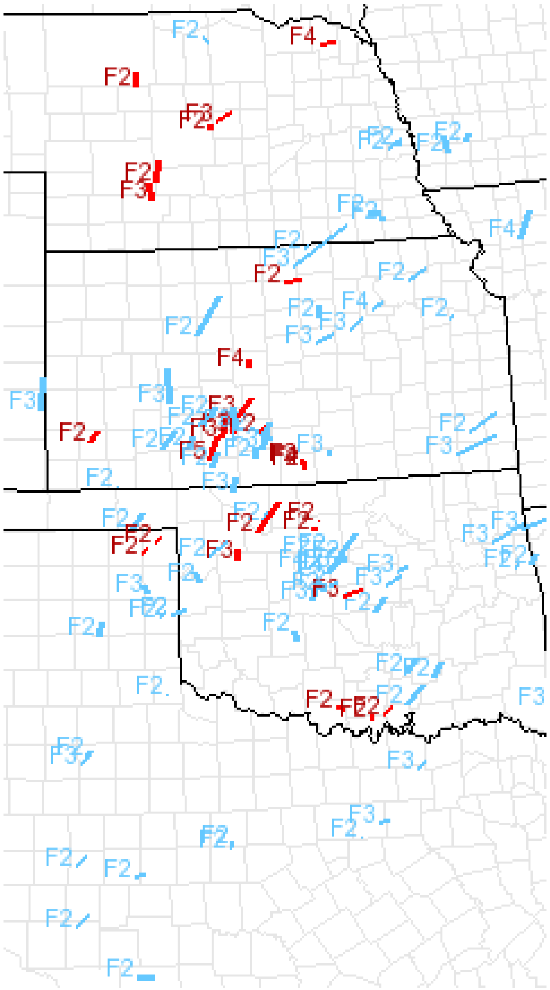


Figure 3: Tornado tracks and ratings for the sigtor cases listed in Table 1 (red) and all other nocturnal, significant tornadoes from 1999–2009 (light blue). *Click image to enlarge.*

To provide a consistent framework for determining which characteristics of the local environment are critical for nighttime tornado development, a similarly sized null-case set was compiled which featured a similar large-scale pattern. This was accomplished through manual comparison of automated upper-air analyses for the March–June period from 1999–2009 to the synoptic pattern in Figs. 1 and 2. Prospective null cases must have: 1) exhibited both a manual match to the sigtor pattern at 500 hPa and 850 hPa, and 2) included severe thunderstorms during the afternoon or evening, but no nocturnal tornadoes. Complete examination of the 11 spring seasons resulted in the identification of 18 nontornadic (nontor) cases (Table 2).

All of the identified nontor cases (see Fig. 4 as an example) were associated with various thunderstorm modes (i.e., supercells, multicells, quasi-linear convective systems, etc.) that produced severe hail and/or damaging winds over the central and southern Great Plains within the same convective day (1200 UTC to 1200 UTC). These events included a combination of diurnally driven storms that dissipated near or just after sunset, diurnal storms that persisted into the night, or nocturnal storms that lasted through a portion of the night. Weak tornadoes (one EF1 and two EF0s) were reported in three of the cases. However, the report times for these were between three and four hours *prior* to sunset.

b. Pattern-matching method

To test the utility of our manual pattern-matching approach, an automated map analog retrieval system (MARS) was employed which uses the National Centers for Environmental Prediction (NCEP) North American regional reanalysis (NARR; Mesinger et al. 2006) data. MARS compares the geopotential heights at 850 hPa and 500 hPa and the precipitable water reanalysis gridded fields at 0000 UTC for a user-defined input date to the same gridded fields for all of the dates available in the system database. The current MARS dataset contains reanalysis grids for each day at 0000 UTC from 1979–2009, resulting in over 11 000 dates for comparison. MARS returns a root mean square error (RMSE) for the three reanalysis gridded fields for each of the dates in the database. This allows the user to see which dates in the database most closely match the pattern of the input date.

Table 1: List of nocturnal, significant tornado events, with violent (F/EF4+) tornado events in bold.

Date	Location	Time of initiation	# Nocturnal F/EF2+	Highest F/EF rating	Time (UTC)
3 June 1999	S-central NE	nocturnal	2	F3	0419
4 June 1999	N-central NE	daytime	1	F2	0222
21 April 2001	**Southwest KS**	**daytime**	**1**	**F4**	**0215**
17 April 2002	Northwest OK	daytime	2	F3	0432
7 May 2003	S-central OK	nocturnal	3	F2	0754
9 May 2003	Central OK	daytime	1	F3	0328
23 June 2003	**Northeast NE**	**nocturnal**	**1**	**F4**	**0243**
12 May 2004	**S-central KS**	**daytime**	**3**	**F4**	**0139**
11 May 2005	Southwest KS	daytime	1	F2	0202
1 April 2006	Southwest KS	daytime	1	F2	0219
20 April 2007	Southwest NE	daytime	2	EF2	0302
4 May 2007	**Southwest KS**	**daytime**	**4**	**EF5**	**0200**
23 May 2007	TX Panhandle	daytime	2	EF2	0350
24 April 2008	N-central KS	daytime	1	EF2	0523
25 April 2009	N-central OK	daytime	2	EF2	0310

Table 2: List of nontornadic events.

Date	Location of severe storms	Period of initiation	Most notable reports
7 April 1999	TX Panhandle	daytime	Hail up to 2.5 cm diameter
29 April 2000	W-central TX into eastern CO	daytime	Hail up to 8.9 cm diameter
5 April 2001	Northeast KS, eastern NE, and western IA	nocturnal	Hail up to 3.8 cm diameter
9 April 2001	Eastern KS	daytime	Hail up to 4.4 cm diameter
2 May 2001*	Western TX and western OK	daytime	F0 tornado and hail up to 7 cm diameter
15 April 2002	Western TX	daytime	TSTM wind damage
18 April 2002*	Central and eastern KS	daytime	F0 tornado and hail up to 4.4 cm diameter
20 April 2002	Southern and eastern KS	daytime	Hail up to 4.4 cm diameter
26 April 2002	Southeast NM, western TX into eastern CO and KS	nocturnal	Hail up to 7 cm diameter
3 April 2003	Southern and central OK and northern KS	daytime	Hail up to 9.5 cm diameter
26 March 2004	Eastern MT, northeast WY and the western Dakotas	daytime	Hail up to 3.8 cm diameter
9 April 2005	NE, southeast SD, southwest MN and the TX Panhandle	nocturnal	Hail up to 3.2 cm diameter and 40 m s^{-1} TSTM wind gust
20 April 2005	Central and southern NE, central and eastern CO, central KS, western OK and the TX Panhandle	daytime	Hail up to 10.8 cm diameter and 39 m s^{-1} TSTM wind gust
5 April 2006	Southeast SD	nocturnal	Hail up to 2.2 cm diameter
23 April 2006	Central and eastern CO, southern NE, KS, northern OK and the TX Panhandle	daytime	Hail up to 6.4 cm diameter and 36 m s^{-1} TSTM wind gust
12 April 2007	TX Panhandle, western and central OK	daytime	Hail up to 4.4 cm diameter and 45 m s^{-1} TSTM wind gust
7 April 2008*	Southern KS, central and eastern OK, and northwest TX	daytime	EF1 tornado and hail up to 7 cm diameter
16 April 2008	Central and southern KS	nocturnal	Hail up to 4.4 cm diameter and 36 m s^{-1} TSTM wind gust

*Tornadoes occurred during the daylight hours

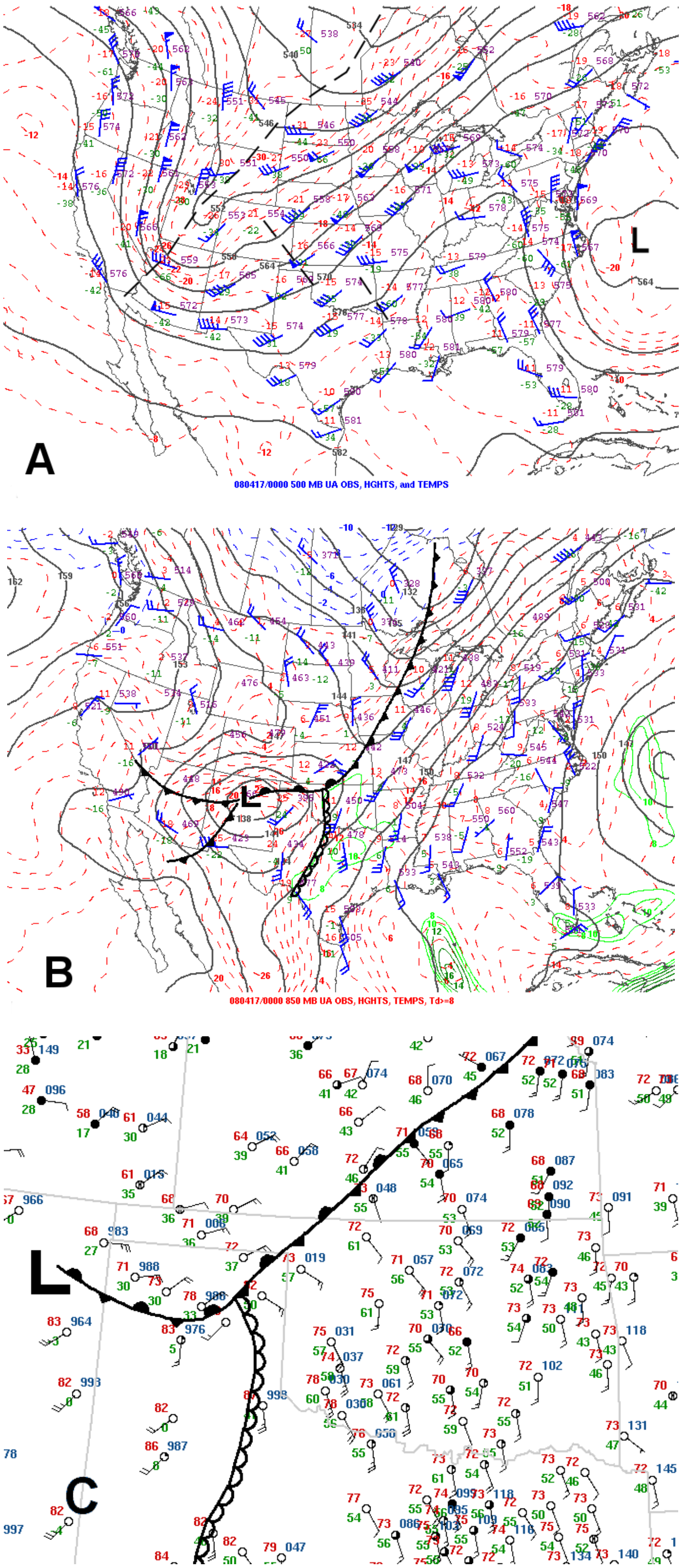


Figure 4: Same as Fig. 1, except for 0000 UTC 17 April 2008. *Click images to enlarge.*

Each of the sigtor and nontor cases (Tables 1 and 2) were used as input dates to MARS, with the RMSE of the 500-hPa geopotential height field used as a quantitative measure of how closely the pattern matched. For example, using 0000 UTC 4 June 1999 as an input date to MARS, the RMSE for the remaining 14 cases in the sigtor subset were recorded and then averaged (8.9). The input date was excluded from this calculation because its RMSE is zero. The mean RMSE for the remaining 14 sigtor cases then was compared to the RMSE distribution for the entire MARS database (over 11 000 data points), allowing for a quantitative assessment of our manual pattern-matching approach.

The results of the above-mentioned process are shown in Fig. 5 for the sigtor case set. For each date in the sigtor subset, the mean RMSE for the remaining 14 cases was below the 25th percentile of RMSE for the entire MARS database. Furthermore, in 12 of the 15 sigtor cases (80 percent), the mean RMSE for the remaining 14 cases was at or less than the 10th percentile of the RMSE for the entire MARS database. Though not shown, the results were similar for the nontor subset. This confirms that our manual pattern-matching approach was successful.

c. Synoptic pattern

A general overview of the identified synoptic pattern is provided in Fig. 6, which displays composite maps of 500-hPa geopotential heights and sea-level pressure for the sigtor and nontor cases, similar to Schultz et al. (2007). The mean and standard-deviation fields were created using 0–h RUC-2 analysis grids, valid 0000 UTC for each event contained in the two case sets. Our methodology ensured a consistent large-scale pattern for the sigtor and nontor cases, characterized by a major trough over the western United States and prevailing southwesterly midlevel winds downstream over the Great Plains. At the surface, a lee cyclone is analyzed over southeast Colorado into northeast New Mexico, resulting in a southerly low-level flow regime from the western Gulf of Mexico through the central plains.

As shown in Fig. 6, the primary trough is generally near or west of the Continental Divide, resulting in the most substantial mid- and upper-level forcing for ascent remaining well to the west of the Great Plains at the time of the sigtor events. This is in contrast to the synoptically evident tornado outbreak pattern (Johns and Doswell 1992), Miller Type B tornado pattern (Miller 1972) and the classic synoptic severe weather pattern developed by Barnes and Newton (1986), where the severe storms develop immediately in advance of a strong, progressive extratropical cyclone. Instead, forcing mechanisms such as low-amplitude short-wave troughs and jet streaks have been observed within similar large-scale patterns downstream from the primary trough within the southwesterly flow field over the central or southern Rockies (Roebber et al. 2002; Lemon and Umscheid 2008). These features are often manifest in satellite imagery as cirrus streaks or plumes and can enhance lower-tropospheric processes such as lee cyclogenesis and LLJS formation.

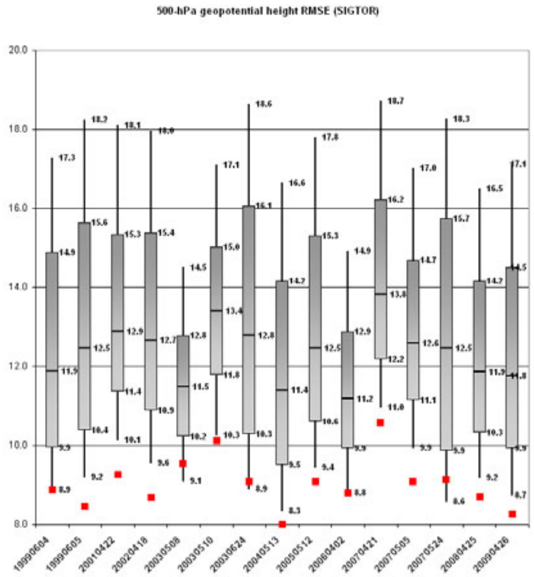


Figure 5: Box-and-whiskers diagram of 500-hPa geopotential height RMSE (from MARS) for the sigtor cases. The shaded box covers the 25th–75th percentiles, the whiskers extend to the 10th and 90th percentiles, and the median values are marked by the heavy dashed line within each shaded box. The red squares denote the mean RMSE for the remaining 14 cases in the sigtor subset. *Click image to enlarge.*

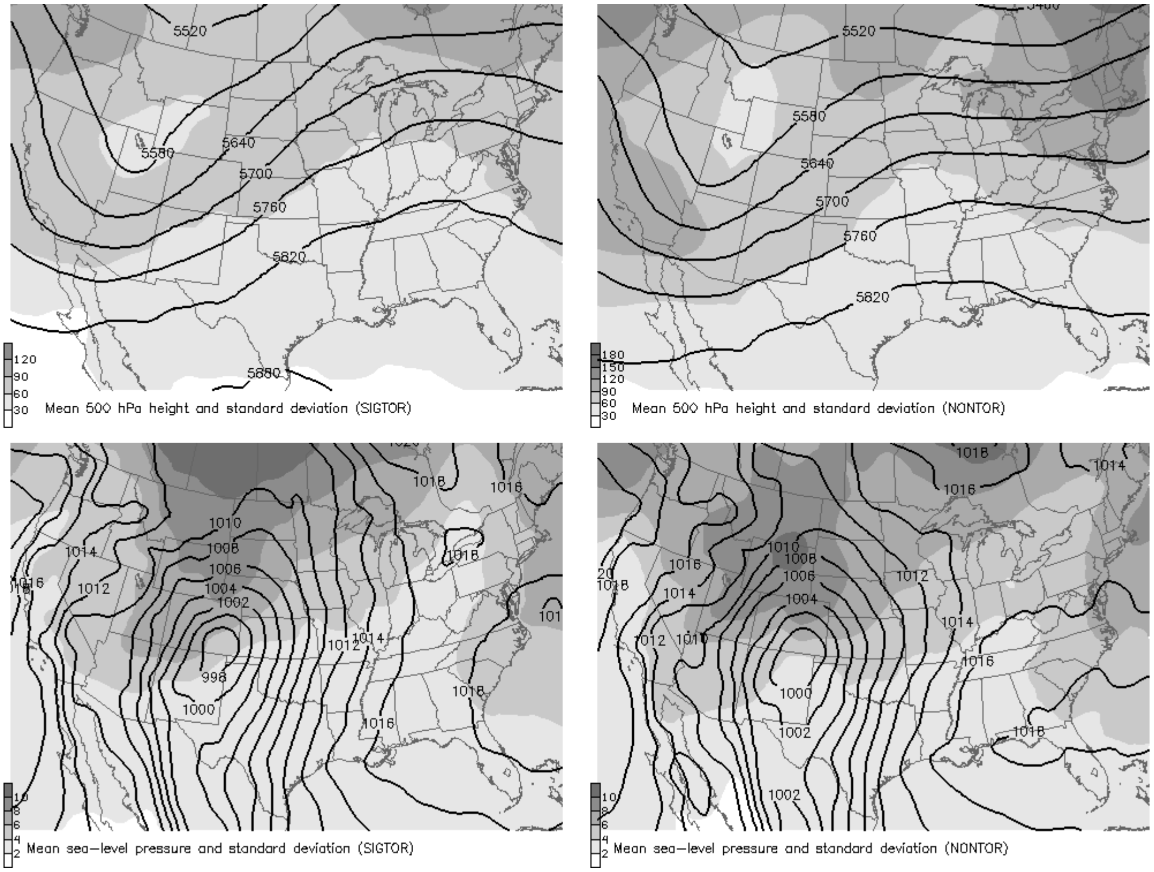


Figure 6: 0-h RUC-2 analysis grids, valid 0000 UTC, of mean and standard deviation (fill) 500-hPa geopotential heights (in meters—top) and mean sea-level pressure (in hPa—bottom) for the sigtor cases (left) and nontor cases (right). *Click image to enlarge.*

Another commonly observed midlevel feature is a short-wave trough that is weakening over the north-central United States or south-central Canada. Although not resolved in the mean geopotential height fields in Fig. 6, a representative illustration of this weakening, short-wave trough is provided in Figs. 1 and 2. The surface cyclone associated with the short-wave trough can aid in the poleward transport of low-level moisture from the Gulf of Mexico, a process that is hastened by the primary, deepening lee cyclone over the High Plains. Additionally, a cold front associated with initial surface low is often observed to link with the High Plains lee cyclone. This boundary becomes stationary or assumes warm frontal properties with time, serving in conjunction with the dryline as foci for storm initiation during these nocturnal episodes.

This study has accounted for only about one-third of all nocturnal, significant-tornado events in the Great Plains from 1999–2009. Recent departures from the identified synoptic pattern include multiple EF2–EF3 tornadoes over the central and southern High Plains on 28 March 2007 and an EF4 tornado in south-central Oklahoma on 10 February 2009. These events were associated with a more synoptically evident (Johns and Doswell 1992) pattern where an amplified midlevel trough is emerging over the Great Plains. Figure 7 is a comparison of the composite synoptic pattern between the documented sigtor events and an independent set of 13 nocturnal sigtor cases, two of which are the above-mentioned events. Note the difference in amplitude and eastward displacement of the 500-hPa trough associated with the more synoptically evident nocturnal sigtor cases. The implication is that the stronger mid- and upper-level forcing for ascent would be located over the Great Plains, as opposed to farther west across the Great Basin into the central and southern Rocky Mountains in the sigtor cases.

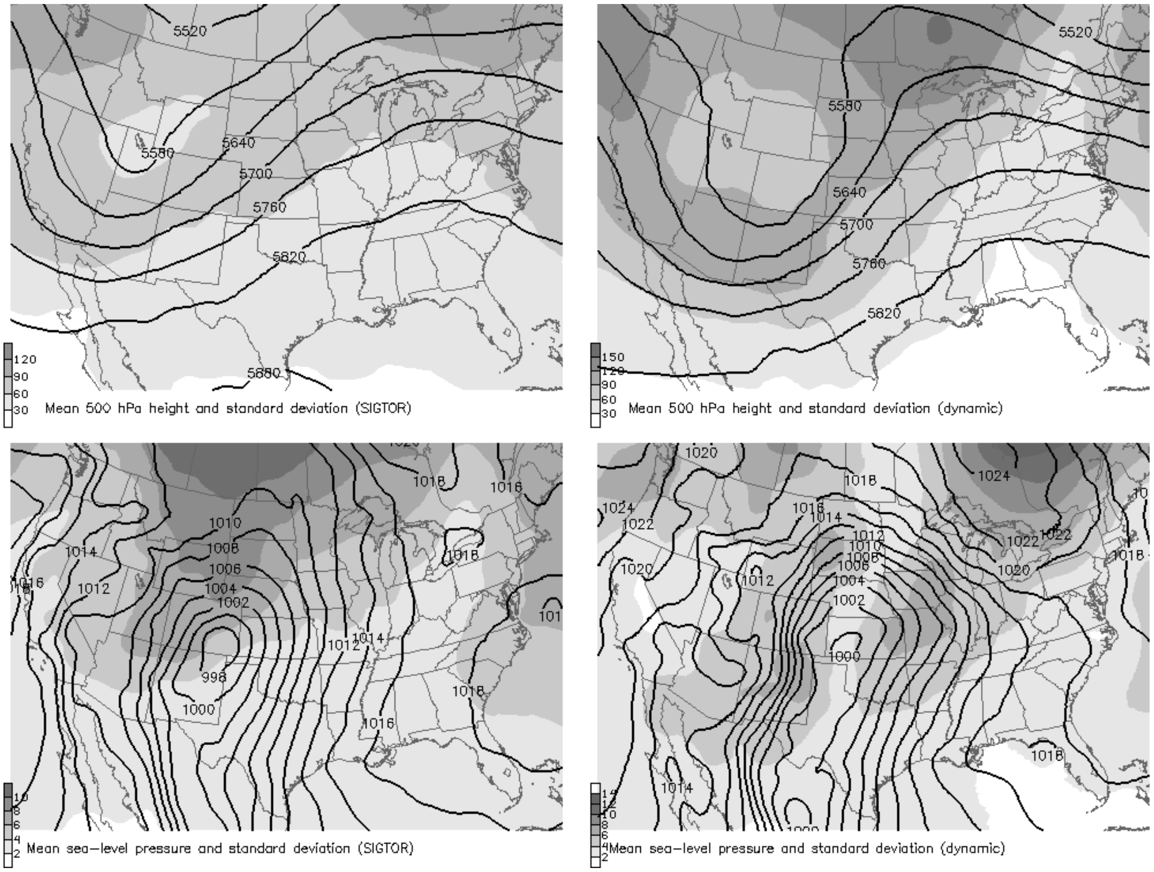


Figure 7: Same as Fig. 6 except for the sigtor cases (left) and an independent subset of 13 more synoptically evident (Johns and Doswell 1992) nocturnal tornado events (right). *Click image to enlarge.*

c. LLJS

A notable component of the identified pattern is the development of a LLJS around 0000–0300 UTC, which is as much as 3–6 h prior to documented NBLWM formation (e.g., Blackadar 1957; Wexler 1961; Holton 1967; Bonner 1968) and the result of different dynamical processes. Reiter (1969) documented the presence of lower-tropospheric wind maxima over the Midwest in conjunction with synoptic or subsynoptic-scale forcing. Hoecker (1963) and Bonner (1966) showed examples where LLJS formation occurred in association with a lee trough or cyclogenesis east of the Rocky Mountains. Furthermore, Uccellini and Johnson (1979) and Uccellini (1980) demonstrated how upper-level jet streaks (ULJS) and deepening synoptic systems can contribute to the development of and/or intensification of the LLJS, regardless of time of day.

An important characteristic of the LLJS is its ability to transport heat and moisture (Means 1952, 1954; Bonner 1966) rapidly poleward, contributing to the destabilization of the pre-convective environment. Often times, this convective instability is released owing to ascent in the exit region of the LLJS (Beebe and Bates 1955; Uccellini 1990). In addition to modifying the thermodynamic characteristics of the local environment, Maddox (1993) illustrated how the development of the nocturnal LLJS can dramatically increase storm-relative helicity (SRH; Davies-Jones 1984; Davies-Jones et al. 1990), which can promote supercell development and intensity.

For the purpose of this study, the LLJS was defined as a southerly wind maximum that develops at or below 1500 m AGL with speeds ≥12 m s^{-1} (Bonner, 1968). However, this low-level wind maximum did not necessarily represent the greatest speed in the tropospheric wind profile; stronger winds were usually present in the middle and upper troposphere. The development and evolution of the LLJS in this synoptic setting was documented through the use of plan view and time–height displays of the

NOAA 404-MHz Profiler Network (NPN) and Weather Surveillance Radar-1988 Doppler (WSR-88D) velocity azimuth display (VAD) data. These data were used to identify spatial characteristics of the LLJS on an hourly basis from 0000–0600 UTC for each of the 33 cases.

However, caution must be exercised when drawing conclusions from these data sources. Gauthreaux et al. (1998), Wilczak et al. (1995), and Holleman et al. (2008) have documented the impact of bird migrations on WSR-88D VAD and NPN speed estimates. Nonrandom errors as large as 15 m s^{-1} were observed in wind data measured by 915- and 404-MHz wind profilers (Wilczak et al., 1995), with positive biases of 4.8–12.4 m s^{-1} noted in raw weather radar wind speed estimates (Holleman et al. 2008). Because bird migrations are common at night in the spring, the NPN and WSR-88D VAD data used in this study possibly were affected as well.

Quality-control checks are made for bird contamination during the RUC-2 data assimilation process (Benjamin et al. 2002), so 0-h analysis plan view grids at 900 and 850 hPa and grid-point soundings were compared to the NPN and WSR-88D VAD data along the LLJS. Comparisons were made at 0000, 0300, and 0600 UTC in order to determine whether a bias in the observational data was evident. Similar to the results of Wilczak et al. (1995) and Holleman et al. (2008), mean positive biases ranging from 0.3–1.3 m s^{-1} at 0000 UTC to 2.7–5.7 m s^{-1} at 0600 UTC were observed in the NPN and WSR-88D VAD data for both the sigtor and nontor cases. Nonetheless, the authors believe that these data still hold value, particularly in identifying spatial and temporal characteristics of LLJS evolution.

In light of the positive bias brought about by bird migration, the NPN and WSR-88D VAD data were used in conjunction with 0-h RUC-2 analysis grids to analyze LLJS evolution. Results indicate a very similar evolution of the LLJS from 0000–0300 UTC for both the sigtor and nontor cases (Fig. 8) with the most rapid intensification occurring during this time period.

d. Near-storm environments

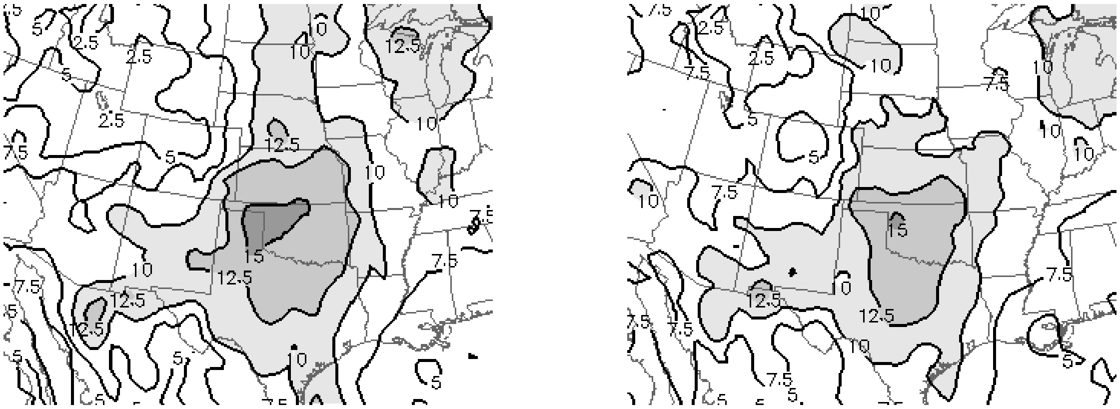
The previously described method of pattern-matching has assured a similar synoptic-scale regime for the sigtor and nontor case sets, including LLJS formation. Therefore, it is instructive to consider the application of an ingredients-based approach (Doswell et al. 1996) to the identified pattern in order to determine if any important differences exist between the sigtor and nontor environments.

A relatively straightforward approach is to evaluate sounding-derived ingredients near the tornadic storms. For the nontor cases, this application becomes more ambiguous because storms may not have been present during the late evening and nighttime hours. A methodology has been developed to address this concern, and it is not reliant on the presence of storms.

As mentioned previously, the LLJS is not only effective in the poleward transport of heat and moisture, but it also can serve to enhance low-level wind shear. Therefore, a representative location for sounding-derived environmental analysis was determined by where the axis of the LLJS overlapped the northern extent of warmest surface temperatures and dewpoints. Often, this location coincided with the intersection of the LLJS and a west–east oriented surface boundary (Fig. 9). In other cases, the specified location coincided with a moisture gradient or secondary warm front (Metz et al. 2004) in the warm sector (Fig 10). Because the average beginning time of the most intense tornado for each of the sigtor cases was 0323 UTC, a temporal criterion of 0300 UTC was chosen to evaluate the characteristics of the warm-sector environment.

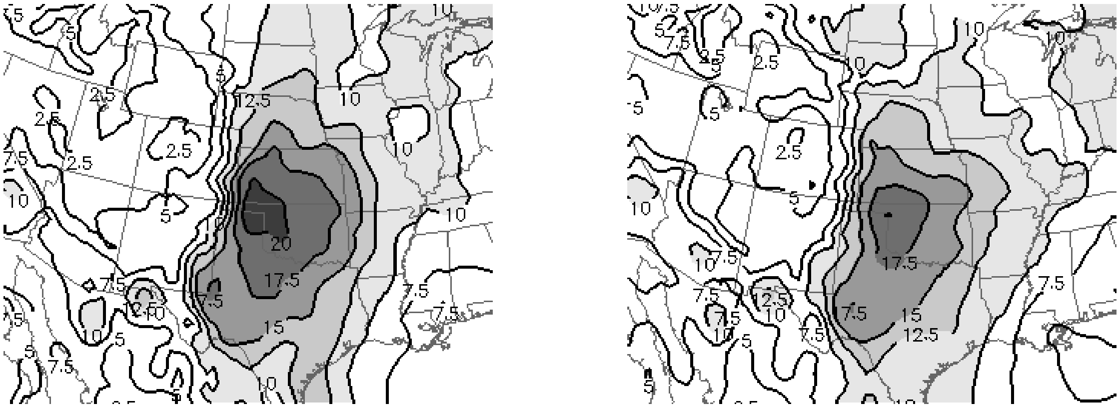
The sounding location determined by our method was compared to the starting point of the highest-rated tornado for each of the sigtor cases (not shown). On average, our approach defined a proximity location within about 100 km of the observed tornado occurrence, similar to the proximity criteria of Potvin et al. (2010).

Once the sounding location was specified for each case, a combination of Rapid Update Cycle-2 (RUC-2; Benjamin et al. 2002) analysis grids and RUC-2 analysis profiles (Benjamin et al. 2004) were used to construct soundings for the analysis of the sigtor and nontor environments (Thompson et al. 2003; hereafter T03). RUC-2 analysis grids were used from 1999–2003, with the RUC analysis profiles used from 2004–2009. The RUC-2 analysis grids were available at either 20- or 40-km horizontal grid spacing (based on availability), on isobaric surfaces with 25-hPa vertical grid spacing. However, RUC-2 analysis profiles provide full model resolution in



850 hPa isotachs at 0000 UTC (m s−1 SIGTOR)

850 hPa isotachs at 0000 UTC (m s−1 NONTOR)



850 hPa isotachs at 0300 UTC (m s−1 SIGTOR)

850 hPa isotachs at 0300 UTC (m s−1 NONTOR)

Figure 8: 0-h RUC analysis grids of mean 850-hPa isotachs (m s^{-1}), valid 0000 UTC (top) and 0300 UTC (bottom), for the sigtor cases (left) and the nontor cases (right). *Click image to enlarge.*

the vertical. Both data types were displayed using the UNIX version of the Skew-T Hodograph Analysis and Research Program (NSHARP; Hart and Korotky 1991) software.

RUC-2 analysis grids were also used in the creation of plan view isobaric and sea-level pressure analyses, depicting the synoptic pattern. These analyses were created using the General Meteorology Package (GEMPAK; desJardins et al. 1991).

3. RUC-2 sounding analysis results

Our data collection methodology has assured a similar synoptic-scale pattern for the sigtor and nontor cases (as shown in Fig. 6). This approach provides a consistent framework in which to investigate potentially meaningful differences in the warm-sector environments for both subsets using RUC sounding data. Because of known cool and dry biases near the ground (T03), the sounding profiles were modified with nearby surface observations, similar to Thompson et al. (2007) and Davies (2004). Although this study will be compared to similar work, differences in sample size should be recognized when considering the statistical results.

a. Thermodynamic parameters

Doswell et al. (1996) described three ingredients for thunderstorms: lower tropospheric moisture, conditional instability, and some lifting mechanism, such as a convergent boundary. The first two of those ingredients often are combined into the CAPE parameter to assess environmental buoyancy. As recommended by Craven et al. (2002), the mean temperature and dewpoint in the lowest 100-hPa mixed layer (ML) were used in all of the thermodynamic calculations. All CAPE computations included the virtual temperature correction (Doswell and Rasmussen 1994).

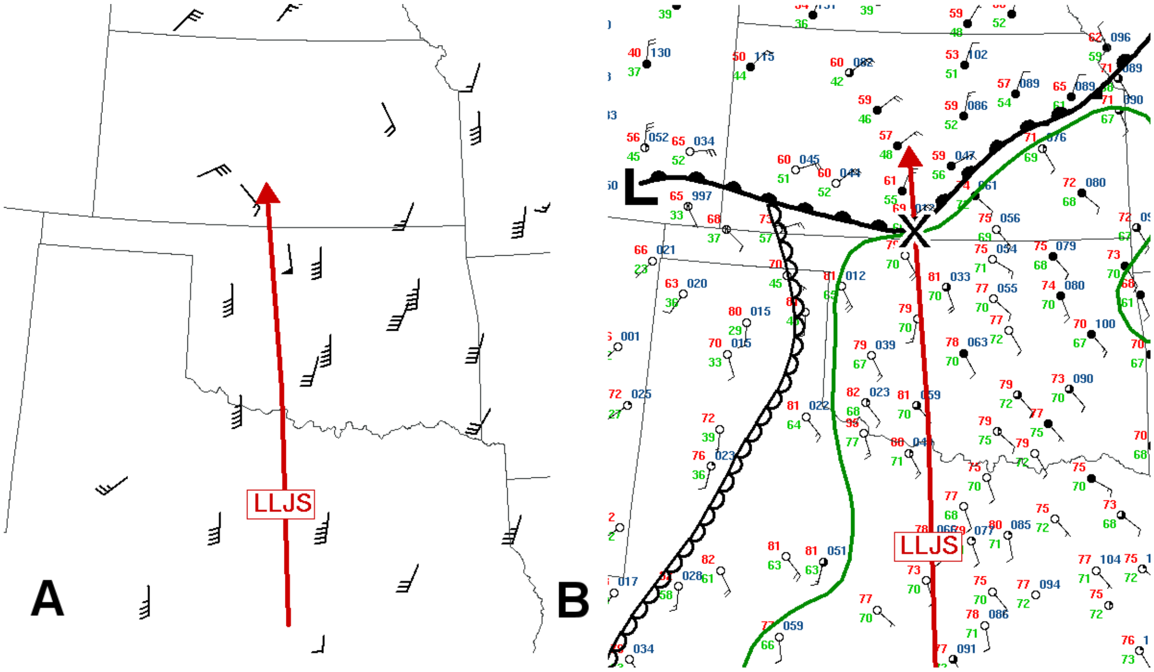


Figure 9: Illustration of how the location for sampling the environment was determined (0300 UTC 13 May 2004). a) The LLJS axis (red line with arrowhead) was determined manually using NPN and WSR-88D VAD wind data at 1 km AGL. b) The LLJS axis was superimposed on the surface map which includes standard frontal symbols. The "X" denotes where the LLJS intersected the northern extent of the manually determined warmest temperature and dewpoint in the warm sector (green line). *Click image to enlarge.*

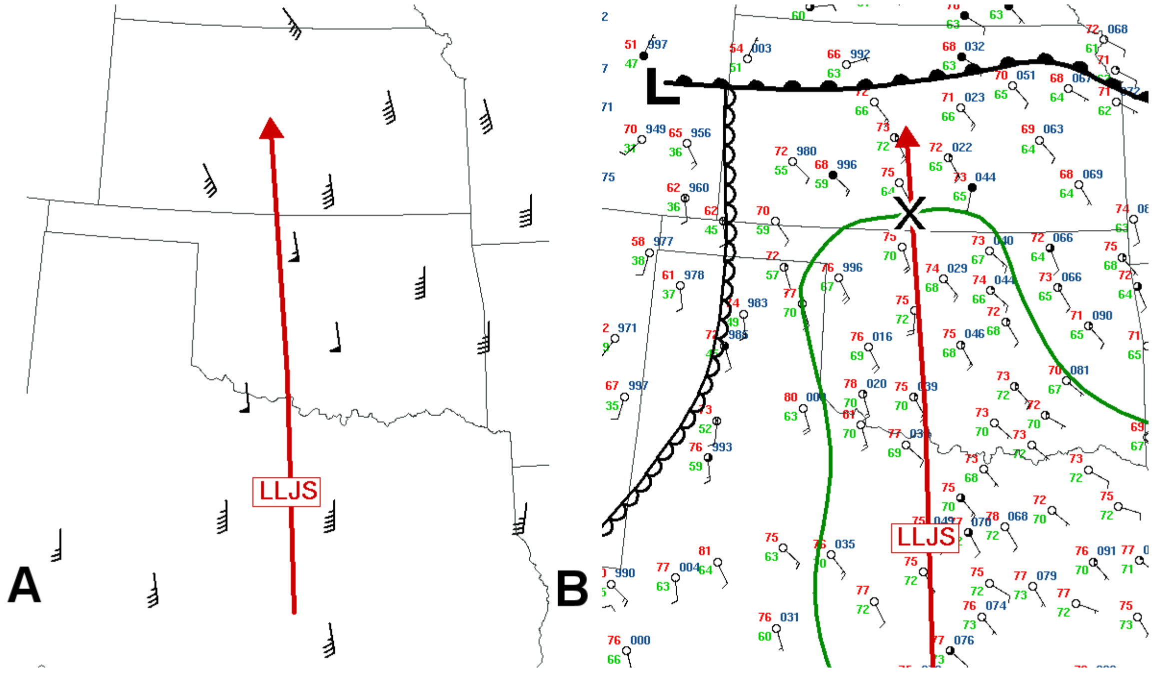


Figure 10: Same as Fig 9, except for warm front displaced to the north of the warmest temperatures and dewpoints. Analysis valid 0300 UTC 5 May 2007. *Click image to enlarge.*

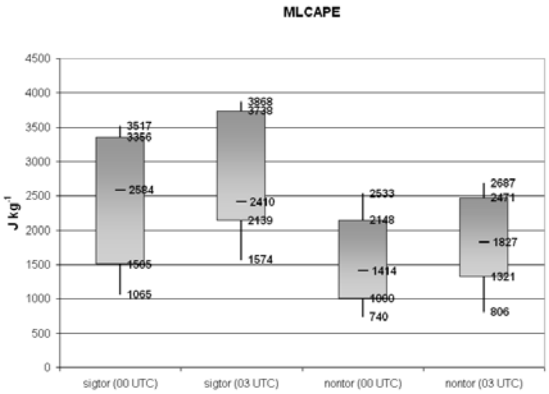


Figure 11: Same as Fig. 5, except for 100-hPa mean parcel CAPE (MLCAPE, J kg^{-1}) at 0000 and 0300 UTC for the sigtor (15) and nontor (18) cases. *Click image to enlarge.*

Both the sigtor and nontor environments are associated with moderately to strongly unstable environments, but the MLCAPE values for the sigtor events are almost one quartile larger at both 0000 and 0300 UTC (Fig. 11). The 0300 UTC median value of 2410 J kg^{-1} for the sigtor subset is close to the median value of 2654 J kg^{-1} for the Plains nighttime significant tornado subset found in Davies and Fischer (2009; hereafter DF09) and the median value of 2152 J kg^{-1} for the significantly tornadic supercells in T03.

The MLCAPE *increases* locally from 0000 to 0300 UTC in both subsets, a result that is contrary to the typical diurnal tendency. Time trends in ML mixing ratio (Fig. 12) and 3–6-km AGL lapse rate (Fig. 13 and Table 3 for mean values) indicate that this observation is due primarily to increasing boundary-layer moisture.

Assessing lower-tropospheric static stability is considerably important in forecasting the development of tornadic storms, especially after dark. CIN (presented as absolute values herein to avoid the negative sign) provides an estimate of negative buoyancy that must be overcome for deep, moist convection to initiate or persist. Tornadic storms typically are associated with lower absolute values of CIN than other classes of deep, moist convection (Rasmussen and Blanchard 1998, hereafter RB98; Davies 2004; DF09). Exceptions do occur where significant tornadoes are observed in stable, near-surface environments (Fischer and Davies 2009; hereafter FD09). In these relatively infrequent cases, a plausible hypothesis advanced by FD09 is that the combination of strong low-level shear and conditional instability allow for the maintenance of supercells with intense mesocyclones (Rotunno and Klemp 1982), such that the mesocyclone overwhelms the ambient CIN and continues to force surface-based parcels to their respective levels of free convection (LFCs).

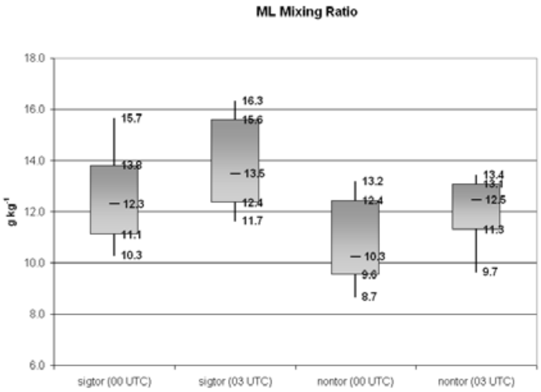


Figure 12: Same as Fig. 5, except for ML mixing ratio (g kg^{-1}). *Click image to enlarge.*

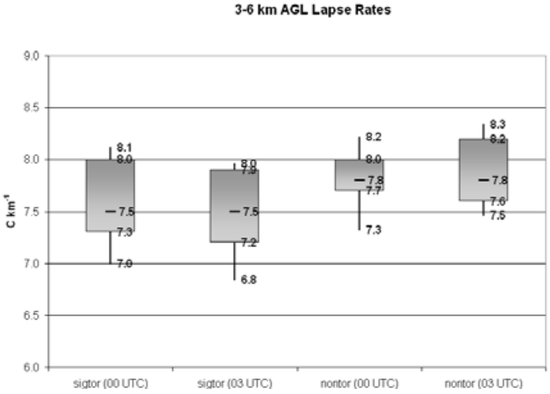


Figure 13: Same as Fig. 5, except for 3–6 km AGL lapse rate. *Click image to enlarge.*

The results in Fig. 14 are consistent with RB98, Davies (2004), DF09, and FD09 in that the sigtor cases were associated with notably less MLCIN than for nontor cases. In fact, this discrimination increases between 0000 UTC and 0300 UTC, where the 90th percentile CIN value for the sigtor cases is less than the 25th percentile CIN value for the nontor counterparts. This separation may be attributed to higher boundary layer moisture content in the sigtor cases (Fig. 12) which effectively limits radiational cooling and resultant MLCIN accumulation. Although MLCIN more than doubles between 0000 UTC and 0300 UTC for both the sigtor and nontor cases, the

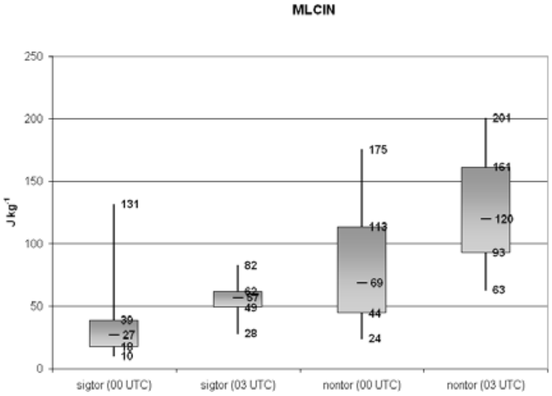


Figure 14: Same as Fig. 5, except for MLCIN (J kg^{-1}). *Click image to enlarge.*

respective median sigtor values of 27 and 57 J kg^{-1}are in good agreement with the median value of 50 J kg^{-1} for the Plains subset of nocturnal tornado cases in DF09. Moreover, the interquartile range for the sigtor cases is much smaller than that for the nontor events (i.e., 49–62 J kg^{-1} versus 93–161 J kg^{-1}) at 0300 UTC.

Kis and Straka (2010) noted a distinct tendency for weaker buoyancy and increased near-ground static stability in significant nocturnal tornado events compared to similar afternoon events. However, our results indicate that MLCIN remains relatively small with large MLCAPE into the nighttime for the sigtor case set. The majority of sigtor environments sampled in Kis and Straka (2010) were from the Ozarks and mid Mississippi Valley to the Gulf Coast states. The differences in MLCAPE values between the Kis and Straka (2010) dataset and the sigtor cases at 0300 UTC in this study are quite similar to that observed in DF09 between their Plains and Gulf Coast subsets.

All other variables being equal, RB98, Craven and Brooks (2004), T03, and more recently, DF09 have shown that the probability of significant tornadoes increases with decreasing LCL heights. Although not explicitly quantifying a physical process that directly relates to tornado formation, lower LCL heights are consistent with the hypothesis of Markowski et al. (2002) that increased low-level relative humidity is associated with positive buoyancy in the rear flank downdraft outflow, and hence an increased probability of tornadoes. In our case sample, MLLCL heights are slightly lower for the sigtor cases for both times (not shown), though the differences are too small to be resolved in an operational forecast setting (not shown). MLLCL heights lower by more than a quartile in both subsets between 0000 and 0300 UTC. This would be expected given the observed boundary-layer moistening (Fig. 12) and surface temperatures which cooled by an average of 2.7°C and 3.4°C for the sigtor and nontor cases, respectively. The median MLLCL value for the sigtor cases (993 m AGL at 0300 UTC) agrees well with both T03 (1004 m AGL for their sigtor events) and DF09 (996 m AGL for their Plains nighttime sigtor events).

The MLLFC (Fig. 15) discriminates more clearly between the sigtor and nontor cases than the MLLCL (not shown). Similar to MLCIN (Fig. 14), this discrimination becomes even more

Table 3: Mean values of the thermodynamic and kinematic parameters from Figs. 11–19 for the 15 sigtor and 18 nontor cases at 0000 and 0300 UTC, based on RUC-2 sounding data. Values considered to be statistically significant at the 95% confidence level are in bold. Note these mean values differ from the medians given in the box-and-whiskers diagrams (Figs. 11-19).

Mean value	**Fig.**	**Sigtor 00 UTC**	**Sigtor 03 UTC**	**Nontor 00 UTC**	**Nontor 03 UTC**
MLCAPE (J kg^{-1})	11	**2159**	**2770**	**1635**	**1809**
MLMIXR (g kg^{-1})	12	**12.1**	**13.9**	**10.9**	**12.0**
3-6 km LR (C km^{-1})	13	7.6	**7.5**	7.8	**7.9**
MLCIN (J kg^{-1})	14	54	**55**	88	**158**
MLLCL (m AGL)	15	1448	1006	1585	1145
MLLFC (m AGL)	16	**2364**	**1975**	**2839**	**2750**
0–6-km vector shear mag. (m s^{-1})	17	23.5	23.0	22.0	21.0
0–1-km SRH (m^2 s^{-2})	18	169	345	140	305
ESRH (m^2 s^{-2})	19	188	**395**	146	**231**

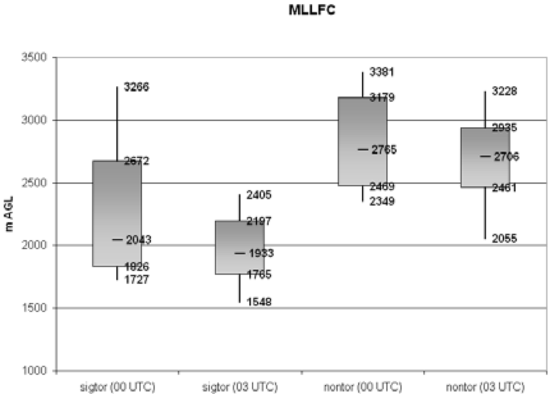


Figure 15: Same as Fig. 5, except for MLLFC (m AGL). *Click image to enlarge.*

apparent from 0000 to 0300 UTC with the 90th percentile (relatively high values) of the sigtor cases falling below the 25th percentile (relatively low values) of the nontor cases, a result similar to that of Davies (2004). This is an expected result because MLCIN is indirectly accounted for by the MLLFC (i.e., larger MLCIN values are typically associated with greater LFC heights).

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b. Kinematic parameters

In addition to the three basic ingredients for thunderstorms, vertical wind shear represents an important control that is instrumental in determining the degree of storm organization. Cloud model simulations by Weisman and Klemp (1982), along with observational studies (e.g., Markowski et al. 1998; RB98; Bunkers 2002), indicate that a vector shear magnitude of roughly 15–20 m s^{-1} over the lowest 6 km is necessary to support persistent, rotating updrafts. Once a supercell forms, Davies-Jones et al. (1990), Rasmussen (2003), T03, and DF09 have shown that significant tornadoes typically are associated with larger SRH.

Historically, SRH has been measured using fixed layers such as 0–1 or 0–3 km AGL, with more recent results from Esterheld and Giuliano (2008) indicating that even a shallower near-ground layer is optimal. Recently, Thompson et al. (2007) developed an approach that incorporates the thermodynamic characteristics (i.e., CAPE and CIN criteria of 100 J kg^{-1} and 250 J kg^{-1}, respectively) of the lower troposphere in order to define an "effective inflow layer." The SRH calculated through the depth of the effective inflow layer was defined as the effective SRH (ESRH). Thompson et al. (2007) found ESRH to be an improved measure of low-level shear in elevated supercell environments, as well as a better discriminator between sigtor and nontor environments than fixed-layer SRH calculations.

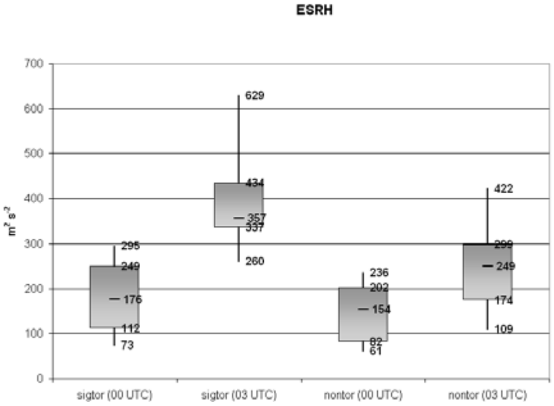

Figure 16: Same as Fig. 5, except for ESRH (m^2 s^{-2}). *Click image to enlarge.*

Recall that the data collection methodology resulted in a similar synoptic pattern for both subsets, including LLJS evolution (section 2c). This LLJS evolution is reflected in the corresponding increase in 0–1-km SRH between 0000 and 0300 UTC with considerable overlap between the sigtor and nontor cases (not shown). In contrast, the ESRH (Fig. 16) shows considerably better discrimination. This is particularly the case at 0300 UTC, where the 75th percentile of the nontor cases fall below the 25th percentile of the sigtor subset. This tendency is similar to that of MLCIN and MLLFC, which both account for negative parcel buoyancy in the low-level thermodynamic profile. Therefore, a better discrimination between the two subsets can be arrived at through the incorporation of low-level thermodynamic characteristics with an assessment of low-level shear. This notion is supported by the results of a two-sample Student's *t* test for equal and unequal variances (Milton and Arnold 1990) which was performed on the thermodynamic and kinematic fields listed in Table 3. Parameters such as MLCAPE, ML mixing ratio, MLCIN, 3–6-km AGL lapse rate, MLLFC, and ESRH were shown to be statistically significant at either or both 0000 and 0300 UTC. However, the two-tailed *p* value was the lowest for MLCIN and MLLFC (0.0002 and 0.0003, respectively) at 0300 UTC.

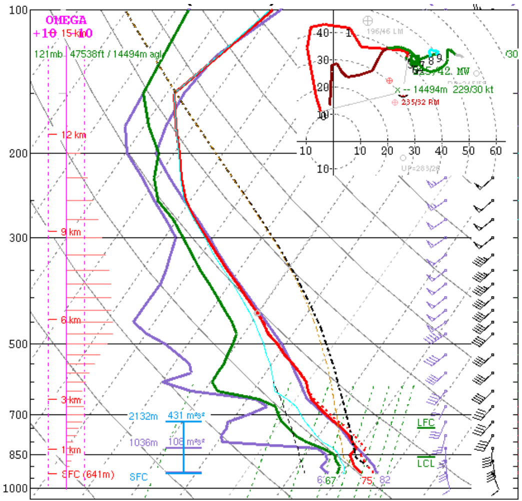

Figure 17: Overlay of 0-h RUC analysis profiles for Pratt, KS, valid 0000 UTC (purple) and 0300 UTC on 5 May 2007. Boundary layer conditions for both soundings were modified using observed surface and sounding data. The lowest 3 km of the hodograph for the 0300 UTC profile is in light red**.** *Click image to enlarge.*

The results from this section suggest that the kinematic environment for the sigtor and nontor cases is similar, and likely modulated by the synoptic pattern which was consistent for both subsets. This includes the advection of an EML into the central and southern plains (Fig. 13) by the prevailing southwesterly winds in the mid troposphere. The key differences between the sigtor and nontor cases appear to reside on the mesoscale, namely the characteristics of the low-level thermodynamic profile. Indeed, Figs. 12, 14, and 15 suggest that the sigtor environment features a moister boundary layer with less MLCIN and lower MLLFC heights.

A good illustration of these results is shown by a case example for the evening of 4 May 2007 (Fig. 17) which demonstrates the change in the local environment at Pratt, KS between 0000 and 0300 UTC. Aside from slight cooling below 850 hPa, little change is observed through the remainder of the temperature profile from 0000 to 0300 UTC. In contrast, the dewpoint profile exhibits considerable moistening below 300 hPa, with a notable increase in the ML mixing ratio from 12.4 g kg^{-1} at 0000 UTC to 14.4 g kg^{-1} by 0300 UTC 5 May 2007. Thus, despite the observed cooling of the boundary layer, the increase in moisture contributes to a local increase in MLCAPE from 3543–3773 J kg^{-1} between 0000 and 0300 UTC.

In addition to the increase in MLCAPE and lowering of the LCL and LFC heights, the most notable change in wind speeds is observed through the lowest 1–2 km AGL. In fact, 0–1-km SRH and ESRH increase markedly between 0000 and 0300 UTC, from 99 m^2 s^{-2} and 92 m^2 s^{-2} to 368 m^2 s^{-2} and 431 m^2 s^{-2}, respectively. As has been shown, these rapid environmental changes actually can increase the tornado threat at the time of day when, from a climatological perspective, the risk typically diminishes.

4. Summary and discussion

A handful of sigtor events, exhibiting a similar synoptic pattern as recalled by the authors, motivated this exploratory study. Questions regarding associated processes within the pattern that contributed to the development of nighttime tornadoes, led to the expansion of the sigtor sample and identification of a similarly sized nontor sample. The nontor events featured a similar synoptic pattern and were associated with severe weather, excluding nighttime tornadoes.

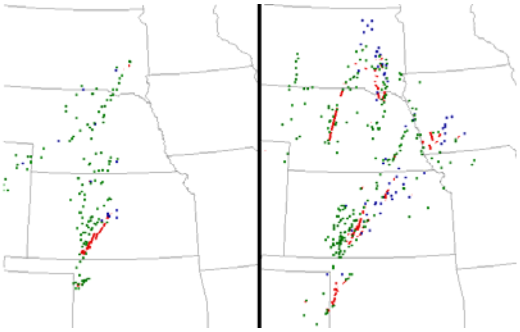

Figure 18: Severe weather reports from 1200 UTC 4 May 2007 to 1200 UTC 5 May 2007 (left) and from 1200 UTC 5 May 2007 to 1200 UTC 6 May 2007 (right). Tornadoes are denoted by the red dots and dashes, while large hail is green. Wind damage and/or severe wind gusts are blue. *Click image to enlarge.*

The identified synoptic pattern is characterized by a midlevel trough over the western United States, a developing or deepening lee cyclone in the lower troposphere over the central or southern High Plains, and the development of a LLJS in the 0000–0300 UTC timeframe. This occurrence is 3–6 h prior to the formation of the NBLWM observed under quiescent synoptic-scale conditions.

Nighttime Great Plains tornado occurrence is not strictly limited to this pattern. Other synoptic-scale regimes support nocturnal sigtor episodes, including a more synoptically evident pattern characterized by a progressive, amplified midlevel trough emerging into the Plains.

The study design assured a similar synoptic-scale pattern for the sigtor and nontor case sets, including LLJS evolution. Therefore, an ingredients-based approach (Doswell et al. 1996) was applied to distinguish between the sigtor and nontor environments. Their thermodynamic and kinematic characteristics were assessed using RUC-2 soundings. A technique was developed to identify a sounding location at the average time of the highest rated tornado (0300 UTC), regardless of the presence of a storm (as with a few of the nontor cases). The sounding location was specified as the intersection of the LLJS axis with the northern extent of the warmest temperatures and dewpoints in the warm sector at 0300 UTC.

Statistical analysis of the results indicates that low-level thermodynamic parameters, such as MLCIN, MLLFC, and ESRH, most strongly discriminate between the sigtor and nontor environments. Moreover, the discriminatory value of these parameter fields improved from 0000 to 0300 UTC, suggesting that the presence of richer boundary layer moisture in the sigtor cases likely counteracts the effects of radiational cooling in limiting CAPE and enlarging CIN after sunset.

Based on these results, forecasters should be alert to rapid local increases in boundary-layer moisture content after dark, coincident with a backing and strengthening of the low-level wind field. This often can signal destabilization and an increasing threat for tornadic thunderstorms at the time of day when, climatologically, the risk typically diminishes.

The large MLCAPE observed in the sigtor cases appear to be unique to the Great Plains environment, where steep midlevel lapse rates associated with the EML contribute to large parcel buoyancy. Results from Kis and Straka (2010) and DF09 indicate considerably weaker MLCAPE for significant, nocturnal tornado events in other geographical areas such as the mid Mississippi Valley and the Gulf Coast states.

Documented sigtor cases typically precede the progression of the primary midlevel trough east of the Rockies by roughly 24 h. As a result, major severe weather outbreaks can follow the nocturnal sigtor events over the same geographic region. For example, during 4–5 May 2007, regional severe weather outbreaks occurred over the Great Plains (Fig. 18), with the most intense storms focused over western and central Kansas. Although the 5 May event was more widespread (including more tornadoes), the 4 May Greensburg, KS tornado was the most devastating of the two-day sequence.

Often the anticipation of the next day’s severe weather potential can overshadow the comparatively more isolated, but possibly more significant threat to life and property leading up to these events. Moreover, these nocturnal tornado episodes represent a noticeable departure from the late afternoon climatological peak in Plains tornadoes, when relatively unobstructed visibility aids in storm spotting and public severe weather warnings. As a result, we hope that the results of this study will allow for more reliable and accurate forecasts of these events which present a great challenge to the integrated warning system (Doswell et al. 1999).

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REVIEWER COMMENTS

[Authors' responses in *blue italics*.]

REVIEWER A (Jonathan M. Davies):

Initial Review:

Recommendation: Accept with minor revision.

Overview: This is a well-written paper with good operational application for severe weather forecasters. An important (but sometimes overlooked) synoptic pattern that can support significant nighttime tornadoes in the Plains is documented, often with the main tornado activity confined to after dark. This is coupled with an examination of important ingredients present with this pattern when nighttime tornadoes do occur (e.g., dynamic and early intensification of the low-level jet, resulting increases in SRH and sizable MLCAPE, along with atypically weak MLCIN after dark), confirming work in other studies regarding nighttime tornado environments.

Because this is an exploratory paper, I have no problem with the sample size of 35 cases, which is much more useful than an individual case study or two that can't demonstrate whether certain ingredients and issues truly extend to a larger set of similar cases operationally.

Although I make a number of comments here, I don't think major revisions are needed. The discussion points below are intended to enhance an already well-written and -researched paper, and the authors can consider the relatively minor changes that are suggested.

Substantive comments:

1) The formal definition of "Great Plains" found in numerous sources specifies the prairies from the Canadian border of the north central U.S. southward to western Texas. Why was the study limited to the area in Fig. 3, excluding North Dakota, South Dakota, and the southern/central plains of Texas? Are the majority of nighttime tornado occurrences in the Plains during the past 10 years limited to the area in Fig. 3? Is this an area where SPC forecasters more specifically have had difficulty in anticipating nighttime tornadoes? I think it is important to clarify this.

The initial cases that piqued our curiosity occurred in OK and KS during the spring, so we formulated a project to identify nocturnal tornado cases in OK/KS and immediately adjacent Plains states during the same time of year, in a similar synoptic pattern. The northern Plains may experience a similarly favorable pattern for nocturnal tornado production, but we have not recognized such a pattern in our collective operational experience.

2) The particular synoptic pattern discussed in this paper is an important one for forecasters to know well regarding nighttime tornado potential.

However, the focus and exclusive emphasis on this one pattern (e.g., Fig. 6) could be a little misleading for forecasters regarding other patterns that support nighttime tornadoes in the Plains. I know you briefly mention the issue of other more dynamic patterns in the final paragraph of the Introduction section. But because it is not difficult to find other quite different 500-mb patterns that also support significant nighttime tornadoes in the Plains (see the 500-mb examples below from May 2008 with 2 deaths in Kansas and also June 2010 in Iowa), I think it might be helpful to add a little discussion to further emphasize that this is only one (though a relatively frequent one) of several patterns that may support tornadoes after dark. This could be expanded slightly at the end of the introduction, and could also be noted briefly in the concluding section to better situate your pattern contextually within a range of patterns that are capable of supporting nighttime Plains tornadoes.

To this end, you could mention that more dynamic cases not examined in this study typically feature a much larger, deeper and/or sharper upper trough moving out into the Plains (that's more specific than simply saying "more dynamic"). Examples of this are the 10 February 2009 case you note in passing and the 23 May 2008 case, 500-mb pattern shown here. You also could mention that in late spring or summer, significant nighttime tornadoes in the Plains can on occasion be associated with west-northwest flow just east of a ridge (e.g., the 25 June 2010 case, 500-mb pattern shown here). You even could suggest briefly in your concluding section that future work be directed at other patterns that support nighttime Plains tornadoes to see if the environmental ingredients examined in your study (e.g., increasing SRH from early LLJ intensification, sizable MLCAPE along with atypically weak MLCIN after dark) provide a common thread between the different patterns.

We completely agree with your concern. As mentioned in the manuscript, our work has been motivated by a handful of significant, nocturnal tornado events in the central and southern Plains that seem to exhibit a similar synoptic pattern which is not yet "synoptically evident." Some of these events turned out to be more substantial than what was indicated in operational forecasts leading up to the event. In contrast, the nighttime Plains tornado events associated with an amplified midlevel trough emerging from the Rockies are typically better anticipated from a forecasting standpoint.

In addition to clarifying that the documented pattern is one of many in which significant, nocturnal tornadoes can occur in the Great Plains (addressed in section 2 "Data and methods" as well as section 5 "Summary and discussion") we have included a mean 500-hPa height and sea-level pressure analysis from 13 more "evident" events and compared it to the mean 500-hPa height and sea-level pressure analysis from the sigtor cases (Figure 6).

3) Just a reinforcing comment... The lead shortwave mentioned in [section 2c] seems to be an important feature associated with many nighttime tornado settings. The fact that it "lifts out" to the northeast and dampens keeps the associated surface front from penetrating very far southward, which leaves the initial Gulf moisture brought northward by the lead shortwave in position for deepening and enhancement within the boundary layer when the next piece of energy comes out of the western trough. This improves the potential for larger MLCAPE, less MLCIN, and thus a more surface-based environment after dark when the next shortwave approaches or the main trough moves out into the Plains, increasing the chance of nighttime tornado development.

4) The general increase in CAPE from 00 UTC to 03 UTC in most Plains tornado events after dark discussed in sections 3 and 4 is an important point that is well made in your paper.

However, the RUC soundings shown at PTT in [former] Fig. 13 are probably not an accurate example of the typical amount of this increase, because the specific 00 UTC RUC profile used for the comparison was in error regarding low-level moisture due to the RUC model mixing dry air immediately above ground level eastward far too aggressively in the PTT/P28 area on the late afternoon and early evening of 4 May 2007. An informal study of the Greensburg environment at (http://www.jondavies.net/050407greensburg/050407greensburg.htm) and the skew-T graphic below illustrate this.

In the skew-T graphic included here, notice how much more moist the overlain 00 UTC WRF sounding (red and green) at PTT is in low-levels compared to your 00 UTC RUC profile from [former] Fig. 13, which dramatically affects the MLCAPE computation. In this case, when cross-referencing surface observations and dew point map analysis (not shown), the WRF appeared much more representative of the low-level moisture environment at 00 UTC than the RUC. Comparing the WRF thermodynamic profiles between 00 UTC and 03 UTC (not shown here) suggests that the MLCAPE increased from roughly 3400–3500 J kg^{-1} to around 3800–3900 J kg^{-1}, a local increase of only 300–500 J kg^{-1} rather than the 3000 J/kg (!) you suggest. Notice that this revised MLCAPE increase estimate matches much better the MLCAPE increases suggested by the box and whisker diagrams in your Fig. [11].

I'll also mention that both the PTT and P28 RUC analysis soundings at 02 UTC (the last profile estimates available before the Greensburg tornado, not shown) continued to indicate an overly dry boundary layer immediately above ground, grossly under-representing the true MLCAPE in the Greensburg environment. The RUC model did not adjust to pick up on the depth of the local moisture surge in the PTT/P28 area until 03 UTC, which was after the Greensburg tornado struck.

Although I wouldn't call it a major revision, I do suggest either carefully pointing out the RUC problem with the 00 UTC PTT sounding in Fig. [17] via appropriate caveats and adjusting your MLCAPE increase estimate downward considerably, or using another sounding where the RUC appeared to be more representative of low-level moisture for MLCAPE computation purposes and accuracy in stating a representative MLCAPE increase more consistent with [former] Fig. 15. It helps to occasionally remind forecasters that model-based soundings are not always a proper estimate of environment, and a little checking using current surface observations and common meteorological sense is sometimes required to spot and adjust for this.

Since there was a 0000 UTC observed sounding at Lamont, OK, we used those data in conjunction with the 0000 UTC DDC sounding and surface observations to modify the boundary layer profile in the RUC sounding for PTT. We have also added a paragraph encouraging forecasters to check model-based soundings for representativeness.

5) Related to the MLCAPE increase you discuss in sections 3 and 4, from an observational standpoint using hourly surface maps rather than model-based data, it might be worth suggesting/reinforcing that forecasters watch for areas of increasing dewpoints within the warm sector on surface maps near dark, along with increasing/backing surface winds (both suggesting that LLJ intensification is occurring) to help anticipate potential for nighttime tornadoes. In the Greensburg case, surface dewpoints at PTT between 00–02 UTC, prior to the large tornado, increased from 63º F to 68º F (suggesting strong dynamically-forced low-level moisture advection via the LLJ), with backing and increasing surface winds, even though surface temperatures decreased from 82º F to 79º F.

6) [Y]ou mention observations from Kis and Straka (2010) that seem to conflict with your Plains observations. This is probably because the vast majority of significant tornadoes sampled in the Kis and Straka study were east of the area of your sample in Fig. 3, and were largely collected from the mid-Mississippi River Valley and the Deep South. Davies and Fischer (2009) found that MLCAPE with nocturnal tornado events in the eastern/southeastern U.S. tends to be notably less than with Plains events, which may in part explain the Kis and Straka results (weaker buoyancy associated with significant tornadoes) that do not appear applicable to central Plains nighttime tornado episodes. The difference in geographical locales between your study and the Kis and Straka study may be worth emphasizing for clarity.

A related suggestion... To remind readers that there is a geographical context for assessing ingredients/parameters associated with significant nighttime tornadoes, I think it would be useful to mention in section 4a or the concluding section that nighttime tornadoes east of the Plains tend to be associated with smaller MLCAPE and MLCIN (see Davies and Fischer 2009). This is probably because the EML is not an issue in most nighttime tornado episodes east of the Plains, whereas larger nocturnal CAPE settings with significant boundary layer moisture are likely required in Plains nighttime tornado events to help overcome the presence of the EML and generate a relatively surface-based environment. Davies (2004) also noted that the warm layer aloft associated with the EML is probably a major contributor to why nighttime and morning tornadoes tend to be less frequent in the Plains compared to the Gulf coast region.

Both 5 and 6 are very good suggestions which were incorporated into the manuscript.

7) Regarding your discussion of MLLFC, MLLFC heights in tornadic and nontornadic settings were also examined in conjunction with MLCIN in Davies (2004), with similar results.

This has been included.

[Minor comments omitted...]

Second review:

Recommendation: Accept.

General Comments: Apart from a few minor formatting issues in the Word version I received, my opinion is that this paper is ready for publication.

The authors have addressed very well any concerns I had, and I'd like to see this work become available for operational forecasters as soon as possible.

[Minor comments omitted…]

REVIEWER B (Matthew J. Bunkers):

Initial Review:

Reviewer recommendation: Accept with minor revisions.

General comments: This paper is well written and contributes to our knowledge of severe storm environments by highlighting a pattern for significant nocturnal tornadoes. Perhaps the main drawback is that it is not an all-encompassing pattern; however, the underlying physical importance of reduced nighttime stability for sigtor events can be applied to other events that don't fit the synoptic pattern. I have two major concerns that deal with the reproducibility of the results and the potential impact of bird migration on VWP winds. Otherwise, my comments are mostly minor in nature, and thus I recommend acceptance after minor revisions. I would like to see the paper for a quick second look, but do not need to complete another full-blown review—unless the paper changes substantially from its current condition.

EJSSM scientific content checklist

1. References in support of an assertion – good
2. Speculation – kept at a minimum
3. Significance of results – your box-and-whiskers plots speak for themselves, and statistical testing is not needed here—see below
4. Reproducibility – needs clarification; see major comments below
5. Proof – hypothesis generally is well supported
6. Relevance – good
7. Originality – good, and also reinforces other work
8. Comparisons with existing work – not done directly, but referenced appropriately
9. Negative results – N/A

EJSSM quality of presentation checklist

1. Quality of figures – generally good, but some need larger font
2. Quality of the English – good
3. Organization – good
4. Completeness – generally good, but a few citations/references need fixing

Major comments:

1. On p. 2 you stated, "*…and the subjective matching of objectively analyzed, observed upper-air data to the identified synoptic pattern.*" How exactly did you match a case to the pattern? In other words, if you were going to tell me to find some cases for you, what guidance would you give me so I could go about the collection of data? This boils down to reproducibility of your results.

Manually determined matches were those which exhibited the primary midlevel trough west of the Rocky Mountains, southwesterly flow aloft over the Plains, lee cyclogenesis over the High Plains of NM/CO/KS/TX/OK at 0000 UTC on the day of the event., and the occurrence of severe thunderstorms.

2. On p. 4 you stated, "*…a nontor (null) case set was collected through a similar method of positive pattern matching on the synoptic scale, but without the occurrence of nighttime tornadoes….*" Again, how would I do this? Can you provide an algorithm?

There is no algorithm. Instead, the methodology employs manual pattern matching based on the above-mentioned features. The similarity of our sigtor and notor cases, as intended, is demonstrated in [former] Fig. 5 of the revised manuscript. The revised manuscript focuses more on the differences in the significant tornado ingredients resulting from the similar patterns, as opposed to the patterns themselves.

3. On p. 5 you stated, "*…using a subjectively determined, representative dew point value….*" As with the previous two comments, how would someone who wants to replicate your study perform this step? Would I pick the isodrosotherm that is closest to the warm front?

The low-level jet stream axis was used in conjunction with the northern extent of the warmest surface temperatures and dew points within the warm sector. This location often coincided with a boundary (fig. 9). In other cases, the specified location was coincident with a moisture gradient or secondary warm front (fig. 10).

4. You refer to NPN and WSR-88D wind profiles. These are sometimes affected by bird migration, especially in the spring and fall, when birds can affect the magnitude of low-level jets. Even though your results may not change materially, this component of your data needs to be addressed. Refer to the following three references.

Gauthreaux, S. A., Jr., D. S. Mizrahi, and C. G. Belser, 1998: Bird migration and bias of WSR-88D wind estimates. *Wea. Forecasting*, **13,** 465–481.

Holleman, I., H. van Gasteren, and W. Bouten, 2008: Quality assessment of weather radar wind profiles during bird migration. *J. Atmos. and Oceanic Tech.*, **25,** 2188–2198.

Wilczak, J. M., and Coauthors, 1995: Contamination of wind profiler data by migrating birds: Characteristics of corrupted data and potential solutions. *J. Atmos. and Oceanic Tech.*, **12,** 449–467.

We appreciate the references and have acknowledged the issues with bird migrations in the interpretation of the NPN and VAD data. Moreover, we compared the observed data to 0-h RUC analysis grids, since bird-migration algorithms are employed during data assimilation.

5. On. p. 15 you stated, "*However, the 0–1-km BWD for the observed NPN and WSR-88D VAD data were a quartile stronger than the RUC soundings.*" Please reconsider this result ([former] Fig. 24) in light of the previous major comment about migrating birds. To me the fact that the 0–6-km BWD is similar between observed and RUC makes sense because the birds don't necessarily fly at 6 km, but more likely would affect the 1-km winds.

We agree and have removed both figures from the manuscript.

6. Finally, I think you are justified in not presenting results from statistical significance tests. Recent publications (e.g., Nicholls 2001; Ambaum 2010) suggest there isn't a great deal of utility in these tests. If any reviewers require you to use them, please note the caveats in these two papers.

Ambaum, M. H. P., 2010: Significance tests in climate science. *J. Climate*, **23,** 5927–5932.

Nicholls, N., 2001: The insignificance of significance testing. *Bull. Amer. Meteor. Soc.,* **81,** 981–986.

[Minor comments omitted...]

Second review:

Recommendation: Accept with minor revisions.

General Comments: You have satisfactorily addressed all of my major comments, and notably improved the paper. I thus recommend acceptance after minor revisions. This time I have placed all of my comments in your manuscript using the MS Word "track changes" feature. However, I do want to reiterate that I was confused regarding Table 1, Fig. 3, and the corresponding text—mainly with respect to the counting of nocturnal sigtor events.

[Minor comments omitted...]

REVIEWER C (Jerry M. Straka):

Initial Review:

Reviewer recommendation: Accept with minor revisions.

Synopsis: This paper is a nice attempt at trying to identify in nearly similar synoptic conditions what severe-storm forecast parameters are important in identifying, if significant nocturnal tornado events will occur or not occur. It was motivated by two violent, after sunset, tornadic cases. This is a paper from which forecasters can learn something about significant nocturnal tornado events. I recommend that after addressing issues described below that this paper be accepted for publication. I would like to read the paper again after it is revised.

Major Comments: One weakness that was pointed out in an apparent internal review was that the data sample was small. I tend to agree with this and in a sense the authors might be more forthcoming in noting this in the paper, and noting that study is sort of a study of a number of cases rather than a major statistical study such that one of the authors has done in the past.

We agree and have made note of this in the manuscript.

The authors missed an opportunity to include some cases in their significant nocturnal tornado list. The very long-lasting 29 May 2004 supercell in Oklahoma produced a very late F3 tornado halfway between Oklahoma City and Tulsa, near Depew OK, and earlier nocturnal event, a F2 tornado, in Edmond, OK. Also there was an EF4 tornado southwest of Ardmore, OK in 2009? *[Editor's Note: This was the Lone Grove, OK tornado of 10 February 2009.]* In addition, there was F3 in Twin Oaks, KS in March 12, 2006. Now that I think of it I think the authors missed a few other cases too, but I don't have my list handy. Was there a reason these cases were not used in this? Did they not fit the type of synoptic environment for which you chose to examine? A table that lists the days of the non-tornadic events should probably be included.

As noted in the manuscript, the study was motivated by a handful of nocturnal, significant tornado episodes that all seemed to match a specific synoptic pattern that was not "synoptically evident." So, the intent was not necessarily to assess all Great Plains, nocturnal, significant tornado environments, but what characteristics of the indentified pattern where critical to nighttime tornado development. The 29 May 2004 storm pointed out by the reviewer was part of a "high risk" outbreak of severe weather that continued from the afternoon into the evening, much like 3 May 1999, which is no longer a part of this investigation.

We have included a table (Table 2) that lists the days of the non-tornadic events.

In your table of tornado cases and intensities, all tornadoes are since 3 May 1999, and indicated by the enhanced Fujita scale rating. Was it not until later in the 2000s (2007?) that the enhanced Fujita scale rating system was adopted by the NWS? *[Editor's note: The EF Scale was adopted officially in February 2007.]*

We have made the distinction in Table 1.

After looking at the event days, I noted that some of the events were ongoing events from daytime and early evening events while others were entirely nocturnal events. It would be useful if the authors would identify each event as such.

We have made the distinction in Table 1.

The study defines nocturnal as after "apparent" sunset. What is "apparent" sunset? Wouldn't it be better to use synoptic cases after that occurred entirely after twilight was over? I did notice the mean time of the highest EF rating was stated as being 105 min. Still, some of the cases were during what would be considered early twilight. I would like to see tornadoes indicated as being twilight tornadoes from storms that formed during the daylight and those in which the storm formed either after sunset, or in your case after twilight.

Similar to the argument forwarded by Ashley et al. (2008), we felt that local sunset was a sufficient estimate of nocturnal sky conditions for each of the cases.

In your first hypothesis, what were the subjectively determined dewpoints for the proximity of all of the cases? Was the dewpoint the same for all cases or varied based on what might appear to be some condition? The criterion supposedly is similar to Potvin et al. (2010). As that paper is not available at this time it would be useful, even at later dates if you described what they considered to be a proximity sounding as compared to your definition of a proximity location to the LLJ and surface moisture or dewpoint and a careful description of each. Also, I think you need to be more careful writing a hypothesis than you did in this paper.

We agree that the initial draft was not as detailed as it should have been with respect to the definition of how the representative environment was determined Potvin et al. (2010) suggested proximity criteria of within 40-80 km and 0-2 hours of a storm, in an effort to remove storm contamination from the background environment.

The [National] Profiler Network (NPN) is horrible at determining winds below 2000m AGL (F. Carr–personal communication and Y. Richardson–personal communication) for a variety of reasons. I would talk to these people first before putting to much credibility into your observed LLJ evolution. Some of the same reasons apply to VAD winds. Furthermore, many have found that the LLJ evolution is not well described by models, nor is the evolution of the boundary layer after sunset (as found in study in progress by this reviewer). All of these issues should be stated and explored before putting too much confidence into the evolution of the LLJs that you describe in your paper.

We have acknowledged this concern (which was echoed by reviewer B) in the manuscript and used 0-h RUC analysis grids (which use bird-migration algorithms in data assimilation) for comparison. As noted in the manuscript, we feel that these observational data still hold value, specifically in spatially defining the bounds of the LLJ.

Deamplification of the shortwaves in the longwave pattern over the [north-central] USA or [south-central] Canada and the enhancement of moisture transport northward is pure speculation. This should be more closely explored or deleted.

This is not necessarily speculation, but the collective experiences of the authors who forecast severe storms on a daily basis. In accordance with the request of reviewer D, we have better defined the specific physical processes that can initiate the poleward advancement of moisture from the Gulf of Mexico.

In your kinematics section could you might include a 0–8-km bulk shear box-and-whisker plot. I think that would be interesting and useful to see.

The results are similar to that of the 0–6 km vector shear magnitude, so we chose not to include it as a figure.

Second Review:

Reviewer recommendation: Accept.

Overview: I have reviewed the response to everyone's reviews and carefully read the paper. Without significant amounts of work, the paper is in about the best shape it probably can be technically and scientifically. I would like to recommend the revision of this paper in its present form for publication at this time.

REVIEWER D (David M. Schultz):

Initial Review:

Reviewer recommendation: Accept with major revisions.

General Comments: I have provided an annotated manuscript. I have used track changes, and have made revisions to the text. Depending on your version of Word, you may not be able to see the tracked changes, so please ensure that all revisions that I have made make it into the next version of your manuscript.

My major issues that I elaborate upon in my annotated manuscript.

1) More precise and complete description of how the datasets were constructed.

2) Elimination of map-room jargon and excessive speculation that could be proven.

3) Revised figures that are readable.

4) Vague wording throughout the manuscript. Be specific and quantifiable.

5) Unclear what the main result is: synoptic analysis shows little difference between the two composites, and wind shear is apparently not different between the two composites. Temperature profiles may be what is important.

6) Unclear how LLJ was determined.

7) Omitted citations.

Substantive Comments:

You need to describe your method in more detail. Are these 35 cases all the possible cases during this 11 year event, or just a collection that you were able to determine/recall easily? Did you look at all months, or just during the principal severe weather season?

We appreciate these questions. We have added more detail to our methodology.

What do you mean match [the identified synoptic pattern]? How close is a "match"? By what criteria did you decide? Carbin's MARS program would be one way to quantify your "match". Have you considered using that tool to quantify your ability to match events?

As stated in the manuscript, a handful of nocturnal, significant tornado events which exhibited a similar synoptic-scale pattern were the motivation for the study. This pattern served as the template for the manual matching of prospective events. The manual matching utilized geopotential heights at 500 and 850 hPa along with surface maps valid 0000 UTC on the day of the event.

To our knowledge, there has been no peer-reviewed research that demonstrates MARS' ability to provide accurate pattern matches.

I am confused. You determined your dataset based on how closely a case fit with your synoptic pattern? That biases the dataset. How many nocturnal tornado events were omitted using this data selection criteria? You need to more thoroughly discuss your approach and why you constructed the dataset this way and not some other way that would be more complete and less biased.

You are correct in your interpretation of how the dataset was compiled. Indeed, there is a bias in the events with respect to the large-scale pattern. However, this is not necessarily the case with the thermodynamic and kinematic parameters contained within the pattern.

This is vague ["critical" role of LLJ in air mass destabilization]. Are you saying that no LLJ is present in nontor cases?

We have modified this section of the manuscript. Similar to our response to reviewer B, we have re-assessed the salient points that we chose to highlight. Instead of drawing specific attention to the LLJ (which was present in both the sigtor and nontor cases), the important findings were the differences in thermodynamic characteristics of the lower troposphere.

I don’t understand what you are implying with a temporal criterion. Can you be more clear?

Since the average touchdown time for the most intense tornado for each of the sigtor cases was 0323 UTC, we chose 0300 UTC as the temporal criterion to investigate the warm sector environments for both the sigtor and nontor cases.

I still don’t know how [the] proximity location is determined. Also, are you sure you want to use the term “proximity” which has baggage associated with proximity soundings?

Again, we acknowledge your concern as well as those of reviewer B. We have re-written our methods in hopes that our approach has more clarity.

If it is similar [to Potvin et al. (2010)], how is it different? Please explain.

Potvin (2010) suggests proximity criteria within 40–80 km and 0–2 h, and we’re using within 100 km and 0–1 h.

Why aren’t you showing us composite analysis of the fronts? Why these cases? Do all cases have these fronts? If the tornadic storm is along or north of the front, then is it an elevated storm? Does it then fall into the classification of Horgan et al. (2007)’s elevated storms? If so, please cite that paper, as well.

The sigtor storms were not elevated to the north of the surface fronts—they all either formed along the surface front, or remained in the warm sector.

These composites look like any other severe weather outbreak in the Plains (e.g., Newton, Miller). What is special about this pattern that makes it responsible for nocturnal tornadoes? It is not clear.

We disagree. Synoptically evident (Johns and Doswell 1992) severe weather events in the Plains typically feature a high-amplitude, progressive, midlevel trough emerging from the Rockies, not displaced west of the Continental Divide. See Fig. 6.

Is this [seasonal distribution of the favored synoptic pattern] just because tornadoes are most likely during this season? Because you haven't described how you created your dataset, the reader can't be sure that this annual distribution is meaningful.

The study has been refined to focus on the principal severe weather season in the Great Plains (March-June). This section of the manuscript has been removed.

This material [500-hPa spaghetti diagram] should appear with the composite to show the variability. What precisely is reproducible about this composite? Trough in the west? That's about it. How is that useful for nocturnal tornadoes in particular?

The spaghetti diagram (former Fig. 9) has been removed in favor of standard deviation which was added in Fig. 5. Being able to demonstrate that the synoptic-scale pattern for the sigtor and nontor cases is important because it verifies that our manual method of matching was successful. Thereafter, we show that it is not necessarily the large-scale pattern that useful for nocturnal tornadoes, but the ingredients brought together by the pattern.

If the wind is maximum after 0600 UTC, why is the tornado maximum 0300 UTC?

Our results indicate that the characteristics of the thermodynamic environment are the strongest discriminators between the sigtor and nontor cases. Even though the LLJS may continue to strengthen after 0300 UTC, that does not necessarily mean that the thermodynamic characteristics of the environment will remain favorable as well.

You haven't addressed the issue of why the increasing wind speed is more important than the wind speed itself.

The rate-of-change of the LLJS is important because it is symptomatic of a dynamical process as discussed in Section 2c.

[Section 2b] Are the majority of your cases supercells? Why not create a climatology of storm morphologies since you have the dates? (I see now that later in the paper you say all sigtor events are supercells. This fact should be stated earlier. Was this a criterion in picking your cases?)

All of the sigtor cases were supercells. Some of nontor cases contained supercells.

Maybe there is an associative relationship between the increase of the low-level wind speed and tornado occurrence, but you haven't demonstrated that maintenance is important.

Again, we have re-focused the manuscript to indicate that it is the thermodynamic characteristics of the environment that more strongly discriminates between the sigtor and nontor cases. Indeed, the low-level shear enhancement associated with the LLJS development is important, but it is also present in the nontor events.

[Table 2] You could run statistical significance tests and boldface all the numbers that are significantly different from the others. This would be useful as an overview of your results. Also, add another column that references the figure number for the convenience of the reader.

Related figure numbers have been added to the table to aid the reader. However, we have chosen not to calculate the statistical significance (i.e., Student's t-test) of the difference in the means due to small sample sizes.

"Presumed radiational cooling". You are saying that the higher RH reduces cooling, but then saying that radiational cooling is important to lowering the LCL. Do you have evidence that the temperatures decrease enough after sunset (0100 to 0300 UTC) to account for these changes in LCL?

Statistical analysis showed a mean surface temperature decrease of 2.7º C for the sigtor cases and 3.4º C for the nontor cases. This information has been included in the manuscript.

You have not addressed the results of Esterheld and Giuliano (2008, EJSSM), which directly addresses your primary question. Please cite their work. Could you please address the relevance of their results to yours? For one thing, they said that 10–500 m SRH was superior to other depths. Your results?

Esterheld and Giuliano (2008; hereafter EG08) used profiler and mesonet winds with observed storm motions to calculate 10–500 m SRH. Our cases did not necessarily meet the spatial and temporal criteria of EG08, and our RUC soundings were limited to 25-hPa vertical resolution. We are not confident that the RUC analyses can fully resolve any "kinked" hodograph structure in the low levels based on just a couple of data points, and our sample is too small to make any generalizations about the ability of the RUC to reproduce the findings of EG08. Instead, we're comparing our work to the much larger sounding samples of T03 and T07, based on the same data source (RUC analyses).

[re: Enhancement of low-level wind shear by development of LLJS] If this is the case, then all your arguments about the importance of the LLJ are out of the window. This is quite problematic to your manuscript.

We agree and have refined the focus of the study.

[Minor comments omitted...]

Second Review:

Reviewer recommendation: Accept with major revisions.

General Comments: Although the manuscript has undergone significant revision, I still have fundamental problems with this manuscript. If these problems are not addressed, the manuscript should not be published. My annotated manuscript shows the scope of the problems. Other issues are listed below.

FUNDAMENTAL PROBLEMS

1. The paper is titled, "A synoptic-scale environment associated with significant nocturnal tornado events in the Central and Southern Great Plains." Indeed, the first 12 pages of the manuscript seem to address the synoptic-scale patterns associated with these events. What concerns me is that the authors have not demonstrated several key aspects to this pattern.

a. The authors have not made a convincing argument that their proposed synoptic pattern is any different than the same pattern for nontornadic nocturnal events (Fig. [6]). The authors seem to have a different take on this figure at different points in the manuscript. Indeed, the authors say, "Slight differences do exist...These differences can have notable impacts on low-level trajectories...." This statement is unproven, however. Yet, at the beginning of section 3, the authors say that "the synoptic-scale patterns are necessarily similar." Further clarification is needed in the manuscript about whether these differences are important, and, if so, some quantitative information about how their differences matter.

We acknowledge your concerns and hope the manuscript now more clearly describes the methods of our research. Our intent is not to demonstrate how the synoptic pattern differs; rather which ingredients within the specified synoptic pattern most strongly discriminate between the sigtor and nontor subsets.

b. The authors have not made a convincing argument that their proposed synoptic pattern is any different than the same pattern for tornadic daytime events ([former] Fig. 6). Johns and Doswell (1992) define the classic and synoptically evident patterns as being "characterized by an unusually strong, progressive extratropical cyclone. Typically, in such situations, an upper-level jet stream is associated with corresponding wind maxima at mid- and low levels, and a vertical wind profile favorable for supercell development results...Tornado potential is enhanced if the associated upper shortwave trough is moving rapidly, if it is negatively tilted, and/or if there is significant upper difluence ahead of the trough." The authors say in their response that "synoptically evident severe weather events in the Plains typically feature a high-amplitude, progressive, midlevel trough emerging from the Rockies, not displaced west of the Continental Divide." Frankly, I don't see it. The difference in the surface low center is about 100 km or less. What about the sigtor composite 500-mb flow pattern suggests the trough is not moving "rapidly" however that is defined? The synoptically evident composite does not have difluence over the central Plains. The difference in trough axis is only 200 km farther east for the synoptically evident composite. Could this displacement be explained because nocturnal events will have the trough farther west than daytime events? Can you demonstrate in what way the patterns in Fig. 5 differ from this pattern in Fig. 6?

Actually, Fig. 6 (now Fig. 7–right) is a composite of an independent set of 13 ***nocturnal*** *tornado events over the central and southern plains in which the midlevel trough was emerging from the Rockies. The location of the midlevel trough axis is farther east than that shown in Fig. 5 (now Fig. 6) and much farther east than the cases shown in Figs. 1 and 2.*

c. In fact, I would argue that these patterns in [former] Figs. 5 and 6 are not that different from the previously published classic severe weather patterns published by Miller, Barnes and Newton (1986), etc. If so, then what makes this pattern worthy of being published?

The Barnes and Newton (1986) sketch of a synoptic-scale pattern associated with severe weather (Fig. 10a in Johns and Doswell, 1992) much more closely resembles Fig. 6 (now Fig. 7–right)with the surface cyclone located ~400-500 km in advance of the midlevel trough axis. In contrast, the surface low is ~700–800 km in advance of the midlevel trough axis in the sigtor and nontor composite diagrams. We feel that these differences do matter, with the strongest mid- and upper-level forcing for ascent occurring to the west of the plains during the documented nocturnal tornado events.

d. I don't see where in the paper that further discussion of the methods is provided. Specifically, how many total events were considered? What percentage of all cases of nocturnal significant-tornado outbreaks do the cases in the paper represent? At least twice in the manuscript, the authors claim that they will address the frequency of this pattern, but I don't see any quantitative information addressing this concern.

We have addressed these concerns in the current version of the manuscript.

e. Table 1 shows that for all, except three, events the convection was initiated during the daytime, the violent tornadoes occurring later (0139 to 0754 UTC). Given that supercells were formed in all these cases (as described by the authors, but not described in the manuscript), does it really matter that the tornadoes formed during the night? In other words, supercells were initiated during the daytime. Given that supercells are persisting after dark, would you expect that the answer to what causes some supercells to spawn tornadoes after dark or during the day would be captured in the synoptic-scale pattern?

What interests us in the documented sigtor events is why the most intense tornadoes occur after dark and not during the late afternoon or evening which is more typical based on climatology. Certainly, we do not expect the synoptic-scale pattern alone to tell us whether tornadoes will occur during the day or at night. Our results suggest that the large-scale pattern can serve to enhance vertical shear (e.g., development of the LLJS in both the sigtor and nontor cases), though the characteristics of the low-level thermodynamic environment most strongly discriminate between the two subsets.

f. The title of the manuscript and on p. 6 the authors suggest that they will be examining large-scale (synoptic-scale) patterns associated with nocturnal significant-tornado outbreaks. But, given all of the above about how little is new here, is the title of the manuscript appropriate for the contents of the manuscript?

*We used the term nocturnal significant-tornado ****events***** as opposed to "outbreaks" which would indicate a more widespread occurrence of nighttime tornadoes. We have modified the title of the manuscript to better describe the focus of the research.*

OTHER ISSUES

The results of Esterheld and Giuliano should be cited, even if the RUC sounding data is not adequate for applying their method. The purpose of Mead and Thompson is to distinguish nocturnal significant-tornado events from nocturnal nonsignificant-tornado events. Although their work was not limited to nocturnal events, Esterheld and Giuliano did precisely that. Thus, citing their research needs to be included as one possible means by which a forecasting scheme could be implemented.

We have included the citation in the manuscript.

LLJS: Fig. 10b shows the jet stream at an angle to the winds. Why? I am not convinced that marking some wind maximum at the surface in this haphazard way is useful for forecasting the location of the tornadoes. Indeed, as is my concern with the 500-mb patterns, the 850-mb wind fields are not particularly different (Fig. 7).

Please note that the LLJS is determined by the profiler and VAD observations as shown in Figs. 9a and 10a. The LLJS is simply annotated on the surface map (Figs. 9b and 10b) to show where it intersects the northern edge of the warmest and most moist segment of the warm sector.

I don't understand the authors' refusal to calculate the Student t test for their data. Their argument that their sample size is too small does not bother them when they create composites or box-and-whisker plots, or even making physical distinctions between the two groups. Standard tables of the Student t statistic commonly have values of sample size less than 10, so mathematically it is a valid concept.

We performed the Student t test on the thermodynamic and kinematic fields in Table 3, listing all statistically significant in bold font.

[Minor comments omitted...]

There is no distinction between the two groupings in Figs. 15 and [former] 17. This is not surprising as these quantities are not expected to change to any large degree overnight, is that right? Also, biasing your selection of cases toward supercells means that these data will be grouped more tightly and indistinguishable.

There would be a tendency for MLLCL heights to lower from 0000 to 0300 UTC owing to the onset of radiational cooling in the boundary layer. With regard to Fig. 17 (now removed), the nontor case set is composed of a mixture of supercell and non-supercell storm modes which is likely why there is a larger inter-quartile range when compared to the sigtor cases which were all supercells.

In response to my previous comment, the authors say that there is no peer-reviewed research on MARS. Although true, the authors' rebuttal neglects the fact that the MARS approach *quantifies* the similarities between two synoptic patterns through calculation of a root-mean-square error over a domain. This is a concept that has been applied in published studies to quantify the Euclidean distance between two fields. Thus, my comment was not so much about the MARS approach specifically, but quantification of the pattern matching. You could use MARS or you could use some other approach, but the authors have not addressed the quantification question. Other than visually, how can you be sure that the Mead and Thompson cases are distinct from the synoptically evidence cases? The composite fields in Figs. 5 and 6 do not support any distinction.

Based on your suggestion, we have utilized MARS to make a quantitative assessment of our ability to manually match the patterns. We have added a [sub]section (b. Pattern matching method) in the Data and Methods to describe the approach.

[Minor comments omitted...]

Third Review:

Reviewer recommendation: Accept.

General Comments: I am quite impressed. The moment I received Corey's email that the revised manuscript was uploaded, I downloaded it and started reading it. Given the seriousness of my concerns in the last round, the authors have addressed all my concerns satisfactorily. I now recommend publication.