Tornadoes with Cold Core 500-mb Lows

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ABSTRACT

Tornadoes that occur in close proximity to midlevel closed lows with a core of cold temperatures aloft are not uncommon, particularly in the central United States. Although several informal studies have shown that severe weather and tornadoes can occur with these midlevel lows, little in the way of formal work has been published documenting features and ingredients of such systems, especially those that produce what are sometimes called cold core tornadoes. Of particular concern is that these tornadoes can be associated with surface and low-level moisture that appears deceptively small or marginal regarding severe weather potential, yet on occasion tornadoes of F2 or greater intensity can develop. In other cases, vertical shear may appear relatively weak at locations close to the midlevel low, suggesting little potential for tornadoes. These "atypical" characteristics can result in poor anticipation by forecasters of tornado events associated with closed 500-mb lows. This note documents some synoptic and mesoscale features commonly associated with tornado events in close proximity to cold core 500-mb lows using four tornadic cases in Kansas as examples, including photographs to show the small nature of storms associated with such systems. Recognition of surface patterns with a particular organization of boundaries and surface heating positioned near midlevel lows, along with the presence of some amount of buoyancy, can help with the operational awareness of the potential for tornadoes in many 500-mb closed low settings.

1. Introduction

Synoptic settings that produce severe weather through the positioning of a closed midlevel low and cold pool aloft near a surface low and low-level moisture axis were identified by Miller (1972), who noted that storms associated with this "type D pattern" in some cases produced tornadoes. Goetsch (1988) used the terminology "cold core outbreak" to describe severe weather events with similar synoptic patterns, and noted that some tornadoes associated with these scenarios could produce significant damage. Davies (1990; 1993a, hereafter D93a) photographed tornadoes from low-topped storms during two Kansas events (see Fig. 1 and Fig. 2) that had synoptic settings similar to the patterns described by Miller (1972) and Goetsch (1988). The small size of supercell storms associated with such events was emphasized in D93a, and additional synoptic features important to such systems were suggested. Monteverdi and Quadros (1994) presented common synoptic features of tornado-producing systems in California, which often involve cold core midlevel lows. In Canada, McDonald (2000) discussed forecasting "cold core tornadoes" over the northern prairies associated with synoptic patterns having features similar to those discussed in Miller (1972), Goetsch (1988), and D93a. Most recently, a preliminary climatology of closed cold core 500-mb lows in the central and eastern United States was assembled by Davies and Guyer (2004, hereafter DG04). The preliminary DG04 study suggested that tornadoes occurring in close proximity to such systems were not uncommon, and highlighted surface features relative to midlevel lows that appear to favor tornadoes.

It was noted in Goetsch (1988) that the potential for severe weather near closed 500-mb lows is frequently underestimated by forecasters, and recent operational experience suggests that tornado potential in particular can often be overlooked (DG04) in close proximity to such systems. This is due in part to low-level moisture that often appears marginal (e.g., Johns 1982). Surface dewpoints associated with tornadic storms near 500-mb closed lows can appear limited (e.g., 8°–12°C; mid-40s

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FIG. 1. Small supercell and sunlit tornado in south-central KS on 11 Mar 1990. The view is toward the northeast from south of Stafford, KS. (Photo by the author.)

to mid-50s °F), resulting in deceptively small values of total convective available potential energy (CAPE; Moncrief and Miller 1976), sometimes as low as 400–600 J kg^{-1}. This affects common parameters such as the significant tornado parameter (STP; Thompson et al. 2003) used in supercell tornado forecasting, which often do not properly indicate tornado potential in such settings. An additional problem is the lack of vertical shear close to the 500-mb low in some cases that may suggest little potential for supercell tornadoes. McDonald (2000) even suggested that some tornadoes with such systems could involve nonsupercell or nonmesocyclone processes (Wakimoto and Wilson 1989; Brady and Szoke 1989).

FIG. 2. Tornado spawned by a small supercell in south-central KS on 28 Apr 1991. The view is toward the west from northeast of Pratt, KS. (Photo by the author.)

FIG. 3. Tornado passing just west of Wakeeney, KS, on 10 Apr 2005. (Image from video by T. Ummel.)

The purpose of this paper is to note some common synoptic and mesoscale features and ingredients associated with closed cold core 500-mb lows (henceforth denoted "CC500L" for brevity) that produce tornadoes. Recognition of these features and ingredients can help with the operational awareness of CC500L systems capable of generating tornadoes near the midlevel low, particularly when instability, surface moisture, or other characteristics appear marginal or "less supportive" relative to more typical tornado environments. The section that follows will look at the meteorological setting and environment associated with four CC500L tornado events in Kansas. The concluding section is a summary and discussion.

2. Examples of CC500L events

a. 10 April 2005

Spring 2005 was an active period for CC500L systems moving across the central plains, and several of these systems produced tornadoes. One in particular on 10 April 2005 produced several sizable and long-lived tornadoes in northwest Kansas (see Fig. 3 as an example). Although none struck communities and the strongest were only F1 in intensity, one or two of the tornadoes might have been rated more intense had they hit nearby towns such as Wakeeney, Hays, or Russell, Kansas.

A visible satellite image at 2045 UTC 10 April 2005 shown in Fig. 4 indicates the location of two supercell storms that were soon to become tornadic. Figure 5 is a composite diagram showing the observed position of the CC500L at 0000 UTC 11 April 2005, and the location of primary tornadoes that occurred in the late afternoon. The surface low and relevant boundaries at 2200 UTC 10 April 2005 are also shown in Fig. 5, along with selected surface isodrosotherms and the axis of warmest observed surface temperatures. Notice that surface dewpoint values in northwest Kansas ahead of the "cold" front (of Pacific origin, acting as a sharp dryline) were not particularly large (only 12°–14°C; 54°–57°F) where the tornadoes occurred. This was in contrast to larger dewpoints (>15.5°C or 60°F) that were located over northern Oklahoma and southern Kansas where nontornadic thunderstorms occurred later that afternoon and evening. However, vertical wind shear in the lowest 6 km was large (>25 m s^{-1} or ~ 50 kt) and very supportive of supercells (see hodograph in Fig. 10a in section 2b). Notice also that the tornadoes occurred near an intersection of boundaries northeast of the surface low where the surface moisture axis had advected northwestward beneath colder temperatures aloft ($-18°$ to $-20°$C at 500 mb, not shown).

The composite diagram in Fig. 5 and location of tornadoes matches preliminary work from DG04 that summarized ingredients and features associated with tornado-producing CC500L systems. These include a

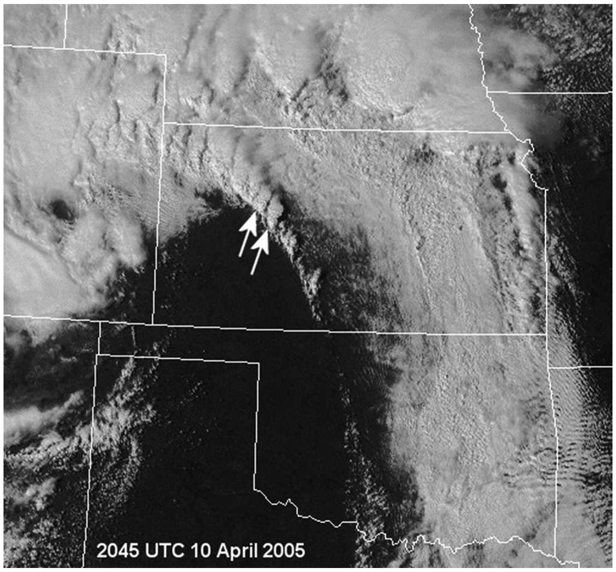

FIG. 4. Visible satellite image of KS–OK area at 2045 UTC 10 Apr 2005. Cells that became tornadic during 2100–2200 UTC are indicated by white arrows.

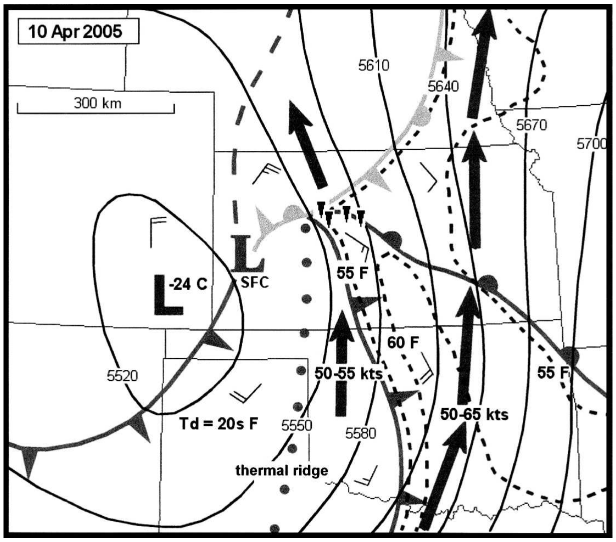

FIG. 5. Composite chart showing selected surface features observed at 2200 UTC 10 Apr 2005 and 500-mb features observed at 0000 UTC 11 Apr 2005. Surface low (annotated "SFC") and frontal symbols are conventional, surface wind barbs (kt) are shown at selected locations, isodrosotherms are shown at 5°F intervals (dashed curves) for surface dewpoint values ≥55°F, and surface thermal ridge axis is indicated by thick dots. Contours at 500 mb are shown at 30-m intervals (solid curves). Low pressure center at 500 mb is also indicated, annotated with associated central temperature (°C), and heavy arrows indicate axes of maximum 500-mb winds (kt). Primary tornado locations during 2130–2330 UTC are shown with solid inverted triangles.

surface "focus" area of intersecting boundaries, typically a Pacific front/dryline intersecting a warm front or stationary front, located within roughly 320 km (~200 statute miles) of the CC500L center. In the 10 April 2005 case, clear skies in the dry air behind the Pacific front/dryline (see Fig. 4) generated surface heating close to and under the cold air aloft. This helped enhance the surface thermal ridge axis (Fig. 5) that "pointed" toward the boundary intersection focus area over northwest Kansas, and probably generated a local increase in low-level lapse rates (Davies 2006) at the northwest tip of the moist axis and warm sector.

An analysis sounding from the Rapid Update Cycle model (RUC; Benjamin et al. 2004) located near Wakeeney, Kansas, at about the time of the tornado in Fig. 3 is shown in Fig. 6, adjusted in the lowest 100 mb using local surface observations. Note that while total CAPE was relatively small (around 1000 J kg^{-1} for a mixed-layer parcel), the equilibrium level was quite low, near 8 km AGL (below 300 mb). A sounding from D93a (see his Fig. 9) associated with the small tornadic supercell shown in Fig. 1 (see case study later in this section) was similar, with roughly 900 J kg^{-1} of total CAPE and an equilibrium level near 400 mb. The photo in Fig. 7 confirms the low equilibrium level height in Fig. 6 and shallow depth of the storm, with the top of the storm tower *and* the tornado both visible in the same image, similar to Fig. 1. Such shallow rotating storms are often referred to as "minisupercells" (e.g., Burgess et al. 1995), and their small size is typical of tornadic storms in CC500L environments where the tropopause is low near the 500-mb low aloft. This has ramifications for radar detection of such storms and has been well documented (e.g., Burgess et al. 1995; Grant and Prentice 1996; Jungbluth 2002).

Because buoyancy in environments similar to Fig. 6 is "squeezed" into a much shallower vertical layer than in more "typical" spring tornadic environments where buoyancy extends to 12 km and higher, vertical acceleration of updraft parcels would occur over a shallower depth. This could impact low-level stretching beneath storm updrafts in vorticity-rich areas, particularly near a boundary intersection focus area such as mentioned earlier in Fig. 5. Enhanced vertical velocities and associated low-level horizontal velocity gradients in such settings would contribute significantly to the tilting of the horizontal streamwise vorticity (Davies-Jones et al. 1990) available with backed surface winds near the surface low and boundary intersection (e.g., Maddox et al.1980; Markowski et al. 1998). This would be relevant to tornado development, even though total CAPE might be relatively small, often less (e.g., 400–600 J kg^{-1}) than seen in Fig. 6.

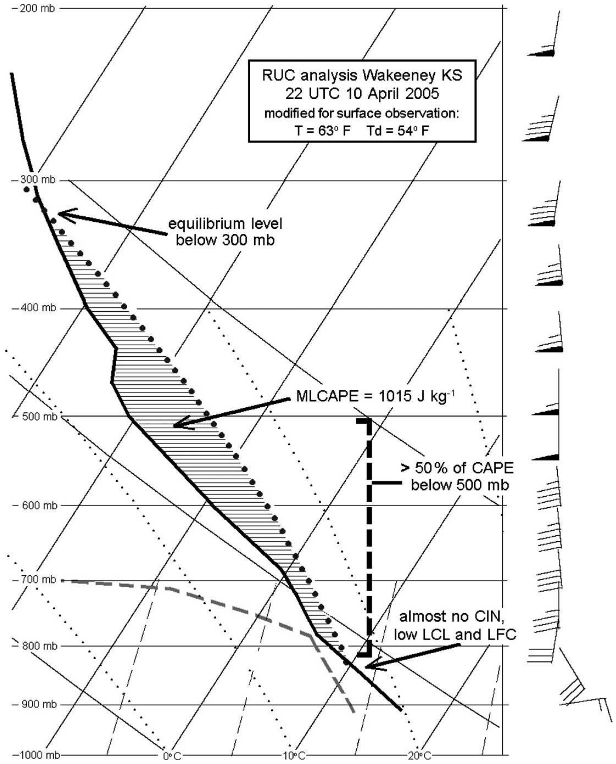

FIG. 6. Skew *T*–log*p* diagram of RUC analysis profile for Wakeeney, KS, at 2200 UTC 10 Apr 2005, modified in the lowest 100 mb based on actual surface observations. Solid black curve is temperature profile, dashed gray curve is dewpoint profile, and dotted curve is lowest 100-mb lifted parcel above the lifted condensation level. Area of positive CAPE is hatched, and important features are labeled. For viewing simplicity, the virtual temperature correction is not shown.

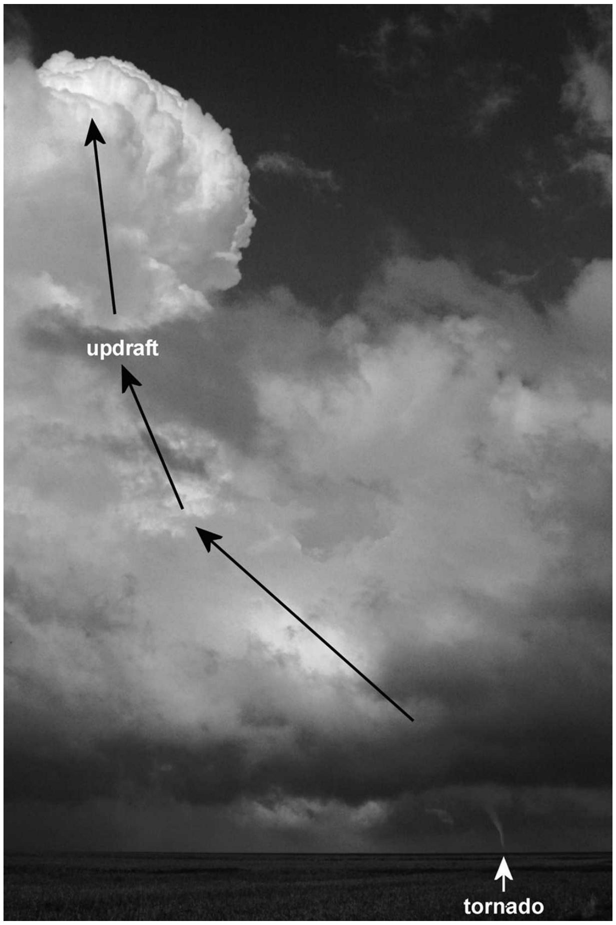

FIG. 7. Low-topped supercell updraft with a tornado visible below on 10 Apr 2005 northwest of Wakeeney, KS, shortly before 2200 UTC. Tornado and tilted updraft are indicated by white and black arrows, respectively. View is toward the northeast. (Photo by the author.)

b. 1 July 2004

Although preliminary work from DG04 suggested that the frequency of CC500L systems over the central United States peaks in spring (April and May), tornadic episodes can occur in autumn (e.g., 1 November 2000 in North Dakota), winter (e.g., 7 January 1992 in Nebraska), or summer. A tornadic event in north-central Kansas on 1 July 2004 serves as an example of a summer event when surface boundaries and features associated with CC500L systems can be more subtle and less well defined.

The tornadic storm location at 2130 UTC 1 July 2004 is shown in the visible satellite image in Fig. 8. Figure 9 summarizes relevant features on the afternoon of 1 July 2004, similar to Fig. 5. The CC500L was not as strong as in the prior case, with 30-m contours barely enclosing the low at 500 mb (see Fig. 9). But the midlevel low was quite evident over northwest Kansas in satellite loops and model-derived wind fields. Similarly, surface moisture gradients were not as well defined as on 10 April 2005, but careful analysis highlighted the presence of a surface boundary intersection between a weak dryline feature and a warm front east of the surface low (see Fig. 9). Because it was summer, surface dewpoint values at this location were much higher than in the 10 April 2005 event (20°–22°C; 68°–72°F), but accompanying wind fields were much weaker. This can be seen by comparing the size of the RUC near-storm hodographs presented in Fig. 10a (10 April 2005) and Fig. 10b (1 July 2004), showing this event to have very weak midlevel flow and only 8 m s^{-1} (16 kt) of 0–6-km shear. Stronger midlevel winds present over the Texas Panhandle area and Oklahoma (Fig. 9) suggested that an environment more supportive of supercells and possible tornadoes was located *south* of Kansas.

The tornado occurred near the boundary intersection east of the surface low (see Fig. 9) northwest of Salina, Kansas, and was photographed by the author (Fig. 11)

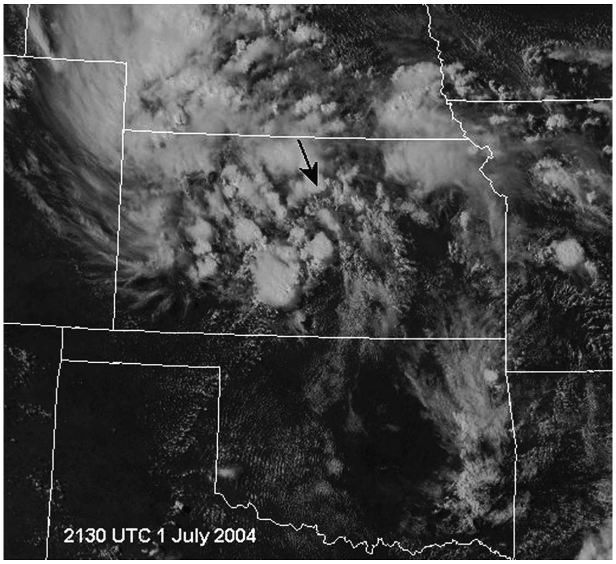

FIG. 8. Satellite photo as in Fig. 4 but at 2130 UTC 1 Jul 2004. The cell that was tornadic at the time of this image is indicated by a black arrow.

originating from a small storm distant from radar. The tornado was relatively short lived (6–7-min duration) and appeared weak compared with those during the 10 April 2005 case, traversing open country with no apparent damage and no other severe weather reported. The subtle synoptic setting associated with this case suggested less threat for tornadoes than on 10 April 2005, but it is notable that this July event had several features and ingredients in common with the April event and those noted in DG04. Comparing Fig. 9 with Fig. 5, these include the surface boundary intersection area east of the surface low and the proximity of the midlevel low. Although more clouds were present around the CC500L than on 10 April 2005, with no true "dry" sector or broad area of clear skies, a local area of sunshine was observed immediately south of the warm front and tornadic cell, probably enhancing low-level lapse rates feeding into the storm. A surface thermal ridge axis was evident (see Fig. 9) at midafternoon pointing northward into the boundary intersection area where the tornadic storm occurred, and the CC500L was centered only 160–200 km (~100–125 statute miles) to the west.

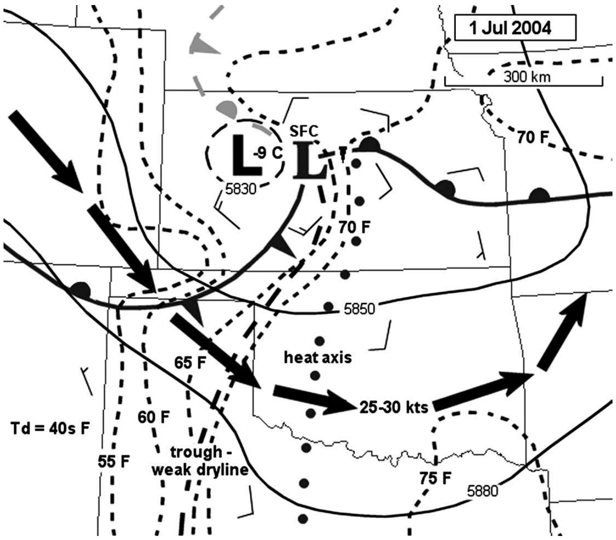

FIG. 9. Composite chart as in Fig. 5 but for surface features observed at 2100 UTC 1 Jul 2004 and 500-mb features observed at 0000 UTC 2 Jul 2004. Tornado location at 2135 UTC is shown with solid inverted triangle.

c. 11 March 1990

This CC500L event was examined in D93a, but is revisited here along with a similar event from 1991 (see the following case) to discuss features that were undocumented in the D93a study, which was informal in nature.

Figure 12 is a composite map, similar to Figs. 5 and 9, showing relevant features in the late afternoon on 11 March 1990 when a small tornadic supercell produced tornadoes over central Kansas (see low-topped storm with tornado in Fig. 1 earlier). As in the 10 April 2005 case, wind fields were strong at all levels with a well-defined surface dryline (again, a front of Pacific origin). During the afternoon, two surface lows were evident (one in northeast Colorado, the other over southwest Kansas, seen in Fig. 12). A weak warm front (not documented in D93a) extended southeastward from the surface low northeast of Dodge City, providing a boundary intersection and focus area within 200–250 km (approximately 125–155 statute miles) of the CC500L that was located near the Kansas–Colorado border (see Fig. 12). A surface thermal ridge was present in the drier air oriented from western Oklahoma northward toward the Kansas low, and surface dewpoints of 12°–14°C (54°–57°F) were ahead of the Pacific front/dryline. With these ingredients available, it is likely that low-level lapse rates were enhanced at the edge of the surface moisture axis near the boundary intersection area just east of the surface low and relatively close to the CC500L aloft.

The informal study in D93a neglected to show or mention the warm front and the resulting boundary intersection with the Pacific front/dryline. This appears to be an important feature that needs emphasis in CC500L tornado cases based on the preliminary work in DG04 and the events presented here. The position of the surface thermal ridge axis "pointing" into the

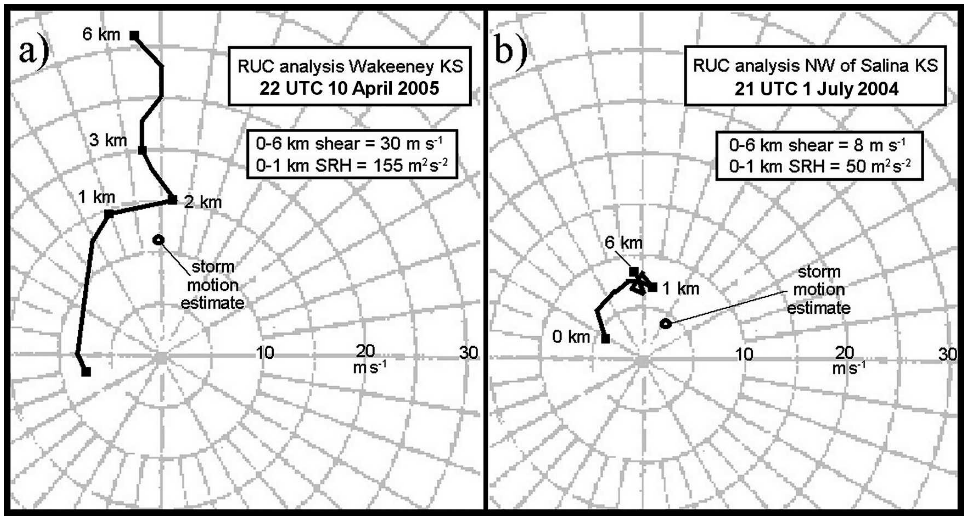

FIG. 10. Ground-relative hodographs through 6 km AGL from RUC analysis profiles associated with the (a) 10 Apr 2005 and (b) 1 Jul 2004 cases discussed in the text. Each ring increment on the background grids represents 5 m s^{-1} (10 kt). Small heavy circles are storm motion estimates. Computed 0–6-km shear and 0–1-km storm-relative helicity values are shown in each graphic.

boundary intersection area from the south or southwest also appears to be an important ingredient not mentioned in D93a.

d. 28 April 1991

A composite map for this case on the afternoon of 28 April 1991, similar to Figs. 5, 9, and 12, is shown in Fig. 13. As with the other cases examined, a surface low (in west-central or southwest Kansas) was positioned relatively close to a CC500L moving northeastward over the Oklahoma–Texas Panhandle area. Surface dewpoints at the northwest tip of the warm sector were 13°–15°C (55°–59°F), and a boundary intersection east of the surface low appeared to provide a general focus area where tornadoes occurred. Similar to the 11 March 1990 event, the axis of a surface thermal ridge was ori-

FIG. 11. Tornado northeast of Lincoln, KS, on 1 Jul 2004. View toward the northeast. (Photo by the author.)

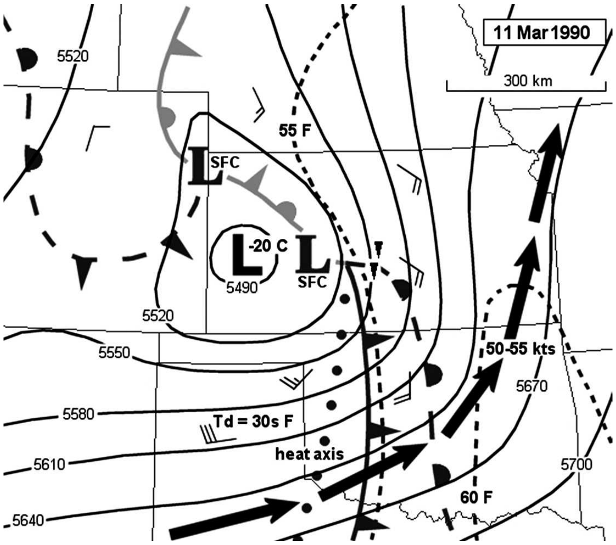

FIG. 12. Composite chart as in Fig. 5 but for surface features observed at 2200 UTC 11 Mar 1990 and 500-mb features observed at 0000 UTC 12 Mar 1990. Tornado locations during 2300–2345 UTC are shown with solid inverted triangles.

ented south to north from western Oklahoma into Kansas, pointing into the area near the surface low. Wind fields for this case were not as strong as on 11 March 1990, but still exhibited speeds of 15–20 m s^{-1} (approximately 30–40 kt, not shown) at 500 mb where the tornadoes occurred. Photos from this CC500L event showed that the main tornado, also shown in Fig. 2 (F1 intensity, 11-mi path), occurred from a very shallow cell, and is photographed from the reverse angle in Fig. 14. Later tornadoes from other cells appeared as brief dust whirls or columns (without condensation funnels) beneath flat cloud bases and low-topped updrafts that produced little precipitation (see Fig. 15), similar in appearance to some nonmesocyclone tornadoes.

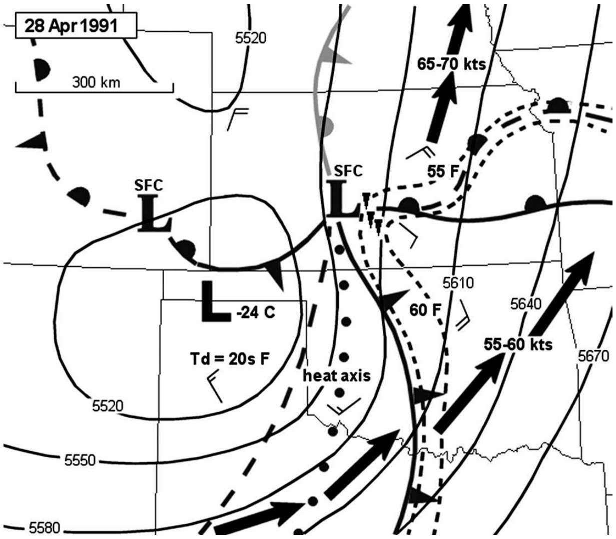

FIG. 13. Composite chart as in Fig. 5 but for surface features observed at 2100 UTC 28 Apr 1991 and 500-mb features observed at 0000 UTC 29 Apr 1991. Tornado locations during 2130–2230 UTC are shown with solid inverted triangles.

3. Summary and discussion

This note is not an exhaustive investigation of CC500L events, but does serve to highlight some common features and ingredients for the purpose of increasing forecaster situational awareness in diagnosing tornado potential with CC500L systems. From the cases examined here and in the preliminary climatological study in DG04, tornado events occurring near a CC500L are generally associated with the following features (shown in Fig. 16) that suggest important ingredients and processes.

1) A surface warm sector with dewpoints usually 10°–12°C (low to mid-50s °F) or greater located within roughly 320 km (~200 statute miles) of the CC500L. The proximity of the midlevel cold core low to the warm sector and adequate moisture would likely increase buoyancy close to the ground (see Fig. 6 in section 2), with little if any convective inhibition (CIN; Colby 1984). This would in turn impact upward parcel acceleration and stretching beneath updrafts (e.g., Davies 2004). Enhanced upward low-level velocities and lateral variations in these velocities near updrafts would convert available horizontal streamwise vorticity into vertical vorticity (tilting), which could contribute to tornadogenesis (Davies-Jones et al. 1990).
2) A surface boundary intersection or "focus" area (usually east/northeast/southeast of the surface low) located within roughly 320 km (~200 statute miles) of the CC500L. This is often the intersection of a dryline (or a front of Pacific origin acting as a dryline) with a warm front or an outflow boundary behaving as a localized front. This boundary intersection and the surface winds spiraling around the nearby surface low would likely focus and enhance storm-relative helicity known to contribute to supercell tornado environments (Davies-Jones et al. 1990).
3) A surface thermal ridge, typically within the dry sector and associated with sunshine, extending northward or northeastward into the surface boundary intersection area east of the surface low. This thermal ridge would likely increase low-level lapse rates in the local area where the "nose" of the thermal

FIG. 14. Low-topped storm with tornado on 28 Apr 1991 northwest of Pratt, KS. View is toward the northeast. Tornado is the same as in Fig. 2 but from the reverse angle. (Photo by P. Corrigan.)

ridge axis meets the edge of the surface moisture axis near the boundary intersection. This steepening of low-level lapse rates could enhance the local environment, increasing the potential for rapid parcel ascent and stretching in low levels (e.g., Davies 2006) with storm updrafts developing near the boundary intersection.

Fortunately, most tornadoes that occur with CC500L systems are only F0 or F1 intensity, but on occasion F2 or greater intensity tornadoes do occur. Tornadoes at the northwest edge of the warm sector in CC500L settings are sometimes erroneously referred to as "cold air funnels" (Cooley 1978), which are typically a phenomenon *behind* cold fronts (Doswell and Burgess 1993)

FIG. 15. Dust whirl tornado northeast of Pratt, KS, on 28 Apr 1991, under an updraft producing little precipitation. View is to the west. (Photo by the author.)

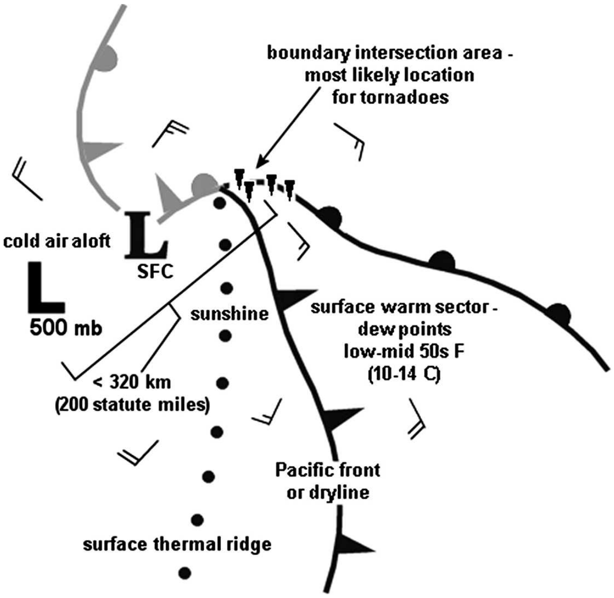

FIG. 16. Composite diagram adapted from Davies and Guyer (2004) showing common features associated with tornado-producing CC500L systems.

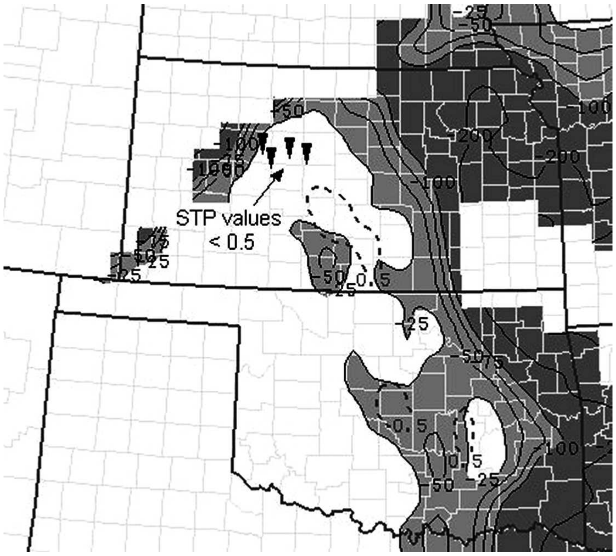

FIG. 17. Significant tornado parameter (STP ≥ 0.5 dashed) from SPC mesoanalysis at 2200 UTC 10 Apr 2005. Also shown is mixed-layer CIN ≥ 25 J kg^{-1} (light shading) and ≥100 J kg^{-1} (heavy shading). Primary tornado locations are shown as in Fig. 5.

with little potential for surface damage. Tornadoes occurring just east of the surface low in CC500L settings are *associated with the warm sector* (Doswell and Burgess 1993) and are legitimate tornadoes that can sometimes do significant damage, even though surface moisture amounts may appear somewhat marginal.

Environments associated with many CC500L events can elude detection using standard parameters and forecasting methodologies based on more typical or "mainstream" supercell environments emphasized in empirical studies such as Johns et al. (1993), Rasmussen and Blanchard (1998), and Thompson et al. (2003). Because the majority of tornadic storms associated with CC500L systems are supercells (often minisupercells, as shown by photographs in this study), the contributing processes are likely no different than in more typical tornadic supercell environments. However, the relative combination of ingredients can *appear* to be somewhat different in CC500L events because of relatively small total CAPE amounts and narrow axes of surface moisture, as well as relatively weak midlevel winds close to the 500-mb low. A result of these environment characteristics is that composite parameters such as STP (Thompson et al. 2003) and the energy–helicity index (Hart and Korotky 1991; Davies 1993b) frequently do not work well with CC500L events. An example is shown in Fig. 17 from the Storm Prediction Center (SPC) mesoanalysis (Bothwell et al. 2002) during the 10 April 2005 tornado event (section 2), where STP values were depicted as negligible in the area where several tornadoes occurred. This aspect of many CC500L events merits emphasis in forecaster training.

It is also conceivable that nonsupercell or nonmesocyclone tornado processes (Wakimoto and Wilson 1989; Brady and Szoke 1989) may play a role in some CC500L tornado cases that involve weak wind fields but surface boundaries having preexisting vertical vorticity, a possibility also suggested by McDonald (2000). Recent CC500L tornado events on 30 March 2005 in northern Iowa and 5 April 2005 in southwest Kansas with relatively weak deep-layer shear but well-defined surface boundaries and steep near-surface lapse rates (Davies 2006) appear to fall into this category. The visual appearance of dust whirl tornadoes such as on 28 April 1991 (Fig. 15 in section 2) from updrafts in their early stages with little precipitation also hints at the possible involvement of nonmesocyclone processes. This is an aspect of CC500L tornado events that may require additional forecaster awareness, as well as investigation in further research.

Thermodynamic characteristics associated with many CC500L tornado events appear to be somewhat different from those associated with typical supercell tornado environments, and also deserve further study. Thermodynamic profiles from the 10 April 2005 case in section 2 (Fig. 6) and from D93a suggest that buoyancy with many CC500L tornado events is squeezed into a shallow depth relative to the ground, the result of cold air aloft and lower tropopause levels associated with closed midlatitude 500-mb low systems. Wicker and Cantrell

(1996), using a sounding from D93a, demonstrated that supercells in environments with surface-based CAPE of only 600 J kg^{-1} can generate surface mesocyclones that are similar in strength to those in settings with 2–3 times more CAPE and comparable vertical shear. Additionally, McCaul and Weisman (2001) found that the compression of buoyancy into the lower troposphere could at least partially compensate for smaller amounts of total CAPE regarding updraft strength and generation of surface vorticity. Future research might focus on ways to diagnose environments where total CAPE, though relatively small (e.g., <1000 J kg^{-1}), is configured unusually low in the vertical, and examine to what degree this could relate to tornado potential.

The fact that CC500L events can generate tornadoes in environments that at first glance appear only marginally unstable or sometimes weakly sheared presents a continuing challenge for forecasters. It is hoped that this note will serve to increase operational recognition of some features and ingredients associated with many such events. Future research of CC500L events may shed light on other "atypical" tornado occurrences, particularly those that involve environments associated with relatively small buoyancy.

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