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Three Strong Tornado Events in 2008 associated with Boundary Intersections and Narrow Instability Axes near 700-mb Lows

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

1. Introduction

Three significant tornado events in May and June of 2008 in the central and northern plains were associated with boundary intersections and narrow instability axes in relatively close proximity to closed lows at 700 mb. These tornado events were:

- 1 May 2008 in northwest Iowa (the Rock Valley, Iowa tornado, rated EF2)
- 22 May 2008 in northern Colorado (the Windsor, Colorado tornado, rated EF3, with 1 death)
- 6 June 2008 in north-central Minnesota (2 tornadoes near Park Rapids, Minnesota, rated EF2 and EF3)

All of these events involved strong tornadoes in settings with varying degrees of forecast difficulty. The first (1 May 2008) was well forecast, with a tornado watch issued in advance. The second (22 May 2008) was not well anticipated, with a tornado watch issued only while initial tornado reports were coming in. No tornado watch was in effect during the third event (6 June 2008). These variations illustrate how difficult it is to forecast some tornado events that occur within narrow instability axes (often at the northwest edge) when a pool of cold air is aloft nearby due to the presence of a midlevel low to the west. Sometimes features are subtle, and can be overlooked by forecasters when larger convective available potential energy (CAPE) is evident some distance to the east and south.

This paper will briefly examine these cases, noting some common features that were similar to those found in many so-called "cold core" tornado settings (e.g., McDonald 2000; Davies 2006b), even though one might not consider these "classic" cold core events.

2. 1 May 2008 tornadoes in northwest Iowa

Between roughly 0000 and 0100 UTC on 2 May 2008 (7:00 and 8:00 pm CDT on 1 May 2008), 5 tornadoes occurred in a concentrated area of northwest Iowa. The strongest was rated EF2 (see Fig. 1) near the town of Rock Valley, on the ground for nearly 25 minutes with a path length of 13 miles.

Fig. 1. Tornado near Rock Valley, Iowa. Photo by Bonnie Fedders.

The synoptic setting involved a large closed 500-mb low (not shown) over far northwest Nebraska, within a large trough moving from the Rocky Mountains into the central plains. The 700-mb reflection of this low at 0000 UTC was located over south-central South Dakota (Fig. 2), bringing cold air aloft closer to northwest Iowa. About an hour and 15 minutes before the first tornado, the surface map at 2245 UTC (Fig. 3) showed a surface low over southeast South Dakota, with a Pacific front acting as a dryline extending southeastward into Iowa. A couple of advancing warm fronts were also evident, intersecting this boundary over northwest Iowa near the

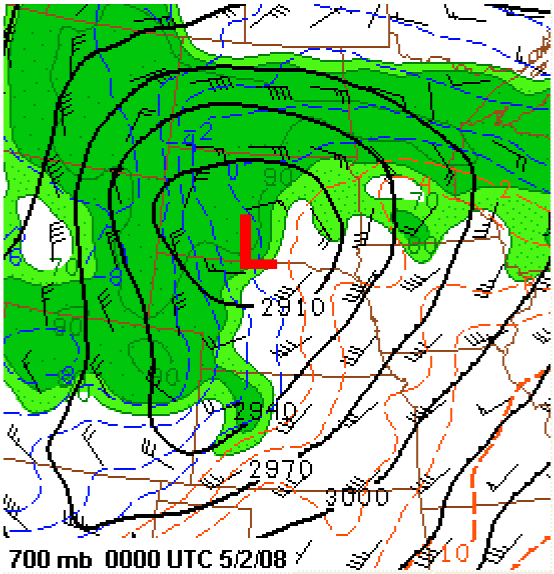

Fig. 2. SPC 700-mb mesoanalysis at 0000 UTC 2 May 2008. Isotherms (dashed) at 2°C intervals, height contours (solid) at 30 m intervals, relative humidity > 70% shaded (green), wind barbs conventional, low indicated by "L".

Corresponding author address:

Jonathan M. Davies
9101 Alpha Ridge Rd., Trimble, MO 64492
e-mail: daviewx@gmail.com URL: www.jondavies.net

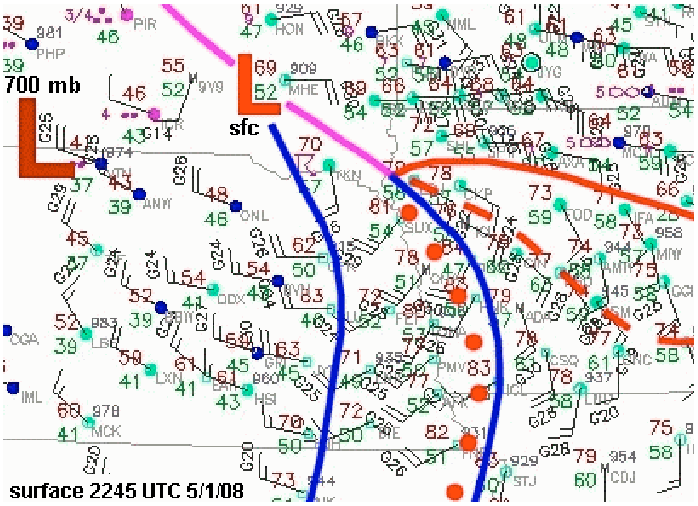

Fig. 3. Surface map at 2245 UTC 1 May 2008. Surface observations conventional, with cold fronts blue, warm fronts red, and occluded front purple. Red dots are surface thermal axis, low positions at 700 mb and surface indicated by "L".

Missouri River north of Sioux City, Iowa (SUX).

Mesoanalysis graphics at 2300 UTC from the Storm Prediction Center (SPC) suggested that this boundary intersection was located at the northwest edge of a narrow axis of surface-based total CAPE and low-level CAPE (Fig. 4). A low-level thermal axis was pointing into this area from the south (see Fig. 3, and Fig. 4b), associated with sunshine and clear skies on satellite (not shown) immediately behind the Pacific front/dryline.

Nontornadic storms had already developed between 2100 and 2200 UTC (not shown) over southeast South Dakota. Storms then began to develop on or very near the boundary intersection northwest of Orange City, Iowa (ORC) around 2350 UTC (see Fig. 5), and rapidly became tornadic within a matter of minutes, including the long-lived tornado near Rock Valley, Iowa (Fig. 1).

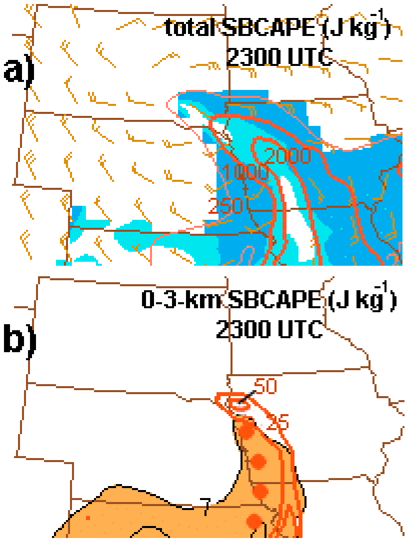

Fig. 4. Total surface-based CAPE (a) & 0-3-km CAPE (b)(J kg^{-1}) from SPC mesoanalysis 2300 UTC 1 May 2008, contours labeled. Blue shading in (a) is CIN ≥ 25 kg^{-1}, orange shading in (b) is 0-3-km lapse rate ≥ 7°C km^{-1}, red dots are thermal axis.

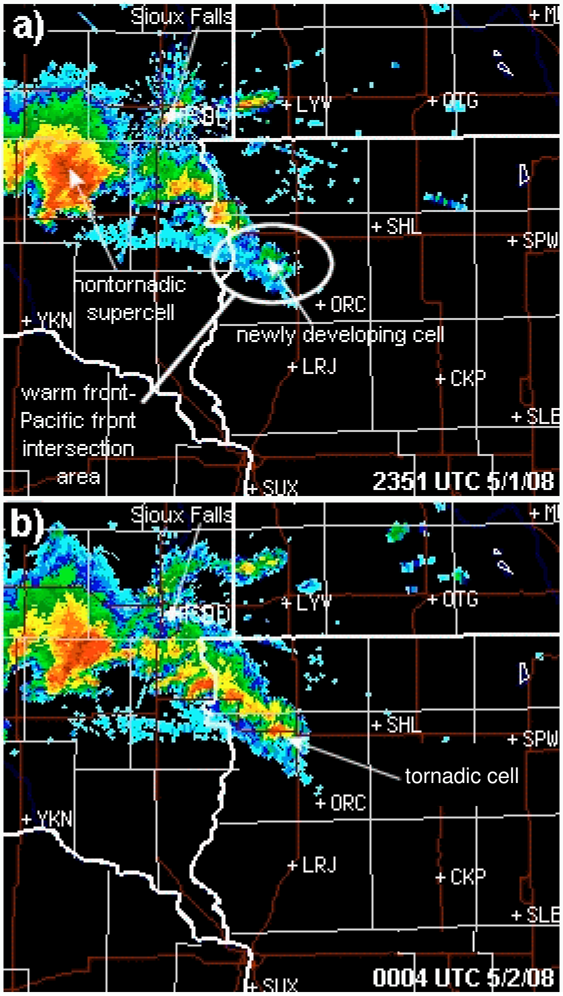

Fig. 5. Radar base reflectivity from Sioux Falls, South Dakota at 2351 UTC 1 May 2008 (a), and 0004 UTC 2 May 2008 (b). Elevation angle is .5°, and red colors indicate reflectivity ≥ 50 dBZ. Important features are indicated.

The RUC analysis profile just southeast of the tornadic cell at 0000 UTC for Orange City, Iowa, is shown in Fig. 6, using a mixed-layer lifted parcel to provide information supplemental to that shown with the surface-based SPC graphics from Fig. 4. This profile was modified in the lowest 150 mb to reflect observed temperature and dew point at 2345 UTC. The profile suggests that a pocket of cold air was present at 700 mb, resulting in a "fat" area of CAPE at this level (low in the profile), with the temperature below 0° C at 3 km above ground. Also notice the steep lapse rate (essentially dry-adiabatic) in the lowest 2 km. This low-level lapse rate calls to mind the thermodynamic environments associated with many non-supercell / non-mesocyclone tornadoes (Brady and Szoke 1989; Davies 2006a). When combined with the "fat' area of CAPE centered near 700 mb, the steep low-level lapse rates would probably strongly enhance low-level stretching of rising air parcels beneath storm updrafts. This thermodynamic setting and the boundary-related vorticity in the local area may help suggest why the first

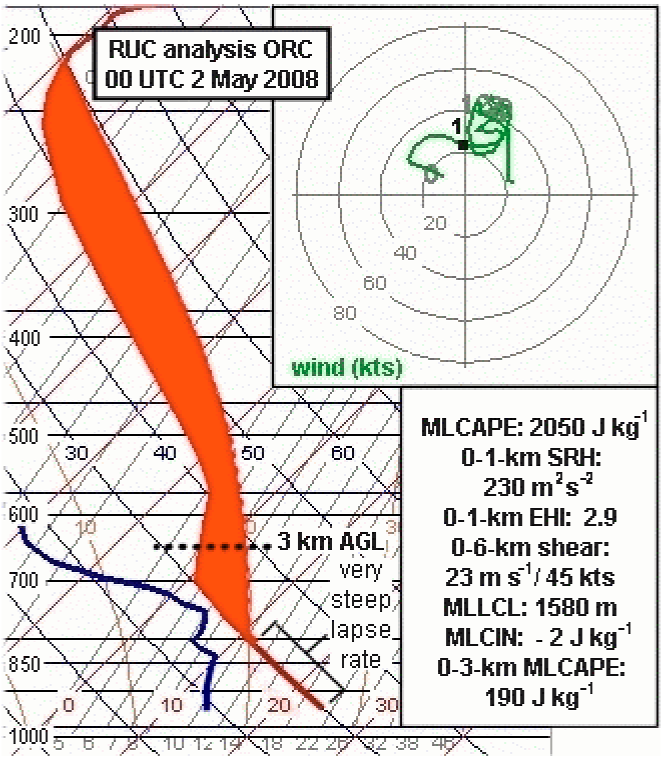

Fig. 6. SkewT-logP diagram and hodograph of RUC analysis profile at Orange City, Iowa, 0000 UTC on 2 May 2008. Red shading is mixed-layer total CAPE (J kg^{-1}). Important parameters and features are shown.

tornado formed rapidly in the early stages of its parent storm, even with a relatively high lifting condensation level (LCL) height at 1500 to 1600 m above ground.

The tornadic cell also developed supercell characteristics, probably because of the sizable storm-relative helicity (SRH) and deep-layer shear in the environment as seen in Fig. 6. Given the combination of characteristics in the local environment suggesting both mesocyclone and non-mesocyclone processes, this event may have been something of a “hybrid” tornado case, as suggested by some events in Davies (2006a). It is also interesting that it had some of the elements of a “cold core” case (Davies 2006b) with the surface boundary intersection, narrow instability axis, and midlevel low to the west (though somewhat distant) with cold air aloft, along with plentiful low-level CAPE.

3. 22 May 2008 Windsor, Colorado tornado

The tornado that hit Windsor in northeast Colorado on 22 May 2008 (Fig. 7) was on the ground for 34 miles and 50 minutes, between roughly 1726 and 1816 UTC (11:26 am and 12:16 pm MDT). It was rated EF3, and killed 1 person. The tornado was unusual for Colorado because of the time of day (late morning), direction of movement (north-northwest), and the size (path width up to a *mile* wide at times) just east of the mountains.

Fig. 7. Tornado between Greeley and Windsor, Colorado on 22 May 2008. From video by KUSA-TV.

At midday on 22 May 2008, a huge upper trough was nearly stationary over the western half of the United States, with a large 500-mb low (not shown) located over southwest Utah and northwest Arizona, rather distant from northeast Colorado. At 700 mb, the SPC mesoanalysis (Fig. 8) indicated that one low was centered over northeast Utah, while a second low was forming over south-central Wyoming, bringing colder air not far aloft closer to northeast Colorado.

The surface map was complex at 1645 UTC (Fig. 9), roughly 40 minutes before the initial touchdown of the Windsor tornado. A dryline was over western Kansas, with several cold fronts or surface wind shifts evident over Colorado. The lead front (a Pacific front, behind the western Kansas dryline) was over eastern Colorado and intersected a strong advancing warm front, providing a boundary intersection north-northeast of Denver, south of Greeley (GXY). This was east of a surface low parked against the foothills that was pulling moist air upslope along the warm front. The boundary intersection area was visible on satellite at 1645 UTC (Fig. 10), with a broad axis of clear skies evident to the southeast, suggesting significant surface heating. This corresponded with the surface thermal axis pointing into this area shown in Fig. 9.

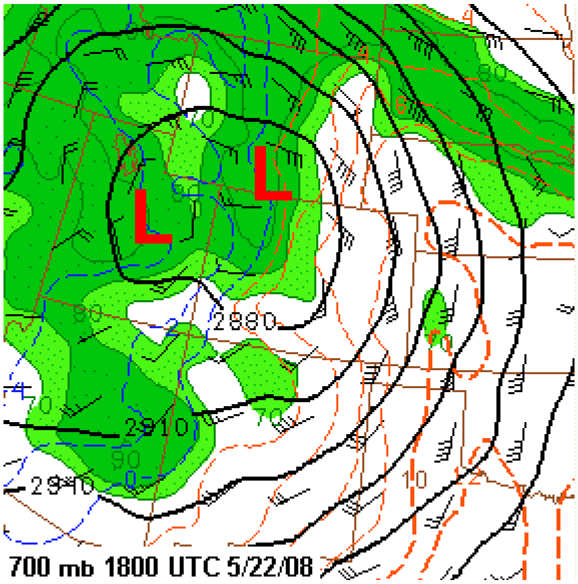

Fig. 8. 700-mb SPC mesoanalysis as in Fig. 2, except at 1800 UTC 22 May 2008 over central Rocky Mountains.

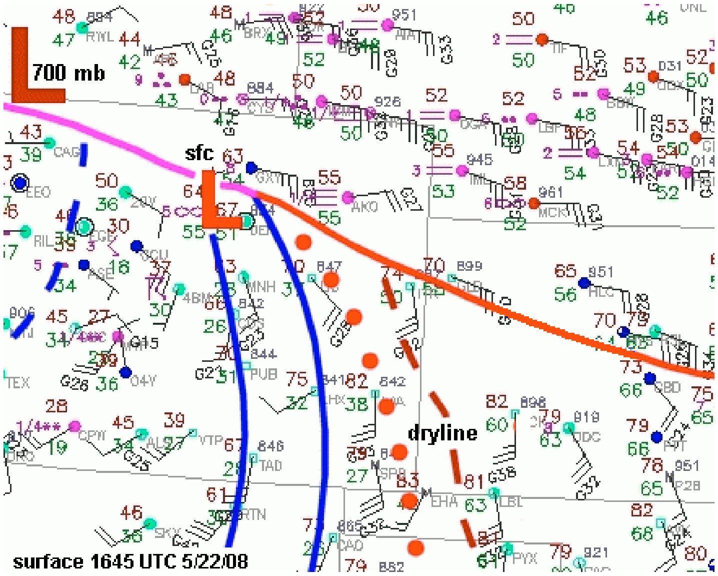

Fig. 9. Surface map as in Fig. 3, except at 1645 UTC 22 May 2008 over Colorado/Kansas area.

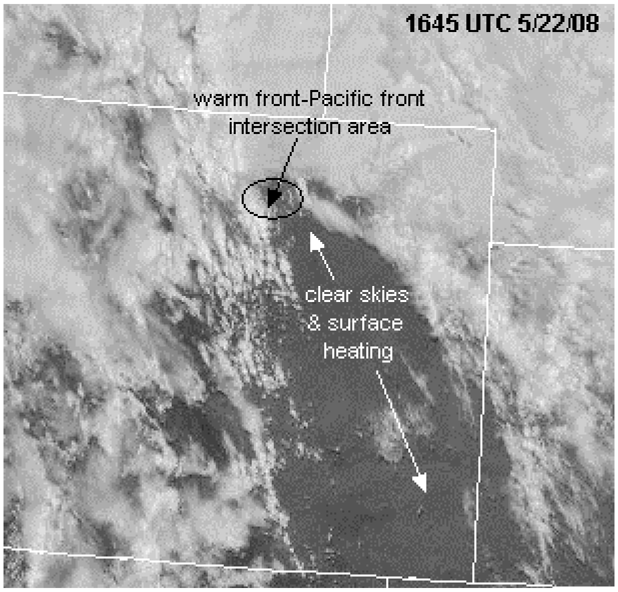

Fig. 10. Visible satellite photo at 1645 UTC 22 May 2008. Important features are indicated.

Mesoanalysis graphics from SPC at late morning (Fig. 11) showed a narrow axis of surface-based CAPE extending west-northwest through northeast Colorado along the advancing warm front. Although total CAPE at 1700 UTC (Fig. 11a) appeared to be twice as large over western Kansas, low-level surface-based CAPE (Fig. 11b) was clearly maximized over the Denver/Greeley area when compared to areas farther southeast. This was due to the proximity of cold air aloft associated with the western trough and lows aloft (Fig. 8), and mid-50s surface dew points (^{o} F) advecting westward into high terrain a mile above sea level.

Between 1630 and 1700 UTC, a thunderstorm developed explosively at the boundary intersection north-northeast of Denver (see radar in Fig. 12), and by 1715 UTC was exhibiting rotation on radar. The long-lived Windsor tornado began a few minutes later, less than an hour into the storm's lifetime.

Analysis profiles from the RUC model at Greeley for 1700 UTC and 1800 UTC are shown in Fig. 13, modified in the lowest 150 mb based on surface observations at the same times, like Fig. 6. These

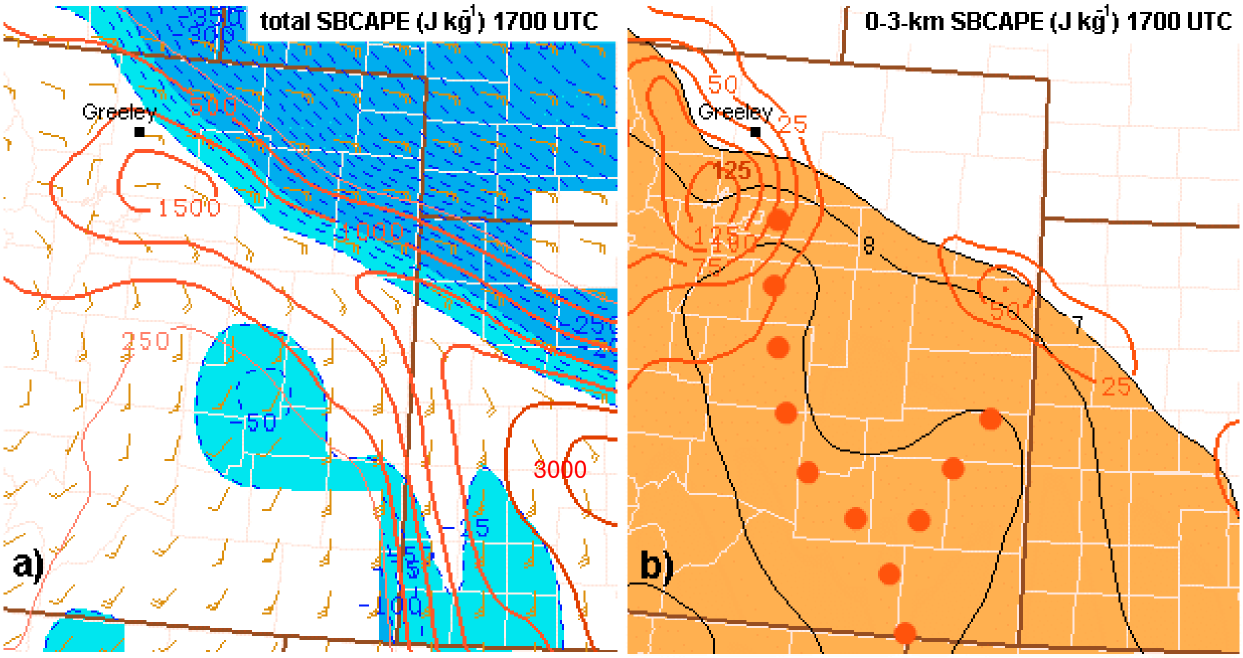

Fig. 11. Total CAPE (a) and 0-3-km CAPE (b), as in Fig. 4, except from SPC mesoanalysis 1700 UTC 22 May 2008, with more detail. Thermal axes of steepest 0-3-km lapse rate are shown in (b) with red dots.

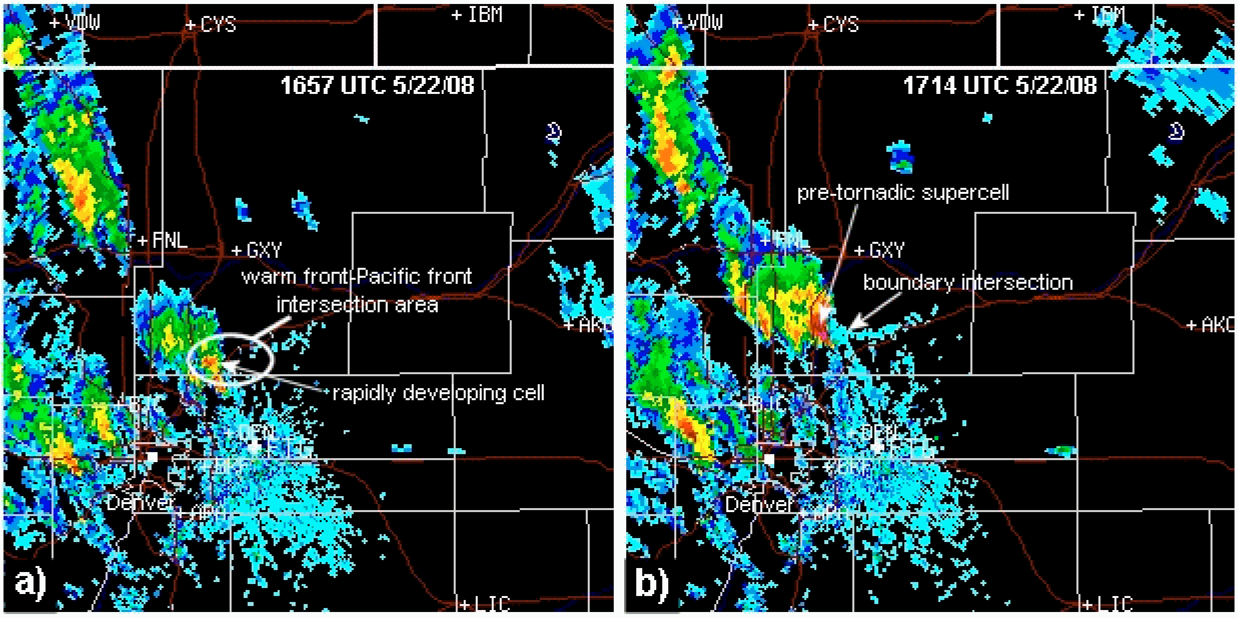

Fig. 12. As in Fig. 5, except Denver, Colorado radar at 1657 UTC (a) and 1714 UTC (b) on 22 May 2008. Important features are indicated.

indicated large increases in total mixed-layer CAPE and SRH as the warm front lifted northward past Greeley near the boundary intersection. Also, temperatures in Fig. 13 at 600 mb or 3 km above ground (roughly equivalent to 700 mb east of the high plains, considering elevation) were below 0° C. With little convective inhibition (CIN), this thermodynamic setting probably facilitated rapid storm development and intense stretching in updrafts. When combined with the strong shear environment (large SRH and large deep shear, see Fig. 13b), there was excellent support for strong tornado development. The LCL heights near the advancing warm front were also quite low, which favored supercell tornado development, given the other favorable factors (instability and shear).

As with the 1 May 2008 case, the following were

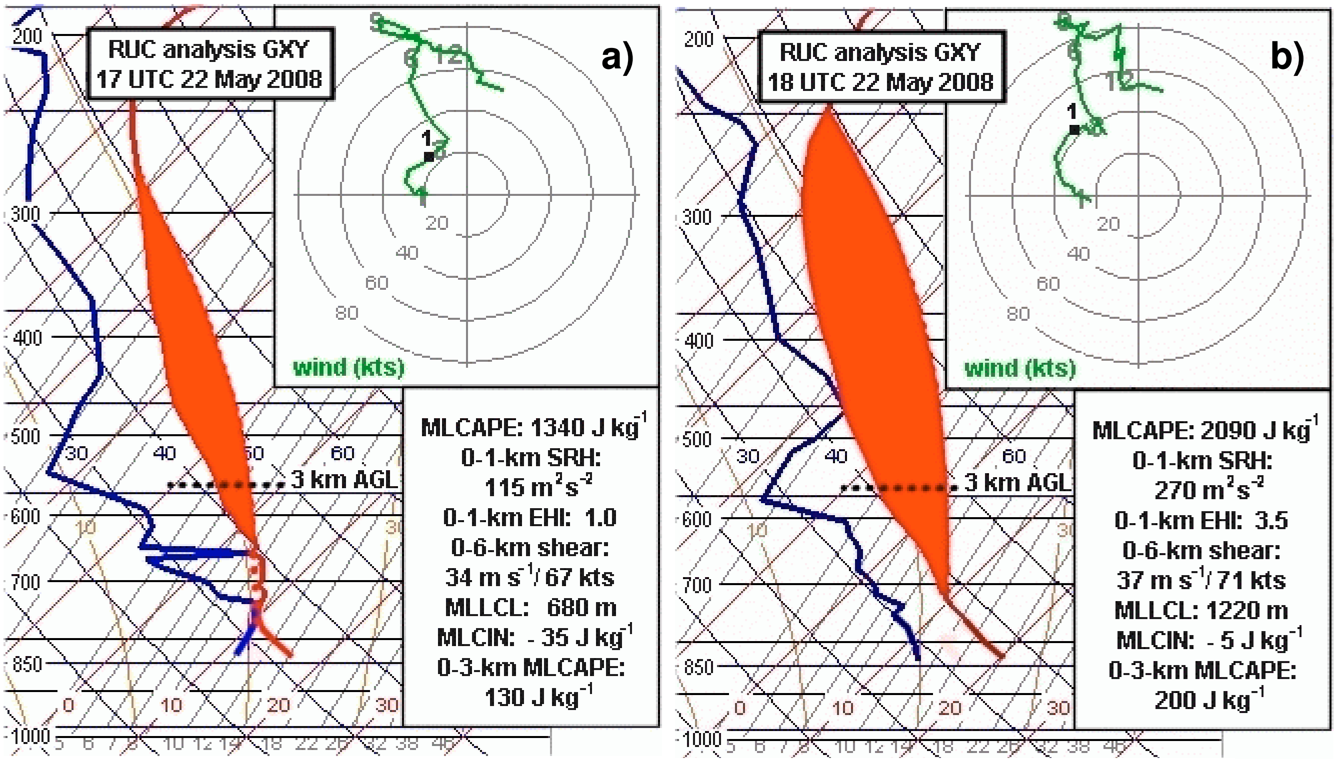

Fig. 13. SkewT-logP diagram and hodograph of RUC analysis profile as in Fig. 6, except at Greeley, Colorado, 1700 UTC (a), and 1800 UTC (b), on 22 May 2008.

Fig. 14. Tornadic supercell viewed from Park Rapids, Minnesota, looking northeast. It is unclear whether the white area at center was the tornado, or only a rain shaft. Photo by Sarah Smith, Park Rapids Enterprise.

present: a prominent surface boundary intersection, narrow instability axis, and cold air aloft associated with a distant midlevel low resulting in plentiful low-level CAPE. The supercell formed at the boundary intersection and moved north-northwest with the advancing warm front, influenced by backed upper flow around the deep midlevel trough and lows to the west.

4. 6 June 2008 tornadoes north-central Minnesota

On 6 June 2008, two strong tornadoes (EF2 and EF3) hit Wadena and Hubbard counties of north-central Minnesota between 1415 and 1450 UTC (9:15 and 9:50 am CDT). The tornado tracks totaled roughly 20 miles from the same small supercell storm (see photo in Fig. 14). The forecast setting was subtle for this morning event, with no SPC outlook for severe weather over this specific area, and no tornado watch in effect until after the tornadoes had occurred. An additional problem was that SPC mesoanalysis parameter graphics were not updating at 1300 and 1400 UTC, so that severe weather parameter guidance was not available immediately prior to the event.

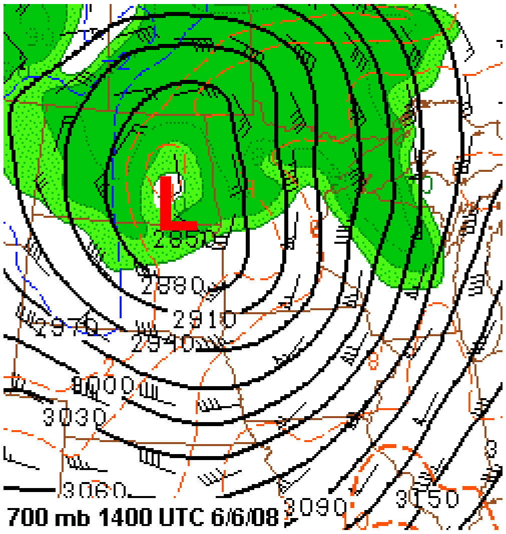

Fig. 15. 700-mb SPC mesoanalysis as in Fig. 2, except at 1400 UTC 6 June 2008 over northern plains.

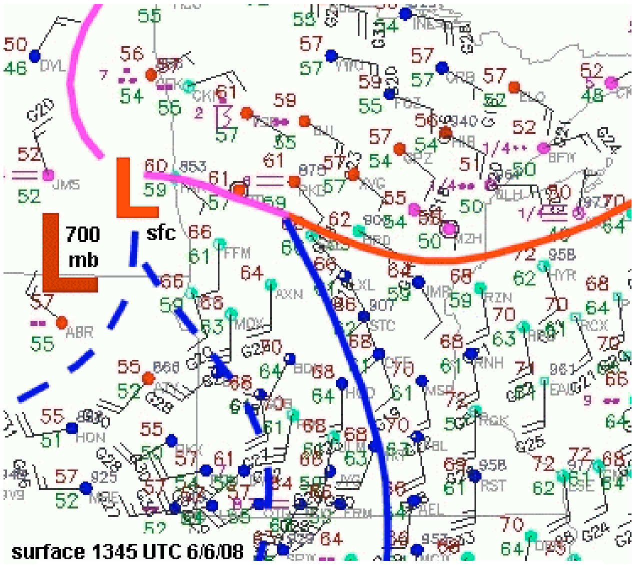

Fig. 16. Surface map as in Fig. 3, except at 1345 UTC 6 June 2008 over Minnesota/eastern Dakotas area.

Upper air mesoanalysis graphics were available from SPC at 1400 UTC, showing a 500-mb closed low (not shown) over south-central North Dakota, and a 700-mb closed low (Fig. 15) on the North Dakota–South Dakota border north of Aberdeen. These were embedded in a large negatively tilted trough at 500 mb (not shown) that was lifting northeast through North Dakota and the northern half of Minnesota.

The surface map at 1345 UTC (Fig. 16), about 30 minutes before the initial tornado touchdown, showed an advancing warm front oriented east-west through central Minnesota. A Pacific front (*not* acting as a dryline, but as only a wind shift) intersected the warm front between Alexandria (AXN) and Park Rapids (PKD), Minnesota. On satellite at 1345 UTC (Fig. 17), cloud cover was extensive and there was no “clear slot” to suggest a concentrated thermal axis of surface heating, unlike the prior two cases examined. The

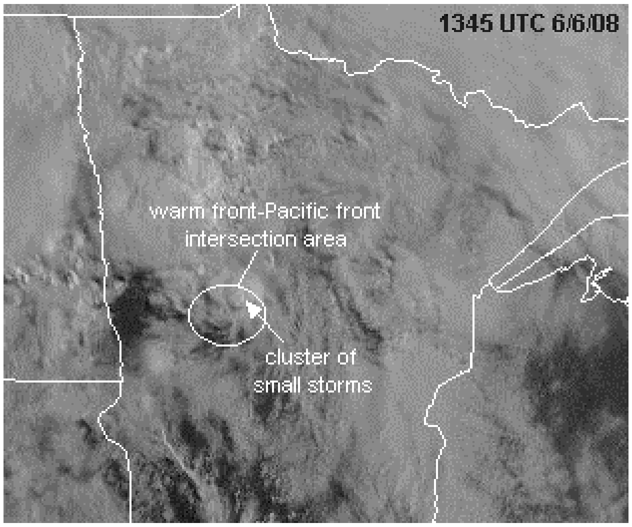

Fig. 17. Visible satellite photo as in Fig. 10, except at 1345 UTC 6 June 2008 over northern Minnesota.

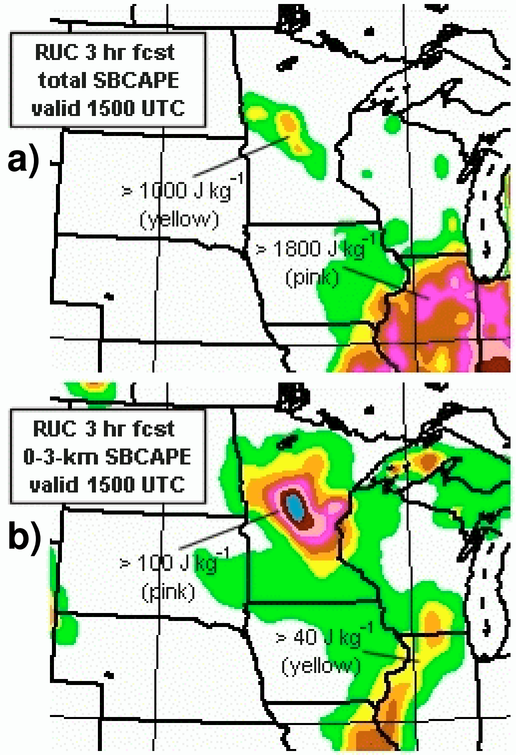

Fig. 18. Total CAPE (a) and 0-3-km CAPE (b), similar to Fig. 4 except from RUC model 3-hour forecast valid at 1500 UTC 6 June 2008, using 1200 UTC data. Significant color values are indicated.

surface map in Fig. 16 confirms that temperatures south of the warm front were spread out in a broad area of mid 60s to near 70 (° F), with no focused thermal axis.

Because SPC mesoanalysis graphics were not updating until after the tornadoes had occurred, RUC model 3-hr forecasts of total surface-based CAPE and low-level CAPE are shown in Fig. 18, valid at 1500 UTC from 1200 UTC data. This information would have been available to forecasters prior to the tornado event, in lieu of the SPC graphics. Note that the forecast showed an isolated and narrow area of total CAPE (Fig. 18a) over central and north-central Minnesota near the aforementioned boundary intersection, and bountiful low-level CAPE (Fig. 18b) indicating a very moist surface-based environment at the same location. For that early in the day without benefit of strong surface heating, this was an impressive area of instability, given the *morning* setting. The closed 500-mb low (closer than in the previous two cases) and 700-mb low to the west both contributed to the instability via cold air aloft.

Showers and small thunderstorms were already in progress at 1300 UTC (not shown) north of Alexandria near the warm front. As these lifted northward with the front and boundary intersection, they encountered the colder air aloft and favorable CAPE suggested by the RUC forecast, and intensified over Wadena County. The southeastern or “tail end” cell produced the strong tornadoes beginning around 1415 UTC (Fig. 19) from northern Wadena into Hubbard counties near the towns of Park Rapids and Emmaville. The storms were so

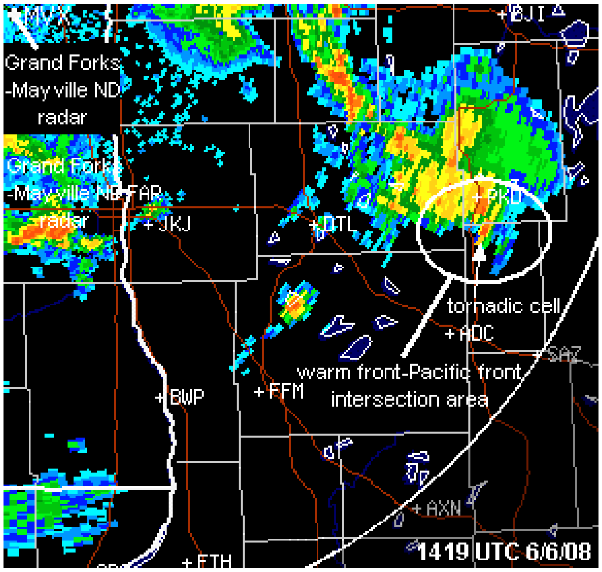

Fig. 19. As in Fig. 5, except northwest /north-central Minnesota area from Grand Forks-Mayville, North Dakota radar at 1419 UTC 6 June 2008. Important features are indicated.

small and distant from the closest radar (Grand Forks-Mayville, North Dakota) that tornado warnings were based entirely on spotter reports.

The RUC analysis profile at Park Rapids, Minnesota at 1400 UTC is shown in Fig. 20, unmodified because

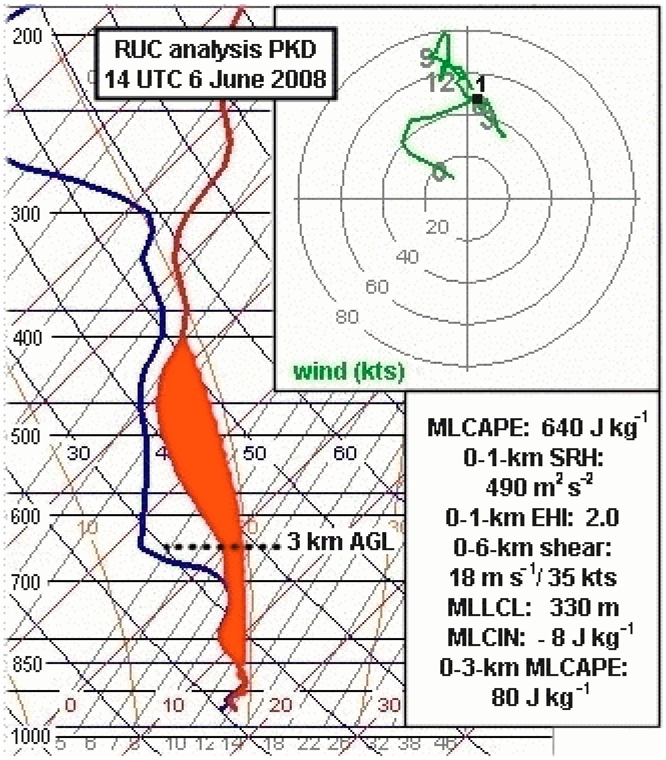

Fig. 20. SkewT-logP diagram and hodograph of RUC analysis profile as in Fig. 6, except at Park Rapids, Minnesota, 1400 UTC on 6 June 2008.

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the surface observation matched the RUC data very well. With all the total CAPE located below 400 mb, this profile was a "classic" small supercell profile, the type associated with many so-called "cold core" tornado cases (see Davies 1993; Davies et al. 2006b). With temperatures at 3 km above ground (between 600 and 700 mb) near 0° C, the proximity of cold air aloft related to the midlevel low resulted in plentiful low-level CAPE. Even though the total mixed-layer CAPE was relatively small (only around 600 J kg^{-1}, typical of many "cold core" tornado cases), the "bunching" of the CAPE relatively low in the profile suggested an environment with potential for rapid upward parcel acceleration and stretching in updrafts. Given that SRH in the setting was quite large in Fig. 20, supported by adequate deep shear, tilting and stretching of horizontal vorticity would likely be optimized along the advancing warm front. In addition, with the surface temperature at Park Rapids warming from 61 to 66° F as the warm front passed between 1400 and 1500 UTC (not shown), CAPE feeding the tornadic storm increased as well.

As with the prior cases examined, several common ingredients were associated with this event: a boundary intersection along an advancing warm front, small/narrow instability axis, and cold air aloft due to a midlevel low to the west (closer than in the prior cases examined) resulting in plentiful low-level CAPE. The presence of sufficient surface warmth and moisture in combination with the cold air aloft (tied to the 700-mb and 500-mb lows) fueled this unusual morning "cold core" event, even with cloud cover and an unfavorable time of day lacking strong surface heating from the sun.

5. Conclusion

Although the cases examined differ in specific mix of local ingredients and time of day, all had some common pattern recognition features that might serve as a "heads up" for forecasters to watch carefully in similar situations. These features were:

- A boundary intersection detectable from careful surface analysis along an *advancing warm front* (suggesting strong warm advection) east or southeast of a nearby surface low, within a well-organized surface pattern.
- A relatively small or narrow surface-based axis of significant instability at the boundary intersection, not much wider than 100 statute miles.
- A 700-mb low within roughly 200 statute miles to the west, with accompanying cold air aloft near 0° C or less at roughly 3 km above ground. (Temperatures at this level typically range from +4 to +10° C during the warm season.)
- The presence of significant low-level CAPE around the boundary intersection area, due to the low-level moist axis overlain by the cold air aloft noted above.

These features are similar to those found in so-called "cold core" tornado cases associated with closed 500-mb lows (McDonald, 2000; Davies and Guyer 2004; Davies 2006b). The main difference from a "typical" cold-core case in the 1 May 2008 and 22 May 2008 cases was that the 500-mb lows were much more distant (significantly more than 200 miles). Meanwhile, the associated *700-mb lows* were relatively close to the area of tornado occurrence (within roughly 200 miles). The close proximity of the 700-mb lows in these cases was important in suggesting the presence of notable cold air not very far aloft that was spreading over the northwest tip of the warm sector near the boundary intersection and advancing warm front. A difference in the 6 June 2008 case was the tornado occurrence at mid morning with significant cloud cover, divorced from the strong midday or afternoon heating typically associated with "cold core" tornado events.

What can be learned from these 3 events is that ingredients and features often found in so-called "cold core" tornado cases can be helpful in detecting other situations with similar ingredients but not falling within such a rigid categorization. That includes cases having a large closed 500-mb low centered within a very large trough, but farther west relative to the surface low than typical for most "cold core" cases (e.g., the 1 May and 22 May 2008 cases). It also includes times of day other than afternoon, *if* enough warmth and moisture is present in combination with cold air aloft to generate surface-based instability for storms without strong surface heating from the sun (e.g., the 6 June 2008 case).

The cases here reinforce the fact that strict or rigid categorization of cases (e.g., "cold core") is something that the atmosphere resists. Instead, it is preferable to focus on common features suggesting relevant ingredients and processes for tornado development, such as cold air not far aloft that can facilitate rapid low-level stretching near a warm frontal boundary intersection with notable surface moisture. These basic features can be useful for heightening awareness with forecasters in situations where tornado potential may otherwise not be readily apparent.

6. References

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