Meteorological Setting for a Catastrophic Event:
The Deadly Joplin Tornado of 22 May 2011

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ABSTRACT

The tornado that struck Joplin, MO on 22 May 2011 resulted in the first triple-digit death toll from a single tornado in the United States since the 1950s. This paper documents the meteorological setting for this exceptional event, as no published studies have done so yet. Synoptic-scale surface and upper air maps, a brief radar overview, environmental parameters via the SPC mesoanalysis and soundings, and mesoscale surface analysis are used to examine the background setting that led to the deadly tornado. Several other tornado days in the same general area with synoptic patterns similar to the Joplin tornado day also are examined from the standpoint of environmental parameters for comparison. The results show the Joplin tornado case to be an example of very supportive ingredients developing from a favorable evolution of synoptic-scale features; similar patterns have produced several deadly tornadoes in recent years. A couple of mesoscale boundaries also may have contributed to increased tornado potential in the Joplin area. Informal comments published elsewhere have described the environment for this event as "unfavorable" for violent tornadoes. The findings here contradict and refute that characterization, and show that the background environment for the Joplin tornado was actually quite favorable for supporting strong or violent tornadoes.

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1. Introduction

The Joplin, MO tornado at late afternoon on 22 May 2011 killed 158 people directly, and injured over 1150 (NCDC 2011). It ranks as the seventh deadliest U.S. tornado, and the most deadly since the 1947 Woodward, OK tornado over 60 y ago (Edwards 2017; Kuligowski et al. 2013).

Indeed, more than 100 deaths with a single U.S. tornado had not occurred since the early 1950s when the U.S. Weather Bureau (now the National Weather Service) started attempting tornado forecasts for public consumption (e.g., Bradford 2001). The tornado was difficult to see (Fig. 1) and formed rapidly on the southwestern edge of Joplin, which likely contributed to the exceedingly high death toll. But the fact that such a long period (58 y) passed without a triple-

digit death toll from a single U.S. tornado highlights the Joplin event as a truly catastrophic and exceptional occurrence to be studied from a meteorological perspective, particularly in an age where meteorology and technology are much more advanced than in the 1950s.

Figure 1: Image of Joplin tornado (arrow), looking northwest from Interstate 44 on the southwestern edge of Joplin at 2237 UTC. Contrast is enhanced, from video by the author.

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Several studies have been done regarding the Joplin tornado from a sociological perspective regarding public response to warnings, as well as damage and recovery efforts (e.g., NOAA 2011; Kuligowski et al. 2013; Smith and Sutter 2013; Paul et al. 2014). However, no meteorological studies of the Joplin tornado setting and its context compared to other events have been published, although one informal study (Van Leer et al. 2012) described the setting as "unfavorable" for strong or violent tornadoes, and modeled storm-scale processes and cell mergers as a possible contributing factor to the tornado.

The purpose of this paper is to examine and document the meteorological setting leading to the Joplin tornado for reference and learning purposes. Several aspects of the 22 May 2011 setting will be investigated. First, the large-scale synoptic setting from surface and upper-air information will be evaluated. Second, local radar evolution of cells prior to the tornado will be reviewed and summarized.

Next, background environmental factors will be examined. These include wind shear, instability, and composite parameters from recent studies and operational experience found to be associated with strong and violent tornadoes, focusing on graphics from Storm Prediction Center (SPC) mesoanalysis products (Bothwell et al. 2002), and local observed and model-derived soundings. Finally, the possible involvement of mesoscale boundaries from surface, radar, and satellite data will be investigated.

Because case studies of single events without reference to other similar or contrasting cases are of limited value, a separate section briefly will examine key parameters from several other tornado events during the period 2008–2015 in the same general area. These events, having similar synoptic settings to the Joplin tornado day, will be used for comparison.

2. Synoptic setting

At midafternoon on 22 May 2011, roughly 1.5 h before the Joplin tornado, thunderstorms were occurring from Wisconsin southward ahead of a primary surface low and Pacific cold front, which extended into a secondary low over southeastern Kansas (Fig. 2), where the front had
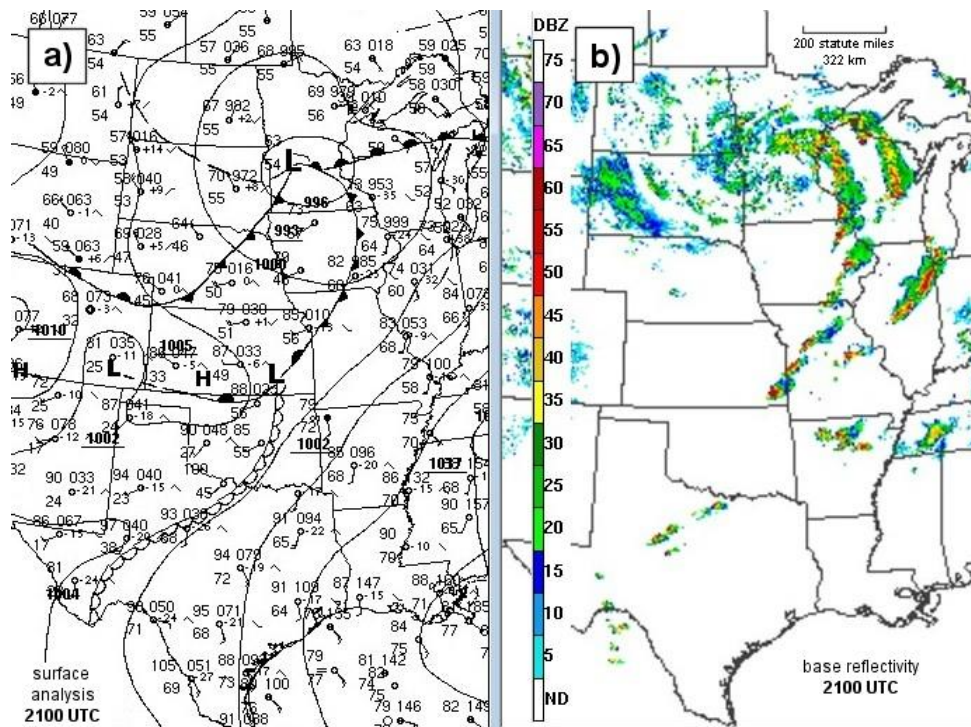

Figure 2: Surface map and radar over central U.S. at 2100 UTC 22 May 2011: a) Surface observations and frontal analysis from National Meteorological Center (NMC), and b) lowest elevation base-reflectivity mosaic from SPC archive. *Click image to enlarge.*

become stationary and a dryline extended southwestward. Thunderstorms were increasing in intensity and coverage along the front at the west edge of the broad warm and moist sector over western Missouri, into southeastern Kansas near the secondary low. Other thunderstorms were occurring within the warm sector over central Illinois into east-central Missouri, and were also scattered over Arkansas.

A closed low was evident at all levels aloft (Fig. 3) over the northern Plains, above the primary surface low in Fig. 2a. An upper trough extended southward from this closed low into eastern Kansas and northern Oklahoma, with substantial divergence (Fig. 3a) located over western Missouri and southeastern Kansas, ahead of the secondary low where storms were continuing to develop.
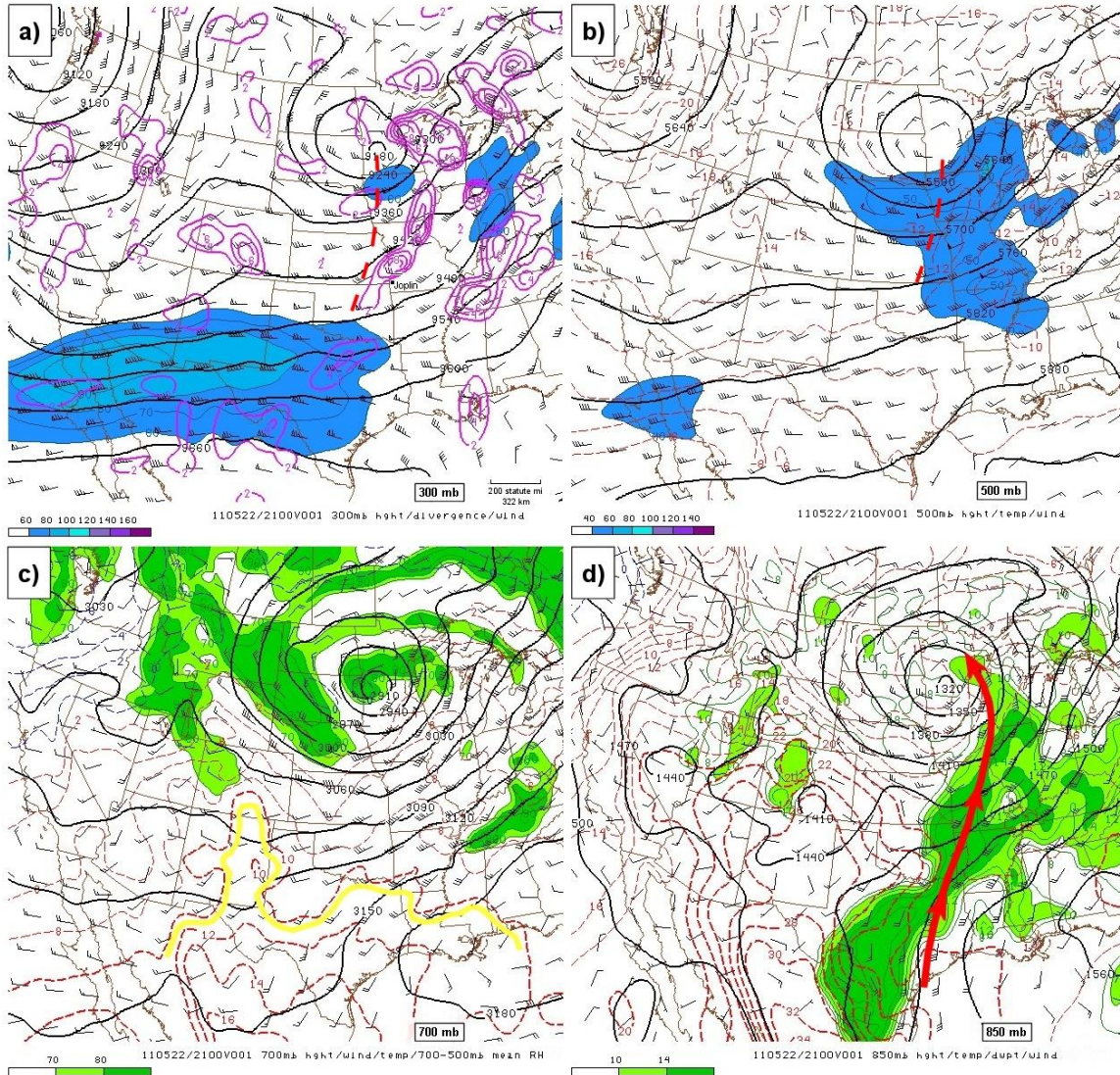

Figure 3: Objective analyses of winds (kt) and geopotential heights (m MSL) over the central and western U.S. at 2100 UTC 22 May 2011 from SPC mesoanalysis: a) 300 hPa; b) 500 hPa; c) 700 hPa; and d) 850 hPa. In a), winds ≥60 kt (31 m s^{-1}) are shaded blue; divergence ≥2 s^{-1} is analyzed in purple. In b), winds ≥40 kt (21 m s^{-1}) are shaded blue. In c), relative humidity ≥70% is shaded green. In d), dew point ≥10°C is shaded green. In b), c), and d), temperature (°C) is analyzed in dashed red. Also, in a) and b), heavy red dashed line indicates trough axis associated with closed upper low; in c), yellow line approximates edge of "cap" or warmest portion of the elevated mixed layer; in d), broad red line with arrows indicates low-level jet stream axis. *Click image to enlarge.*
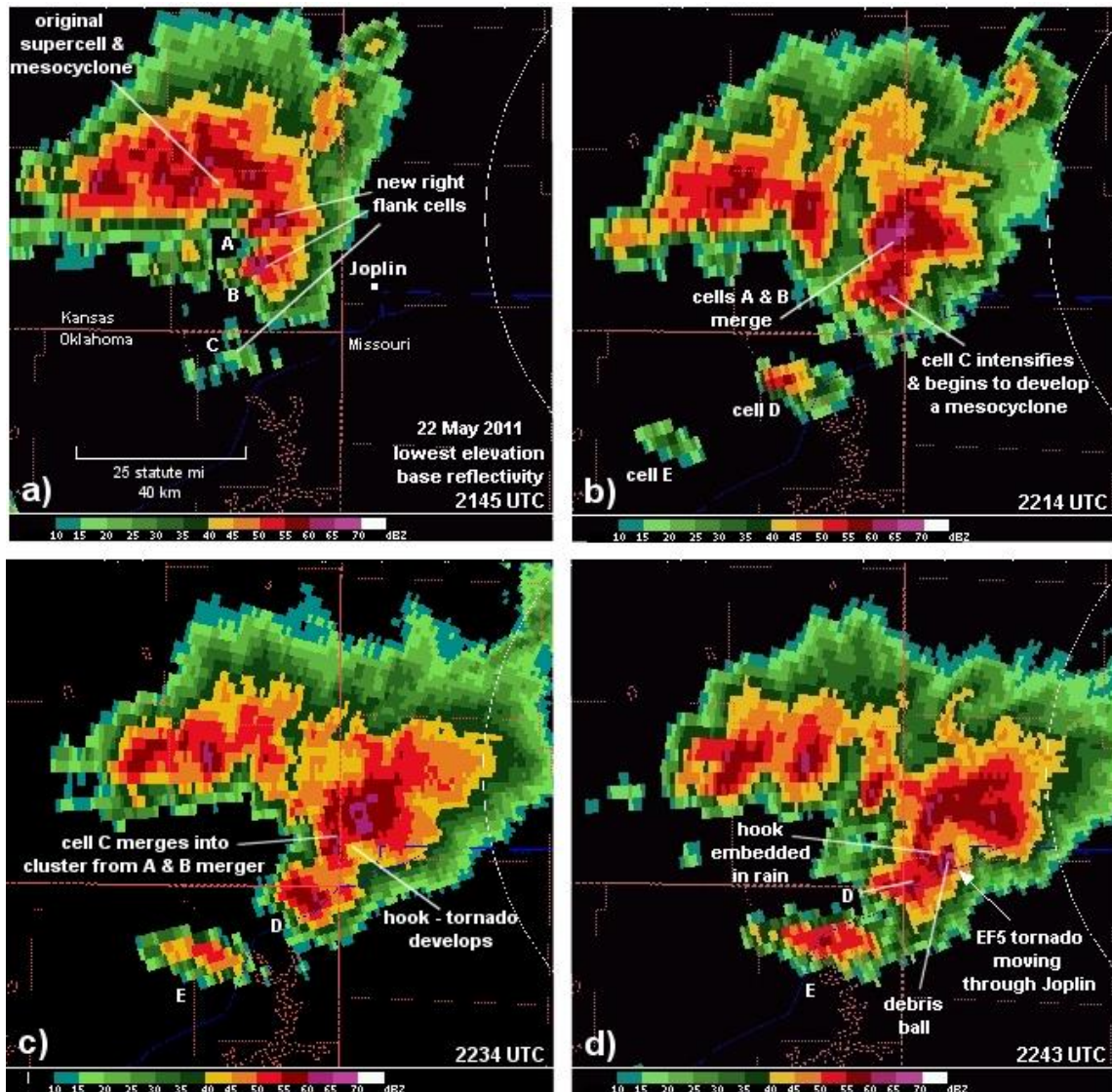
Figure 4: Radar base reflectivity (0.5° elevation angle) over southwestern Missouri, southeastern Kansas, and northeastern Oklahoma, from Springfield, MO WSR-88D on 22 May 2011 at: a) 2145 UTC; b) 2214 UTC; c) 2234 UTC; and d) 2243 UTC. Initial supercell and subsequent cells A, B, C, D, and E are labeled for tracking continuity, along with relevant features. *Click image to enlarge.*

Although the strongest jet stream winds were over the southwestern U.S. (300 hPa, Fig. 3a), the strongest midlevel winds (in excess of 40–50 kt or 21–26 m s^{-1}), were over the central U.S. associated with the 500-hPa trough (Fig. 3b). These midlevel winds extending southward across Missouri and into northeastern Oklahoma appeared more relevant to the Joplin tornadic storm environment than the jet-level wind field higher aloft, and will be discussed further in section 4.

At 700 hPa (Fig. 3c), the warmest temperatures (>10°C) were located over the southern High Plains and much of Texas, indicating that the warmest portion of the elevated mixed layer (EML, Carlson and Ludlum 1968) and associated "capping" was well to the south and west of the Joplin area. A low-level jet stream (e.g., Palmén and Newton 1969) with winds 30–40 kt (15–21 m s^{-1}) was apparent at 850 hPa (Fig. 3d) from eastern Texas to southwestern Missouri and farther north, driving a deep moist layer (850 hPa dew points >16°C) into southwestern Missouri.

Potential for significant tornadoes was clearly anticipated by forecasters on 22 May 2011. Morning severe thunderstorm outlooks at 1300 and 1630 UTC from SPC (not shown) placed southwestern Missouri in a "moderate" risk for severe weather, with at least a 10% probability of a significant tornado within 25 miles (40 km) of Joplin. A tornado watch (not shown) was also issued by SPC at 1830 UTC, covering southwestern Missouri and adjacent areas.

After 2200 UTC, a cluster of thunderstorms east of the secondary low over southeastern Kansas merged together into a large supercell near Joplin in southwestern Missouri, where the deadly tornado developed at 2234 UTC. The following section and Fig. 4 (prior page) will briefly summarize the evolution of these storms from radar.

3. Brief radar overview

As noted in the previous section, afternoon thunderstorms developed southward along the surface cold front into southeastern Kansas near the secondary surface low. A supercell formed between 1900 UTC and 2100 UTC near this low, and a very brief weak (EF0) tornado was reported near Parsons, KS at 2110 UTC (not shown). No other tornadoes materialized from this initial supercell, which can be seen at the upper left center of the 2145 UTC radar reflectivity image in Fig. 4a.

After 2145 UTC, this supercell and its associated mesocyclone began to lose structure and weaken, and three new cells intensified rapidly immediately to the southeast on its right flank (see letters A, B and C in Fig. 4a). The two northernmost new cells (A and B) merged shortly after 2200 UTC, while cell C strengthened and developed a mesocyclone by 2214 UTC near the Missouri-Kansas-Oklahoma border as it approached Joplin from the southwest (see Fig. 4b). This resulted in the issuance of a tornado warning for the full city of Joplin at 2217 UTC.

By 2230 UTC, cell C and its mesocyclone near the west side of Joplin merged into the cluster formed by the prior merger of cells A and B, and the killer tornado formed quickly over southwestern Joplin at 2234 UTC (see Fig. 4c). This "new" supercell from the sequence of mergers during the previous 30 min developed a large hook (Fig. 4d) as the massive EF5 tornado

plowed through Joplin moving from west to east, with a prominent "debris ball" (e.g., Burgess et al. 2002) visible on radar. Van Leer et al. (2012) investigated via numerical simulations the possibility that storm mergers prior to the Joplin tornado may have contributed to its rapid formation and intensity in the local setting.

As mentioned in section 1, the tornado was difficult to see (Fig. 1), owing to shadowing and rain falling into the Joplin supercell from newly formed cells D and E (Figs. 4b–4d) approaching from the southwest, as well as the haziness of the nearly saturated local atmosphere, with both surface temperatures and dew points in the 70s $^{\circ}$F. Even though a tornado warning was issued for Joplin 17 min in advance of the tornado, these viewing problems, as well as a low cloud base and the rapid formation of the tornado on the southwestern side of the city, likely contributed to the very large death toll (NOAA 2011).

4. Storm environment

In recent years, research on environments associated with tornadoes (e.g., Rasmussen and Blanchard 1998; Rasmussen 2003; Thompson et al. 2003; Davies and Fischer 2009; Thompson et al. 2012), along with operational forecasting experience, has shown that factors such as low-level wind shear (e.g., storm-relative helicity, Davies-Jones et al. 1990) combined with buoyant instability (e.g., CAPE, Moncrieff and Miller 1976) are useful in tornado forecasting. These derived fields and other parameters related to severe weather are readily available in real-time via Storm Prediction Center (SPC) mesoanalysis products (Bothwell et al. 2002), and are used here to examine the storm environment preceding the Joplin tornado.

Figure 5 indicates that large mixed-layer (ML) CAPE (>4000 J kg^{-1}) was in place over southeastern Kansas and southwestern Missouri during mid to late afternoon on 22 May 2011 ahead of the evolving storm cluster discussed in the previous section. This, along with an absence of significant convective inhibition (CIN, Colby 1984), was evidence of deep, rich low-level moisture uniformly available within the lowest 1 km to support powerful storm updrafts.

Figure 6 shows that 0–1-km storm-relative helicity (SRH) *increased* during the 2000–2200 UTC time period over southwestern Missouri near Joplin, growing from roughly 150 m^2 s^{-2} to >250 m^2 s^{-2}. This was probably due to backing

surface flow in response to falling surface pressures ahead of the southeastern Kansas surface low and some dynamic strengthening of the low-level jet stream ahead of the midlevel trough.
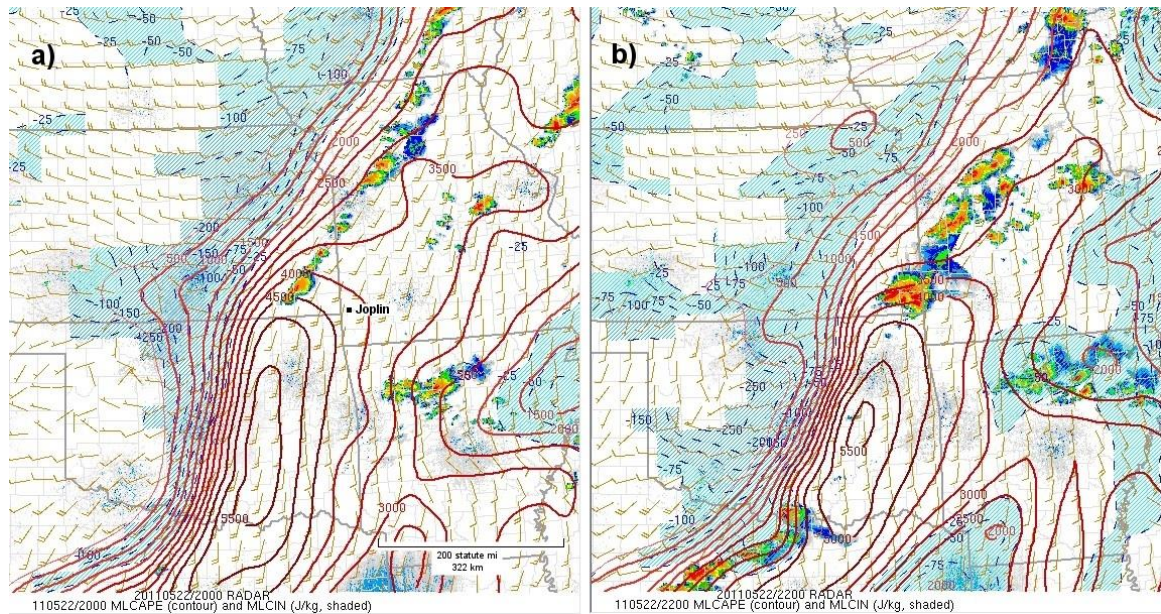
Figure 5: MLCAPE and MLCIN (J kg^{-1}), and radar base reflectivity (as in Fig. 2), from SPC mesoanalysis over Missouri, Kansas, Oklahoma, and Arkansas area on 22 May 2011 at: a) 2000 UTC; and b) 2200 UTC. MLCAPE contours are red; MLCIN >25 J kg^{-1} is shaded blue. Surface wind barbs (kt) are in gold. *Click image to enlarge.*

Figure 6: As in Fig. 5, except 0–1 km SRH (m^2 s^{-2}), contours in blue. Estimated storm motion barbs (kt) after Bunkers et al. (2000) are in gold. *Click image to enlarge.*

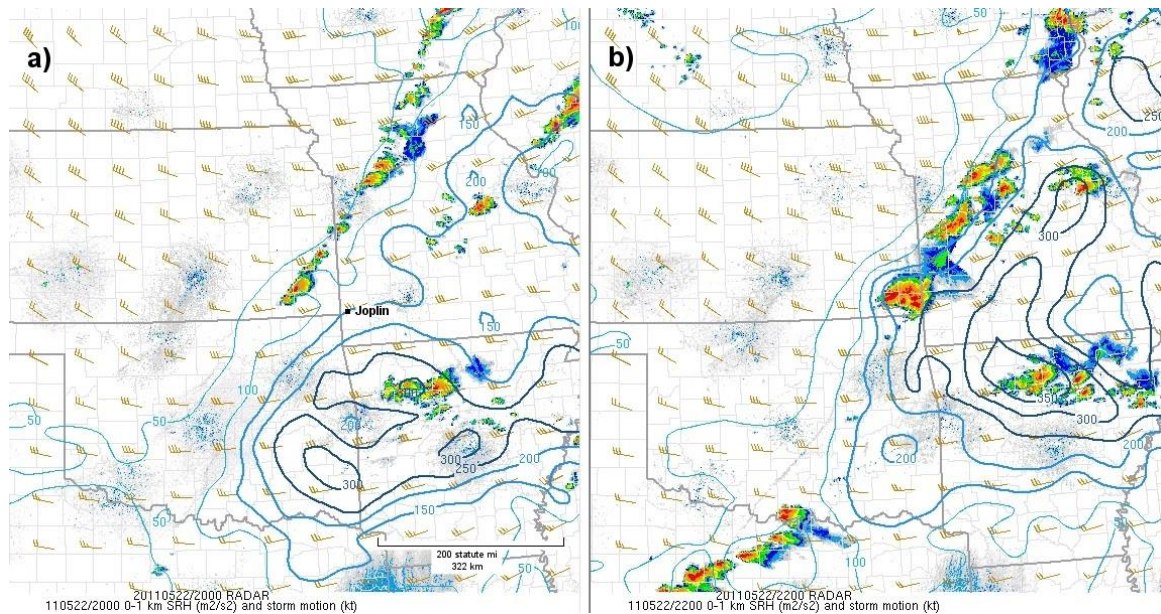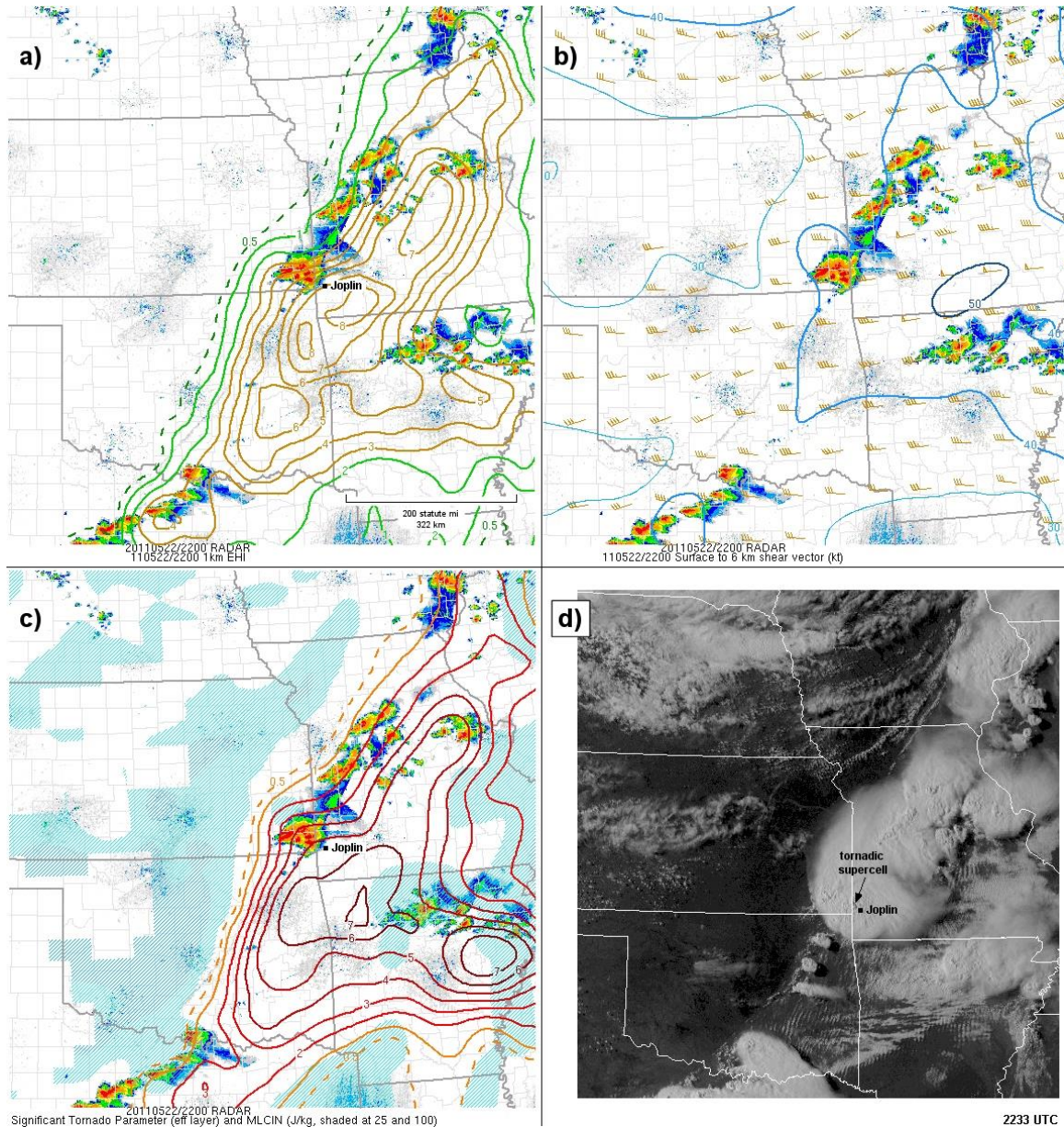Figure 7: As in Figs. 5 and 6, except: a) 0–1 km EHI (dimensionless, green and gold contours); b) 0–6 km bulk wind shear (kt); and c) effective STP (dimensionless, red contours), with MLCIN as in Fig. 5. Visible satellite image at 2233 UTC in d) is for visual reference. Radar in a), b), and c) same as Figs. 5 and 6. *Click image to enlarge.*

Given this significant increase in SRH, the statement by Van Leer et al. (2012) that the Joplin environment was "low shear" and "not favorable for the EF5 tornado" is highly questionable and likely incorrect.

The energy-helicity index (e.g., EHI, Davies 1993) is a simple bulk diagnostic parameter that can suggest where CAPE and SRH together are more favorable for supporting strong storm

rotation and possible tornadoes. Figure 7a shows an EHI maximum over southwestern Missouri at 2200 UTC, with values of 7.0 to 8.0. That is quite large, especially considering that 0–6-km bulk wind shear (Fig. 7b) across the same area was more than enough (>40 kt or 21 m s^{-1}) to support supercell storms.

The effective version of the significant tornado parameter (STP; Thompson et al. 2004)

is a more complex diagnostic indicator that includes SRH, deep-layer shear, and CAPE, based on lifting a range of parcels to indicate whether an environment is surface-based, and to estimate the potential depth of storm inflow through which updrafts can utilize available wind shear (i.e., "effective" SRH and deep-layer wind shear). Despite its added complexity, Fig. 7c shows a very similar pattern to that of EHI, with values of 5.0 to 6.0 over southwestern Missouri and northwestern Arkansas.

A Rapid Update Cycle (RUC) model sounding for Joplin at 2200 UTC (Fig. 8), 30 min before the tornado, illustrated the deep moist layer and very unstable environment over southwestern Missouri, with both ML and surface-based (SB) lifted parcels resulting in large CAPE values above 4000 J kg^{-1}. An EML also was evident, with a much drier layer of air (from 820 to 630 hPa) above the moist boundary layer, and a slight temperature inversion between 820 and 780 hPa, but no significant "capping."

Regarding the wind profile in Fig. 8, the hodograph curled back toward the center of the grid in upper levels due to weaker winds above

9 km AGL, instead of extending outward or rightward as in more "classical" wind environments associated with violent tornadoes, such as the 27 April 2011 "Dixie super outbreak" (not shown). However, the environment was still significantly sheared in low levels and through a deeper layer, with 0–1-km SRH >200 m^2 s^{-2}, and 0–6-km bulk wind shear of 45 kt (23 m s^{-1}). The weaker winds above 500 hPa over southwestern Missouri (see also Fig. 3a in section 2) probably helped contribute to the "high precipitation" nature of the tornadic storm (Rasmussen and Straka 1998) and resulting visibility problems. This sounding also suggests that winds near and above 300 hPa (roughly 9 km MSL) do not need to be especially strong to support violent tornadoes, if wind speeds and shear characteristics are stronger and appear more favorable through levels below.

The closest observed sounding in time and space was at Springfield, MO at 0000 UTC 23 May 2011 (Fig. 9), released 20–40 min after the Joplin tornado and located 35–40 mi (56–64 km) east-northeast of the tornadic supercell. This profile confirmed the highly unstable environment (roughly 4000 J kg^{-1} MLCAPE
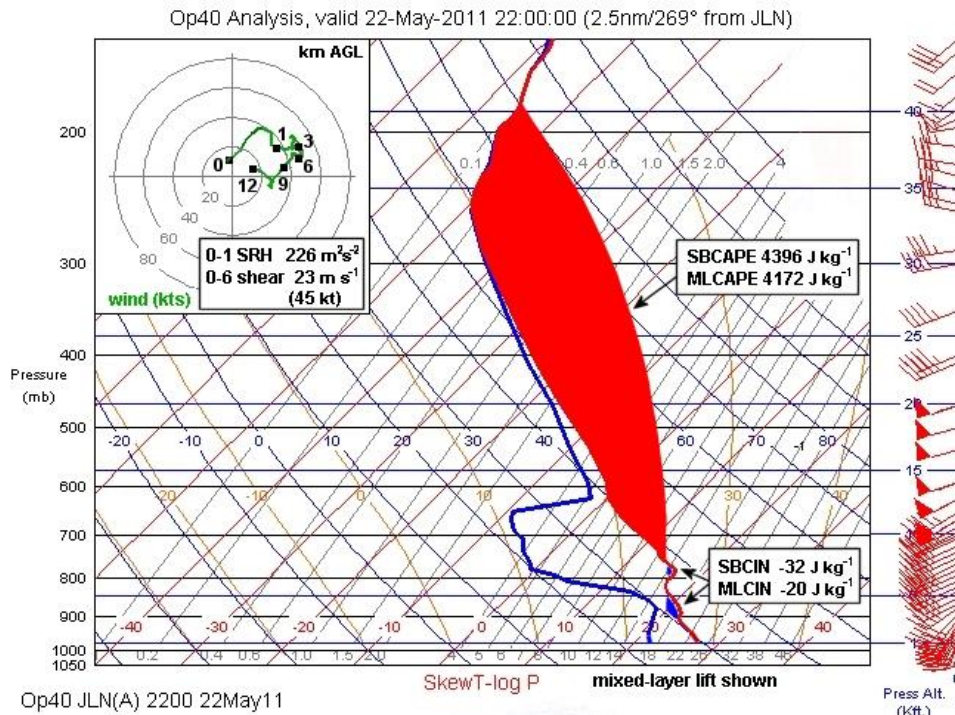

Figure 8: RUC analysis sounding (skew *T*–log*p* diagram) and hodograph for Joplin, MO at 2200 UTC 22 May 2011. Lowest 100 hPa mixed-layer lift is shown; MLCAPE is red shading; MLCIN is blue shading. The virtual temperature correction (Doswell and Rasmussen 1994) was used for all thermodynamic computations, but is not shown for viewing simplicity. *Click image to enlarge.*

Figure 9: As in Fig. 8, except observed radiosonde sounding and hodograph for Springfield, MO at 0000 UTC 23 May 2011. *Click image to enlarge.*

and SBCAPE) and the sizable bulk shear through 6 km (45 kt or 23 m s^{-1}), although the 0–1-km SRH was somewhat less (around 175 m^2 s^{-2}). The upper portion of the hodograph was also more complicated than the earlier Joplin model-derived sounding, with several "zig-zags" and segments doubling back on themselves, but it is possible that the ongoing tall supercell complex located southwest of the sounding site was affecting the upper wind flow downwind. Regardless, allowing for positioning and timing, both soundings (model and observed) showed significant combinations of CAPE and wind shear, again contradicting the description of the local environment as "unfavorable" by Van Leer et al. (2012).

So, from the above guideline parameters via the SPC mesoanalysis and local model and observed soundings, strong support for tornadoes was indicated, if discrete or semi-discrete supercells formed over southwestern Missouri. Even though the Joplin supercell developed from a merger of several storms (section 3) and was part of a cluster of storms (not a discrete supercell), the large supercell itself likely had unimpeded inflow from the favorable environment to its southeast, being located at the southeast end of the storm cluster (see Figs. 4c and 4d from section 3).

5. Mesoscale boundaries

Mesoscale boundaries are an additional factor that can affect tornado development (e.g., Rasmussen et al. 2000; Markowski et al. 1998a,b) through local enhancement of horizontal vorticity for supercells located on or near such a boundary. This is particularly true if nearby environmental characteristics already appear favorable for supporting tornadoes.

As noted in section 2, at early afternoon on 22 May 2011, storms were developing in central Illinois into east central Missouri. A careful examination of radar, satellite and surface data from 1700 to 2000 UTC suggests that this development marked the remnants of an outflow boundary and convergence zone, probably originating from overnight convection hours earlier.

Figure 10a shows a cloud arc oriented east-northeast to west-southwest over central Missouri at 1745 UTC. Later, scattered convection was forming along this feature at 1932 UTC (Fig. 10b), well east of the storms developing near the cold front from north-central Missouri into southeastern Kansas. The
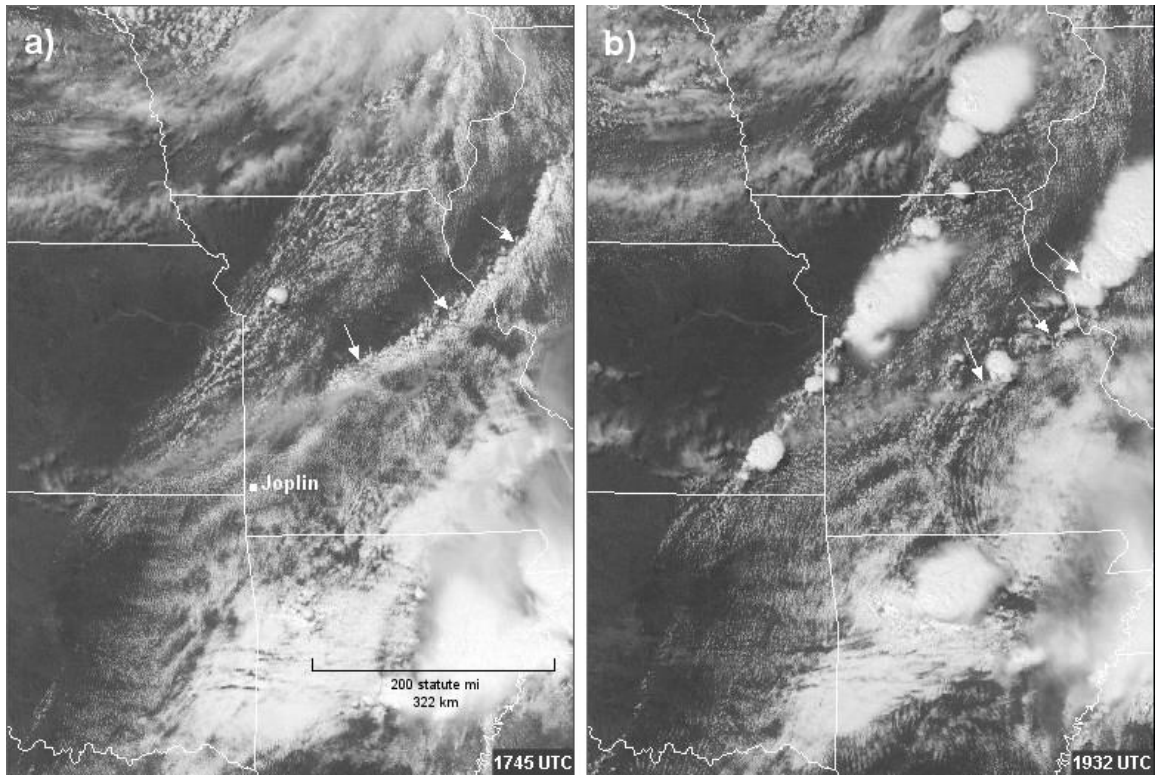
Figure 10: Visible satellite images over Missouri, Kansas, Oklahoma, and Arkansas area at early to midafternoon on 22 May 2011: a) 1745 UTC; and b) 1932 UTC. White arrows indicate mesoscale boundary over Missouri and Illinois as described in text. *Click images above and below to enlarge.*
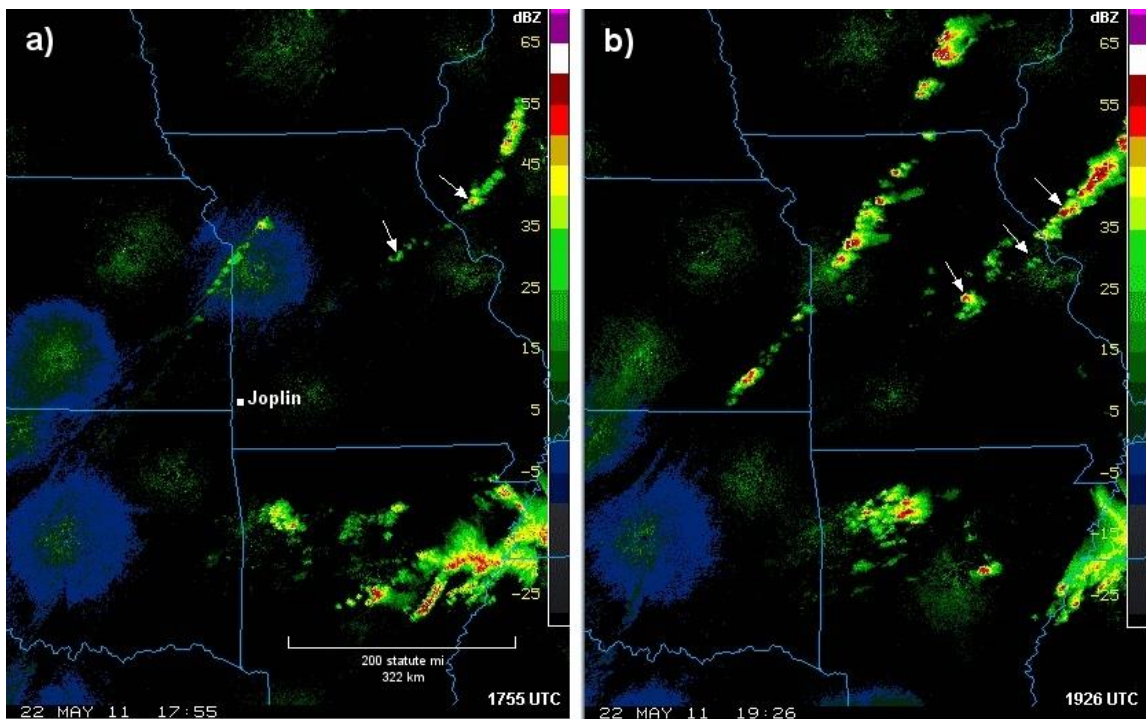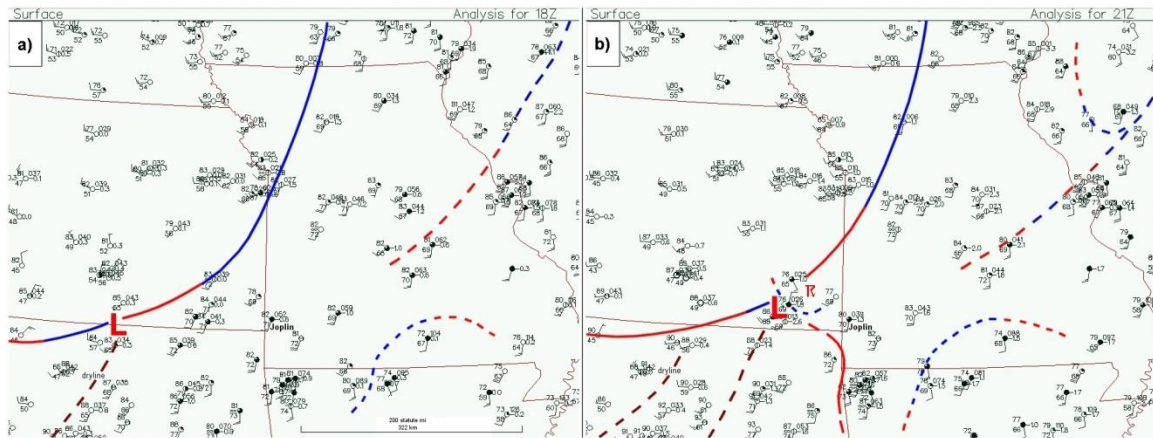
Figure 11: Composite radar reflectivity images for same area as in Fig. 10 on 22 May 2011: a) 1755 UTC; and b) 1926 UTC. White arrows indicate mesoscale boundary over Missouri and Illinois discussed in text.

Figure 12: Standard surface map plots (°F) with mesoscale analysis of surface fronts and boundaries over Missouri-Kansas area on 22 May 2011: a) 1800 UTC; and b) 2100 UTC. Long-dashed red-blue line over Missouri and Illinois is remnant boundary discussed in text; short-dashed red-blue lines are recent outflow. *Click on image to enlarge.*

boundary also could be seen in composite radar images at 1755 UTC through 1926 UTC (Fig. 11), where storms developed from central Illinois into central Missouri along an east-northeast to west-southwest axis.

On surface analyses, the boundary was also visible from early into midafternoon, shown in Fig. 12 as a dashed red-blue line over Illinois into Missouri. In these images, it appears as a weak wind shift from south or south-southwest to west-southwest surface winds, but with little difference in temperature and dew point across it, making the boundary difficult to locate over southwestern Missouri.

For this reason, apart from several east-northeast to west-southwest cloud "ridges" visible on satellite in Fig. 10b, it is not clear whether the boundary extended southwestward to near the Joplin area. The F5 Hesston, KS tornado case examined by Davies et al. (1994) involved an outflow boundary suggested by satellite data that was difficult to detect in surface map observations. Perhaps the boundary did extend into the Joplin area to provide some degree of local horizontal vorticity augmentation, but that cannot be confirmed from the available data, and is discussed here only as a possible contributing factor to tornado development.

Another mesoscale feature of note was a subtle localized "warm front" that appeared in surface data around 2100 UTC southwest of Joplin (Fig. 12b, red line), possibly induced by anvil shadowing from the storms over southeastern

Kansas. The resulting temperature gradient and baroclinity (Markowski et al. 1998b) near this feature may have enhanced local horizontal vorticity in the Joplin area, an additional potential contributing factor to the tornado.

One last mesoscale issue to discuss briefly was the scattered storms that were occurring over Arkansas during the afternoon, visible in Figs. 10 and 11: did these have any effect on the environment over southwestern Missouri that day? After examining loops of radar, satellite, and surface data from the morning hours onward (not shown), these storms seemed to have no direct influence on the day's events near Joplin, as outflow generated was not strong enough to spread northwestward into the Joplin area, a result of generally small temperature-dew point spreads (≤ 10°F) over central and northwestern Arkansas. Also, a moderate to strong low-level jet stream remained in place over eastern Oklahoma into southwestern Missouri, contributing to ongoing advection and maintenance of deep moisture along an axis west and northwest of the Arkansas storms (Fig. 5).

6. Comparative cases

As mentioned in section 1, isolated case investigations without comparison to events in similar settings are of limited value for study. This section will look briefly at several other tornado settings in the same general area for comparison to the Joplin tornado day on 22 May 2011.

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Weather maps for April, May and the first half of June during the period 2008–2015 were surveyed to find spring days with a similar surface pattern to the Joplin tornado day, and where one or more tornadoes were reported during the time frame 1800 UTC to 0400 UTC (encompassing afternoon heating and through midevening) in the area of Kansas, Missouri, Oklahoma, and Arkansas indicated in Fig. 13. The tornado days were limited to surface patterns where a primary low or warm front–cold front intersection point was located over the northern Plains or upper Midwest, along with a cold front trailing into a secondary low or "triple point" located within the Kansas, Missouri, Oklahoma, or Arkansas area where tornadoes were reported, shown in Fig. 13. In other words, spring tornado days were selected that qualitatively matched the general synoptic setting seen in Fig. 2 from section 2.

Applying these limiting criteria, 14 spring tornado days were found, listed in Table 1 along with the Joplin tornado day. In addition to the strongest tornado with the longest track and the number of tornadoes occurring that day within the designated area in Fig. 13, selected environmental parameter values are shown from archived SPC mesoanalysis maps near the time and location of the strongest tornado.
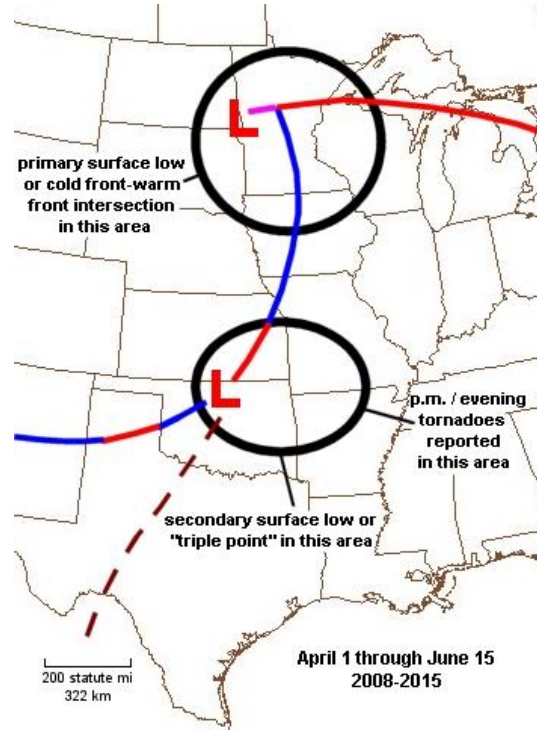

Figure 13: Composite schematic showing general surface synoptic pattern over central U.S. and areal delineations used to select spring tornado comparison cases in Tables 1 and 2.

Table 1: Tornado days April 1–June 15 2008–2015 with synoptic settings as described in text, similar to the 22 May 2011 Joplin tornado day (highlighted); selected parameter values near the time and location of strongest tornado, from SPC mesoanalysis, are shown.

Date	No. of TORs	Strongest Tornado & Path Length		Deaths	EHI	Effective STP	MLCAPE ($J\ kg^{-1}$)	0–1 km SRH ($m^2\ s^2$)	0–6 km Bulk shear	
									kt	($m\ s^{-1}$)
1 May 2008	10	EF1	17 mi	none	3.3	~ 3.0	3000	175	50	26
13 May 2008	1	EF0	0.1 mi	none	0.9	~ 1.0	1200	125	50	26
6 June 2008	5	EF0	0.1 mi	none	3.0	~ 2.0	2700	175	30	15
12 June 2008	6	EF0	3.5 mi	none	1.9	~ 2.0	3000	100	60	31
30 April 2010	7	EF3	20 mi	1	3.8	~ 4.0	2000	300	60	31
8 June 2010	5	EF0	2 mi	none	2.3	~ 2.0	3000	125	35	18
10 April 2011	1	EF0	6 mi	none	0.6	~ 0.5	500	200	60	31
21 May 2011	9	EF3	10 mi	1	3.8	~ 3.0	2000	300	40	21
22 May 2011	16	**EF5**	22 mi	**158**	6.3	~ 6.0	4000	250	45	23
15 April 2012	1	EF1	2 mi	none	1.6	~ 2.0	1000	250	60	31
6 May 2012	4	EF0	0.2 mi	none	0.8	~ 0.5	3000	40	25	13
20 May 2013	20	**EF5**	14mi	**24**	3.3	~ 3.0	3500	150	55	28
31 May 2013	14	**EF3-5**	16 mi	**8**	3.5	~ 6.0	4500	125	55	28
8 May 2014	3	EF1	2.5 mi	none	0.9	~ 0.5	600	250	40	21
10 May 2015	2	EF2	15 mi	none	2.3	~ 2.0	1500	250	50	26

Table 2: Mean parameter values for tornado days from Table 1, grouped as described in text and column 1.

From Table 1 Case Groupings	Deaths	Mean EHI	Mean Effective STP	Mean MLCAPE (J kg^{-1})	Mean 0-1-km SRH (m^2 s^2)	Mean 0-6-km Bulk Shear kt (m s^{-1})	
At least 1 tornado ≥ EF1 and track ≥ 10 mi (7 cases)	192	3.8	3.7	2930	220	48	25
All tornadoes EF0—EF1 and track < 10 mi (8 cases)	none	1.5	1.3	1875	160	51	26

In Table 1, EHI and STP values were largest for the days with higher-rated tornadoes and longer tornado tracks. This can be seen more clearly via an additional table (Table 2) that splits the 15 cases in Table 1 into two groups: one group (7 cases) where the highest-rated tornado was at least EF1 and the track >10 mi (16 km) long, and another 8 cases where the tornadoes were all weak (EF0–EF1) with tracks <10 mi. Emphatically, the mean EHI and STP values in Table 2 were more than twice as large for the higher-rated, longer-track tornado days. Indeed, referring back to Table 1, the Joplin tornado day had the *largest* EHI and STP values of all cases.

It is also interesting to observe in Tables 1 and 2 that five of the seven higher-rated, longer-track tornado days resulted in deaths. In fact, three of these days involved EF5 tornadoes (the 31 May 2013 El Reno tornado, though officially rated EF3 from damage alone, could well have been EF5 based on nearby mobile-radar observations, e.g., as discussed in Marshall et al. 2014). This simply confirms that surface patterns similar to that shown in Fig. 13, when accompanied by strong combinations of CAPE, low-level wind shear, and deep layer shear, can be prominent and deadly tornado producers.

7. Discussion

As seen in the prior section, the deadly Joplin tornado on 22 May 2011 was associated with strong background environmental characteristics and a surface pattern that has produced several strong and violent tornadoes in recent years over
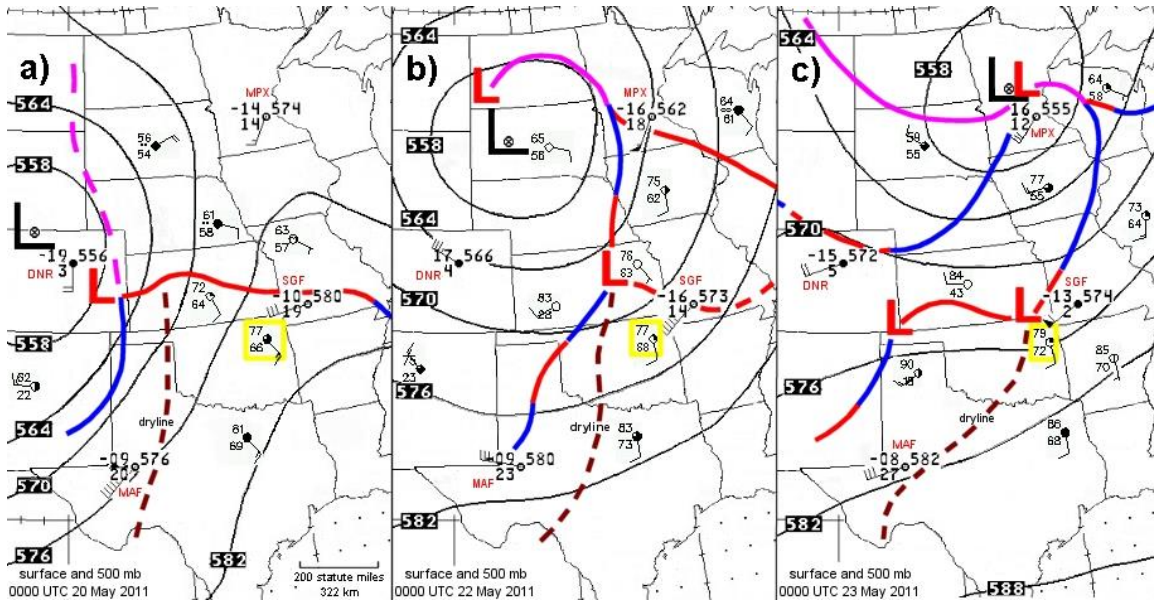

Figure 14: Surface fronts (conventional, in color) and 500-hPa contours (black lines, decameters MSL) from observed NMC analyses at: a) 0000 UTC 20 May 2011; b) 0000 UTC 22 May 2011; and c) 0000 UTC 23 May 2011. 500-hPa observations (conventional, °C) are shown at Springfield, MO (SGF), Minneapolis, MN (MPX), Denver, CO (DNR), and Midland, TX (MAF), along with selected surface observations (°F). Surface observations in northeastern Oklahoma, southwest of Joplin, MO, are in yellow box. *Click image to enlarge.*

the central Plains, including three EF5 tornadoes. Figure 14 shows the evolving surface and upper-air synoptic-scale features in the days prior to the Joplin tornado that resulted in these very favorable environmental ingredients (Fig. 15).

In Fig. 14, the midlevel low and corresponding upper trough (section 2) moved slowly northeastward from Colorado and Wyoming to Minnesota. Because of the slow upper progression and movement to the northeast (instead of east or southeast), the surface cold front associated with the upper system was also slow to move into the central Plains, allowing low-level moisture on southerly flow from the Gulf of Mexico to spread and deepen northward as a warm front surged from Kansas to Wisconsin. With at least three days of continuous, moist low-level flow ahead of the slow upper system, dew points upwind of the Joplin area over northeastern Oklahoma (see yellow square in Figs. 14a, 14b, and 14c) rose from the mid 60s °F (upper teens °C) to the low 70s °F (lower 20s °C), contributing to increased buoyancy (section 4) by the afternoon and evening of 22 May 2011. During the same period, observed 500-hPa southwesterly flow with the slow approach of the upper trough increased from 30 kt (15 m s^{-1}) to near 60 kt

(31 m s^{-1}) at Springfield in southwestern Missouri (SGF in Figs. 14a, 14b, and 14c), setting up a significantly sheared wind environment (also section 4) to combine with increasingly large CAPE.

Unsurprisingly, the other two EF5 tornadoes in Table 1 from the prior section (the 20 May 2013 Moore, OK and 31 May 2013 El Reno, OK tornadoes) were associated with similarly slow-moving upper systems (not shown). In both those cases, 500-hPa lows and their accompanying troughs moved northeastward from Wyoming to the eastern Dakotas or Minnesota, allowing low-level moisture to flow northward and deepen over the southern and central Plains for several days, while midlevel flow and resulting wind shear increased with the unhurried approach of the driving upper systems.

In all these cases, because the primary "push" of the upper systems was northeastward during a protracted period, the associated surface cold fronts trailed back to the southwest from a primary low over the northern Plains to a secondary low or dryline–cold front triple point over Kansas or Oklahoma, similar to the pattern of surface fronts and lows discussed in sections 2 and 6 (refer back to Fig. 2 and Fig. 13). This
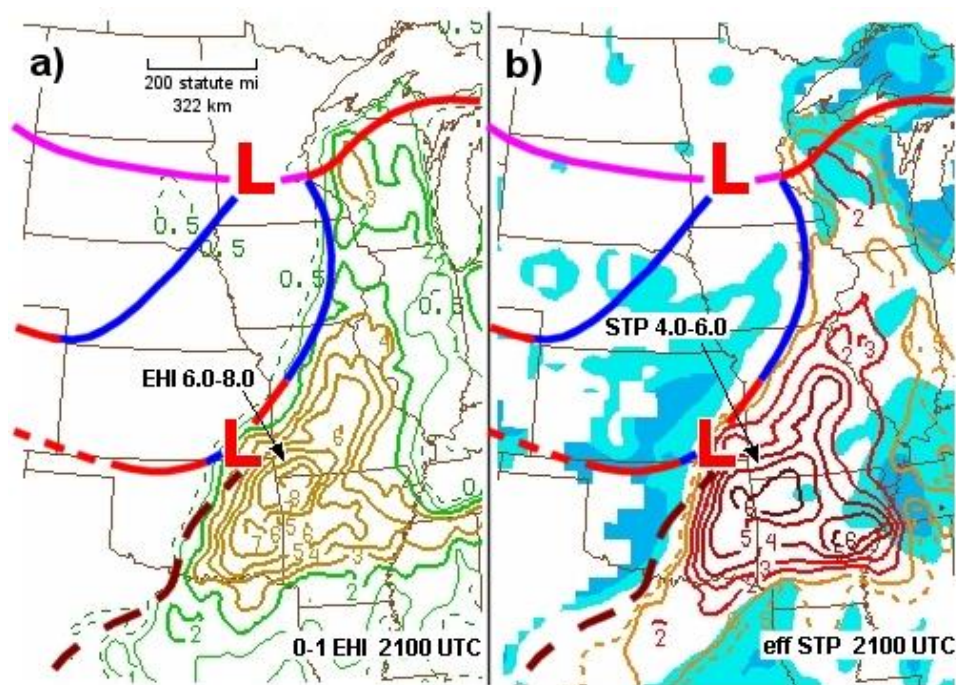

Figure 15: Composite parameters, and surface fronts and lows (as in Fig. 2), over central U.S. at mid-afternoon (2100 UTC) on 22 May 2011: a) 0–1 km EHI (as in Fig. 7a); and b) effective STP (as in Fig. 7c).

southern "hang back" section of the trailing fronts then became a location for significant severe weather and tornadoes due to the deep, moist boundary layer in place and increasing flow aloft near the base of the upper troughs when storms initiated near the secondary surface low or triple point.

This type of surface and upper-air evolution can result in robust background environmental ingredients, as on the Joplin tornado day (Fig. 15), and appears to offer favorable ingredients for strong or violent tornadoes, *if* the atmosphere is not "capped" and thunderstorms do initiate near or east of the secondary low. At midafternoon on 22 May 2011, the resulting large areal maximum of diagnostic[1] EHI and STP values (4.0–8.0 or more, see Fig. 15) coincided well with the location of the southeastern Kansas surface low (e.g., Moller 1980) during afternoon heating. This combination of ingredients (Doswell et al. 1996) and synoptic pattern suggested strong support and potential for significant tornadoes with any persistent supercell storms that might form in that area.

Based on the storm-environment properties examined in section 4, the characterization of the Joplin tornado environment by Van Leer et al. (2012) as "low shear" and "unfavorable" for violent tornadoes is erroneous and inaccurate. Although winds above midlevels near 300-hPa were not particularly strong in the Joplin case, deep-layer wind shear through midlevels was quite supportive of organized supercell storms, and low-level shear was moderate to strong. In fact, when both wind shear and CAPE are considered, the Joplin environment appeared very favorable for supporting tornadic supercells, and exhibited the largest EHI and STP values of all the comparison cases examined in section 6.

Possible additional factors (section 5) that may have contributed to the tornado were a mesoscale boundary over central Illinois into central Missouri that may have extended southwestward near the Joplin area, and a localized warm front that formed at midafternoon southwest of Joplin. These both

could have provided local low-level enhancement of horizontal vorticity for the tornadic supercell, although that is not directly confirmable from conventional data.

In conclusion, when key background environmental ingredients (as in Fig. 15) result from a relatively slow evolution of surface and upper-air features (similar to Fig. 14), meteorologists should be *very alert*. The resulting extended increase in low-level moisture and buoyancy, along with enhanced low-level and deep-layer wind shear, can signal increased potential for strong or violent tornadoes. The deadly Joplin tornado case is a prime example.

ACKNOWLEDGMENTS

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[1] This acknowledges the many caveats regarding use of diagnostic parameters cautioned by Doswell and Schultz (2006) in the forecast process.

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REVIEWER COMMENTS

[Authors' responses in *blue italics.*]

**REVIEWER A (Corey M. Mead):**

Initial Review:

Recommendation: Accept with minor revisions.

General comments: This study documents the synoptic and mesoscale environment associated with the 22 May 2011 Joplin, MO tornado event; something that has yet to appear in formal literature. The author acknowledges that a single case study without reference to similar or contrasting cases is of limited value. As such, key environmental parameters from the Joplin event are compared to other tornado-producing events which matched the same general surface pattern within the same geographic region.

Aside from documenting the event, an apparent motivation for this work is an informal study which characterized the Joplin environment as "unfavorable" for strong or violent tornadoes. The author successfully demonstrates that the CAPE-shear parameter space is more than sufficient for significant tornado occurrence.

The manuscript is well structured, and both scientifically and technically sound. I recommend acceptance with minor revision.

Substantive comments: Section five focuses on the presence of a mesoscale boundary which is suggested to have enhanced tornado potential as the Joplin storm interacted with it. I have closely inspected radar, satellite and surface observational data and admittedly struggle to see evidence of the boundary over southwest Missouri, as shown in Fig. 12. Certainly, from central Missouri into west-central Illinois, there is a clear demarcation of the boundary in the surface mass field and storms eventually form along it. However, over southwest Missouri, the only signal in the data is a concentrated band of clouds which becomes more obscure by about 1900 UTC. I have attached a series of annotated surface maps [below], derived from the METAR data and visible satellite.
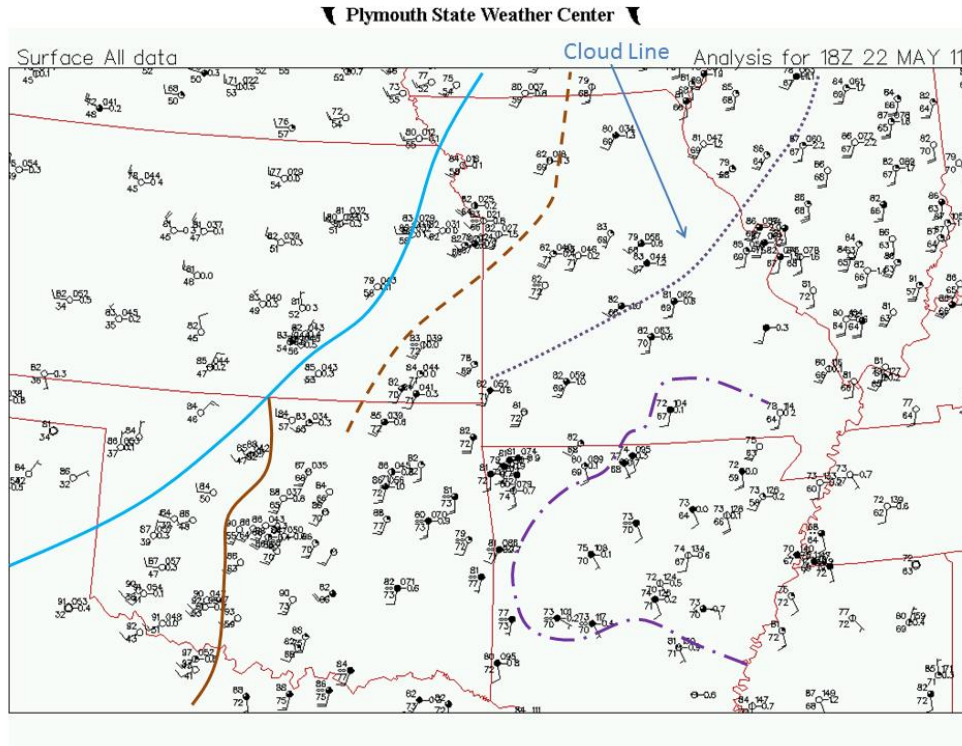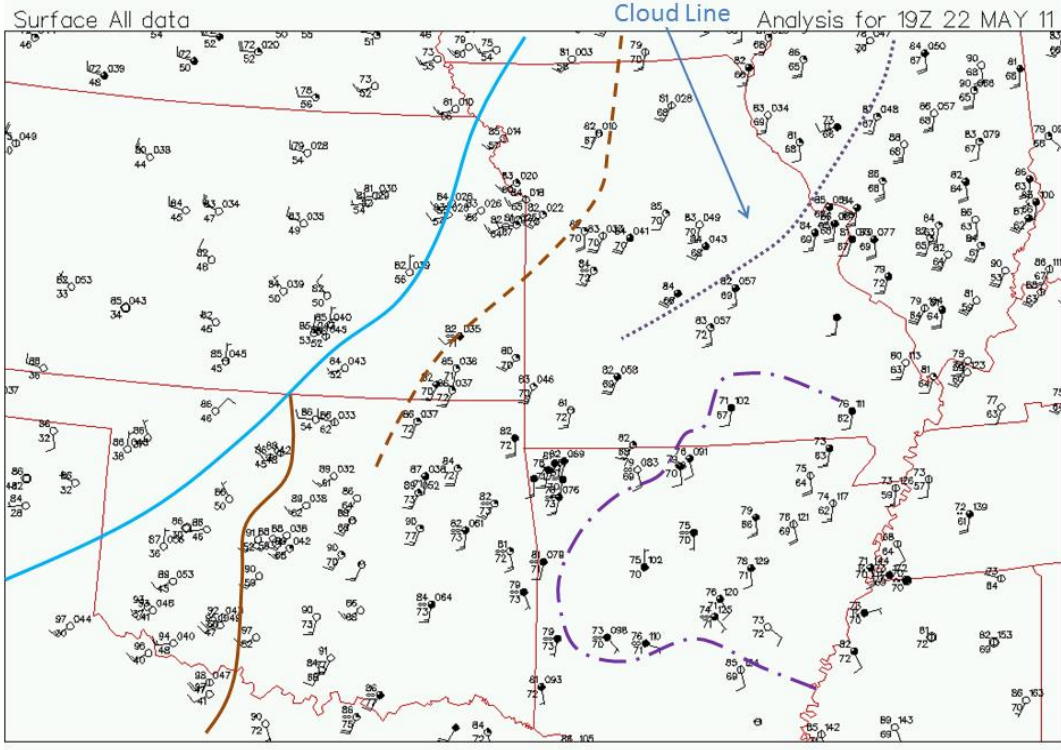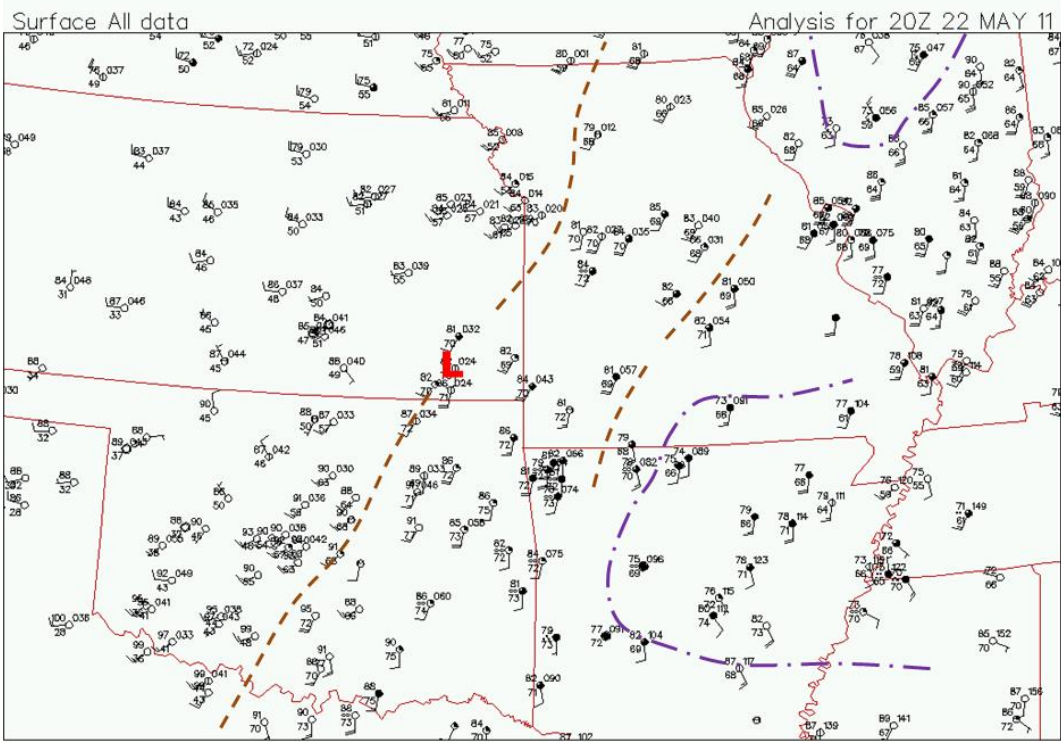
The influence of the secondary low on the local wind field is apparent during the mid to late afternoon. Over southwest Missouri, gusty southwest winds steadily weaken and back to south-southeast in the 2000–2200 UTC time frame. By 2100–2200 UTC, a subtle warm front—perhaps arising from anvil shadowing—becomes better defined from the low over southeast Kansas into extreme northeast Oklahoma. Based on the surface observations, I would be more inclined to think that the low-level wind response (and resulting increase in near-ground shear as depicted in Fig. 6) is more a function of the deepening surface low to the west than the presence of a boundary as suggested in Fig. 12.

Because Corey issued the tornado watch covering Joplin four hours prior to the tornado, his review and comments are valuable and very helpful. As a result, I have revised discussion of the boundary in section 5 to downplay its potential role. This feature is definitely difficult to find in the surface data over southwest Missouri during the afternoon, and Reviewer C (Daniel Reilly) also makes the same point.

I do feel it is important to discuss this pre-existing boundary and its possible involvement in this case because it shows up so well in satellite and radar data into central Missouri from late morning into early afternoon, and I have seen several cases where boundaries (including Hesston in 1990) were visible on satellite and/or radar data, but were hard to find in the surface data. It is also interesting how the surface wind direction observations at Pittsburg KS (north-northwest of Joplin) remain southwesterly from 1800–2100 UTC ahead of the southeast Kansas outflow, while Joplin's wind direction backs during the same period, becoming south-southeast by 2200 UTC (as Corey pointed out). These wind direction differences between two sites that are <30 mi apart make me wonder if that's a westward reflection of the boundary. But I do agree that is impossible to confirm. I have accordingly adjusted Fig. 12 (surface analyses) to show the boundary extending from Illinois only into central Missouri, and have left its extension trailing into southwest Missouri an open question.

I also agree with Corey's opinion that the backing of surface winds at Joplin was largely in response to falling pressure with the southeast Kansas low. I've made that point in the text in section 4, when discussing Fig. 6 and the increasing SRH. Corey also mentions the appearance of a subtle warm front in the surface data during 2100 UTC to 2200 UTC over far northeast Oklahoma. I have added that feature to Fig. 12b (along with some outflow features from the surface analyses Corey included with his review—they were very helpful and much appreciated). I have also added brief discussion of this local warm front and its possible anvil shadowing origin in section 5 of the text.

In a number of places, 500-hPa winds are used as a proxy for determining whether the environment was supportive of organized storm modes. Perhaps a better option would be to use bulk-shear magnitude (either 0-6 km or effective bulk shear) which has been shown to successfully discriminate between disorganized and organized storms.

This is an excellent point, and belies some carelessness on my part. Reviewer B (Chuck Doswell) also emphasized this in his review. To address this, I've added a SPC graphic of 0–6-km bulk shear as Fig. 7b, and revised Tables 1 and 2 to show 0–6- km bulk-shear magnitude instead of 500-hPa wind. I've also made appropriate changes in the text (section 4).

[Minor comments omitted…]

Second Review:

Recommendation: Accept with minor revisions.

General Comments: The author has sufficiently addressed my previous substantive concerns, so I recommend acceptance with minor technical revision.

[Minor comments omitted…]

REVIEWER B (Charles A. Doswell III):

Initial Review:

Recommendation: Accept with minor revisions.

Substantive Comments:

Section 2: I have a problem with a surface analysis that has no observed data on it, and includes no isotherms and isodrosotherms. The reader is forced to accept the analysis without any means of ascertaining its validity. This is, of course, the "industry standard—a typical presentation—but I find it unacceptable in a scientific paper. This figure needs to be changed either to show an analysis of the temperature and dewpoint or modified to include surface observations.

I have reworked Fig. 2 to show both the NMC surface analysis with selected surface observations, and the SPC radar mosaic over the central U.S.

Do you mean a low-level jet stream or a nocturnal boundary-layer wind maximum? The term "low-level jet" is ambiguous. Looks to be the low-level jet stream and it's the wrong time of day for the nocturnal boundary-layer wind maximum.

This was an oversight. I've changed this to "low-level jet stream" for clarity, and changed the reference to Palmén and Newton (1969), to avoid confusion with the nocturnal low-level jet.

Section 3: Fig. 4 shows no direct evidence for a mesocyclone.

This is not a radar study, and I'm not using Fig. 4 as "evidence" for certain features. I'm simply doing a brief radar overview to summarize the evolution of storms (no velocity images) prior to the Joplin tornado. This provides some context for later sections of the paper through locating and labelling some key features. I have added in the text that a tornado warning was issued for the full city of Joplin at 2217 UTC, based on the mesocyclone detected on radar with cell C (as labelled in Fig. 4b at 2214 UTC), which is certainly evidence for the existence of that mesocyclone.

If Van Leer et al. could not conclude that storm mergers were a factor in the Joplin storm, then this either needs to be modified to say that, or this point shouldn't be made, since there seems to be no conclusive evidence for it. If it's speculation, what value does it offer?

I've changed this to simply state that the study was done, and dropped the portion about it being "speculative."

Section 4: Is 500 hPa flow >40 kt an "ingredient" for supercells? I don't think so.

Reviewer A (Corey Mead) also pointed this out, which is sloppy writing on my part. I've changed this to 0–6-km shear in the text, and also added Fig. 7b. Tables 1 and 2 have also been changed to show 0–6-km shear magnitude instead of 500-hPa wind.

Section 5: More troublesome jargon with no clear meaning. Just how does this "interaction" contribute to the rapid formation and intensification?

I've rewritten much of section 5 to downplay the role of the boundary (see comments from Reviewer A-Corey Mead, and Reviewer C-Daniel Reilly), and in doing so, have eliminated some imprecise wording. I've also attempted to clarify specifically that the boundary (and also the localized warm front mentioned by Reviewer A) may have provided enhanced horizontal vorticity contributing to tornado development. The Rasmussen and Markowski references in this section support this.

Section 6: Is this some sort of startling revelation? Sure doesn't seem that way to me, from an ingredient-based viewpoint.

It's not a startling revelation, and this point is well taken. I do think it is important to note that the Joplin tornado environment had the largest EHI and STP magnitudes of all the cases in Table 1. But I have changed the wording to read that the information in this section "simply confirms" that a strong background environment (ingredients), combined with this synoptic pattern, can be a prominent tornado producer, to get away from any impression that this is a "revelation."

Section 7: The author has made a case for recognition of the threat associated with a particular pattern. As might be expected, being an ingredients-based forecasting advocate, I find this notion of looking for patterns to be perilous for forecasters. Any thoughts about how this pattern recognition approach compares with ingredients-based methods?

I don't see that I'm advocating any particular approach, neither pattern vs. ingredients or vice versa. Rather, I was trying to show how important both are together (i.e., background-environment ingredients resulting from evolution of upper air features and the associated surface pattern).

In revisiting my original draft of the final section, I can see it could be interpreted as emphasizing "pattern" over ingredients, which was not good writing or structure, and not my intent. I have therefore removed the original Fig. 14 (showing the 500 hPa maps associated with the Moore and El Reno tornadoes in 2013), and replaced it with a three panel graphic showing the evolution of both surface fronts and 500 hPa contours in the days leading up to the Joplin tornado. Then, I've rewritten the concluding section to emphasize the evolution of these features and suggest how they resulted in the diagnostically favorable environment on the Joplin day (Fig. 15). That's an attempt to bring the focus more on meteorological processes (and ingredients) rather than "pattern recognition."

Another point of Fig. 15: when background environment ingredients appear strongly maximized east of a surface low (a favored severe weather location or "pattern"), that should definitely heighten forecaster situational awareness. In the text, I added the Moller (1980) reference (always a favorite paper for me about severe weather analysis) regarding the surface low location relative to the most favorable diagnostic background environment, and also a reference to Chuck's 1996 paper about ingredients-based forecasting.

[Minor comments omitted…]

Second Review:

Recommendation: Accept with minor revision.

General Comment: Having read the author's responses and the revised paper, I have no further comments and am satisfied the paper has been improved.

[Minor comments omitted…]

REVIEWER C (Daniel Reilly):

Initial Review:

Recommendation: Accept with minor revisions.

General/Substantive Comments: Good work. Nice example of combining pattern recognition, CAPE and shear analysis and derived parameter fields in post-assessing environment for the development of this EF5 deadly tornado. Certainly an important case to study and understand. I also appreciate the inclusion of model and observed soundings in addition to the mesoanalysis maps. The radar time series showed the presence of cell mergers although probably rightly referred to the idea of their importance as speculative (still seeking out the Van Leer et al. paper/abstract to get a handle on their modelling efforts). I also like how you compared this event with others with similar synoptic patterns showing this event was not unique as providing a setup up for tornadoes and potentially violent ones if instability and shear patterns line up. There were a few points I thought weren't clear from the information presented. There is a reference to an observed sounding "appearing more scrambled." I have an idea what that means but might want to try to define.

I understand that this needs to be clarified. In section 4, I have rewritten the paragraph that discusses the SGF 0000 UTC observed sounding to specify that the upper portion of the hodograph has several segments that double back on themselves ("zig-zags"). I've also tried to suggest why this part of the wind profile was different from the RUC-model analysis sounding at Joplin a couple hours earlier—possibly having to do with the ongoing tornadic supercell's location just upwind of the sounding site and its potential influence on the upper wind flow.

I also wasn't convinced that the mesoscale boundary presented in section 5 actually extended as far west as Joplin, at least from the data shown. It certainly did appear more evident in satellite, radar and obs over eastern Missouri but was difficult to trace all the way to the site of tornadogenesis given available data. If you look at the analysis in Fig. 12 there is very little difference in temp, dewpoint or wind direction on either side of the analyzed surface trough over western Missouri (more so over eastern and central). Likewise not as clear in satellite and radar. So I think this assertion from page 11 may be overstated:

"The Missouri portion of this boundary was quasistationary at midafternoon, trailing west-southwestward into the Joplin area."

This was also emphasized by Reviewer A (Corey Mead), and has been addressed by some rewriting of section 5 and adjustments to Fig. 12. (See my comments in response to Reviewer A.)

Thank you for writing up the Joplin case and providing a great analysis. So important for us operational forecasters to be able to recognize these environments and be in a position to issue watches then warnings as this storms spin up quickly.

Second Review:

Recommendation: Accept.

General Comment: [The author] has addressed my concerns from the first review, I think the paper is ready to publish from my perspective. Thanks for the opportunity to review this. Tornadogenesis is a topic that has always interested me from a research point of view.