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Environments of Significant Tornadoes Occurring within the Warm Sector versus Those Occurring along Surface Baroclinic Boundaries

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ABSTRACT

Archived, hourly-analysis proximity soundings from the operational Rapid Update Cycle (RUC) model are used to examine the vertical wind profiles and thermodynamic parameter space associated with significant tornadoes (rated F2+/EF2+) occurring in the warm sector (33 events) of synoptic cyclones, as well as those occurring along surface baroclinic boundaries (52 events), during the period 1999–2010 over the central and eastern United States. These tornadoes were associated with either the warm sector or a surface baroclinic boundary through the use of subjective surface analyses, supplemented by visible satellite and WSR-88D imagery. A key finding is that measures of ground-relative wind speed, storm-relative helicity, and bulk wind difference are much stronger for warm-sector significant tornado events. In contrast, thermodynamic parameters did not distinguish between the two regimes. Among all of the parameters examined, the observed and predicted speed of the parent supercell showed the most substantial differences between warm-sector and boundary significant tornado environments.

1. Introduction

The association between low-level baroclinic boundaries and significant tornadoes has received substantial attention during the last few decades. A preliminary investigation by Maddox et al. (1980) attributed this association to the enhanced moisture convergence and cyclonic vertical vorticity that reside along a boundary as low-level winds veer from easterly on the cool side to south-southwesterly on the warm side. Field projects, such as the Verification of the Origins of Rotation in Tornadoes Experiment (VORTEX; Rasmussen et al. 1994), have extended our physical understanding of the boundary–significant-tornado relationship further. Of the 47 F1+ (for the F scale, see Fujita 1971) rated tornadoes observed during the 1995 phase of that study, nearly 70% occurred within 10 km on the warm side of a boundary to 30 km on the cool side (Markowski et al. 1998a). Whereas Maddox et al. (1980) proposed that vertical vorticity was the origin of low-level updraft rotation as storms interacted with a boundary, Markowski et al. (1998a) and Rasmussen et al. (2000) indicated that horizontal vorticity generated on the cool side is augmented through horizontal accelerations within the inflow of a supercell, then tilted into the vertical and stretched by the updraft, yielding strong low-level rotation. These observations led to an additional hypothesis: that the large scale rarely produces sufficient vorticity for the occurrence of significant tornadoes. As such, a source of augmented streamwise vorticity is needed that is many times greater than observed in the ambient environment, a process most likely at the meso-β scale in association with baroclinic boundaries. Therefore, their conclusions indicate that significant tornadoes rarely should be observed away from boundaries.

Despite the strong association between significant-tornadoes and low-level boundaries, many cases of warm sector significant tornado outbreaks occur in the absence of boundaries (and attendant interactions) detectable with standard observation networks. Such events include Palm Sunday (11 April 1965; Fujita et al.

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1970), the 3−4 April 1974 Super Outbreak (Corfidi et al. 2010), the 3 May 1999 Oklahoma/Kansas tornadoes (Thompson and Edwards 2000), and several events comprising the May 2003 extended tornado episode (Hamill et al. 2005). Many of these warm-sector events are characterized by strong upper-level jet streaks which favor intense surface cyclogenesis. Furthermore, increasing westerly flow fields aid in downstream advection of an elevated mixed layer (EML; Carlson et al. 1983), emanating from the Rockies and desert plateau region, then spreading across the Great Plains with occasional intrusions east of the Mississippi River (Banacos and Ekster 2010, Corfidi et al. 2010). Beneath the EML, warm, moist air is drawn poleward by an intensifying low-level jet stream (LLJS), which forms in response to the strengthening low-level cyclone, and leads to the development of a broad warm sector with substantial CAPE. As the upper jet and associated upper trough emerge out of the western United States, thunderstorm initiation often occurs along a cold front or dryline, which trails equatorward from the surface low.

A particularly important aspect of correctly anticipating warm-sector significant-tornado events is identifying the dominant convective mode before storm initiation. Environments characterized by weak large-scale ascent and only weak low-level linear forcing favor discrete thunderstorm development (Dial et al. 2010), which predominate during significant-tornado events (Thompson and Edwards 2000, Smith et al. 2012, Thompson et al. 2012). Due to the strong deep-layer wind fields that accompany the upper-level jet, intense vertical wind shear favors long-lived supercells as the discrete storms move off of their initiating boundary and quickly traverse the broad unstable warm sector, increasing the potential for long-track, significant tornadoes (Bunkers et al. 2006a, Garner 2007).

In order to obtain representative estimates of parameters used to diagnose significant-tornado environments, numerous proximity sounding studies have been carried out (Maddox 1976; McCaul 1991; Brooks et al. 1994; Kerr and Darkow 1996; Rasmussen and Blanchard 1998, hereafter RB98; Rasmussen 2003; Craven and Brooks 2004). Three fundamental constraints generally were used to construct a database in these studies, which include: 1) defining the spatial distance between the observed sounding and the event, 2) defining the temporal difference between the sounding release time and the event time, and 3) ensuring that the air mass sampled by the sounding represents the general inflow environment of the tornadic thunderstorm. The resultant sample size can be increased by enlarging the spatial distance between the sounding and event, and by increasing the temporal difference between sounding release time and event time. However, Potvin et al. (2010) showed that arbitrarily tightening the spatial and temporal criteria does not necessarily ensure a more representative sample. Their analysis revealed that a favorable spatiotemporal distance between the thunderstorm being studied and the sounding does exist (40−80 km, and 0−1 h), which is close enough to be representative of the background environment, yet far enough to minimize convective feedback from the storm itself.

Building upon the concepts outlined in previous proximity sounding studies, Thompson et al. (2003; hereafter T03) used Rapid Update Cycle (RUC; Benjamin et al. 2004a and 2004b) hourly analysis soundings in order to obtain a relatively large database in a short amount of time. Associated benefits included the ability to match individual soundings with radar-observed storm types, as well as obtaining a close spatial and temporal (generally 40 km and 30 min, respectively) distance between the grid point sounding and the supercell of interest. A drawback of this method was the presence of any errors in temperature, moisture, and winds that might be associated with the RUC analyses, including unrepresentative profiles that occur when the model convective parameterization (Grell 1993) is activated. Results from T03 captured similar signals obtained in previous proximity sounding studies, such as increasing values of CAPE and vertical wind shear associated with a greater threat for significantly tornadic supercells.

A central theme of this study is to take the methods outlined in the RUC proximity sounding study of T03, and sample two different significant-tornado producing regimes: the warm sector of synoptic cyclones, and surface synoptic fronts and pre-existing thunderstorm outflow boundaries. The methods used to construct a significant-tornado database composed of warm-sector and boundary events will be given in section 2. Significantly tornadic storm attributes occurring in both settings, along with other relevant climatological information, will be presented in section 3. The principal dataset used to analyze the significant-tornado environments are RUC analysis proximity soundings, parameter results from which will be given in section 4. Finally, a summary and discussion will conclude the paper in section 5.

2. Methodology

A database of 79 Rapid Update Cycle (RUC) model analysis proximity soundings developed by T03 and Thompson et al. (2007; hereafter T07), spanning from April 1999 to June 2001, and January 2003 through March 2005, was used to examine the environments associated with significant tornadoes occurring in the warm sector and those interacting with surface baroclinic boundaries. These model analysis soundings were valid within a 40-km radius and 30 min of a radar-identified supercell. The 1999−2001 RUC soundings were at 40-km horizontal grid spacing with 25-hPa vertical resolution. The 2003−2005 RUC sounding dataset are from the native grid, which includes full model resolution in the vertical and a horizontal grid spacing of 20 km. In addition, six significant-tornado RUC soundings were archived in 2010 using the same proximity criteria as T03 and T07, but with a horizontal grid spacing of 13 km and full model resolution in the vertical. All versions of the RUC used in this study rely on convective parameterization schemes, as opposed to high-resolution numerical models that explicitly resolve convection.

RUC verification statistics presented by Benjamin et al. (2002a), Benjamin et al. (2004a, b), and Coniglio (2012) show that incremental improvements to temperature, moisture, wind speed and direction have been achieved as the RUC evolved from its 40-km version to 13-km version, especially in the lower troposphere. As the RUC40[1] transitioned to the RUC20, emphasis was given to improvements in quantitative precipitation forecasts. The RUC20 also made better use of observations compared to the RUC40 through improved algorithms for calculating observation-background differences. Other improvements over the RUC40 included more frequent updates of the RUC20 lateral boundaries, improved land-surface physics, improved upper-level winds and temperatures due to higher vertical and horizontal resolution, and improved orographically induced precipitation and circulations. The transition from the RUC20 to RUC13 occurred in June of 2005. The latter assimilated new observation types, such as METAR clouds, global positioning system-derived precipitable water, radar reflectivity, and mesonet winds, and included changes to model physics, such as a modified Grell-Devenyi convective parameterization (Benjamin et al. 2004c). Using balloon soundings from the second Verification of the Origin of Rotation in Tornadoes Experiment, Coniglio (2012) showed that the RUC13 estimated a planetary boundary layer depth that typically was shallower than in its corresponding verification sounding. This under-mixed boundary layer subsequently resulted in a cool and moist bias near the surface.

The Mann-Whitney U-test (Mann and Whitney 1947) was used to determine if significant differences in mean thermodynamic parameter values were observed between the RUC sounding datasets. Results indicate that the difference in means is statistically insignificant for all mean-layer thermodynamic parameters [the mean layer (ML) is defined over the lowest 100 hPa], except for the ML mixing ratio, with the RUC13 soundings being more moist (mean ML mixing ratio of 16.7 g kg^{-1}) compared to the RUC40 and RUC20 soundings (mean ML mixing ratios of 12.8 and 13.3 g kg^{-1}, respectively). However, the RUC13 soundings depicted high-end tornado environments, which may explain partially why they are significantly more moist. This is evident in comparing the mean F/EF scale and tornado path lengths between the three different sounding datasets. The mean RUC13 EF scale of 3.5 and mean tornado path length of 67 km exceeded the RUC40 and RUC20 mean F/EF scales of 2.7 and 2.5, respectively, and mean tornado path length of 30 km and 43 km, respectively. In addition to statistical tests performed for the thermodynamic parameters, 850-hPa and 500-hPa wind speeds also were tested. Differences in mean values when compared for all three sounding datasets were found to be statistically insignificant.

Subjectively analyzed surface maps were used to classify each tornado as either a warm-sector or boundary event. The maps were contoured for temperature, dewpoint and pressure, valid for the hour of tornado

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[1] This nomenclature is used herein to specify the horizontal grid spacing (km) of the RUC version mentioned.

occurrence, and supplemented with visible satellite and Weather Surveillance Radar-1988 Doppler (WSR-88D) reflectivity imagery. For example, if the parent storm moved off of its initiating boundary (such as a cold front or dryline) and produced a significant tornado in the warm sector where no detectable surface baroclinic boundary or pre-frontal wind shift interactions were observed using standard operational data sources, then that significant tornado was classified as a warm-sector event (Fig. 1).

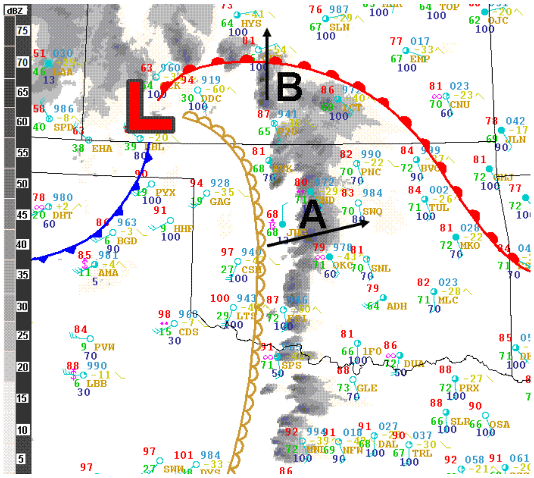

Figure 1: Synoptic surface cyclone from 10 May 2010, featuring a low over southwestern Kansas, a warm front east-southeastward across southern Kansas into northeastern Oklahoma, and a dryline extending southward into western Oklahoma and northwestern Texas. The grey shading is radar reflectivity (dB*Z*). Arrow A demonstrates a storm moving off its initiating dryline and traversing the warm sector. Arrow B demonstrates a storm moving northward across the warm front. *Click image to enlarge*.

Though detectable surface baroclinic boundary interactions were not observed for significantly tornadic warm-sector thunderstorms, this does not eliminate the possibility of boundary interactions from taking place at a smaller scale. Markowski et al. (1998b) provide observational evidence, which was later simulated by Frame and Markowski (2010), that elongated low-level baroclinic zones can be produced beneath anvils that spread downwind from supercell updrafts. Anvil shadows may provide a source of augmented horizontal vorticity favorable for tornadogenesis. Long anvils are most likely when the environmental winds aloft are strong. In addition, the longer the anvil becomes, the greater the parcel residence time will be within the anvil-generated baroclinic zone, given that the low-level storm-relative inflow vector is favorably aligned with the baroclinic zone. Markowski et al. (1998a) also argue that strongly sheared environments favor elongated forward-flank baroclinic zones, which could augment horizontal vorticity associated with intense vertical wind shear over the lowest few kilometers AGL.

A surface baroclinic boundary was defined as a transition zone between two differing air masses, with the “cool side” associated with lower temperatures, and the “warm side” characterized by higher temperatures. Increased confidence in boundary placement was achieved by identifying cloud lines apparent in visible satellite imagery, when available. A cold front was defined as the leading edge of an area of strong horizontal temperature gradient, where the advancing cold air mass is replacing a warmer air mass downstream. A warm front was characterized by a weaker horizontal temperature gradient when compared with a cold front, with the advancing warmer air mass replacing colder air located downstream. A stationary front was defined as a baroclinic zone in which neither the cold or warm air mass is advancing. Finally, pre-existing outflow boundaries produced by earlier convection were included in this study when they could be identified in the subjective surface analyses and visible satellite imagery.

Using the definitions above, if a radar-identified thunderstorm produced a significant tornado within a subjectively analyzed surface baroclinic zone (i.e., a temperature gradient), then that tornado was classified as a boundary event. No attempt was made to determine the spatial distance from a tornadic storm to the surface boundary. Although multiple significant tornadoes may have occurred across a large region during a particular convective episode, only one sounding associated with the highest F/EF scale rating and/or longest path length tornado was included per significant-tornado day (a 24-h period valid from 1200 UTC to 1159 UTC). The F/EF scale rating and path length were determined using the program Severe Plot (Hart and Janish 2003) and *Storm Data* (NCDC 1999–2010). In addition, since warm-sector events were found to be rare compared to boundary events, deference was given to the warm sector when multiple significant tornadoes occurred in the warm sector and along baroclinic boundaries, in order to obtain a larger warm-sector sample size. This resulted in the exclusion of four boundary proximity soundings. Using these criteria, 33 warm-sector events and 52 boundary events were identified. In addition to those RUC analysis significant-tornado proximity soundings, 22 warm-sector RUC soundings and 75 boundary RUC soundings were also identified for weak tornadoes, using the methods outlined above (Table 1). These weak-tornado proximity soundings provide a means of comparison with the significant-tornado soundings, and are included in the results section in order to complement the discussion.

Table 1: List of RUC analysis proximity soundings matched with warm-sector significant tornadoes (WST), surface baroclinic boundary significant tornadoes (BST), warm-sector weak tornadoes (WSWT), and surface baroclinic boundary weak tornadoes (BWT).

Model (Year)	WST	BST	WSWT	BWT
40-km RUC (1999–2001)	15	30	9	28
20-km RUC (2003–2005)	12	22	13	47
13-km RUC (2010)	6	0	0	0

After sounding collection and classification were completed, the model surface temperature, dew point, wind speed, and direction were modified in a UNIX-based version of the Skew-T Hodograph Analysis and Research Program (NSHARP; Hart and Korotky 1991). Similar to the Storm Prediction Center surface mesoscale analysis (Bothwell et al. 2002), these modifications should result in more accurate estimates of wind and thermodynamic parameters (Coniglio 2012). The surface observations used to modify the RUC analysis soundings were chosen from the closest surface observation site upwind of the tornadic storm. As noted in T03, surface observation sites often corresponded to RUC sounding sites, making the selection of surface modification data relatively simple. Following these sounding modifications, the NSHARP program then calculated a large array of thermodynamic and wind shear parameters.

Each RUC analysis proximity sounding represents the approximate ambient inflow sector of the tornadic storms. This is crucial for interpreting the severe-weather parameters for boundary events, since the resolution of the RUC analyses may not detect small-scale augmentations to CAPE and vertical wind shear occurring along the boundaries.

Twenty-two parameters were recorded for each RUC analysis proximity sounding. Thermodynamic parameters included the surface temperature, surface dew point, mean mixing ratio in the lowest 100 hPa, ML lifted condensation level (MLLCL), and ML level of free convection (MLLFC). Measures indicating instability and buoyancy included the ML convective inhibition (MLCINH), MLCAPE, 0–3-km MLCAPE, and the 700−500-hPa lapse rate. In addition to the thermodynamic parameters, ground-relative wind speeds were recorded at 850, 500 and 250 hPa (Grams et al. 2011). Measures of storm-relative helicity (SRH; Davies-Jones et al. 1990) were recorded for the 0−1 km, 0−3 km, and effective (T07) layers. Bulk wind difference (BWD; T07) was assessed for the 0−1 km, 0−6 km, 0−8 km, and effective layers. The internal dynamics (ID) method for predicting supercell storm motion (Bunkers et al. 2000) also was used to assess sounding-based differences in how storms move across their environments.

Means and correlation coefficients were computed for each parameter, in order to determine differences between the two significant-tornado regimes. A more detailed analysis of the data distribution was achieved through the use of box-and-whiskers plots. In addition, since the sample size is small in the current study (particularly for warm-sector events), the Mann-Whitney U-test was used to assess the statistical significance in the difference in means, since it is more robust when dealing with non-normal distributions (Mann and Whitney 1947).

The entire lifespan of each significantly tornadic storm was analyzed using archived WSR-88D level-II data, except for two storms for which no radar data were available. Full volumetric data were examined in order to determine storm type, convective mode, storm longevity, and the elapsed time between storm initiation and tornadogenesis. Storm initiation was determined by the appearance of a ≥35-dBZ reflectivity core appearing in the midtroposphere (i.e., ≥3 km AGL). Storm type then was examined by evaluating the reflectivity structure and apparent rotational characteristics of each cell. Every storm in this study was classified as a supercell based on the appearance of reflectivity structures indicating the presence of a hook echo, bounded weak echo region, and tight concave shaped forward-flank reflectivity gradient, combined with persistent mid-level rotation (~30 min or more) characterized by a peak cyclonic azimuthal shear of 20 m s^{-1} (T03).

Each supercell was tracked until either dissipation or evolution into another storm type was observed, yielding supercell longevity. Translation speed of each supercell was determined manually by tracking the echo centroid. In addition, the amount of time between supercell initiation and significant tornadogenesis was determined through the archived radar data and tornado-occurrence time (via Severe Plot and *Storm Data*). Finally, convective mode was analyzed for each event using the methods of Smith et al. (2012). From their study, three possible modes can be assigned to the events in this research: 1) discrete right-moving (RM) supercell, 2) RM supercell in a cluster, and 3) RM supercell in a line. The discrete mode applies to a RM supercell not attached to any other cells with ≥35-dB*Z* reflectivity. A cluster occurred when additional storms with ≥35-dB*Z* reflectivity were connected to a RM supercell. Finally, an RM supercell in a line requires that a supercell be embedded within a contiguous band of ≥35-dB*Z* reflectivity with a length ≥100 km and a length to width ratio ≥3:1 (Fig. 2).

3. Storm attributes

Five attributes were analyzed for each significantly tornadic supercell using archived WSR-88D reflectivity data, the program Severe Plot, and *Storm Data*. These storm attributes include 1) observed supercell speed, 2) tornado path length, 3) supercell longevity, 4) convective mode during the significantly tornadic phase of the parent supercell, and 5) the length of time between storm initiation and significant-tornado occurrence. In order to gain further insight into how these storm attributes relate to the tornado parameter space, correlation coefficients (given by the parameter *r*) were calculated between each attribute and severe-weather parameters.

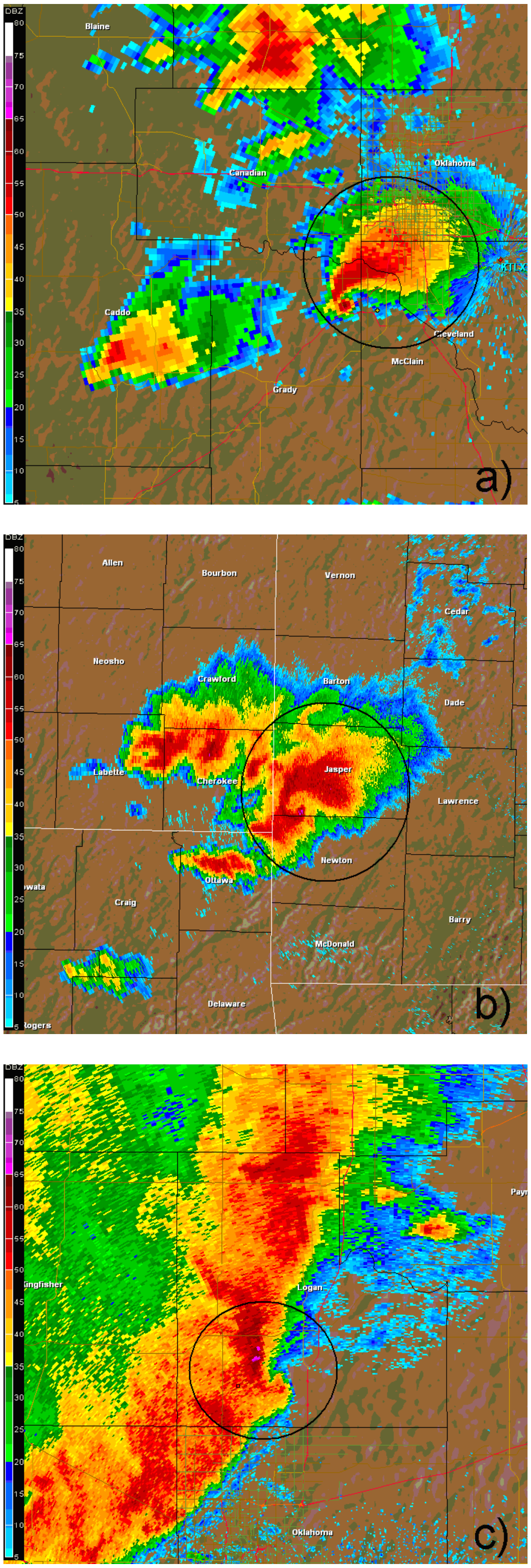

Figure 2: Examples of convective mode (circled): a) discrete RM supercell, b) RM supercell in a cluster, c) RM supercell in a line. *Click images to enlarge*.

Supercell motion is composed of an advective component, generally derived by the mean wind measured through a deep layer of the atmosphere, and a propagational component that is transverse to the mean shear due to nonhydrostatic effects associated with mid-level updraft rotation (Weisman and Klemp 1982). One goal of this study is to determine any differences between the speeds of significantly tornadic supercells moving across the warm sector versus those interacting with baroclinic boundaries. The mean and median speeds derived from radar data indicate substantial differences.

Warm-sector significantly tornadic storms move faster, with a mean value of 20 m s^{-1}, than significantly tornadic storms occurring along boundaries, which are characterized by a mean value of 13 m s^{-1}. The difference in means is statistically significant at the >99% confidence level. In addition, substantial separation exists between the warm-sector 25th percentile and the boundary 75th percentile (Fig. 3). The warm-sector 10th percentile is also larger than the boundary median value, and the warm-sector 75th percentile is greater than the boundary 90th percentile. The observed storm speeds calculated from WSR-88D data were most closely correlated with the RUC forecast internal dynamics (ID) method for predicting supercell motion (Bunkers et al. 2000), with the warm-sector correlation equal to 0.80, which is larger than the boundary correlation of 0.57.

Tornado path length is a function of 1) the speed of the parent storm, and 2) the duration of the tornado. Indeed, tornado path length shares its largest correlation with the observed storm speed, with r = 0.42 for warm-sector events compared to 0.55 for boundary events. More importantly, the difference in mean tornado path length between warm-sector and boundary events is nearly 24 km, and is statistically significant at the 99% confidence level, with a mean path length in the warm sector of 42 km, and a mean path length for boundary events of 18 km. This large difference in means is likely attributed to a few long-path warm-sector tornadoes, with the maximum path length examined in the warm sector being 239 km, while the maximum path length along a boundary being only 54 km. Taking this into account, the difference in median values is much less, with the median warm-sector path length being 20 km, and the median boundary path length being 15 km.

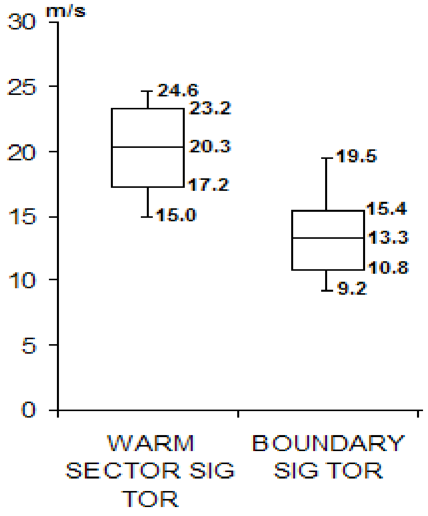

Figure 3: Box-and-whiskers plot for observed supercell speed (m s^{-1}). The boxed region represents the interquartile, from 25th–75th percentiles (bottom to top), with median lines. Whiskers extend to the 10th and 90th percentiles.

Warm-sector significantly tornadic supercells have a mean life span of 4.6 h, compared to 3.5 h for significantly tornadic supercells interacting with boundaries, with a difference in means that is statistically significant at the 99% confidence level. Bunkers et al. (2006a, 2006b) showed that long-lived supercells (lifespans ≥4 h) were more likely to produce significant tornadoes than short-lived supercells (≤2 h). Long-lived supercells are favored in environments characterized by strong 0−8-km BWD, as well as low LCL heights and large 0−1-km SRH, favoring significant-tornado production. In addition, supercells that maximize their residence time within a favorable zone of moisture and CAPE, such as an expansive warm sector, or a storm motion vector which parallels a low-level boundary, are most likely to be long-lived. In this study, supercell longevity within the warm sector was correlated most strongly (r = 0.53) to the effective-layer significant tornado parameter (STP; Thompson et al. 2004), while the correlation with 0−8-km BWD was slightly lower at 0.43. Conversely, supercell longevity along boundaries was most strongly correlated with effective BWD, albeit at a more marginal value of 0.39.

Bunkers et al. (2006a) showed that discrete and isolated supercells last longer, since interference from storm mergers is less frequent. Conversely, shorter-lived supercells are more likely to occur when embedded within thunderstorm clusters or lines, due to a greater potential for storm mergers. Thus, some of the difference in mean supercell longevity observed in the current study may be explained by differences in convective mode between warm-sector and boundary storms.

An examination of convective mode shows that significantly tornadic supercells occurring in the warm sector and along boundaries were dominated by discrete RM supercells as well as RM supercells in thunderstorm clusters. However, 56% of the warm-sector significantly tornadic storms were discrete RM supercells, and 40% were embedded within thunderstorm clusters. In comparison, 37% of the boundary supercells were discrete RM supercells, while 63% were embedded within thunderstorm clusters. These results suggest that significantly tornadic storms occurring along baroclinic boundaries may be more prone to adverse interactions with surrounding thunderstorms, which could limit their longevity.

The length of time between storm initiation and significant-tornado occurrence may be operationally useful to warning forecasters, since it gives information on how quickly the significant-tornado threat will develop when faced with either a warm-sector or boundary regime. An examination of the mean and median values for warm-sector and boundary events shows that significant tornadoes developing on boundaries occur more quickly after storm initiation (mean value of 1.5 h) than warm-sector significant tornadoes (mean value of 2.1 h), and the difference in means is statistically significant at the 98% confidence level. This result indicates that processes along boundaries are favorable for more rapid significant tornadogenesis, while warm-sector environments favor a slower storm evolution. The length of time between storm initiation and significant tornadogenesis is most strongly correlated to supercell longevity, with an $r = 0.63$ in the warm sector, and $r = 0.74$ for boundaries. Thus, the time between supercell initiation and the first significant tornado increases when the environment yields conditions that are increasingly favorable for long-lived supercells.

A total of 1020 injuries were associated with significant tornadoes occurring within the warm sector, which is much greater than the 432 injuries associated with significant tornadoes occurring along boundaries, even though there are 19 more boundary events examined in this study. The same trend is observed for fatalities. The total number of fatalities associated with significant tornadoes in the warm sector is 59 (mean value of 1.8), while the total number of fatalities associated with boundary events is 21 (mean value of 0.4). Of additional interest, seven violent (F/EF4+) tornadoes occurred in the warm sector, and seven also occurred along boundaries. For warm-sector events, 90% of the injuries and 85% of the fatalities occurred with the seven warm-sector violent tornadoes. However, only 20% of the injuries and 23% of the fatalities associated with boundary events were caused by the seven boundary violent tornadoes. Considering that warm-sector violent tornadoes have a much longer mean path length (68 km) than boundary violent tornadoes (16 km), it is speculated that warm-sector violent tornadoes had a greater probability of encountering structures and people, thus increasing the potential for casualties.

The geographical distribution of warm-sector significant tornadoes (Fig. 4) examined in this study shows that these events were most frequent over Oklahoma, Kansas, Mississippi, Arkansas, and Illinois. This distribution of events roughly represents the climatological "tornado alley" of the central and southern plains (Kansas and Oklahoma), as well as a cool-season maximum over the southern Mississippi River Valley. This cool-season maximum is reinforced in that 66% of the significant tornadoes over Mississippi and Arkansas occurred between the months of January and April. In contrast, significant tornadoes occurring along boundaries were observed most frequently in Nebraska and Texas, followed by Minnesota, North Dakota and Iowa (Fig. 5). The occurrence of boundary significant tornadoes showed a general northward, southward, and westward expansion compared to the distribution of warm-sector events. This may reflect the fact that mesoscale boundaries can become established over any region under a multitude of synoptic patterns, while warm-sector events are dominated by climatologically favored synoptic-scale regimes.

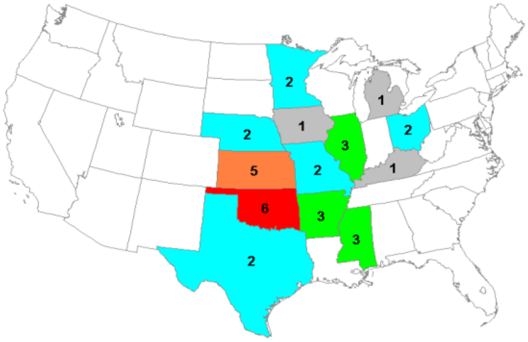

Figure 4: Geographical distribution of warm-sector significant-tornado events. Red and orange represent higher counts of significant tornadoes, while green and blue represent a lower number.

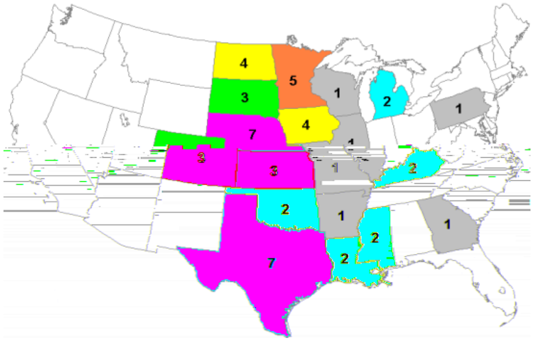

Figure 5: As in Fig. 4, except for significant tornadoes occurring along boundaries.

Warm-sector significant tornadoes were observed during every month of the year, with a peak of 33% during May, preceded by a gradual increase from February through April (Fig. 6). Compare this with boundary events, which peak at 34% during the month of May, tailing into the June and July (Fig. 7). Significant tornadoes occurring along boundaries are more likely during late spring into summer, as no boundary event occurred during December, January, or February; and only 5% of the boundary events occurred between August and November. In comparison, warm-sector significant tornadoes are most favored during the late winter into late spring. These results also conform to the climatological maximum in significant-tornado occurrence during the month of May (Concannon et al. 2000).

Finally, the time of significant-tornado occurrence is broken down into periods by UTC time: evening (0000–0359, overnight (0400–1159), morning (1200–1559), midday (1600–1959),

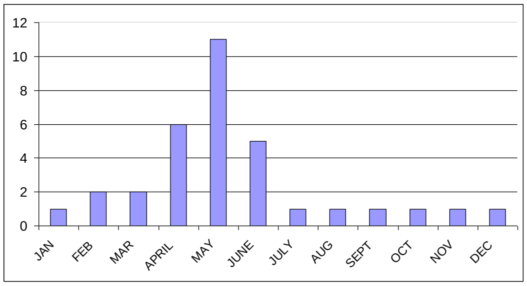

Figure 6: Number of warm-sector significant tornadoes by month during the period of study 1999-2010.

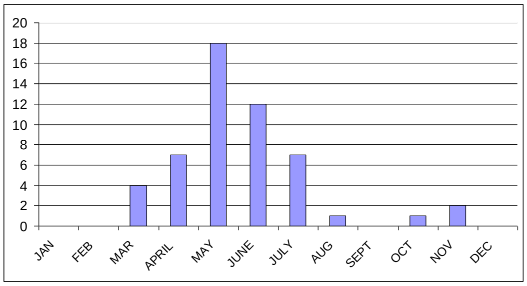

Figure 7: Same as in Fig. 6, except for significant tornadoes occurring along boundaries.

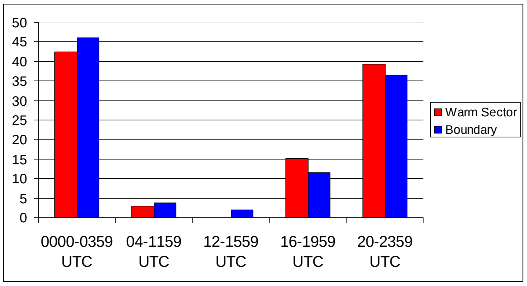

Figure 8: Percentage of significant tornadoes by time of day. Red bars represent warm-sector events, and blue represents boundary events.

and late afternoon (2000–2359; Fig. 8). The most frequent time of day for significant tornadoes is similar for both warm-sector and boundary events, with 39% and 36%, respectively, during the late afternoon, and 42% and 46%, respectively, during the evening. The most infrequent time for significant tornadoes is during local overnight and morning hours. These results are fairly consistent with past studies on the diurnal frequency of tornado occurrence (e.g., Kelly et al. 1978).

4. RUC sounding-derived parameters

a. Thermodynamic parameters

Table 2 lists mean thermodynamic parameter values that are evaluated commonly during operational severe-weather forecasting. These results indicate that CAPE is substantial for both warm-sector and boundary tornado environments, MLCINH and MLLCL heights are low, and mid-level lapse rates are steep. However, the Mann-Whitney statistical test reveals that the difference in means when comparing significantly tornadic warm-sector and boundary events is statistically insignificant for all of the thermodynamic parameters evaluated in this study. Box-and-whiskers plots created for these parameters indicate large interquartile overlap between all significant- and weak-tornado categories (not shown).

b. Low-level wind profile

The LLJS is an important feature in many tornado events because it aids in the transport of warm and moist air into the severe storm environment, while enhancing low-level convergence, warm air advection, and frontogenesis—all of which are important sources of mesoscale ascent. Mead and Thompson (2011) also showed that the LLJS can modify the magnitude of low-level vertical wind shear substantially. For these reasons, the 850-hPa ground-relative wind speed, which is used as a proxy for the LLJS, was analyzed in addition to low-level vertical wind shear parameters.

An evaluation of the mean 850-hPa ground-relative wind speed for warm-sector and boundary significant tornadoes reveals that warm-sector environments are characterized by substantially stronger LLJSs, with the difference in means found to be statistically significant at the >99% confidence level (Table 3). Figure 9 further demonstrates the dramatic differences between warm-sector and boundary LLJSs, with no overlap occurring between the inter-quartiles ranges. In addition, no inter-quartile overlap is present between the warm-sector weak-tornado box plot and the weak-tornado boundary box plot, which suggests that strong LLJSs are an important component of warm-sector tornado environments in general.

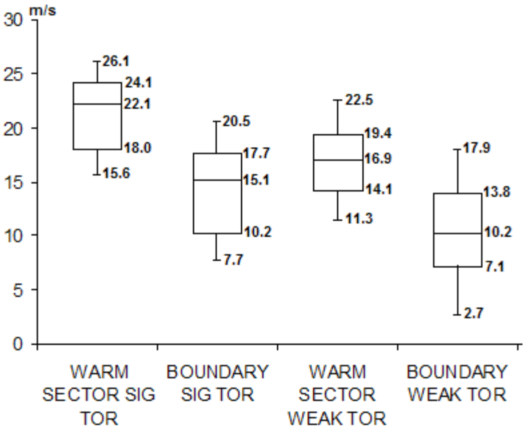

Figure 9: As in Fig. 3, except for 850-hPa ground-relative wind speed (m s^{-1}).

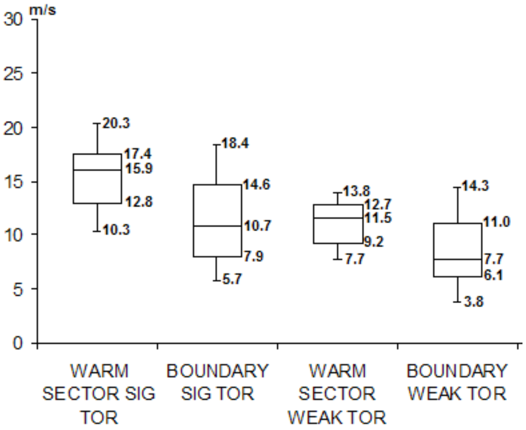

Figure 10: As in Fig. 3, except for 0−1-km bulk wind difference (m s^{-1}).

Given the presence of a stronger mean LLJS for warm-sector significant-tornado environments, it is not surprising that they were characterized by 0−1-km BWD that is 4 m s^{-1} larger, 0−1-km SRH that is 86 m^2 s^{-2} larger, 0−3-km SRH 70 m^2 s^{-2} larger, and effective SRH 78 m^2 s^{-2} greater than for boundary environments. All low-level shear parameters were associated with a difference in means that was statistically significant at the >97% confidence level. Figure 10 shows that warm-sector significant tornadoes are associated with larger values of 0−1-km BWD, with little overlap observed between the 25th percentile of warm-sector events and the 75th percentile of boundary events. In addition, the warm-sector significant-tornado box plot displays no overlap with the warm-sector weak-tornado box plot, which provides additional evidence that low-level vertical wind shear can distinguish between significant- and weak-tornado environments, as demonstrated in previous proximity sounding studies (Rasmussen 2003, T03).

Table 2: List of mean thermodynamic parameter values for warm-sector significant tornadoes (WST), surface baroclinic-boundary significant tornadoes (BST), warm-sector weak tornadoes (WSWT), and surface baroclinic-boundary weak tornadoes (BWT).

	MLCAPE (J kg^{-1})	**MLCINH (J kg^{-1})**	**MLLCL (m AGL)**	**MLLFC (m AGL)**	**0–3-km MLCAPE (J kg^{-1})**	**700–500-hPa LAPSE RATE (ºC km^{-1})**
WST	2221	26	942	1674	96	7.2
BST	2427	42	1063	1865	92	7.5
WSWT	1634	26	1041	1547	108	6.7
BWT	2002	47	1256	1927	82	7.4

Table 3: List of mean ground-relative wind speed, SRH, and BWD for warm-sector significant tornadoes (WST), surface baroclinic-boundary significant tornadoes (BST), warm-sector weak tornadoes (WSWT), and surface baroclinic-boundary weak tornadoes (BWT). Ground-relative wind speeds (GRW), bulk wind difference (BWD), and storm speed are in m s^{-1}. Storm-relative helicity (SRH) is in m^{2} s^{-2}.

	850-hPa GRW	**500-hPa GRW**	**250-hPa GRW**	**BWD01**	**SRH01**	**SRH03**	**EFFSRH**	**BWD06**	**BWD08**	**EFFBWD**	**Bunkers Storm Speed**
WST	21	30	40	15	283	357	318	29	32	28	20
BST	13	22	30	11	197	287	240	24	28	24	12
WSWT	16	23	33	11	182	245	209	22	26	22	15
BWT	10	18	28	8	143	256	205	22	26	22	10

c. Deep-layer wind profile

Both the 500- and 250-hPa ground-relative wind speeds are associated with a difference in means that is statistically significant at the >99% confidence level. The mean warm-sector significant-tornado 500-hPa ground-relative wind speed is 8 m s^{-1} greater than the mean boundary significant-tornado 500-hPa speed. In addition, the mean warm-sector 250-hPa ground-relative wind speed is 10 m s^{-1} larger than the mean boundary 250-hPa speed. Figure 11 also shows that there is no interquartile overlap between the warm-sector and boundary 500-hPa ground-relative wind speeds. Very little overlap is observed between the two significant-tornado 250 hPa interquartile ranges (not shown).

All three measures of deep-layer BWD were larger for warm-sector significant-tornado environments, the difference in means being statistically significant at the 97% confidence level. Per Fig. 12, the offset between the significant-tornado median values and inter-quartile ranges indicates that warm-sector environments are more strongly sheared through a deep layer than boundary environments. In addition, a further reduction in the overlap between warm-sector significant-tornado and weak-tornado box plots is observed, which may be operationally meaningful when forecasting the potential risk of significant tornadoes in the warm sector. The characteristics of the 0−6-km BWD distributions are similar to the 0−8-km and effective BWD (not shown).

d. Storm speed

Among all of the RUC parameters examined, the ID method for predicting supercell speed displayed the largest separation between inter-quartile ranges (Fig. 13). In addition, the mean speed for warm-sector significantly tornadic storms was found to be 8 m s^{-1} greater than the boundary significant-tornado mean, and the difference in means is statistically significant at the >99% confidence level. As such, significantly tornadic supercells in the warm sector are likely to move faster than those along baroclinic boundaries. In addition, weakly tornadic warm-sector storms were also found to move faster than either significantly tornadic or weakly tornadic storms interacting with boundaries.

5. Summary and discussion

A total of 85 significant tornadoes were examined in this study: 33 in the warm sector of synoptic cyclones and 52 interacting with surface baroclinic boundaries. It was found that warm-sector significant tornadoes had longer path lengths than those on boundaries, which is partially attributed to the faster storm motions observed across the warm sector. Warm-sector significantly tornadic supercells had longer lifespans than those along boundaries. This longevity difference may be influenced by the tendency for warm-sector storms to be discrete, and boundary storms to occur in thunderstorm clusters, the latter associated with storm interactions. Warm-sector events, on average, also took longer to experience significant tornadogenesis than boundary supercells.

From an operational forecasting perspective, large CAPE, low MLCINH, and low MLLCL heights characterize the majority of tornado environments examined in this paper. The magnitude of the vertical wind shear produced at the synoptic scale discriminates strongest between warm-sector and boundary significant-tornado regimes. If strong low-level and deep shear are present across the warm sector, and fast storm motions are forecast, then warm-sector significant tornadoes are favored. Conversely, if vertical wind shear is weak and slow storm motions are forecast, then operational forecasters should concentrate on surface baroclinic boundaries where augmentation of shear and vorticity is possible, and the probability for significant tornadoes is enhanced.

The way in which a supercell moves across its environment, as well as the length of time it resides within a favorable zone of tornado ingredients, has important implications for its significant-tornado potential. For instance, Markowski et al. (1998a) showed that tornadoes occurring along low-level boundaries are likely within 10 km on the warm side to 30 km on the cold side. Therefore, a slowly moving storm, residing within this zone for a greater amount of time, would be more favored to produce a tornado compared to a more quickly crossing storm. Warm-sector tornadic storms tend to translate faster. As such, warm-sector width must be sufficient to allow time for significant tornadogenesis to occur before the parent storm moves into a more hostile downshear environment.

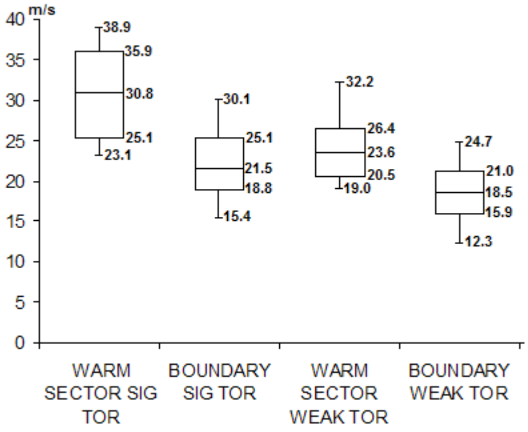

Figure 11: As in Fig. 3, except for 500-mb ground-relative wind speed (m s^{-1}).

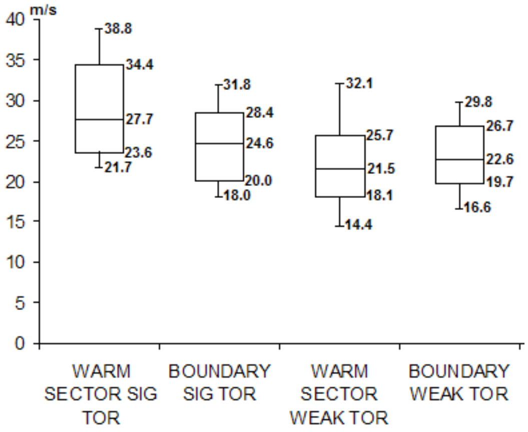

Figure 12: As in Fig. 3, except for 0−6-km bulk wind difference (m s^{-1}).

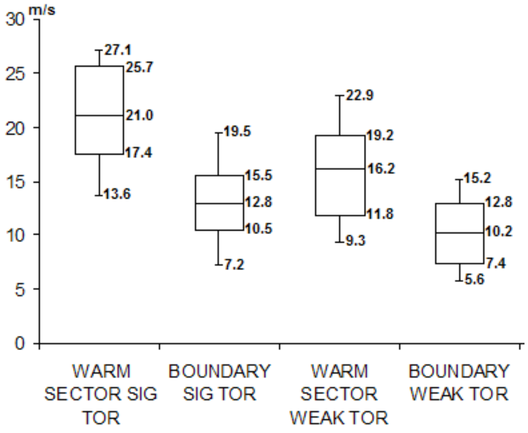

Figure 13: As in Fig. 3, except for the ID method for predicting supercell speed (m s^{-1}).

ACKNOWLEDGMENTS

The author thanks Richard Thompson and Steve Weiss for their comments and suggestions during various stages of this research, as well as Greg Dial for providing guidance during the statistical analysis. In addition, the author thanks John Brown and Stan Benjamin for answering several questions related to the Rapid Update Cycle. Finally, the author is grateful to Josh Boustead, Michael Evans, Jeffrey Frame, and Robert Maddox for reviewing and commenting on this manuscript.

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REVIEWER COMMENTS

[Authors' responses in *blue italics*.]

REVIEWER A (Joshua M. Boustead):

Initial Review:

Recommendation: Accept with major revisions.

General Comments:

The paper compares environments of significant tornadoes occurring in the warm sector to those that occur along boundaries. Using RUC proximity soundings, the author explores both thermodynamic and bulk wind differences of environments in proximity to the significant tornadoes. The author uses subjective surface analyses supplemented with radar and satellite data to identify if the significant tornado occurred near a discernible boundary. Overall I enjoyed the research and think that it will make a nice contribution to the operational forecast community. The research does fit within the scope of the journal, but does suffer from deficiencies that need to be remedied before the paper can be published. There are 4 major concerns with the science of the research, which are listed in detail below. Below the major concerns, there are numerous grammar and editing concerns listed that also need to be addressed.

The "Rasmussen table" below summarizes my evaluation of this study. General and specific comments follow the table.

Criterion	Satisfied	Deficient, but can be remedied	Deficient; *cannot* be remedied by modifying the paper	Deficient, *not known* if it can be remedied by modifying the paper
1. Does the paper fit within the stated scope of the journal?	X			
2. Does the paper 1) identify a gap in scientific knowledge that requires further examination; 2) repeat another study to verify its findings; or 3) add new knowledge to the overall body of scientific understanding?	X			
3. Is the paper free of errors in logic?		X		
4. Do the conclusions follow from the evidence?		X		
5. Are alternative explanations explored as appropriate?				X
6. Is uncertainty quantified?		X		
7. Is previous work and current understanding represented correctly?		X		
8. Is information conveyed clearly enough to be understood by the typical reader?		X		

Major Comments: I certainly support the use of significant tornadoes for the study as the long-term trend in Storm Data appears to be more stable, but wonder about the comparison of significant tornadoes to weak tornadoes in the study. Alexander and Wurman (2008) indicated that the wind speeds for tornadoes sampled by mobile Doppler radar resulted in a bell shaped curve when compared to the Fujita/Enhanced Fujita Scale with the majority of the tornadoes of F/EF2 strength. I know that you were able to find statistically significant results comparing F/EF2 and weak tornadoes, but I wonder if a comparison between significant tornadoes and supercells occurring in the warm sector or near a boundary that didn't produce a tornado would produce more meaningful results?

This concern is valid and would be a worthwhile undertaking. However, the purpose of this study is to compare the environments of significant tornadoes occurring in the warm sector with those occurring along baroclinic boundaries. The inclusion of weak tornadoes is of secondary importance, and is provided to complement the primary results (i.e., SIGTOR environments), as stated in the methodology.

Methodology...it is not stated in the paper how close to a boundary a storm has to be to considered in the boundary cases, and how far a storm has to move off an initiating boundary for the storm to be considered in the warm sector.

I state in the methodology that if a storm resides within a subjectively analyzed surface baroclinic zone (associated with a warm front, stationary front, outflow boundary, or even a cold front), then it was classified as a boundary case. No attempt was made to determine the distance from the surface representation of the boundary (as would be analyzed on a surface chart).

Since the temperature gradient associated with a cold front would reside behind the front, any storm that moves downstream from the cold front would by definition be in the warm sector. Drylines are not identified by a temperature gradient, but the same basic argument applies—any storm moving downstream from the dryline would be in the warm sector.

The author indicates that "deference" was given to tornadoes in the warm sector to increase the number of events for the study, but doesn't provide an explanation to how this was done. This needs to be clarified. Such as, were there any criteria to how many individual tornadoes were used from one particular day? Were there any criteria to space and time to tornadoes that were included? How many tornadoes would there have been included if deference wasn't given? Also, the study used the Thompson et al. (2007) database of RUC soundings that goes through 2005, but would including the years 2006–2011 provide additional warm-sector tornadoes so that more than one tornado per day would not have to be used?

The primary constraint on this study was the pre-existing archive of RUC proximity soundings provided by Thompson et al. (2003), and Thompson et al. (2007). Many of these soundings were excluded from the study because they did not meet the definition of a warm sector or baroclinic boundary significant tornado event. The small number of baroclinic boundary SIGTOR soundings that were excluded because of the deference to the warm sector totaled four (from four different tornado days). This is a statistically insignificant number of excluded soundings, and I don't believe the results would be changed in any meaningful way if they were included.

Addressing your second point, I do not have access to RUC analysis proximity soundings for the period 2006–2009, six soundings were collected from 2010, and no soundings were collected for 2011.

I was a little confused going throughout the paper with the terms shear and bulk wind difference. There were a few instances where the author talks about shear, but then also mentioned bulk wind difference (such as on pp. 11 and 12). I would like some clarification, maybe in the methodology section, as to which is used in the paper and then be consistent in the text throughout.

All instances of the term shear (or low-level/deep-layer shear) have been changed to bulk wind difference (BWD) where appropriate.

The author uses the Mann-Whitney test for statistical analysis but does not explain the advantages or disadvantages of using this test, or why this test was picked over other tests such as Student's *t* test. Additional information in this area would be helpful to the reader.

The Student's t*-test assumes that the observations with two groups are normally distributed and the variances are equal in the two groups. Since the sample size is small in my study (particularly for warm sector SIGTORs), I turned to the Mann-Whitney U-test, which is considered to be more robust when dealing with non-normal distributions. This information has been added to the methodology.*

General comment: The author indicates that there was no statistically significant differences found when looking at thermodynamic properties, but then provides details of two of these (MLCINH and MLLCL). If there are not important findings from these two parameters maybe consider removing them? (I would move this to major comments.)

I agree with this point. The thermodynamic section has been modified to be more concise, and removes the long discussions on MLCINH and MLLCL.

Conclusion…this may be a cause and effect error here. The length of time a supercell resides near a boundary was not covered in this study. Although the boundary storms move slower on average, no evidence was given on how long each storm resided near the boundary.

This point is valid as well. I made an addition to the discussion that more clearly states that I am speculating as to why a slower storm speed along boundaries may be important for significant tornado potential. This kind of detailed examination of storm-boundary interaction is beyond the scope of my paper, but several forecasters at the SPC, including myself, have begun preliminary work addressing this interaction.

[Minor comments omitted...]

Second review:

Recommendation: Accept with minor revisions.

General Comments: Revisions by the author of the manuscript have made improvements, and it is now easier to read and understand. I only have two remaining substantial comments to clear up which are specified below the Rasmussen table. If these two items can be cleared up to the editor's approval, I do not feel another round of reviews would be necessary. Below the two major comments and several minor comments that should also be remedied.

The "Rasmussen table" below summarizes my evaluation of this revised study. General and specific comments follow the table.

Criterion	Satisfied	Deficient, but can be remedied	Deficient; *cannot* be remedied by modifying the paper	Deficient, *not known* if it can be remedied by modifying the paper
1. Does the paper fit within the stated scope of the journal?	X			
2. Does the paper 1) identify a gap in scientific knowledge that requires further examination; 2) repeat another study to verify its findings; or 3) add new knowledge to the overall body of scientific understanding?	X			
3. Is the paper free of errors in logic?		X		
4. Do the conclusions follow from the evidence?	X			
5. Are alternative explanations explored as appropriate?	X			
6. Is uncertainty quantified?	X			
7. Is previous work and current understanding represented correctly?	X			
8. Is information conveyed clearly enough to be understood by the typical reader?		X		

Although the author indicates in his response to my initial comments that, "All instances of the term shear (or low-level/deep-layer shear) have been changed to bulk wind difference (BWD) where appropriate," this does not seem to be the case though. In section 4b there are a couple of instances where wind shear and bulk wind difference appear to be interchanged again. This also refers to Table 3 as well where columns are labeled SHR for 1, 6, and 8. There is also a mention of this in the conclusion section in the second full paragraph. This should be cleared up before publication.

I modified the first paragraph of section 4b to remove the instance of vertical wind shear. Table 3 has been modified to remove vertical wind shear. In the summary/discussion, I specifically noted the "magnitude of the vertical wind shear," which is what bulk wind difference represents.

I appreciate the response from the author to my concern in regards to the "difference" given to warm sector events, and I now understand what was meant here. The only remaining question that the author will hopefully clarify in the manuscript before publication is does this mean that on the days where there were boundary and warm sector significant tornadoes that the warm sector sounding were always used instead of the boundary soundings? If not, what were the criteria to give difference to the warm sector over the boundary on certain days? Finally, were there days where more than one warm sector significant tornado used from the same day?

As stated in the methodology, if a RUC sounding was available for both a warm sector and boundary tornado event, the warm sector sounding was always used. This excluded only a few boundary soundings. There were no days in which multiple warm sector soundings were used.

[Minor comments omitted...]

REVIEWER B (Michael Evans):

Initial Review:

Reviewer recommendation: Accept with minor revisions.

General comments:

Thanks for the opportunity to review this paper. To summarize my comments below, I felt that the overall quality of the presentation of this paper was outstanding; very well written with good figures and references. However, there are some scientific issues that I discuss below that I would like to see clarified or discussed in more detail. Based on my review, my recommendation for this paper is for it to be accepted for publication pending minor revisions; however I would like to see the revisions prior to publication. The following are comments based on my review of the paper.

Substantive comments: The most difficult challenge faced for a study such as this was the partitioning of the events into two distinct categories, such as "baroclinic boundary" vs. "warm sector". This could become quite challenging for events in the warm sector of cyclones, where subtle meso-scale boundaries could be in place to help with tornadogenesis. As such, the author needs to be very careful about their methodology for discriminating between "boundary" and "warm-sector" events, to insure that any subsequent studies could duplicate their methodology.

I agree with the reviewer's concerns. Each event included in this study was carefully screened for surface baroclinic boundary interactions. A majority of the "boundary" events occurred along synoptic-scale baroclinic zones, with a few mesoscale baroclinic zones identified (most often pre-existing thunderstorm outflow boundaries). Warm sector cases were for the most part very straight forward. Storms either emanated off of a cold front or a dryline, then moved downstream across an environment devoid of baroclinic boundaries (using standard observational data sources). Interactions with prominent wind shift boundaries were not observed.

There was some confusion in my mind about whether the environment at the interpolated sounding site was used to determine the event type, or whether the environment at tornado touchdown was used. This could be a significant issue in cases with subtle, small-scale boundaries, as the author states that "the model analysis soundings were valid with a 40-km radius and 30 min of a radar identified supercell". In the second paragraph of the methodology section, the author states that "subjectively analyzed surface maps, visible satellite and WSR-88D reflectivity data were used to classify each sounding as being a warm sector or boundary event." So this leads me to believe that the classification was based on the environment at the model analysis sounding. However, the second paragraph then goes on to describe a scenario where a storm is classified after it moves off its initiating boundary and produces a tornado away from the boundary. This leads me to believe that the classification is being done based on the author's analysis of the environment at tornado touchdown (which may be 40 km and/or 30 min away from the analysis sounding). The rest of the manuscript also seems to indicate that the classification was based mainly on the location of tornado [genesis], and not necessarily the location of the sounding. So, I would appreciate some clarification on this.

The radar-identified thunderstorm and its location on the respective subjectively analyzed surface chart were used as the method of classifying whether the tornado event was in the warm sector or on a baroclinic boundary. I have attempted to remove any words in the manuscript that lead to uncertainty with regard to this aspect in the methodology.

The small-scale nature of boundaries associated with many of these events is also a concern. How sure is the author that some "warm sector" events did not occur at locations with subtle small-scale boundaries associated with previous or on-going convection that were missed in the analysis? I'm sure that the answer to this question is that the author did as a good a job as was possible, given the observational data that was available, and the challenges associated with finding these small-scale boundaries. However, the difficulty associated with identifying these small, subtle boundaries might make this study hard to duplicate. Some brief discussion on this issue would be appropriate.

Using operational data sets (i.e., surface observations, radar, and visible satellite imagery), I made a best effort to identify tornadic thunderstorms interacting with surface baroclinic boundaries associated with an observable temperature gradient. I cannot discount the possibility of storms interacting with boundaries that are not resolved by the data sets available. However, I have no way of quantifying this uncertainty. I added two additional sentences at the end of the second paragraph in the methodology to emphasize this possibility.

Another issue related to identification of boundaries: I wonder how many of the "non-boundary" events occurred in close proximity to significant frontal zones aloft? The strong, deep vertical wind shear associated with many of these events indicates that they must have occurred in a large-scale environment associated with significant baroclinicity, based on thermal wind arguments. So, my guess would be that many of these events occurred with frontal zones aloft. If that is the case, then it may be misleading to characterize these events as not occurring along "baroclinic boundaries". Maybe "surface" or "low-level baroclinic" boundaries would be more precise?

Addressing the first comment: Although a frontal zone aloft may play a role in the initiation of thunderstorms, the current peer-reviewed literature does not suggest that frontal boundaries above the surface play an important role in tornadogenesis. Therefore, I did not attempt to identify these kinds of fronts.

I agree that the strong deep-layer vertical wind shear is most certainly a result of large-scale significant baroclinicity of the kind that promotes extra-tropical cyclone development. However, these shears are observed across much of the warm sector, and not concentrated immediately along narrow frontal zones aloft. I agree with your final point, and have specified surface baroclinic boundaries throughout the paper to clear up any confusion with upper-level baroclinic zones.

Environments associated with strong deep-layer shear associated with fronts aloft make sense, however I am still not sure that I understand why an environment without a low-level baroclinic zone would have strong low-level shear. I understand how strong pressure gradients can produce strong low-level winds in these cases, but not strong shear. Thermal wind theory indicates that strong geostrophic wind shear requires baroclinicity. So, is the strong shear being generated by some kind of non-geostrophic process? I am assuming that these significant tornadoes occurred with surface-based convection (not elevated), so that the strong shear would not be associated with decoupling and the usual Great Plains nocturnal jet. In my experience, which admittedly is mostly for the eastern U.S., strong low-level shear in a convective environment is usually associated with veering winds, warm advection, and low-level baroclinicity. Some discussion or clarification of this would be appreciated.

Non-geostrophic processes may have contributed to the strong vertical wind shear observed for warm sector environments. Uccellini and Johnson (1979) and Uccellini (1980), as well as Beebe and Bates (1955) showed that the low-level jet stream accelerates beneath the exit region of ejecting upper-level jet streaks. This often leads to strong and widespread low- and deep-layer vertical wind shear favorable for supercells and tornadoes across the warm sector of synoptic-scale cyclones. Thus, the role of low-level baroclinic boundaries in producing favorable shear for supercells/tornadoes may be less important for warm sector environments associated with strong ETC's.

At one point in the manuscript, the author points out that the RUC analysis of shear may be misleading at locations near boundaries, in that the resolution of the RUC may be inadequate to detect small-scale augmentations to the buoyancy and vertical wind shear occurring along these boundaries. I think that this is a good point, and I agree that this could compromise your results. This factor may require more discussion in the manuscript. Would analysis soundings from higher resolution models help to resolve this problem? How serious is this problem?

I don't have additional soundings or higher resolution model data sets to address this problem for the events examined. Therefore, I can only speculate on how significant the problem may be.

In the introduction, the author states that work from Markowski and Rasmussen indicated that "the occurrence of significant tornadoes requires a source of augmented streamwise vorticity that is many times greater than what is observed within the ambient environment, and this augmentation is most likely to occur at the meso-beta scale in association with baroclinic boundaries". However, the next paragraph goes on to indicate that there have been many significant events that have occurred in the absence of low-level boundaries. This study also seems to indicate that low-level baroclinic boundaries may not be necessary for tornadogenesis. Some discussion on this apparent discrepancy might be appropriate in this paper. Do the results of this study disprove the hypothesis given in the 2nd paragraph of the introduction? If so, what might be generating the streamwise vorticity for these "non-boundary" cases? Might it just be that the thermal boundaries in the warm sector cases are too small to observe using standard operational data sets? If that is the case, then maybe the best way to describe the presence of baroclinic boundaries in tornadic environments is that a continuum of boundary scales exists, from large-scale to very small-scale and subtle.

The results do not disprove the hypothesis given in the 2nd paragraph of the introduction. I made a slight modification to the 2nd paragraph in order to include an additional information from Rasmussen et al. (2001), which reads as: "These observations led to an additional hypothesis, that the large-scale rarely produces sufficient vorticity for the occurrence of significant tornadoes, therefore a source of augmented streamwise vorticity that is many times greater than what is observed within the ambient environment is needed, and this augmentation is most likely to occur at the meso-beta scale in association with baroclinic boundaries. Therefore, significant tornadoes should rarely be observed away from boundaries."

One possible mechanism for mesoscale boundary production for warm-sector significantly tornadic storms is elongated baroclinic zones produced beneath anvils spreading downstream from the updraft (Markowski et al. 1998b). Temperature deficits near the surface beneath the area shaded by the anvil may lead to augmented horizontal vorticity. Long anvils are most favored with large-scale environments characterized by strong upper-level winds. Long anvils would result in the largest parcel residence times within the anvil-generated baroclinic zone, given the low-level storm-relative inflow vector is favorably aligned with the baroclinic zone. In addition, Markowski et al. (1998a) argue that strongly sheared environments (such as those for warm sector significantly tornadic synoptic-cyclones) favor elongated forward-flank baroclinic zones which could provide a source of augmented horizontal vorticity necessary for tornadogenesis. Paragraph 3 has been added to the methodology to discuss this possibility. A reference to Markowski et al. (1998b) has been added.

Finally, the results indicated that warm sector events tended to be associated with more injuries, fatalities, and damage, possibly due to the longer-lived nature of these events. Was there any indication that your "warm sector" events were associated with stronger tornadoes than your baroclinic zone tornadoes, as measured by the EF scale?

The mean F/EF scale rating for warm sector significant tornadoes is 2.81, while the mean for boundary significant tornadoes is 2.59. So, warm sector events were associated with slightly stronger tornadoes compared to the boundary events. However, the difference in means is statistically insignificant.

[Minor comments omitted...]

Second Review:

Reviewer recommendation: Accept with minor revisions.

General comments: Thanks again for the opportunity to review this paper. After reviewing the paper for a second time, I continue to find it to be well-written, and I am certain that it will be of great interest to operational meteorologists. It contains lots of good information, and I have certainly learned a few things while going through it, along with having some other good information reinforced. Below are a few comments after my second review. My recommendation continues to be to accept for publication pending minor revisions.

Substantive comments: After a second review of this paper, here is my take on what has been found. I believe that I am beginning to understand better why the warm sector events are associated with more shear than the boundary events. (Initially, I found this to be counter-intuitive, as I assumed that boundaries should be associated with more vertical wind shear than non-boundaries). It seems that these warm sector events are typically associated with deep cyclones and lots of large-scale baroclinicity, and therefore lots of low-level and deep-layer shear, which is well-sampled by the coarse RUC model analysis. The strong wind fields associated with these storms result in fast storm motions, and the storms typically move quickly away from their initiating boundaries. This means that when tornadogenesis occurs, it is at some distance away from the initiating boundary. Since these storms are quickly separated from their initiating boundary, they tend to be isolated, and therefore they can last for long periods of time in a favorable high-shear, unstable environment, without interference from other storms. Their long life cycles allow for plenty of time for storm-scale augmentation of low-level vorticity (such as anvil shading or baroclinic generation of vorticity along the forward flank downdraft) to eventually generate a tornado, in the absence of a mesoscale boundary.

By contrast, the typical boundary event may actually be associated with a weaker large-scale cyclone, less large-scale baroclinicity, and weaker wind fields than the warm sector events. The weaker wind speeds result in slower storm motions, and the storms are more likely to remain close to their initiating boundaries. The shear in the immediate vicinity of these storms, very close to the boundary, may be every bit as large as the shear in the immediate vicinity of storms in the warm sector events, but the 20 to 40 km resolution of the RUC does not allow for the shear to be fully resolved near the small-scale boundaries. However, the larger-scale environments associated with these events are actually not as baroclinic as in the warm sector events, therefore the large-scale shear that the RUC is able to analyze is smaller for the boundary events. These storms tend to have short life cycles, since they are susceptible to destructive interference from other nearby storms along the boundary. However, they can produce tornadoes more quickly than the warm sector events, since they are able to ingest vorticity from the nearby mesoscale boundary, in addition to vorticity from storm-scale processes, and maybe from storm mergers.

As a side note: I would be interested in knowing whether I am right to assume that the warm sector events tend to be associated with the deeper cyclones and more large-scale baroclinicity. This could be considered outside of the scope of the work, but I wonder if a composite analysis would show this?

I think that the author covered much of the above pretty well in the manuscript. From my point of view, the key thing to realize is that the differences being found between the two types of events in this study are differences in shear and wind speed on scales that are resolvable by the 20–40 km RUC. These differences are probably valid in the inflow region of the storms, but these differences may not be valid in the immediate vicinity of the storms. I am not saying that this makes these findings are invalid; in fact they should be quite useful to forecasters, since forecasters often evaluate potential storm environments using model data with resolutions that are insufficient to fully resolve small-scale boundaries and the associated shear. My main point here is that the reader should realize that this is a study of the large-scale inflow associated with these storms, and not necessarily the immediate storm environment.

After reading the paper again, I still have a few issues that I would like to see clarified, mainly in the methodology section.

1) During the course of the study, the resolution of the RUC changed from 40 km to 20 km. I wonder if this had an impact on the results, given the issues related to resolution that I discussed above. One possibility would be to check whether results from the sounding parameter section were similar if one were to only use data from 2003–2005, vs. the entire data set. If the results are similar, then that would indicate that the change in resolution did not make a big difference in the study results.

I performed statistical tests which evaluated the difference in mean thermodynamic and wind parameters for the RUC40, RUC20, and RUC13 warm sector significant tornado proximity soundings. The tests revealed that the difference in means for all mean-layer (ML) thermodynamic parameters is statistically insignificant, except for ML-mixing ratio, in which the RUC13 was more moist in the boundary layer than the RUC40 and RUC20. The difference in means for 850 hPa, 500 hPa, and 250 hPa wind speeds was statistically insignificant for all three sounding data sets. This information has been added to the methodology.

2) I am wondering how drylines were handled in the methodology. It seems that temperature was used to determine boundaries. Since the big difference across a dry line is moisture, and not necessarily temperature, would the methodology ignore dry lines?

Drylines were analyzed as an elongated zone generally oriented in a north-south direction where the change in surface dewpoint indicates the presence of a large moisture gradient, using standard METAR surface observations. I modified the methodology to specify that temperature and dewpoint were contoured.

3) I don’t understand how this study could be done without defining some kind of “distance from the boundary” criteria for a warm sector vs. boundary event. Don’t you need some kind of threshold?

The resolution of the observations available to me during this study wouldn’t allow a detailed/accurate calculation of the distance between storm and boundary.

4) At one point in the methodology section, it is indicated that events with numerous tornadoes, some of which occurred along boundaries and some of which occurred in the warm sector, were counted as warm sector events. I am guessing that most of these events were high-end events, that may have been associated with particularly strong low-level wind fields. Does counting these event as only warm sector events bias your findings toward finding that warm sector events have stronger wind fields? What if you were to count these events as both warm sector and boundary events (i.e. “double count” them)?

The major constraint on this study is the use of a pre-existing database of RUC analysis soundings that were taken in near proximity to tornadic supercells. These tornadic supercells were identified as occurring either in the warm sector, or on a boundary, thus their associated proximity sounding can’t be double counted as both a warm sector and boundary sounding. The sounding either represents the environment of the warm sector, or of a boundary, but certainly not both.

Thanks again for the opportunity to review this paper.

REVIEWER C (Jeffrey Frame):

Initial Review:

Reviewer recommendation: Accept with major revisions.

General comments: This manuscript includes a statistical analysis of severe thermodynamic and dynamic severe weather parameters obtained from RUC proximity soundings for both significant (EF2+ or F2+) tornadoes occurring both in the warm sector of extratropical cyclones and along baroclinic boundaries. This analysis shows that thermodynamic parameters are roughly the same for significant tornadoes occurring in both environments, but that dynamic parameters (e.g., vertical wind shear, storm-relative helicity, etc) are significantly greater for warm sector events. While this analysis is interesting, I believe that the results are misinterpreted as being a function of the storms occurring within the warm sector and not along baroclinic boundaries. I think that a more correct interpretation of these results is that the strong vertical wind shear that typifies many significant tornado outbreaks necessarily leads to fast storm motions, by which storms quickly propagate away from their initiating boundaries and into the warm sector. This interpretation is supported by many findings from this paper, including a strong correlation between warm sector tornadoes and supercell propagation speed. A more detailed discussion of this follows in the comments. There are also a few other major issues regarding how other types of boundaries, such as drylines, were treated in the study and how multiple significant tornadoes from the same date were included in the sampling.

Major comments:

1. As stated in the General Comments, I believe that the statistically significant differences found in the vertical wind shear-derived parameters between significant tornadoes occurring within the warm sector and significant tornadoes occurring along boundaries can best be explained by the differences in storm motion between strongly sheared environments (more favorable for significant tornadoes) and weakly sheared environments (less favorable for significant tornadoes).

The shear is not a function of the speed of the storm. Instead, the storm speed is a function of the shear and deep-layer mean flow.

In strongly-sheared environments typical of significant tornado outbreaks (e.g., southerly winds near the surface veering to westerly and increasing in speed with height such that the environmental hodograph possesses significant clockwise curvature and length), the thermal wind relationship and friction will generally result in faster ground-relative storm speeds, while in more weakly sheared environments, slower ground-relative storm speeds will usually result.

Yes, I agree.

Given that the overwhelming majority of supercell and other storms initiate along some type of surface boundary, it follows that faster moving storms are much more likely to move away from their initiating boundary than slower moving storms, especially if the deep-layer mean shear vector (which is related to storm motion through Bunkers and other methods) is directed normal to the initiating boundary.

Yes, I agree.

Boundary-normal shear also tends to favor more discrete supercell thunderstorms (e.g., Markowski and Richardson 2010, Figure 9.2). Storms are even more likely to move off of their initiating boundary if the propagation speed of that boundary is not determined by the low or middle level atmospheric flow, but rather by differential vertical mixing, as is the case for drylines. Interpreting the results in this way will change the interpretation of many of the conclusions presented, as discussed below.

The fact that tornadic storms move off their initiating boundary due to the environmental factors you listed above is not a major result.

> For example, Figs. 7 and 8 present the number of warm sector and boundary significant tornadoes by month, and illustrate that nearly all cool season tornadoes occur within the warm sector, and not along boundaries. I think that a more useful interpretation of this result is that the strong storm speeds that arise owing to the fast jet stream common during the cool season quickly allow any storms to propagate away from their initiating boundaries.

Yes, you are describing a possible reason for why storms are more likely to move off their initiating boundary during the winter and spring. I don't disagree with your reasoning.

> It is also possible that the strong linear forcing for ascent commonly found along boundaries during the cool season quickly forces a linear mode there, meaning that many isolated supercells likely will be located in the warm sector.

I didn't examine the magnitude of forcing for ascent, but it is probable that ascent is stronger along boundaries, so storms that interact with a boundary for a greater period of time are more likely to be of a non-discrete form, while weaker forcing for ascent over the warm sector favors a discrete convective mode.

> Similarly, Fig. 12 shows that warm-sector events are associated with greater values of 850 hPa wind speed, and hence greater values of low-level bulk wind difference (Figure 13) than are events that occur along boundaries. Noting, however, that significant tornadoes are commonly associated with deepening or intense mid-latitude cyclones, which themselves are associated with strong low-level pressure gradients and hence fast low-level flow and strong low-level shear (due in part to surface friction), one can reach the conclusion that again, fast storm motions, owing to the strong midlevel wind speeds commonly associated with such events are the cause of the significant tornadoes occurring away from their initiating boundaries. One can make an identical argument for the 500-hPa flow and 0–6 km bulk wind difference presented in Figs. 14 and 15.

Again, I don't disagree with your reasoning. But how does that influence tornadogenesis?

> While it is noted that storm motion is the most statistically significant discriminator between warm-sector and boundary significant tornadoes, there is little analysis as to why this may be (e.g., on p. 6) or as to what effect this may have on the ability of storms to move away from their initiating boundaries before causing significant tornadoes.

The primary focus of the paper is on the tornado parameter space, not on the background dynamical processes that promote the parameter values observed. However, I do provide a reference for supercell storm motion (Bunkers et al. 2000), which describes that supercell storm motion is a function of the mean wind through a deep-layer, and a propagation component transverse to the mean shear. I do understand your desire to see a more detailed analysis of the storm-motion vector with respect to the geometry of the warm sector…but this is a project that I would rather follow up on in a separate study.

> In fact, the role of boundaries in the initiation of convection is absent from the manuscript entirely.

That is not true. I state in the methodology…that storms move off their initiating boundary and produce tornadoes in the warm sector.

> Storm speed is a function of the large-scale environment in which the storms are embedded; no evidence is presented that storms in the warm sector will move faster, or cause more significant tornadoes than storms along boundaries provided the environments are equal. I believe that this additional analysis and reinterpretation of many of the results presented herein will greatly strengthen this manuscript.

First, the stronger wind fields at 850 hPa, 500 hPa, and 250 hPa for warm sector events do provide evidence that warm sector storms will move faster. Second, I do provide direct evidence that warm sector storms will move faster—that data show that they do move faster. Third, I never implied that fast storm motions will cause more significant tornadoes compared to storms interacting with boundaries.

2. The manuscript states that baroclinic boundaries were identified through the calculation of temperature gradients, but no mention is made of how certain types of boundaries (e.g., drylines, prefrontal troughs, or upper-level fronts) were accounted for in the study (in last paragraph in section 1, for example) or if they were even included.

This paper is not a climatology of boundaries that enhance the potential for tornadoes. The focus of the paper is on the parameter space for significant tornadoes occurring in the warm sector versus boundaries.

Drylines are important thunderstorm-initiation mechanisms. For example, in the Oklahoma tornado outbreaks of May 3, 1999; May 10, 2010; and May 24, 2011; tornadic thunderstorms were all directly initiated by drylines, then propagated away from them, but the manuscript does not state if drylines were identified in a method different from that used to spot surface fronts, or even if they were included at all.

The dryline did not lead to the initiation of most tornadic storms during the 3 May 1999 outbreak. A horizontal convective roll (HCR) initiated storm A, and the nocturnal portion of that tornadic event appeared to initiate in the warm sector within the exit region of the strengthening low-level jet stream.

I added cold fronts and drylines as an initiating boundary for warm sector storms in the methodology….

If drylines are to be included, I strongly recommend using virtual temperature or equivalent temperature to identify all types of surface boundaries, as this will allow the "warm" (moist) side of a dryline to also be the side of the boundary typically most supportive of deep moist convection, preserving consistency with other types of baroclinic boundaries. It also must be stated somewhere how surface wind shifts owing to pre-frontal troughs or upper-level fronts were treated or excluded, as these can also be important features in the initiation of warm sector convection (e.g., June 17, 2010) or tornadogenesis.

Drylines were analyzed as a boundary that focused supercell initiation. They were quite easy to identify using dewpoint temperature.

No attempt was made to located upper-level fronts as a cause for storm initiation. I do not know of any peer-reviewed literature that describes upper-level fronts as a feature which will enhance the potential for tornadogenesis. Therefore, I don't believe it is relevant for this study.

No warm sector tornadic thunderstorm in the data set used in this study occurred within a surface wind shift associated with a pre-frontal trough. I added to the methodology that no wind shift interactions were observed for warm sector tornadic storms.

I am also uncertain as to exactly how thunderstorms were defined as to being within a baroclinic zone. Was a distance threshold applied to determine whether or not a storm was within a boundary? For example, if a storm produced a tornado 5 or 10 km in front of a satellite cloud line or radar fine line whose exact location was not resolvable by the surface observations, would this tornado be considered as occurring along a boundary or within the warm sector? I believe that this additional clarification will greatly benefit the submitted manuscript through the removal of ambiguity.

I matched the time of tornado occurrence with the radar echo and associated subjectively analyzed surface chart. If the radar echo was located within an analyzed temperature gradient, it was defined as a boundary event. No attempt was made to determine the spatial distance from the surface representation of a boundary a tornadic storm. Furthermore, the visible satellite and radar imagery increased confidence in the presence of a boundary, but the subjectively analyzed surface charts were the primary tool for locating boundaries associated with a baroclinic zone. I added this information to the methodology.

3. On page 3, it is noted that when multiple significant tornadoes occurred on the same date, both along baroclinic boundaries and within the warm sector, "deference was given to the warm sector, ... to obtain a larger warm sector sample size." While it is obviously important to have a statically significant sample size of events, it is just as important that any sorting or grouping of these events occur without

biasing or influencing the results. For example, if I were to conduct a study as to whether the Interstate highway system was a cause of significant tornadoes within supercells, but count dates on which significant tornadoes occurred both near and far from Interstate highways as having occurred only near Interstate highways in order to get a larger sample of tornadoes occurring near Interstates, I may end up with a result that is vastly different from reality: that Interstates are related to the development of significant tornadoes within supercells. I believe that your analysis would be strengthened with a discussion of how the results change if major events are "double counted;" that is, for dates on which significant tornadoes occurred both along boundaries and within the warm sector, each relevant proximity sounding is included in the proper statistical category (warm sector or boundary). If no significant difference is found from the current results, then my concerns are unfounded and this should be stated. If, however, significant differences are discovered, I believe that the sampling methodology must be modified in a way as to not bias the results toward warm sector tornadoes.

The deference to warm sector events resulted in the exclusion of four boundary proximity soundings, which is a statistically insignificant number of soundings. I added this information to the methodology.

4. I think that there are a couple portions of the manuscript that can be shortened, or else deleted altogether. The analysis of injuries and fatalities on page 8 is one section I believe can be shortened. It is rather obvious that tornadoes that move faster and are on the ground longer are likely to cause more injuries and fatalities, as stated in the manuscript.

I agree, it is obvious to you and me, but it may not be obvious to other readers. Therefore, I would like to keep that part of the discussion.

The detailed discussion of statistically insignificant thermodynamic parameters that begins on page 9, and continues through most of page 10 should be deleted as it adds little to the paper or overall conclusions: If these results are insignificant, why present them? The statistical insignificance of these parameters can easily be grouped into one of the sentences in the first paragraph of section 4a that describes the similar statistical insignificance of other thermodynamic parameters.

I agree. I shortened this section considerably. One paragraph describes the null results, and the presentation quickly moves on to more meaningful results.

[Minor comments omitted...]

Second review:

Recommendation: Accept with minor revisions.

General comments: This revised manuscript presents a statistical study of the differences between environments supportive of tornadoes occurring along boundaries and those occurring within the warm sector. I believe that this manuscript has been significantly improved over the previous version, as much of the extraneous material has been removed and the scope of the manuscript is more focused and limited. I believe that all of my major and minor comments from my previous review have been satisfied, and I believe that only a few minor changes remain before the manuscript is ready for publication. My primary comment, regarding the ability of faster storms to move off their boundaries and into the warm sector is now present in the manuscript, and I think this aids the interpretation of the results. Note that while many of these remaining comments focus on grammatical or other stylistic issues, a few of these comments offer what I believe is needed extra interpretation of the results in a few areas.

[Minor comments omitted...]