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A Study of Synoptic-Scale Tornado Regimes

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ABSTRACT

The significant tornado parameter (STP) has been used by severe-thunderstorm forecasters since 2003 to identify environments favoring development of strong to violent tornadoes. The STP and its individual components of mixed-layer (ML) CAPE, 0–6-km bulk wind difference (BWD), 0–1-km storm-relative helicity (SRH), and ML lifted condensation level (LCL) have been calculated here using archived surface objective analysis data, and then examined during the period 2003−2010 over the central and eastern United States. These components then were compared and contrasted in order to distinguish between environmental characteristics analyzed for three different synoptic-cyclone regimes that produced significantly tornadic supercells: cold fronts, warm fronts, and drylines. Results show that MLCAPE contributes strongly to the dryline significant-tornado environment, while it was less pronounced in cold-frontal significant-tornado regimes. The 0–6-km BWD was found to contribute equally to all three significant tornado regimes, while 0–1-km SRH more strongly contributed to the cold-frontal significant-tornado environment than for the warm-frontal and dryline regimes.

1. Background and motivation

Parameter-based and pattern-recognition forecast techniques have been essential components of anticipating tornadoes in the United States during the past half century (Schaefer 1986; Doswell et al. 1993). Initial efforts to classify environments known to have produced tornadoes include Beebe (1956) and Miller (1972), among others, and focused mainly on composite means of surface and upper-level data for tornado days. These studies highlighted synoptic-scale cyclones characterized by a warm, moist low-level air mass extending poleward beneath a cold, dry midlevel air mass. Changes in wind speed and direction with height were also observed, and attributed to the presence of a low-level southerly jet stream beneath the exit region of strong mid and upper-level jet streaks. These proximate jets were shown to enhance vertical wind shear as well as to aid in destabilization and the release of convective instability (Beebe and Bates 1955; Uccellini and Johnson 1979).

As detailed in Hobbs et al. (1996), synoptic-scale cyclones that foster tornado development evolve with time as they emerge over the central and eastern contiguous United States (hereafter, CONUS). Tornadic thunderstorms over the Great Plains may emanate from a dryline initially. For example, the dryline environment described by Bluestein et al. (1988) associated with tornadoes on 7 May 1986 was characterized by a hot, deeply mixed afternoon boundary layer west of the dryline, and a low-level moist layer east of the dryline surmounted by steep midlevel lapse rates. Resulting CAPE values ranged from 3000–4000 J kg^{-1}. Proximity hodographs showed clockwise turning of wind vectors with height, and speed shear over the lowest 6 km AGL (hereafter all height references are AGL) around 22 m s^{-1}.

As the synoptic-scale cyclone matures and moves east of the Great Plains, a cold front may overtake the dryline. A preliminary study by Guyer et al. (2006) found that 55% of cool-season significant tornadoes (rated at least F2) from 1984–2004 in the Gulf Coast states occurred in the warm sector along or ahead of a cold front attendant to a synoptic-scale low-pressure system. Environments associated with

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these events featured a moist surface air mass (mean dewpoint of 18°C) but weak 700–500-mb lapse rates (6.0–6.8°C km^{-1}), which resulted in mixed-layer (ML) CAPE values generally ranging from 900–1700 J kg^{-1}. Due to the southward migration of the polar jet during the cool season, combined with strong flow in the 1–2-km layer, vertical speed shear was pronounced.

In contrast to tornadic storms moving into the warm sector away from drylines and cold fronts, tornadic storms occurring on boundaries are located along the edge of the warm sector within baroclinic zones. Boundaries that favor tornadic supercell development range from synoptic-scale warm fronts and stationary fronts, to outflow boundaries produced by earlier thunderstorms. Most research studying tornadic storms along baroclinic boundaries shows that the augmentation of vorticity in a baroclinic zone beyond what occurs in the ambient environment increases the potential for significant tornadoes as thunderstorms interact with it (e.g., Maddox et al. 1980; Markowski et al. 1998; Rasmussen et al. 2000).

Current understanding of the parameter space favorable for significant tornadoes primarily focuses on environments of supercells (Lemon and Doswell 1979; Doswell et al. 1993) that acquire low-level updraft rotation and produce specific thermal characteristics in rear-flank downdrafts (RFDs). While deep-layer shear is used to forecast supercells (Weisman and Klemp 1982, Thompson et al. 2003; hereafter T03), the shear profile over the lowest 1 km appears to be more relevant to low-level mesocyclone development and increased tornado potential (Rasmussen 2003; T03). Proximity sounding studies also have found that significant tornadoes are more likely when the height of the lifted condensation level (LCL) is <2000 m, which favors a greater potential for buoyant RFD's (Rasmussen and Blanchard 1998; Markowski 2002; Markowski et al. 2002; T03).

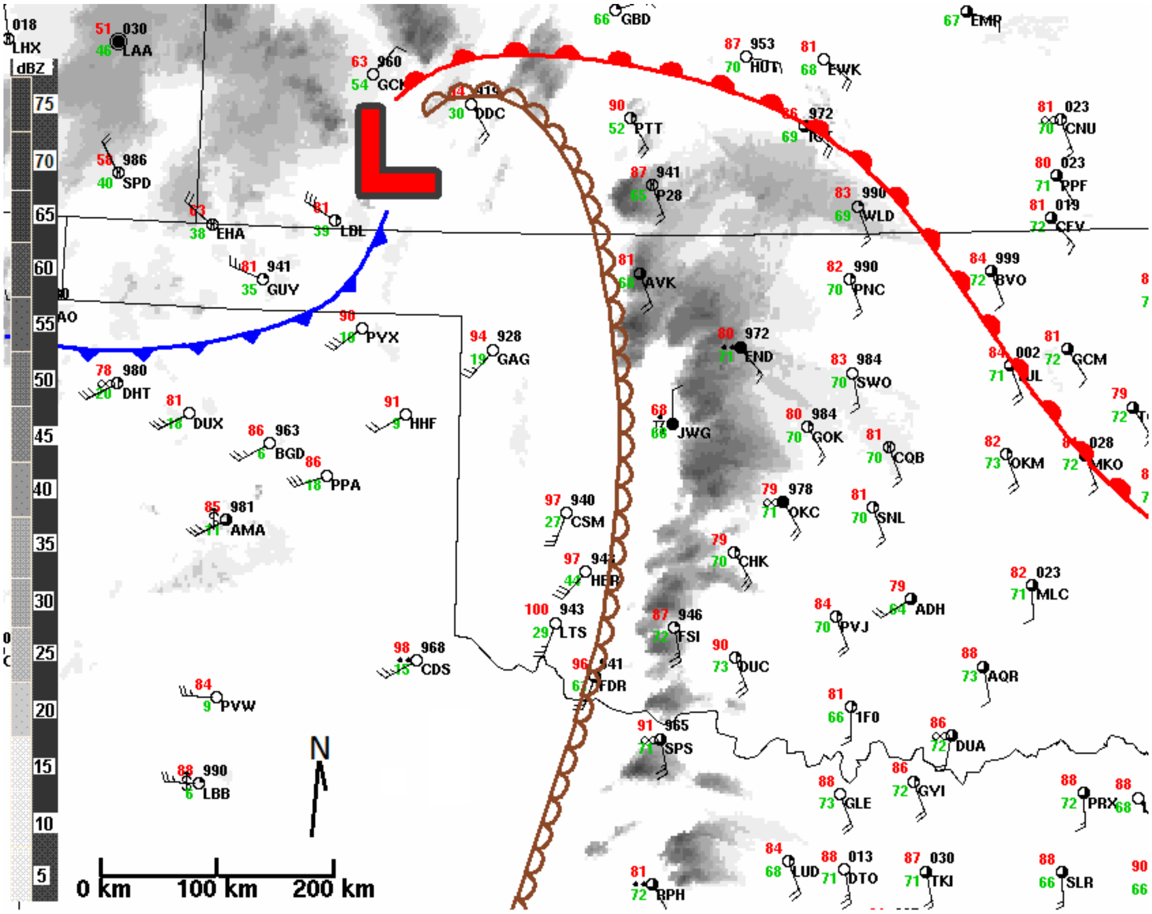
Combinations of CAPE and vertical wind shear also are used in composite indices. Though these composite indices have been shown to discriminate more strongly between tornadic and nontornadic environments when compared to their individual components (Rasmussen and Blanchard 1998), it is important to understand that no composite index will perform favorably under every meteorological situation (Doswell and Schultz 2006). The significant tornado parameter (STP; T03; Thompson et al. 2004) combines normalized values of CAPE, deep-layer bulk wind difference (BWD), storm-relative helicity (SRH), and LCL height into a composite index. Each parameter was selected from a sample of tornadic and nontornadic Rapid Update Cycle (RUC; Benjamin et al. 2004a,b) model proximity soundings. Thresholds used to normalize each parameter were derived from statistically significant differences that distinguish between significantly tornadic and weak or nontornadic supercell environments.

The motivation for this paper is to evaluate the most important tornado forecast parameters for three prominent synoptic-scale regimes associated with significant tornadoes: cold fronts, warm fronts, and drylines. Because the STP shows favorable skill in discriminating between significant and weak tornado environments, the relative contribution of its components (MLCAPE, 0–6-km BWD, and 0–1-km SRH) have been used to distinguish the three environments. In addition, MLLCL height, ML convective inhibition (CIN), and convective mode also were evaluated in this study. Section 2 will present the methods used to collect and classify events, as well as the data source and method of computation for the STP. Results will be given in section 3, and a summary and discussion will conclude the paper.

2. Methodology

For the 2003–2010 period, all recorded tornadoes (12 552) and their respective attributes (such as F/EF-scale rating, tornado path length, fatalities, and injuries) were evaluated for possible inclusion in this study using the online program Severe Plot [Hart and Janish 2012; (http://www.spc.nssl.noaa.gov/climo/online/sp3/plot.php)] and the online version of NOAA Storm Data [NCDC 2012; (http://www.ncdc.noaa.gov/stormevents)]. Though the primary focus of this study is on the environments of significant tornadoes, weak tornadoes were included for comparison purposes.

The Storm Prediction Center severe thunderstorm events website (http://www.spc.noaa.gov/exper/archive/events/) then was used to determine whether these tornadoes occurred with a synoptic cyclone. A synoptic cyclone is defined for this study as an area of surface low pressure with winds flowing counterclockwise in the northern hemisphere, and not associated with a tropical cyclone. The cyclone had to display closed isobars around the center of surface low pressure, as well as a frontal-wave structure that emanated from the surface low. Typical cyclones generally resembled the idealized extratropical cyclone described by Heuboer et al. (1996), though the size of the cyclones analyzed in the current study varied from an area of several states to almost the entire CONUS. Archived surface meteorological aviation report (METAR) plots also were used for subjective pressure analysis, gradients in temperature and dew point (as in Garner 2012), as well as streamlines during the hour of tornado occurrence, which allowed surface frontal features associated with the cyclone to be determined. In addition, archived visible and infrared satellite imagery were used to aid further in determining frontal location. These procedures allowed the identification of one or more of the following boundaries: the dryline, the warm front, and the cold front (Figs. 1 and 2).



<u>Figure 1</u>: Example of a typical surface dryline and warm front, associated with tornadoes on 2100 UTC 24 May 2011. Boundaries are drawn and observations plotted conventionally, with English units for temperature (red) and dewpoint (green). For wind observations, half barb is 5 kt (2.5 m s^{-1}), full barb is 10 kt (5 m s^{-1}). Grey shading is composite radar reflectivity representation of thunderstorms emanating off of the dryline, and moving poleward toward and across the warm front.

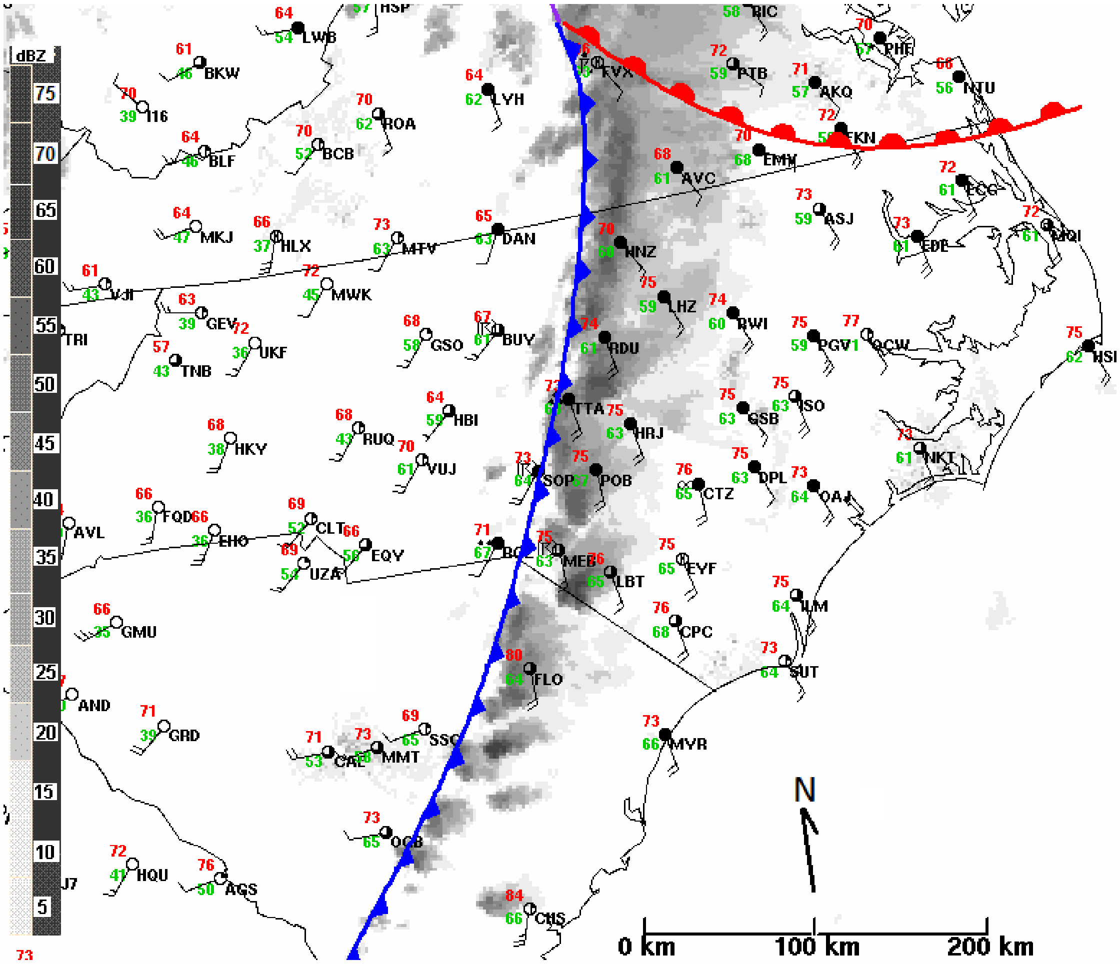


Figure 2: As in Fig. 1, except for a cold-frontal regime from southern Virginia across the Carolinas on 1900 UTC 16 April 2011.

Though tornadoes associated with drylines, warm fronts, and cold fronts can occur under quiescent large-scale conditions, only boundaries associated with a synoptic-scale cyclone were included as a way to standardize the background environment for all tornado events. A tornado was associated with a synoptic cyclone if it was located within the bounds of the warm sector (or on the fringe, in the case of warm-frontal events). The warm sector is typically downshear of a cold front or dryline, and upshear from a warm front. In addition, tornadoes were only included in this study if their parent storm emanated from a cold front or dryline, or interacted with a warm front. If a storm emanated from a dryline or cold front, any tornadoes occurring downshear across the warm sector were binned with either of those respective boundaries. If a storm crossed the baroclinic zone of a warm front, any tornadoes produced were classified as warm-frontal.

These criteria yielded 580 significant and weak tornadoes associated with one of the synoptic cyclone boundaries. For clarification, if a synoptic-cyclone was associated with a significant tornado, any weak tornadoes occurring with the same cyclone were excluded from this study. Thus, the total number of tornadoes occurring with a cyclone during the 2003–2010 period is >580. Out of the 580 tornadoes, 153 were dryline-related, 234 from a cold front, and 193 occurred on a warm front. For significant tornadoes, 97 (26%) were warm-frontal, 103 (27%) were dryline, and 180 (47%) were cold-frontal. For weak tornadoes, 96 (48%) were warm-frontal, 50 (25%) were dryline, and 54 (27%) were cold-frontal. No distance criteria were set for storms that emanated from a cold front or dryline, but on average, storms associated with each boundary type produced tornadoes 108 km from drylines, 51 km from cold fronts, and 13 km from warm fronts.

Following these steps, archived hourly mesoscale surface objective analysis fields (SFCOA; Bothwell et al. 2002; Schneider and Dean 2008) were used to extract MLCAPE, 0–6-km BWD, 0–1-km SRH, MLLCL height, and MLCIN from the nearest SFCOA grid point using the date, time, latitude, and longitude for the start of each tornado or cluster of tornadoes. The SFCOA was a RUC based objective analysis scheme (now the Rapid Refresh model as of 2012; Benjamin et al. 2007), using observations to modify surface conditions in 1-h RUC forecasts. Thus, changes to the RUC occurring during the 2003–2010 period of study are carried through to the SFCOA dataset (some of these changes are reviewed in Garner 2012). This step yielded 144 grid points associated with one or more significant tornadoes; 67 being cold-frontal, 50 warm-frontal, and 27 dryline-related. If a cluster of tornadoes occurred, then the grid point that matched up with the time, latitude, and longitude for the highest F/EF rating or longest path length was used to extract the SFCOA data.

Two formulations of the STP were available for this project. The first iteration, termed the fixed-layer STP (T03) is calculated in the following manner:

$$\begin{aligned} \mathrm{STP} = {} & (\mathrm{MLCAPE}/1000\ \mathrm{J\ kg^{-1}}) \\ & \times (\mathrm{SHR6}/20\ \mathrm{m\ s^{-1}}) \\ & \times (\mathrm{SRH1}/100\ \mathrm{m^{2}\ s^{-2}}) \\ & \times [(2000\ \mathrm{m} - \mathrm{MLLCL})/1500\ \mathrm{m}], \end{aligned} \qquad (1)$$

where SHR6 is the 0–6-km BWD, and SRH1 is the 0–1-km SRH. Thompson et al. (2007) showed that measures of SRH and deep-layer BWD were more physically meaningful when defined by an effective inflow layer and storm depth, which better accounted for elevated storm environments, as well as for very tall and short storms. In addition, these measures of effective low-level and deep-layer shear showed a better ability in discriminating between significantly tornadic versus nontornadic supercells.

Accordingly, Thompson et al. (2004) revised the original STP calculation as follows:

$$\begin{aligned} \mathrm{EFF\text{-}STP} = {} & (\mathrm{MLCAPE}/1500\ \mathrm{J\ kg^{-1}}) \\ & \times (\mathrm{EFF\text{-}BWD}/20\ \mathrm{m\ s^{-1}}) \\ & \times (\mathrm{EFF\text{-}SRH}/150\ \mathrm{m^{2}\ s^{-2}}) \\ & \times [(2000\ \mathrm{m} - \mathrm{MLLCL})/1500\ \mathrm{m}] \\ & \times [(250\ \mathrm{J\ kg^{-1}} + \mathrm{MLCIN})/200\ \mathrm{J\ kg^{-1}}], \end{aligned} \qquad (2)$$

where EFF-BWD is the effective bulk wind difference, EFF-SRH is the effective SRH, and MLCIN is the mixed-layer convective inhibition. This effective-layer version of the STP, including MLCIN, reduces false alarms and shrinks the range of values by roughly 50% when compared to the fixed-layer STP. However, both formulations of STP show roughly the same ability to discriminate between significantly tornadic versus nontornadic supercells, with values ≥1 indicating an increasingly favorable environment for significant tornadoes. Though it would have been preferred to use the more recent STP due to its inclusion of effective versions of BWD and SRH, the latter parameters were not added to SFCOA until 2005. Therefore, the fixed-layer components of the STP calculation were used throughout the 2003–2010 dataset.

Fixed-layer STP was calculated for each event using the parameters extracted from SFCOA, and the individual STP components were analyzed using box and whiskers plots and the Mann and Whitney (1947) test. In addition, the sum of the normalized MLCAPE, 0–6-km BWD, and 0–1-km SRH was calculated, and then each normalized parameter was re-normalized by the sum of the three parameters in order to assess the fractional contribution of each parameter to the STP (expressed as a percentage when multiplied by 100), and thus to determine its relative importance to each of the three tornado regimes. The contribution of the MLLCL height was not included in this calculation, since it is used as a limiting factor in the STP. In other words, a high LCL height (roughly >2000 m) negatively impacts the potential for significant tornadoes, but LCL heights decreasing below 2000 m do not result in a progressively greater significant tornado threat (R. Thompson 2012, personal communication).

Following the component evaluation, each tornadic storm was analyzed for convective mode during its tornadic phase, using Weather Surveillance Radar-1988 Doppler (WSR-88D) reflectivity imagery, following the methods of Smith et al. (2012). Three modes occurred in this research—all supercells: 1) discrete right-moving (RM), 2) RM in a cluster, and 3) RM in a line. The discrete mode applies to an RM supercell not attached to any other cells with ≥35-d*BZ* reflectivity. A cluster is defined as any additional grouping of storms with ≥35-d*BZ* reflectivity connected to a RM supercell. Finally, classification of a RM supercell in a line requires that a supercell be embedded within a contiguous band of ≥35-dBZ reflectivity ≥100 km and a length to width ratio ≥3:1.

3. Results

a. Background characteristics

Figure 3 indicates where the majority of significant tornado regimes were observed in this study across the CONUS. For significantly tornadic dryline events, 85% were clustered over northwestern Texas and the eastern Texas Panhandle northward and eastward into western to central Oklahoma and Kansas. The remaining 15% occurred from southwestern into northeastern Arkansas. On the other hand, 58% of the significant warm-frontal tornadoes occurred over the central and north-central CONUS, with the remaining 42% over southern Arkansas, eastern Louisiana, and western Mississippi, as well as the Lower Ohio Valley into the southeastern CONUS. Finally, 91% of significantly tornadic cold-frontal events occurred from the mid-Mississippi Valley southward into the lower Mississippi Valley, with an eastward extension across the Ohio Valley, and a second extension southeastward into Alabama and Georgia. Weakly tornadic dryline events also were clustered over the southern and central Plains. Warm-frontal events were concentrated mainly from the central and southern CONUS east-northeastward across the mid-Mississippi Valley. Weakly tornadic cold-frontal events followed a similar distribution as their significant counterparts (not shown).

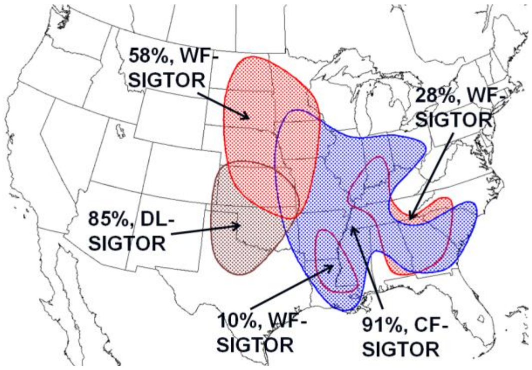


Figure 3: CONUS geographical distribution of event regimes for significantly tornadic drylines (brown line and fill), warm fronts (red lines and fill), and cold fronts (blue line and fill) for the period 2003–2010. Corridors of significant tornado occurrence for each regime are highlighted by color-filled areas and percentage values.

Figure 4 shows that significantly tornadic cold-frontal events increased in frequency through the winter, peaked during April, and then became more infrequent during the summer. A secondary peak appeared in November. The cool season bias displayed by cold-frontal significant tornado events may have implications on thermodynamic variables, as discussed in Guyer et al. (2006), and quantified further in section 3b of the current study. Similar to cold-frontal events, significantly tornadic warm-frontal events increased in number during the winter and early spring, with a peak in May—one month later than cold-frontal events, which decreased from April to May. Thereafter, frequency was consistently low during the summer (although greater than cold-frontal events), with a secondary peak in November. In contrast to cold- and warm-frontal events, significantly tornadic dryline events are almost exclusively a springtime phenomenon, the peak being in May. No dryline events were observed in this study during the summer, fall, and early winter.

Weakly tornadic cold-frontal events displayed a peak frequency during April, with secondary maxima during September and November. Weakly tornadic warm-frontal events peaked during April and May, and were relatively infrequent during the summer, fall, and early winter. The seasonal distribution of weakly tornadic dryline events were very similar to significantly tornadic dryline events, confined strictly to the spring (not shown).

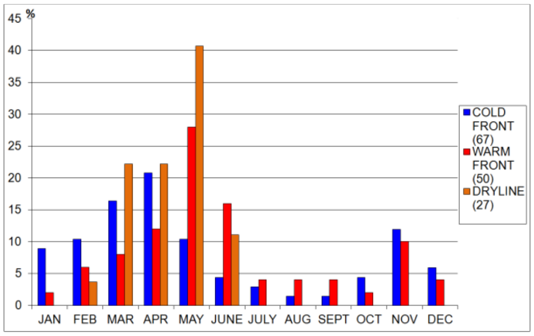


Figure 4: Monthly distribution of regimes for significantly tornadic cold fronts (blue), warm fronts (red), and drylines (brown) for the period 2003–2010. Total number of cases for each regime is given in the legend.

The diurnal frequency of significant tornado occurrence for all three regimes is predominantly during the late afternoon and evening (Fig. 5).

However, 42% of cold-frontal and 28% of warm-frontal events also were observed from early morning into the early afternoon. In contrast, dryline significant tornado events were confined almost exclusively to 2000–0359 UTC, demonstrating that this regime is more dependent on the diurnal heating cycle.

Dryline regimes produced a slightly greater number of significant and weak tornadoes per event compared to cold- and warm-frontal regimes (Table 1). In addition, warm fronts were associated with a greater number of violent tornadoes. Dryline environments, on average, yielded longer mean tornado path lengths (44.7 km), followed by cold fronts (30.8 km), and warm fronts (25.1 km). The mean number of fatalities by significantly tornadic regime was greatest for drylines as well, while no fatalities occurred with any of the weak tornado events. Finally, significantly tornadic dryline regimes resulted in a larger average number of injuries compared to those with fronts.

b. Environments

Mean STP values (Table 2) across all significantly tornadic regimes ranged from 3.4 (cold front) to 5.2 (dryline), and the difference in means when comparing between each type was found to be statistically insignificant (confidence levels <85%). Mean STP values for the weakly tornadic frontal regimes ranged from 1.6 (warm front) to 1.8 (dryline). When comparing significantly tornadic to weakly tornadic regimes, the difference in means was statistically significant for all three boundaries. Much of the interquartile values observed in box and whisker plots for weak tornadoes was located below the median of significant tornadoes (Fig. 6). Thus, the STP did not discriminate between significant tornado regimes, but did between significantly and weakly tornadic environments, as found in Thompson et al. (2003; 2004).

On average, MLCAPE in significant tornado regimes was larger for dryline significant tornadoes (2301 J kg^{-1}), and lowest for cold-frontal significantly tornadic regimes (997 J kg^{-1}), with warm-frontal events residing in between (1713 J kg^{-1}). The difference in means between dryline and cold-frontal events and dryline and warm-frontal events was found to be statistically significant at the >97% confidence level. Comparisons of MLCAPE values from this study to T03 showed that the mean value for dryline events is virtually the same as the mean for significant tornadoes in T03, while the mean value for cold-frontal events is more than 1000 J kg^{-1} smaller than the mean significant tornado value in T03.

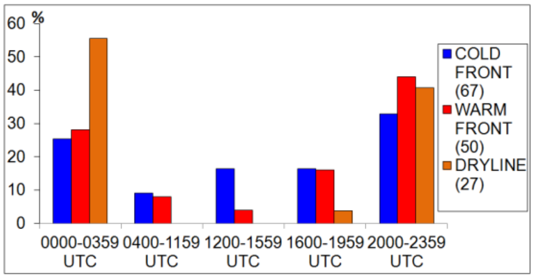


Figure 5: As in Fig. 4, but for temporal frequency of regimes.

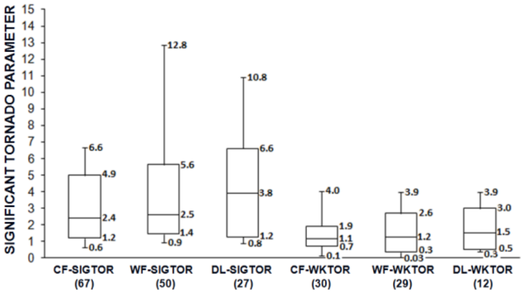


Figure 6: Box-and-whiskers plot for various tornadic regimes versus the STP. The boxed region represents the interquartile range, divided at the median. Whiskers represent 10th and 90th percentiles. Abbreviations on the abscissa stand for CF (cold front) SIGTOR (significant tornado), WF (warm front), DL (dryline), and WKTOR (weak tornado). Sample size for each regime are given in parentheses.

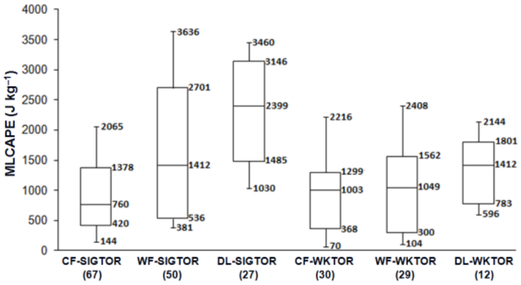


Figure 7: As in Fig. 6, except for MLCAPE (J kg^{-1}).

Figure 7 also shows a reduction in interquartile overlap moving from the significantly tornadic dryline box plot to the cold-frontal box plot, with the dryline and cold-frontal interquartile values being completely separated. Weakly tornadic dryline regimes were also found to occur with greater mean MLCAPE values compared to cold-frontal and warm-frontal weakly tornadic regimes, though the difference in means was statistically insignificant. Interestingly, the weakly tornadic box plot for dryline regimes suggests that MLCAPE is slightly larger for those environments compared to significantly tornadic cold-frontal regimes, which supports the notion mentioned previously that seasonal differences contribute to the range in MLCAPE values observed between cold fronts and drylines.

Given that dryline significant tornadoes occur during the spring mainly over the central and southern Plains, the probability for steep midlevel lapse rates overspreading a warm moist boundary layer is high and favors large MLCAPE values. On the other hand, significant tornadoes occurring near cold fronts were more likely during the cooler months of the year and in regions east of the Great Plains. Thus, weaker midlevel lapse rates are more probable, and favor low MLCAPE values. This is confirmed by examining the surface dewpoint and 700–500-mb lapse rate extracted from the SFCOA archive. Dryline regimes were associated with a mean lapse rate of 7.4°C km^{-1}, while cold-frontal and warm-frontal regimes were associated with weaker lapse rates of 6.6–6.9°C km^{-1}. The difference in means between the dryline and other two regimes is statistically significant at the >99% confidence level. The mean dewpoint for all three significant tornado regimes ranged from 17.2 (cold-frontal) to 18.7°C (warm-frontal).

Table 1: Average tornadoes per frontal regime, mean maximum F/EF-scale rating per event, total number of violent tornadoes for each frontal regime, mean tornado path length per event, mean number of fatalities per event, and mean number of injuries. Significant tornado ("Sig Tor") rows are in boldface. "Weak Tor" stands for those regimes producing weak tornadoes. Total number of tornado events for each regime is given in the left column (parentheses).

	Tornadoes per Event	Mean max F/EF Rating	Violent Tor Events	Mean Path Length (km)	Mean Fatalities	Mean Injuries
Cold Front-Sig Tor (67)	**2.6 sigtors**	**2.5**	**6 (8.9%)**	**30.8**	**1.1**	**17.4**
Warm Front-Sig Tor (50)	**1.9 sigtors**	**2.7**	**10 (20%)**	**25.1**	**1.0**	**16.4**
Dryline-Sig Tor (27)	**3.8 sigtors**	**2.8**	**5 (18.5%)**	**44.7**	**2.9**	**37.5**
Cold Front-Weak Tor (30)	1.8 weaktors	0.46	–	6.3	0	**0.16**
Warm Front-Weak Tor (29)	3.3 weaktors	0.41	–	5.6	0	**0.06**
Dryline-Weak Tor (12)	**4.1 weaktors**	**0.58**	**–**	**6.3**	**0**	**0.25**

Table 2: Mean parameter values for each tornadic regime. Boldface and acronyms as in Table 1.

	MLCAPE (J kg^{-1})	0–6-km BWD (m s^{-1})	0–1-km SRH (m^2 s^{-2})	MLLCL Height (m)	STP
Cold Front-SigTor (67)	**997**	**28**	**356**	**843**	**3.4**
Warm Front-SigTor (50)	**1713**	**28**	**272**	**840**	**4.4**
Dryline-SigTor (27)	**2301**	**28**	**246**	**1141**	**5.2**
Cold Front-WeakTor (30)	1041	28	232	941	**1.7**
Warm Front-WeakTor (29)	1127	24	204	934	**1.6**
Dryline-WeakTor (12)	**1412**	**27**	**178**	**1144**	**1.8**

Interestingly, the difference in means between cold-frontal and warm-frontal significant tornado regimes was statistically insignificant for 700–500-mb lapse rates, but was significant in terms of surface dewpoint, with warm-frontal regimes being more moist. In addition, though midlevel lapse rates become progressively steeper from cold-frontal environments to dryline environments, the correlation between lapse rate and MLCAPE was consistently low for all three regimes (<0.47), and was much higher between surface dewpoint and MLCAPE (ranging from 0.61–0.79).

Comparisons of MLCAPE were also made for significant tornadoes associated with cold fronts and drylines during the months of May and June in order to further resolve warm and cool season bias. The mean value for cold-frontal tornadic environments (10 events) was 1920 J kg^{-1}, and the mean for drylines (14 events) was 2863 J kg^{-1}. In addition, box and whiskers plots revealed that the upper 75% of the dryline distribution was nearly separated from the lower 75% of the cold-frontal distribution (not shown). Despite the large offset in interquartile values, the difference in means was statistically insignificant at the 93% confidence level. Thus, dryline MLCAPE values were still larger than cold-frontal MLCAPE values during the warm season, but the differences were not as extreme as when cool season cold-frontal events were included.

Table 3 and Fig. 8 show that the MLCAPE contribution to the STP was greatest for significantly tornadic dryline environments (37%), with a progressively lower contribution found for warm-frontal (29%) and cold-frontal (17%) regimes. The difference in means for the MLCAPE contribution to the STP was found to be statistically significant when comparing significantly tornadic dryline regimes to warm fronts (96% confidence level), drylines to cold fronts (>99% confidence level), and warm fronts to cold fronts (>99% confidence level). Weakly tornadic regimes displayed a similar order, though differences between dryline and cold-frontal regimes were not as large.

Mean values of 0–6-km BWD were identical among all three significantly tornadic types (28 m s^{-1}, Table 2), and the difference in means when regimes were compared with each other was found to be statistically insignificant (confidence levels ≤40%). Large interquartile

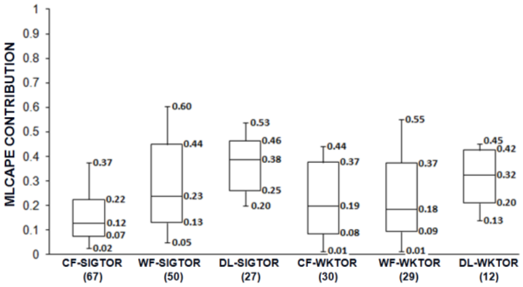


Figure 8: As in Fig. 6, except for the fractional contribution of MLCAPE to the STP.

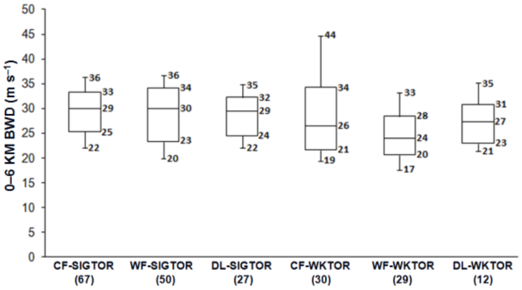


Figure 9: As in Fig. 6, except for 0–6-km BWD (m s^{-1}).

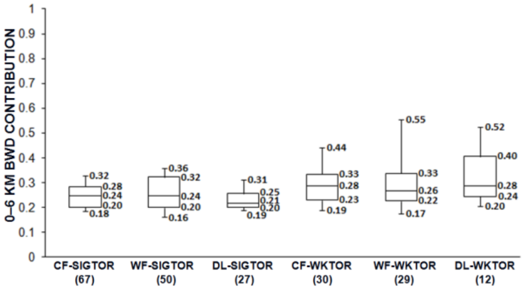


Figure 10: As in Fig. 6, except for the fractional contribution of 0–6-km BWD to the STP.

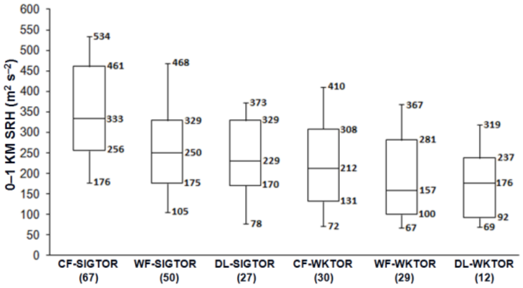


Figure 11: As in Fig. 6, except for 0–1-km SRH (m^2 s^{-2}).

Table 3: Mean parameter contributions (fractional contribution × 100) to the STP for each tornadic regime. Boldface and acronyms as in Table 1.

	Cold Front-SigTor (67)	Warm Front-SigTor (50)	Dryline-SigTor (27)	Cold Front-WeakTor (30)	Warm Front-WeakTor (29)	Dryline-WeakTor (12)
MLCAPE	**17%**	**29%**	**37%**	23%	25%	32%
0–6-km BWD	**25%**	**26%**	**24%**	31%	32%	33%
0–1-km SRH	**58%**	**45%**	**39%**	46%	43%	35%

overlap also was observed in box-and-whisker plots (Fig. 9). Given that the distribution of 0–6-km BWD is similar for all regimes, it is not surprising that the contribution of deep-layer shear to the STP is also similar. For significantly tornadic events, the mean contribution ranges from 24% to 26%, and for weakly tornadic events, the mean contribution is from 31% to 33%. Interquartile overlap is also substantial, as seen in Fig. 10.

In contrast to 0–6-km BWD, the 0–1-km SRH contributed much more strongly to the total STP for cold-frontal regimes. This was especially true for significantly tornadic cold-frontal regimes, which displayed a mean 0–1-km SRH value of 356 m^{2} s^{-2}, and a mean contribution value of 58%. Warm-frontal environments were associated with a mean value of 272 m^{2} s^{-2}, and a mean contribution of 45%, while significantly tornadic dryline regimes were affiliated with a mean value of 246 m^{2} s^{-2}, and a mean contribution of 39%.

Statistically significant differences in means (≥99% confidence level) were found when comparing the cold-frontal regime with warm-frontal and dryline regimes, and this was also true for the contribution from 0–1-km SRH to the STP. In addition, box and whiskers plots shown in Figs. 11 and 12 also demonstrate that the upper 50% of the distribution for significantly tornadic cold-frontal events resides above the lower 50% of the distribution for warm-frontal and dryline events. Similarly, weakly tornadic cold-frontal regimes were associated with the greatest contribution to total STP from 0–1-km SRH, and dryline weakly tornadic regimes experienced the lowest contribution. As shown in Fig. 7, MLCAPE values are similar for significantly tornadic and weakly tornadic cold-frontal regimes. In contrast, 0–1-km SRH shows a much stronger ability to discriminate between the two environments.

The magnitude of the low-level jet stream is one possible factor contributing to the difference observed in 0–1-km SRH between the three regimes. In order to test this hypothesis, archived 850-hPa wind speeds associated with significant tornadoes occurring in the warm sector from Garner (2012) were used (at the time of the current research, low-level jet information was not part of the SFCOA archive). The Garner (2012) dataset was divided into events that occurred when significantly tornadic cold-frontal regimes were most likely (October through April), versus when significantly tornadic dryline regimes were predominant (May and June). The mean 850-hPa wind speed was 2 m s^{-1} larger for cool season events, and the difference in means was statistically significant at the 99% confidence level. This provides evidence that significantly tornadic cold-frontal regimes, which are most favored during the cool season, are likely associated with a stronger low-level jet, which would support larger SRH values than dryline regimes.

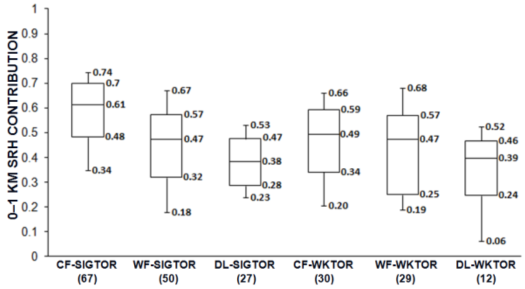


Figure 12: As in Fig. 6, except for the fractional contribution of 0–1-km SRH to the STP.

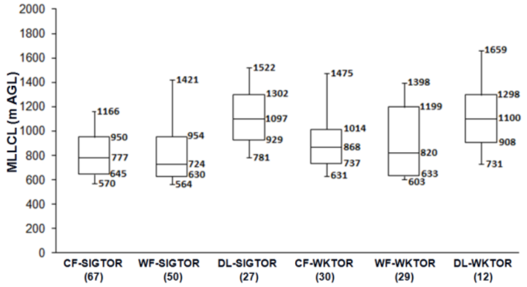


Figure 13: As in Fig. 6, except for MLLCL height (meters).

Mean MLLCL heights were lower for cold-frontal (843 m) and warm-frontal (840 m) significantly tornadic environments than for dryline significant tornado regimes (1141 m). The difference in mean MLLCL height between dryline–cold-frontal and dryline–warm-frontal regimes was statistically significant with confidence levels >99%. Box and whiskers plots (Fig. 13) also demonstrate that the dryline tornadic environment is less humid than the other two regimes, given that the upper 75% of the significantly tornadic dryline distribution resides above the lower 75% of the distribution for cold and warm-frontal events. Despite the higher MLLCL heights associated with dryline regimes, the maximum value in this study was 1767 m, very close to the upper bound (1750 m) for significantly tornadic storms found in T03. Weakly tornadic environments were similar to significantly tornadic environments. Cold-frontal and warm-frontal regimes were associated with lower MLLCL heights (941 and 934 m, respectively) compared to the dryline regime (1144 m), and the difference in means was found to be statistically significant at the >99% confidence level.

Though MLCIN is not part of the fixed-layer STP, this parameter has been included in the results because of its importance in tornado forecasting (Davies 2004), and because of its inclusion in the effective-layer STP. Mean values of MLCIN for all significant tornado regimes ranged from 41–56 J kg^{-1}, and the difference in means was statistically insignificant. Box and whiskers plots also show that the overlap between interquartile values is substantial (Fig. 14). However, mean values of MLCIN for warm-frontal and dryline weak tornado environments are slightly larger (73 and 71 J kg^{-1} respectively) than their significant tornado counterparts, and the upper 50% of the weak tornado MLCIN distribution extends well above the upper 50% of the significant tornado distribution (differences in 75th percentile values were 57 and 21 J kg^{-1}, respectively). Thus, there is some evidence that MLCIN can aid in distinguishing between significant and weakly tornadic environments for warm-frontal and dryline regimes.

c. Convective modes

Parameter evaluation can allow reasonable forecasts of the conditional threat of tornadoes for a certain environment. However, in many cases, the convective mode ultimately can influence the tornado threat. As such, convective mode was determined for comparisons between each frontal type, as well as intra-frontal types (with respect to significant and weak tornadoes). Figure 15 summarizes the results for significantly tornadic frontal regimes. Dryline events were dominated by discrete RM supercells, while RM supercells embedded within storm clusters were more common for cold-frontal and warm-frontal regimes. In addition, 16.4% of cold-frontal events occurred with an RM supercell in a line, contrasting with 6% of warm-frontal and no dryline events.

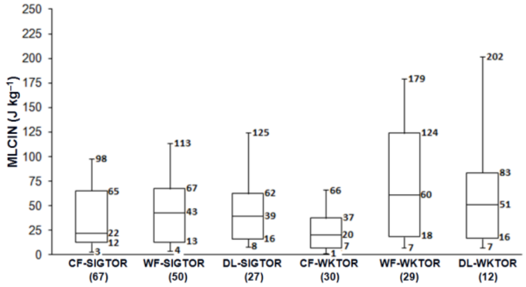


Figure 14: As in Fig. 6, except for MLCIN (J kg^{-1}).

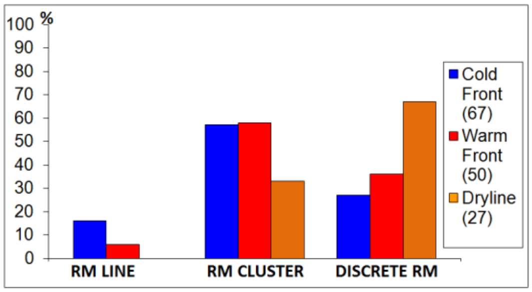


Figure 15: As in Fig. 4, except for convective mode. RM stands for right-moving supercell.

For weakly tornadic convective modes (not shown), cold-frontal regimes were most often associated with RM supercells in clusters (53.3%), followed by discrete RM supercells (43.3%), and supercells embedded in lines (3.3%). More weak-tornado warm-frontal events were associated with RM discrete supercells (65.5%) compared to significantly tornadic warm fronts, 31% of the events were supercells embedded in storm clusters, and 3.4% occurred with a line. Finally, similar to significantly tornadic dryline regimes, weakly tornadic drylines were dominated by discrete RM supercells (83.3%), the remainder embedded in storm clusters.

4. Summary and discussion

By assessing the individual components in the STP, it has been demonstrated that the magnitude of shear and buoyancy favorable for tornadic supercells is different for cold fronts, warm fronts, and drylines. For example, the mean STP value for all three regimes is similar. However, for drylines, large CAPE and lower SRH are associated with significant tornadoes, while lower CAPE values and higher SRH are more likely with significantly tornadic storms emanating from cold fronts. Significantly tornadic warm-frontal regimes reside in between these two extremes. Thus, forecasters should be aware that certain components of an index may be more important for one type of tornadic regime, and less important for other regimes, as pointed out in Doswell and Schultz (2006).

Because MLCAPE is similar for both significantly and weakly tornadic cold-frontal regimes, operational forecasters should put emphasis on identifying areas where 0–1-km SRH is large (roughly >250–300 $m^2\ s^{-2}$) when forecasting conditions favorable for significant tornadoes. In addition, attention should be given to locating sources of mesoscale and synoptic-scale upward vertical motion, which can aid in steepening lapse rates (Banacos and Ekster 2010). This process, in addition to areas of greater surface heating along and ahead of cold fronts can result in locally increasing buoyancy and enhancing the significant tornado threat when strong 0–1-km SRH is already in place. For drylines, 0–1-km SRH showed a lower ability in discriminating between significantly and weakly tornadic storms, while MLCAPE values >1500–2000 J kg^{-1} delineated the transition from weakly to significantly tornadic environments.

Differences in MLCAPE were shown to be influenced by the magnitude of the midlevel lapse rate and low-level moisture. For dryline significant tornado environments, both the 700–500-mb lapse rate and surface dewpoint are large, thus MLCAPE values are greatest for this regime. This result is not surprising since dryline significant tornado environments are most frequent during the spring. For warm-frontal regimes, surface dewpoints are highest among all regimes studied, but midlevel lapse rates are weaker than for drylines, which may partially explain why MLCAPE values are smaller. Cold-frontal regimes were associated with the weakest midlevel lapse rates and smallest surface dewpoints, which contributes to the lowest MLCAPE values among all three regimes. The weaker MLCAPE environment is expected since cold-frontal significant tornado events occur most frequently during the cool season. On the other hand, differences in low-level vertical wind shear are closely tied to the strength of the low-level jet stream (Mead and Thompson 2011), which was shown to be stronger during the cool season when cold-frontal regimes predominate. These environmental differences provide an opportunity for further detailed study into the synoptic-dynamic processes that influence the supercell-tornado parameter space.

Higher MLLCL heights in the vicinity of drylines, up to ≈1500 m, do not appear to diminish the threat for significant tornadoes, while lower MLLCL heights along warm fronts and cold fronts were pronounced during significant tornado events. Since dryline regimes more often are associated with discrete storm development, the higher MLLCL height may not be as detrimental to significant tornado production, since greater storm spacing would result in less destructive interference by storm mergers and outflow. On the other hand, warm-frontal and cold-frontal significantly tornadic thunderstorms occur in the midst of storm clusters and occasionally lines, yet the lower MLLCL height may mitigate the effects of storm interactions, mergers, and outflows.

Finally, results from this study show little variation in 0–6-km BWD exists between cold-frontal, warm-frontal, and dryline tornado regimes. This suggests that the primary contribution of deep-layer vertical wind shear to the significant tornado environment may be in creating favorable conditions for supercell development. Supercell development in turn would provide a greater window of opportunity for producing significant tornadoes due to their long-lived quasi-continuous updrafts.

ACKNOWLEDGMENTS

The author thanks Roger Edwards, Richard Thompson, Andy Dean, Israel Jirak, and Ariel Cohen for their reviews and suggestions during the initial stages of this research. In addition, the author acknowledges the formal reviews provided by Peter Banacos, Matt Bunkers, and Greg Mann, which resulted in a greatly improved manuscript.

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REVIEWER COMMENTS

[Authors' responses in *blue italics.*]

REVIEWER A (Matthew J. Bunkers):

Initial Review:

Recommendation: Accept with moderate–major revisions.

General comments: This is a worthwhile study because it examines the environments of tornadic storms by frontal regime, and this may be helpful to operational forecasters, especially new/young forecasters. The distribution of dryline events in space and time is quantified, which is consistent with qualitative assessments of dryline activity. Your study points out the importance of looking at individual variables instead of focusing on composite parameters (even though the latter are still useful). For example, if a cold front environment exists, then low-level shear appears to be a relatively important (and possibly limiting) ingredient. If a dryline environment exists, then large CAPE often is needed. If a warm front exists, there appears to be a balance of the various ingredients (e.g., a "goldilocks" scenario).

Figure quality is generally good (especially Figs. 1 and 2), though some modifications are needed for the labeling. When reading your paper I asked myself, "How can I use this as a forecaster?" This became clearer with time, but I believe it would be good to hone in on this in your conclusion.

I do not see any fatal flaws, but because I have moderate-to-major comments, I would like to review the paper again.

Major comments: There is a little too much background information, and this should be tightened to get to the motivation of your paper more quickly. First, the second paragraph of section 1 could be reduced to just the first sentence, which then can be combined with the third paragraph.

Substantial modifications have been made to the introduction. Several paragraphs have been deleted, or reduced in size and combined with other paragraphs in order to minimize the amount of background information. The second paragraph of section 1 has been reduced to the first sentence, and was combined with the third paragraph.

I don't think you need to re-hash the development and evolution of extratropical cyclones across the central CONUS, and instead could reference Hobbs et al. (1996) in this first sentence.

The reference to Hobbs et al. (1996) has been added, and the development/evolution of extratropical cyclones across the central CONUS has largely been deleted.

Second, the fourth paragraph beginning with "Current understanding of the parameter space …" also could be reduced. Specifically, the "Idealized modeling studies…" sentence can be deleted with WK82 cited in the following sentence if desired (right after "…used to forecast supercells").

The "idealized modeling studies…" sentence has been deleted, but the WK82 reference remains.

The Rasmussen (2003) citation could be moved up one sentence to the end of "…and increased tornado potential" and then the sentence defining SRH can be deleted. The last two sentences also could be combined but there are a couple of different possibilities so I'll leave that up to you.

The Rasmussen (2003) citation has been moved up one sentence, and the sentence defining SRH has been deleted. The last two sentences referring to LCL height have also been combined.

Finally, the second-to-last paragraph of section 2 could be reduced by deleting the "Examples of composite indices include…" sentence; this is peripheral to what you are doing.

This paragraph has been deleted.

Hobbs, P. V., J. D. Locatelli, and J. E. Martin, 1996: A new conceptual model for cyclones generated in the lee of the Rocky Mountains. *Bull. Amer. Meteor. Soc.*, **77**, 1169–1178.

The methods need to be clarified. First, how far away can a tornado event be from a synoptic cyclone in order to be associated with it? And how far away from any of the three boundaries can a tornadic storm be and still be associated with that boundary? You didn't provide distance criteria.

In the methodology, I have added:

"A tornado was associated with a synoptic cyclone if it was located within the bounds of the warm sector (or on the fringe, in the case of warm-frontal events), which is typically downshear of a cold front or dryline, and upshear from a warm front. In addition, tornadoes were only included in this study if their parent storm emanated from a cold front or dryline, or interacted with a warm front."

I have also added:

"No distance criteria was set for storms that emanated from a cold front or dryline, but on average, storms that formed from drylines produced tornadoes at a distance of 108 km from the boundary, cold-frontal storms produced tornadoes 51 km from the boundary, and warm frontal storms produced tornadoes 13 km from the boundary."

I believe this clarification to my methodology should alleviate any concerns about reproducibility. For example, a tornadic storm that forms elsewhere in the warm sector (not on one of the three synoptic boundaries) clearly would not be included. If someone tried to reproduce this study, it should be clear which tornadic storms would be included, and which tornadic storms would not be included.

Second, regarding "…streamlines during the hour of significant-tornado occurrence…" on p. 3, what if a significant tornado didn't occur? How then would you associate surface frontal features with a cyclone?

The word "significant" has been removed from the sentence, which should eliminate confusion.

Third, you had 3865 tornadoes near a synoptic cyclone: 153 (4%) with a dryline, 234 (6%) with a CF, and 193 (5%) with a WF. That means 3285 (85%) of the tornadoes were not associated with any of these three boundaries—yet they were associated with a synoptic cyclone. This is a large number to ignore, and I think something needs to be said about that. In effect your results imply 85% of your cases were in the warm sector, or else along mesoscale boundaries such as outflows.

I appreciate the reviewer pointing out the confusion this part of the methodology has created. I erroneously mixed up a few of the numbers I intended to present. The previous version of my manuscript didn't reflect on the fact that I excluded weak tornadoes if a significant tornado occurred with a synoptic *boundary. Thus, the total number of tornadoes associated with all of the cyclones included in this study is higher than 580.*

I now state:

"These criteria yielded 580 significant and weak tornadoes associated with one of the synoptic cyclone boundaries. For clarification, if a synoptic-cyclone was associated with a significant tornado, any weak tornadoes occurring with the same cyclone were excluded from this study. Thus, the total number of tornadoes occurring with a cyclone during the 2003–2010 period is higher than 580. Out of the 580 tornadoes, 153 tornadoes were associated with storms that emanated from a dryline, 234 from a cold front, and 193 occurred on a warm front. For significant tornadoes, 97 (26%) were warm-frontal, 103 (27%) were dryline, and 180 (47%) were cold-frontal. For weak tornadoes, 96 (48%) were warm-frontal, 50 (25%) were dryline, and 54 (27%) were cold-frontal."

Following that statement in the same section:

"This step yielded 144 grid points associated with one or more significant tornadoes; 67 being cold-frontal, 50 warm-frontal, and 27 dryline. If a cluster of tornadoes occurred, then the grid point that matched up with the time, latitude and longitude for the highest F/EF rating or longest path length was used to extract the SFCOA data."

Fourth, on p. 5 you indirectly state that all of your 580 tornadoes were associated with supercells. If that is correct, then I recommend you state that explicitly (e.g., "Three modes occurred in this research—all supercellular:").

I have modified the last paragraph in section two to explicitly state that all storms were supercellular.

Finally, your methods should be clearer in stating that your focus is on significant tornadic events. I was a bit confused reading through your paper the first time because the results predominantly show graphs for significantly tornadic events, but you secondarily mention weakly tornadic events (sometimes with "not shown" wording). I never gathered this from reading your methods section.

I have made changes throughout the paper to make it clear that significant tornadoes are the primary focus of this study, for example, the last paragraph of the introduction.

MLCIN and MLLCL should be used more in your study. First, even though MLCIN is not a component of the fixed-layer STP, this variable should be evaluated because it is important to forecasting and it is part of the effective-layer STP. Presumably you have the data for MLCIN from 2003−2010, but if not then you could use SBCIN or MUCIN. At any rate, CIN is important for tornado environments as other studies have shown (e.g., Davies 2004).

MLCIN has now been added to the study, as requested. The MLCIN results can be found in the second to last paragraph in section 3.

Second, I'm not sure why you wouldn't look at the contribution of the MLLCL height to the STP (top of p. 5) like you did for the other three variables. Its factor can range from 1.3 to -1.3, which is nearly the same as the range for the 0–6-km BWD. The fact that it can make the STP go to zero or negative also is relevant.

Davies, J. M., 2004: Estimations of CIN and LFC associated with tornadic and nontornadic supercells. *Wea. Forecasting*, **19,** 714–726.

I agree that this is a valid concern. I originally included the MLLCL height contribution to the STP in an early draft of this study. However, after a lengthy discussion with Rich Thompson, we concluded that it could not be renormalized. The problem stems from the way the STP is calculated, particularly the MLLCL component. The MLLCL equation: [(2000 m – MLLCL)/1500 m] cannot be renormalized and displayed as a fractional contribution to the STP that ranges from 0 to 1. The fractional contribution will always reside around a small value. Thus, I felt it would be more appropriate to analyze the MLLCL height separately.

The description of overlap and separation of the box-and-whiskers plots should be more quantitative. For example, you mention "…separation between interquartile ranges was large (Fig. 6)." What do "separation" and "large" really mean? There clearly is overlap of the interquartile ranges in Fig. 6, so the weakly tornadic distributions are not truly separated from the significantly tornadic distributions. A better way to quantify this would be to state that the 75th percentile of the weakly tornadic distributions is below the 50th percentile of the significantly tornadic distributions—or something analogous. Similar clarification is needed later ("large separation between") where you could indicate there is at least a 25% offset between the CF-SIGTOR distribution and all the others. Another term to be careful with is "overlap". More quantitative information should be included here too (e.g., I think you need to specify that the DL-SIGTOR 25th percentile is near the 75th percentile of the CF-SIGTOR and WF-SIGTOR).

The revised manuscript has made a strong attempt to provide a more quantitative description of the box and whiskers plots given in section 3.

Substantive comments: How can focusing environments over smaller areas reduce predictability when compared to synoptically evident outbreaks? If a person only has to focus on a small area it should become easier to determine where tornadoes would occur. With synoptically evident outbreaks it is clear that tornadoes will occur but there still can be problems determining the areas that will and will not experience tornadoes.

This sentence has been removed.

At the start of section 3 you mentioned 144 significantly tornadic events and 71 tornadic events associated with surface cyclones, which is 215 events total. However, in section 2 you indicated 176 events associated with synoptic cyclones. What numbers are correct?

This has been clarified in the methodology. Refer to response given in #8 of "major comments."

The discussion and presentation of Fig. 3 is a bit confusing. First, you mentioned in the text and delineated in the figure 100% of the area for significantly tornadic cold-frontal regimes, yet you only mentioned and showed 85% for drylines and 91% for cold fronts. A second confusing thing is that the figure refers to significantly tornadic regimes only, yet the text presents a mix significant/weakly tornadic results. Finally, not all areas are labeled on Fig. 3. To fix this I suggest the following: (1) better labels for Fig. 3 (e.g., 85%, sigtor, DL; 91%, sigtor, CF; 58%, sigtor, WF), (2) include and label all areas on Fig. 3, or else state something in the caption why not 100% of the areas are delineated, (3) add a "not shown" phrase in your discussion of weakly tornadic regimes, and (4) discuss the significantly tornadic regimes first, then your weakly tornadic regimes second. The discussion of Fig. 4 would also benefit by talking about the significantly tornadic regimes first and the weakly tornadic regimes second. I find it confusing when mixing the two. Finally, including the period of study (2003–2010) and the number of cases in the captions would be helpful.

Labels in Fig. 3 have been modified according to what you suggested, the caption has been modified according to [your] suggestion, "not shown" has been added at the end of the first paragraph under section 3, and significantly tornadic regimes have been discussed first in order to reduce confusion.

There is a notable difference in May for the WF and CF tornadoes, as well as the trend from April to May. WF tornadoes increased sharply from April to May but CF tornadoes decreased. Thus I suggest rewording near the bottom as "…increased in number during the winter and early spring, but with a peak in May—one month later than cold-front events, which decreased from April to May."

This suggestion has been incorporated into the paragraph.

Most of the figures could benefit from better labeling. For example, Figs. 4 and 5 should have the number of events for each regime listed in the legend, and the graphs or captions should indicate the period of study (2003–2010). Tables 1–3 should have the number of cases for each of the six regimes in the first column. Figures 6–13 should have the number of cases for each of the six regimes listed along the abscissa; the ordinate also needs to be labeled for <u>all</u> figures. The number of cases could be included just above the bars for the regimes in Fig. 14.

Labels for figures 4 through 14 have been added, as suggested by the reviewer.

Table 3 also could be interpreted horizontally, instead of just vertically as you did. For example, Table 3 illustrates that 0–1-km SRH contributes 58% to the STP for CF-SIGTOR events, but MLCAPE only contributes 17%. When compared to the CF-WKTOR row, MLCAPE is larger but 0–1-km SRH is smaller than for CF-SIGTOR. Interestingly, the WF-SIGTOR row percentages don't differ all that much from the WF-WKTOR row.

Table 3 has been changed from vertical to horizontal.

Related to the previous comment, there are a lot of numbers thrown around in your paper. My head was spinning trying to keep things straight when I first read through the paper. I think it is paramount for you to succinctly summarize the most important operational findings at the end of the paper. I think what you are saying is that the key to a successful forecast is to assess the individual ingredients, but whatever the case that needs to be clear. Perhaps a bulleted list would help.

The summary and discussion has been modified substantially in order to highlight the most important operational findings.

[Minor comments omitted...]

Second Review:

Recommendation: Accept with minor revisions.

General comments: Several modifications have been made to the paper to clarify and strengthen it. I am satisfied with respect to all of my previous major comments; the background has been improved, the methods are better clarified, information has been included on MLCIN and MLLCL, and the box-and-whiskers plots are appropriately compared. The abstract also is well-written and drives home the key points of your paper. I have no more major comments, and only have a handful of substantive comments, along with a modest amount of minor/technical-editing comments.

I think the paper is acceptable for publication after considering these revisions, and I therefore do not need to review the paper again.

Substantive comments:

P. 1, first paragraph: I'm not sure "coupled" is warranted here since I don't believe the studies prior to Uccellini and Johnson (1979) that you cited examined this aspect of lower and upper jets. Perhaps nearby or proximate would work, or else just use "coupled" with quotes around it?

I deleted the word "coupled" and inserted the word "proximate".

Introduction: You never formally identified the tornado ingredients, and in fact I'm not sure we know them like we do for deep moist convection. We know what variables are strongly related to tornadogenesis (i.e., low-level shear and LCL heights), and we know that RFDs are important for supercell tornadogenesis, but I'm not sure we can state unambiguously and precisely what ingredients are needed for a tornado. Perhaps instead of saying ingredients here you could use "tornado-related variables," or something similar?

This is a good suggestion. I deleted "ingredients," and inserted "forecast parameters" in its place.

Distance criteria: What if you had a storm that emanated from a dryline and produced tornadoes periodically as it tracked northeast toward a warm front (e.g., crossing near PTT in your Fig. 1a)? When does it cease to be a dryline storm and become a warm front storm?

A storm in this hypothetical situation would be classified as a dryline storm as long as it continues to traverse the warm sector located downshear from the dryline. If it produces tornadoes during that time, then those tornadoes would be binned under the dryline category. If the storm at some point enter the baroclinic zone of the warm front and produced additional tornadoes, those tornadoes would be binned under the warm-frontal category. I added this information.

Your discussion of Fig. 3 is much better, but I still wonder why you show and discuss 100% of the sigtor warm frontal area, but you don't do the same for the dryline and cold frontal areas? What about labeling the two red hatched areas in the southeastern U.S. as 42% for the warm frontal area? Maybe I'm just missing something, but the reasons for this aren't clear to me.

Figure 3 highlights corridors of the CONUS that experienced these events on a frequent basis. In addition, I discuss were the remaining 15% of dryline significant tornadoes occurred (Arkansas), and discuss were the vast majority of cold-frontal significant tornadoes occurred (91% of all sigtor cold-frontal events). What I have done is no different than what Johns and Hirt (1987) did for their derecho study (highlighting the corridor from southern MN southeastward into the Upper OH Valley, despite additional events occurring elsewhere across the CONUS).

To follow up on my reply given above:

After coordinating with Matt Bunkers, it was agreed that uncertainty could be eliminated by labeling the two warm-frontal corridors in Fig. 3, and adding more descriptive information to the beginning of the 1st paragraph in section 3a.

I was a little confused by the sentence that refers to the "notion" of the seasonal differences. I was expecting to find reference to this earlier in your paper. I do see where you inferred this on the previous page, so perhaps you could state something like "…which supports the notion mentioned on the previous page that seasonal…."

This sentence now reads: "Interestingly, the weakly tornadic box plot for dryline regimes suggests that MLCAPE is slightly larger for those environments compared to significantly tornadic cold-frontal regimes, which supports the notion mentioned previously that seasonal differences contribute to the range in MLCAPE values observed between cold fronts and drylines."

REVIEWER B (Greg Mann):

Initial Review:

Recommendation: Accept.

There are no major comments regarding the content of the manuscript.

A side note that has no bearing on the merits of publication -the restriction imposed by requiring a surface low will result in appreciable under-sampling. Many events occur with synoptic-scale fronts and elevated disturbances, while not possessing a closed surface low.

I agree with the reviewer, under-sampling has occurred as a result of my chosen methodology. In order to address this fact, I have added the following sentence to section 2, page 3, 1st full paragraph, last sentence:

"Though tornadoes associated with drylines, warm fronts and cold fronts can occur under quiescent large-scale conditions, only boundaries associated with a synoptic-scale cyclone were included as a way to standardize the background environment for all tornado events."

REVIEWER C (Peter C. Banacos):

Reviewer recommendation: Accept with major revisions.

Synopsis: This paper investigates the individual factors comprising the significant tornado parameter and uses a composite methodology and statistical analysis to examine how the contribution of each of those factors varies in tornado environments near three synoptic boundary types (cold fronts, warm fronts, and drylines). Overall, the author has done a nice job. The paper is well-written and includes effective figures to elucidate key points. However, there are some scientific issues to address. Also, clarification is needed on how this work might specifically benefit forecasters and/or further our physical understanding of tornadic environments.

Major comments: I'll preface by saying that as a forecaster I utilize the significant tornado parameter (STP) as it effectively highlights areas of concern for tornadoes, especially given operational time pressures and deadlines. I don't have any reservations using it for the intended purpose.

Despite demonstrated utility as a diagnostic (e.g., Thompson et al. 2003, Fig. 19) at its core the STP is: 1) non-dimensional and 2) has no physical meaning, making the research oddly framed. It's not clear if a STP value of, say, "3" arrived at through high CAPE/low SRH (plus the other factors) is any more or less important than an STP value of "3" arrived at through low CAPE/high SRH (does it matter, and if so how?). These types of limitations in interpretation are inherent to *any* combined parameter. The paper's focus is on how the atmosphere arrives at a given STP value based on relative contributions of its associated convective parameters, but fails to dig into more meaningful physical considerations. We've known for quite a while that varying synoptic environments are capable of producing significant tornadoes, and such differences can result in large CAPE/SRH imbalances. That certain combinations of CAPE/SRH/LCL height are more or less likely along specific types of synoptic boundaries is interesting, but I'm not sure the results shed new light on the nature of the parameter space associated with tornadoes, or how the synoptic environment works to make the mesoscale environment more favorable for tornadoes (i.e., dynamical considerations).

This research shows that for the three regimes examined, the way the STP arrives at a value is statistically significant. With that being said, the STP is not the focus of this study. The focus is an environmental comparison between the three regimes. The STP is just a tool used to accomplish that goal. Differences in the parameter space from one part of a cyclone to another have not received much attention in the literature. Thus, I believe that the information presented in my study could be useful for other forecasters when applied in an operational setting.

The results, in fact, do shed new light on why we observe the range in values in the CAPE-shear parameter space, and that range is regime dependent. In order to dig a little deeper into the reason MLCAPE and SRH display particular values for a particular regime, I have examined lapse rates and surface dewpoint in the MLCAPE section, and the 850-hPa jet in the SRH section. Dynamical considerations are beyond the scope of this paper, though I believe the references provide an adequate description of the important dynamical processes involved.

Does the research suggest anything about the likelihood of tornadoes with respect to how the atmosphere "arrives" at a given value of STP? In the context of the stated motivation for the work, there is a lack of support in the paper for why a forecaster should focus on the relative contributions to STP vary if we can't say what tangible effect that actually has on the tornado threat.

The motivation for the paper has been clarified, and now reads:
"The motivation for this paper is to evaluate which tornado ingredients are most important for three prominent synoptic-scale regimes that have been associated with significant tornadoes: cold fronts, warm fronts and drylines. Because the STP shows favorable skill in discriminating between significant and weak tornado environments, the relative contribution of its individual components: MLCAPE, 0–6-km BWD and 0–1-km SRH have been used to highlight important differences between the three environments. In addition, MLLCL height, MLCIN and convective mode were also evaluated in this study."

And to clarify once again, evaluation of the STP is not the motivating factor in this study. It (and its components) is used as a tool to examine differences between the three regimes.

Stepping back from the STP, creation of composite mean soundings or hodographs for significant and weak tornadoes along each boundary type (cold front, warm front, dryline) might offer some additional insights and would be helpful from a pattern recognition standpoint. I know this isn't available solely using SFCOA, but use of VAD wind profiles or archived RUC model soundings would be useful for this purpose and would represent an analysis of the synoptic environment not tied directly to the STP.

This is a good idea. Unfortunately, for a composite mean hodograph, the profiler archive is limited to the middle of the nation, which would exclude a large number of events (particularly cold frontal events east of the Mississippi). For a mean composite sounding, a RUC model sounding archive does not exist for that purpose. The Thompson et al. RUC sounding archive is available, but those soundings are not matched up with the vast majority of storms I have examined.

Interpretation of results: It's apparent in your Fig. 4 that tornadic events along the three boundary types are seasonally skewed. This fact alone almost certainly affects the disparity in the CAPE composite relative to boundary type (Fig. 7), which is something not mentioned in the interpretation of the convective parameters. This would also impact the percentage contributions of each variable toward STP. If you were to consider, for example, just May tornadoes and associated boundaries it would be interesting to see how the distribution of each of the variables making up STP would turn out.

This idea has been implemented in the MLCAPE section.

Terminology: I disagree with the concept of warm fronts, cold fronts, and drylines as separate "synoptic regimes" (Abstract and throughout the paper), primarily because they can coexist and/or overtake within a single synoptic-scale cyclone. Fronts and drylines are atmospheric discontinuities of distinct character, whereas a synoptic regime might generally be thought of as encompassing the structure of an extratropical cyclone as a whole. It would be better to state that the significant tornado parameter is being examined along different synoptic *boundaries* as opposed to regimes.

The primary reason for going with "regime" versus "boundaries" is that these are very different environments embedded within the larger-scale cyclone, and thus classifying them as separate regimes seemed appropriate. For example, the circulations associated with each boundary are different, the way ingredients are put together for tornadic storms are unique, the storms themselves are initiated and organized in different ways, and the interaction between large-scale and mesoscale processes are different for each boundary. In addition, stating that the significant tornado parameter is examined along different synoptic boundaries implies that the tornadoes (and their environments) being studied are occurring immediately on the boundary, and that isn't the case for drylines and cold fronts. In other words, it is not the characteristics of the boundary itself that are being studied, but the regime encompassing the boundary, which in turn yields the environment that results in significant tornado occurrence. This seems to be a case of personal preference and interpretation, but I will defer to the editor if he believes regime should be changed to boundary.

Reproducibility of results: It's not clear from my reading if any objective distance criteria were applied in associating storms with a particular boundary. There is discussion of supercells "emanating" and "interacting" with the three boundary types, but at what point does it become a gray area or perhaps a true "warm sector" storm not associated with a synoptic boundary? For others expanding on your work in the future, such issues should be clarified.

The methodology now reads:
"No distance criteria was set for storms that emanated from a cold front or dryline, but on average, storms that formed from drylines produced tornadoes at a distance of 108 km from the boundary, cold-frontal storms produced tornadoes 51 km from the boundary, and warm-frontal storms produced tornadoes 13 km from the boundary."

As long as the parent storm emanated from the dryline or cold front (or interacted with a warm front during the tornadic phase), then that storm was associated with its original boundary during regime classification. No storms initiating in the warm sector (and not on one of the three boundaries) were included in the study. In addition, transition from dryline to cold front (as storms were occurring) was observed.

Suggest mentioning that the SPC SFCOA is RUC-based. Are there any changes to the RUC during the study period that might have influenced SFCOA? Also, the word "surface" is a bit of a misnomer since the variables you are looking at are based on 1-h RUC forecasts (surface and aloft) tweaked with the current hour's surface data; it's more than just a surface objective analysis.

The methodology now mentions that SPC SFCOA is RUC-based. In addition, I have included a reference to Garner (2012), which provided a general description of changes to the RUC during my period of study.

After talking with Phillip Bothwell, he advises sticking with surface objective analysis (SFCOA).

Start of section 3a: I'm having difficulty reconciling the different tornado totals by boundary type listed here versus what is listed on the second column of page 3. For instance, the dryline tornado count is 153 on page 3 but only 39 (27 SIG and 12 weak) on page 5. Please clarify. A table to summarize weak/significant tornadoes by boundary type might also be helpful for the reader.

Clarification has been made to the tornado counts given in the methodology. It now reads as:

"These criteria yielded 580 significant and weak tornadoes associated with one of the synoptic cyclone boundaries. For clarification, if a synoptic-cyclone was associated with a significant tornado, any weak tornadoes occurring with the same cyclone were excluded from this study. Thus, the total number of tornadoes occurring with a cyclone during the 2003–2010 period is higher than 580. Out of the 580 tornadoes, 153 tornadoes were associated with storms that emanated from a dryline, 234 from a cold front, and 193 occurred on a warm front. For significant tornadoes, 97 (26%) were warm-frontal, 103 (27%) were dryline, and 180 (47%) were cold-frontal. For weak tornadoes, 96 (48%) were warm-frontal, 50 (25%) were dryline, and 54 (27%) were cold-frontal."

Summary: The author states that: "…MLLCL *contributed* less to the significantly tornadic dryline environment…". Yet the inclusion of LCL height as a factor in STP is suggested only as a "limiting factor" for tornado occurrence and was not otherwise evaluated as a contributor when considering the percentages of each variable toward the total STP. This apparent contradiction should be addressed.

This contradiction has been removed in the summary/discussion section.

[Minor comments omitted…]

Second Review:

Recommendation: Accept with minor revisions.

Synopsis: The author has adequately addressed most of my previous concerns, and has done a nice job in preparing the revised manuscript. This is a well-organized presentation that quantifies differences in tornado-related convective parameters with respect to fronts and drylines when tied to a synoptic cyclone and with the occurrence of both strong and weak tornadoes. My remaining comments are for clarification purposes, and mostly involve some minor wording changes. Again, nice work…

Main comments: The focus on the significant tornado parameter (STP) largely remains as a means of understanding relative contributions toward tornado potential. I would have preferred less focus on the STP since it is not a physically derived quantity, as outlined in my first review. The reader can make their own judgment; I don't wish for this point to otherwise take away from the interesting and useful results with respect to the physically derived *individual* components (CAPE, 0–1-km SRH, etc.) and their variation in tornado environments along the three boundary types examined (cold fronts, warm fronts, drylines). My main point is that the reader shouldn't confuse these STP components as forcing terms or residuals in the way one might partition theoretically derived equations in dynamic meteorology or thermodynamics to understand how certain terms contribute to the whole (e.g., the QG omega equation). As of yet, there exists no physically-based unifying equation for tornado potential; as long as the reader understands that, all else should be fine.

This is an important point made by the reviewer, and I agree with it. No physically based equation exists for tornado potential, and I hope that the reader understands that the STP is used in this research as a means of summarizing shear/buoyancy characteristics associated with the three different regimes examined.

I have made minor changes to the manuscript in order to remove any implication that the STP is viewed as a unifying equation for tornado potential. For example, in the first sentence of the summary/discussion, I removed the word ingredients, and modified the sentence so that it now reads: "By assessing the individual components in the STP, it has been demonstrated that the magnitude of shear and buoyancy favorable for tornadic supercells is different for cold fronts, warm fronts, and drylines."

It should be noted in the analysis that statistical significance doesn't necessarily imply cause and effect - there are seasonal and geographical differences in the frequency of each boundary type that drive some of the differences in the convective parameter values (better described in this version of the paper), in additional to synoptic-dynamic factors that influence things like hodograph shape and storm motion. Now that the author has established some values, there may be opportunities for future work to examine more specifically *why* the average parameter space along each boundary type looks the way it does in significant tornado events. A brief mention of avenues for future work could be added to the conclusion.

I added the following sentence to the end of paragraph 3 in the summary/discussion: "The environmental differences between the three regimes provide an opportunity for further detailed study into the dynamical processes that influence the tornado parameter space."

I'd soften the language a bit to say that the motivation of the paper is to determine which tornado ingredients are *usually* the most important for each boundary type (e.g., it's not unequivocally true along warm fronts that the fractional contribution of 0-1 km SRH will exceed the fractional contribution of MLCAPE, etc.). There are situational dependencies that can produce significant tornadoes that run counter to what might be described as the "typical" parameter space, as can be inferred from the box and whisker plots (Figs. 8 and 12).

The sentence [in question] now reads: "The motivation for this paper is to evaluate which tornado forecast parameters are usually the most important for three prominent synoptic-scale regimes that have been associated with significant tornadoes: cold fronts, warm fronts, and drylines." Note the insertion of "usually."

If time permits, it might be interesting to do a box and whisker diagram for normalized CAPE, which would likely show large differences between the various regimes based on the 700–500-hPa lapse rate differences mentioned in the text.

This is a good idea. However, NCAPE is not part of the list of SFCOA archived parameters that are available for statistical analysis.

[Minor comments omitted…]