1.5 TORNADOES WITHIN WEAK CAPE ENVIRONMENTS ACROSS THE CONTINENTAL UNITED STATES

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1. INTRODUCTION

Given the well-established importance of buoyancy and vertical shear for severe convective storms, tornadoes occurring within weak buoyancy regimes can pose appreciable challenges to operational forecasters (Vescio and Thompson 1998, Guyer et al. 2006). Such weak buoyancy (with typically high vertical shear) scenarios generally have greater predictive uncertainty with potential for higher false alarm ratios (FAR) and more limited probability of detection (POD) (Dean and Schneider 2008). In an effort to better document this spectrum, climatology of tornadoes that have occurred with weak buoyancy is presented for the continental United States for 2003-2009. For purposes of this study, weak buoyancy was defined by Mixed-Layer (ML) CAPE of 500 J/kg or less (“weak CAPE”). A number of prior research studies have identified common scenarios for tornadoes within weak CAPE regimes, such as hurricanes/tropical cyclones (McCaul 1991), "cold core" mid-latitude closed lows (Guyer and Davies 2006, Davies 2006), as well as a number of cool season environments such as low-topped California storms (Hanstrum et al. 2002), the Gulf Coast region (Guyer et al. 2006), and Tennessee/Ohio Valleys (Smith et al. 2008). Others have documented singular events in other regions and/or regimes, such as Markowski and Straka (2000) with a late October tornado event in Oklahoma. This study is an initial step to holistically document the frequency of occurrence with such patterns and environments. Seasonal, temporal, geographic, and EF-scale climatologies are given for weak CAPE tornadoes, in addition to relational examinations of weak buoyancy tornadoes to a broader spectrum of higher buoyancy tornado environments.

2. METHODOLOGY AND ENVIRONMENT DATABASE

Tornado statistics for the contiguous U.S. (CONUS) were derived from the Storm Prediction Center (SPC) “ONETOR” tornado database, which is based upon official StormData tornado reports. Estimated tornado environment information, which for purposes of this study was available for seven years (2003-2009), was utilized from a SPC database as described by Dean et al. (2006). Within this database, severe storm reports are objectively linked to estimated storm environments as derived from hourly SPC Mesoscale Analysis grids (40 km x 40 km), which are based on a blend of objectively analyzed surface METAR observations and RUC analysis fields (Bothwell et al. 2002). Such a method is highly conducive to provide estimates of environmental data fields for a large number of cases. However, it should be recognized that the assignment of environment information for each severe report may not always be optimally “environmentally representative” of the actual near-storm environment because of grid spacing and/or temporal sampling limitations. An example of this includes events occurring within a strong baroclinic gradient.

3. WEAK CAPE TORNADO DATABASE

A total of 9321 tornadoes were associated with gridded SPC mesoanalysis data during the 7-year period of 2003-2009. Of those, 2587 tornadoes occurred in environments characterized by weak CAPE, which accounts for roughly the lowest quartile (27.8%) of all tornado cases with respect to MLCAPE. Also of note, 1410 tornado events, or more than half of the weak CAPE tornadoes, were associated with ≤250 J/kg MLCAPE (15.1% of all tornado cases). Of the 2587 weak CAPE tornadoes, there were 199 (7.7%) significant (E)F2-(E)F5 tornadoes. The weak CAPE tornado dataset only included a very few “violent” tornadoes (0.1% of the database), with 3 (E)F4 tornadoes, but no (E)F5 tornadoes. Table 1 depicts the numbers and respective percentage of weak CAPE versus all other tornadoes by (E)F-scale rating. These numbers reflect that weak CAPE, as a singular factor, does not preclude significant tornadoes as (E)F2+ tornadoes comprised 7.7% of the weak CAPE tornado dataset, as compared to 10.7% of the >500 J/kg MLCAPE tornado dataset. Figs. 1 and 2 depict all weak CAPE tornadoes and (E)F2+ weak CAPE tornadoes, respectively, between 2003-2009, with each of these reflecting higher concentrations over the southeastern United States.

4. WEAK CAPE TORNADO CLIMATOLOGY

A number of prior research studies have identified common scenarios for tornadoes within weak CAPE regimes (i.e. tropical cyclones, "cold core" mid-latitude closed lows, low-topped California storms, Gulf Coast cool season). This weak CAPE tornado dataset allows the opportunity to explore the interrelationship and relative frequency of such previously documented occurrences. Diurnal, monthly, seasonal, and geographical climatologies are given for the 7-year weak CAPE tornado dataset.

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	≤500 J/kg MLCAPE Tornadoes	**>500 J/kg MLCAPE Tornadoes**
2003-2009 Tornadoes (% of respective database)	2587	6734
(E)F0 Tornadoes	1607 (62.1%)	4223 (62.7%)
(E)F1 Tornadoes	781 (30.2%)	1788 (26.6%)
(E)F2 Tornadoes	166 (6.4%)	527 (7.8%)
(E)F3Tornadoes	30 (1.2%)	166 (2.5%)
(E)F4 Tornadoes	3 (0.1%)	28 (0.4%)
(E)F5 Tornadoes	0 (0.0%)	2 (0.0%)

Table 1. Numbers of tornadoes stratified by ≤500 J/kg MLCAPE and >500 J/kg MLCAPE for 2003-2009, with breakdowns of each respective database by (E)F-Scale.

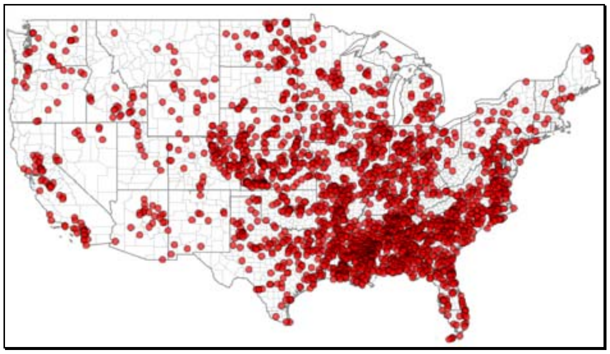

Figure 1. Plot of all tornadoes associated with ≤500 J/kg MLCAPE for 2003-2009.

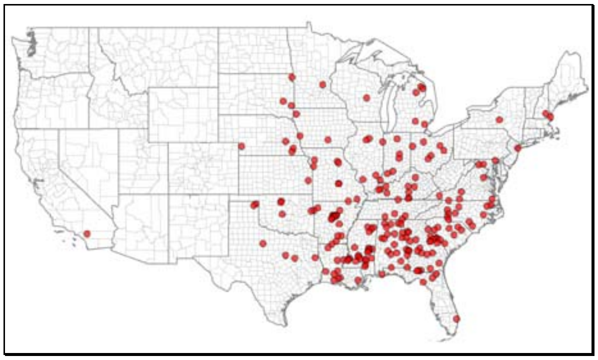

Figure 2. Same as Fig. 1, except (E)F2+ tornadoes.

4.1 Time of Day

As compared to higher buoyancy tornado events, the weak CAPE tornado dataset reflects a slightly more subdued and earlier diurnal peak in the afternoon, with a higher percentage of tornadoes in the morning, early afternoon, and overnight hours (Fig. 3). Relative to all tornadoes, weak CAPE tornadoes were proportionally most common during the overnight/morning hours. Between 07-17 UTC, weak CAPE tornadoes account for hourly ranges of 40-55% of all tornadoes (Fig. 4), suggesting that conditional tornado threats during the late night and morning hours only require sufficient CAPE to sustain convective updrafts if other environmental factors are favorable.

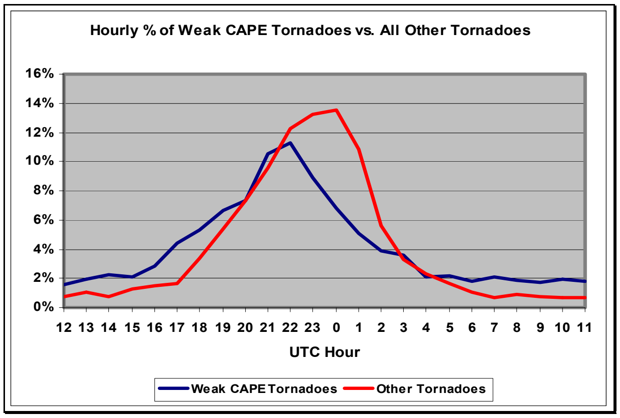

Figure 3. Hourly (in UTC) percentage of all tornadoes associated with ≤500 J/kg MLCAPE (blue) as compared to those associated with >500 J/kg MLCAPE (red) for 2003-2009.

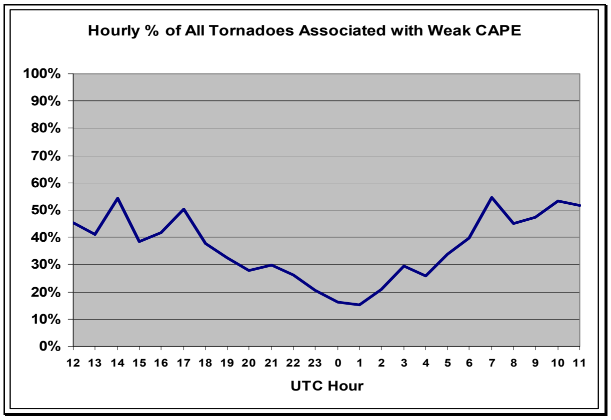

Figure 4. Hourly (in UTC) percentage of all tornadoes associated with ≤500 J/kg MLCAPE for 2003-2009.

4.2 Monthly and Seasonal

The majority of weak CAPE tornadoes were found to occur during the cool season and the spring/fall transitional months, the latter of which includes late summer-autumn maxima associated with tropical cyclones (Fig. 5). The leading monthly occurrence of weak CAPE tornadoes was April (396 total), followed by May (362), September (309), and March (306). Relative to all tornadoes, the highest monthly frequency of weak CAPE tornadoes was during the months of December-February, where around 60% of all tornadoes each month were found to have occurred with ≤500 J/kg MLCAPE (Fig. 6). The highest proportion of significant tornadoes also occurred during the cool season months of November-February, with a monthly peak in February of 17% of all weak CAPE tornadoes being (E)F2 and greater (Fig. 7). Furthermore, it was found that around 10% of all February tornadoes were (E)F2 and greater in combination with weak CAPE.

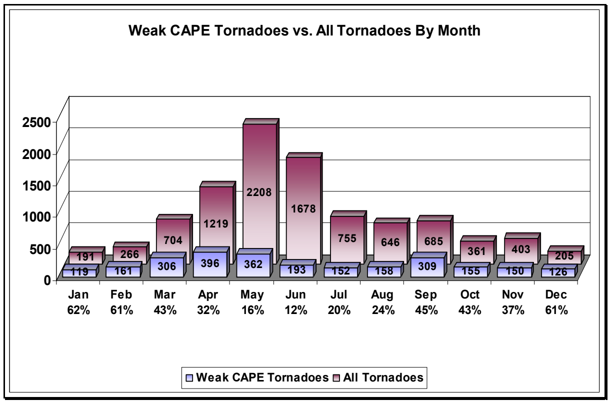

Figure 5. Weak CAPE tornadoes (violet) as compared to all tornadoes (pink) for each month 2003-2009.

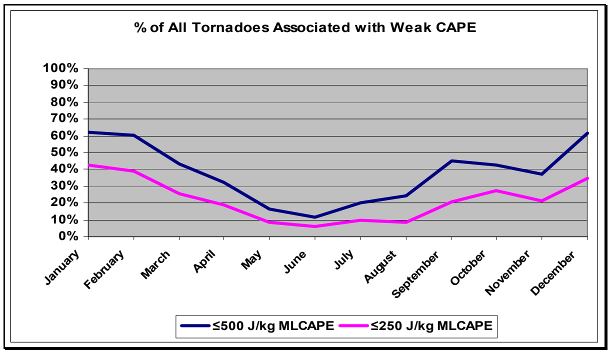

Figure 6. Monthly percentage of all tornadoes associated with ≤500 J/kg MLCAPE (blue) and ≤250 J/kg MLCAPE (pink) for 2003-2009.

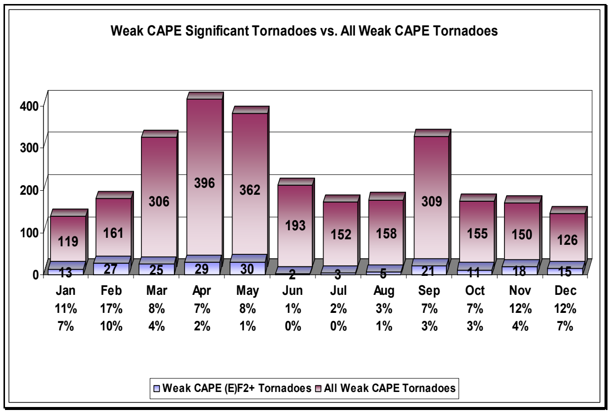

Figure 7. Weak CAPE (E)F2+ tornadoes (violet) as compared to all weak CAPE tornadoes (pink) for each month 2003-2009. Top percentage is the monthly portion of (E)F2+ tornadoes as compared to all weak CAPE tornadoes. The bottom percentage is the monthly portion of (E)F2+ weak CAPE tornadoes as compared to (E)F0-5 tornadoes irrespective of CAPE.

Figs. 8-11 depict locations of all ≤500 J/kg MLCAPE tornadoes by meteorological season. Weak CAPE tornadoes during meteorological winter (December-February, Fig. 8) were observed primarily in the Gulf Coast and Southeast states, with secondary maxima in the middle Mississippi and Ohio River

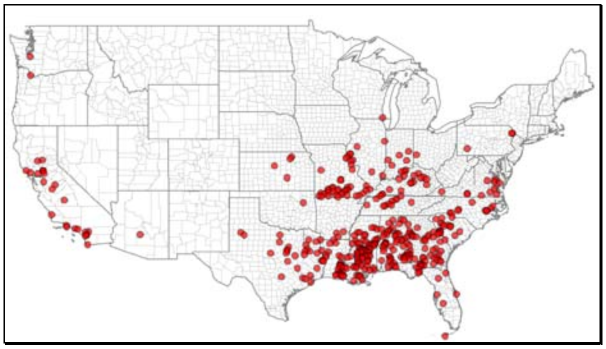

Figure 8. Plot of meteorological winter (December-February) tornadoes associated with ≤500 MLCAPE for 2003-2009.

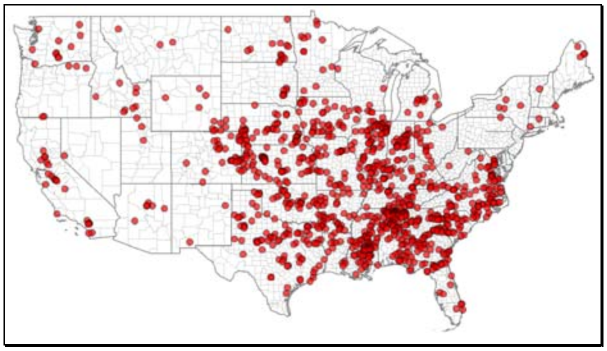

Figure 9. Same as Fig. 8, except meteorological spring (March-May).

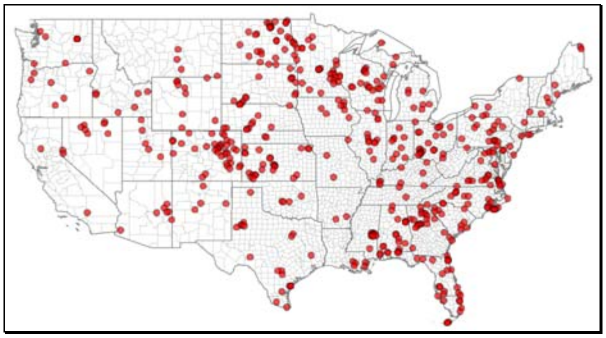

Figure 10. Same as Fig. 8, except meteorological summer (June-August).

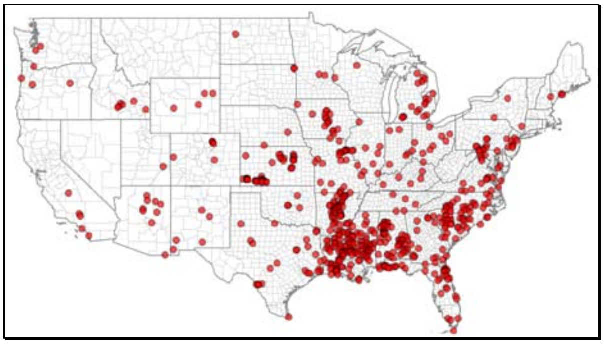

Figure 11. Same as Fig. 8, except meteorological autumn (September-November).

Valleys, as well as California. With the onset of spring (March-May, Fig. 9), weak CAPE tornadoes were more common across a greater spatial extent of the Plains, Midwest, as well as the southeast U.S. to the Mid-Atlantic States. By meteorological summer (June-August, Fig. 10), weak CAPE tornadoes were more common across the upper Midwest, northern Plains, central High Plains, and portions of the eastern U.S.; however, a lower frequency of occurrence is noted across much of the remainder of the CONUS. During meteorological autumn (September-November, Fig. 11), weak CAPE tornadoes are again prevalent across much of the Gulf Coast region and southeast United States. This is partially associated with tornadoes occurring with landfalling/inland-moving tropical cyclones.

4.3 Regional and State-by-State

In a first step to examine regional occurrence in greater detail, state-by-state statistics were determined for weak CAPE tornadoes. On a state-by-state basis for states having at least 25 weak CAPE tornadoes during 2003-2009, Fig. 12 features the dominant month of weak CAPE tornado occurrence, including an accompanying percentage of annual weak CAPE tornadoes occurring that month. Table 2 is a ranking of weak CAPE tornadoes by state, as well as a relative percentage of weak CAPE tornadoes as compared to the more inclusive tornado dataset (if at least 25 weak CAPE tornadoes 2003-2009). Similarly, Table 3 ranks (E)F2+ tornado occurrence by state, with corresponding portions of weak CAPE significant tornadoes as compared to all significant tornadoes irrespective of CAPE.

Consistent with the results in Figs. 8-11, the states with the greatest number of weak CAPE tornadoes are located from the Plains eastward to the mid- and southern Atlantic coast, and over California. Many of these states exhibit peak occurrence in the spring or the fall months. In addition, for many of the states, the tabular data indicate a relatively high conditional probability of significant tornadoes, given the occurrence of a tornado during these peak months.

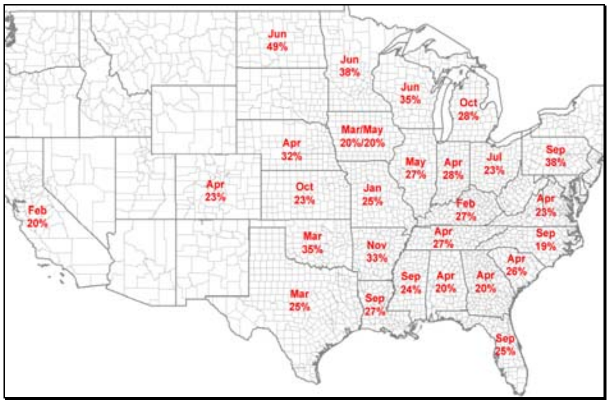

Figure 12. Month with the highest number of weak CAPE tornado occurrences for (27) states with at least 25 weak CAPE tornadoes during 2003-2009. Accompanying percentage is that month's portion of annual weak CAPE tornadoes for each state.

# of ≤500 J/kg MLCAPE Tornadoes	**% of All Tornadoes associated with ≤500 J/kg MLCAPE *for States with ≥25 Tornadoes***
AL 235	CA 90% (54)
MS 202	AL 52% (235)
TX 158	MS 48% (202)
GA 136	GA 46% (136)
KS 133	LA 45% (127)
LA 127	OH 45% (44)
IL 106	MI 43% (39)
FL 106	NC 42% (103)
NC 103	PA 40% (29)
AR 99	IN 38% (64)

Table 2. State-by-state rankings of ≤500 J/kg MLCAPE tornadoes (2003-2009) by total numbers and as a percentage of all tornadoes (states with ≥25 weak CAPE tornadoes).

# of (E)F2+ Tornadoes with ≤500 J/kg MLCAPE	**% of (E)F2+ Tornadoes with ≤500 J/kg MLCAPE *for States with ≥5 (E)F2+ Tornadoes***
AL 23	OH 86% (6)
GA 23	AL 59% (23)
MS 22	NC 52% (11)
AR 15	MI 46% (5)
NC 11	SC 41% (9)
KY 11	MS 40% (22)
LA 10	LA 39% (10)
SC 9	GA 37% (23)
MO 8	VA 31% (5)
OH/IN/TX 6	IN 26% (6)

Table 3. State-by-state rankings of ≤500 J/kg MLCAPE (E)F2+ tornadoes (2003-2009) by total numbers and as a percentage of all (E)F2+ tornadoes (states with ≥5 (E)F2+ tornadoes).

5. WEAK CAPE TORNADO ENVIRONMENTS

In order to examine the environments associated with weak CAPE tornadoes, relational examinations were made to additional meteorological variables and severe convective parameters, and these were compared to relatively higher buoyancy tornado producing environments (>500 J/kg MLCAPE).

5.1 Vertical Wind Shear

Weak CAPE tornado environments were found to be associated with slightly higher values of 0-6 km bulk shear compared to tornadoes occurring with stronger buoyancy (Fig. 13). A somewhat stronger discrimination appears to exist with low level storm relative helicity computations, such as 0-3 km SRH and 0-1 km SRH (Fig. 14). In both the "effective shear" and "effective SRH" computations (Thompson et al. 2007) as shown in Figs. 13-14, it appears that the buoyancy-dependent nature of these calculations contributed to lower values of effective shear/SRH (as compared to traditional fixed layer computations) given the weak

CAPE nature of the events under study. For example, the cloud-bearing layer of storms developing in weak CAPE situations is often comparatively shallow, and the effective inflow layer can also be more limited in vertical depth. Both of these factors may contribute to lower values of effective shear and SRH compared to the traditional fixed layer computations.

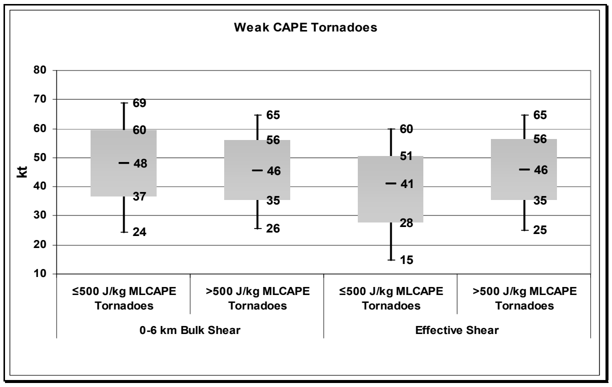

Figure 13. Box and whisker diagrams of deep layer vertical shear (kt) of ≤500 J/kg MLCAPE tornadoes vs. >500 J/kg MLCAPE tornadoes for 2003-2009. Each box is representative of the 25th to 75th percentiles of values, with the outer whiskers representing the 10th and 90th percentiles.

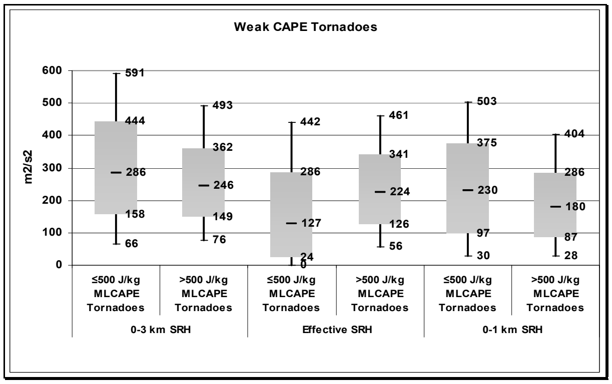

Figure 14. Same as Fig. 13, except 0-1 km SRH, Effective SRH, and 0-1 km SRH (m^2/s^2).

5.2 Thermodynamics

While this study defined weak CAPE tornadoes as ≤500 J/kg MLCAPE, comparisons for this dataset were made to alternative CAPE computations such as surface-based CAPE (SBCAPE) and Most-Unstable CAPE (MUCAPE) (Fig. 15). Mid-level (700-500 mb) and low level (0-3 km) lapse rates were found to be comparatively lower than higher buoyancy tornado environments (Fig. 16), with 50% of weak CAPE tornado events having a 700-500 mb lapse rates of 6.0 C/km or less. This is likely attributable to the prevalence of moist-tropical-type environments and/or cool season environments, where an appreciable elevated mixed layer is lacking within many of the weak CAPE tornado environments. It should not be surprising that weak CAPE tornadoes were also associated with lower surface temperatures and dewpoints than higher buoyancy cases (Fig. 17). The majority of weak CAPE tornado cases tended to be associated with surface temperatures in the 60s - lower 70s °F and with surface dewpoints in the upper 50s - middle 60s °F. Given implications of cooler near-surface temperatures and lesser vertical mixing, weak CAPE tornado events tended to coincide with higher low level relatively humidity (Fig. 18) and lower cloud bases/LCLs (Fig. 19).

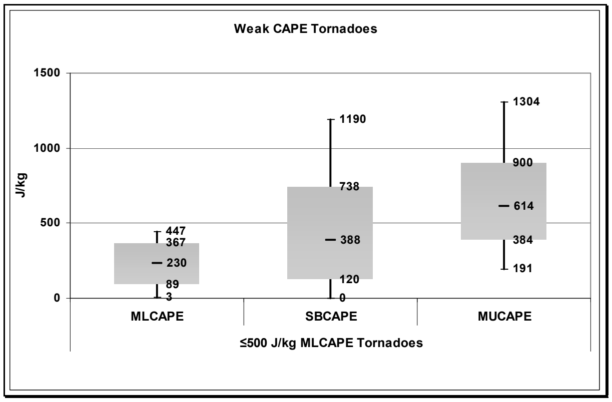

Figure 15. Same as Fig. 13, except MLCAPE, SBCAPE, MUCAPE (J/kg) for weak CAPE tornadoes.

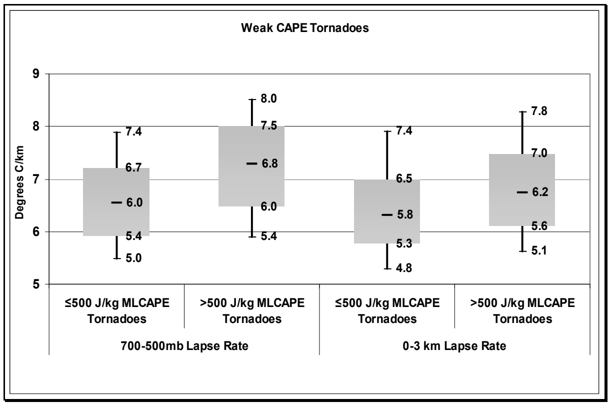

Figure 16. Same as Fig. 13, except 700-500 mb Lapse Rate and 0-3 km Lapse Rate (°C/km).

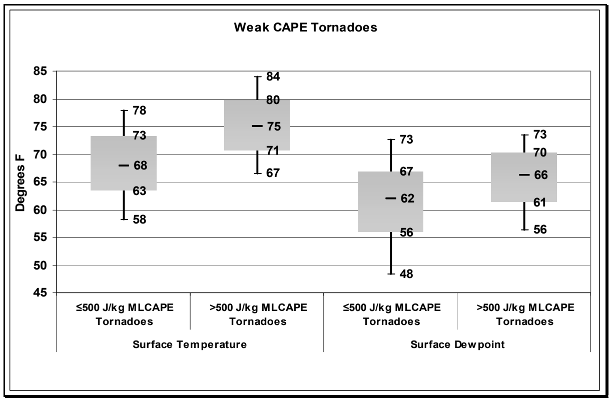

Figure 17. Same as Fig. 13, except Surface Temperature and Surface Dewpoint (°F).

While values of low level moisture (by proxy of surface dewpoints in this study) tended to be lower in weak CAPE tornado events, it is noteworthy that values of precipitable water exhibit considerable overlap with tornadoes that occur within higher buoyancy regimes (Fig. 20), especially given that many of the weak CAPE tornado events occur during the cool and/or transitional seasons (section 4.2). Thus, while specific measures of buoyancy are a limited or poor singular discriminator of tornadoes, this perhaps suggests that high atmospheric moisture content (such as measured by precipitable water and/or 100-mb mixing ratios) could contribute to an improved situational awareness mindset during the cool and/or transitional seasons when a minimal threshold of CAPE is present.

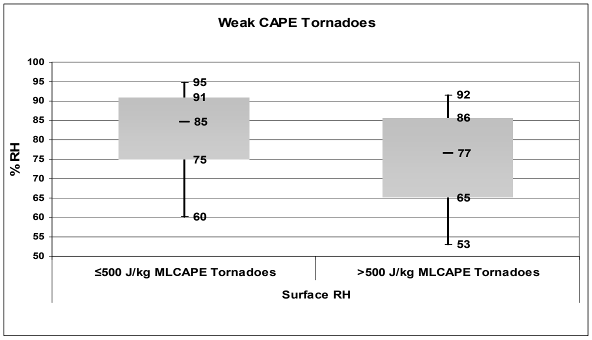

Figure 18. Same as Fig. 13, except Surface Relative Humidity (%).

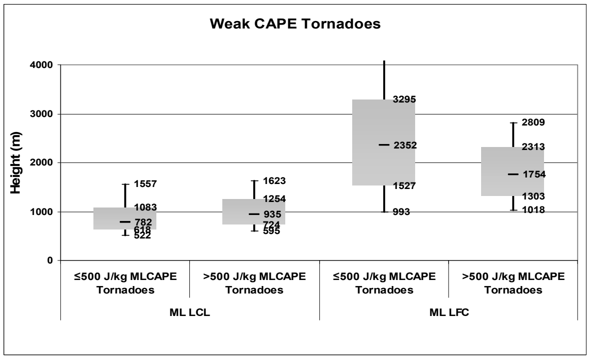

Figure 19. Same as Fig. 13, except mean layer LCL and LFC (m).

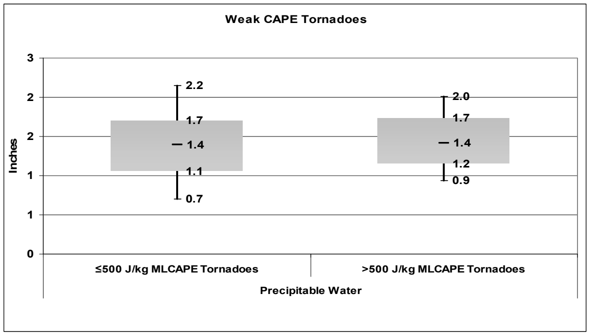

Figure 20. Same as Fig. 13, except Precipitable Water (in).

5.3 Composite Parameters

Additional comparisons were made to derived composite parameters, such as the Supercell Composite Parameter (SCP – Thompson et al. 2004) and Significant Tornado Parameter (STP – Thompson et al. 2003, 2004) (Figs. 21 and 22). Of note, these parameters rely on a normalized linear dependency of CAPE, such as a denominator of MLCAPE of 1500 J/kg in the case of STP. Given that the Thompson et al. dataset is dominated by higher CAPE cases and spring events, it was not surprising that the majority of weak CAPE tornado events were associated with STP values below 1.0, including 64% of (E)F2+ tornadoes (and 82% of all tornadoes). While operational forecasters have found considerable utility is such conditional composite-type parameters, this serves as a reminder that an appreciable number of tornadoes can and do occur with relatively low SCP and STP values, especially when scenarios conducive for weak CAPE tornadoes are prevalent.

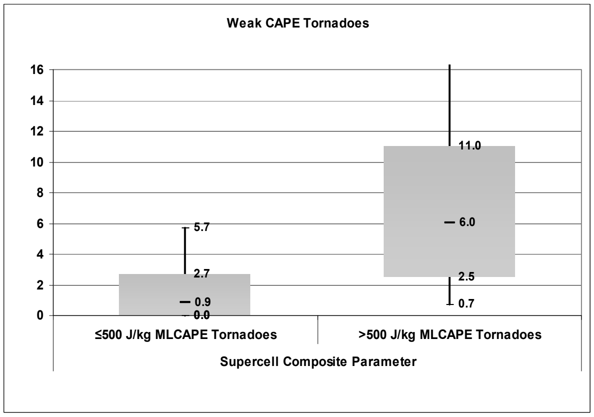

Figure 21. Same as Fig. 13, except Supercell Composite Parameter (SCP).

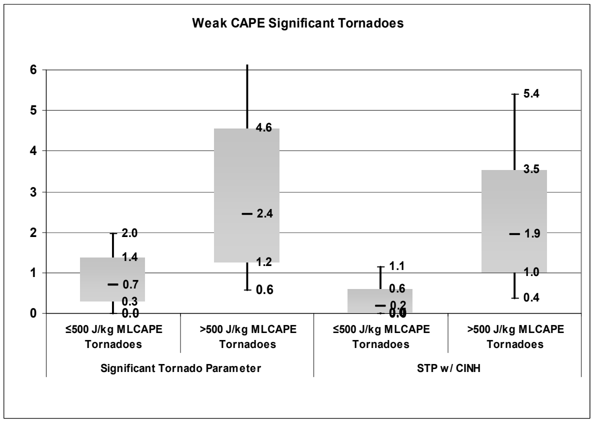

Figure 22. Same as Fig. 13, except Significant Tornado Parameter (STP – Thompson et al. 2003) and Significant Tornado Parameter with CIN (STPC – Thompson et al. 2004) for (E)F2+ tornadoes only.

6. SUMMARY AND FUTURE WORK

The prevalence of weak CAPE environments across the continental United Sates has inherent ramifications on the predictability (lower probability of detection and higher false alarm ratio) of tornadoes (Schneider and Dean 2008), with additional implications on operational forecast ability and meteorological situational awareness. As a compliment to a number of prior cool season studies and other low CAPE tornado conducive regimes such as landfalling hurricanes/tropical systems, this work is a preliminary step in investigating weak buoyancy tornado producing regimes using a large data sample.

Relative to higher buoyancy (>500 J/kg MLCAPE) tornadoes, weak CAPE tornadoes were found to occur more frequently during the cool season and transitional spring/autumn months, with a higher overnight/morning frequency of occurrence. It was found that weak CAPE tornadoes occur in modestly cooler surface temperatures and lower surface dewpoints, although precipitable water values were similar to the higher buoyancy tornado environments. While some measure of buoyancy is inherently necessary for thunderstorms, this study reinforces previous findings that tornadoes, including significant tornadoes, can and do occur within weak buoyancy regimes, and that measures of CAPE alone can be poor discriminators of tornado likelihood and intensity.

Future work will include more comprehensive examinations of synoptic and mesoscale patterns, in addition to further relational analysis to convective parameters and indices, perhaps segmented by convective mode, regional area, and/or by month of occurrence.

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