P4.58 THE ROLE OF LOW-LEVEL INSTABILITY ON TORNADO INTENSITY

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1. **Introduction**

Studies by Thompson et. al. (2003, hereafter T03), Thompson et. al. (2004), Togstad et. al. (2011, hereafter T11), Grams et. al. (2012, hereafter G12), and others have discovered parameters that can be used to discriminate atmospheric conditions associated with higher probabilities of significant tornadoes (an intensity of EF2 and higher) versus non-significant tornadoes. There has been much less research regarding parameters that distinguish environmental conditions favorable for violent tornadoes (EF4 and EF5). Although violent tornadoes only account for less than one percent of all reported tornadoes (McCarthy and Schaefer 2004), they are responsible for 66 percent of all fatalities associated with tornadoes (Ashley 2007). Even though the number of violent tornadoes is relatively small, the authors felt that the environments associated with the tornado subset were worth investigating to discover if a discriminating signal exists to assist operational meteorologists forecasting these rare events.

T03 was an influential study which researched supercell environments in which significant tornadoes were reported using proximity soundings from the Rapid Update Cycle (RUC-2). T03 found that the differences between significant tornado (F2 or greater) and nontornadic supercell environments were most pronounced with 0-1km storm relative helicity (SRH) and 0-1km relative humidity (RH) or mixed-layer lifted condensation level (MLLCL) height, while combination or composite parameters showed the strongest ability to distinguish between the two types. However, this study examined all F2 or greater tornadoes and the resulting statistics were likely weighted toward environments of F2 and F3 tornadoes because of sample size disparity. G12 studied a large sample of significant tornadoes and found that composite and kinematic parameters provided a greater discrimination when forecasting significant tornado events than using thermodynamic parameters, but again any signal from the violent tornadoes would likely be overwhelmed. Cohen (2010, hereafter C10) did concentrate on violent tornadoes, but focused on low-level kinematic, instability, and composite parameters similar to T03. Some research has been completed on low-level thermodynamic parameters regarding tornadoes that occur in non-typical environments. Davies (2002, hereafter D02) found significant tornadoes (EF2+) that develop in environments with relatively weak shear typically do so when there is sizable convective available potential energy (CAPE) in the low-levels of the atmosphere (0-3 km). Davies (2006, hereafter D06) later researched tornadoes that occurred in environments with high lifted condensation level (LCL) heights. This study found that adequate low-level moisture and low-level CAPE in the presence of steep low-level lapse rates could help explain tornadogenesis in high LCL environments. Both D02 and D06 found that low level instability may have some effect on tornadogenesis and possibly tornado intensity.

Positive values of 0-3 km CAPE are typically associated with air masses containing ample low level moisture. Many of the studies previously mentioned have found low-level moisture to be a good indicator of an environment capable of producing a tornado. Regardless of LCL height, environments with ample low level instability would lead to higher vertical velocities near the surface. Markowski and Richardson (2010, hereafter MR10) state that once a tornado becomes established, tilting of the surface-layer horizontal vorticity by the extreme vertical velocity gradient associated with the tornado updraft itself probably contributes to the near-ground vertical vorticity in a significant way. This suggests that as long as the extreme vertical velocity gradient of the updraft continues, the tornado should be able to continue. If low-level instability is related to low-level vertical velocity, then the degree of low-level instability could have an effect on the intensity of a tornado once the tornado is established. This study will not only examine the potential relationship of low level thermodynamic parameters with violent tornadoes, but will also look at the effects of low-level kinematic fields and other parameters to see if similarities or further differences are evident between violent tornadoes (EF4 and EF5), non-violent tornadoes (EF1, EF2, EF3) and significant tornadoes (EF2, EF3, EF4, EF5) previously researched.

2. **Data and Methodology**

Many studies have used proximity soundings to assess near storm environments when researching parameters associated with severe weather (Rasmussen and Blanchard 1998 (hereafter RB98); Evans and Doswell 2001; Davies 2006; Potvin et. al.

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2010 (hereafter P10); and many others). While most of these studies have relied on RUC sounding data, other recent studies have used North American Regional Reanalysis (NARR) data to determine environments associated with severe weather or tornadoes (Gagne et. al. 2012, hereafter G12; Cavanaugh and Schultz 2012; Gensini and Ashley 2011). The NARR data from a horizontal grid with 32 km resolution and a 3 hour temporal resolution provides closer representations of the environment for each storm both spatially and temporally (G12). The number of storms previous studies have used for significant tornadoes have ranged from 54 in T03, 153 in T11, and up to 1265 in P10. To obtain a similar sample for violent tornadoes as T11, data was collected for all violent tornadoes between 1990 and 2011. A sample of EF3 tornadoes was collected from 2006 to 2011, and EF2 and EF1 tornadoes were collected from 2009 to 2011. One year of EF1 tornadoes would have given a sufficient sample size, but a 3 year range helps reduce any yearly bias. EF0 tornadoes were not collected and analyzed due to complexities involved with weak and possibly brief tornadoes (RB98). Tornado reports with intensity were collected from National Weather Service Storm Data Reports.

To mitigate a bias of a particular event, only one sounding within a predefined proximity was collected on tornado days. Any tornado that occurred within two degrees latitude and two degrees longitude on the same day was omitted from the dataset. Two degrees latitude is around 200 km which is the spacing of the meso α scale, and this is the horizontal scale on which convective systems typically occur (MR10). Similar to other proximity sounding studies (RB98 and T03), data quality checks were performed to ensure accurate environmental conditions were represented by removing any sounding with less than 10 J kg^{-1} of 100 mb mean mixed-layer parcel CAPE (MLCAPE). This removed soundings contaminated by convection or outflow from the dataset. After these checks were in place the sample dataset included: 576 EF1, 221 EF2, 130 EF3, and 117 EF4 and EF5 tornadoes. The data were grouped into three categories: violent (EF4 and EF5), non-violent (EF1, EF2, EF3) and significant (EF2, EF3, EF4, EF5). The non-violent and violent groups are plotted in Fig. 1. Although the primary focus of this study is on violent versus non-violent, a dataset of significant tornadoes was defined to compare the data of previous studies to this study.

Because the temporal resolution of the NARR data is 3 hours and the environmental conditions before the tornado occurrence was needed, the NARR dataset at the valid time preceding the tornado report was used as the pre-storm environment. Vertical profiles of temperature, dewpoint, and wind speed and direction were interpolated (bilinear between the nearest four horizontal grid points) to the latitude/longitude where the tornado began. The NARR dataset contains 29 pressure levels with 25 hPa resolution between 1000-700hPa and 300-100 hPa, and 50 hPa resolution between 700-300hPa. Using these profiles, many thermodynamic and kinematic parameters throughout these layers were calculated via the NSHARP software (Hart and Korotky 1991). A comparison of each field was then conducted to search for any signals that would aid discrimination between violent and non-violent tornado environments.

3. NARR Sounding Errors

There has been little research using proximity soundings constructed from NARR data. Therefore, data comparisons from observed soundings were gathered to decide whether the NARR dataset was accurate for use in this study. 0000 UTC NARR soundings were used and compared with 0000 UTC observed rawinsonde observations (RAOBs) from across the country. Each tornado was crosschecked with upper air sites and if a tornado occurred within 65 km of an upper air site, the 0000 UTC sounding data was obtained for comparison with the NARR data. This criterion led to a sample size of 33 soundings to compare. Fig. 2 shows the sites used and the number of times each site matched with a tornado in the dataset. Comparisons of the NARR dataset errors were made between the errors found in T03 when the RUC-2 soundings were compared with RAOBs.

Both surface-based CAPE (SBCAPE) and MLCAPE were compared to determine which parameter would be better suited for this study (Table 1). SBCAPE had a mean absolute error (MAE) of 614 J kg^{-1}, but a mean bias of only -78 J kg^{-1}. MLCAPE had a smaller MAE, but the bias was more negative than SBCAPE at -153 J kg^{-1}. For the study, the MLCAPE was used because of the smaller MAE despite that the bias was slightly larger than the SBCAPE. T03 also used MLCAPE due to smaller errors. Craven et al. (2002) also stated MLCAPE was the best at determining potential parcel ascent.

0-6 km shear values from the NARR dataset were also compared to observed soundings. The MAE was 3.9 m s^{-1} with a bias of -2.9 m s^{-1}. This equates to a slight negative bias. However, the 90th percentile value was 1.6 m s^{-1}, and the slight negative bias was not expected to greatly influence the data. With the acceptable biases of the MLCAPE, SBCAPE, and 0-6 km shear values, the NARR dataset was determined to be reasonably representative of the near-storm environment.

4. Violent Tornado Parameters Results

Many studies have looked at the near-storm environment for significant tornadoes, but little research exists on violent tornadoes. The infrequent occurrence of violent tornadoes, when compared to the climatology of significant tornadoes, means that any signal discriminating environments supportive of violent tornadoes gets overwhelmed when combined with the larger significant tornado database. Also, when examining the data, the non-violent tornado dataset cannot be directly compared with the weak tornadoes dataset of previous studies as the EF2 and EF3 tornadoes would skew the data.

a) Previously researched parameters

T03 examined various thermodynamic, kinematic, and composite parameters to distinguish environments of various modes of severe weather produced from right-moving supercells. C10 concentrated on violent tornadoes, but the focus was primarily on kinematic fields and MLCAPE/SBCAPE. Neither study investigated low-level instability. Some of the parameters used in T03 and C10 were examined to determine if these parameters had any signal associated with environments favorable for violent tornadoes (Table 2).

Box and whisker plots (Fig. 3) of MLLCL heights were first examined between the three categories studied. T03, RB98, and other studies have found that low LCL heights can help discriminate environments between significant and non-significant tornadoes. The dataset used in this study showed little variability in the LCL heights between the violent, non-violent or significant tornadoes, with mean values for all three categories ~1140 m. Given these findings, MLLCL can be a key discriminator for environments between significant tornadoes and weak tornadoes as previous research has found, but is unlikely able to distinguish between non-violent and violent tornado environments.

MLCAPE (Fig. 4) was compared and similar relationships can be seen within the data that were found within the previous studies. The mean values of MLCAPE increased by approximately 200 J kg^{-1} from non-violent tornadoes to significant tornadoes, and increased approximately 400 J kg^{-1} between significant and violent tornadoes. When comparing the values of MLCAPE between this dataset and T03, there was ~300 J kg^{-1} less MLCAPE for the significant tornadoes category. This could be attributed somewhat to the -153 J kg^{-1} MLCAPE bias the NARR data had when compared to observed soundings. The mean MLCAPE for violent tornadoes was 2090 J kg^{-1}, which is very similar to the mean of 2097 J kg^{-1} C10 found within its dataset for violent tornadoes. In agreement with other studies, the data indicated higher values of MLCAPE seemed to be associated with stronger tornadoes, including violent.

Veritical wind shear was found to be an important discriminator between supercells and non-supercells with a vertical shear magnitude of 15 to 20 m s^{-1} needed to support rotation within the storm (RB98). MR10 states that most significant tornadoes and nearly all violent tornadoes are produced by supercells and therefore bulk wind shear is an important consideration when forecasting tornadoes. The mean values of 0-6 km shear (Fig. 5) increased from 19 m s^{-1} for non-violent tornadoes to 21 m s^{-1} for significant tornadoes, but actually decreased slightly to 18 m s^{-1} for violent tornadoes. These values are all within the range previously found to support supercells, but do not seem to distinguish between violent tornadoes and non-violent tornadoes.

T03 found that 0-1 km shear differences became more apparent between significantly tornadic and non-tornadic supercells. The differences between the mean value of 0-1 km shear (Fig. 6) in this dataset between significant tornadoes and non-violent tornadoes were negligible. The mean for significant tornadoes was 10 m s^{-1} which is nearly identical to what T03 found. However, the values of 0-1 km shear actually decrease to 8.3 m s^{-1} for violent tornadoes. While 0-1 km shear has been shown to distinguish environments between non-tornadic and significant tornadoes, it does not stratify tornado intensity.

T03 found storm relative helicity (SRH) values increased between the non-tornadic supercell and significant tornado categories. For 0-3 km SRH (Fig. 7) the means between non-violent and significant tornadoes in this dataset do increase slightly between the two categories, but like shear, decrease with violent tornadoes. This same relationship is also apparent with the 0-1 km SRH (Fig. 8). The mean 0-3 km SRH for significant tornadoes was 247 m^2 s^{-2} which compares with the value of 250 m^2 s^{-2} found in T03. The mean 0-1 km SRH for significant tornadoes was 171 m^2 s^{-2} which compares reasonably with the 185 m^2 s^{-2} found in T03. Given the similarity of the comparison values, there is increased confidence regarding the validity of decreased values of SRH within the violent tornado dataset. The noticeable decrease in 0-1 km wind shear and SRH in the 0-1 km and 0-3 km layers between violent and non-violent tornado environments is unlikely to be a coincidence.

b) New parameters researched for violent tornadoes

D06 and D02 found relationships between low-level lapse rates and 0-3 km CAPE with tornadogenesis and perhaps tornado strength in the high plains. However, Davies did not study violent tornadoes. Therefore, low level lapse rates and low level CAPE were examined for any possible relationships between non-violent tornadoes and violent tornadoes (Table 3).

The 0-2 km lapse rates were first examined (Fig. 9). The mean lapse rates between the non-violent and significant were negligible, with mean lapse rates of 7.8 C km^{-1} and 7.9 C km^{-1} respectively. However, a substantial increase to a mean of 8.4 C km^{-1} was evident for violent tornadoes. Another interesting finding is the 10th percentile for violent tornadoes of 6.7 C km^{-1} is equal to the 25th percentile value for non-violent tornadoes. This suggests that while non-violent tornadoes do occur with steeper lapse rates, many tornadoes also occur with much smaller lapse rates. The same cannot be said for violent tornadoes.

The 0-3 km lapse rates (Fig. 10) showed similar relationships between the three categories. The environments associated with significant tornadoes and non-violent tornadoes had mean 0-3 km lapse rates of 7.6 C km^{-1} and 7.5 C km^{-1} respectively. The mean lapse rates for violent tornadoes increased to 7.9 C km^{-1}. There was also the significant increase with the 10th percentile values of the 0-3 km lapse rates which leads to the same conclusions. Non-violent tornadoes occur across a large spectrum of low-level lapse rates, but violent tornadoes occur primarily in environments characterized by steeper low-level lapse rates.

The higher low level lapse rates associated with the violent tornadoes may be the cause for the decrease in low level shear and helicity values previously shown for violent tornadoes when compared with significant and non-violent tornadoes. High lapse rates in the lowest levels of the atmosphere are typical of a deep mixed layer. Heating of the boundary layer during the day is driven by the ground below due to sensible heat flux. This drives the mixed layer to a nearly dry-adiabatic lapse rate (9.8 C km^{-1}). Because the mixing promotes homogeneity, wind speeds would tend towards constant values within the mixed layer. This means that shear and helicity values would be lower than an atmosphere where low level lapse rates are not as high. This is also why the 0-2 km lapse rates associated with environments in which violent tornadoes occur are slightly higher than the 0-3 km lapse rates.

Previous studies, including T03 have shown low-level moisture (0-1 km mean RH, MLLCL) can have a significant importance on the increased likelihood of a significant tornado versus a non-tornadic storm. The best parameter to tie low-level lapse rates and moisture together is 0-3 km MLCAPE. MR10 states that CAPE requires the presence of relatively large lapse rates and high values of lower tropospheric moisture. CAPE values can be increased either by increasing the lapse rates and/or the moisture available at the lifting level.

Larger values of 0-3 km MLCAPE would be either due to high amounts of low-level moisture and/or steep low-level lapse rates. This parameter was analyzed (Fig. 11) to see if there was any importance with this parameter on violent tornadoes. There were slight increases in the mean values between non-violent and significant tornadoes. The mean 0-3 km MLCAPE values for non-violent tornadoes was 72 J kg^{-1}, and significant was 78 J kg^{-1}. However, another substantial increase was noted for violent tornadoes with a mean of 99 J kg^{-1}.

Although the increases of the low-level lapse rates and the 0-3 km MLCAPE appear to be important for environments supportive of violent tornadoes, the overall mathematical difference is small. The differences between the mean of 0-2 and 0-3 km lapse rates are 0.3 to 0.5 C km^{-1} and the difference of the mean 0-3 km MLCAPE is 21 J kg^{-1}. Based on operational forecast experience, and the contouring intervals typically attributed to these parameters on the Storm Prediction Center's Mesoanalysis website (Bothwell et. al 2002), operational meteorologists are very unlikely to notice differences in environments supportive of violent tornadoes based on any one of the parameters alone.

Because each parameter individually shows mathematical skill at discriminating violent tornado environments, the authors investigated a method to make the difference in means more apparent to operational forecasters while maintaining focus on low level instability; we multiplied the parameters together. While this operation has little physical meaning, higher numbers are well correlated with less 0-3 km static stability, resulting in an index for evaluating low-level instability (LLI, Fig. 12). 0-3 km lapse rates were preferred over 0-2 km lapse rates because of the influence the mixed layer has in the 0-2 km layer. This layer is also the same as that used for the low level CAPE calculation. This LLI will be treated as a value versus an atmospheric quantity to evaluate environments favorable for violent tornadoes. Therefore, this number is left without units. Again, there were small increases between the non-violent tornado category and the significant tornado category. This mean value increased by 45 from 557 to 602. However, the value jumped 206 between significant and violent environments. Violent tornadoes occurred with a mean product of 808. This relationship is similar to that of the 0-3 km MLCAPE and lapse rates computed separately. There is a substantial difference with the mean values being separated by about 200, and significant differences with the 25th to 75th percentiles shown in the box and whisker plots. The LLI does give the operational meteorologist an easier method to distinguish environments supportive for violent tornadoes.

5. Statistical Analysis

Since 0-3 km lapse rates and 0-3 km MLCAPE were identified as the best discriminatory parameters between non-violent and violent tornado environments from the box and whisker plots, analysis was performed to determine if there was a statistically significant difference in the samples of these parameters. Weiss (2008) discusses techniques for evaluating statistical significance when comparing two population means based on independent samples on the shape of the distribution of the populations in question. Therefore, before evaluating the statistical significance of the data, tests were performed to determine the normality of the distribution of each individual population and histograms were completed to evaluate the general shape of each distribution.

Evaluating the distribution of 0-3 km MLCAPE values indicated that this was a non-normal distribution (for both violent and non-violent populations) whose mode was skewed to the left of the "bell-curve" shape typical of normal distribution datasets. Because the sample populations taken from violent and non-violent tornado environments have similarly shaped histograms and both distributions are non-normal, Weiss recommends employing the use of a non-parametric test, called the Mann-Whitney test, to evaluate the null hypothesis that the two population means are equal. This test indicated that, at the 99% confidence level the data provides sufficient evidence that the means of the populations are not equal to one another. Next, a test to determine whether the mean of the 0-3 km MLCAPE associated with violent tornado environments is greater than the mean of the 0-3 km MLCAPE associated with non-violent tornado environments (similar to a right tailed t-test) was also performed. At the 99% confidence level, the data provided sufficient evidence to conclude that the mean 0-3 km MLCAPE values associated with environments in which violent tornadoes occurred exceed the mean 0-3 km MLCAPE values associated with environments in which non-violent tornadoes occurred.

Evaluating the distribution of the 0-3 km lapse rate values associated with environments in which violent and non-violent tornadoes occurred indicated that both of these populations were near-normal and their histograms were very close to the expected “bell shape” typical of normal datasets. In this instance, Weiss recommends employing a non-pooled t-test to test the null hypothesis that the means of these populations are the same. This test indicated that, at the 99% confidence level, the data provided sufficient evidence that the means of the populations are not equal to one another. Additionally, a right tailed t-test revealed at the 99% confidence level, the data provided sufficient evidence to conclude that the mean of 0-3 km lapse rate values associated with environments in which violent tornadoes occurred exceed the mean of 0-3 km lapse rate values associated with environments in which non-violent tornadoes occurred.

While these results provide statistical support for the utility of 0-3 km MLCAPE and lapse rates as useful discriminators between environments associated with violent and non-violent tornadoes, Weiss points out that there is an important distinction to be made between statistical significance and practical significance. That is, just because these environmental parameters have been shown to be statistically significant discriminators between violent and non-violent tornado environments, it does not speak to their ability to help an operational meteorologist discriminate between these environments.

As a result, a different approach was taken to the tests for statistical significance in which different values for the null hypothesis were chosen in an effort to gauge the magnitude of difference between the means of the associated violent and non-violent tornado environments that remain statistically significant at the 95% confidence level. These tests indicated that at the 95% confidence level, the mean of the sample population of 0-3 km MLCAPE associated with violent tornado environments was 17 J kg^{-1} greater than the mean of the sample population of non-violent tornado environments. These tests also showed that at the 95% confidence level, the mean of the sample population of the 0-3 km lapse rate associated with violent tornado environments was 0.27 C km^{-1} greater than the mean sample population of non-violent tornado environments.

The same tests were applied to LLI as above; the Mann-Whitney test was used because the distributions of data are non-normal but similarly shaped for LLI associated with violent and non-violent tornado environments. At the 99% confidence level, a right tailed Mann-Whitney test indicates that the data provides sufficient evidence to conclude that the mean of the sample population of LLI associated with violent tornado environments is greater than the mean of the sample population of LLI associated with non-violent tornado environments. Applying the same approach to determine practical significance as above, tests concluded that at the 95% confidence level, the mean of the sample population of LLI associated with violent tornado environments was a quantity of 162 greater than the mean of the sample population of non-violent tornado environments. Also, computing a confidence interval for the difference of the means of these two populations results in the conclusion that with 99% confidence, the difference in the means will fall between 112 and 389. These results seem to offer an operational meteorologist a better chance to notice the difference in low-level instability associated with violent tornado environments, perhaps raising confidence in the potential for violent tornadoes when all other conditions are equally favorable for severe convective storms, and tornadoes in general.

6. Conclusions

Violent tornado environments had significant increases of 0-2 km lapse rates, 0-3 km lapse rates, 0-3 km MLCAPE, and the product of the 0-3 km lapse rates and 0-3 km MLCAPE (LLI) when compared with the non-violent dataset. These parameters are all potentially important to discovering environments supportive for violent tornadoes. MR10 stated that once a tornado is established, tilting of the surface-layer horizontal vorticity by the extreme vertical velocity gradient associated with the tornado updraft itself probably contributes to the near-ground vertical vorticity in a significant way. In theory, higher values of low-level instability would maximize the vertical velocities of the thunderstorm updraft and subsequently increase near-ground vertical vorticity. Thus, higher values of vertical vorticity could lead to a stronger tornado. MR10 clearly states that this is only important with an established tornado, and this is apparent with the data as well. The current study, as well as T03 and other research have established that low-level wind fields such as 0-1 km shear and 0-1 km & 0-3 km helicity are crucial to not only tornadogenesis but also with intensification into the EF2 and EF3 strength. Low-level instability is then important because it is required to strengthen a strong tornado further to EF4 and EF5 intensity. Therefore, when forecasting environments favorable for violent tornadoes, an operational forecaster should closely investigate low-level instability in addition to low-level shear.

Acknowledgements:
The authors would like to thank Gregory Patrick for reviewing our paper before publication.

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Table 1. Mean parameter values, mean absolute errors (MAEs), and mean errors or bias for a comparison between NARR soundings and observed soundings for 33 cases.

Parameter	Mean	MAE	Bias
SBCAPE (J kg^{-1})	2524	614	-78
MLCAPE (J kg^{-1})	2050	447	-153
0-6 km shear (m s^{-1})	24.7	3.9	-2.9

Table 2. Comparison of previously researched mean proximity soundings parameter values for violent tornadoes, significant tornadoes (sigtor), and non-violent tornadoes. Data was obtained by the NARR dataset.

Parameter	Violent	Sigtor	Non-violent
MLLCL (m)	1146	1140	1140
MLCAPE (J kg^{-1})	2090	1693	1487
0-6 km shear (m s^{-1})	18	21	19
0-1 km shear (m s^{-1})	8.3	10.0	9.9
0-3 km helicity (m^2 s^{-2})	219	247	238
0-1 km helicity (m^2 s^{-2})	142	171	165

Table 3. Comparison of newly researched mean NARR proximity soundings parameter values for violent tornadoes, significant tornadoes (sigtor), and non-violent tornadoes.

Parameter	Violent	Sigtor	Non-violent
0-2 km lapse rates (C km^{-1})	8.4	7.9	7.8
0-3 km lapse rates (C km^{-1})	7.9	7.6	7.5
0-3 km CAPE (J kg^{-1})	99	78	72
0-3 km CAPE x 0-3 km LR	808	602	557

Fig.1. Map of all violent and non-violent tornadoes used in this study. Violent tornadoes are marked by a + and non-violent tornadoes are marked by an x.

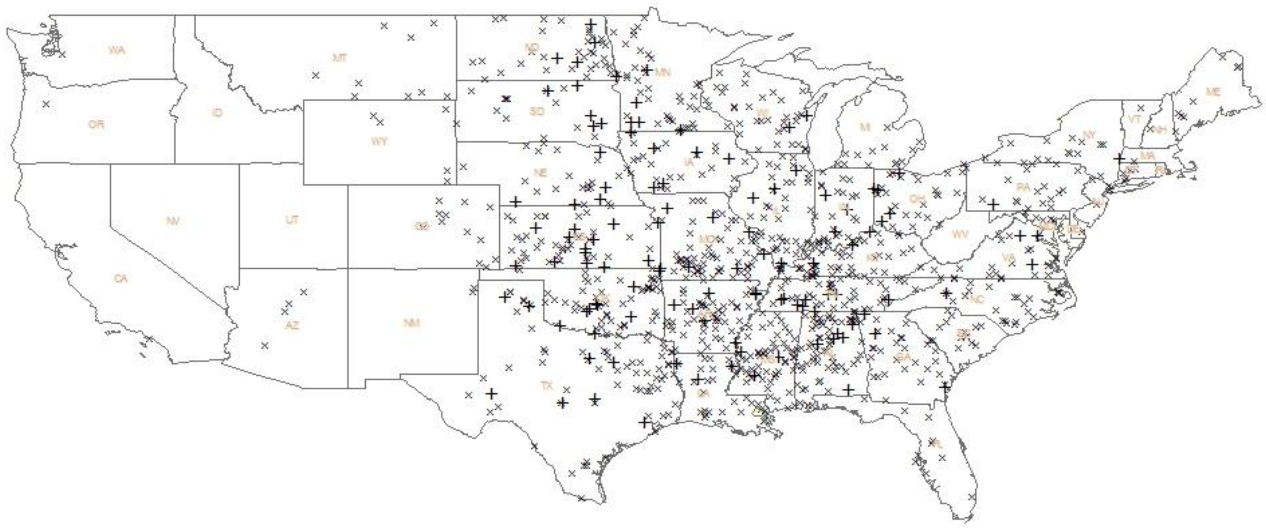

Fig. 2. Comparison sites used with the number of times listed.

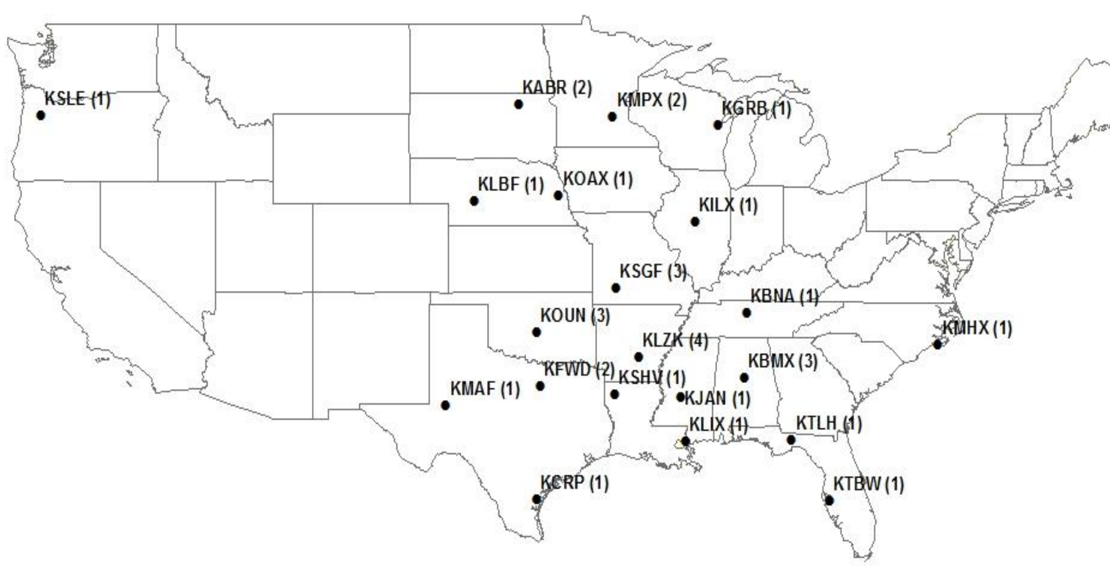

Fig 3. Box and whiskers plot of MLCAPE values (J kg^{-1}) with a sample of non-violent tornadoes (927 cases), significant tornadoes (468 cases), and violent tornadoes (117 cases). The shaded box covers the 25^{th} to the 75^{th} percentiles, the whiskers extend to the 10^{th} and 90^{th} percentiles. The median values are marked by the line within each shaded box.

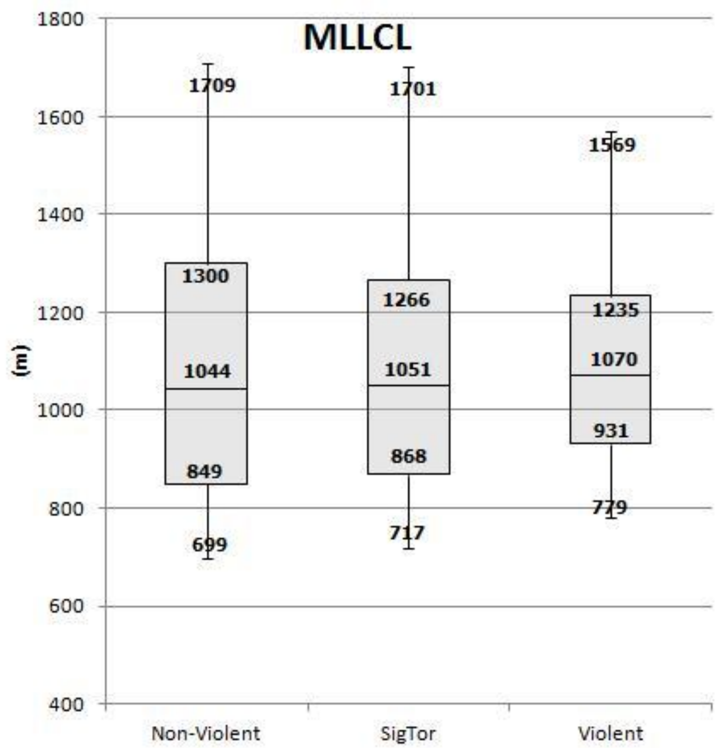

Fig. 4. Same as Fig. 3 except for MLCAPE (J kg^{-1}).

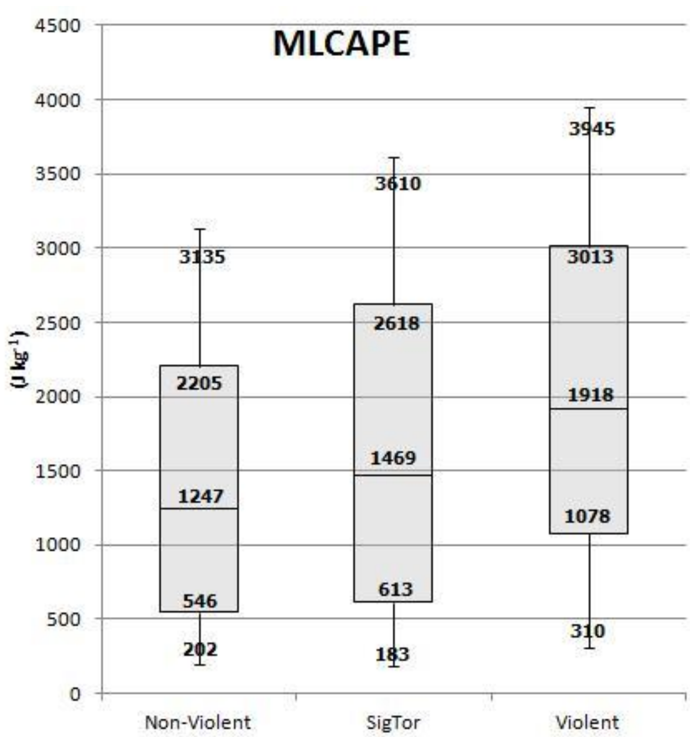

Fig. 5. Same as Fig. 3 except for 0-6 km shear (m s^{-1}).

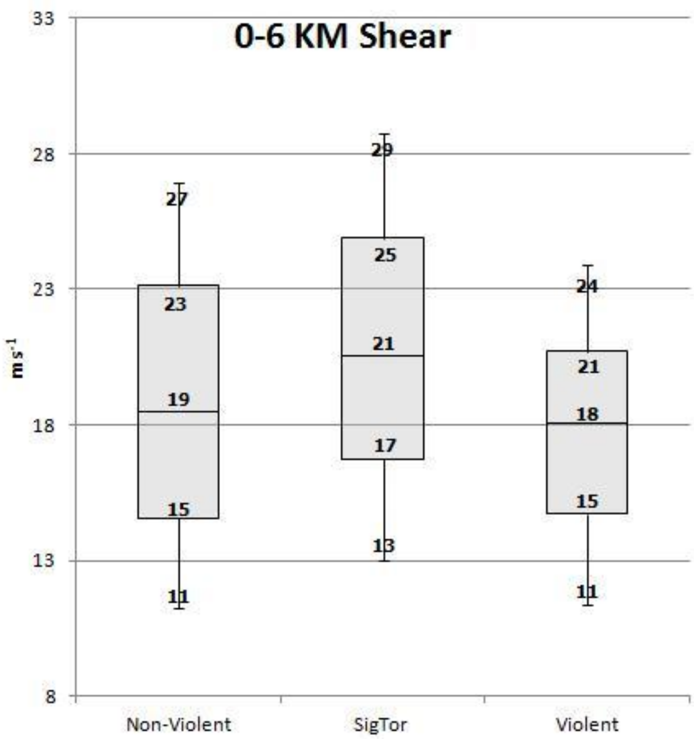

Fig. 6. Same as Fig. 3 except for 0-1 km shear (m s^{-1}).

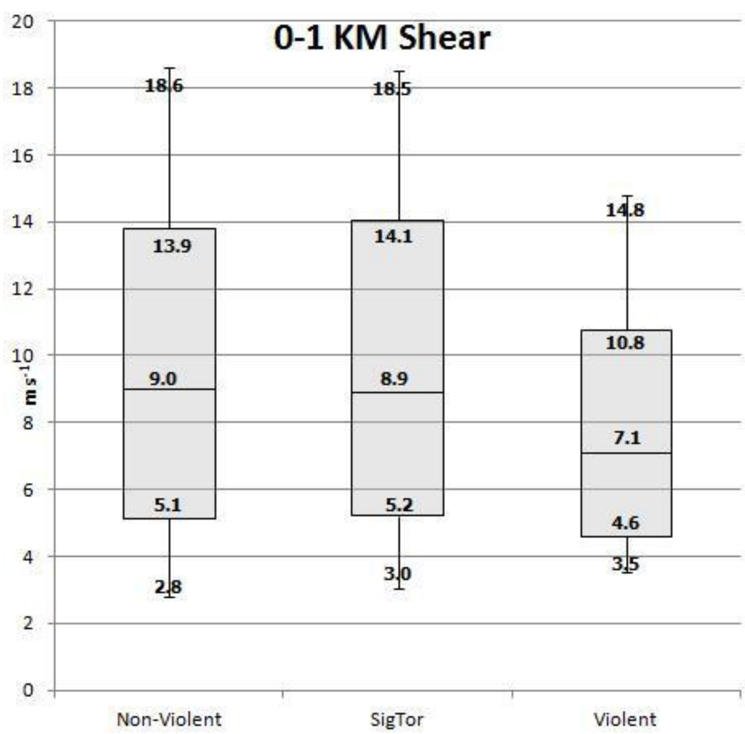

Fig. 7. Same as Fig. 3 except for 0-3 km helicity ($m^2 s^{-2}$).

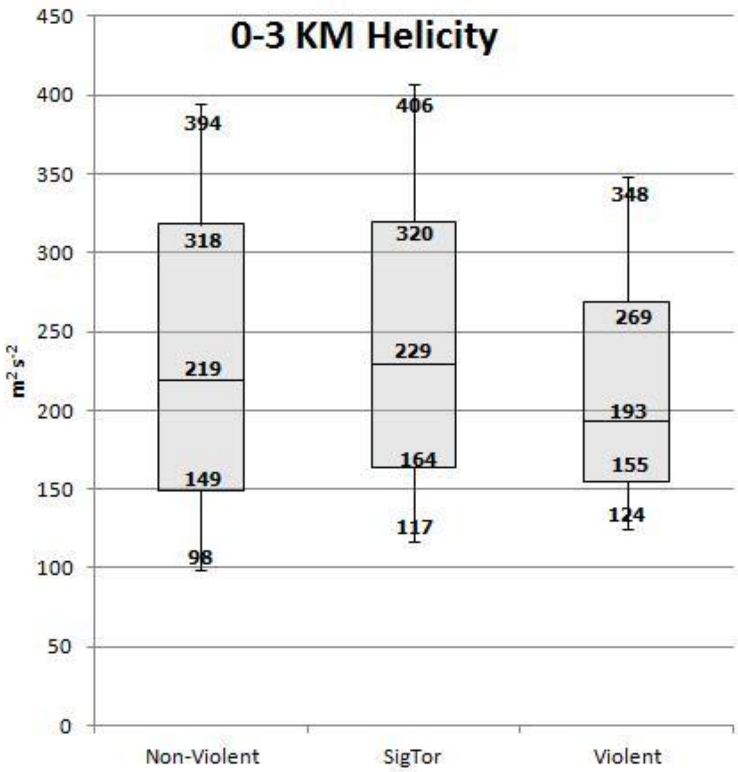

Fig. 8. Same as Fig. 3 except for 0-1 km helicity ($m^2 s^{-2}$).

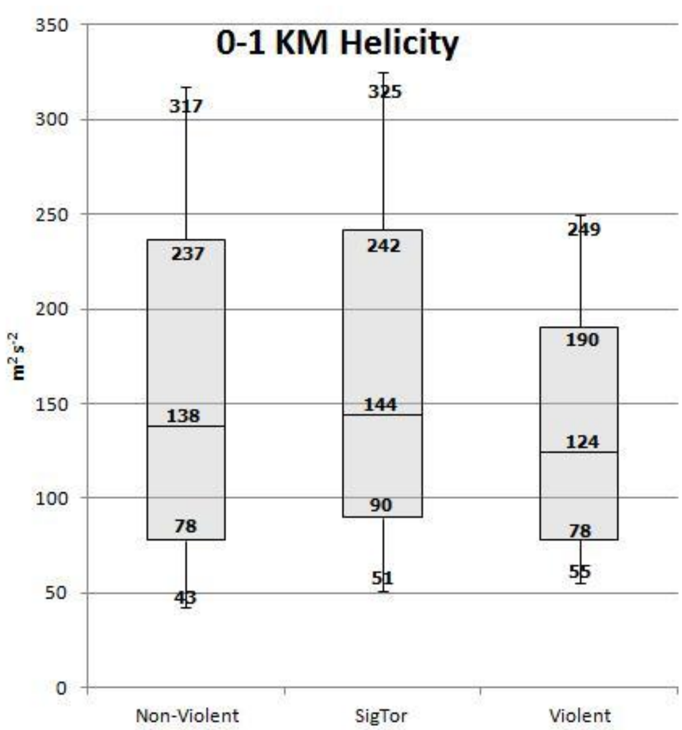

Fig. 9. Same as Fig. 3 except for 0-2 km lapse rates (C km^{-1}).

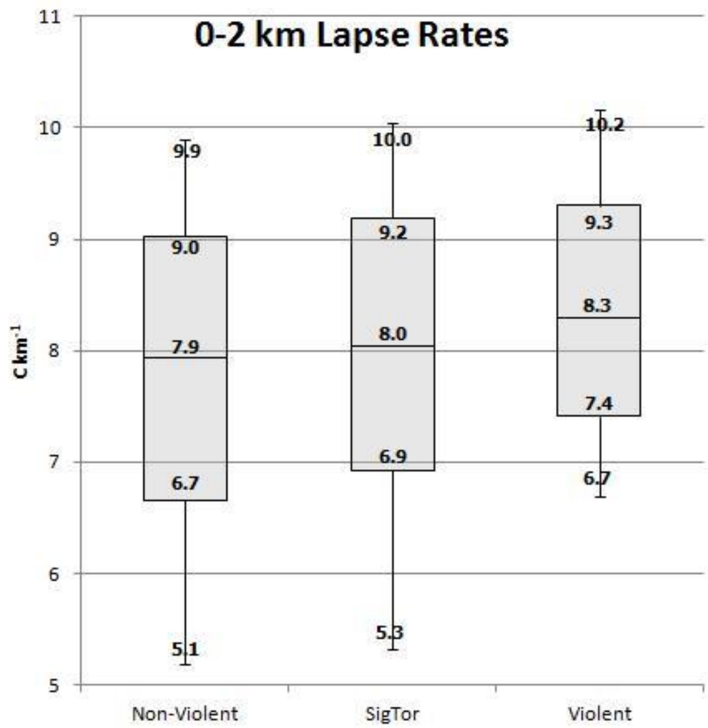

Fig. 10. Same as Fig. 3 except for 0-3 km lapse rates (C km^{-1}).

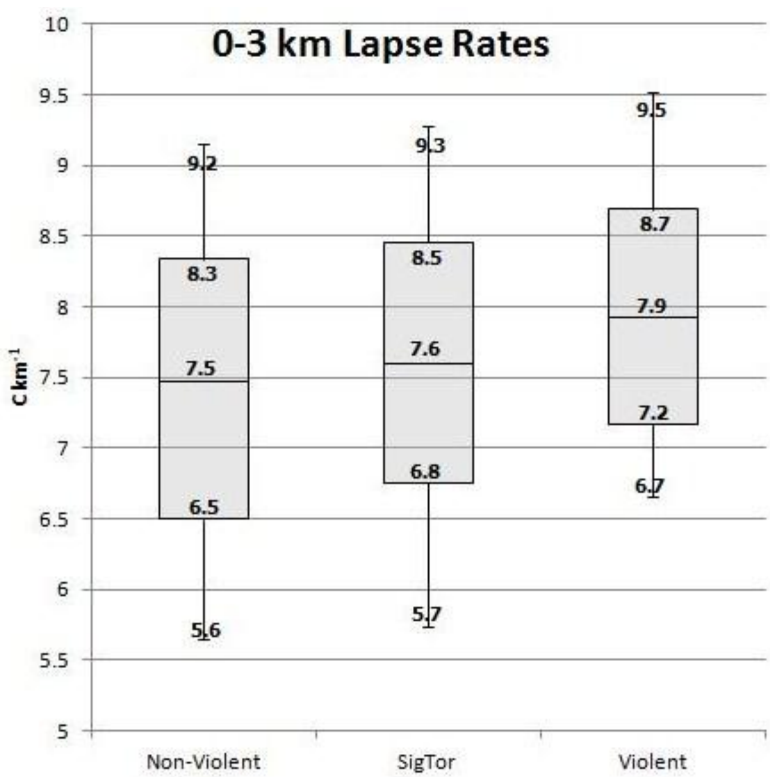

Fig. 11. Same as Fig. 3 except for 0-3 km MLCAPE (J kg^{-1}).

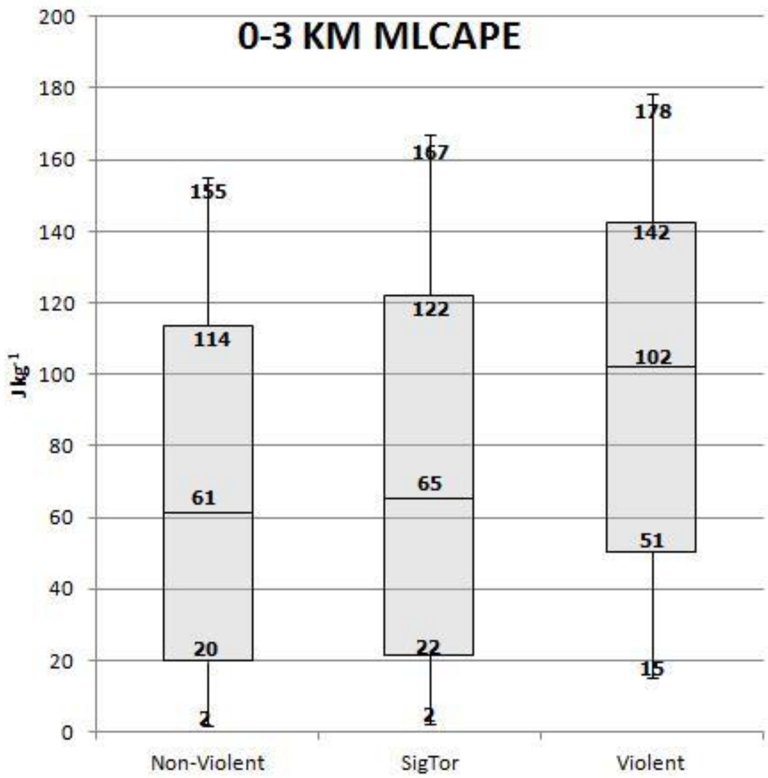

Fig 12. Same as Fig. 3 except for a product of 0-3 km lapse rates and 0-3 km CAPE.