P12.14 A SOUNDING-DERIVED CLIMATOLOGY OF SIGNIFICANT TORNADO EVENTS IN THE GREENVILLE-SPARTANBURG, SOUTH CAROLINA COUNTY WARNING AREA (1948-2006)

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1. Introduction

Numerous climatological studies of soundings and sounding-derived parameters associated with supercells and significant tornadoes (ST), defined as those rated F2 to F5 on the Fujita Scale, exist in the meteorological literature (e.g., Rasmussen and Blanchard 1998; Rasmussen 2003; Thompson et al. 2003). However, most of these studies have focused on events occurring in the central portion of the United States. The results of these studies generally agree that supercell thunderstorms and tornadoes typically require moderate to large levels of instability and high values of wind shear. However, experienced forecasters in the eastern United States can attest to the fact that this combination is extremely rare. This implies that supercells, and especially ST are extremely rare in comparison with the Great Plains and the lower Mississippi Valley.

Nevertheless, a recent severe weather climatology by Hart (2005) indicated that the Greer, SC WSR-88D (KGSP) coverage area ranked within the top 30% (39th out of 141) in ST occurrence[†] across the United States. More surprisingly, KGSP ranked in the top 12% (16th) in terms of the average annual probability of occurrence of ST.

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† Tornadoes occurring within a 229 km radius of each radar site were considered in this study. It should be noted that the coverage area of KGSP encompasses a larger area than the Greenville-Spartanburg, SC County Warning Area (1.65×10^5 km^2 vs. 5.5×10^4 km^2).

Based on these results, a region-specific climatology would be beneficial to forecasters in the southeast United States in order to identify environments that may be conducive to ST development. This study will present a climatology of soundings and sounding parameters associated with ST in the Greenville-Spartanburg, SC (GSP) County Warning Area (CWA).

Section 2 contains the methodology and an explanation of the various data sources used to create this climatology. Section 3 presents several composites of reanalysis soundings associated with ST occurrence. Section 4 details the results of a statistical analysis of various parameters yielded by soundings that were constructed from reanalysis data. The paper concludes with a discussion of the results in section 5.

2. Data procedures

The Storm Prediction Center (SPC) storm events database (Kelly at al. 1978), was used in compiling a climatological database for the GSP CWA during the 1948 to 2006 period. This database and the manner in which tornadoes are documented in general have deficiencies that have been addressed in previous studies (e.g., Doswell and Burgess 1988). Due to these deficiencies the “Significant Tornadoes” publication (Grazulis 1993, referred to hereafter as G93) was consulted to cross-check the SPC database. This resulted in the addition of several tornadoes to the local database.

Dates with at least one ST were identified as "ST" days. Days with more than one ST were identified as "ST outbreak days." Thirteen of the 60 days qualified as outbreak days. Six-hourly data from the National Centers for Environmental Prediction - National Center for Atmospheric Research (NCEP-NCAR) reanalysis (Kistler, 2001) were retrieved for each of the 60 days via the Earth System Research Laboratory's (ESRL) on-line database. For each ST day, reanalysis data were examined at the two grid points nearest the GSP CWA (35^o N, 82.5^o W; 35.0^o N, 80.0^o W). Values of air temperature, relative humidity, u and v component of the wind, and geopotential height at the surface, 925 hPa, 850 hPa, 700 hPa, 600 hPa, 500 hPa, 400 hPa, and 300 hPa, 250 hPa, 200 hPa, and 150 hPa levels were documented for each day at the latest time prior to tornado occurrence. From these parameters, the dewpoint temperature, the 700 hPa to 500 hPa lapse rate, and the magnitude and direction of the wind vector were calculated. The bulk wind shear in the surface to 500 hPa layer was also calculated to serve as a proxy to 0-6 km bulk shear.

From the raw reanalysis data, two soundings were constructed for each of the 60 days using Environmental Research Service's Rawinsonde Observation (RAOB) software. The sounding that was deemed most representative of the tornadic environment was selected for further analysis. In the majority of cases, this was the sounding nearest the location of the tornado event(s). From these soundings, values of surface-based Convective Available Potential Energy (CAPE) were documented through the entire depth of the sounding and in the 0-3 km layer. In addition, Storm Relative Helicity (SRH) in the 0-3 km and 0-1 km layers was documented. Finally, the values of Bulk Richardson Number (BRN) and the Energy Helicity Index (EHI) were recorded. From this collection of data, the median and average values were calculated for each of the above fields, as well as for values of 700 hPa to 500 hPa lapse rate and surface to 500 hPa bulk shear. This statistical data is presented in box-and-whisker plots in Section 4.

From the reanalysis date, the location of major weather features was documented in order to subjectively group ST occurrences into various synoptic categories. Based on this analysis, four categories of "ST days" were identified by the position of the synoptic-scale surface low pressure center near the time of ST occurrence (Fig. 1). The four ST categories identified were: 1) Great Lakes (GRL), 2) Ohio/Tennessee Valley (OTV), 3) Eastern Great Plains (EPL), and 4) Southeast Tropical Cyclone (TCY). Twenty-one days were categorized as GRL events. Sixteen days were used to develop the OTV composite. Seven days were identified as EPL events. Six days were used in developing the TCY composites. On 10 of the ST days, there were no significant areas of low pressure, or the position of the low did not fit any of the four categories.

Once the sounding data were documented, composite soundings were constructed using the RAOB software for each of the four ST synoptic categories. Composite soundings were also developed for ST outbreak days and for all 60 ST days.

3. Composite soundings

A composite sounding was developed for each ST category by averaging the soundings described in section 2. Only mandatory levels were used in development of these soundings. The absence of intermediate data may diminish the accuracy of the sounding parameters. However, high resolution reanalysis data were not available for all 60 days. Not surprisingly, the parameter values yielded by the composite soundings are in some instances significantly different than the averages from the individual soundings. Table 1 details the mean and median values produced by the individual soundings vs. the values yielded by the composite soundings.

Figure 2 is the composite sounding for the GRL category. A veering wind profile is indicated with approximately 23.2 m s^{-1} of deep layer (0-6 km) shear. This is slightly less than the mean deep layer shear magnitude (24.5 m s^{-1}) found by Thompson et al. (2003; hereafter referred to as T03) to be associated with significant supercell tornadoes. Storm relative helicity (SRH) in the 0-1 km (0-3 km) layer is 118 m^2 s^{-2} (205 m^2 s^{-2}). This is weaker than the mean value of 0-1 km and 0-3 km SRH associated with STs (165 m^2 s^{-2} and 223 m^2 s^{-2}, respectively) in T03. Instability parameters indicate surface-based Convective Available Potential Energy (sbCAPE) of 827 J kg^{-1}. This is much less than the mean value of

CAPE[‡] of 2152 J kg^{-1} found by T03 to be associated with STs. However, CAPE in the 0-3 km layer is 124 J kg^{-1}. This is higher than the mean value of 63 J kg^{-1} found by Rasmussen (2003; hereafter referred to as R03) to be associated with STs. The 0-2 km Energy Helicity Index (EHI) in the sounding is 0.9. This value is near the lower threshold of EHI (1.0) utilized by operational forecasters in assessing the potential for supercells (Rasmussen and Blanchard, 1998).

The composite sounding for the OTV category is shown in Fig. 3. The wind profile is very similar to the GRL category. There is 24.7 m s^{-1} of deep layer shear, which is almost identical to the mean value associated with STs in T03. SRH in the 0-1 km layer is 105 m^2 s^{-2}, which is weaker than the values yielded by the GRL sounding, and weaker than the mean value in T03. SRH in the 0-3 km layer is 206 m^2 s^{-2}. This is similar to the value yielded by the GRL composite sounding and less than the mean value in T03. As in the GRL sounding, sbCAPE in the OTV sounding is quite low at 650 J kg^{-1}, though CAPE in the 0-3 km layer is a respectable 71 J kg^{-1}. The 0-2 km EHI in the sounding is only 0.7.

The composite sounding for the EPL category is presented in Fig. 4. A strongly veering wind profile is indicated, with deep layer shear of 24.2 m s^{-1}. SRH in the 0-1 km layer is 142 m^2 s^{-2} while the 0-3 km SRH is 231 m^2 s^{-2}. These values are the highest among the four composites. This is largely due to the backed surface flow. Owing to steeper mid-level lapse rates, the EPL sounding contains higher sbCAPE (901 Jkg^{-1}) than the GRL or OTV composites. However, a lower surface dewpoint is yielding CAPE in the 0-3 km layer of only 57 J kg^{-1}. The sounding produces an EHI of 1.2. This is the largest value of EHI among the four composite soundings, suggesting that the EPL sounding provides the most favorable combination of shear and instability for tornadic thunderstorms.

[‡] T03 used mean parcel CAPE (mlCAPE) in the lowest 100 mb.

A composite sounding for the TCY case is shown in Fig. 5. As in the other composite soundings, a strongly veering wind profile is indicated. However, the profile is almost entirely contained within the upper left quadrant of the hodograph, as opposed to the profiles from the other soundings, which are mostly in the upper right quadrant. The flow is also considerably weaker than in the other composite soundings, particularly in the mid and upper levels of the sounding. This results in deep layer shear of only 14.1 m s^{-1}. Despite the weaker flow, the sounding yields SRH of 76 m^2 s^{-2} in the 0-1 km layer while the 0-3 km SRH is 141 m^2 s^{-2}. It should be noted that the shear parameters in the TCY sounding are much weaker than those yielded by McCaul's (1991) composite of 86 soundings associated with tropical cyclone-related tornadoes.

Surface-based CAPE in the TCY sounding is 1150 J kg^{-1}. CAPE in the 0-3 km layer is 183 J kg^{-1}. These are the highest values of instability among the four categories. The CAPE values in the TCY sounding are slightly larger than that of McCaul's composite. However, it is interesting to note that this study, as well as other studies of tropical-cyclone tornadoes (Gentry 1983; McCaul and Weisman 1996) emphasized the fact that the environment was less buoyant than that of a "typical" supercell environment. The current study suggests that on average, tropical cyclone environments are more buoyant than the "typical" ST environment over the GSP CWA, particularly in the low levels.

Considering that ten of the thirteen outbreak cases were identified as GRL and EPL events, it is not surprising that the outbreak sounding (Fig. 6) closely resembles the GRL and EPL composites. The outbreak sounding contains 23.8 m s^{-1} of deep layer shear. Values of 0-1 km and 0-3 km SRH are 123 m^2 s^{-2} and 240 m^2 s^{-2}, respectively. The sounding yields 849 J kg^{-1} and 93 J kg^{-1} of sbCAPE and 0-3 km CAPE, respectively. The EHI in the sounding is 1.2, equivalent to the highest EHI produced by the four composite soundings from each of the ST categories.

4. Sounding parameter climatology

Section 3 detailed the composite soundings developed for each ST category, and provided some discussion of the sounding parameters yielded by those composite or "average" soundings. This section will provide statistical analysis of various parameters derived from each of the 60 ST soundings.

A box-and whiskers plot presenting the distribution of 0-6 km bulk wind shear for the 60 ST soundings (Fig. 7) indicates the median value of deep-layer shear is 23.3 m s^{-1}. The 1st quartile value of 0-6 km shear is 18.8 m s^{-1} while the 3rd quartile is 28.3 m s^{-1}. The maximum shear value associated with ST occurrence is 37.2 m s^{-1}. The minimum value is 5.9 m s^{-1}.

A box-and whiskers plot analyzing the values of 700 hPa to 500 hPa lapse rate is shown in Fig. 8. The median value of mid-level lapse rate is 5.9 ^{o}C km^{-1}. The majority of the lapse rate values associated with ST occurrence are within the range of 5.5 ^{o}C km^{-1} and 6.4 ^{o}C km^{-1}. The maximum value of mid-level lapse rate in the 0-6 hour period prior to ST is 7.6 ^{o}C km^{-1} while the minimum value is 4.4 ^{o}C km^{-1}.

The analysis of surface-based CAPE associated with ST occurrence (Fig. 9a) shows the mean value of sbCAPE is 977 J kg^{-1}. Values of sbCAPE are generally contained within the range of 448 J kg^{-1} (1st quartile) to 1583 J kg^{-1} (3rd quartile). The minimum value of sbCAPE associated with a ST is 33 J kg^{-1}. The maximum value is 4312 J kg^{-1}.

An analysis of CAPE in the 0-3 km layer (Fig. 9b) indicates a median value of low-level CAPE of 108 J kg^{-1}. The 0-3 km CAPE associated with ST occurrence is typically within the range of 61 J kg^{-1} and 155 J kg^{-1}. The minimum 0-3 km CAPE yielded by an ST sounding is around 0 J kg^{-1} and the maximum is 314 J kg^{-1}.

A box-and-whiskers plot presenting the distribution of 0-3 km SRH values associated with ST in the GSP CWA (Fig. 10a) reveals a median value of 182 m^2 s^{-2}. Most of the values associated with ST occurrence are in the range of 140 m^2 s^{-2} to 286 m^2 s^{-2}. The maximum value is 584 m^2 s^{-2}. The minimum value of 0-3 km SRH is 55 m^2 s^{-2}.

The analysis of 0-1 km SRH in Fig. 10b indicates the median value associated with ST occurrence is 95 m^2 s^{-2}. Values of 0-1 km SRH are generally contained within the range of 70 m^2 s^{-2} (1st quartile) and 130 m^2 s^{-2} (3rd quartile). The maximum value associated with ST is 337 m^2 s^{-2}. The minimum value of 0-1 km SRH is 20 m^2 s^{-2}.

A box-and-whiskers plot indicating the distribution of Energy Helicity Index (EHI) associated with ST occurrence (Fig. 11) indicates the median value of EHI is 1.0. Values of EHI associated with ST generally range from 0.6 to 1.4. The maximum value of EHI is 3.6. The minimum value is 0.1.

Distribution of Bulk Richardson Number (BRN) associated with ST occurrence in the GSP CWA (Fig. 12) indicates the median value of BRN is 11.5. Values of BRN typically range from 5.0 (1st quartile) to 23.0 (3rd quartile). The maximum value of BRN associated with ST is 140.0 and the minimum is 0.0.

Examination of Table 1 reveals shear parameters are comparable to previous climatological studies of tornadic convection, especially for 0-3 km SRH and 0-6 km bulk shear. However, the mean value of CAPE associated with ST in the GSP CWA is less than half that in T03 whereas the mean value of 0-3 km CAPE in the current study (117 J kg^{-1}) is approximately 45% *greater* than in R03. This suggests that the initial acceleration of the updraft may be more important than the overall strength and depth of the updraft in dictating the tornadic potential of a thunderstorm, at least in the GSP CWA.

5. Summary

A sounding and sounding parameter climatology was developed for all of the ST that have occurred across the GSP CWA since 1950. For each of the 60 ST days, a sounding was constructed from NCEP-NCAR reanalysis data at the gridpoint deemed to be most representative of the tornadic environment. Various instability and wind shear parameters were documented for each sounding. From these individual soundings, a composite sounding was developed for each ST category. In most of the categories, values of SRH and bulk wind shear were comparable to previous studies of proximity soundings associated with ST. Instability parameters were often significantly lower than in other studies, particularly with regard to deep layer instability. However, values of composite CAPE in the 0-3 km layer were comparable, and in some cases larger, than those in previous studies. This seems to indicate that the character of the environment in the lowest 3 km may be the most important factor in distinguishing ST environments from non-ST environments.

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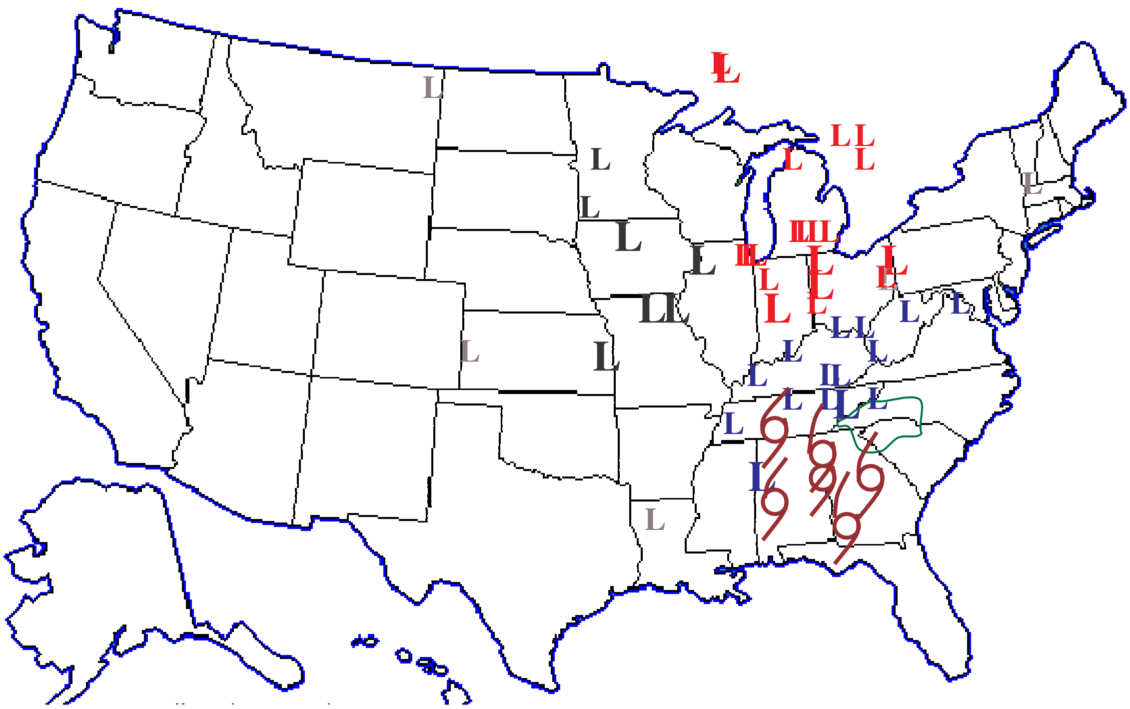

Figure 1. Map illustrating the position of the synoptic low pressure center in the 0-6 hour window prior to significant tornado occurrence in the GSP CWA. Brown circles with curved lines represent tropical cyclones. "Ls" represent locations of surface low pressure. Map labels are color-coded according to ST synoptic category. Red represents Great Lakes (GRL). Blue is Ohio/Tennessee Valley (OTV). Black is Eastern Great Plains (EPL). Lows with a gray font were not included in any of the four categories.

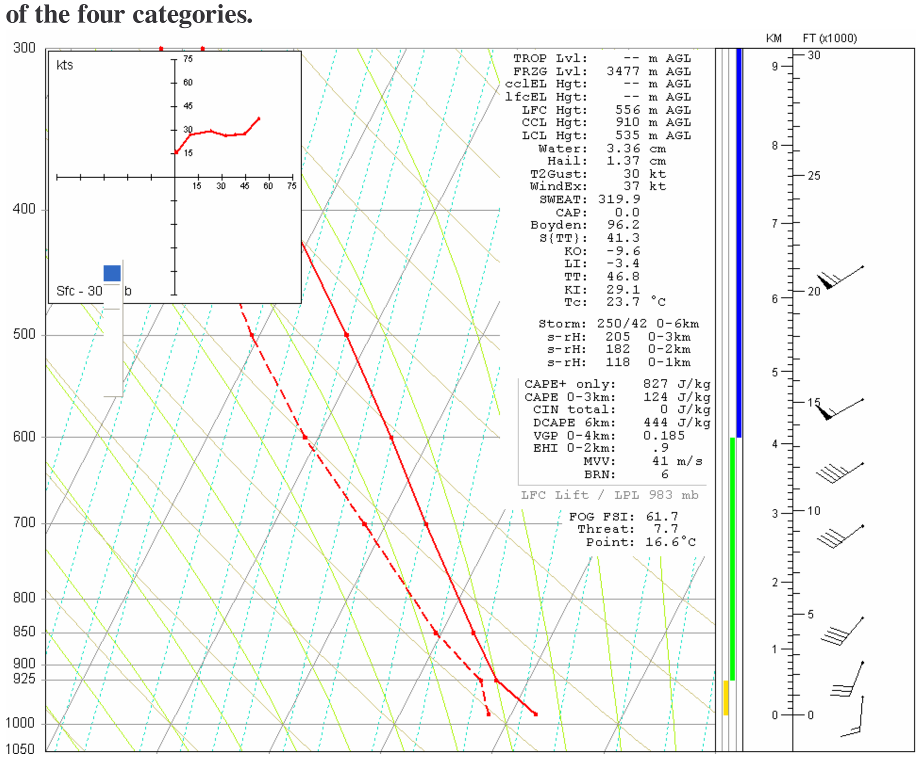

Figure 1. Skew-T/log p diagram representing the composite sounding for the Great Lakes (GRL) ST synoptic category.

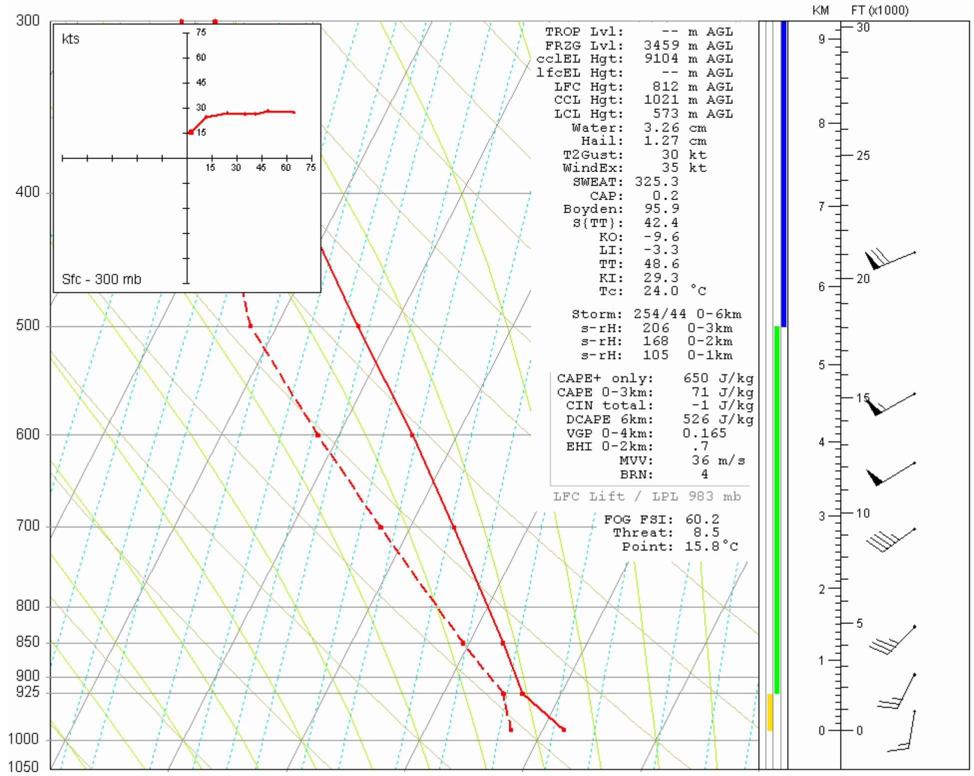

Figure 2. Same as in Fig. 2 except for the Ohio/Tennessee Valley (OTV) composite.

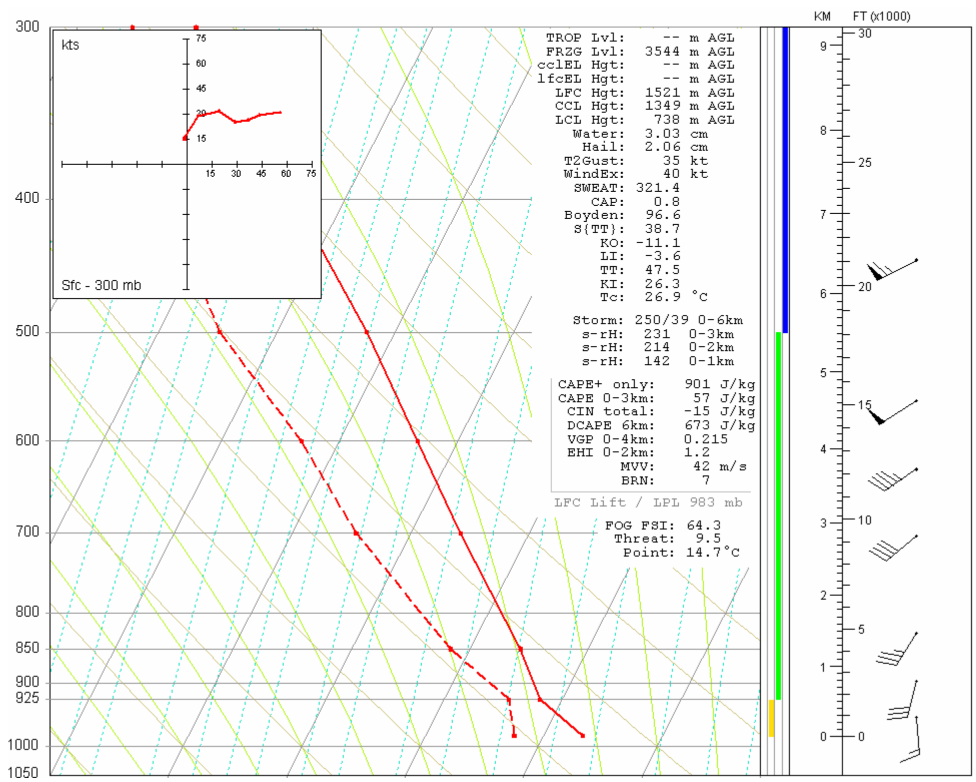

Figure 3. Same as in Fig. 2 except for the Eastern Great Plains (EPL) category.

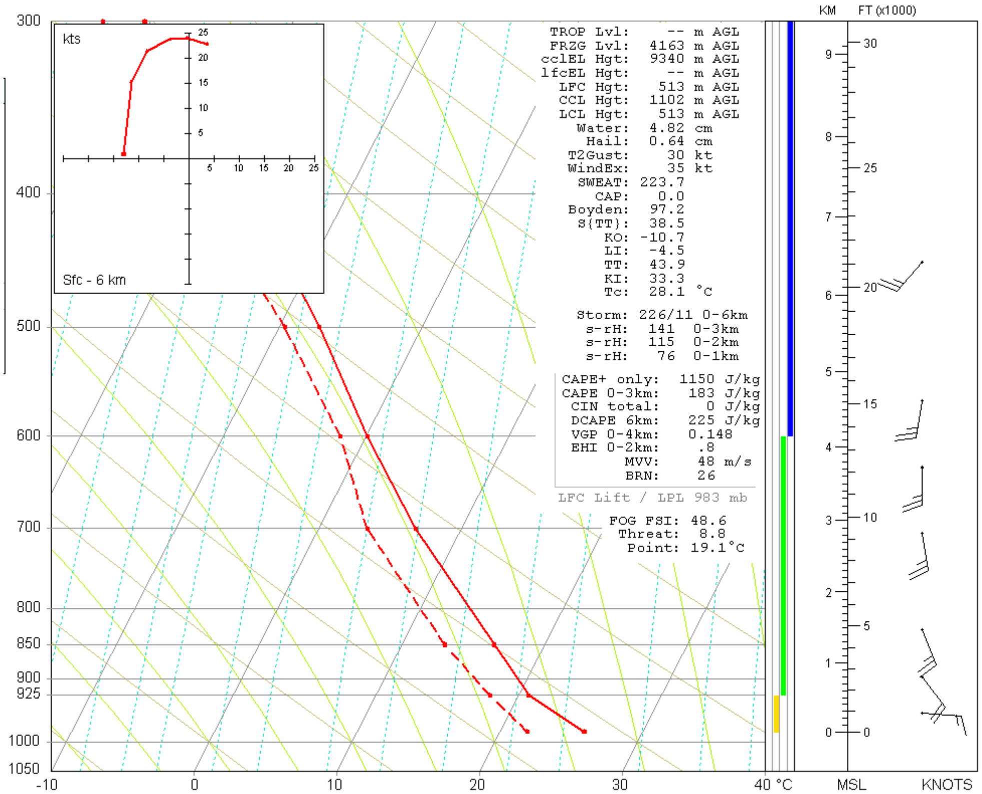

Figure 4. Same as in Fig. 2 except for the Southeast Tropical Cyclone (TCY) category.

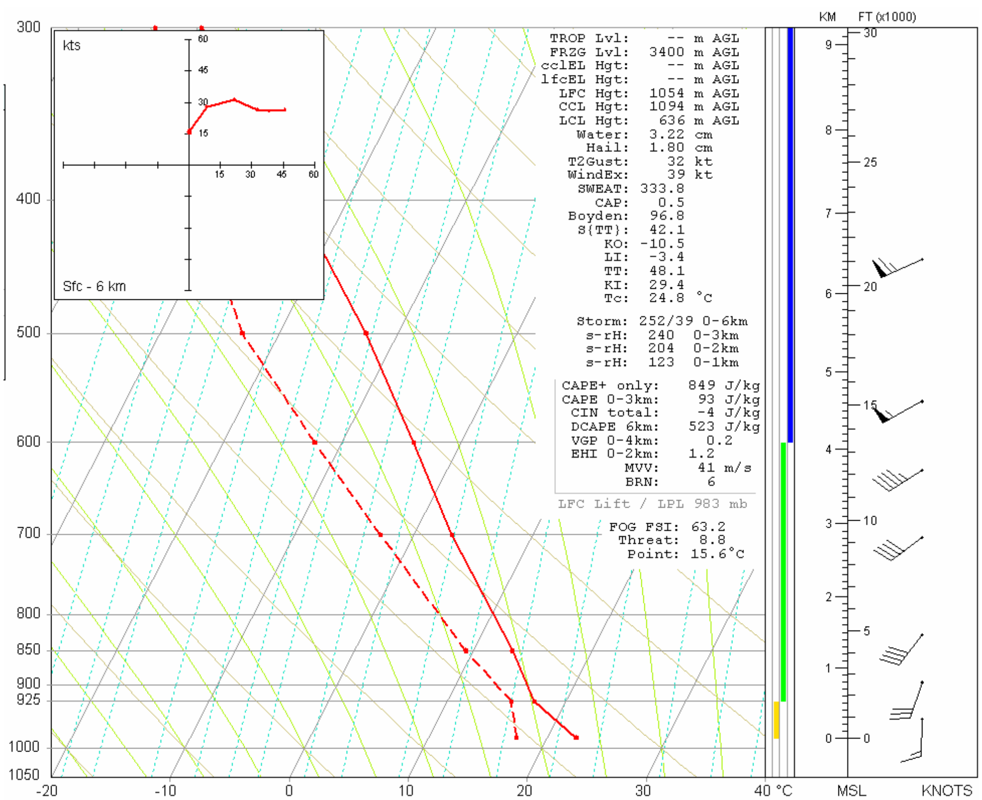

Figure 5. Same as in Fig. 2 except for ST outbreak days.

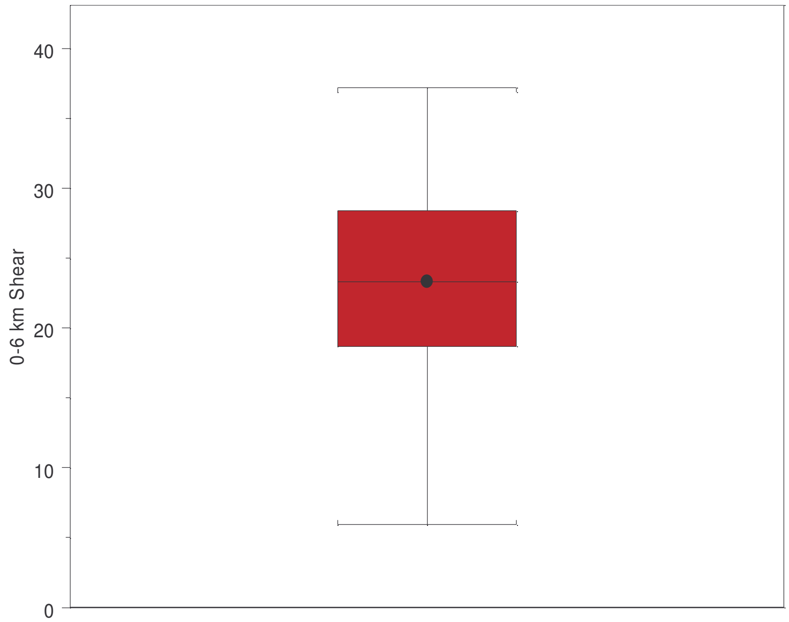

Figure 7. Box and whiskers graph of 0-6 km wind shear (m s^{-1}) from the 60 ST soundings. Red box denotes the 2nd and 3rd quartile, with horizontal bar and red dot marking the median value. Vertical lines extend from the box to the 10th and 90th percentile. Dot outside of the box plot represents an outlier.

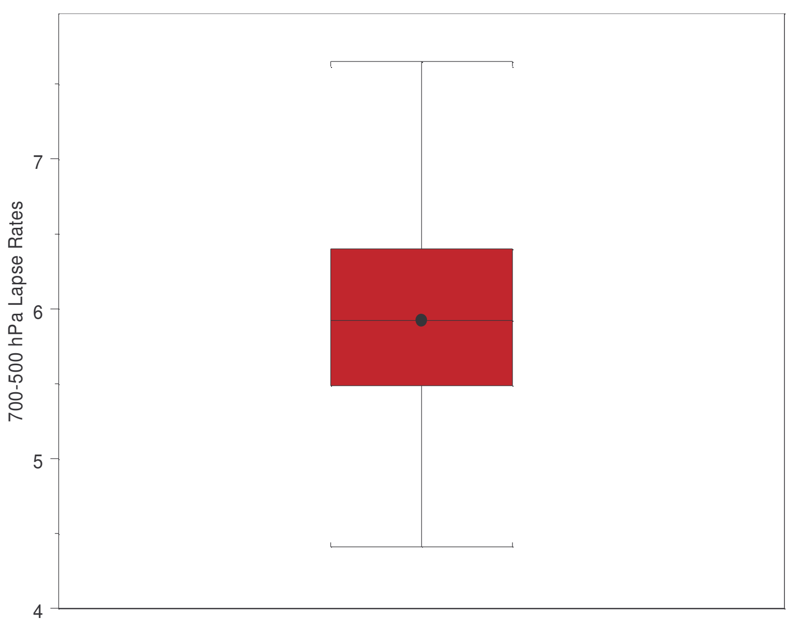

Figure 8. Same as in Fig. 7 except for 700 hPa to 500 hPa lapse rates (^{o}C km^{-1}).

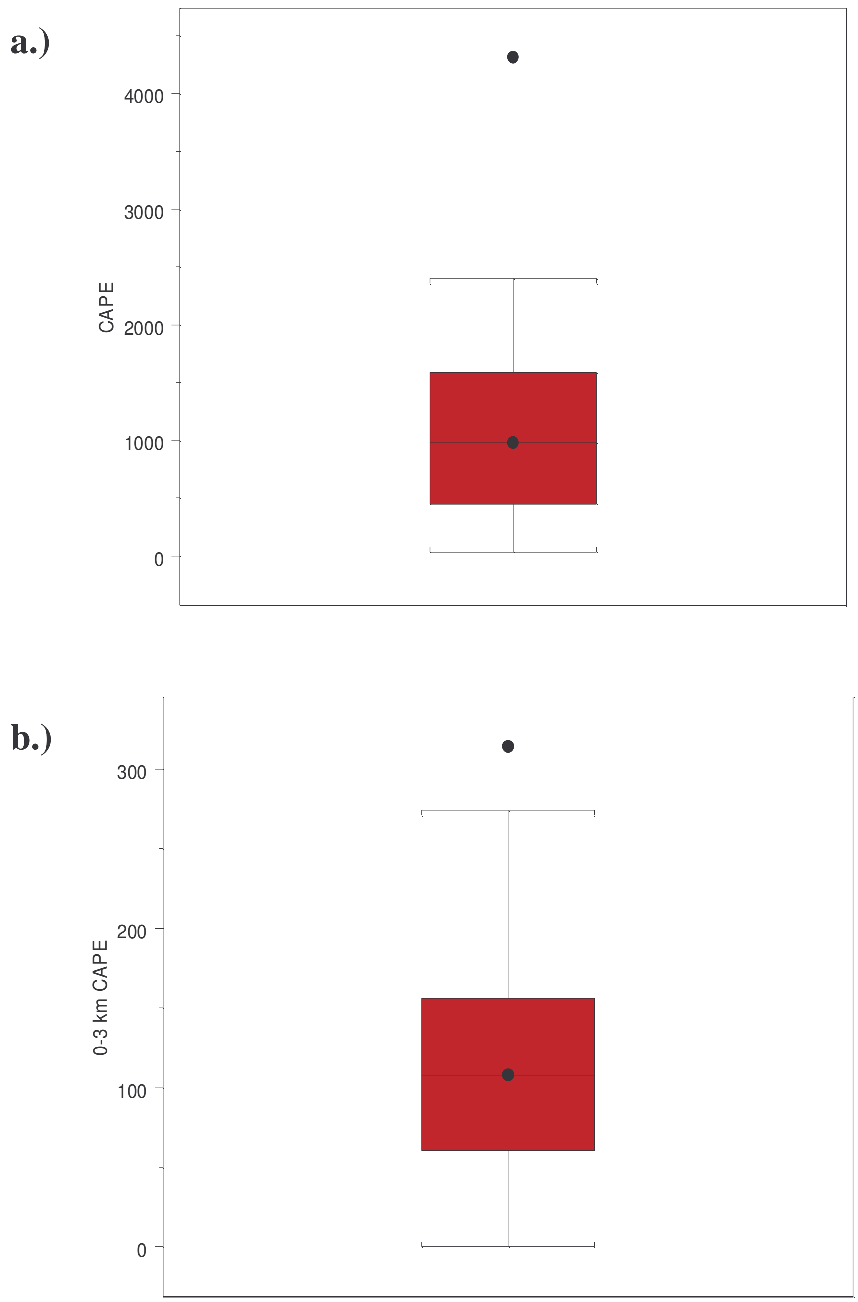

Figure 9. Same as in Fig. 7 except for a) Surface-based CAPE and b) 0-3 km CAPE (J kg^{-1}).

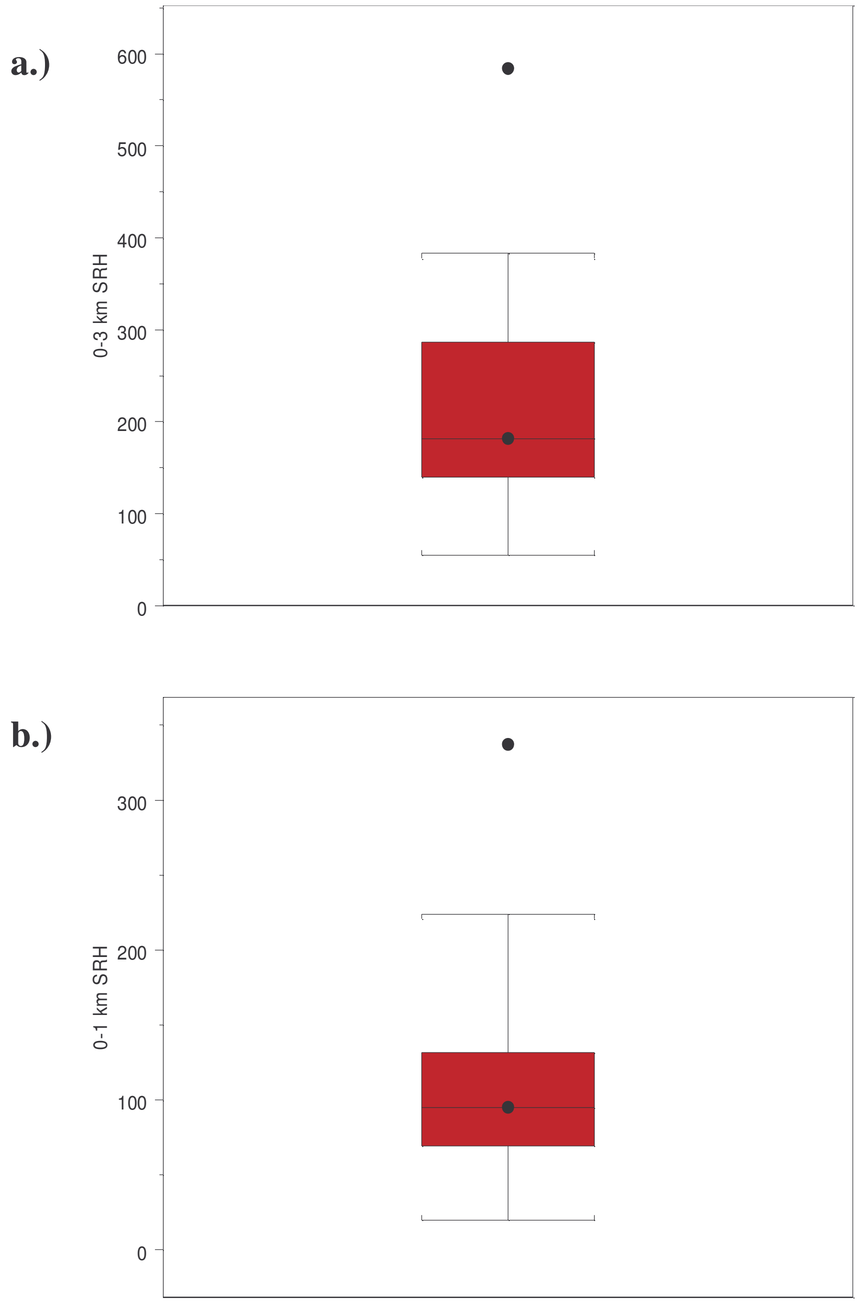

Figure 10. Same as in Fig. 7 except for a) 0-3 km Storm Relative Helicity and b) 0-1 km Storm Relative Helicity (m^2 s^{-2}) .

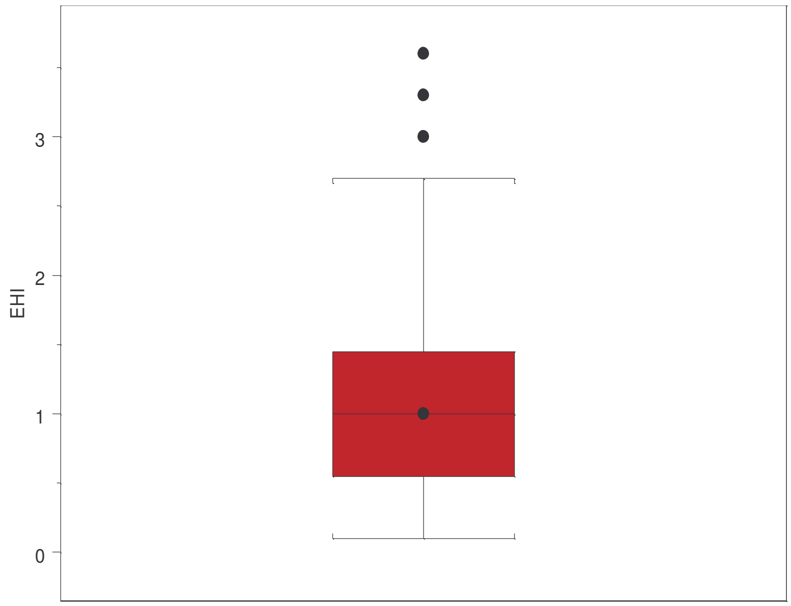

Figure 11. Same as in Fig. 7 except for Energy Helicity Index.

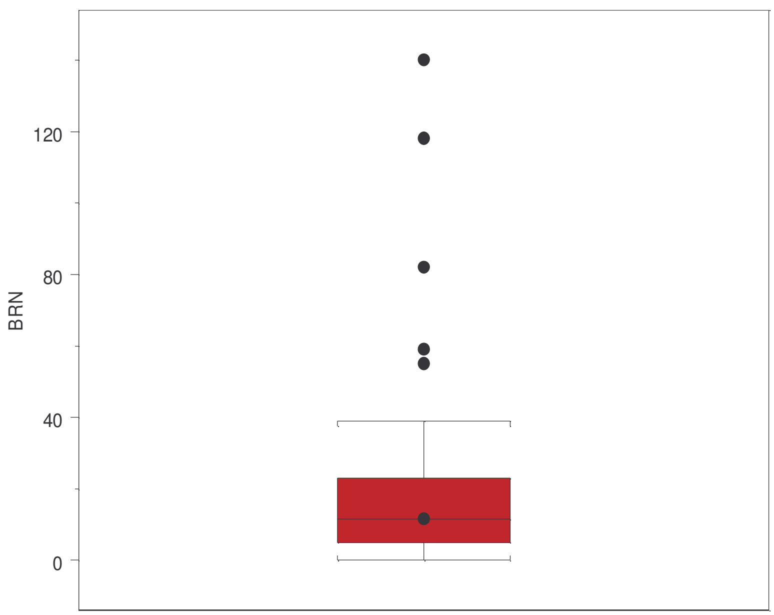

Figure 12. Same as in Fig. 7 except for Bulk Richardson Number.

Table 1. Mean and median values of sounding parameters associated with significant tornadoes across the western Carolinas and northeast Georgia. The third column contains values yielded by the composite soundings described in section 4. The values in the fourth and fifth columns are mean and median values from individual "ST day" soundings. The sixth column represents average values from Thompson at al. (2003, T03). *The 0-3 km CAPE value in the last column is from Rasmussen (2003), as T03 did not analyze this parameter.

Category	Parameter	Composite Value	Mean Value	Median Value	T03
Great Lakes (GRL)	0-6 km Shear ($m\ s^{-1}$)	23	25	23	25
	0-1 km SRH ($m^2\ s^{-2}$)	124	125	103	165
	0-3 km SRH ($m^2\ s^{-2}$)	205	238	219	223
	sbCAPE ($J\ kg^{-1}$)	827	1019	1030	2152
	0-3 km CAPE ($J\ kg^{-1}$)	124	125	107	64*
	EHI	0.9	1.2	1.0	2.1
Ohio/Tenn Valley (OTV)	0-6 km Shear ($m\ s^{-1}$)	25	26	28	24.5
	0-1 km SRH ($m^2\ s^{-2}$)	105	121	122	165
	0-3 km SRH ($m^2\ s^{-2}$)	206	238	255	223
	sbCAPE ($J\ kg^{-1}$)	650	839	881	2152
	0-3 km CAPE ($J\ kg^{-1}$)	71	99	92	64*
	EHI	0.7	1.2	1.2	2.1
Eastern Great Plains (EPL)	0-6 km Shear ($m\ s^{-1}$)	24	25	27	24.5
	0-1 km SRH ($m^2\ s^{-2}$)	142	120	107	165
	0-3 km SRH ($m^2\ s^{-2}$)	231	222	172	223
	sbCAPE ($J\ kg^{-1}$)	901	1348	1473	2152
	0-3 km CAPE ($J\ kg^{-1}$)	57	84	72	64*
	EHI	1.2	1.7	1.7	2.1
Southeast Tropical Cyclone (TCY)	0-6 km Shear ($m\ s^{-1}$)	14.1	16.1	16.7	24.5
	0-1 km SRH ($m^2\ s^{-2}$)	76	90	93	165
	0-3 km SRH ($m^2\ s^{-2}$)	141	142	147	223
	sbCAPE ($J\ kg^{-1}$)	1150	1377	1284	2152
	0-3 km CAPE ($J\ kg^{-1}$)	183	172	173	64*
	EHI	0.8	0.8	1	2.1
Outbreak	0-6 km Shear ($m\ s^{-1}$)	23.8	24.9	23.9	24.5
	0-1 km SRH ($m^2\ s^{-2}$)	123	119	122	165
	0-3 km SRH ($m^2\ s^{-2}$)	240	246	244	223
	sbCAPE ($J\ kg^{-1}$)	849	1101	1050	2152
	0-3 km CAPE ($J\ kg^{-1}$)	93	109	99	64*
	EHI	1.2	1.5	1.4	2.1
All ST	0-6 km Shear ($m\ s^{-1}$)	-	23.4	23.3	24.5
	0-1 km SRH ($m^2\ s^{-2}$)	-	106	95	165
	0-3 km SRH ($m^2\ s^{-2}$)	-	210	182	223
	sbCAPE ($J\ kg^{-1}$)	-	1067	978	2152
	0-3 km CAPE ($J\ kg^{-1}$)	-	117	108	64*
	EHI	-	1.1	1.0	2.1