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Differences Between High Shear / Low CAPE Environments in the Northeast US Favoring Straight-Line Damaging Winds versus Tornadoes

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Abstract

High shear / low CAPE (HSLC) environments are common in the Northeast US and can occur at any time of year. Severe weather in HSLC environments is notoriously hard to predict, often catching both forecasters and the general public off-guard. The goal of this project is to help forecasters to identify HSLC environments favorable for severe weather in the Northeast US, and to discriminate between HSLC environments that are supportive of tornadoes versus those that favor straight-line damaging winds (SDW).

A 10-year HSLC severe weather environmental climatology was created for the Northeast US (New England, New York, New Jersey, Pennsylvania). This climatology includes 54 different parameters that can be used to identify and describe severe weather environments. HSLC criteria was defined as surface-based CAPE (SBCAPE) $\leq$ 500 J kg^{-1}, most unstable parcel CAPE (MUCAPE) and mixed-layer CAPE (MLCAPE) $\leq$ 1000 J kg^{-1}, and 0–6-km wind shear $\geq$ 18 m s^{-1} (Sherburn et al. 2016). Events included in the climatology consisted of numerous ($\geq$5) straight-line damaging wind reports, or at least 1 tornado report. Each event was classified by the season in which it occurred and the mode (discrete, cluster of cells, quasi-linear convective system (QLCS)) of the storm which produced the reports.

Results show that warm-season HSLC severe events typically occurred either at the beginning or at the tail end of an event in an environment where CAPE values were predominantly too large to meet the HSLC criteria. Storm mode was variable for warm-season events, but cool-season events were dominated by QLCSs. Results show lifted condensation levels (LCLs) as well as low-level shear and wind direction as some of the most skillful parameters at discriminating between tornadic and non-tornadic events. There are various other useful parameters, including but not limited to, surface relative humidity, effective shear magnitude, and convective inhibition. The usefulness of these, and other parameters, at discriminating between HSLC environments favorable for SDW versus tornadoes will be discussed.

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1. Introduction

There are various combinations of convective available potential energy (CAPE) and wind shear that can lead to many different modes of severe weather (Schneider and Dean 2008). Because many significant severe reports occur in higher CAPE cases, they have received significant attention in the literature, especially compared to cases with lower CAPE. Severe weather events that occur in high shear and low CAPE (HSLC) environments still pose a threat to life and property, but are harder to predict than higher CAPE cases (Vescio and Thompson 1998), as evidenced by lower probabilities of detection and higher false alarm rates for tornadoes which occur in these environments (Dean and Schneider 2008). HSLC events have been shown to occur most commonly during the cool season and at night (Sherburn and Parker 2014), when people may be less aware of the possibility for severe weather. The timing and unexpectedness of these events increase the danger they pose to the general public (Ashley et al. 2008).

Another problem for forecasters is detection of tornadoes in HSLC environments. Since HSLC tornadoes often occur at night, and typically have shorter lifespans than higher CAPE tornadoes (Guyer and Dean 2010), they are often under-reported. Similarly, HSLC convection is often difficult to detect by radar (Davis and Parker 2014). The small spatial and temporal scale of HSLC convection can lead to poor sampling by the radar beam (Thompson et al. 2012). HSLC tornadic velocity couplets often appear marginal on radar (Mitchell 1998), which poses a challenge to forecasters tasked with issuing warnings for these storms. Furthermore, the hook echo, a characteristic common to many tornadic storms, (Stout and Huff 1953) is often less obvious on radar for HSLC tornadoes when compared to those which occur in higher CAPE environments (Mitchell 1998).

Newer studies (White et al. 2012) examine the usefulness of using lightning activity to predict increases in severe convection. However, HSLC convective events typically have less lightning than ordinary convection, and many contain no lightning at all (McAvoy et al. 2000). Since many of the typical tools used to detect tornadic signatures are less useful in HSLC environments, it is especially important for forecasters to be aware of the environments in which HSLC convection occurs. Understanding whether the environment is conducive for straight-line damaging winds (SDW) or tornadoes should increase the probability of detection and decrease the false alarm rate for HSLC tornadic events.

HSLC environments have received more attention in the literature recently, and HSLC climatologies have been created both for the contiguous US (Guyer and Dean 2010) and the Southeast US (Sherburn and Parker 2014), where HSLC tornadoes are most common (Doswell et al. 2005). Up to this point, however, the Northeast US has not been a major focus of HSLC research. The goal of this work is to improve forecast accuracy of these HSLC events in the northeast US. Accordingly, an environmental climatology was created and analyzed to determine which parameters are most useful at discriminating between HSLC events that are favorable for straight-line damaging winds (SDW) versus those that are also favorable for tornadoes.

Sherburn and Parker (2014) have done a significant amount of work in developing the severe hazards in environments with reduced buoyancy (SHERB) parameter, a HSLC composite index which can be used operationally. The SHERBE parameter is a variation of the SHERB parameter that also takes into account the effective wind shear magnitude (ESMG). While the SHERBE parameter and its several variations show skill at predicting HSLC events, they are not designed to predict the occurrence of HSLC convection. Furthermore, the SHERBE parameter is designed to separate environments capable of producing significant severe reports from those that produce non-severe HSLC reports. Therefore, while SHERBE shows skill at predicting HSLC tornadic events, it is not specifically designed to discriminate between SDW and tornadic environments. Out of all parameters examined, Sherburn and Parker (2014) found 0–3-km and 700–500-hPa lapse rates to be the most effective at discriminating between severe and non-severe convection in HSLC environments. However, a previous climatology of all tornadic environments showed that 0–1-km wind shear magnitude (S1MG) and direction (S1DR) have significant utility in discriminating between environments which are favorable for tornadoes versus those that are not (Thompson et al. 2003). These results do not necessarily contradict each other, but rather suggest that each of the aforementioned parameters has at least some value for forecasting HSLC severe weather.

Regardless of which parameters are used to describe HSLC environments, the data must be representative of the environment in question. Darden et al. (2015) argues that proximity soundings are not representative of the localized mesoscale environments that can be supportive of tornadogenesis, as sounding data is only available twice daily at select locations. Furthermore, King et al. (2017) shows that HSLC environments can rapidly evolve (e.g. rapid destabilization and increases of CAPE) prior to tornadogenesis. Additionally, topographical influences can lead to environments with locally enhanced favorability for severe convection and tornadoes (Bosart et al. 2006). Therefore, high temporal and spatial resolution model data and observing networks are needed to accurately diagnose HSLC severe weather environments.

2. Data and Methodology:

a) Data

Thunderstorm damaging wind and tornado reports were downloaded from the National Climatic Data Center (NCDC) Storm Events Database. A preliminary analysis was performed using archived Storm Prediction Center (SPC) mesoanalysis data via redteamwx.com. The mesoanalysis data, available hourly, use the initialization from the RUC/RAP numerical weather prediction model as a first guess, then interpolates surface and upper-air observations to create a single dataset. The horizontal grid spacing of the model data is less than ideal at 40 km. Mesoanalysis data could have errors due to the use of model initializations (Coniglio 2012) and could miss small scale features due to the relatively low spatial resolution. However, mesoanalysis data is commonly used in operational forecasting, and the inclusion of observations increases the accuracy of the mesoanalysis data when compared with the model initialization alone (Coniglio 2012). The prominent use of mesoanalysis data operationally and in research (Sherburn and Parker 2014, Schneider and Dean 2008) makes it a suitable data source for this study.

The SPC provided archived mesoanalysis gridded datasets for cases selected by the authors. These grids contained data for each parameter in Table 1. Data were collected for a 10-year period from June 2007–2017. Box and whisker plots were then made using Microsoft Excel. Excel was also used to perform two-tailed T-tests to determine statistical significance of results. Archived radar imagery that was used to determine storm mode was accessed through the National Center for Environmental Information (NCEI) website.

b) Methods

The first step in this research was to compile a list of events that met the HSLC criteria. Storm reports were obtained from the NCDC Storm Events Database for all tornado and wind reports in the Northeast US between June 2007 and June 2017. The Northeast US was defined as New England, New York, New Jersey, and Pennsylvania. There were approximately 320 tornado reports during this time, and over 16,500 convective SDW reports. Tornado reports were first examined to determine if HSLC criteria were met. HSLC criteria are defined in Table 2 (Guyer and Dean 2010, Schneider et al. 2006, Sherburn et al. 2016). The environment at the latitude and longitude of each report was examined between one and two hours before the event occurred using the archived mesoanalysis data on redteamwx.com. Since this dataset is of relatively low spatial resolution, events that met HSLC criteria were placed on a list to be investigated further. Events that came within approximately 250 J/kg of CAPE or five knots of 0–6-km wind shear of the HSLC criteria were also placed on the list to be investigated further to ensure that a borderline HSLC case was not left out of the study.

Due to the large volume of wind reports, the approach for the preliminary analysis was altered. Instead of looking one to two hours before the report, reports were examined in three-hour blocks. For example, all reports that occurred between 1800 and 2100 UTC would be grouped together. Then, the 1900 UTC mesoanalysis data would be used to determine if the HSLC criteria were met. Furthermore, instead of looking at each individual latitude and longitude, reports were grouped by state. For example, if HSLC criteria were met for more than half of a state, these reports would be added to the list for additional investigation. For larger states, such as New York and Pennsylvania, attention was given to the general latitude and longitude of the report (i.e. did the report occur in the eastern versus western or northern versus southern portion of the state).

The SPC provided gridded mesoanalysis datasets for the list of potential HSLC cases requested by the authors. Values for each parameter were then calculated from this dataset at the latitude and longitude of the report, between one and two hours before the report occurred. The ability to calculate values from the gridded data for various parameters at a specific latitude and longitude resulted in a more accurate dataset than could have been obtained using the mesoanalysis data publicly available online. Each report was then reexamined to determine if the HSLC criteria were met. Roughly one third of SDW reports did not meet the HSLC criteria upon this closer reexamination, while the percentage was lower for tornado reports. In total, there were 1,720 reports that me the HSLC criteria: 1,682 were SDW reports while the remaining 38 were tornado reports. Any event that did not have at least five SDW reports or one tornado report was not included in this study.

The data points for each report were collected in compliance with the Goldilocks Zone (Potvin et al. 2010). The Goldilocks Zone allows for two methods of environmental sampling. The first is to look between 40–80 km away from the location of the report up to two hours before the report. The second is to sample anywhere within 40 km from the report, between one and two hours prior to the report. Figure 1 shows a conceptual diagram of the Goldilocks Zone. This study used the second technique, sampling the environment at the point of the report between one and two hours before the report occurred. Potvin et al. (2010) states that these two methods should give results that have no statistical difference. Sampling the environment in this manner ensures that the data being collected is not convectively contaminated by the storm which produced the report, as the goal of this study is to investigate the environments leading up to these HSLC reports.

The reports that met the HSLC criteria were then grouped by events. An event consisted of multiple reports, usually falling all on the same day or spread between two days (for example, an event that stars in the afternoon of day one and continues into the early morning hours of day two would be considered one event). The mean of all the reports from each event was then calculated for each parameter; if individual reports had been examined instead of events, then widespread events would show a disproportionate influence on results compared to more localized cases. These means were then used to create box and whisker plots using excel. Plots were created for events which occurred during the warm season, events which occurred during the cool season, and all events together. The warm season was defined as April through September, while October through March was defined as the cool season, consistent with Vescio and Thompson (1998).

The cool season consisted of events which only produced SDW reports and events which produced both SDW reports and tornado reports. The cool season box and whisker plots contained these two categories, as well as a category for all tornado reports, since the tornado reports were averaged together with the SDW reports for the wind and tornado category. The warm season had these same three categories, but also contained a category for HSLC events that only produced tornadoes. Some of these tornado only events were from isolated convection that produced a tornado without any SDW reports. However, events where tornadoes occurred in a HSLC environment but wind reports occurred in a higher CAPE environment were also included. There were also tornadoes associated with tropical cyclones included in this category.

The mode of the storm which produced each report was determined by analyzing archived radar imagery from the NCEI website. Storm mode classifications consisted of: discrete cells, clusters of cells, quasi-linear convective systems (QLCS), and QLCS events with discrete cells embedded in the squall line (QLCSD events). Figures 2 and 3 show storm mode distributions for the warm and cool seasons respectively. Additional and/or more specific storm mode classifications were not possible due to small sample size and lack of high resolution radar data. Box and whisker plots were created to further break the previously mentioned categories down by storm mode, but sample size was insufficient for many report type/storm mode combinations (e.g. tornado only reports from QLCS events).

3. Results

a) E*vent and storm mode distributions*

This study found a total of 114 events; 91 occurred during the warm season, while just 23 occurred during the cool season. Figure 4 shows the seasonal distribution of wind only events, wind and tornado events, tornado only events, and all tornado reports. The number of events in each category in Fig. 4 is also the sample size for each of the box and whisker plots in the following figures, and for the statistical tests that were conducted. Wind only events are clearly the most common HSLC event type during both the warm and cool season, while wind and tornado events are relatively rare, with a total of only 11 events over the 10-year period that was examined (Fig. 4). No cool-season events produced only tornadoes, and there were only eight cool-season HSLC tornadoes recorded in the Northeast between 2007 and 2017, while there were 30 HSLC tornado reports in the warm season during this period.

The storm mode distribution for the warm season shows QLCS events as the predominant storm mode for both wind only events as well as for wind and tornado events (Fig. 2). However, discrete cells are by far the most common storm mode for events which only produced tornado reports. Discrete cells also account for almost half of all warm-season HSLC tornado reports (Fig. 2). The cool-season storm mode distribution was dominated by QLCS events regardless of event type (Fig. 3), with QLCS events accounting for over half of all wind only events as well as of all tornado reports; QLCS events made up just under one half of all wind and tornado events. Note that the number of events for the storm mode distribution is greater than the total number of events in Fig. 4, as several individual events contained multiple convective modes. These findings largely agree with those of Sherburn and Parker (2014) in that QLCSs are the dominant storm mode for HSLC convection, but the results also show that discrete cells which develop in warm season HSLC environments must be closely monitored for tornado development.

b) *Warm Season*

There were several parameters for the warm season that showed statistically significant differences between event types. A complete list of parameters and p-values for the warm season is shown in Table 3. LCL heights were the most statistically significant parameter for discriminating between wind only versus wind and tornado events ($p = 5.47 \times 10^{-7}$), as well as between wind only events and all tornado reports ($p = 1.71 \times 10^{-4}$). LCL heights were the third most significant parameter for wind only vs tornado only events in the warm season (Fig. 5). These results show that LCLs are significantly lower for events which produce tornadoes, compared to those that only produce SDW damage. Therefore, LCL heights should be given considerable attention by forecasters anticipating HSLC severe weather.

850-hPa wind direction (Fig. 6) was the most significant parameter for warm-season wind only versus tornado only events, with a p-value of 6.26×10^{-4}. 850-hPa wind direction was also statistically significant at the 99.9% level for wind only events compared to all tornado reports, but was not statistically significant ($p = .101$) for wind only versus wind and tornado events. Wind direction at 925 and 700 hPa (box and whisker plots not shown) showed a similar pattern, but with slightly larger p-values. Therefore, wind direction appears to be a useful parameter at discriminating between wind only events versus tornado only events and individual tornado reports, with tornadoes occurring in environments where there is more of a southerly or backed component to the wind direction. Not surprisingly, S1DR is also significant at the 99% level for wind only versus tornado only events and all tornado reports, with a more southerly shear direction for those environments that produced tornadoes (Fig. 7).

Interestingly, several parameters that are typically used for severe weather forecasting were found to show no statistical significance for the different event types. For example, 0–6-km shear magnitude (S6MG) showed no statistically significant difference between wind only versus wind and tornado events, or for wind only events versus all tornado reports. However, SMG was significant at the 95% level for wind only versus tornado only events (Fig. 8). Even more surprisingly, S1MG, a common parameter used in severe weather and tornado forecasting, was only significant for wind only versus tornado only events.

Additionally, composite indices, such as the significant tornado parameter (STP) and supercell composite parameter (SCP) (Thompson et al. 2004), show skill at discriminating between some of the various event types (STP is significant at the 10% level or better for wind only versus all other event types), but these are not the most significant parameters. For example, downdraft CAPE shows higher skill for each warm-season event type than does the STP. This indicates that some of the more conventional parameters may not be the most useful for discriminating between HSLC environments which favor SDW events versus those that also support tornadoes; other alternatives need to be explored in order to increase forecast and warning accuracy. Using the parameters with the greatest statistically significant differences between event types, in addition to those already used for HSLC severe weather forecasting, could allow forecasters to better predict which environments are favorable for SDW events versus which are also favorable for tornadoes.

c) *Cool Season*

Cool-season events were far less common than warm-season events, which lead to smaller sample sizes and less impressive p-values. For this reason, there were no cool-season parameters with a p-value < .01, and only two were significant at the 95% level. Table 4 shows all cool-season parameters and their corresponding p-values for each event type.

The most significant parameter for wind only events versus wind and tornado events was ESMG, with p = .016. For wind only versus all tornado reports, the p-value was .072, which is notable considering that only five parameters showed statistical significance at the 10% level for the cool season. A larger sample size may have shown EMSG to be significant at a higher threshold for SDW events versus all tornado reports. Box and whisker plots for ESMG (Fig. 9) show significantly lower values for wind only events compared to those that also produced tornadoes. Interestingly, stronger effective shear values were not limited to those specific locations where tornadoes were reported, as there is no statistically significant difference between the individual tornado reports and the averages for the wind and tornado events in terms of ESMG (p = .61).

The most statistically significant parameter for wind only events compared to all individual tornado reports was the difference between wind direction at the 700 and 850-hPa levels, with p = .039. Figure 10 shows greater directional difference in wind between these two levels for the tornado reports compared to wind only events. Unlike with ESMG, however, the wind and tornado category shows remarkable similarity to the wind only category, with p = .91. This leads to a key takeaway: There is a difference, in terms of ESMG, between wind reports that occur in conjunction with tornadoes compared to those that do not. However, for wind direction difference between 700 and 850 hPa, wind reports that occur in conjunction with tornado reports show no statistically significant difference from those that do not. For this parameter, only the tornadoes appear to occur in a different environment, namely where there is greater veering of the winds between these two layers.

Other parameters which show skill at discriminating between tornadic and non-tornadic HSLC environments in the cool season are surface relative humidity (RH) and LCL height. Both wind only events and tornado reports show an upper bound of roughly 90% surface RH, but surface RH for all tornado reports is > 84%, while surface RH between 70 and 75% is still relatively common for SDW only events (Fig. 11). LCLs are typically lower for both wind and tornado events and all tornado reports when compared to wind only events (Fig. 12)

There are several parameters which appear to show no statistical significance at discriminating between event types for the cool season. However, closer examination of the box and whisker plots shows that many of these parameters may have been significant had the sample size been larger. For example, S1DR (Fig. 13) appears to, on average, be more southerly for tornado reports compared to SDW only reports. However, due to two outliers (two tornadoes occurred with SDR between 240 and 260 degrees) and the small sample size, these results are not significant.

Many of the typical parameters again do not show skill in deciphering which environments are favorable for tornadoes and which are not. For example, S6DR and S6MG (Fig. 14 and Fig. 15) appeared relatively similar for different event types, especially given the small sample size. Furthermore, the SCP and STP composite indices did not show any usefulness in identifying HSLC environments favorable for tornadic versus SDW only events during the cool season, likely because these parameters are very small when there is little CAPE. Ultimately, speed and directional shear appear to be some of the most important parameters to look at in the cool season. While these are both typically examined by forecasters, use of non-traditional wind shear parameters (i.e. 700 - 850-hPa wind direction instead of S6DR) may prove more accurate in determining which environments are supportive of SDW and tornado reports versus SDW only reports during the cool season.

d) *All Events*

When warm and cool-season events are combined, the results closely resemble those from the warm season (Table 5). LCLs were once again the most statistically significant parameter at discriminating between SDW only versus wind and tornado events, as well as between SDW only events and all tornado reports. S1DR, as well as 925, 850, and 700-hPa wind direction, were all amongst the most statistically significant parameters at discriminating between events which produced wind only reports versus those that also/only produced tornadoes.

Interestingly, the most significant parameter for discriminating between SDW only versus tornado only events was the 500-hPa wind speed, which was significantly lower ($p = 2.69 \times 10^{-5}$) for the tornado only events (Fig. 16). The physical reason why this is the case has not been investigated, as the focus of this paper is more limited to the HSLC climatology and application to forecasting. Nevertheless, one possible reason is that this category compares events which only occurred during the warm season against both warm and cool-season events; it is possible that the mean is lowered by tornadoes produced by tropical cyclones (3 out of 15 events in this category), which typically have weaker upper-level winds than do mid-latitude cyclones. Another parameter that is significant at the 99% level for wind only versus tornado only events is surface based convective inhibition (SBCN) (Fig. 17). SBCN was significant with $p = .0199$ for the warm-season for wind only versus tornado only events, but is the second most significant parameter for discriminating between these two event types when all events are considered together.

These results do not show lapse rates as having significant utility in discriminating between SDW and tornadic cases. In fact, these parameters showed considerable overlap in the box and whisker plots between all categories (Fig. 18 and Fig. 19). None of the tornadic event types were statistically different from SDW only events. While this contradicts the findings of Sherburn and Parker (2014), that study examined reports from a wide geographic area, with a focus in the Southeast US. Sherburn et al. (2016) acknowledges that the accuracy of the SHERBE parameter may decrease in locations where steep lapse rates are more common than in the Southeast US. On the other hand, the finding of ESMG as a significant parameter for discriminating between tornadic versus non-tornadic events, especially in the cool season, agrees with the findings of Sherburn and Parker (2014) and Sherburn et al. (2016). Calculations of the SHERBE parameter using values of lapse rates and ESMG found for this study show that the SHERBE parameter is useful at discriminating between wind only versus wind and tornado events ($p = .056$) and wind only versus all tornado reports ($p = .027$), but is not significant ($p = .14$) for identifying wind only versus tornado only events (Fig. 20). There are several parameters showing more impressive p-values for comparing all event types, which shows that the SHERBE parameter may not be the most useful for discriminating between HSLC wind and tornado environments in the Northeast US.

4. Conclusion

It has been shown that some commonly used parameters for HSLC severe weather forecasting may not show skill at discriminating between HSLC environments which only support SDW events versus those that also support tornadoes. This study found that LCL heights and low-level shear and wind direction are the most significant warm-season parameter for discriminating between these event types. ESMG and 700 - 850-hPa wind direction difference are the most statistically significant parameters for discriminating between SDW versus wind and tornado events and between SDW events versus all tornado reports for the cool season. When warm-season and cool-season events are examined together, LCL heights and 500-hPa wind speeds are the most significant parameters, followed again by low-level shear and wind direction. Use of these parameters to forecast HSLC severe weather could lead to improvement of HSLC severe wind and tornado forecasts in the Northeast US. Ultimately, there is no one parameter that can be used to predict HSLC weather, and there is no guarantee that a parameter that is useful for one event will be useful for the next. However, it is important for forecasters to know which parameters are typically most successful in these HSLC environments and to give consider these parameters when creating a forecast.

Several areas for future research remain. Constructing composite analyses of several of the most significant parameters would be of great operational use. A synoptic-scale analysis of weather patterns associated with HSLC SDW and tornado events could give a better understanding of the large-scale setups for these events and allow for forecasters to anticipate potential HSLC SDW and/or tornado events up to a few days in advance. Additionally, this entire work could be replicated, except by sampling the environment within one hour of each report instead of looking one to two hours ahead of the report. Potvin et al. (2010) shows that the results should show no statistically significant difference from those found in this paper, but such an approach could lead to a larger sample size. Because CAPE rapidly decreases after sunset during the warm season, several warm-season reports were just a few hundred Jkg^{-1} of CAPE away from meeting the HSLC criteria. Taking this approach could increase the sample size enough to clarify p-values that are borderline statistically significant. Future research could also examine HSLC null events versus those that produce severe weather reports, similar to the works of Sherburn and Parker, but with a focus solely on the Northeast.

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Figure 20: Box and whisker plots for SHERBE parameter calculations for all events

Tables

Parameter	Abbreviation	Parameter	Abbreviation
100 hPa mean mixed CAPE	M1CP	Downdraft CAPE	DNCP
Most Unstable CAPE	MUCP	Bulk Richardson Number (based on MLCAPE)	BRNUM
Surface Based CAPE	SBCP	Precipitable Water	INPW
100 hPa mean mixed CIN	M1CN	0-1 KM EHI	EHI1
Surface based CIN	SBCN	0-3 KM EHI	EHI3
100 hPa mean mixed LCL height	MMLH	925-hPa wind speed	WSPD_925
Mixed Layer (100 hPa) virtual LFC	MLFC	850-hPa wind speed	WSPD_850
Surface Temperature	TMPC_SFC	700-hPa wind speed	WSPD_700
Surface Dew point	DWPC_SFC	500-hPa wind speed	WSPD_500
Surface RH	RH_SFC	300-hPa wind speed	WSPD_300
Surface to 1 km shear magnitude	S1MG	925-hPa wind direction	WDIR_925
Surface to 1 km shear direction	S1DR	850-hPa wind direction	WDIR_850
Surface to 6 km shear magnitude	S6MG	700-hPa wind direction	WDIR_700
Surface to 6 km shear direction	S6DR	500-hPa wind direction	WDIR_500
Surface to 8 km shear magnitude	S8MG	300-hPa wind direction	WDIR_300
Surface to 8 km shear direction	S8DR	925-hPa wind speed - surface wind speed	WSPD 925-SFC
Effective shear magnitude	ESMG	850-hPa wind speed - surface wind speed	WSPD 850-SFC
Effective shear direction	ESDR	700-hPa wind speed - surface wind speed	WSPD 700-SFC
Storm relative helicity Surface to 1 km	SRH1	925-hPa wind direction - surface wind direction	WDIR 925-SFC
Storm relative helicity Surface to 3 km	SRH3	850-hPa wind direction - surface wind direction	WDIR 850-SFC
Effective surface helicity	SRH_EFF	700-hPa wind direction - surface wind direction	WDIR 700-SFC
Lower-level lapse rate surface to 3km agl	LLLR	850-hPa wind speed - 925-hPa wind speed	WSPD 850-925

Lapse Rate from 700 to 500 hPa	LR75	700-hPa wind speed - 925-hPa wind speed	WSPD 700-925
Surface wind speed	WSPD_SFC	700-hPa wind speed - 850-hPa wind speed	WSPD 700-850
Surface wind direction	WDIR_SFC	850-hPa wind direction - 925-hPa wind direction	WDIR 850-925
Supercell Composite Parameter	SCCP	700-hPa wind direction - 925-hPa wind direction	WDIR 700-925
Sig Tornado parameter (Effective)	STPC	700-hPa wind direction - 850-hPa wind direction	WDIR 700-850

Table 1: Complete list of parameters examine

Parameter	Criteria
SBCP	≤ 500 J/kg
M1CP	≤ 1000 J/kg
MUCP	≤ 1000 J/kg
S6MG	≤ 18 m/s

Table 2: CAPE and shear requirements for a HSLC environment

Parameter	p-value		
	SDW only vs wind and tornado	SDW vs tornado only	SDW vs all tornado reports
MUCP	0.420448501	0.5258502	0.427379437
M1CP	0.215535711	0.160132858	0.044859701
SBCP	0.762940651	0.060923022	0.13441235
S6MG	0.629001071	0.016190562	0.131902319
SBCN	0.869761622	0.019941942	0.14133794
M1CN	0.732306321	0.06352162	0.031575008
MMLH (LCL)	5.42759E-07	0.004496274	0.000170615
MLFC	0.166668356	0.011364863	0.132008181
TMPC_SFC	0.150721389	0.30955299	0.101236571
DWPC_SFC	0.072253868	0.465068156	0.576880361
RH_SFC	0.013563346	0.059832169	0.029793527
S1MG	0.689604258	0.330468323	0.044162818
S1DR	0.033653604	0.003887255	0.000632012
S6DR	0.598024637	0.212318745	0.106054537
S8MG	0.975191195	0.188595168	0.636011675
S8DR	0.606582476	0.266505808	0.106407126
ESMG	0.090800871	0.512243614	0.238473779
ESDR	0.230073005	0.28516707	0.114300467

SRH1	0.418634902	0.429735209	0.054661049
SRH3	0.293503832	0.314251109	0.041992093
SRH_EFF	0.086133753	0.079520489	0.00545258
LLLR	0.222345959	0.953577344	0.73542623
LR75	0.259162352	0.721300166	0.769487082
WSPD_SFC	0.993335359	0.876844625	0.386367721
WDIR_SFC	0.251181325	0.044557279	0.214991739
SCCP	0.125389681	0.096201089	0.020462959
STPC	0.095978338	0.077131333	0.016747207
DNCP	0.094826502	0.033347496	0.005818075
BRNUM	0.786373745	0.876628867	0.573421677
INPW	0.162109283	0.272274046	0.328822421
EHI1	0.442142895	0.121641482	0.02315716
EHI3	0.380226872	0.064453206	0.018542584
WSPD_925	0.798807629	0.677618741	0.147468615
WSPD_850	0.758261264	0.642824659	0.06914782
WSPD_700	0.356878463	0.736686242	0.258180452
WSPD_500	0.709862092	0.003052993	0.10420735
WSPD_300	0.718896604	0.111859514	0.553230524
WDIR_925	0.025866839	0.006064055	0.004836559
WDIR_850	0.101390974	0.000908996	0.000626611
WDIR_700	0.060526325	0.017521577	0.001527685
WDIR_500	0.368783332	0.123572935	0.032803982
WDIR_300	0.344504964	0.164276595	0.031328706
WSPD 925-SFC	0.79530145	0.679340436	0.148407269
WSPD 850-SFC	0.628110406	0.588336694	0.079684543
WSPD 700-SFC	0.299710349	0.683906604	0.287719584
WDIR 925-SFC	0.93511503	0.5945867	0.10458265
WDIR 850-SFC	0.746130293	0.32123617	0.157259117
WDIR 700-SFC	0.758531429	0.883993166	0.347932332
WSPD 850-925	0.770418901	0.85177474	0.209917085
WSPD 700-925	0.122068287	0.362789573	0.659850304
WSPD 700-850	0.444610041	0.2047527	0.107935738
WDIR 850-925	0.397558509	0.507251707	0.879046939
WDIR 700-925	0.516713021	0.501188015	0.828050214
WDIR 700-850	0.751199576	0.10428916	0.404529829

Table 3: Complete list of warm-season p-values for each parameter for SDW only events compared to wind and tornado events, tornado only events, and all individual tornado reports. Green shading indicates a parameter significant at the 10% level, green at the five percent level, and blue at the one percent level.

Parameter	p-value	
	SDW only vs wind and tornado	SDW vs all tornado reports
MUCP	0.188430229	0.748140342
M1CP	0.582382431	0.808648777
SBCP	0.926077886	0.319253538
S6MG	0.765065647	0.905469044
SBCN	0.288504254	0.329530454
M1CN	0.742680922	0.263571174
MMLH (LCL)	0.161030521	0.073533619
MLFC	0.116778618	0.302515888
TMPC_SFC	0.930734386	0.363573549
DWPC_SFC	0.582837589	0.830197758
RH_SFC	0.514169893	0.071942509
S1MG	0.76411614	0.071380126
S1DR	0.521763838	0.173465718
S6DR	0.996272267	0.702355925
S8MG	0.479330027	0.969309344
S8DR	0.997492713	0.668061695
ESMG	0.015958274	0.072400101
ESDR	0.249323539	0.362491478
SRH1	0.966721368	0.270806892
SRH3	0.953402847	0.570255943
SRH_EFF	0.128385561	0.21593263
LLLR	0.277943367	0.265732978
LR75	0.830237986	0.40603455
WSPD_SFC	0.643568827	0.655159054
WDIR_SFC	0.914509946	0.106440653
SCCP	0.211593833	0.999478818
STPC	0.341085041	0.583255527
DNCP	0.325548239	0.662987703
BRNUM	0.683592531	0.448944973
INPW	0.744425029	0.347193179
EHI1	0.415593071	0.650061959
EHI3	0.388877224	0.699195433
WSPD_925	0.798865741	0.113503579
WSPD_850	0.87930287	0.15541819
WSPD_700	0.837018158	0.419702212
WSPD_500	0.808683965	0.562876566
WSPD_300	0.720277213	0.978852862
WDIR_925	0.708160507	0.299537698
WDIR_850	0.633529814	0.166074333

WDIR_700	0.668657995	0.430295813
WDIR_500	0.985711963	0.832985836
WDIR_300	0.937528783	0.991819621
WSPD 925-SFC	0.842487496	0.080704442
WSPD 850-SFC	0.924847082	0.142031045
WSPD 700-SFC	0.882553599	0.399301032
WDIR 925-SFC	0.230142537	0.825654634
WDIR 850-SFC	0.144742526	0.832922789
WDIR 700-SFC	0.330708422	0.411345973
WSPD 850-925	0.911497015	0.798128654
WSPD 700-925	0.967154846	0.675723463
WSPD 700-850	0.871600999	0.224047995
WDIR 850-925	0.641256493	0.444463067
WDIR 700-925	0.810577695	0.359978777
WDIR 700-850	0.91322628	0.03929784

Table 4: Complete list of cool-season p-values for each parameter for SDW only events compared to wind and tornado events and all individual tornado reports. Green shading indicates a parameter significant at the 10% level, green at the five percent level, and blue at the one percent level.

Parameter	p-value		
	SDW only vs wind and tornado	SDW vs tornado only	SDW vs all tornado reports
MUCP	0.368931396	0.15381176	0.529331205
M1CP	0.25858493	0.08007535	0.071041959
SBCP	0.804499552	0.014129087	0.268694323
S6MG	0.765829749	0.000337303	0.398961197
SBCN	0.863580328	0.000185326	0.262611677
M1CN	0.512917621	0.087736739	0.014111068
MMLH (LCL)	3.05836E-07	0.016784777	5.85359E-05
MLFC	0.846411728	0.022532151	0.548781418
TMPC_SFC	0.126691736	0.84940273	0.146219914
DWPC_SFC	0.454549017	0.130925748	0.505980714
RH_SFC	0.006853881	0.117833295	0.010424371
S1MG	0.485565996	0.876964345	0.241846591
S1DR	0.019270096	0.008667277	0.000211193
S6DR	0.4442094	0.370846055	0.100587514
S8MG	0.844922376	0.022739825	0.761361824
S8DR	0.438498482	0.450917166	0.099457359
ESMG	0.009772498	0.138998788	0.045352738
ESDR	0.99629987	0.668541272	0.520203591

SRH1	0.273292693	0.987297243	0.170707938
SRH3	0.204951476	0.729700471	0.099881695
SRH_EFF	0.028509175	0.050460615	0.003072898
LLLR	0.41151108	0.294020533	0.901794791
LR75	0.678126184	0.565278251	0.617352904
WSPD_SFC	0.48954981	0.598874217	0.56645616
WDIR_SFC	0.238457438	0.040909467	0.093368168
SCCP	0.084558009	0.059197461	0.023563279
STPC	0.042711156	0.076255193	0.020294809
DNCP	0.113881409	0.169891132	0.018993626
BRNUM	0.926657561	0.703274384	0.776990566
INPW	0.610614799	0.173493994	0.552006954
EHI1	0.544577528	0.077557439	0.032362438
EHI3	0.540609076	0.036404038	0.027304972
WSPD_925	0.412658807	0.590926208	0.509362485
WSPD_850	0.411833573	0.548735326	0.345442917
WSPD_700	0.207554394	0.094395341	0.687787516
WSPD_500	0.599154078	2.68858E-05	0.128214387
WSPD_300	0.596409413	0.014828428	0.543328949
WDIR_925	0.017866592	0.011665109	0.00291673
WDIR_850	0.061443577	0.002653457	0.00029306
WDIR_700	0.038943905	0.050843276	0.001602837
WDIR_500	0.317254844	0.260403384	0.056142123
WDIR_300	0.273319951	0.32759278	0.053572663
WSPD 925-SFC	0.415176207	0.604851344	0.530718013
WSPD 850-SFC	0.412574643	0.55825014	0.346950302
WSPD 700-SFC	0.191120471	0.081991166	0.743451697
WDIR 925-SFC	0.596578347	0.82717509	0.132204699
WDIR 850-SFC	0.914986237	0.530733972	0.189148498
WDIR 700-SFC	0.782141624	0.570098462	0.475915071
WSPD 850-925	0.596149763	0.744399074	0.356921203
WSPD 700-925	0.163786048	0.20845034	0.776669518
WSPD 700-850	0.487132858	0.22670621	0.244435171
WDIR 850-925	0.587372794	0.5024937	0.842914012
WDIR 700-925	0.778728591	0.363565157	0.55812348
WDIR 700-850	0.660310043	0.085636403	0.235444254

Table 5: Complete list of p-values for each parameter for SDW only events compared to wind and tornado events, tornado only events, and all individual tornado reports for warm and cool seasons combined. Green shading indicates a parameter significant at the 10% level, green at the five percent level, and blue at the one percent level.

Figures

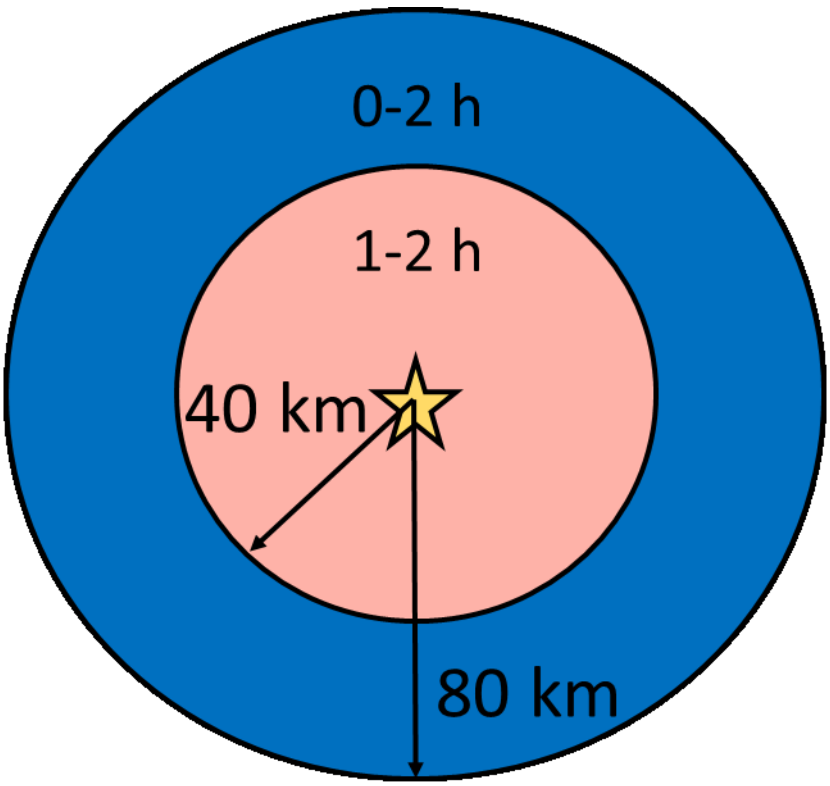

Figure 1: A conceptual model of the Goldilocks Zone (Potvin et al. 2010). Looking in the blue radius at 0–2 hours before the report should give results that are not statistically different from those that would be found looking within the orange radius 1–2 hours before the report.

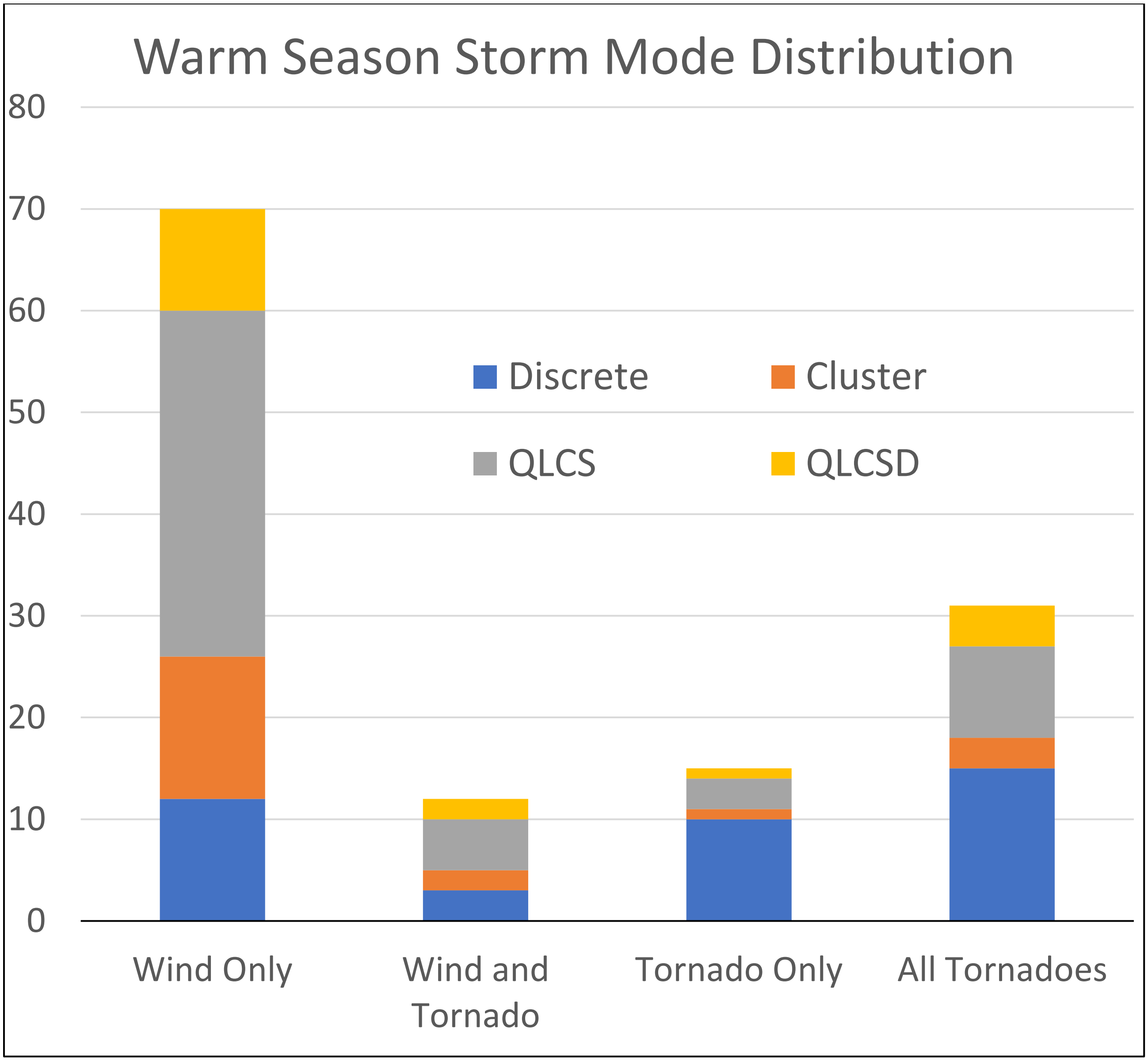

Figure 2: Storm mode distribution for warm-season events

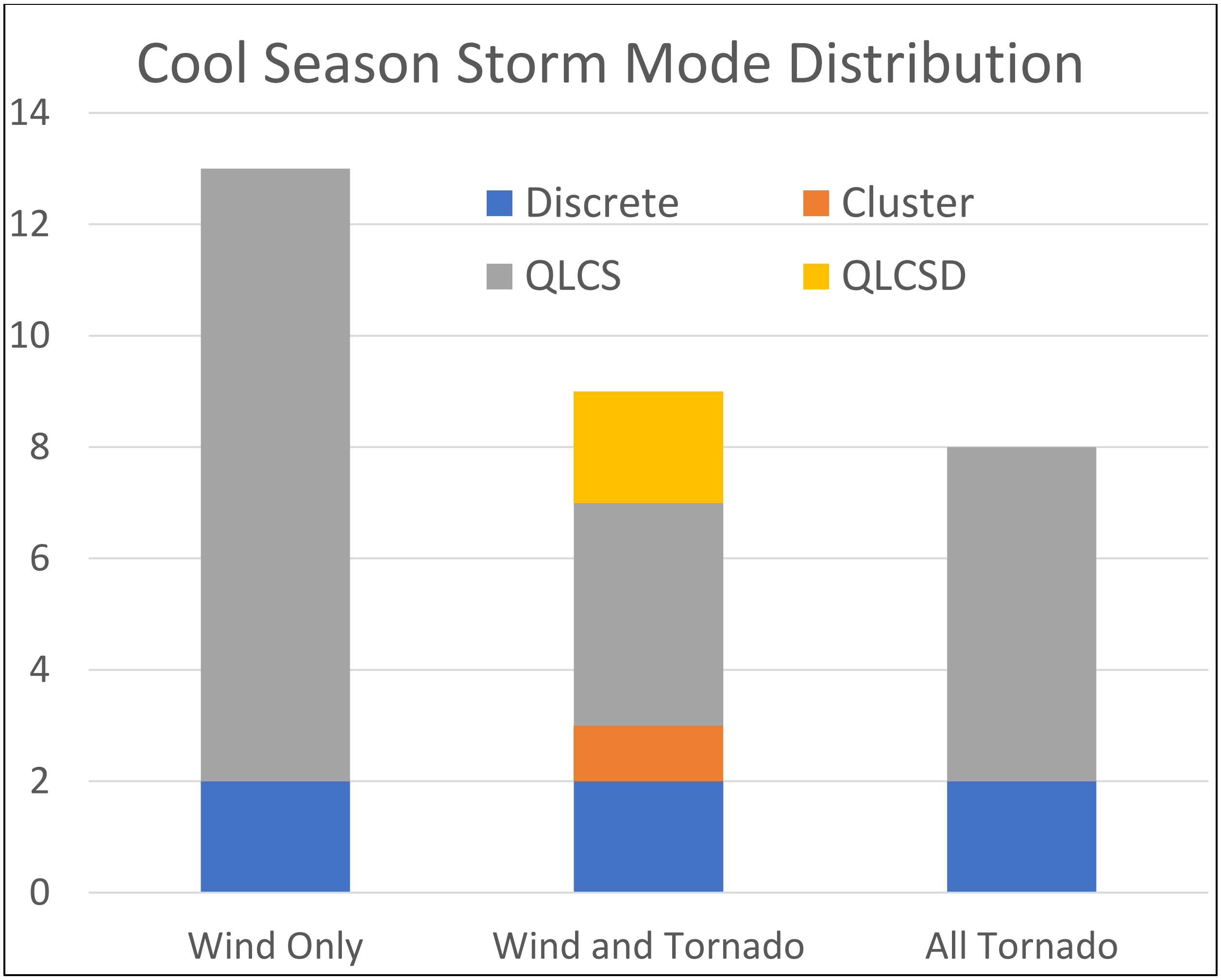

Figure 3: Storm mode distribution for cool-season events

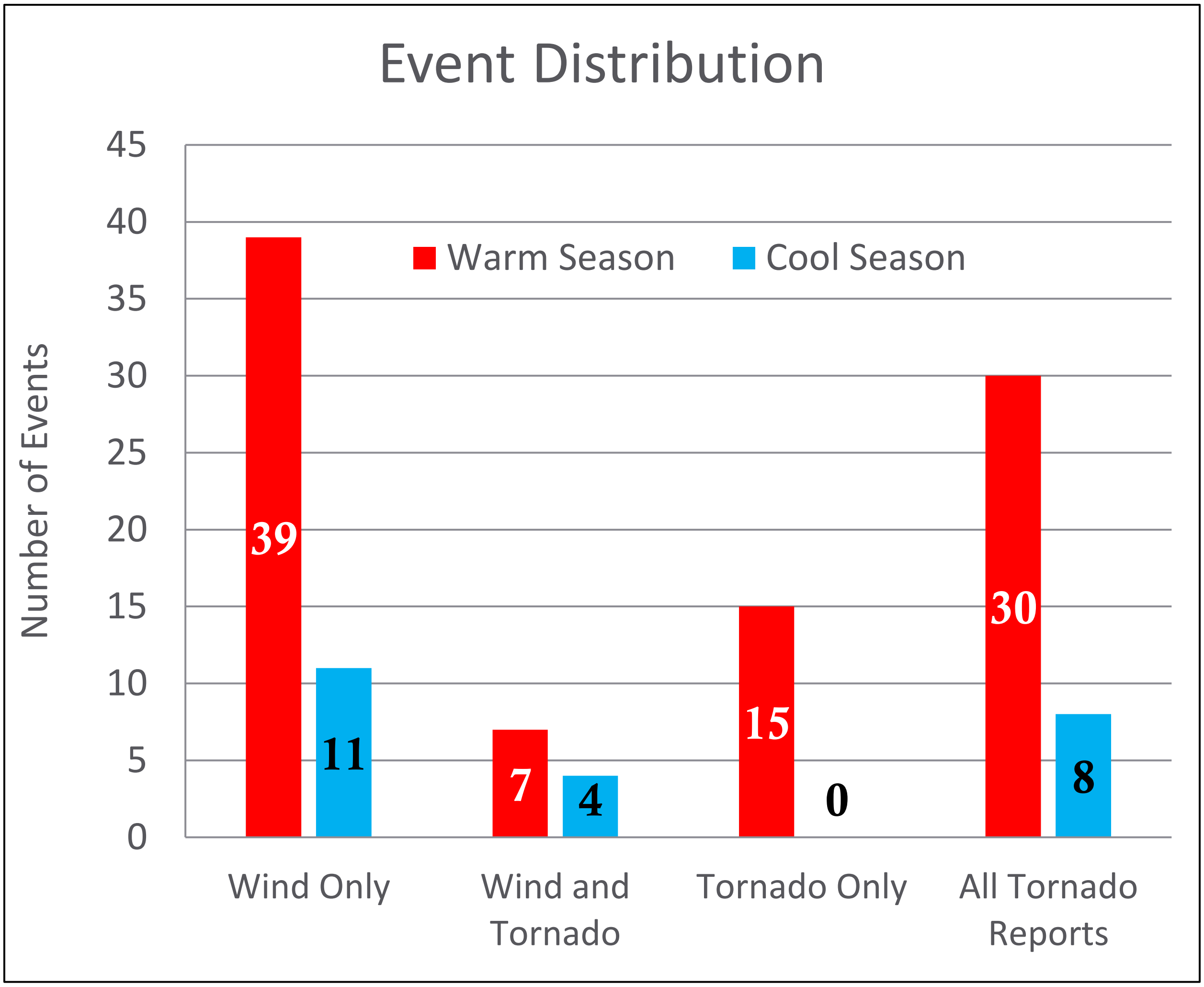

Figure 4: Overall distribution of events by damage report type

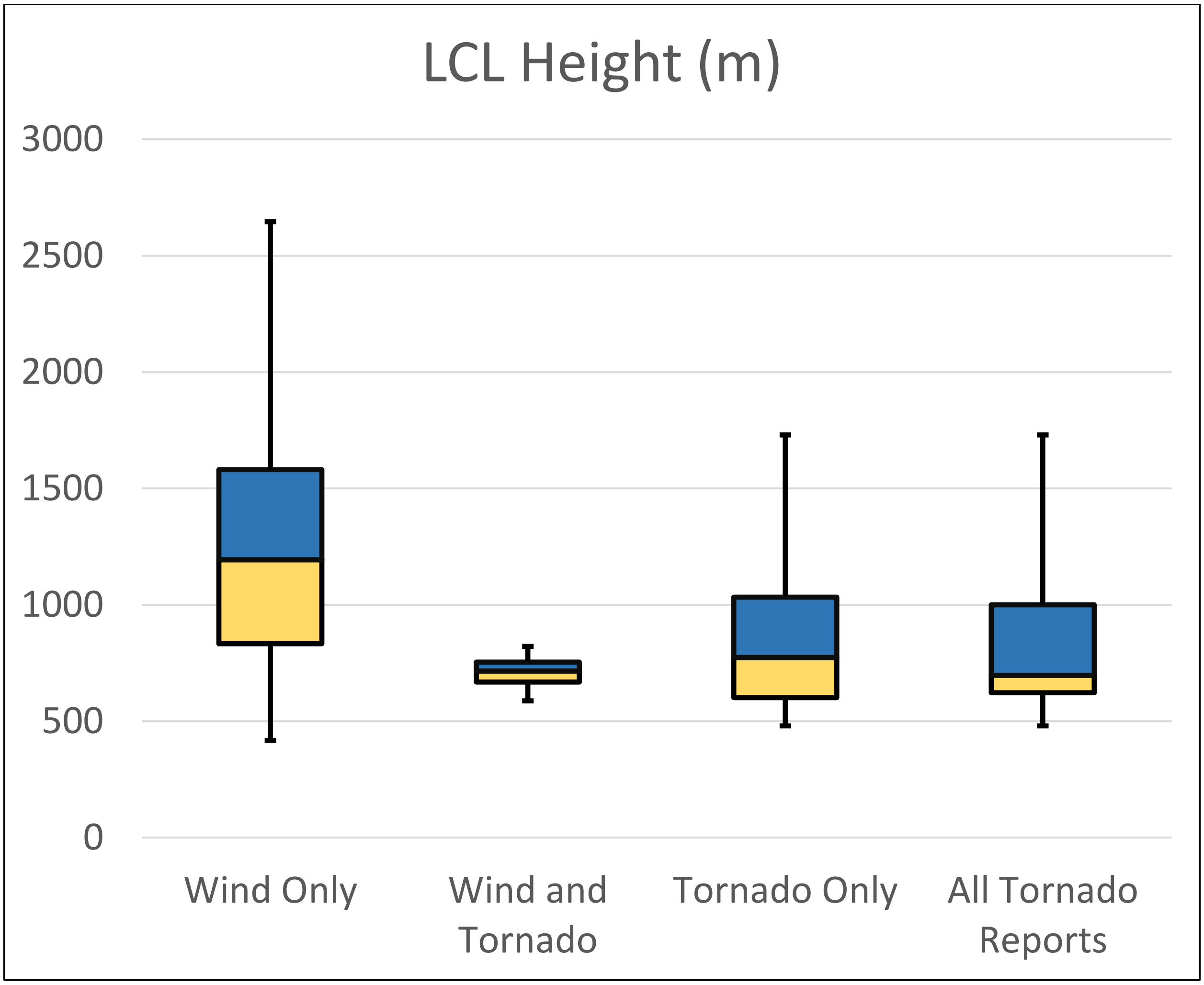

Figure 5: Box and whisker plots for warm-season LCL heights

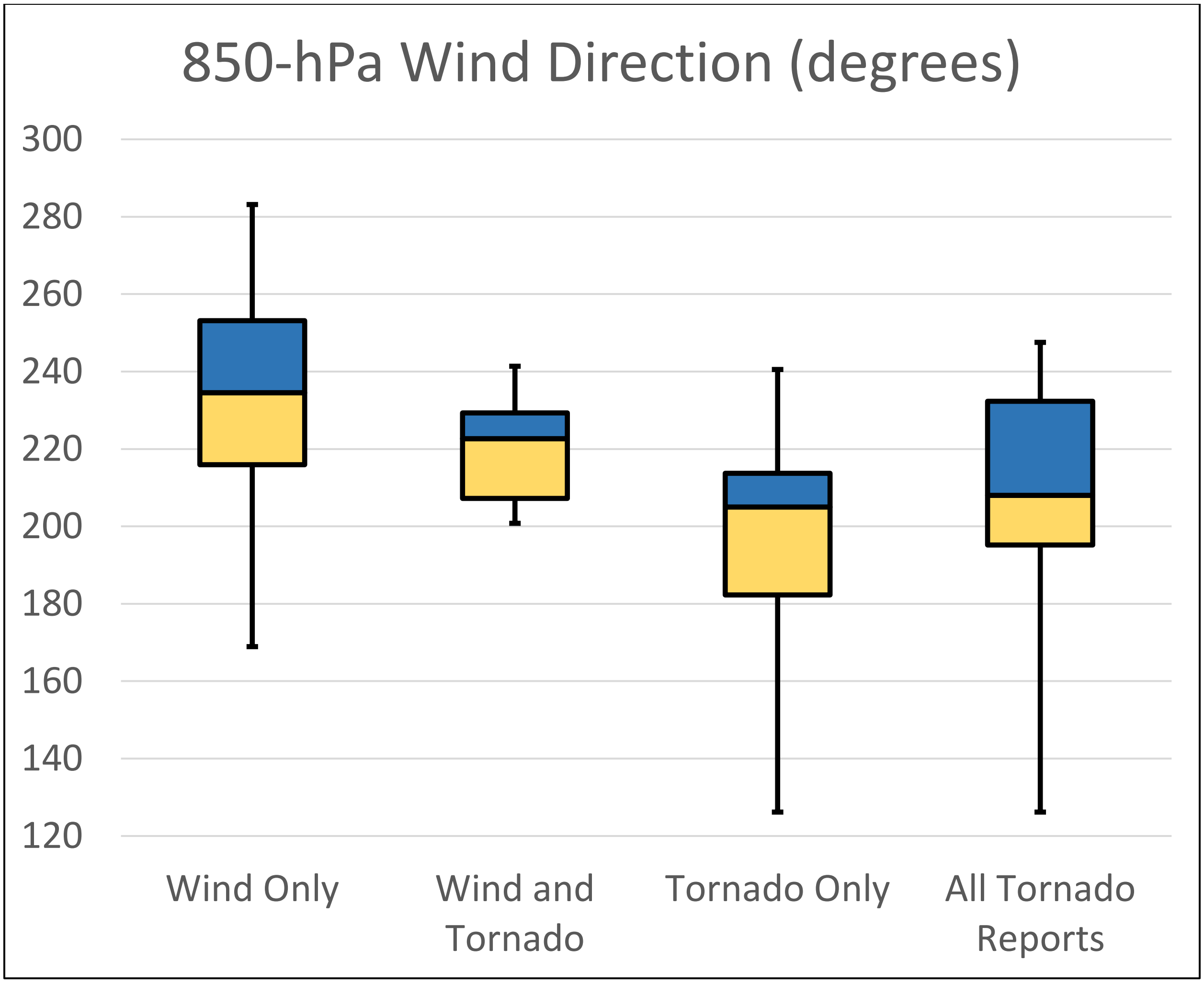

Figure 6: Box and whisker plots for warm-season 850-hPa wind direction

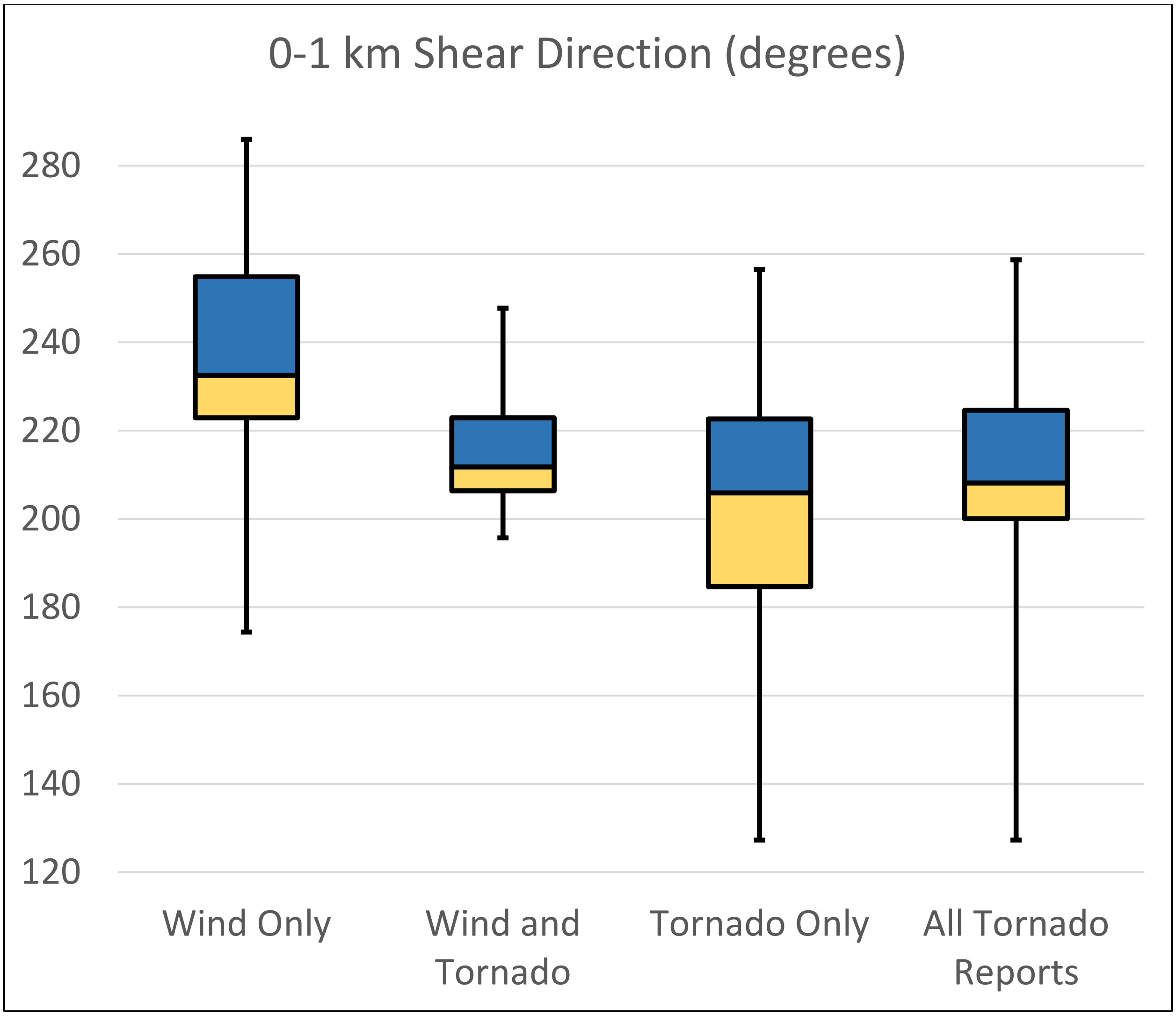

Figure 7: Box and whisker plots for warm-season S1DR

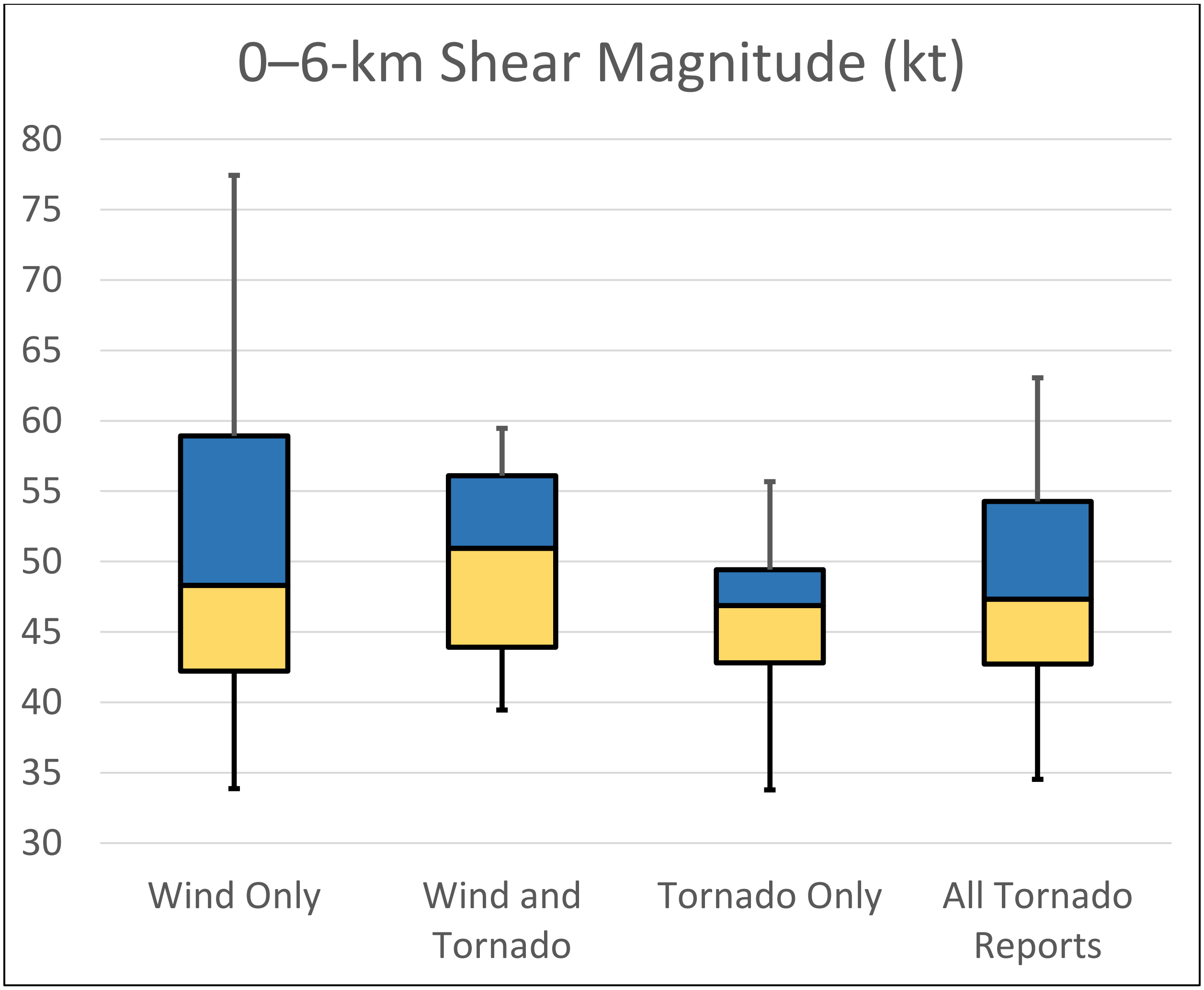

Figure 8: Box and whisker plots for warm-season S6MG

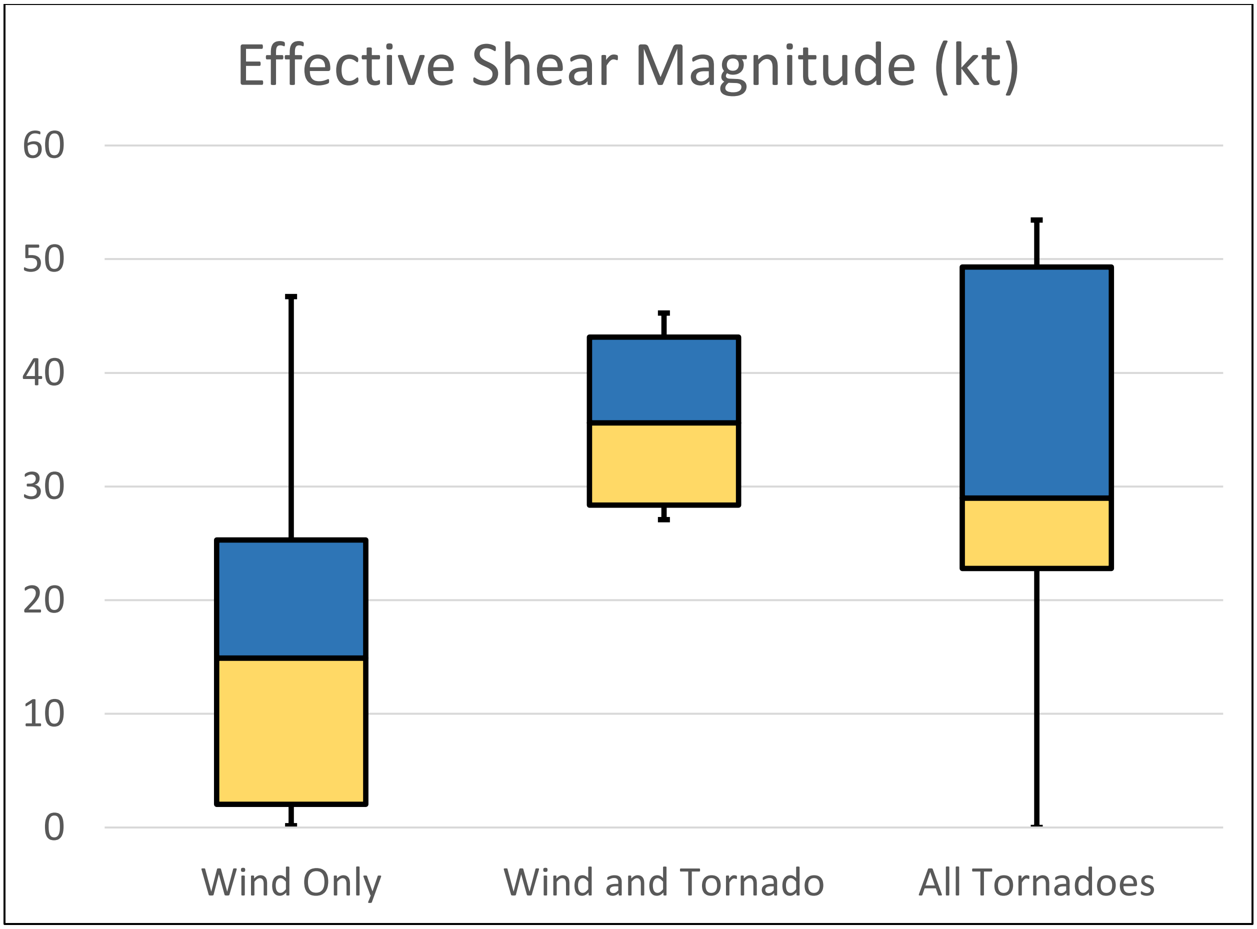

Figure 9: Box and whisker plots for cool-season ESMG

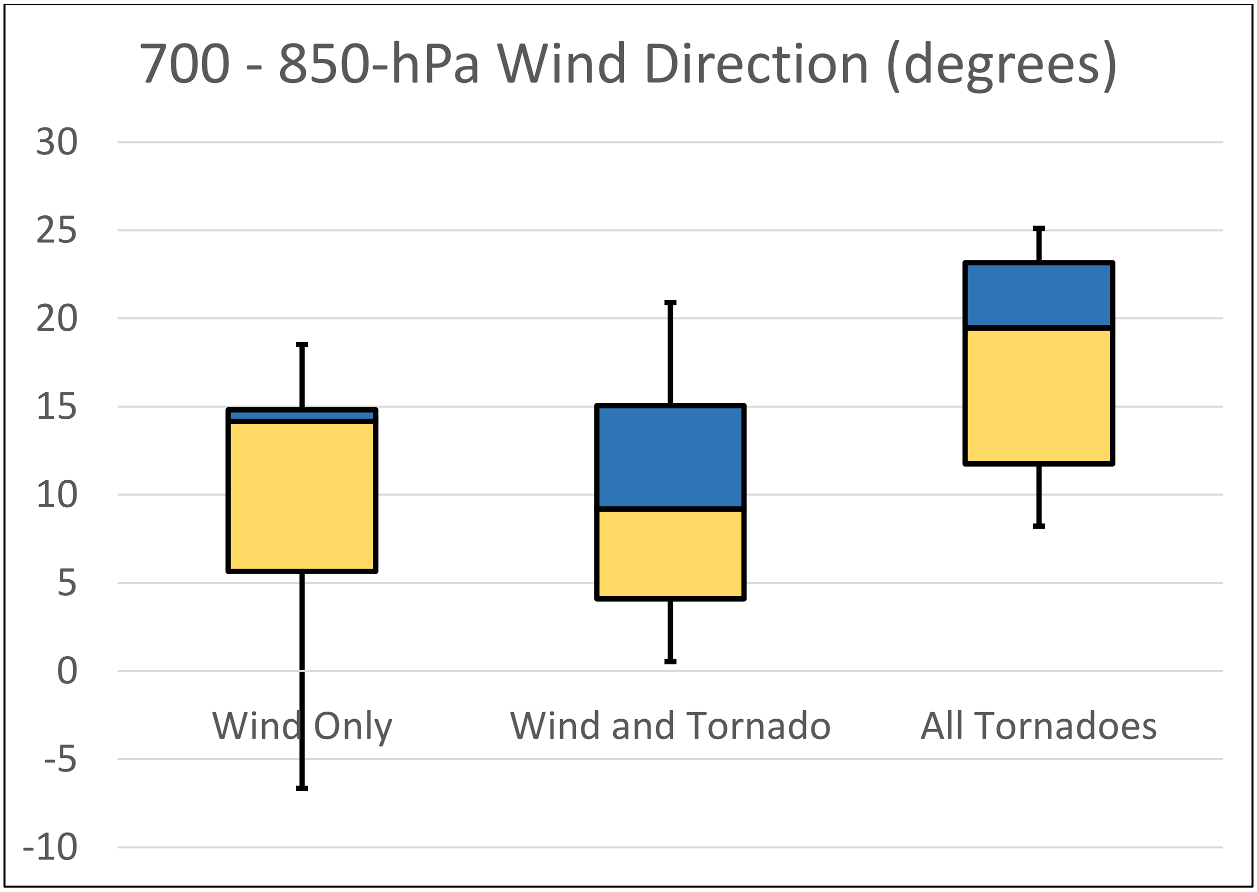

Figure 10: Box and whisker plots for cool-season 700 - 850-hPa wind direction

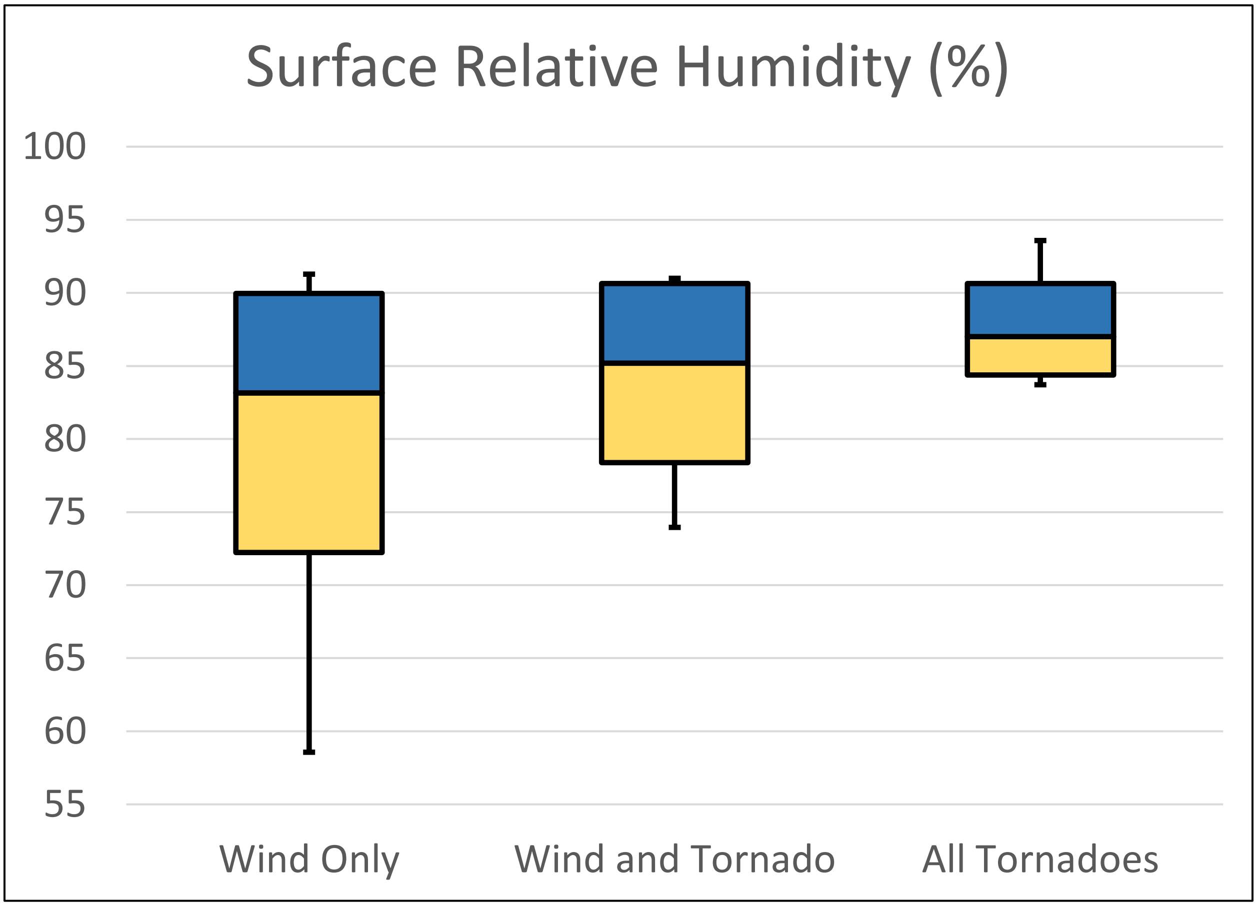

Figure 11: Box and whisker plots for surface RH during the cool season

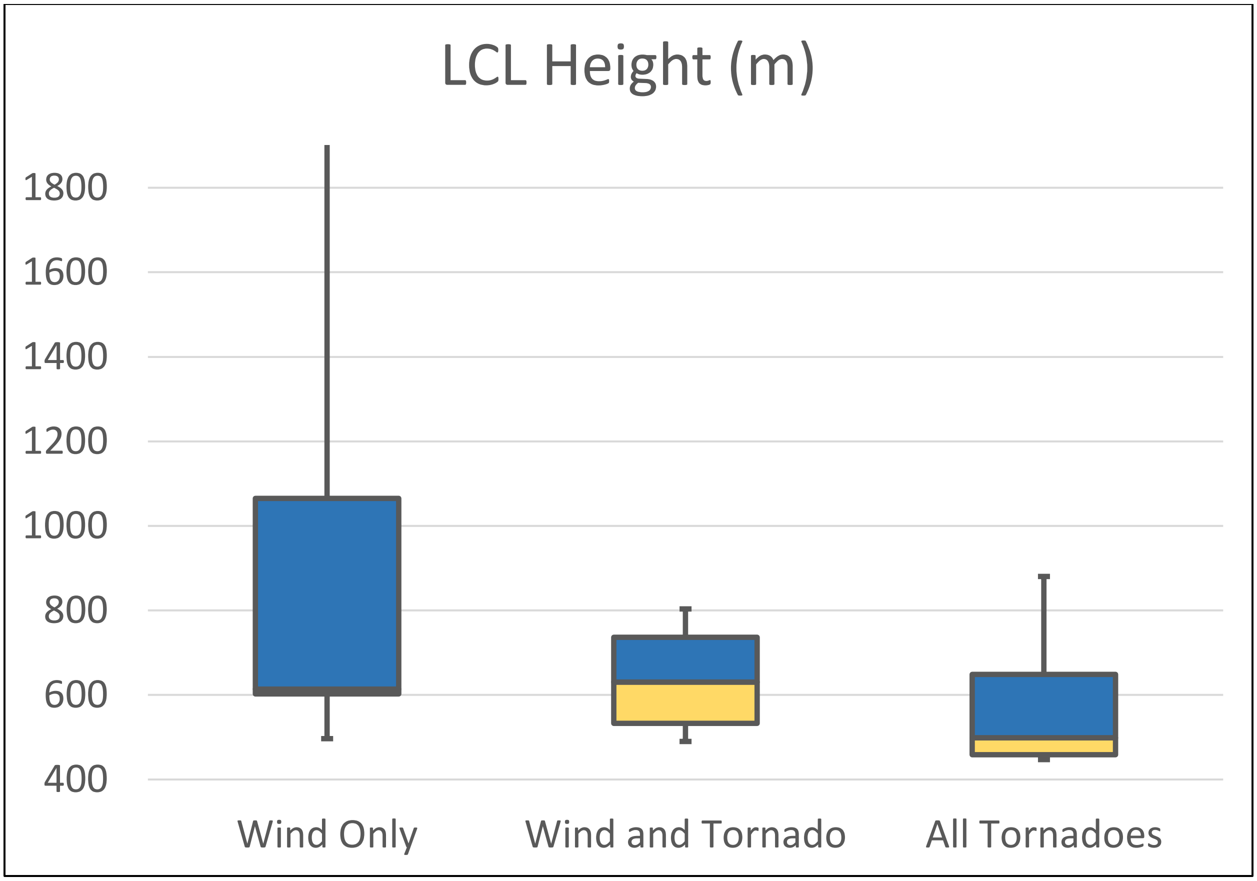

Figure 12: Box and whisker plots for cool-season LCL heights

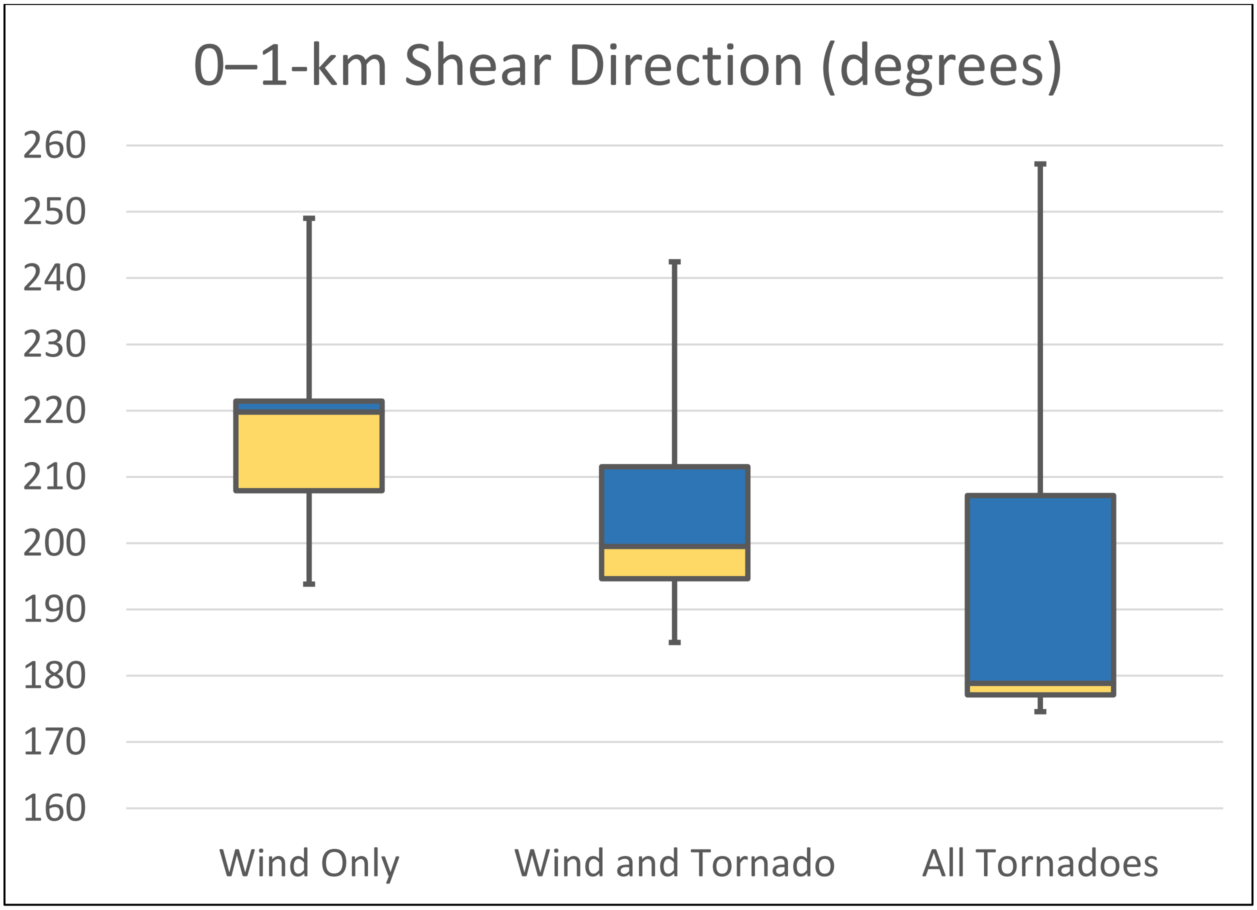

Figure 13: Box and whisker plots for cool-season S1DR

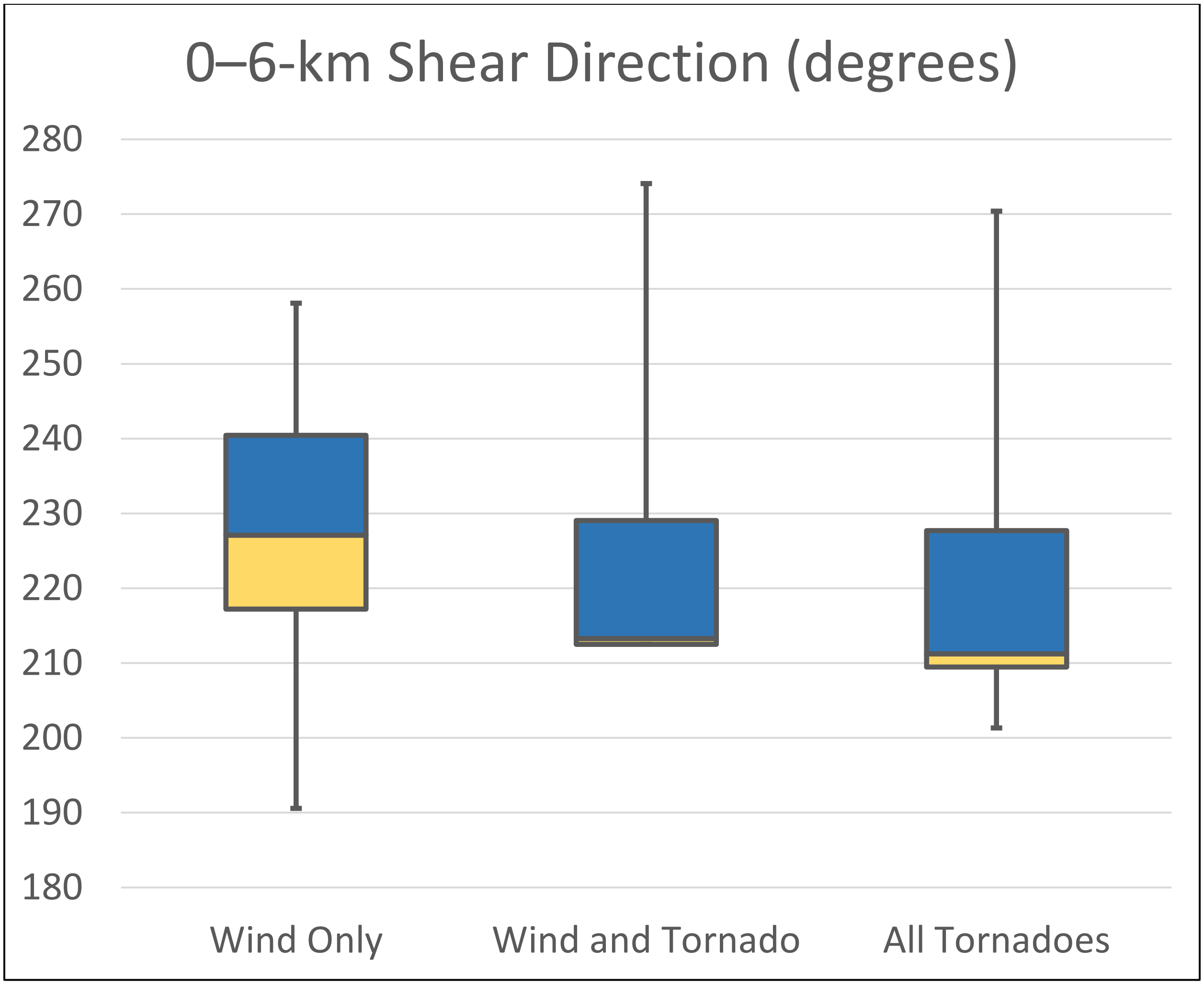

Figure 14: Box and whisker plots for cools-season S6DR

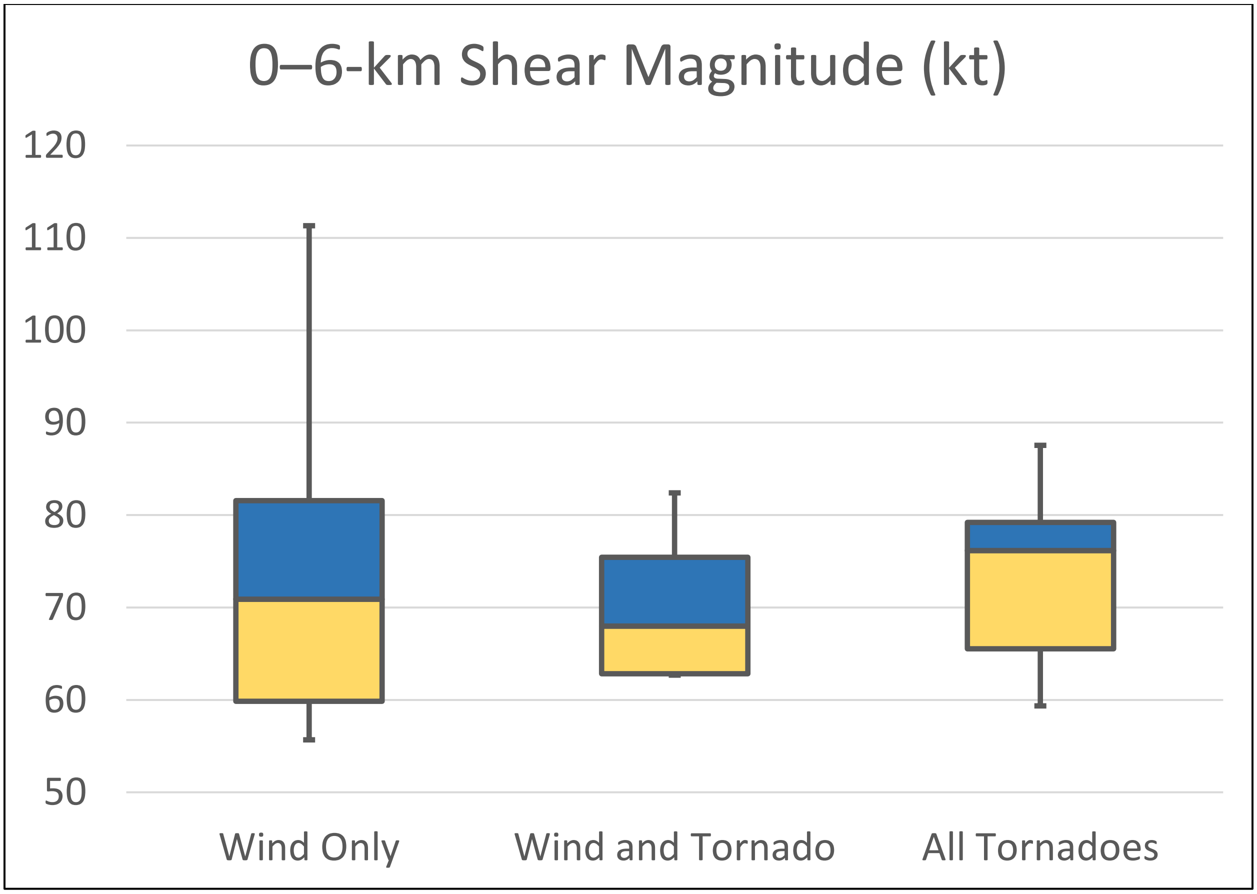

Figure 15: Box and whisker plots for cool-season S6MG

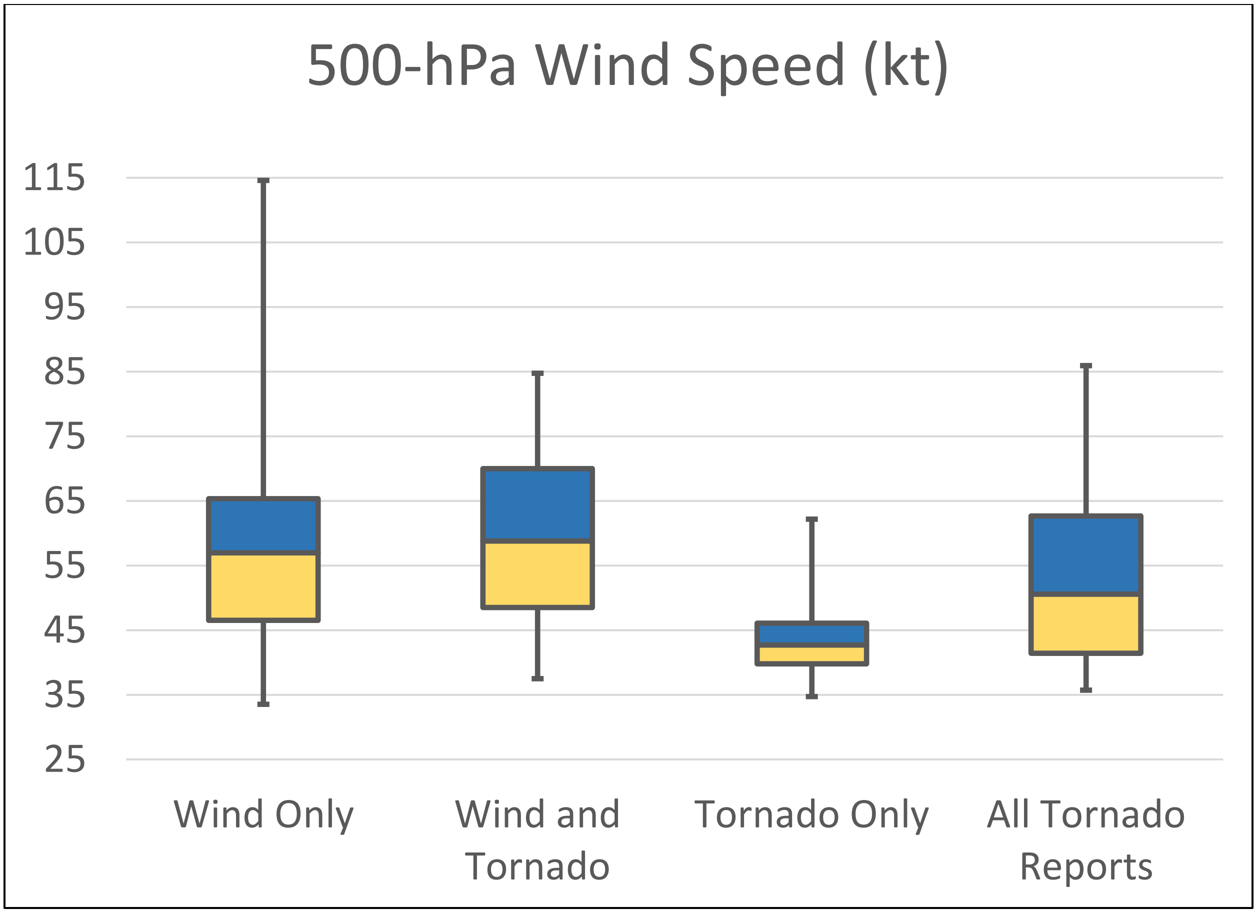

Figure 16: Box and whisker plots for 500-hPa wind speed for all events

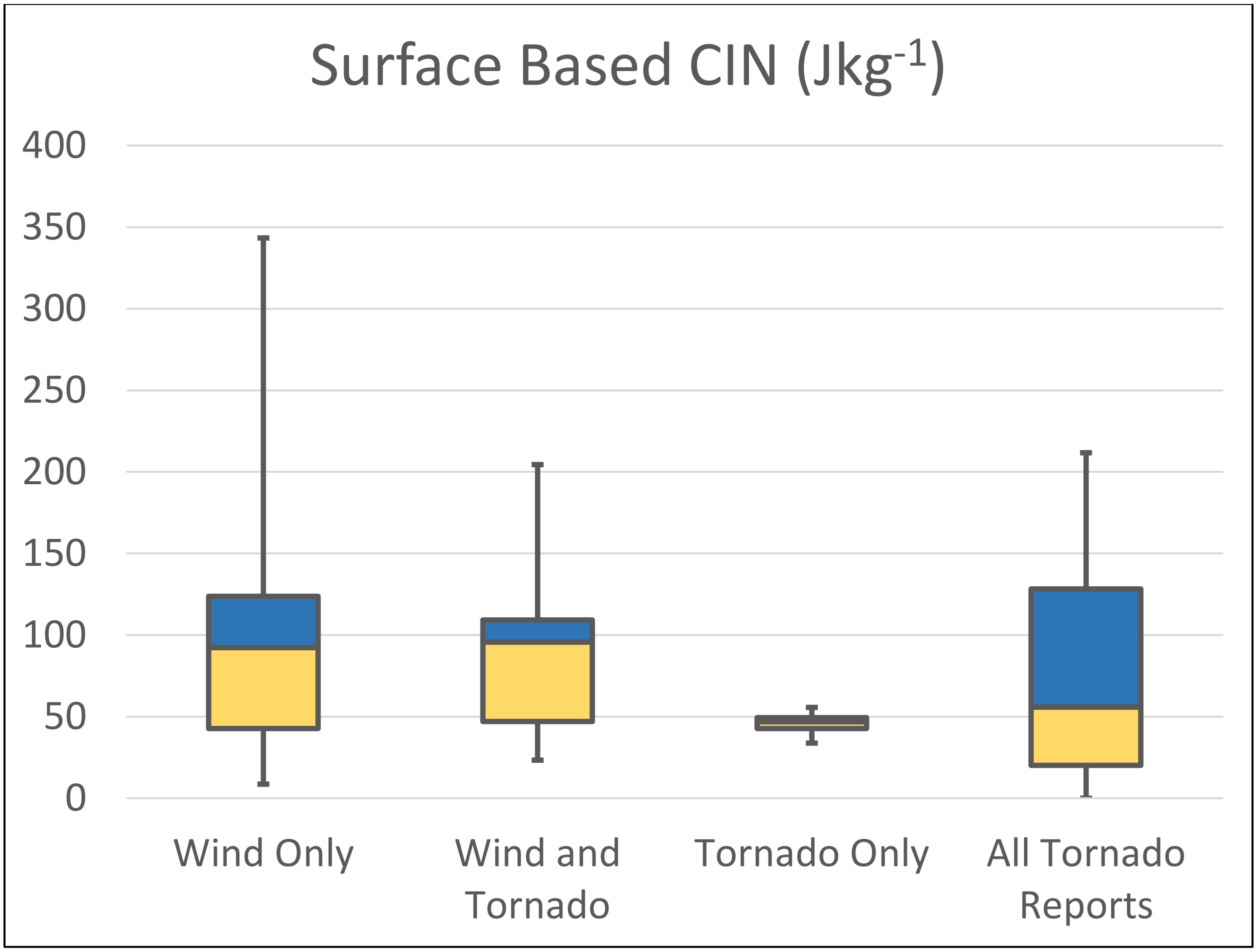

Figure 17: Box and whisker plots for SBCN for all events

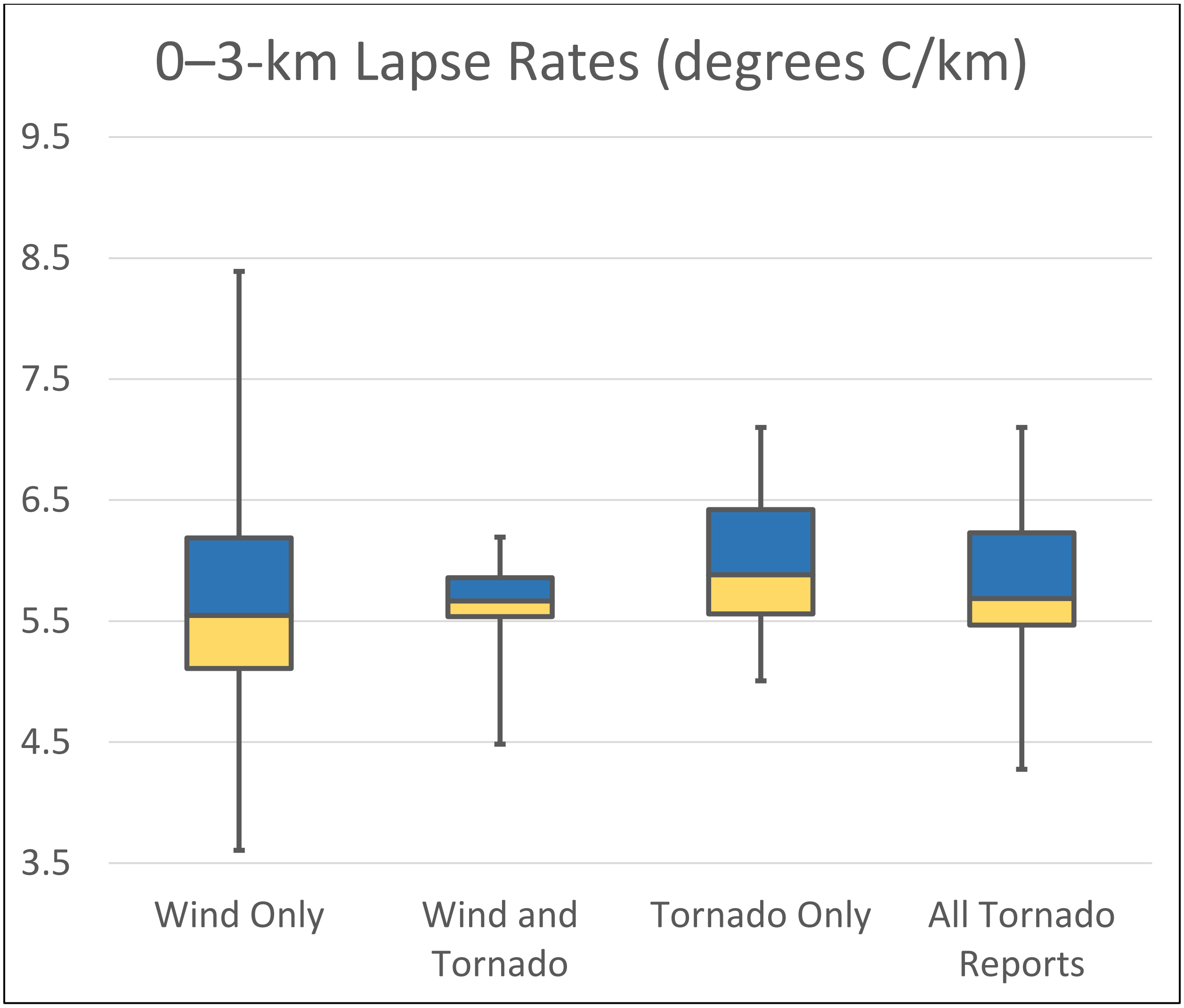

Figure 18: Box and whisker plots for low-level lapse rates for all events

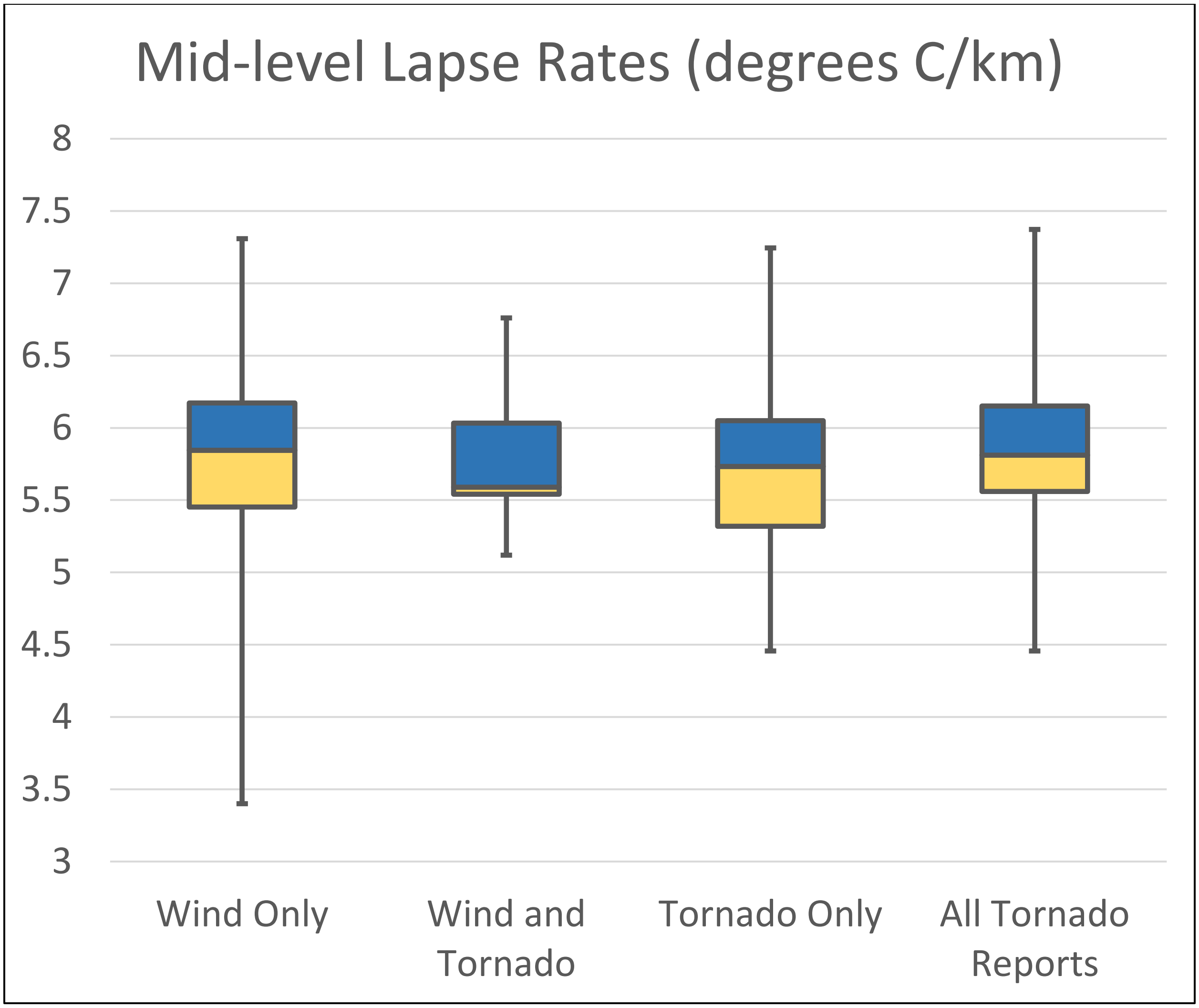

Figure 19: Box and whisker plots for mid-level lapse rates for all events

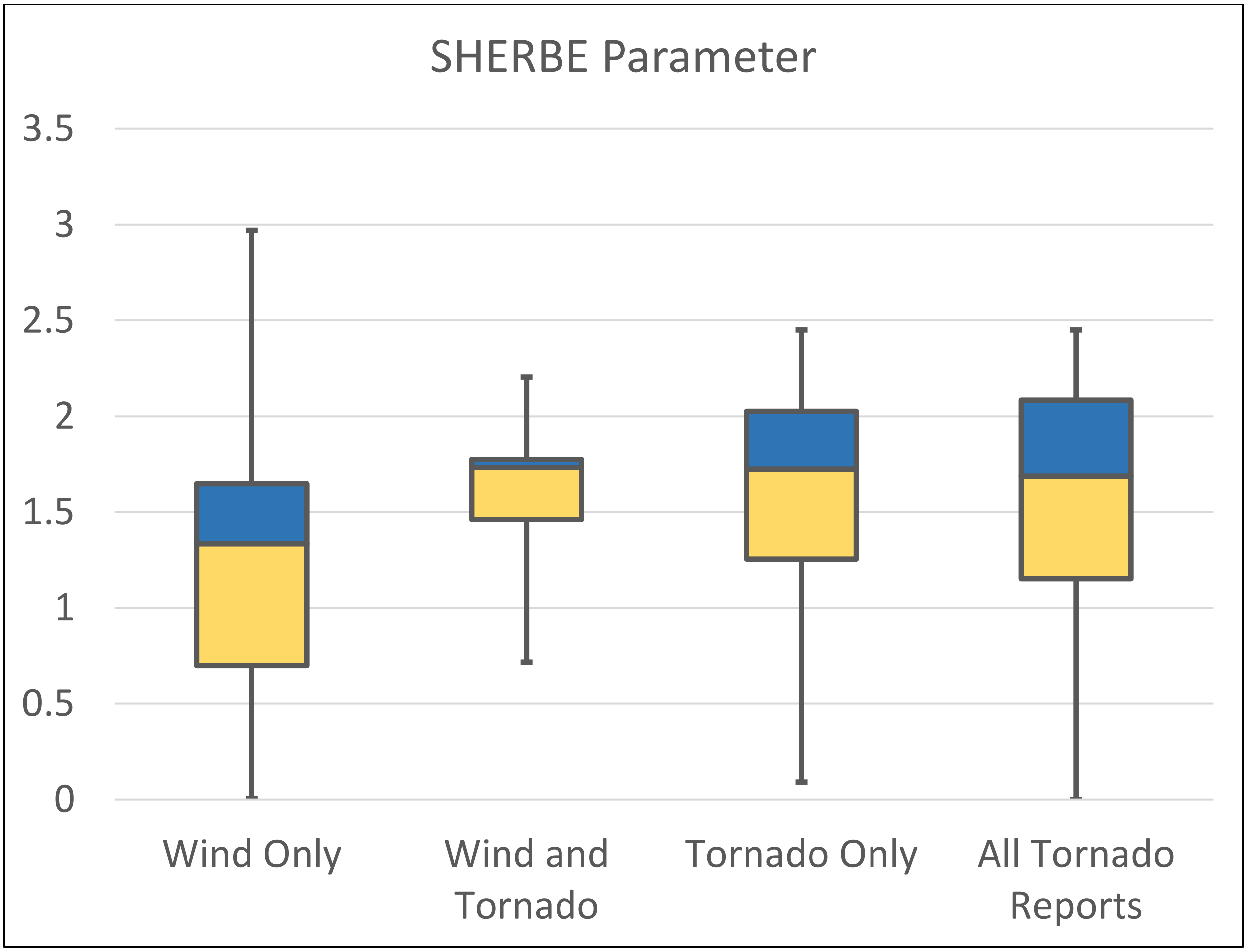

Figure 20: Box and whisker plots for the SHERBE parameter for all events