P1.19 RECONSTRUCTING THE FREQUENCY OF TORNADO OCCURRENCE IN THE CENTRAL UNITED STATES

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1. INTRODUCTION

The official record of tornado occurrences, published monthly in the National Oceanic and Atmospheric Administration (NOAA) periodical *Storm Data*, is based on a log of thunderstorm and tornado events collected by the NOAA Storm Prediction Center (SPC) and NOAA National Severe Storms Laboratory (NSSL). The annual frequency of occurrence of tornadoes of all intensity classes reported in this archive exhibits an almost linear increase from the beginning of the record through the 1990s, as shown in Fig. 1. Annual totals rise from an average of about 200 reports in 1950 to more than 1000 by the early 1990s. An even more dramatic rise in the number of severe thunderstorm reports is indicated by the archive (Fig. 2). On the other hand, the number of strong (F2 or F3 on the Fujita- or F-scale) to violent (F4- or F5-rated) tornadoes recorded in the storm database shows a marked decrease since the late 1970s.

Along with any natural variability, the official tornado record reflects changes in public awareness of tornadoes, improvements in detection capabilities and changes in the procedures used to classify storms (McNulty, 1979; Schaefer and Galway, 1982; Doswell and Burgess, 1988; Schaefer and Edwards, 1999; Doswell et al., 1999). These changes have led to biases in the storm log that confound efforts to quantify the true climatological frequency of tornado occurrence as well as any temporal variations. For example, the reduction in the recorded number of strong-to-violent tornadoes since the mid-1970s is likely a consequence, at least in part, of a systematic change in the procedures used to estimate tornado intensity (Brooks and Craven, 2002). Ratings for tornadoes prior to 1976 were assessed retrospectively using published newspaper articles and photographs whereas since the late 1970's most ratings have been made by local National Weather Service personnel via on-site surveys (Kelly et al., 1978; Schaefer and Edwards, 1999). The dramatic rise in severe thunderstorm reports shown in Fig. 2 coincides with the National Weather Service's establishment of requirements for the verification of severe weather warnings (Schaefer and Edwards, 1999). Schaefer and Livingston (2003), in fact, distinguish three periods of storm reporting and survey practices during the period of record covered by the SPC storm log: the "newspaper era" (1950 to 1976), the "state office era" (1977 to 1996) and the "NWS modernized era" (1996 to present). They acknowledge, however, that the change from one set of damage rating procedures to another occurred over the course of a few years and that many elements of modernization were in place before 1996.

Given the presence of bias in the observed tornado record, a number of studies have focused on estimating a truer mean annual frequency or climatological "risk" of tornadoes (e.g., Kelly et al., 1978; Schaefer et al., 1986, Concannon et al., 2000; Brooks and Doswell, 2001). However, using the official storm archive exclusively does not afford an evaluation of interannual variability in tornado occurrence or an assessment of low frequency variations. Whether it is likely that at least some of the changes implied by the official record of tornado occurrence are real remains essentially unknown. Consequently, it has been impossible to compare existing studies quantifying variations in numerous atmospheric variables to possible changes in tornado frequency. Evidence of climate change and variability in the U.S. during recent decades includes, for example, increases in surface specific humidity and dew point (Gaffen and Ross, 1999), a rise in surface temperature (e.g., Karl et al., 1993), increases in the frequency of heavy precipitation events (e.g., Kunkel et al., 2003) and a general moistening of the lower troposphere (Elliott and Angell, 1997). Since air parcel-based calculations used to quantify the potential for deep moist convection are sensitive to changes in near surface moisture conditions, it is possible that tornadic thunderstorm frequency may be sensitive to changes in near surface conditions.

To determine how useful the tornado log may be in climate and global change analysis and to shed light on the nature of low frequency variations in storm occurrence, a derived frequency of environments favorable to tornado development is compared in this poster to the rate of occurrence implied by the official tornado log. In this study, a reasonably comprehensive set of sounding-based severe weather parameters was used to assess the potential of differentiating tornadic from other types of storm environments. In addition, the goal was to calculate a time series of environments favorable to tornado development that is largely independent of the storm log and thus free of changes in bias that are associated with changes in the reporting practices of severe local storm events. Logistic regression is used to estimate the probably that a sounding is indicative of severe tornadic conditions given a particular configuration of parameter values. The ability of these regression models to discriminate between tornadic proximity soundings and other storm proximity soundings is quantified using skill scores appropriate for the assessment of the prediction of rare events.

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2. DATA

Observations of severe local storm events and twice daily radiosonde observations were used in the analysis. Storm event observations were obtained from the NOAA SPC storm event database and from the NOAA National Climatic Data Center's *Storm Data* database. The databases include observations of tornadoes beginning in 1950 and of thunderstorm winds and hail beginning in 1955.

Radiosonde observations for the period 1958 to 2000 were extracted from the *Radiosonde Data of North America* (RDNA) dataset produced by NOAA's Forecast System Lab and the National Climatic Data Center as well as the from the *Comprehensive Aerological Reference Data Set* (CARDS), formerly available from NCDC. Only raw sounding observations were obtained from CARDS, which has been replaced by the Integrated Global Radiosonde Archive (Durre et al., in press). Soundings from the CARDS data set were used to fill in missing soundings from the RDNA data set whenever possible. A number of sounding-based parameters were calculated using each twice daily (0000 and 1200 UTC) sounding from a sample of 25 stations located in the central United States, as shown in Fig. 3. Many of the commonly used sounding-based severe weather parameters were calculated as well as some traditional indexes no longer widely used in practice. A list of the calculated parameters is provided in Table 1.

During the 1958 to 2000 period, many radiosonde stations were subject to changes in location. In most cases the station move was minor and did not involve the assignment of a new identification number. However, in some cases, a new identifier was assigned and the former site was considered decommissioned. In general, however, in the sample of stations used in this study, decommissioned stations are linked to the coincident commissioning of a replacement station at a relatively nearby location. In that case, in order to form a continuous time series of radiosonde observations for the 1958 to 2000 study period, observations from the two "linked" stations were appended and treated as one time series. Any station moves, with or without a decommissioned station number are denoted by the presence of multiple station symbols in Fig. 3. Many of the station moves involving a station decommissioning occurred in the mid-1990s during the National Weather Service's modernization program.

3. METHODS

Each 0000 and 1200 UTC radiosonde observation was associated with one of six different categories of storm event type using the "proximity method." The proximity method (e.g., Darkow, 1969; Brooks et al., 1994) is simply one in which a storm event in the vicinity of a radiosonde station is used to classify a sounding when the event occurred within specified space and time proximity criteria. The assumption behind this method is that the sounding represents the environment in which the storm formed. In this study, for a sounding to be assigned to that storm event class, a storm event had to occur within 200 km of a radiosonde station and within the period starting two hours before and extending four hours after the 0000 or 1200 UTC observation time.

The number of tornado touchdowns of any magnitude reported within 200 km of the 25 radiosonde sites during the years 1981 to 2000 (roughly the post-newspaper era) is also shown in Fig. 3. Regional variation in the diurnal peak of tornado occurrence, also noted by previous investigators (e.g., Skaggs, 1969; Schaefer and Edwards, 1999), is reflected by differences in the percentage of touchdowns occurring within the 0000 or 1200 UTC proximity time interval across the study region, which is also shown. For example, on the High Plains, 70% or more of nearby tornadoes occur within the 0000 UTC time-interval, but this percentage is smaller in the Deep South and Southeast. On the other hand, the percentage of soundings that meet the 1200 UTC time criteria, though generally small at all locations, is higher in the Southeast than on the High Plains and northern stations.

Six storm event types were used to classify each sounding. The storm types are defined in Table 2. This storm classification is similar to those used by Mead (1997), Rasmussen and Blanchard (1998) and Craven (2001). In these classifications, an attempt is made to distinguish between types of thunderstorm environments, including supercell tornadic (ST) types (F2 or greater tornado) and non-tornadic supercell types (large hail but no significant tornado). In earlier studies only F2 or greater Fujita scale tornadoes were used to mark the tornadic supercell class since the parent thunderstorm of stronger tornadoes is likely to be a supercell. Using the F2 or greater class also avoids the potential misattribution of damage as having been caused by weak tornadoes rather than straight-line winds (Doswell and Burgess, 1988). While there is no guarantee that supercells likewise produce all large hail observations, Mead (1997) and others justify using such reports to classify non-tornadic supercells based on observational experience that suggests that there is a high probability of mid-level updraft rotation coincident with such reports. Note that the numbering in Table 2 is meant to imply a hierarchy of storm severity and, if more than one type of event occurs, the higher class ranking takes precedent.

Logistic regression was used to estimate the probability that a sounding is indicative of an environment in which one or more tornadoes could develop. Forward stepwise selection was used to select which of the parameters listed in Table 1 should be included in the logistic regression model. Models to estimate the probability that a sounding will be type 3 (associated with weak, presumably non supercell tornadoes – see Table 2) or type 6 (associated with significant, presumably supercell tornadoes) were developed. Calibration of the logistic regression models was performed using soundings from the mid-to-late 1990s, roughly the fully modernized era.

4. DISCUSSION AND CONCLUSIONS

A stratified comparison of the various sounding-based calculations was found to be generally in agreement with recent investigations into ST environments by, for example, Craven et al. (2002) and Rasmussen (2003). Specifically, relatively strong discriminators of ST environments include low (lifting condensation level) LCL heights and higher magnitudes of both boundary layer and deep layer wind shear. Although not calculated in other recent studies, mean wind speed through a deep layer of the atmosphere (0 to 6 km above ground level or AGL) also appears to be significantly higher in ST environments than in other storm environments. In addition, there is evidence that the magnitude of Convective Available Potential Energy (CAPE) is larger in soundings classified as significant severe (Type 4 or greater) than in the less severe storm proximity classes (Fig. 4). There is also evidence that the identification of differences between storm environments is complicated by regional and seasonal variation in sounding climatology. Moreover, such variability appears to be present even within a specific class of proximity sounding. Given that the frequency of storm occurrence also varies regionally and seasonally, some type of parameter standardization or regionalized analysis is probably necessary to ensure that apparent sounding differences are not artifacts of sampling variability.

Since sounding parameter calculations were made using all central U.S. soundings during the 1958 to 2000 period, it was possible to scale values according to the local station climatology. Because many of the calculated parameters are zero-bounded and positively skewed, the choice of scaling took the form of local cumulative probabilities calculated using the sample of soundings separately for each calendar. The evaluation of cumulative probability quantiles suggests that values of CAPE associated with ST environments are not only high relative to less severe storm environments, they are also high relative to other significant severe environments (see Figs. 4 and 5). The median CAPE value for ST soundings corresponds to about the 85th percentile of all non-zero values whereas median values for other significant severe classes correspond to roughly the 75th percentile. In addition, low Lifting Condensation Level heights that have recently been shown to be characteristic of ST soundings are also apparently characteristic of weak tornado soundings when values are scaled to the local climatology. In both weak and strong-to-violent tornado proximity soundings, the median LCL height corresponds to about the 20th percentile of all local values. Other types of storm proximity also have lower LCL heights, in general, than non storm soundings, but median values in non tornadic soundings correspond to only about the 30th percentile or higher. Likewise through scaling, the values of boundary layer shear magnitude in tornado soundings correspond to relatively large climatological values. In ST proximity soundings, the median 0 to 1 km AGL bulk shear magnitude is in the upper 10th percentile of all local values (Fig. 5). The median value for weak tornado soundings approaches the upper 20th percentile of all values, and is larger than in other severe non tornadic storm proximity soundings. On the other hand, the high climatological values of mid- and deep layer wind shear magnitude and storm relative helicity associated with ST soundings are not nearly as frequent in weak tornado soundings. Thus, the radiosonde record appears to provide some evidence that events classified as weak tornadoes occur more frequently in environments that are not conducive to supercell development.

Objective selection of parameters for inclusion in logistic regression models was conducted in the form of a forward stepwise selection procedure. Raw parameter values and their percentile counterparts were evaluated separately. When the modeled event was an ST sounding, the multivariate set of statistically significant parameters included CAPE, the height of the LCL, the magnitude of mid-level storm inflow in the form of either bulk shear or storm relative winds and mean wind speed through a deep layer (0 to 6 km AGL). These same factors were selected when the modeled event included weak tornado soundings. In that case, low level shear magnitude was also included in the set of predictors. Virtually identical sets of predictors were retained using the stepwise selection procedure on raw and percentile values. However, when weak tornado proximity soundings were included as the modeled event, logistic regression functions were found to be poorly calibrated, whether based on raw values or on cumulative percentiles. It appears that while weak tornado environments appear to have some factors in common with ST environments that may be useful in differentiating them from other types of storm environment, soundings alone are probably not sufficient to reconstruct the frequency of weak tornadoes. In contrast, logistic regression models of ST sounding events were found to be well calibrated and the discrimination of these soundings from others is in the excellent to outstanding category. The use of raw parameter values versus their percentile equivalents does not appear to impact the nature of ST sounding reconstruction. However, the use of percentile versions of sounding parameter values appears to result in better model calibration.

Based on separate stepwise selection procedures conducted on observations from each of six sub-regions in the central United States, the set of factors identified as characteristic of tornadic supercell environments appears to be reasonably consistent, with the possible exception of the High Plains and Gulf Coast areas. For radiosonde sites on the High Plains, the height of the LCL was not found to be statistically different in severe tornadic environments versus other severe non tornadic environments. For stations along the Gulf Coast, differences in the strength of storm relative winds among the various storm proximity soundings were less pronounced than in other sub-regions. As a result, the skill of estimating significant tornado sounding events using a region-wide logistic regression function was lower in these areas than in other areas of the central United States. Multivariate logistic regression models estimating the probability of ST sounding occurrence were used to reconstruct central United States strong to violent tornado occurrence during the period 1958 to 2000. Like the study by Brooks and Craven (2002), this reconstruction of tornado environments using the radiosonde record does not support the higher frequency of strong to violent tornadoes implied by the official storm log during the so-called newspaper era, roughly 1950 to 1976. In addition, there is evidence of a change in storm damage classification coincident with the National Weather Service's modernization during the 1990s. It appears that tornadoes that formed in environments conducive to supercells are somewhat less frequently classified as strong to violent (F2-rated or greater) in the 1990s relative to previous eras. On the other hand, since the hit rate (not shown) of predicted tornado supercell environments also increased during the 1990s, those storms that were classified as strong to violent may be more accurately classified. In any case, the usefulness of the tornado record for some purposes is likely even shorter than the 30 years suggested by Brooks and Craven (2002).

Rather than a general decline in ST frequency, the reconstruction suggests that strong to violent tornado environments were largely stationary throughout much of the period of record, but may have increased somewhat during the 1990s, as shown in Fig. 6. Since no obvious evidence of artificial discontinuities was found in annual mean values of radiosonde parameters or in the predicted probabilities of ST soundings, the recent increase in ST environments is at least not easily attributed to artificial discontinuities in the radiosonde record. Many of the thermodynamic parameters evaluated in this study, such as the LCL and CAPE, are quantified via air parcel based calculations, which, based on the analysis described above, may be less impacted by artificial changes in radiosondes than temperature and humidity values at mandatory levels. Moreover, while the choice of calibration period for logistic regression models appears to have some impact on the magnitude of bias in the reconstruction, it appears to have little impact on the relative change in bias from one reporting era to another. For these reasons and because there does not appear to be a shift in the diurnal timing of tornado occurrence, the general characteristics of the reconstruction appear to be reasonably robust.

An evaluation in which each sounding parameter was controlled separately in the reconstruction suggests that the increase in reconstructed ST environments during the 1990s is likely associated with changes in thermodynamic factors, CAPE and LCL. On the other hand, the brief period of low tornado frequency circa 1987 may be to be related to variations in kinematic factors, but this is not obvious from the logistic regression diagnostics. Nevertheless, the period around 1987 appears to have been a period of lower frequencies of high wind shear magnitude in the central United States.

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Table 1. List of parameters calculated for each 0000 and 1200 UTC sounding from the 25 central U.S. radiosonde sites.

Parameter	Units
LCL height (air parcel definition = lowest 500 m mean mixed layer)	m AGL
CAPE (air parcel definition = lowest 500 m mean mixed layer)	J kg^{-1}
Convective inhibition (air parcel definition = lowest 500 m mean mixed layer)	J kg^{-1}
0 to 3 km AGL lapse rate	°C km^{-1}
0 to 6 km AGL lapse rate	°C km^{-1}
1 to 3 km AGL lapse rate	°C km^{-1}
2 to 4 km AGL lapse rate	°C km^{-1}
3 to 6 km AGL lapse rate	°C km^{-1}
0 to 6 km AGL mean wind speed	m s^{-1}
0 to 1 km AGL wind shear (magnitude of vector difference)	s^{-1} ($ms^{-1}/\Delta z$)
0 to 3 km AGL wind shear (magnitude of vector difference)	s^{-1} ($ms^{-1}/\Delta z$)
0 to 6 km AGL wind shear (magnitude of vector difference)	s^{-1} ($ms^{-1}/\Delta z$)
0 to 1 km storm relative helicity (storm motion vector based on Bunkers et al., 2000)	m^2s^{-2}
0 to 3 km storm relative helicity (storm motion vector based on Bunkers et al., 2000)	m^2s^{-2}
0 to 4 km storm relative helicity (storm motion vector based on Bunkers et al., 2000)	m^2s^{-2}
Bulk Richardson Number	Dimensionless
Lifted Index (air parcel definition = lowest 500 m mean mixed layer)	°C
Showalter Index (air parcel definition = lowest 500 m mean mixed layer)	°C
K Index	Dimensionless
Severe Weather Threat Index	Dimensionless
Total totals Index	Dimensionless

Table 2. Severe local storm event classification criteria.

STORM TYPE	DEFINITION
0 - No event	No storm event reported within the space and time proximity window
1 - Thunderstorm	Small hail (up to 0.75 inches / 1.9 cm diameter or weak thunderstorm wind (up to 50 knts/128 ms^{-1})
2 - Strong Thunderstorm	Moderate hail (0.75 inches/1.9 cm to 2.00 inch/5.91 or moderate thunderstorm wind (50 knts/128 ms^{-1} to 65 knots/ 167 ms^{-1})
3 - Weak Tornado	F0- or F1-rated tornado, but no significant thunderstorm wind or hail (see types 4 & 5).
4 - Significant Thunderstorm Wind	Severe thunderstorm wind (greater than 65 knots/ 167 ms^{-1}) and no reported tornado
5 - Significant Hail (non-tornadic supercell)	Hail greater than 2.00 inches /5.1 cm diameter; no reported F2- or greater rated tornado
6 - Significant Tornado (tornadic supercell)	F2- or greater rated tornado

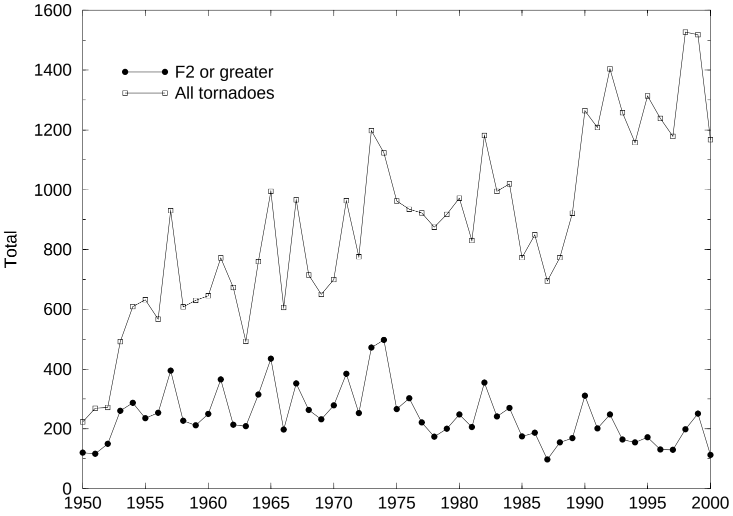


Figure 1. Annual total number of U.S. tornadoes from the SPC-NSSL storm event database.

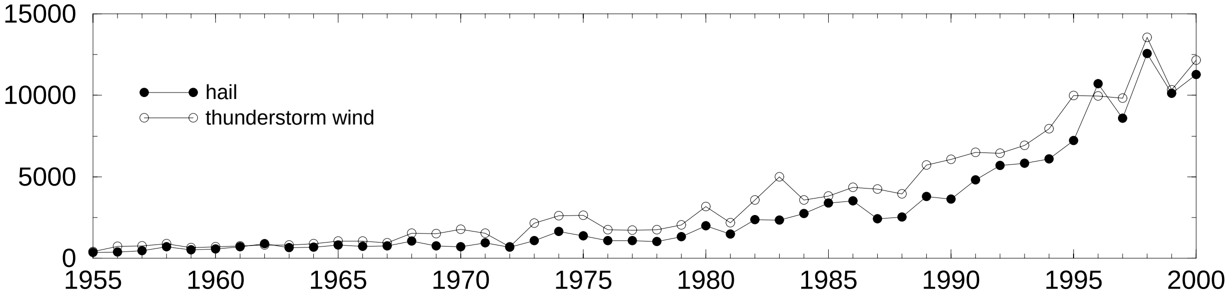


Figure 2. Total annual number of hail and thunderstorm wind reports from the SPC-NSSL/NCDC storm event database.

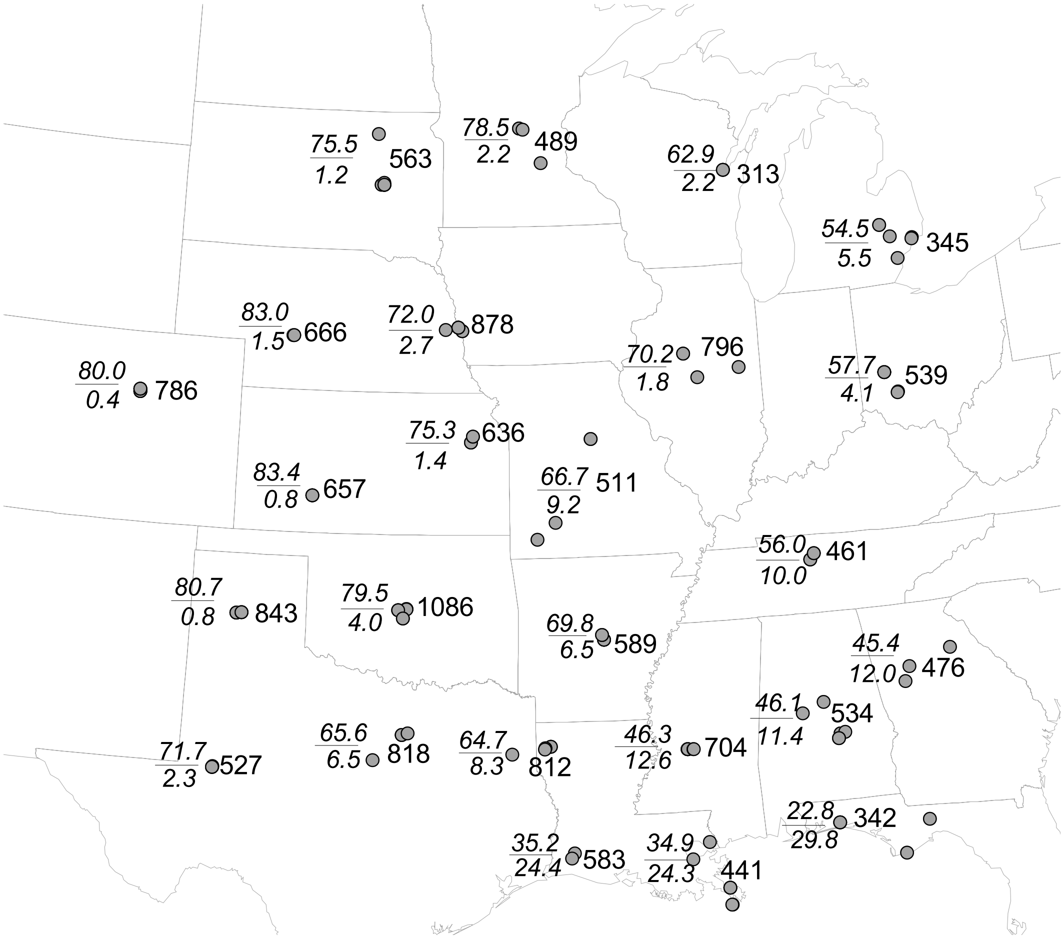


Figure 3. Total number of tornadoes (number to right of station symbols) occurring within 200 km of each radiosonde station from 1981 to 2000 and percentage of total that meet the 0000 UTC (top left) and 1200 UTC (bottom left) proximity criteria. The percentages for strong to violent tornadoes only (not shown) are similar.

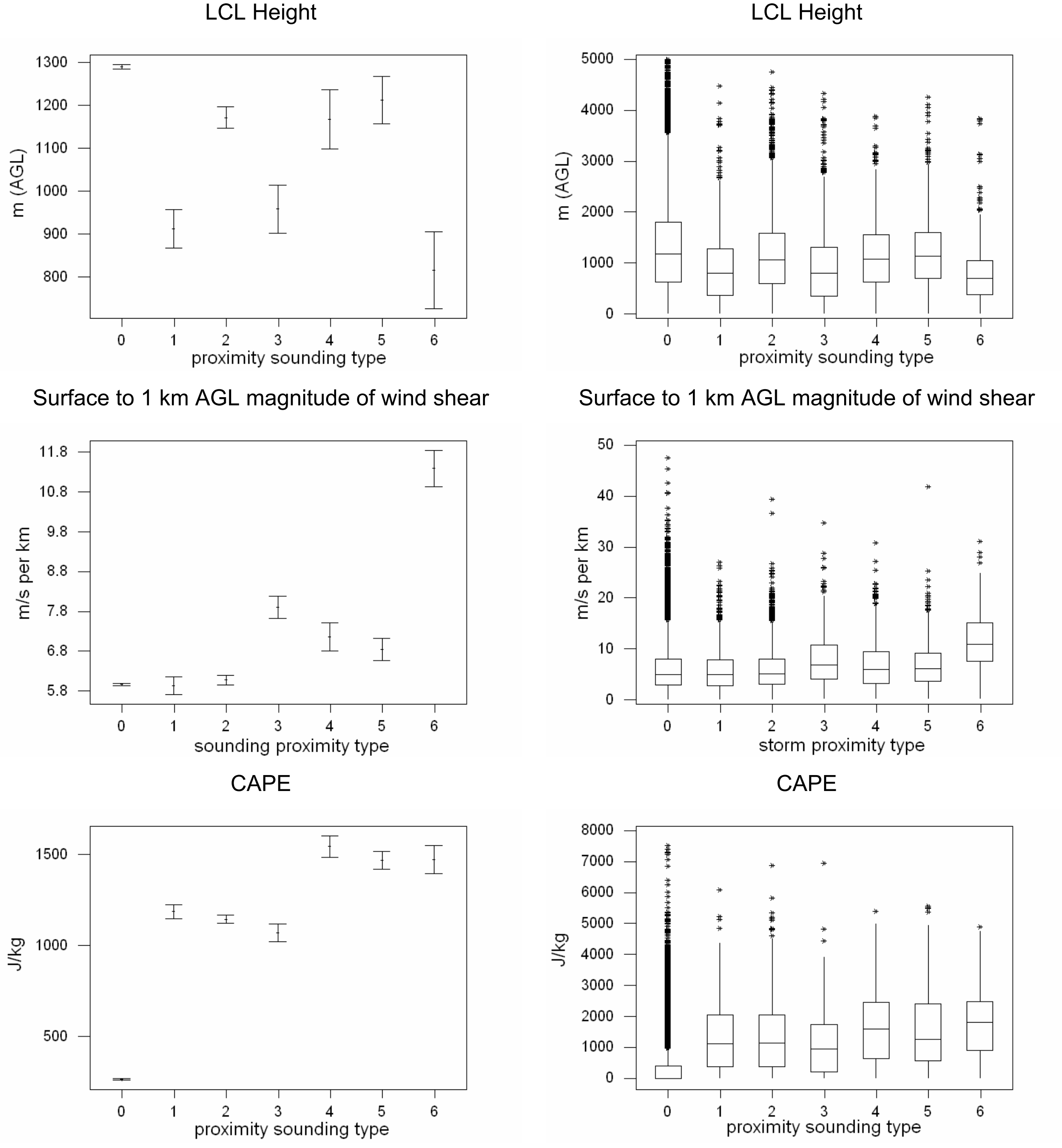
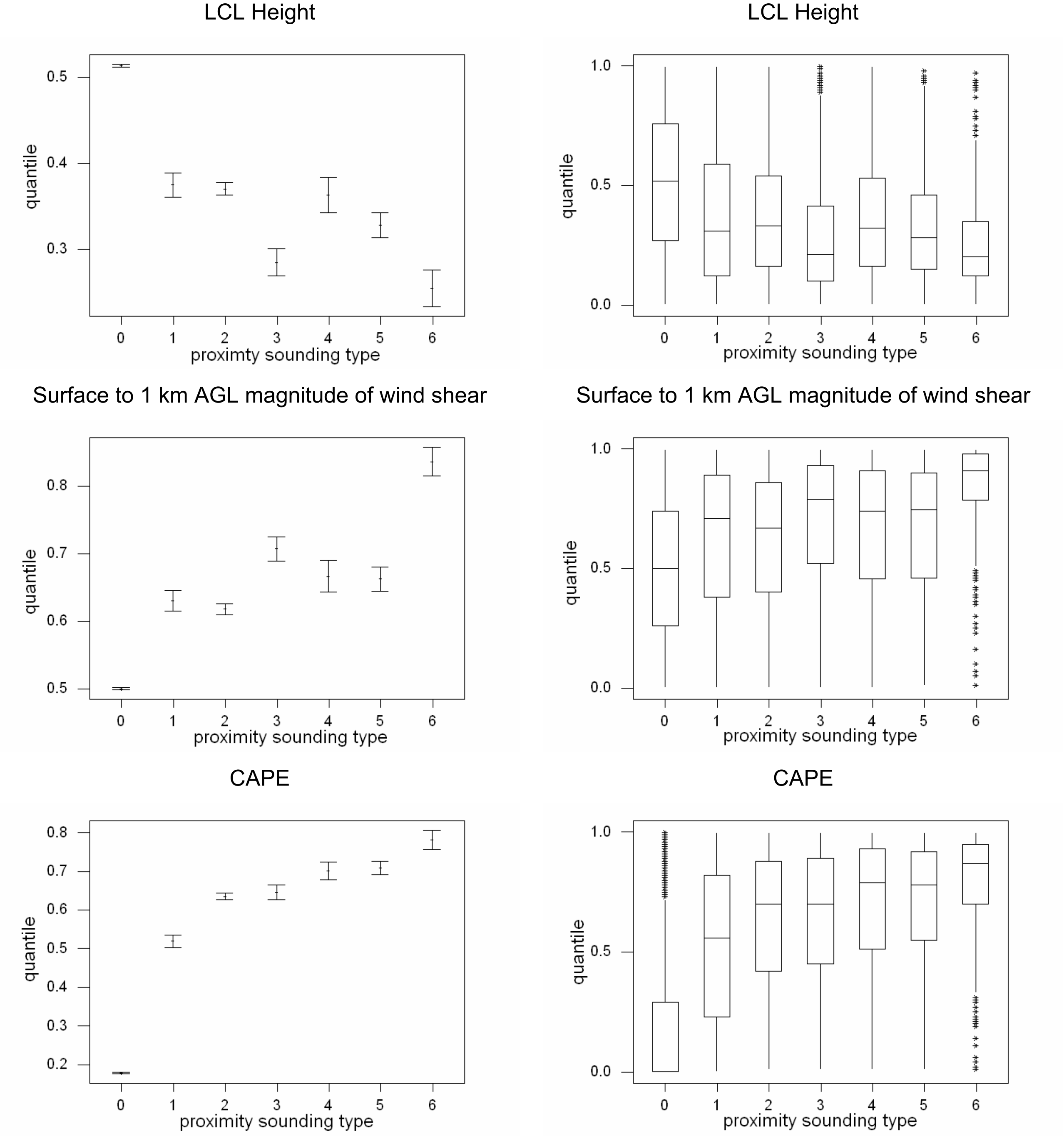


Figure 4. Mean and box plots for selected sounding parameters, stratified by the storm classification shown in Table 4.3. Base period for observations is 1990 to 2000.


LCL Height

LCL Height

Surface to 1 km AGL magnitude of wind shear

Surface to 1 km AGL magnitude of wind shear

CAPE

CAPE

Figure 5. As in Fig. 4 except sounding parameters are expressed according to station- and monthly-specific cumulative probability quantiles.

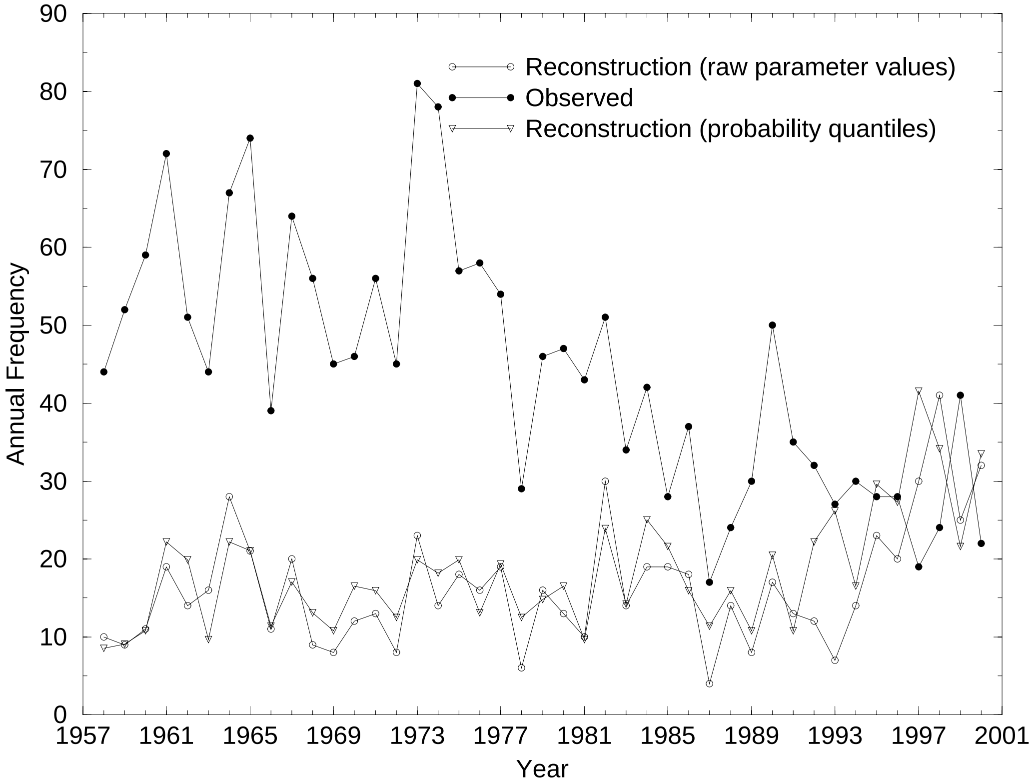


Figure 6. Estimated and observed number of significant tornado soundings.