16B.3 Measured severe wind gust climatology of thunderstorms for the contiguous United States, 2003-2009

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1. Introduction

Reporting inconsistencies within the severe thunderstorm database (Schaefer and Edwards 1999, Brooks et al. 2003) have made climatological interpretation of severe convective wind reports (defined as estimated or measured thunderstorm gusts $\geq$ 50 kt, or thunderstorm produced wind damage) less than ideal. A host of factors that at times greatly vary, such as population biases, density of potential structures to damage, and variability in reporting standards (Weiss et al. 2002), inherently influence the makeup of the severe wind report database. Moreover, past studies have often not differentiated between estimated or measured wind gusts, nor provided distinction between severe gust reports and wind damage reports. Much of the subjectivity and inconsistency can be alleviated if a dataset is compromised of data drawn specifically from a network of surface observing stations that provide measured severe convective wind gusts, thereby lending considerable credibility to the subsequent dataset (Weiss et al. 2002). Many studies have focused their efforts on understanding the climatological frequency of severe wind reports and the synoptic and mesoscale environments associated with these events (i.e., Johns and Hirt 1987, Wakimoto 1985). While not focused solely on measured severe convective wind gusts, these studies provide important insight into the frequency and patterns of severe thunderstorms historically responsible for producing severe wind reports.

The goal of this work is to develop a dataset of measured severe convective wind gusts that were associated with thunderstorms over the contiguous United States. Using this approach, the spatial and temporal frequency distributions of measured wind gusts and associated environmental parameters can be analyzed with respect to different atmospheric regimes, and additionally can be compared to estimated gust and wind damage reports. Finally, Oklahoma Mesonet observations are compared to Oklahoma ASOS/AWOS instrumentation to determine the frequency that each instrumented network observes and records severe wind events.

2. Data and methodology

A surface observation database at the Storm Prediction Center (SPC) contains archived CONUS ASOS/AWOS (1730) and Oklahoma Mesonet observations (130) (Fig. 1) that can be used to extract wind gusts $\geq$ 50 kt (25 m s^{-1}) from 2003 to 2009. Wind gust observations were recorded using the highest two second wind speed if the wind gust was at least 10 knots greater than the two minute average speed (NOAA 1998). If more than one severe wind gust observation occurred at the same station in close time proximity, the data were filtered for the hourly maximum gust and first observed gust, respectively. An extensive manual quality control process was employed to identify gusts that were associated with thunderstorms, rather than from non-convective high wind events and instrumentation malfunctions. To accomplish this, each candidate severe wind observation was first compared to archived gridded lightning data from the National Lightning Detection Network. The observation was remapped onto a 40 km grid, and using the gridded 1 hour lightning data, the observation was determined to be associated with a thunderstorm (a "hit") if lightning occurred during the observation hour within a 3x3 grid box array centered on the reporting station. Each "hit" observation was further scrutinized and underwent additional quality control by comparison with radar reflectivity data. Each observation in the measured dataset was then manually examined using archived University Corporation of Atmospheric Research 2 km base reflectivity radar mosaic data (UCAR 2010). A threshold of 35 dbZ was subjectively chosen to determine if the radar echo present was associated with sufficiently

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strong convection to produce a severe convective wind gust. Every "hit" observation was examined on an individual basis, taking into account factors such as distance from radar echoes, possible terrain effects (i.e. elevation), association with low topped convective squall lines with little if any lightning, and wake lows resultant from thunderstorms, among other situational characteristics. In a few cases, weak reflectivity characteristic of showers in post frontal regimes were noted and these cases were not included. Archived WSR-88D Level II data were then utilized to examine these previously listed situations in which higher reflectivity from the UCAR mosaic was noted to be more distant (i.e. 25-50 mi) from the observing site. Level II data were also used when mosaic radar data were missing, which occurred more frequently over the eastern and western United States prior to late 2008. Lastly, wind gust observations from landfalling tropical cyclones were omitted.

a. Data inconsistencies

It should be stated that several important caveats exist with this dataset. First, it was found that not every ASOS/AWOS site was included in the data archive at the SPC, the reason for which is currently unknown. This resulted in few observing sites near the Canadian border and west of the Intermountain Region (see Fig. 1). Also, an indeterminate number of observing stations may have been added to the existing network or discontinued during the study, resulting in some observation stations having unequal periods of operation that could affect the number of severe wind gusts per station. Using Oklahoma Mesonet sites to investigate this occurrence, this was found to affect only a few Oklahoma Mesonet sites, and may have only slightly influenced the severe wind gust counts for the few Mesonet stations in question. However, due to the very large number of the ASOS/AWOS stations, an attempt to reconcile the counts of stations that may have been added or discontinued during the seven year period was not attempted. Additionally, data were sporadically interrupted and not archived for many locations due to equipment failures. For example, the Elkhart, KS (KEHA) station is located in southwest Kansas centered between observing stations with high frequencies of severe convective gusts. Yet, the archive of KEHA data contained no gusts $\geq$ 50 kt that were not due to instrument malfunction. Other similar situations were examined and determined to be the result of either station malfunction or a lack of archived data. These two factors raise questions about the amount of operating time that certain stations may have had during the seven year period. However, it is assumed that this is a random occurrence and was not more frequent in any part of the domain.

b. Smoothing

A kernel density estimation tool using ESRI ArcGIS ArcMap Spatial Analyst extension software was utilized to examine weighted counts of severe gust occurrence by stations that observed at least 1 severe gust on the same 40 km horizontal grid with a 500 km radius of influence. The kernel estimate chosen is based on the quadratic kernel function described in Silverman (1986, p. 76, equation 4.5), though it is acknowledged that it may be appropriate to examine other smoothing criteria. For a more thorough discussion on the subjectivity of proper spatial smoothing, please refer to Brooks et al. (2003).

c. Storm environment

The resultant quality-controlled measured gust database was paired with available Rapid Update Cycle (RUC) model (Benjamin et al. 2004) based SPC archived hourly mesoanalysis data (Bothwell et al. 2002) to assess estimated near-storm environments associated with severe wind gusts (e.g., Schneider and Dean 2008). The RUC analyses at the lowest model level are used as a first-guess field in an objective analysis of the hourly surface observations, which is blended with the RUC analyses above the ground to create hourly three-dimensional environmental analyses on a 40 km grid. No other modification of the model profiles is done. At each grid point, the vertical profiles are used to calculate dozens of sounding-derived parameters.

3. Results

During the 2003-2009 period, the ASOS/AWOS and Oklahoma Mesonet observation networks recorded 2612 severe convective wind gust observations, yielding an average of 373 observations per year. The vast majority of these observations (2336 or 89%) were sampled by ASOS/AWOS instrumentation. This accounts for only about 3% of the annual wind reports (all gusts and damage) in the severe wind report database for the same seven year period. Although other measured severe wind gusts are logged in the severe wind report database (e.g., state and regional mesonets such as MesoWest, etc.), measured wind gusts account for a small fraction of severe wind reports logged in the severe wind database. This is largely due to the relatively low coverage of surface observing stations relative to thunderstorm coverage, but it also may be related to damage reported to trees and some structures such as power lines that occur with wind gusts < 50 kt.

The severe wind gust count distribution by station (Fig. 2) shows a maximum corridor for measured severe convective wind gust occurrence across the southern and central high Plains region from western portions of Texas and eastern New Mexico northward into western Nebraska and eastern Colorado. The top ten stations with the largest number of measured severe convective gusts during the seven year period (Table 1) occurred in this corridor across the high Plains. A large majority of the measured gusts in this area occurred during the March through July period. A secondary maximum corridor extends from South Dakota and Nebraska east southeastward to the southern Great Lakes states. A large portion of these measured gusts are recorded during the summer months and show a similar orientation to the Johns and Hirt (1987) northwest flow pattern, suggestive that organized MCS activity is responsible for a number of these reports. Severe wind gusts from thunderstorms were observed much less frequently in the Northeast, Southeast, and areas generally west of the Continental Divide, although the latter may be at least be partially impacted by the minimal number of reporting sites in the database west of the Intermountain region.

A comparison between the Oklahoma ASOS/AWOS and Oklahoma Mesonet networks was conducted to determine if the relative frequency of measured severe gusts is a function of observation density. Oklahoma had 46 ASOS/AWOS stations that recorded observations during this period whereas the Oklahoma Mesonet network had 120 stations (Fig. 3). Unsurprisingly, this led to more observations being sampled by the Oklahoma Mesonet than by ASOS/AWOS stations in Oklahoma. The two networks' observation frequency was further examined by convective day events, defined as the occurrence of at least one measured gust between 12 UTC one day and 1159 UTC the following day. ASOS/AWOS and Oklahoma Mesonet sampled 89 and 146 severe convective days, respectively. A majority of the days (57 out of 89 or 64%) in which a severe wind gust was observed by the ASOS/AWOS network, the Oklahoma Mesonet also recorded a severe gust. This resulted in 178 combined days in which a severe convective wind gust was recorded using both observing systems.

To approximate the contribution of this study's measured severe gust dataset to documented measured severe wind reports from Storm Data, the datasets were compared for an identical list of stations. This was done to estimate the number of quality controlled observations that were included as measured severe thunderstorm wind gusts in the severe wind report database. A matching procedure incorporating time, space, and magnitude was performed using the following criteria: ± 3 kt for wind magnitude, ± 0.1° (9.0 km) for latitude and longitude and ± 5 minutes. This yielded 2,217 matches or nearly 85% of the measured wind gusts in Storm Data corresponded to wind gusts in the quality controlled dataset. This suggests that approximately 15% of the measured thunderstorm wind gusts at ASOS/AWOS stations in Storm Data may be questionable concerning their association with thunderstorms. This is partly the result of the stringent matching procedure that in some cases did not capture listed station measured gusts and other phenomena (i.e. wake lows) associated with thunderstorms that were subjectively deemed "non-thunderstorm" in nature by National Weather Service personnel. Specifically examining ASOS/AWOS and Oklahoma Mesonet observations separately, around 85% of observations from each network were also present in the severe wind report database, reflecting the overall percentage.

3a. Smoothing

A spatial smoother was employed to provide a preliminary climatological estimate of measured severe wind gust distributions to account for the finite sampling of measured severe wind gust events across the contiguous U.S. A kernel density estimation plot of ASOS/AWOS stations that observed one or more severe gusts and weighted by wind gust count per station is shown in Fig. 4. An overall estimated trend of greater counts of severe wind gusts are evident over the Plains with a secondary higher frequency axis extending eastward from the central Plains to the middle Mississippi Valley. A notable minimum corridor encompasses the area east of the southern Plains and south of the Ohio Valley across the northern Gulf Coast states. Lower frequency is also noted generally east of the Appalachians from the Carolinas into New England and west of the Continental Divide in the Interior West. It is important to note that the lower frequency over the eastern U.S. is *not* the result of differing station spacing in the high Plains versus the East.

Using the same kernel density estimate constraints applied to the total severe wind report database (estimated gusts, measured gusts, and wind damage) during the same seven year period, a starkly different spatial distribution of severe wind reports is evident (Fig. 5). Compared to Fig. 4, the maximum corridor for the severe wind report estimate is displaced east of the Plains and is located over the Ohio and Tennessee Valleys, Appalachians, and adjacent Carolina and Virginia Piedmont. A much lower estimate encompasses the high Plains and areas west of the Continental Divide, thus a greater contribution to the total severe wind reports originates from measured severe gusts in the high Plains and Intermountain West, with substantially less contribution from measured gusts centered over the Appalachians. This is likely the partial result of a higher frequency of reported thunderstorm wind damage over the eastern one-third of the CONUS. There are non-meteorological factors that likely play a role in these results, including higher population density (Fig. 6) and associated societal infrastructure (more structures, power lines, etc.), and tree biomass density (Fig. 7). The maximum in severe wind report density in the areas around central and southern Appalachian mountain states is located within much higher tree biomass density and population density; whereas both tree biomass density and population density are substantially less over the high Plains region.

3b. Storm environment

Little difference was found to exist in near-storm environmental parameter values (i.e. 100 mb mixed layer CAPE, 0-3 km lapse rate, 0-6 km bulk wind difference, precipitable water, etc.) between subsets of the measured wind gust dataset versus a larger subset of total severe wind reports using similar time and space constraints. One example involved filtering the measured dataset for observations from the southeast United States (i.e. AR, LA, AL, TN, KY, MS, GA, FL, SC, NC, VA) that occurred in a weak 0-6 km bulk wind difference environment (i.e. 20 kt or less) during the summer June through August period (Fig. 8). This particular comparison yielded 87 measured severe wind gusts, whereas using the same wind environment constraints for the total severe wind report database resulted in 8930 wind reports occurring in weak shear situations. Due to little meaningful environmental disparity existing between the measured dataset versus the larger severe wind report database for a variety of regimes, extracting observed severe gust counts and severe wind report counts between the two datasets became the primary focus. A regime characterized as supporting well-organized storms with environment constraints of 100 mb mixed layer CAPE values $\geq$ 1000 J kg^{-1} and 0-6 km bulk wind difference $\geq$ 40 kt yielded 393 measured wind gust observations. Most of these gusts (86%) occurred during the April through July time frame centered over the Plains and middle Mississippi Valley (Fig. 9). These observations also contained a disproportionate number of “significant” gusts $\geq$ 65 kt (Hales 1988) compared to the rest of the measured dataset, with around 10% of these observations considered significant. Conversely, southeast United States weak deep layer shear thunderstorm environments during the June-August period only had about 3% of their measured severe gust observations classified as a significant gust.

4. Summary and future work

The purpose of this work is to develop a dataset of measured severe wind gusts that are associated with thunderstorms over the contiguous United States. This was done by examining data from similar instrumented observing networks (ASOS, AWOS, Oklahoma Mesonet) that provide a consistent and reliable source of measured severe wind gust reports, and then comparing the data to the total severe wind report database that contains inherent subjectivity, biases, and limitations. The measured severe wind observations were subjected to multiple quality control procedures that filtered candidate severe wind observations using lightning data, radar reflectivity, and manual examination of coded observation data.

Analysis of measured severe gust frequency shows a primary corridor over the southern and central Plains states with a secondary axis extending eastward from the central Plains across the middle Mississippi Valley. A much lower observed frequency of measured severe wind gusts from thunderstorms is evident in the southeastern United States northward along the Atlantic Coast to New England. A precipitous drop in frequency is also noted for sites west of the Continental Divide compared to the high Plains region, although few stations west of the Intermountain Region may impact these results. Little overall difference in basic convective environments is noted between subsets of the measured wind dataset compared to the larger severe wind report database. Observations that occurred in environments typically described as supporting organized severe storms were most prevalent over the Plains states and the Midwest similar to the overall distribution of measured severe wind gust observations.

The spatial distribution of severe wind gust observations beckons further development of an explicitly measured severe wind gust dataset. Future work includes continued expansion of the database on a yearly basis with the goal of providing increased support for severe wind forecasting. Due to a current lack of a robust sample of measured severe wind gust events and associated convective mode data, a more detailed examination of level II radar data is needed. These data can then be merged with archive SPC mesoanalysis data to form a multi-faceted database similar to other verification development databases being constructed at the SPC currently.

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References

Benjamin, S. G., and Coauthors, 2004: An hourly assimilation-forecast cycle: The RUC. *Mon. Wea. Rev.*, **32**, 495-518.

Blackard, J.A., and Coauthors, 2008: Mapping U.S. forest biomass using nationwide forest inventory data and moderate resolution information. [Available online at http://fsgeodata.fs.fed.us/rastergateway/biomass/.]

Bothwell, P. D., J. A. Hart, and R. L. Thompson, 2002: An integrated three-dimensional objective analysis scheme in use at the Storm Prediction Center. Preprints, *21st Conf. on Severe Local Storms*, San Antonio, TX, Amer. Meteor. Soc., J117-J120.

Brooks, H. E., C. A. Doswell III, and M. P. Kay, 2003: Climatological estimates for local daily tornado probability for the United States. *Wea. Forecasting*, **18**, 626-640.

Hales, J. E. Jr., 1988: Improving the watch/warning program through use of significant event data. Preprints, *15th Conf. on Severe Local Storms*, Baltimore, MD, Amer. Meteor. Soc., 165-168.

Johns, R. H., and W. D. Hirt, 1987: Derechos: Widespread convectively induced windstorms. *Wea. Forecasting*, **2**, 32-49.

NOAA, cited 1998: ASOS User's Guide, 61 pp. [Available online at http://www.nws.noaa.gov/asos/aum-toc.pdf].

Schaefer, J. T., and R. Edwards, 1999: The SPC tornado/severe thunderstorm database. Preprints, *11th Conf. on Applied Climatology*, Dallas, TX, Amer. Meteor. Soc.,215–220.

Schneider, R. S., and A. R. Dean, 2008: A comprehensive 5-year severe storm environment climatology for the continental United States. Preprints, *24th Conf. Severe Local Storms*, Savannah GA., Amer. Meteor. Soc. [CD-ROM].

Seirup, L. and G. Yetman, cited 2010: U.S. Census Grids (Summary File 1), 2000. [Available online at http://sedac.ciesin.columbia.edu/usgrid/.]

Silverman, B.W., 1986. Density estimation for statistics and data analysis. New York: Chapman and Hall.

UCAR, cited 2010: Image archive, meteorological case selection kit. [Available online at http://www.mmm.ucar.edu/imagearchive/].

Wakimoto, R. M., 1985: Forecasting dry microburst activity over the High Plains. *Mon. Wea. Rev.*, **113**, 1131-1143.

Weiss, S. J., J. A. Hart, and P. R. Janish, 2002: An examination of severe thunderstorm wind report climatology: 1970-1999. Preprints, *21st Conf. on Severe Local Storms*, San Antonio, TX, Amer. Meteor. Soc., 446-449.

Rank	Measured Gusts	Station	Location
1	17	KITR	Burlington, CO
2	16	KLBB	Lubbock, TX
3	14	KLBL	Liberal, KS
4	13	KGDP	Guadalupe Pass, TX
	13	KLAA	Lamar, CO
	13	KHLC	Hill City, KS
7	12	KDDC	Dodge City, KS
	12	KLHX	La Junta, CO
	12	KSPS	Wichita Falls, TX
10	11	K2WX	Buffalo, SD
	11	KGLD	Goodland, KS
	11	KCDS	Childress, TX
	11	KMCK	McCook, NE
	11	KGRI	Grand Island, NE

Table 1. Most measured gusts per station for ASOS/AWOS and Oklahoma Mesonet, 2003-2009.

Figure 1. Locations of all ASOS/AWOS and Oklahoma Mesonet stations for which data were archived and successfully retrieved across the contiguous United States.

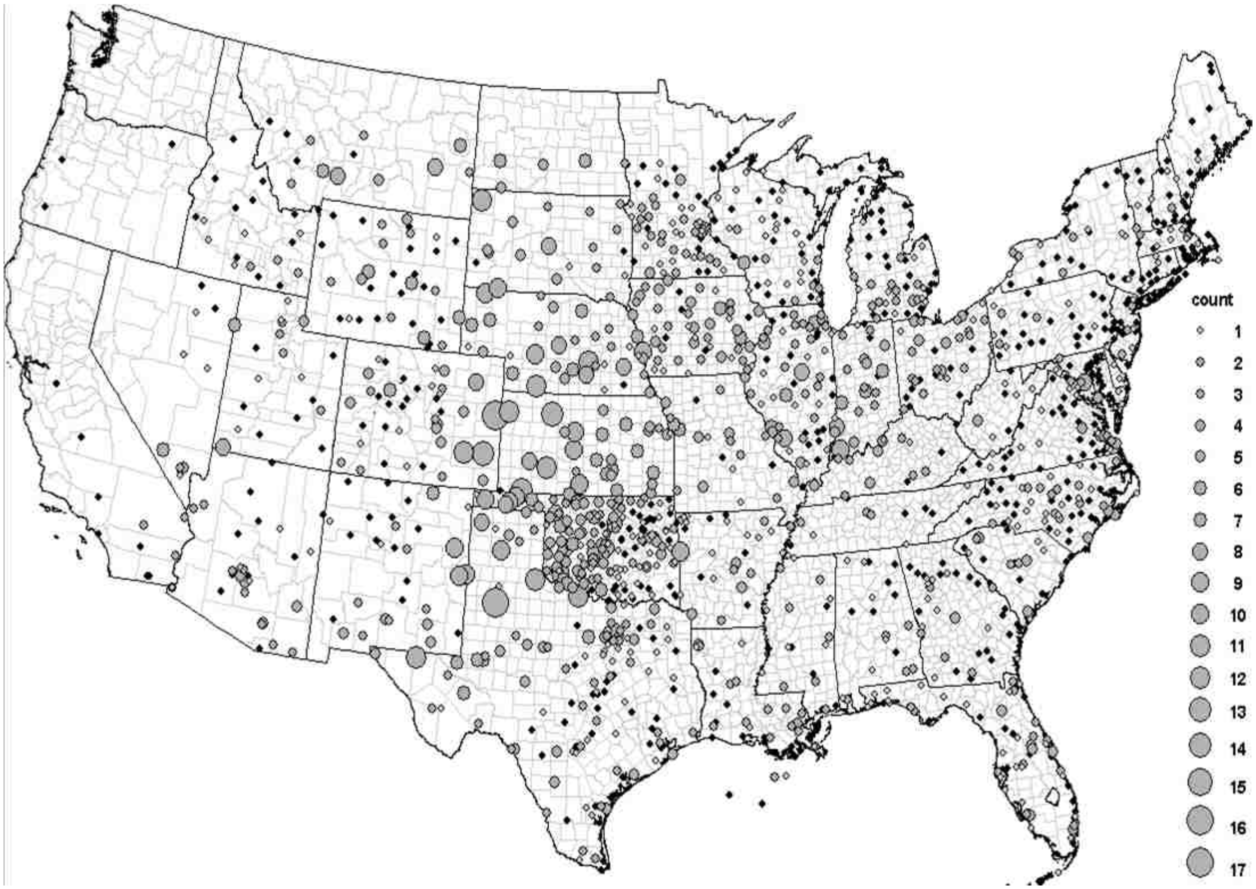

Figure 2. Proportional symbol plot (gray circles) of station counts of measured gusts $\geq$ 50 kts. Black circles are stations that did not have a qualifying thunderstorm wind gust.

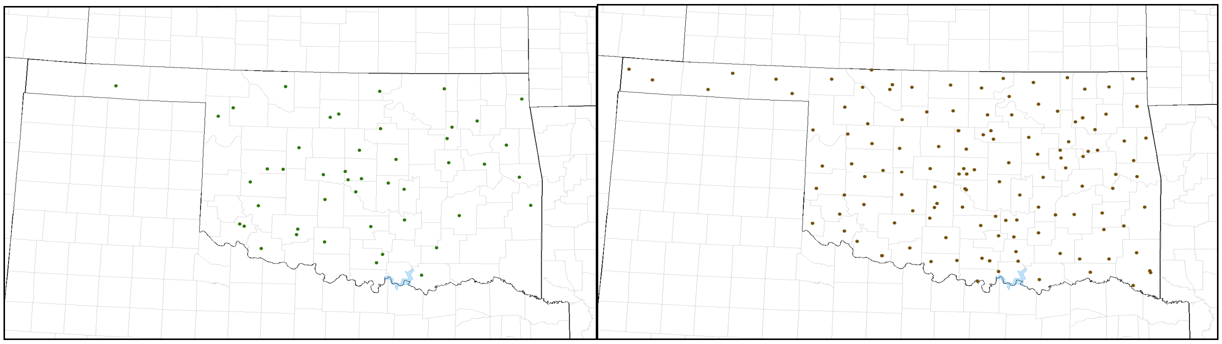

Figure 3. Spatial distribution of Oklahoma ASOS/AWOS stations (left) and Oklahoma Mesonet (right).

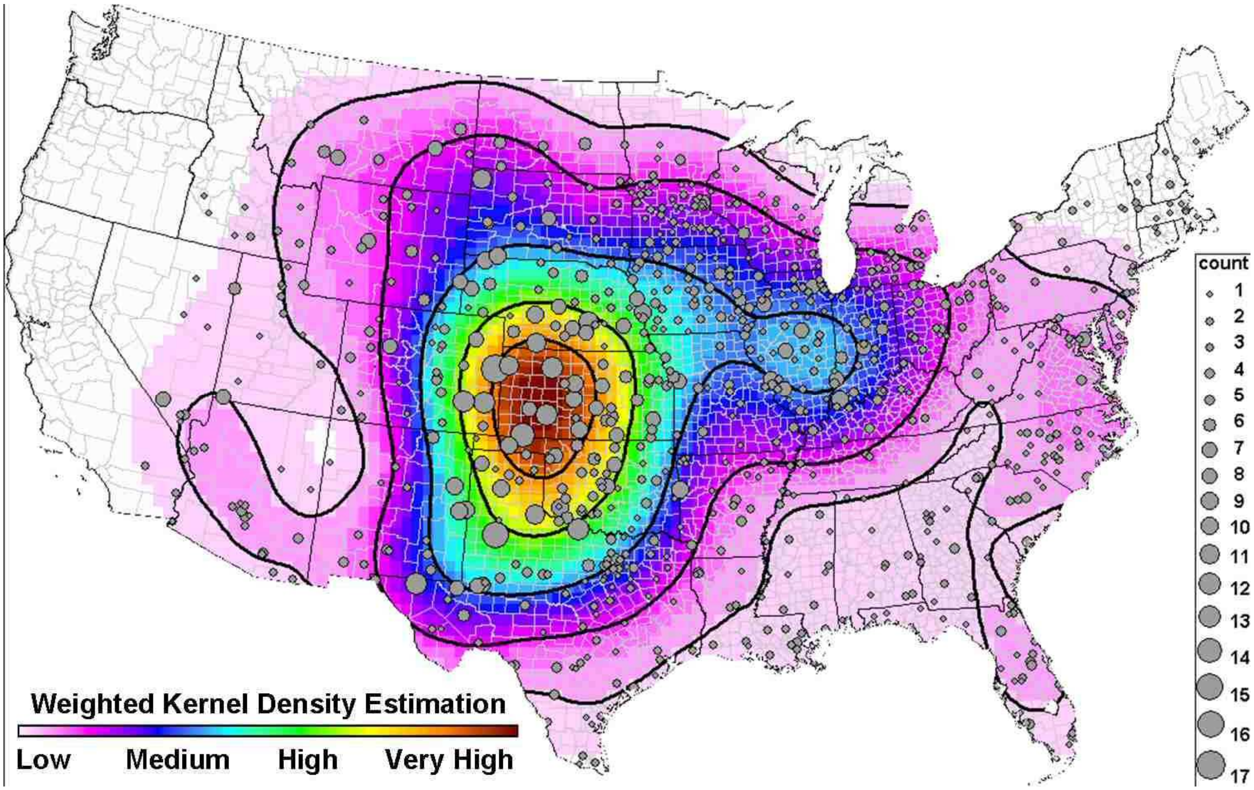

Figure 4. Kernel density estimation plot of ASOS/AWOS stations 2003-2009 that observed ≥ 1 severe gust and weighted by wind gust count per station. The outermost black contour contains 90% of the kernel density estimation of events, with subsequent 75%, 50%, 25%, and 10% contours inward. Proportional symbol plot of stations' counts that measured 50 ≥ kts denoted by gray circles.

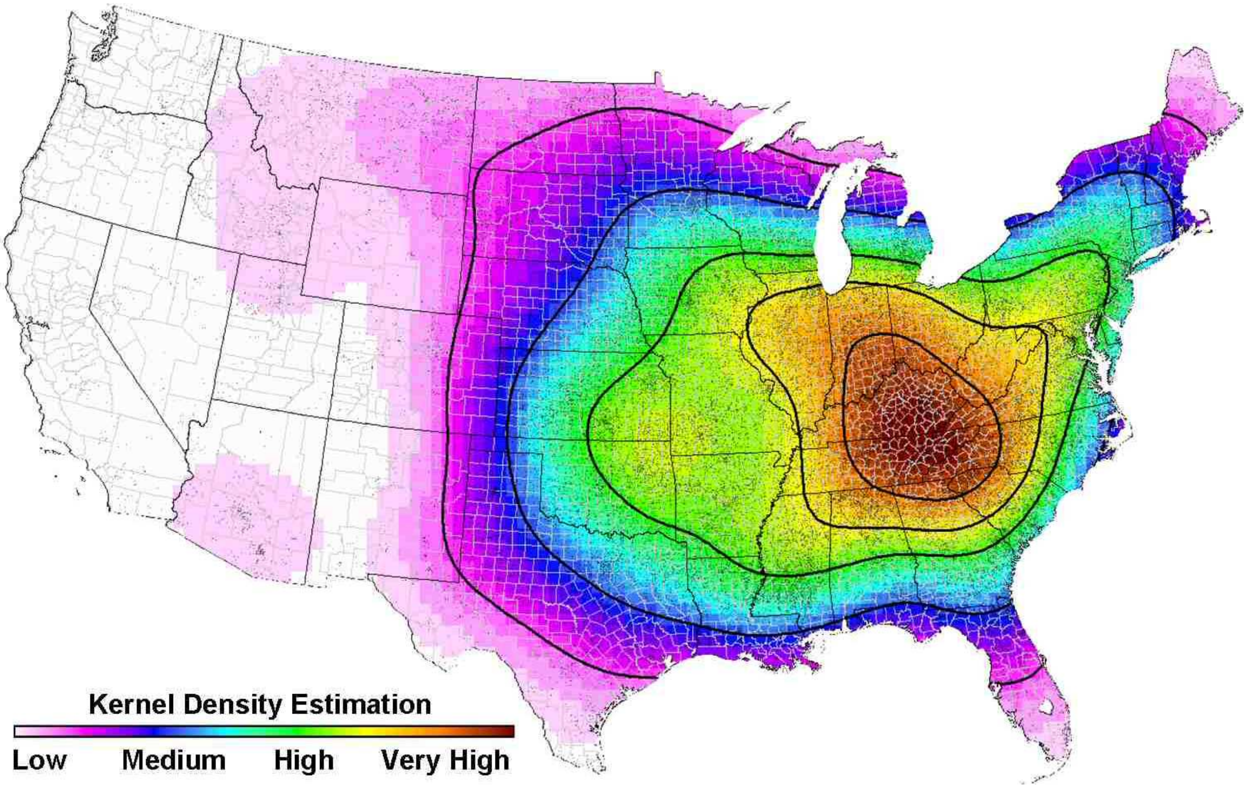

Figure 5. Kernel density estimation plot of total severe wind reports from the severe wind report database 2003-2009. The outermost black contour contains 90% of the kernel density estimation of events, with subsequent 75%, 50%, 25%, and 10% contours inward. Black points represent each severe wind report.

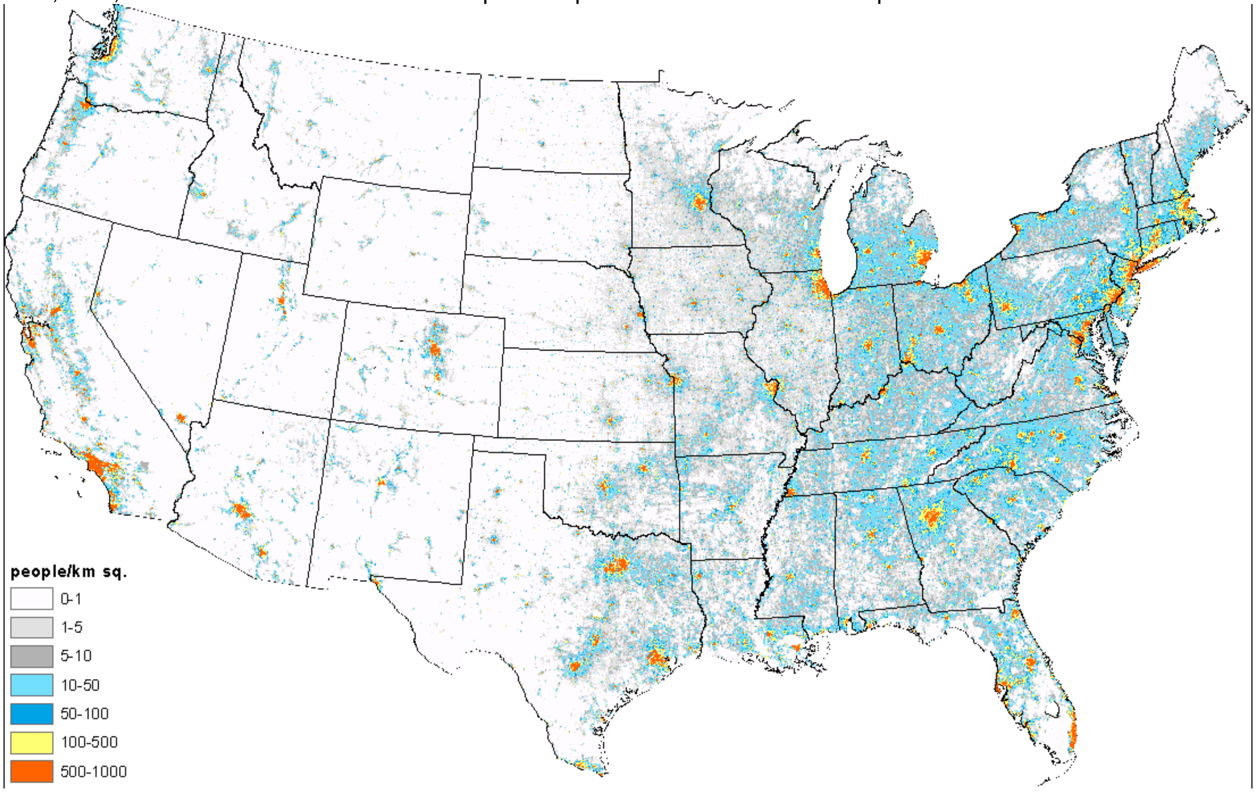

Figure 6. Plot of population density for the United States. The legend at the lower left indicates the color of plotted population density ranges (people km^{-2}).

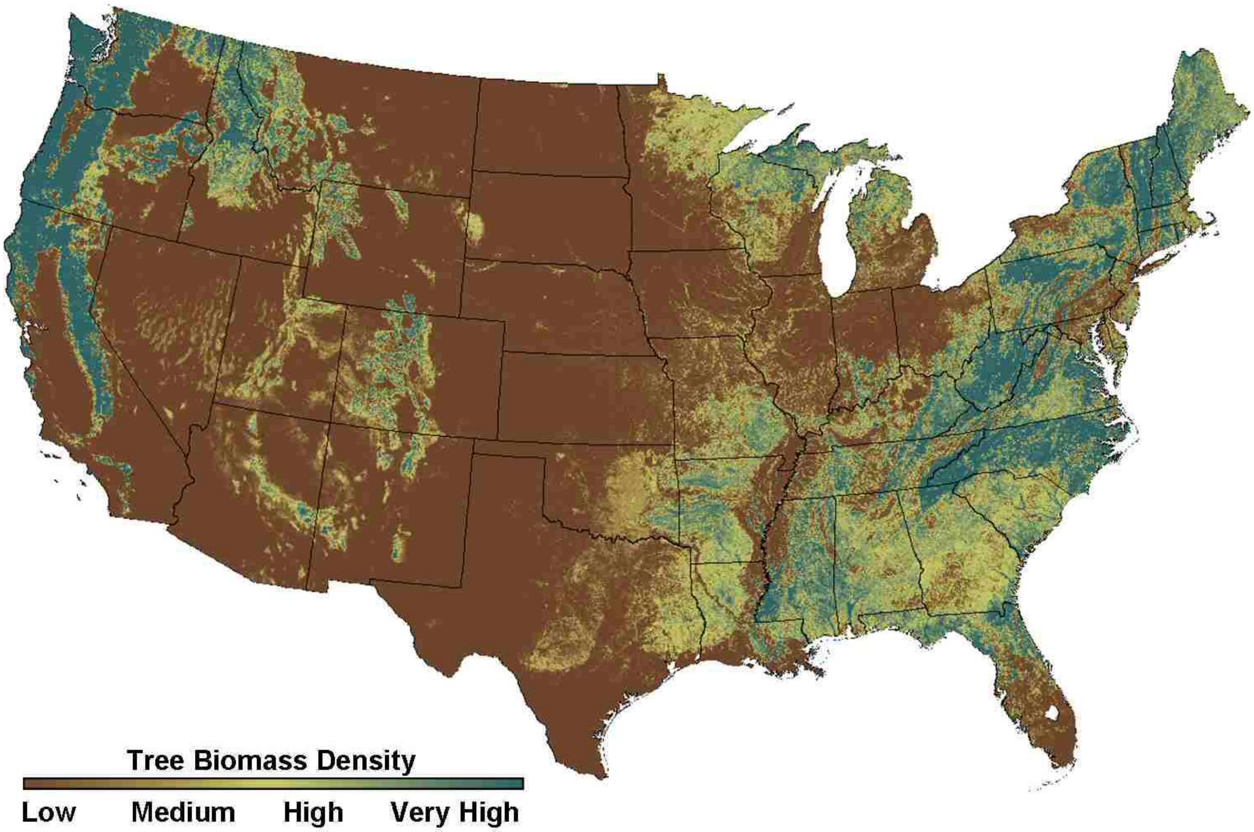

Figure 7. Plot of tree biomass density. The legend at the lower left indicates the color of plotted tree biomass density.

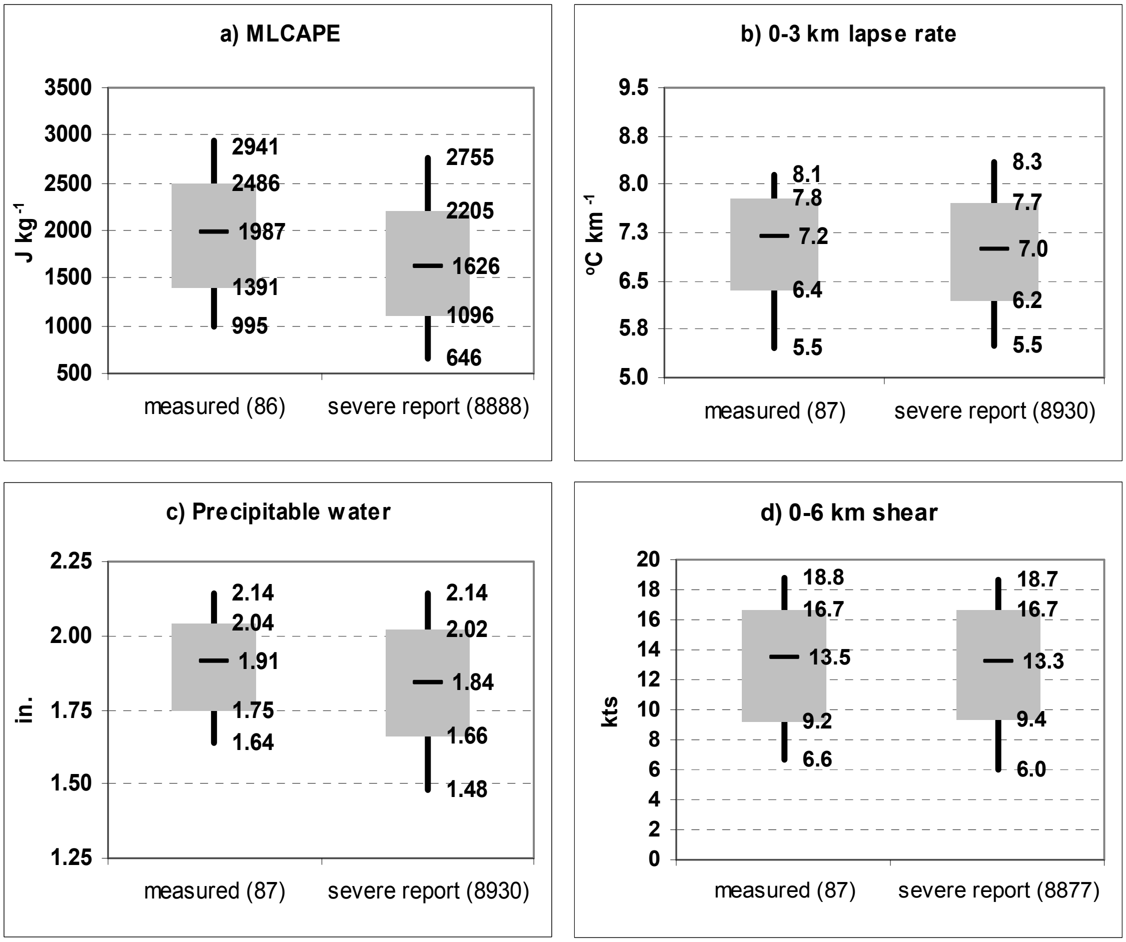

Figure 8. Box and whiskers plot of (a) 100 mb mean layer CAPE (J kg^{-1}), (b) 0-3 km lapse rates (^{o}C km^{-1}), (c) precipitable water (in.), and (d) 0-6 km deep layer shear (kts) for low shear environments during the warm season in the southeast US for measured gusts and severe reports. The shaded boxes span the 25th to the 75th percentiles, and the whiskers extend upward to the 90th and downward to the 10th percentiles. Median values are marked within the box. Sample size is noted in parentheses.

Figure 9. ASOS/AWOS and Oklahoma Mesonet measured severe convective gust station locations associated with an environment with 0-6 km bulk wind difference $\geq$ 40 kt and MLCAPE $\geq$ 1000 J kg^{-1}.