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A mesonet-based analysis of severe convective winds in west Texas.

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A MESONET-BASED ANALYSIS OF SEVERE CONVECTIVE WINDS IN WEST TEXAS

By

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A MESONET-BASED ANALYSIS OF SEVERE CONVECTIVE WINDS
IN WEST TEXAS

By

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A Thesis Approved on

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ABSTRACT

A MESONET-BASED ANALYSIS OF SEVERE CONVECTIVE WINDS IN WEST TEXAS

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April 26, 2022

Multiple studies have investigated the occurrence of severe convective-related winds and have increased our understanding of the forces driving severe winds and their spatial and temporal patterns. Data for these studies have come from airport stations maintained by the National Weather Service. Their standardization across the United States makes them ideal for research, but they are limited in their distribution. This study aims to create a similar climatology of severe surface level winds using a mesoscale network ("mesonet"). Like their ASOS (Automated Surface Observing System) and AWOS (Automated Weather Observing System) counterparts, these stations are standardized and well maintained. This study will contribute a radar-based classification of the convective system associated with each severe wind event and a damage report assessment of Lubbock County. Results show that although comparison to national scale studies is difficult, useful surface-level statistics can be gathered and used to create a detailed severe wind climatology.

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INTRODUCTION

Severe non-tornadic winds, examples of which include straight-line winds, downdrafts, or microbursts, are those winds often but not always associated with convection that exceeds severe wind gust speeds. These severe winds are a leading producer of property damage characteristically different from that of tornadic wind damage. Kuchera and Parker (2006) note that research has mainly focused on two primary causes of severe winds, the first being thunderstorm downdrafts and the second being convective systems that produce quasi-continuous surface winds. Knowing when and where these systems will produce severe winds would be a meteorological breakthrough in forecasters' ability to predict severe events reliably.

It has long been recognized that diurnal patterns exist across the U.S. in relation to severe wind events. Kelly et al. (1985) note that the pattern for non-tornadic severe winds is different from that of severe tornadic winds. Their study also notes that peak occurrences of severe winds fall just before sunset on a normalized solar time scale with a fall off throughout the night until a minimum is reached at sunrise. Brotzge et al. (2011) reinforce these results by finding that severe wind likelihoods begin to increase after “noon” on a normalized solar time scale. Both studies found similar chances of severe winds occurring well after normalized solar time sunset to just before normalized solar time midnight.

Studies have also been performed to determine the climatology of severe wind events nationally across the CONUS. Notable changes in the convective mode related to seasonality and the spatiotemporal distribution of the convective systems across the CONUS (Continental United States) have been observed. Smith et al. (2012) found that quasi-linear convective systems are most notably present throughout the spring in the Ohio Valley and southeastern CONUS regions, shifting north and west in the summer. Meanwhile, disorganized severe wind events were primarily present in the summer months, with centers in the eastern Tennessee/Carolina region and the Great Plains with a significant decrease in activity for the remainder of the year. These study findings reflect similar trends noted in Sherburn and Parker (2014), where a noticeable shift of convective activity occurred from the Southeast and Mississippi Valley regions in the winter to the Great Plains in the summer.

Along with climatological norms across the U.S., researchers know what regional conditions can lead to severe surface winds. Sherburn and Parker's (2014) work on high-shear, low-CAPE (Convective Available Potential Energy) environments suggests that severe convection and accompanying severe wind events can occur across a broad spectrum of CAPE environments. Their study results indicate that high-shear low-CAPE events, defined as surface-based CAPE greater than or equal to 500 J kg^{-1}, most unstable CAPE less than or equal to 1000 J kg^{-1}, and a 0-6 km wind shear greater than or equal to 18 m s^{-1} occur throughout the year, across a substantial portion of the CONUS, and within all seasons.

Environmental humidity has also been shown to play a vital role in developing Mesoscale Convective Systems (MCSs) and their potential severe wind capabilities. Humidity allows regional air pockets to stay unstable as they rise through the atmosphere because a moist air parcel cools slower than a dry air mass. The slower cooling can contribute to an environmental setup conducive to MCS development. Humidity may also play a role in the structural development of an MCS. Mahoney and Lackmann (2011) found in their study, built on findings from Mahoney et al. (2009), that Convective Momentum Transport (CMT) is a significant force in the low-level momentum of MCSs. The researchers used simulations to model idealized MCS conditions. Their study found that drier mid-levels helped to focus areas of CMT within the trailing stratiform region associated with the rear inflow jet of the idealized MCS. This focusing of the CMT was then related to the increase of grid points within the model runs which had elevated occurrences of severe surface winds within the trailing stratiform region of the MCS. Another finding of the model runs performed in Mahoney and Lackmann (2011) suggests that sensitivity to evaporative potential may be strongly linked to increased CMT within the descending rear inflow jet. This increase would reinforce the claim that evaporative cooling plays a role in developing strong surface level winds within the trailing stratiform region, such as the findings in Wakimoto et al. (2006) and Kuchera and Parker (2006).

Atmospheric Scientists have spent years studying the synoptic conditions that allow for severe wind production via atmospheric convection. Seasonality, general storm placement, and severity have all, on a large scale, been thoroughly investigated and continue to be hot topics of research. Only recently have we begun to theorize that there could be “more subtle mechanisms that are important in the damaging wind process.” (Kuchera and Parker 2006). With a three-fold increase in reported severe wind gusts from 1970 to 1999 (Tippett et al. 2015), understanding the climatology of severe winds in a region is of ever-increasing importance. Some of the subtle mechanisms contributing to severe winds have been discussed above. However, these mechanisms were looked at through a sizeable spatial lens, more often than not encompassing the entire CONUS. This was done to compensate for the large spatial distribution of automated weather systems which could reliably and accurately gather atmospheric conditions using standardized instrumentation at standardized temporal intervals. Because of the spatial limitations of systems such as the ASOS (Automated Surface Observing System) and AWOS (Automated Weather Observing System) systems distributed throughout the country, in terms of their ability to resolve smaller scale convective phenomena across large swaths of an area with a high spatial resolution, minimal literature attempts to connect large-scale processes to regional patterns at a local scale.

By developing this climatology with the available data from the West Texas Mesonet (WTM), the study explores multiple goals to aid meteorological and engineering researchers alike. First, the research brings insight to a local severe wind climatology, classified as it relates to large-scale forcing mechanisms giving useful information to forecasters that they can then implement in their day-to-day forecasts. Secondly, a verified real-world wind climatology has been created for this area. This is important because wind engineering models often focus on ring vortices and downbursts but do not consider the atmospheric processes which produce these severe surface winds. These processes can have cascading effects on an engineering model's final output. With this information, the hope is that both fields will now have a clearer understanding of the wind environment around them.

RESEARCH QUESTION AND HYPOTHESIS:

The study began by asking two broad questions. Can the WTM be used to develop a regional climatology of the Lubbock County Warning Area (CWA), and does this reflect similar findings found in the national studies for this region? Can this data, coupled with radar imagery, be used to develop an accurate, verified convective severe wind climatology?

The study hypothesizes that the WTM will provide a standardized regional account of the conditions present within the Lubbock CWA. The results produced by this climatology will be similar to regional results found in national studies.

STUDY AREA:

This study looks at the Lubbock CWA, located in the northern portion of West Texas (Figure 1). The Lubbock CWA consists of 24 counties and has a population of about 474,000 people. This area was chosen because of the spatial distribution of mesonets within the CWA, and radar coverage by the Lubbock, Amarillo, and Midland-Odessa WSR-88D radars.

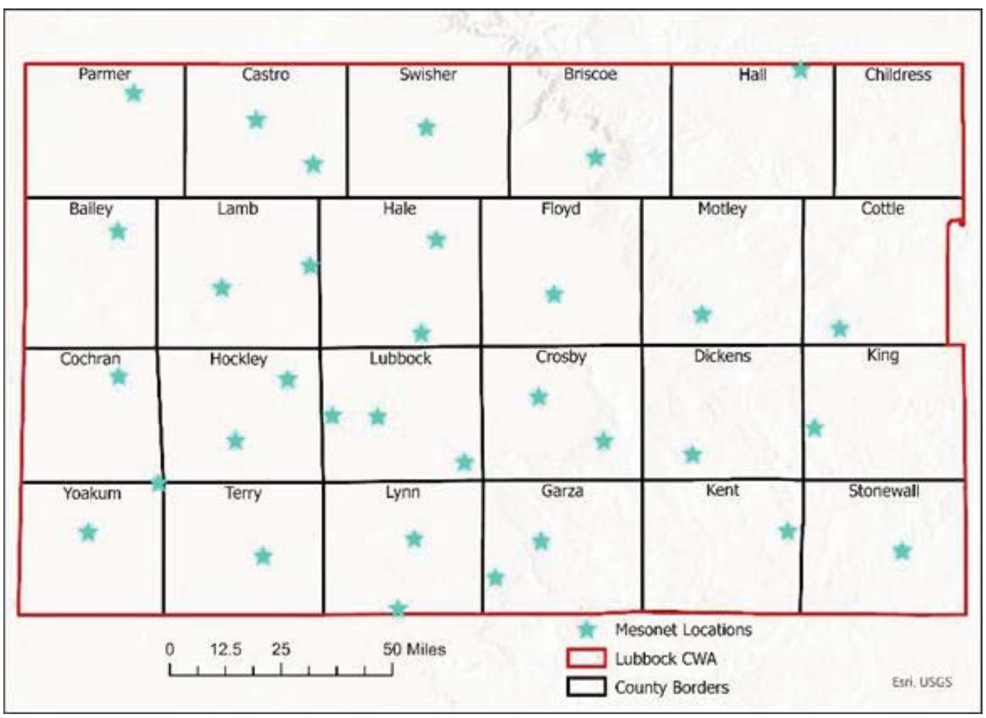

Figure 1: Lubbock County Warning Area with WTM

DATA:

The data for the study comes directly from the WTM as described by Schroeder et al. (2005). This mesonet currently consists of 140 individual stations located throughout West Texas, regions of eastern New Mexico, and a single station located in Colorado. There are now 52 stations within the Lubbock CWA region. However, this study only used 33 of these stations. These 33 stations were chosen because they each collected continuous data over the same 15-year period (January 2005 – December 2019) while providing a relatively uniform spatial distribution across the study area. Hall, Childress, Motley, and Cottle counties were all likely under-sampled due to eliminating two mesonet stations in this area from the dataset, whose inclusion would have cut the temporal period of the study nearly in half. Eliminating these two stations still allowed for some sampling in this region while preserving a much longer duration dataset.

Each mesonet station consists of an array of sensors that have been standardized across the mesonet. These sensors collect wind speed and direction at 10-meter, 2-meter, and 20-foot heights. Temperature and relative humidity are collected at the height of 1.5-meters with additional temperature sensors at 9-meters and 2-meters. Each station is also equipped to measure pressure and precipitation. This study focused on the 10-meter peak 3-second gust, calculated using the readings from the 10-meter anemometer. 10-meter winds are recorded using either the R.M. Young 05103-L

Wind Monitor or the R.M. Young 05103-L Alpine Wind Monitor. Both wind monitors are windmill-style anemometers. In their research, Schroeder et al. (2005) note that the R.M. Young 05103-L and R.M. Young 05103-L Alpine wind monitors measure winds from 1-60 m s^{-1}, have an accuracy of +/- 2%, and a dataset resolution of 0.03 m s^{-1}. As this is the only sensor on the mesonet the study is focused on, all other sensors have been omitted from this writing but can be found within Schroeder et al. (2005), Table 2.

Data from these sensors are recorded in 5-minute intervals. Each 5-minute interval is independent of the previous interval, and a peak 3-second gust can occur at any time within a 5-minute interval. Each 5-minute interval recording is based on the last 5 minutes, meaning that a reading at 10:55 CST, for example, is from data collected between 10:50 CST and 10:55 CST. The benefit of a 5-minute data interval is that it allows researchers to match radar imagery to within 1 or 2 full volumetric precipitation scans of the recorded severe wind gust, either before or after the gust occurred. WSR-88D volumetric scans during precipitation events are either six or five minutes long, depending on which precipitation volume coverage pattern (VCP) the national weather service office opts to set the radar to. This differs from the clear air volume coverage pattern which takes about ten minutes to complete. The 5-minute sampling interval of the WTM coupled with a five or six-minute VCP of the study region during rain events provides imagery as close as possible to the conditions that resulted in the severe wind gust. Because of the nature of data collection between the WTM and the WSR-88D, mesonet data and volumetric radar scans do not line up perfectly. For this study, each recorded severe wind gust was matched to a radar scan within two minutes of the mesonet recording. However, it should not be assumed that repeat studies will have this same occurrence as radar scans and mesonet collection times vary. The closest full volumetric scan across all potential wind gusts before filtering ranged from a few seconds to upwards of seven minutes.

Data was received from the WTM in a .txt file written in comma-delimited format. Each station contains a monthly report for each year resulting in 5,940 individual .txt files. These .txt files contain both the atmospheric and soil condition components of each mesonet station. The .txt file differentiates between atmospheric and soil data lines by giving each an “Array ID” of 1, 2, or 3. This research only focused on the readings with an “Array ID” of 1. An “Array ID” of 2 is the set of instruments monitoring soil conditions and only reports every 15 minutes. An “Array ID” of 3 is only on three specific stations which gather more in-depth wind measurements. These wind measurements were not used in this study.

METHODS:

Data was run through an open-source program called "TXTcollector." This program concatenates .txt files within a folder, allowing you to combine individual .txt documents into one larger file. This program was run for each station for each year to create one file per year, reducing the number of files to 495. Extensive testing was done to ensure that running "TXTcollector" did not eliminate any data and only combined all data lines into one singular document.

Once the yearly files were created, they were imported into Microsoft Excel. Excel imports .txt comma-delimited files natively, typically with little or no transforming of the data needed. Using the import function built within Excel, the data is automatically read and split into the appropriate columns. Some files, either due to their concatenation or default settings, required some transformation steps within Excel to display the data correctly. Data transformations performed in Excel did not alter the data values. Instead, this allowed for a more in-depth search of a column of data for the delimiter contained within, which could not be found automatically.

Following the "README" file provided by the WTM, only the columns which contain information relevant to the study were kept in the Excel window, while the rest were hidden. This resulted in an Excel file that contained ten unique values for each severe wind gust (See Table 1). Two filters were then applied to the data. First, a filter to only show rows of data with an "Array ID" of 1 was applied to the first column. Next, a filter to only show values greater than or equal to 25.7 m s^{-1} was applied to the 10^{th} column, containing the peak 3-second gust data. The 25.7 m s^{-1} filter was applied because this value is the minimum threshold for severe winds as defined by the National Weather Service. All wind gusts lower than this value were excluded from this study.

Table 1: Columns of data remaining after removal of unused data

Array ID
Day (Julian Date)
Local Time (In CST)
Station ID
10m Wind Speed Vector
10m Wind Speed Scalar
10m Wind Direction (in Degrees)
10m Direction Standard Dev.
10m Wind Speed Standard Dev.
10m Wind Peak 3-Second Gust

The remaining data was copied into a new Excel file where the Array ID column was omitted because it was no longer required. This new file type contained all severe wind gusts for all stations for a single year reducing the number of individual files to 15. This approach helped to determine which severe gusts might have occurred from the same convective system. The original Excel file remained unedited to preserve data integrity if mistakes occurred throughout the concatenation and cleanup process. The new excel file was given a unique name following the format "YYYY_Gusts_Severe" and saved for further processing.

Columns were then added to the new file to convert the Julian date into a MM/DD/YYYY format. The raw data timestamp was Central Standard Time (CST) regardless of the time of year and this was converted to Universal Standard Time (UTC). Regardless of whether the date was different, a date was placed within the UTC Date column. This was important for later data gathering steps where UTC Time and Date were used to source radar imagery.

Four columns were then set aside at the end of the new file which housed an available hyperlink that would directly link to that wind gusts' associated radar scan, a column that was used to verify whether or not convection was present anywhere within the Lubbock CWA at the time of the reported wind gust, a classification of the convective type, and any notes that may be needed for each event.

UTC times were used to find weather radar imagery quickly and accurately using the NOAA Weather and Climate Toolkit. The Toolkit allowed for the placement of a shapefile of the mesonet stations which can be loaded and viewed as imagery. Radar images and series were downloaded into the viewer and animated. Animation, coupled with the addition of the WTM station locations within the viewer allowed for the quick identification of stations that may have experienced a severe wind gust while also providing insight into whether any of the stations within the study may have experienced severe wind due to convection. This method allowed for the expedition of the imagery collection stage by ruling out specific dates for severe convective wind events within the shapefile boundaries.

The imagery was collected either as individual scans or as a timed series of scans. Both individual scans and timed series scans were downloaded from the Toolkit in a

KMZ format to preserve the spatial information contained within the scan file. The decision to use single imagery versus a time series of imagery was largely subjective, with time series scans often only being used for multi-hour-long events across the entire study region. Single imagery was used to reference most of the data points to conserve system memory resources, as other scans could always be viewed through the Weather and Climate toolkit if needed. Once imagery collection was completed, the radar hyperlinks in the excel files were updated to link to the specific radar imagery or series in question, and classification began.

Convective systems can be classified in several different ways. The study began with the idea that the research should model the convective classifications system used after two classification schemes implemented independently in Smith et al. (2012) and Schoen and Ashley (2011). Both Smith et al. (2012) and Schoen and Ashley (2011) used a classification system to differentiate between several subtypes of systems. This method works well for large-scale studies, but it was quickly found to be challenging to apply to this study due to the small spatial footprint of the study region, time scale, and the occurrence of ambiguity in how a convective system presented itself on such a fine scale. To add to this, subtype classifications were extremely rare within the dataset. Because of this, rather than including subtypes, the study has six main classification groups for which subtypes are grouped appropriately: Organized Linear, Organized Cellular, Unorganized Linear, Unorganized Cellular, Supercell, and Non-Convective.

Organized linear classifications apply to convective storms with radar echoes greater than 35 dBZ, have persisted for greater than 30 minutes, and have a length of 35 dBZ echoes greater than or equal to 75 kilometers (Figure 2). The 75-kilometer threshold directly results from this threshold being used in previous studies. Although using this threshold mixes imperial and metric forms of measurement, it is far easier to maintain and measure a 75-kilometer requirement than its imperial equivalent of 46.6028 miles. Organized linear systems were measured along the leading edge of convection. For example, if a curve in the structure of the linear system was observed, the measurement of the line followed the curve along qualifying dBZ values. Organized linear systems include the subtypes: Bow Echoes and Squall Lines. Initially, the study aimed to include a secondary classification of these events, but this was dropped due to the issues previously discussed.

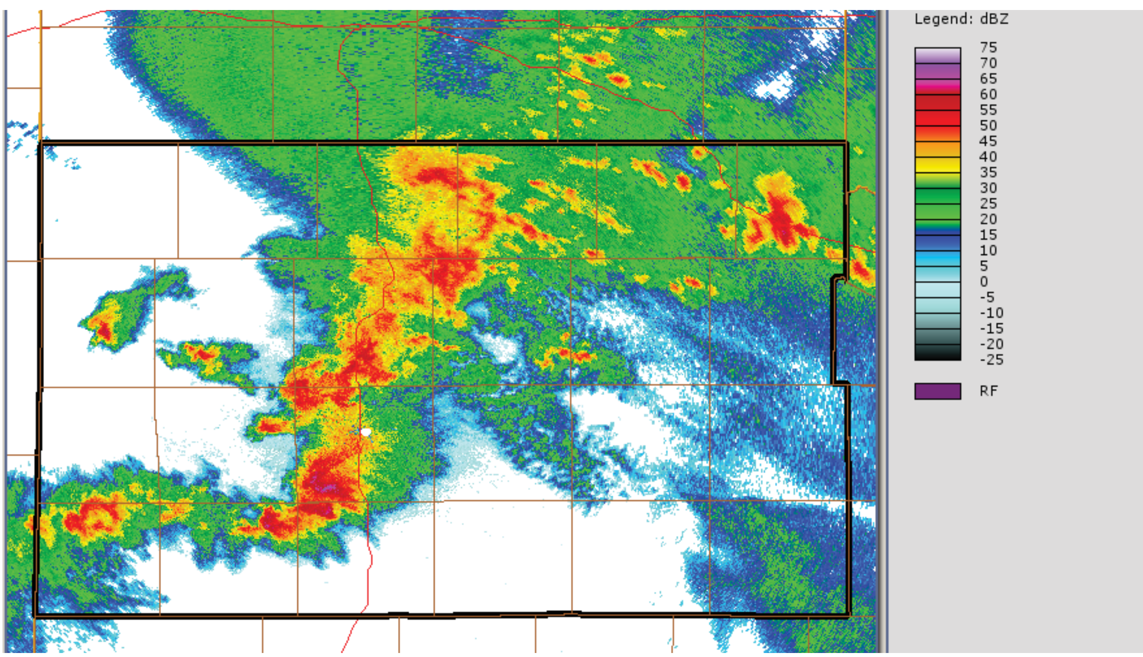

Figure 2: Organized linear example

The organized cellular class (Figure 3) consists of cellular style convection, reaching and maintaining a 35 dBZ echo for 15 minutes or longer (roughly two volumetric scans), and the systems movement is influenced by synoptically driven forces (meaning that all the cellular convection is moving in the same general direction throughout the region). This classification method is unique to the study, as it excludes supercells and instead focuses on the driving mechanism behind the convective systems' motion spatially. This differs from the classification scheme utilized in Smith et al. (2012), where this classification was used to only represent standalone supercells and embedded supercells.

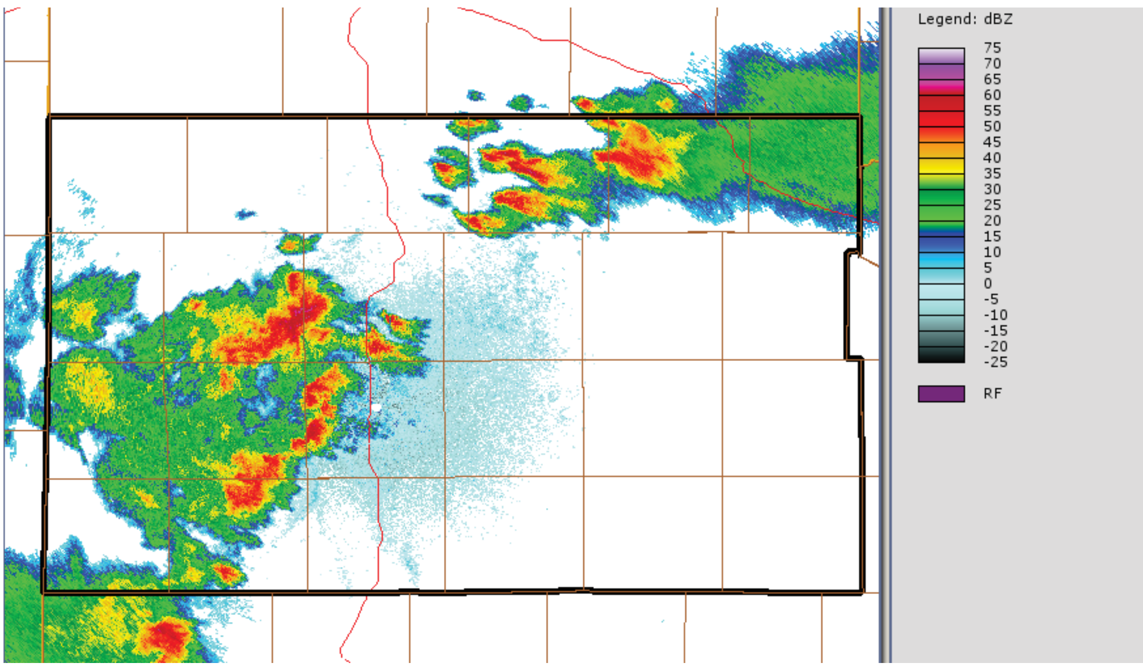

Figure 3: Organized cellular example

An unorganized linear classification was given to any system which contained pockets of 35 dBZ reflectivity, inter-connected by lower reflectivity values that sat along a linear path greater than or equal to 75-kilometers (Figure 4). This mode of convection was common in the region. It did not fit well within any of the existing categories found in previous studies, so it was created as an alternative to including it in a less-fitting category. Spacing between the 35 dBZ cores was overall treated subjectively.

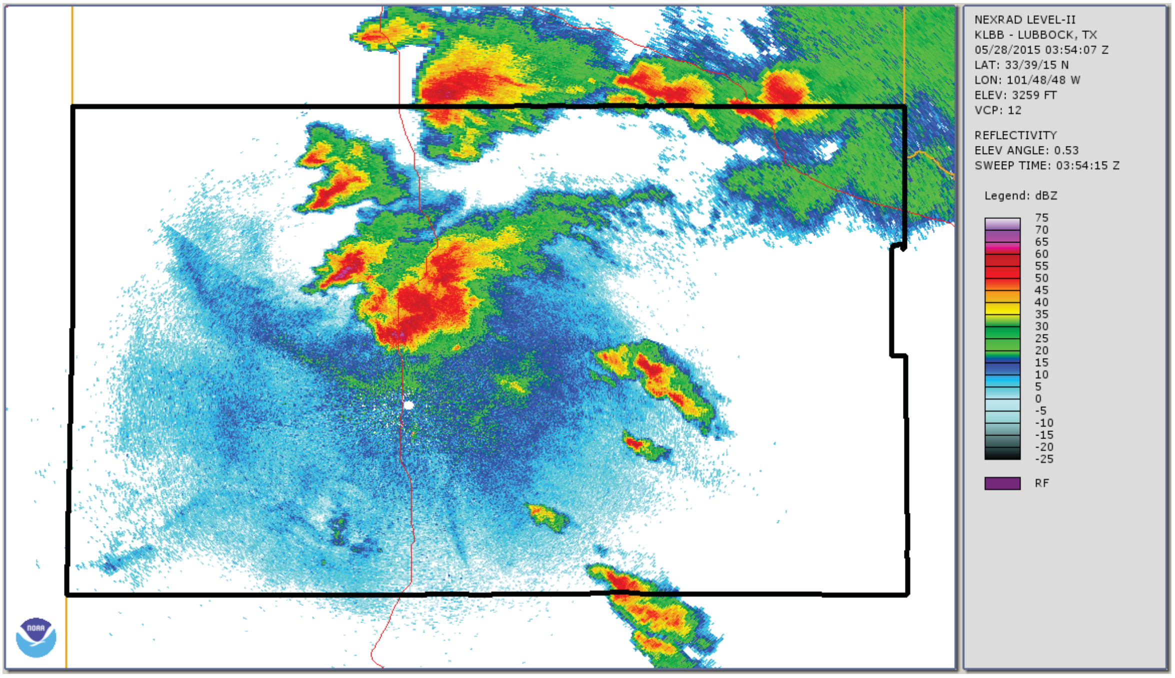

Figure 4: Unorganized linear example

Unorganized cellular convection is another classification that was redefined for this study to better fit the research's needs, although present in previous studies. This convection is characterized by cellular convection evolving from an unstable buoyant atmosphere, but no large-scale organized lifting is present. This convection was required to maintain the 35 dBZ signature for 15 minutes but was classified this way due to its motion across the study area (Figure 5). It was included in this category if each cell was traveling in a different direction, and there was no evidence of a synoptic driving force behind this motion.

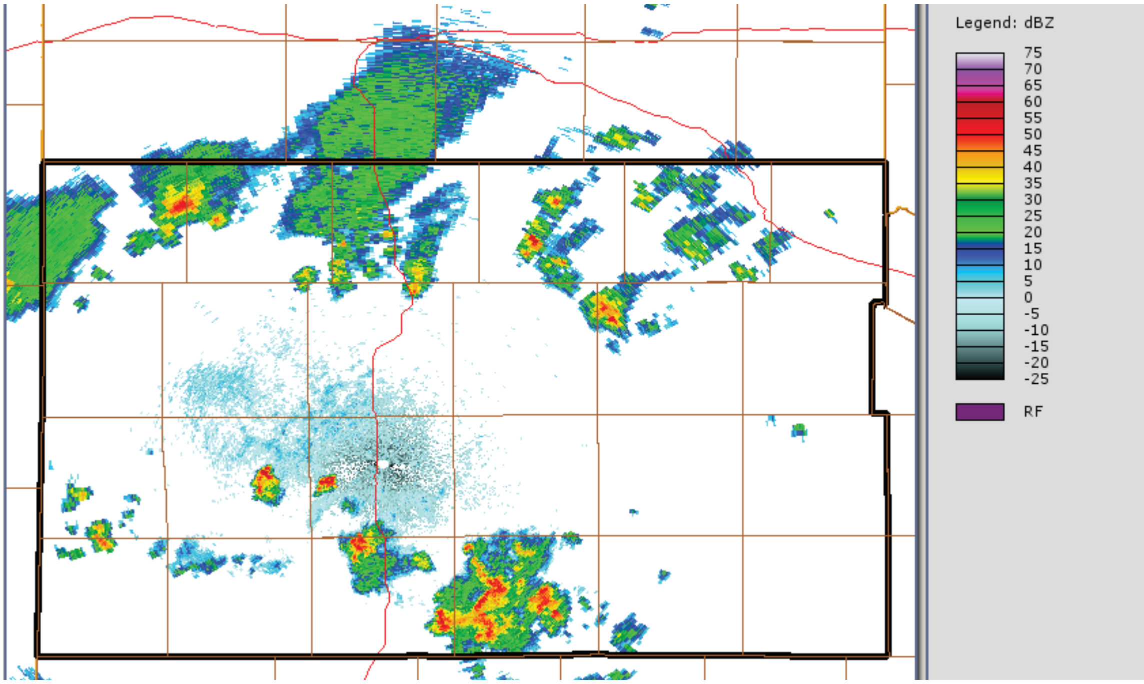

Figure 5: Unorganized cellular example

Supercells were the only subcategory present in previous studies that were considered their own category for this study. Supercells are a very common phenomenon in this region, and there were enough instances of severe winds occurring because of a supercell to include it as its own category. Doing this also freed up the organized cellular category discussed earlier. A supercell was identified by the presence of a couplet within the system which was identified using the velocity scans acquired by the WSR-88D. The supercell category consists of individual and embedded cells in linear systems. Individual cells were relatively easy to classify due to their characteristic "hook" shape, but special care had to be taken to ensure that severe gusts from embedded supercells were recorded into the correct category. It was essential to ensure that the wind gust was driven by a supercell-specific downdraft generated by the embedded supercell and not the linear system transporting it. A combination of radar data and wind direction readings were used to determine, based on the location of the mesocyclone to the mesonet, direction of any outflows visible, and researchers' best judgment which classification category a severe wind gust should be placed into for situations of this nature.

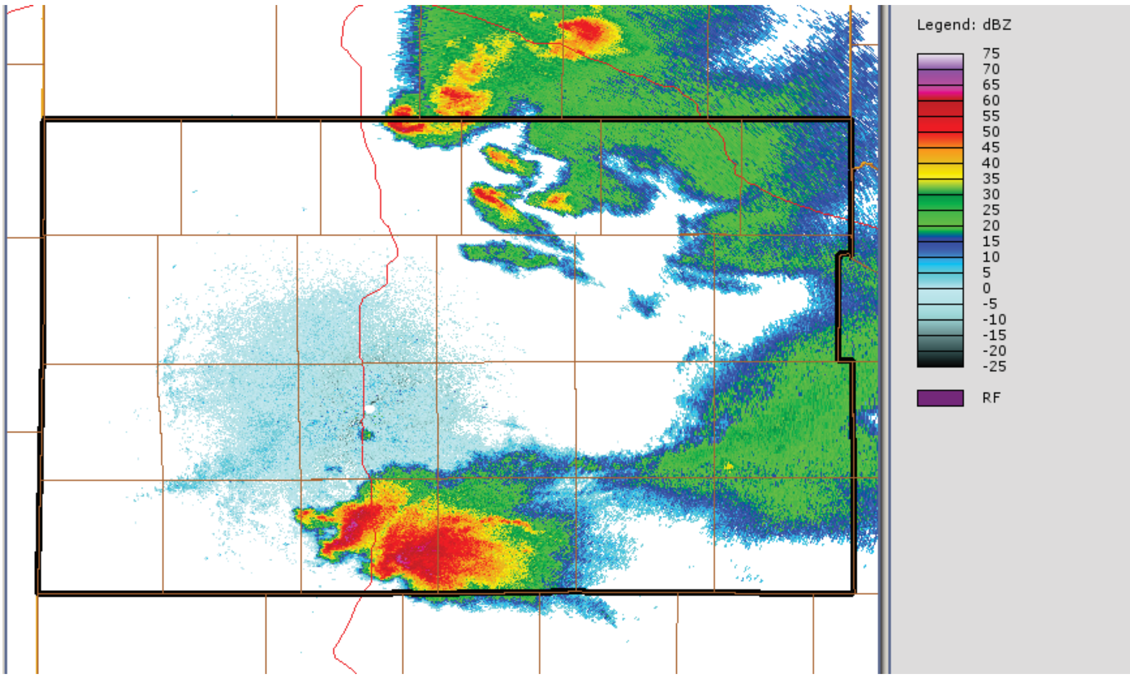

Figure 6: Supercell example

Non-convective winds, as shown in Figure 7 below, were classed based on the presence of convection in the Lubbock CWA in relation to the severe gust which was recorded. If there was no convection present within the Lubbock CWA or surrounding counties (within a 25-mile radius of the mesonet station), the severe wind gust was discarded from the study. This was done because the investigation is only interested in wind gusts potentially caused by convection. If convection greater than or equal to 35 dBZ was present within the Lubbock CWA but was not present within 25-miles of the mesonet, the gust was classified as non-convective. This 25-mile limit was used because it is a limit defined by the Storm Prediction Center when outlining severe probabilities in outlooks.

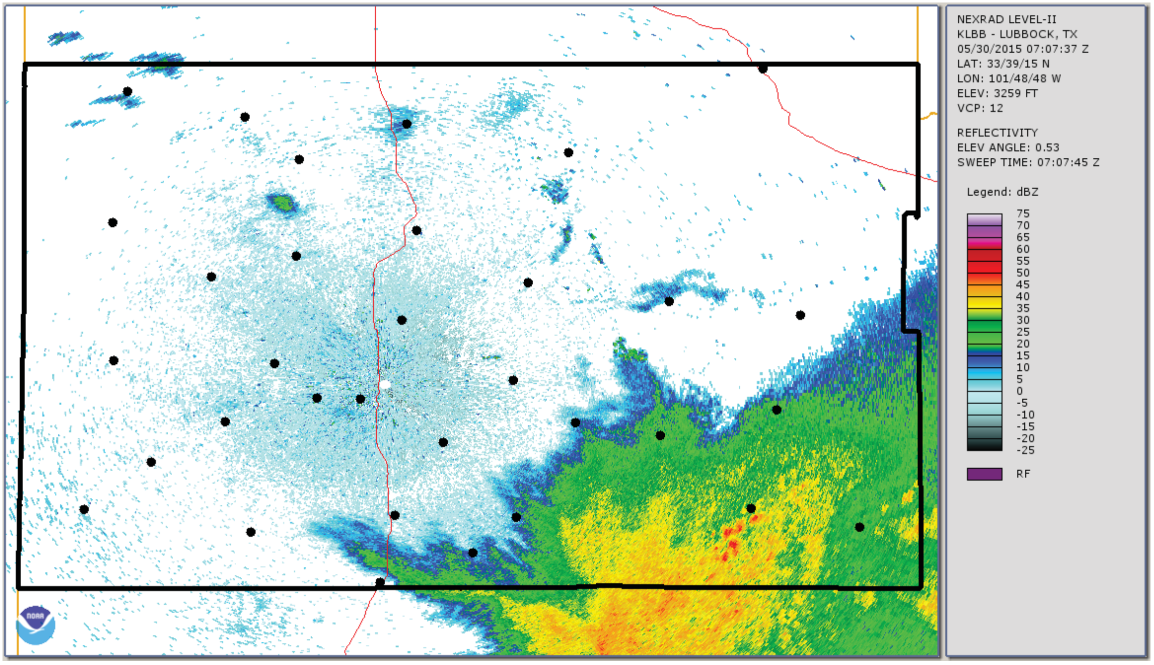

Figure 7: Non-convective example including mesonet locations to provide additional context.

Because atmospheric convection is a very dynamic process, a convective system could present differently along its path through the study area. For this reason, each severe gust was classified individually. This allowed for the study to consider the changes experienced by convective systems as they evolve over time and space.

Once classification was completed, accompanying storm report data for each event was downloaded from the Storm Prediction Center Severe Weather Events Archive, the National Centers for Environmental Information Storm Events Database, and the Damage Assessment Tool produced by the National Weather Service. Attempts were made to match the convective system, which likely caused severe wind damage to its associated damage report. Unfortunately, the study often encountered insurmountable difficulties due to the limitations related to the reliability, spatial distribution, and the spatial location of reports, which will be discussed in detail in the discussion section of this writing. To combat these limitations, the damage report analysis was condensed to focus on the city of Lubbock, in Lubbock County, Texas, using events that crossed mesonet site 33, which sits near the center of the city. Condensing the analysis area was done because of the reliably dense population comparative to its surroundings, the presence of items that could be damaged by severe wind, and to see which convective classifications were more likely or less likely to cause damage across the populated region. This change was also done to allow for a more straightforward count of events. The Damage Assessment Toolkit was more accurate and contained more data than the SPC or NCEI archives and was therefore used for the analysis as the primary source of damage reports for the area.

Once all relevant data was assimilated, sorted, and reviewed, descriptive statistics were generated to paint a detailed picture of the severe wind climate. It is important to remember that the goal of this study was to see if patterns exist in the data at this spatial scale, which could be expanded upon in future studies. Statistical analysis was used on a case-by-case basis when developing maps to provide relevant context and will be reviewed in the discussion section.

Lastly, an analysis was done to see how many events crossed the region and produced severe winds. While the main focus of the study will involve looking at the properties of each individual gust, looking at how many events crossed the region in combination with their associated gusts may produce interesting results. This analysis may also help to remove some bias expected to be present between the larger and smaller convective modes present within this study. In order to do this, an “event” had to be defined. Definitions of “event” proved rather scarce and subjective to the individual study. Doswell et al. (2006) note that “not only is there no general agreement about the definition of a tornado outbreak, the word “outbreak” itself has been used in several different ways.” While Doswell et al. (2006) emphasize tornado outbreaks, the research also looks into primarily non-tornadic severe events and found the same result. Although the system employed in Doswell et al. (2006) ranked events based on severity, it did describe how the study looked into what constitutes a single event. This event classification, however, was based on an interpretation of the number of certain reports depending on which variable was being looked. This method works well for large-scale synoptic systems which are likely to generate numerous reports but fails to address the bias experienced when classifying small scale events. For these reasons, this study did a classification of events based on the time and date if the wind gusts.

More often than not, severe gusts associated with the same event would cluster at times and on dates within the data. This clustering made it relatively quick and easy to match up which gusts corresponded with which event. For the study, a time difference between two gusts greater than or equal to 4 hours was implemented. The spatial location of the gust was also used to determine association with a previous event or not. If the event occurred within 4 hours of another gust but was separated by a lengthy pause in severe recordings, radar was used to verify if the event which caused the first gust also caused the second gust. Using radar in between gusts was helpful particularly for smaller events. If the convection causing these events were entirely different and not likely to be associated with the same airmass, they were analyzed as two separate events. Events could consist of one severe gust or a series of several severe gusts. Events were classified based on the modes of convection present within them. For example, if an event contained only severe supercell convective gusts, it was classified as a supercell event. If a system only contained linear organized gusts, it was classified as organized linear. However, if a linear system contains both organized linear and organized cellular convection, that system was classified as a multi-modal system.

SPATIAL DISTRIBUTION:

Across the 15-year study period, about 34.7 million data points were recorded and needed to be filtered. There were 1042 individually recorded severe wind gusts that had to be analyzed and classified after filtering. It is important to note that the total number of recordings does not account for a 1:1 correlation with the number of severe events across the area. This total refers to a count of all individual 5-minute intervals where a specific station experienced a 3-second peak gust that exceeded the severe wind gust threshold. Often, particularly in organized and/or widespread systems, convective systems would produce multiple wind gusts across the entire CWA and/or produce numerous severe gusts at the same location for an extended period. Before classification began, a heatmap was created to show the spatial distribution of severe gusts across the region (Figure 8). This heatmap showed three distinct hotspots: the first being within Castro County, the second hotspot was within Lubbock County, and the final hotspot spanned Lynn and Garza Counties. To add validity to this heatmap analysis, a Dynamic Hotspot Analysis was run within ESRIs ArcGIS Pro to determine if there were any statistically significant occurrences of severe wind gusts at any of the mesonet sites. ESRI introduced the Dynamic Hotspot Analysis in ArcGIS Pro (also called the Optimized Hotspot Analysis) as a way to aggregate data, identify scaling, and correct for multiple testing and spatial dependence automatically, without the need of extensive user input. The test is run using the Getis-Ord Gi* statistic (ESRI (2021), Optimized Hotspot Analysis). This analysis returned no statistically significant hot spots across the CWA but did identify a statistically significant cold spot located within Motley County. This can also be seen in the heatmap, where values are noticeably lower than the surrounding values.

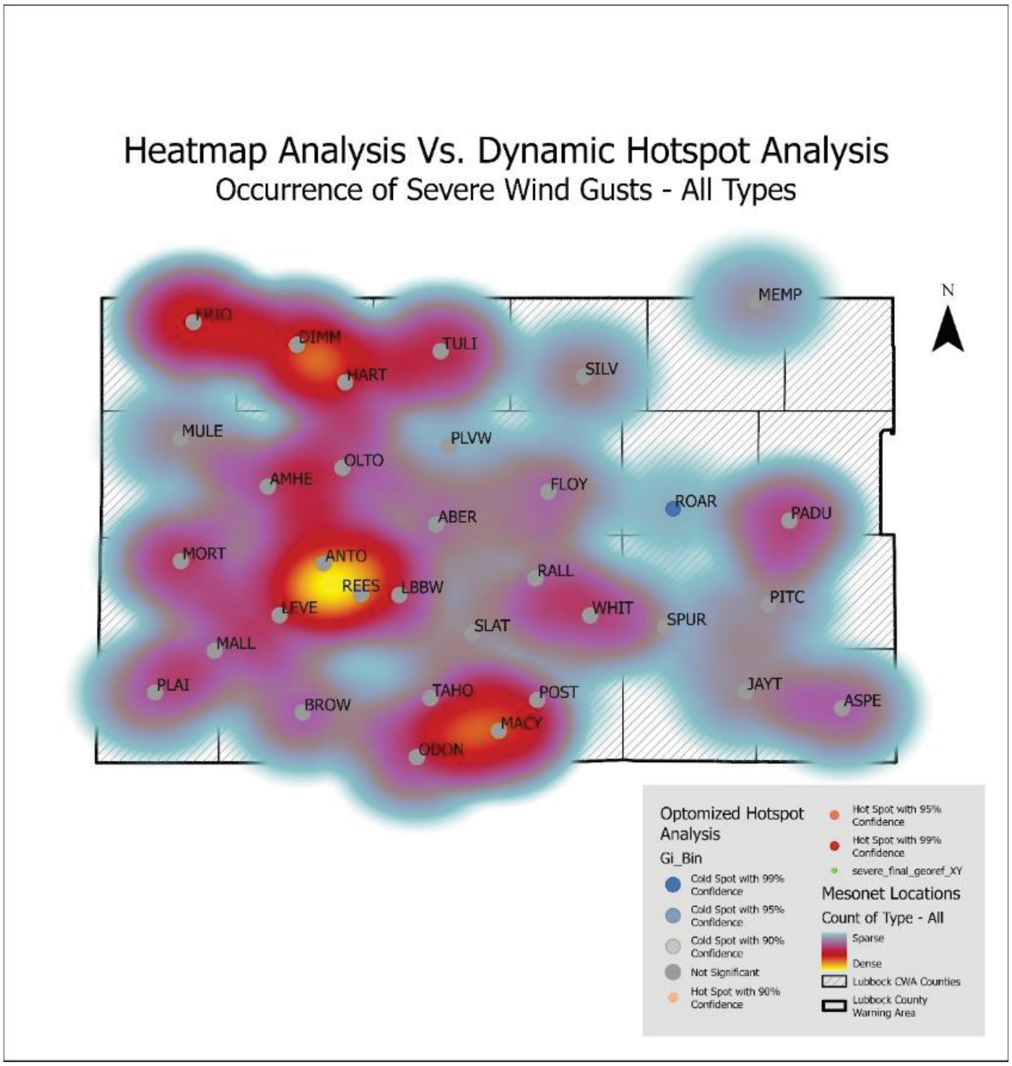

Figure 8: Heatmap analysis (red-to-blue hues), with overlayed Dynamic Hotspot analysis points.

Although at first glance, the heatmap analysis looked promising, it was misleading due to the spatial variations of mesonet sites, particularly around the largest heatmap cluster situated over Lubbock County, where four stations record wind gusts in relatively close proximity to each other. This observation is in contrast to the study areas in far eastern counties, where most counties for this study only had one mesonet site active, including one county which didn't have a mesonet at all. This spatial variability explains why the western extent of the Lubbock CWA was associated with a higher occurrence of severe gusts. Requiring validation of this heatmap with a Dynamic Hotspot Analysis precipitated the needed degree of perspective, which, when considered, shows that no mesonet site experiences a higher count of severe wind gusts to a statistically significant level.

The hotspot analysis does show that one station, Roaring Springs station in Motley County, experienced fewer wind gusts, to a degree of statistical significance with 99% confidence. Theories of this result include a random occurrence in the data, topographical elevation changes, and the location of the mesonet site near the caprock escarpment of West Texas. Elevation change along the escarpment is quite dramatic where the high plans of Texas meet the rolling hills of the lowlands to the east. The location of this particular mesonet sits centrally within this elevation change, which could offer some explanation for this result.

Once classification was complete, another set of figures (below) was developed to display the distribution of all convective modes combined, as well as each individual convective mode's unique distribution across the region. Each map consists of either the total number of gusts experienced by the mesonet station or an individual convective mode, broken up into 5 breaks using the "Natural Break (Jenks)" function in ArcGIS Pro.

Each map has also labeled each mesonet station using its unique four-letter station identifier.

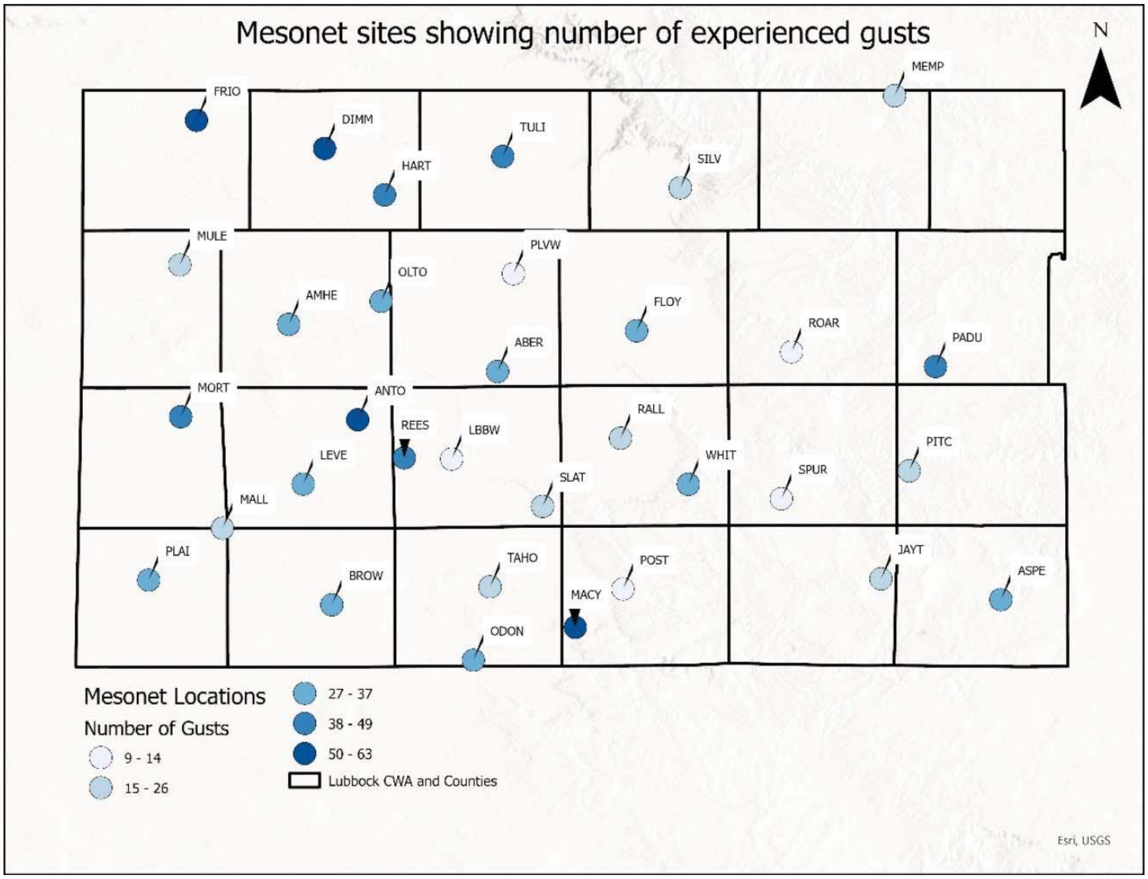

Figure 9: Mesonet sites displaying the number of total severe gusts experienced at that site. The color of the circles indicates count. Bubble labels have been included, with tails pointing to the center of that labels point for clarity. Size variances in the tails are due to the proximity of the bubble label to the circle center, which is a side effect of the labelling hierarchy used. These tails hold no weight to the data displayed but are for reference only.

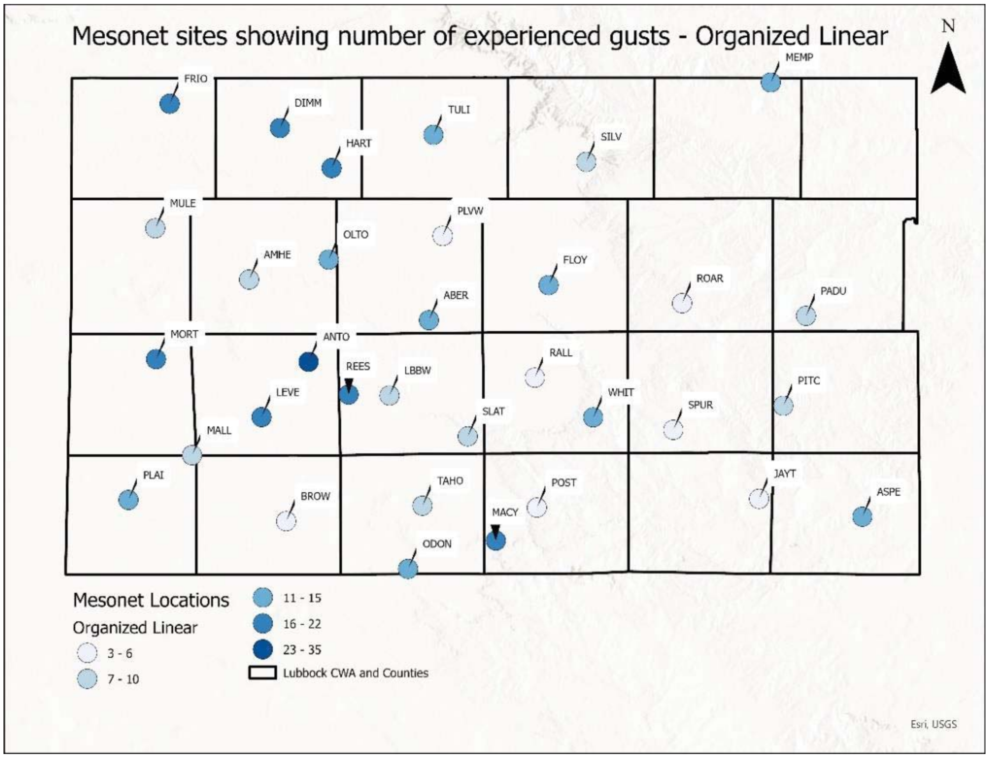

Figure 10 (above): Mesonet sites displaying the number of organized linear severe gusts experienced at that site. For tail size variance, see Figure 9.

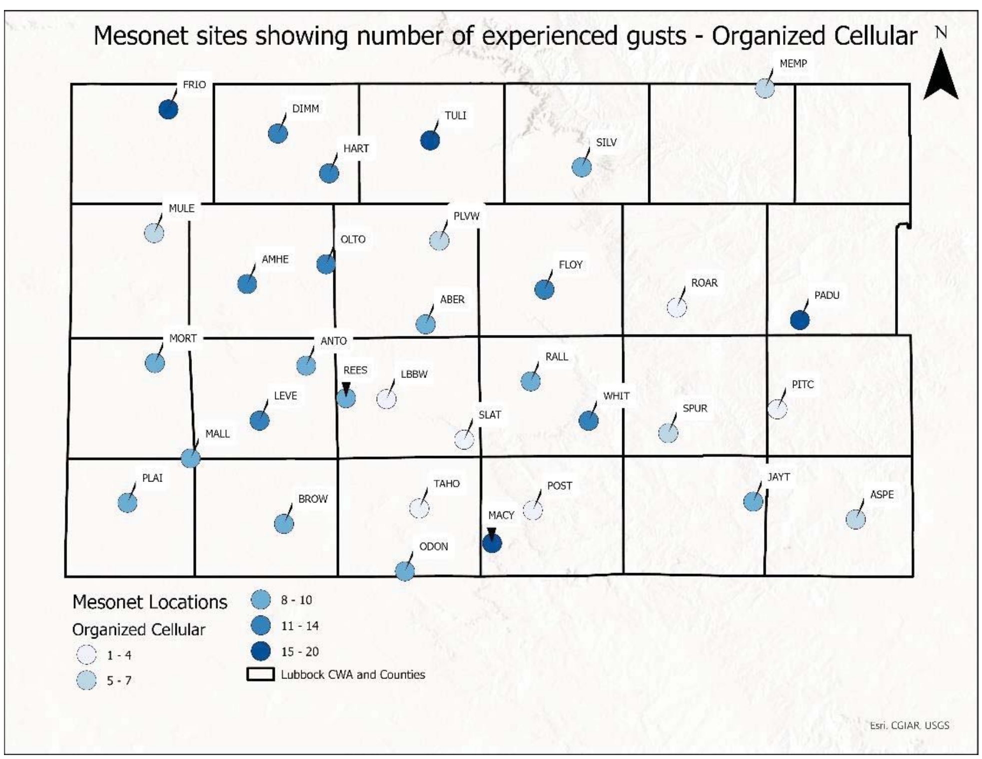

Figure 11: Mesonet sites displaying the number of organized cellular severe gusts experienced at that site. For tail size variance, see Figure 9.

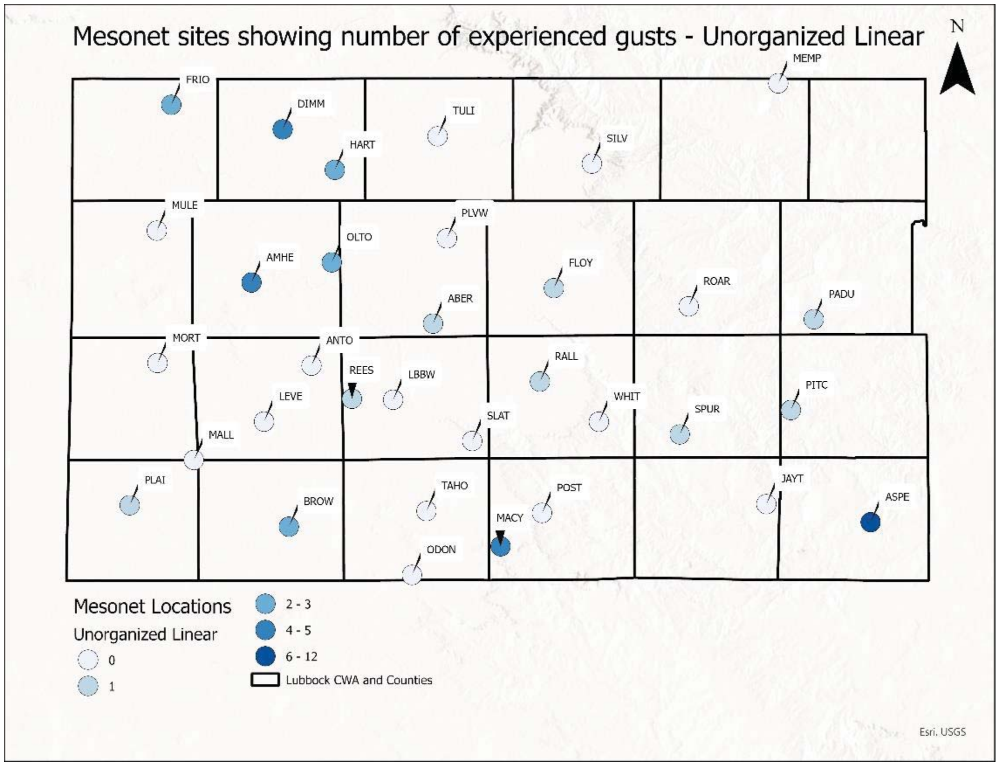

Figure 12: Mesonet sites displaying the number of unorganized linear severe gusts experienced at that site. For tail size variance, see Figure 9.

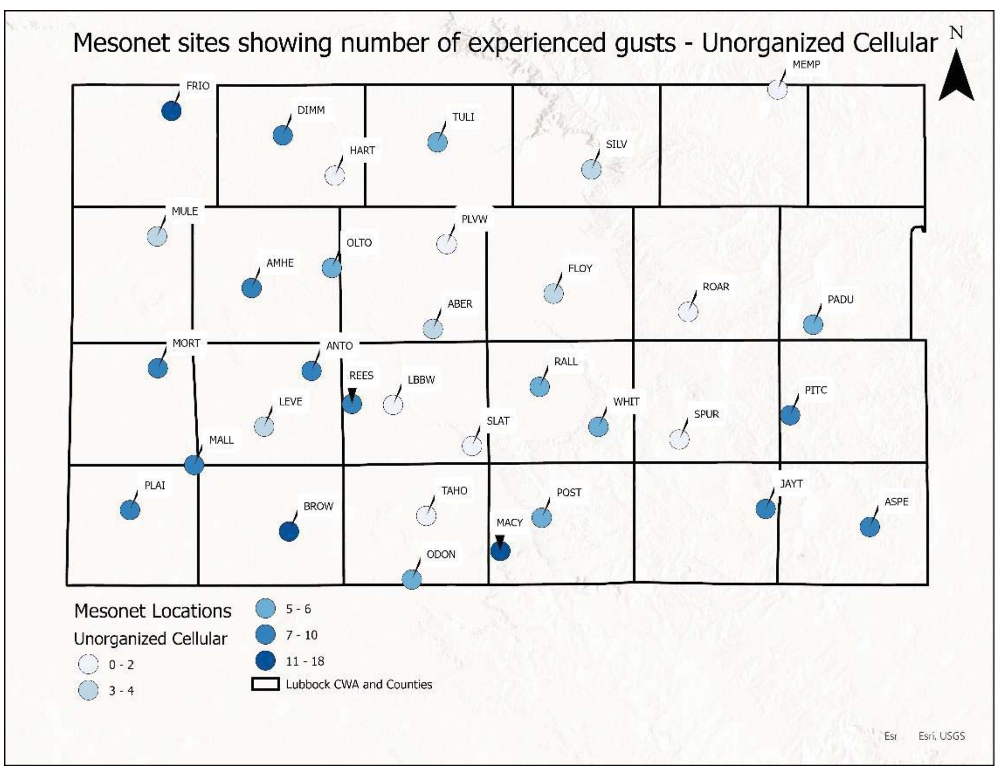

Figure 13: Mesonet sites displaying the number of unorganized cellular severe gusts experienced at that site. For tail size variance, see Figure 9.

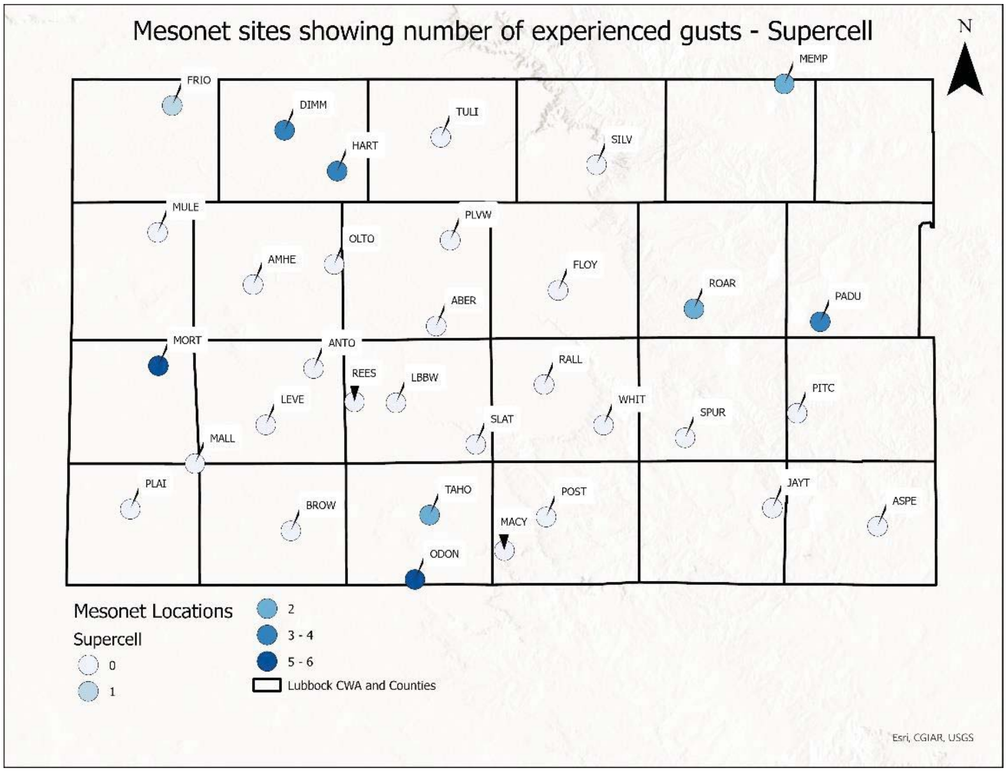

Figure 14: Mesonet sites displaying the number of supercell severe gusts experienced at that site. For tail size variance, see Figure 9.

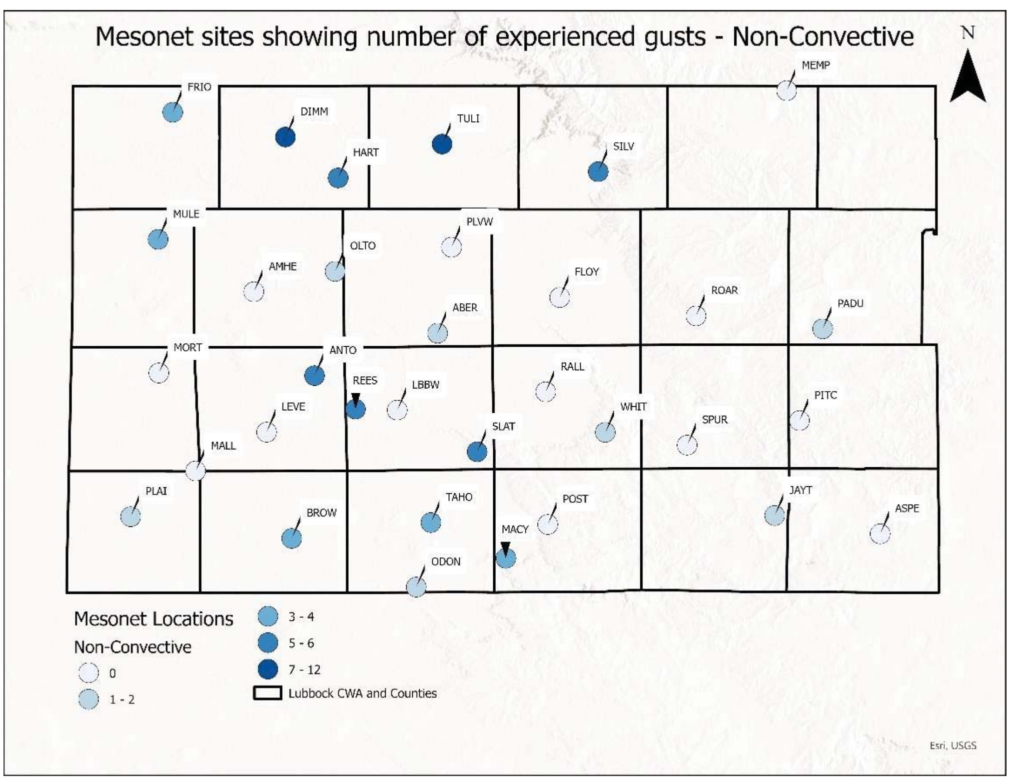

Figure 15: Mesonet sites displaying the number of non-convective severe gusts experienced at that site. For tail size variance, see Figure 9.

These maps (figures 9 through 15) demonstrate the variability of the distribution of convective mode of events across the Lubbock CWA. Organized Linear, Organized Cellular, and Unorganized Cellular, which were the top producers of severe gusts by count, are spread relatively evenly across the entire region. Results show some clustering of unorganized linear in the northwest regions of the Lubbock CWA as well as some clustering of non-convective gusts in the western half of the Lubbock.

When viewing the supercell classification, research shows highly clustered results around very few mesonet stations even though supercells occur in all areas across this region. These highly clustered values are the result of a supercell winds spatial extent. Contrary to an organized linear system that can affect a large region, supercells are highly dependent on how many mesonet stations are present in its comparatively small path across the same region. It is more likely for severe winds produced by supercells to occur between stations and never be measured by a mesonet at all. Because of this, severe supercell gusts are likely under-sampled, biasing the occurrence of severe wind gusts to the spatially larger convective classifications.

DETERMINING WIND DIRECTION:

When discussing how ASOS and AWOS wind readings are used in engineering, Lombardo and Zickar (2019) recognized the importance of wind direction recordings. Their work argues that “thunderstorm winds tend to contribute to and in some cases “control” the extreme wind climate.” For this reason, they conclude that the extreme wind climate needs to be considered independently from that of the non-extreme winds to properly account for structural loading due to possible experienced winds.

This study looks at the wind direction associated with all 1042 gusts recorded. It was assumed that the wind direction recorded within the 5-minute interval was the direction in which the severe wind traveled. This recorded wind direction is the average wind direction for the entire 5-minute interval containing the severe wind gust. Unfortunately, due to the limitations of the WTM, a more precise measurement is not currently available. While interpreting three-second gusts using a five-minute average is not ideal, making this assumption did produce some telling statistics.

To help interpret the direction data produced, descriptive statistics were generated from the “10-meter Wind Direction Standard Deviation” values. These values represent a value in degrees that can be used to interpret variation in motion of the wind across the 5-minute recording timeframe. The statistics derived are shown in Table 2 below.

Table 2: Descriptive statistics for all wind direction standard deviation values

Mean	12.264
Standard Error	0.235
Median	9.825
Mode	7.55
Sample Variance	57.737
Kurtosis	7.338
Skewness	2.243
Range	56.275
Maximum	3.625
Minimum	59.9
Confidence Level (95%)	0.462

The average standard deviation was +/- 12.264 degrees from the recorded wind direction with a confidence interval of +/- 0.462 degrees or less than one degree in either direction. Figure 16 below shows recorded values (black), recorded values with added standard deviation values (blue), and recorded values with subtracted standard deviation values (red). This figure was produced to understand how the winds shift if they were to move just one standard deviation in either direction. This method allowed for the assessment of the consistency of the wind throughout the 5-minute average. Table 3 (below) was created to show the degree requirements for each wind direction. These degree requirements are binned to the generally accepted standard degree requirements for all compass degree conversions. Table 3 also lists the count of occurrences a wind direction fell within the defined numerical boundaries of each binned order.

Table 3: Wind direction, bounding degree limits of each direction, and count of occurrences between said bounding degree values.

Direction	Numerical Bounds in Degrees	Count
N	337.5˚-22.5˚	118
NE	22.5˚-67.5˚	53
E	67.5˚-112.5˚	41
SE	112.5˚-157.5˚	112
S	157.5˚-202.5˚	128
SW	202.5˚-247.5˚	140
W	247.5˚-292.5˚	170
NW	292.5˚-337.5˚	280

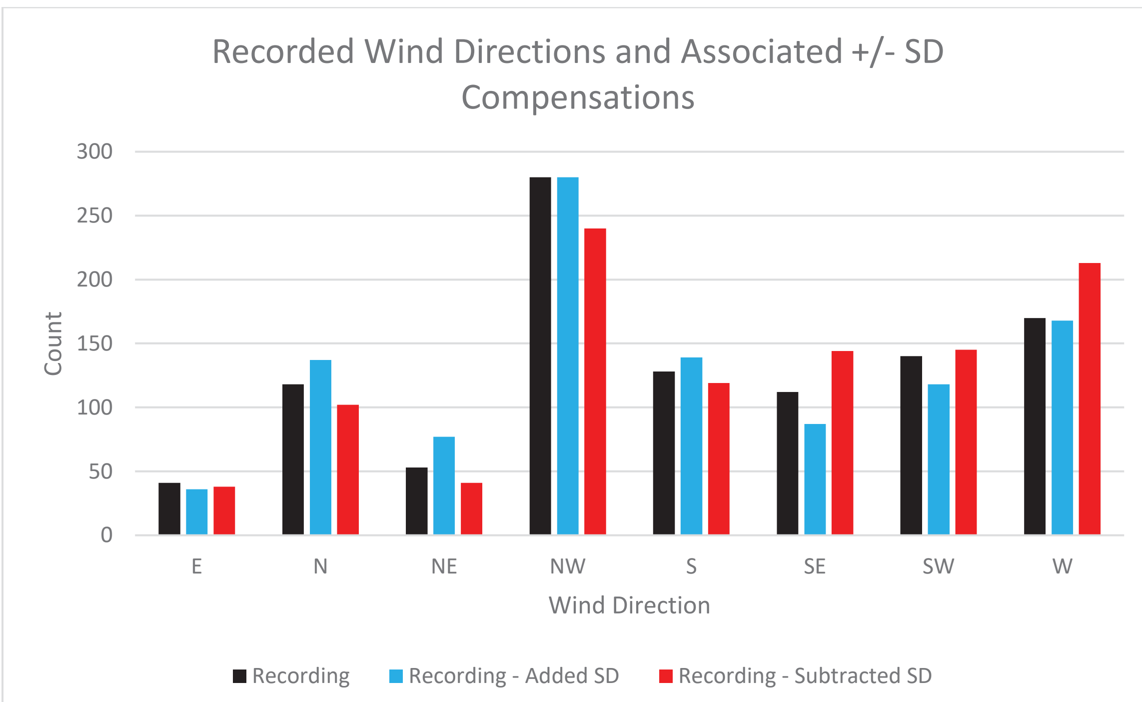

Figure 16: Recorded wind directions (black), recordings with added standard deviation value (blue), and recordings with subtracted standard deviation value (red), converted to letter representation.

The research found that a majority of the severe gusts occur when the average wind direction is from the northwest, 280 total, or 27% of all severe wind gusts. The second highest value was from the west, with 170 recorded gusts, or 16%. When combined, the northwest and west winds account for 43% of all gusts recorded in this study, signaling a strong likelihood that severe gusts may be coming from convective systems presenting these average 10m wind directions. The least number of severe gusts came from the east, with 41 gusts, or 4% of the total. These results are displayed in Figure 17. The topmost histogram of Figure 17 shows the distribution of wind gusts in degrees.

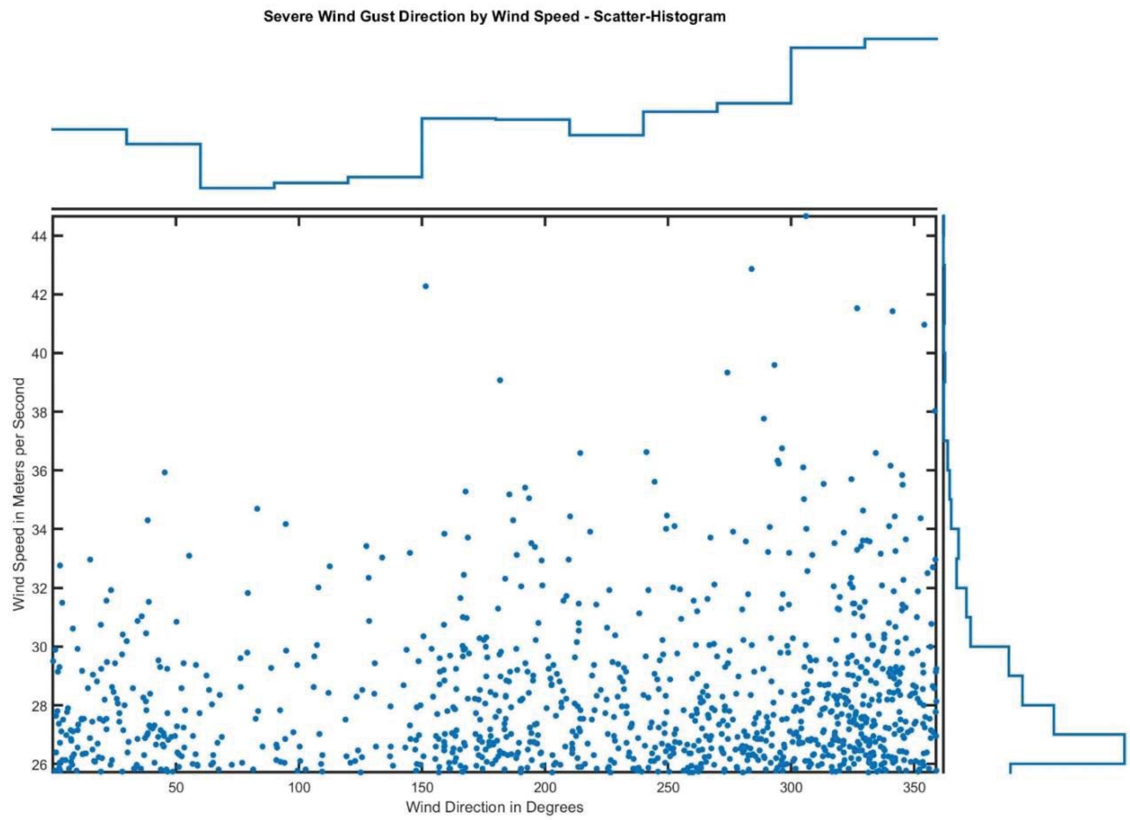

Figure 17: Severe Wind Gust Direction by Wind Speed – Scatter-Histogram

PRODUCTION, VELOCITY, AND FREQUENCY ANALYSIS:

The radar classification was also a goal of the study. It aims to describe the wind direction each gust is experienced at and what convective mode is associated with each gust. The classification modes used were: Non-Convective, Organized Linear, Unorganized Linear, Organized Cellular, Unorganized Cellular, and Supercell. Considering these categories, Organized Linear was the overall major producer of severe wind gusts across the region, totaling 395 recordings, or 38% of the total. Organized Cellular followed this at 306 recordings or 29%. Supercells accounted for the least occurrences, with 29 recordings, or roughly 3% of total gusts. The low supercell count was not unexpected due to the localization of winds and their relatively narrow spatial size compared to the other convective modes. Non-Convective classed wind gusts were only counted if convection was present within the Lubbock CWA, or if the convection located just outside of the Lubbock CWA was within a 25-mile radius of the mesonet station. Had this not been the case, the number of non-convective severe gusts would be far greater. Lastly, of the 1042 gusts analyzed, 59 or roughly 5.5% of the gusts experienced across the Lubbock CWA were significantly severe (exceeding 33.4 m $s^{-1)}$. The convective mode and the number of occurrences are recorded in Table 4 below. As discussed above, due to the spatial disparities between supercells and their larger convective counterparts, these results bias heavily against the supercell classification.

Table 4: Convective mode to count

Convective Mode	Count
Organized Linear	395
Organized Cellular	306
Unorganized Linear	34
Unorganized Cellular	204
Non-Convective	74
Supercell	29
Total	1042

To compensate for this bias, an analysis was performed by looking at each event as a whole. This event analysis was conducted using a subjective breakdown of convective wind gusts into their respective events by analyzing the time of the wind gusts, the dates the gusts occurred, and radar imaging when needed. The results of the analysis are shown in table 5 below. Each classification of events matches that of the classification of gusts within the event. The only difference here is the addition of a "Multi-Modal" category, which is for convective events which contained two or more convective classifications across the Lubbock CWA.

Table 5: Event count by classification

Convective Mode	Count
Organized Linear	58
Organized Cellular	93
Unorganized Linear	8
Unorganized Cellular	78
Supercell	5
Non-Convective	17
Multi-Modal	53
Total	312

Of the events classified, organized cellular events occurred the most often accounting for about 30% of all events, followed by organized cellular which accounted for 25% of all events. Most noticeable is where the change in the organized linear classification. Although it is the top producer of recorded wind gusts across the Lubbock CWA, these convective systems only account for 18.5% of all events recorded. The Multi-Modal classification occurs about 17% of the time. This analysis does aid to reduce the bias among larger convective systems to that of the smaller supercell events, placing supercell and unorganized linear on par with each other and accounting for about 5% of all events when combined (2.2% and 2.8% respectively).

Each classified convective system was then looked at to determine its maximum, minimum, and mean values to compare how each mode presents compared to the others. It was not surprising to see, as shown in Table 5, that all the convective types had severe gust minimums well within two-tenths of a meter per second. As shown in Figure 17 above, when looking at the histogram on the right side of the chart, evidence suggests that the frequency of the severe gust recordings mimics that of a negative exponential distribution curve, where it is expected that larger counts of events will occur at the lowest values of the data. In comparison, higher values will present with lower counts. This data was also visualized using a box-and-whisker plot, where we can see the max values of each convective type are the exception to the rule. Outliers were computed automatically in Microsoft Excel. Excel calculates outliers by following the rule that any value is considered an outlier if it is 1.5 times the interquartile range larger than the third quartile value or any value is 1.5 times the interquartile range smaller than the first quartile value, assuming a normal distribution. See equations 1a and 1b below for formulation.

Equations 1a and 1b: Outlier Rules

1a. $Q3 + ((Q3 - Q1) * 1.5)$ = Upper Outliers

1b. $Q1 - ((Q3 - Q1) * 1.5)$ = Lower Outliers

Table 6: Convective type with accompanying maximum, minimum, and mean wind gust speeds. Each value shown is in m s^{-1}, rounded to two decimal places.

Type	Maximum	Minimum	Mean
Organized Linear	42.86	25.71	28.18258228
Organized Cellular	40.96	25.71	28.07813725
Unorganized Linear	31.92	25.84	27.75794118
Unorganized Cellular	44.66	25.71	28.70
Non-Convective	36.1	25.71	27.78527027
Supercell	41.42	25.84	29.87517241

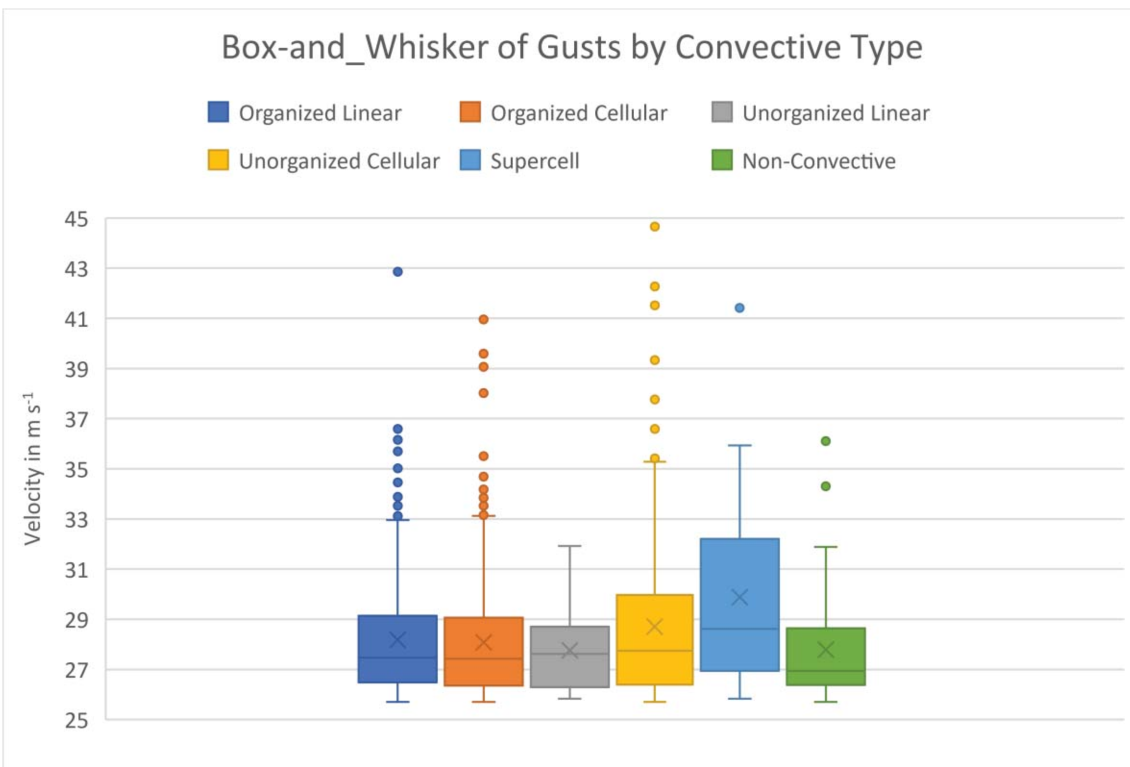

Figure 18: Box-and-Whisker plot of gusts by convective type, including outliers.

Each box and whisker contain a horizontal line that displays the median value of that convective classification's velocity, with the "x" representing the mean value. The top and bottom lines of the box represent the mean values of the third and first quartiles respectively, and the horizontal line connected to the bottom whisker represents the minimum velocity within each classification. The top horizontal whisker line for unorganized linear convection represents the maximum gust experienced for that classification but this is not the same for all of the other convective modes. Because the other modes contain outliers, shown as points above the top horizontal line, the horizontal line indicates the highest value within the threshold defined by equation 1a above.

Combining the results displayed in Figures 17 and 18, it appears that this region experiences a substantial amount of wind gusts within the first 4.5 m s^{-1} of meeting the severe wind classification, about 79% of all gusts recorded, though higher wind speeds are occasionally observed about 21% of the time. The box and whisker plot demonstrates that supercells have the highest mean wind velocity of all classifications. This could, however, be due to the very small sample size compared to other convective modes. Unorganized cellular contributed the highest severe wind gust in the dataset, while organized cellular had the most outliers.

The data from this project was able to demonstrate the variability of the severe gusts throughout the day and year. Figure 19 shows that severe convective gusts begin to increase in March, peak in June, then gradually taper throughout the summer and fall. February was the only month in this study that did not experience a single severe convective wind event at any of the studied mesonet sites. Figure 20 shows measured gusts beginning to increase around 1 PM CST and peaking between 5 PM and 9 PM CST before tapering off throughout the evening and reaching minimum values into the early hours of the morning.

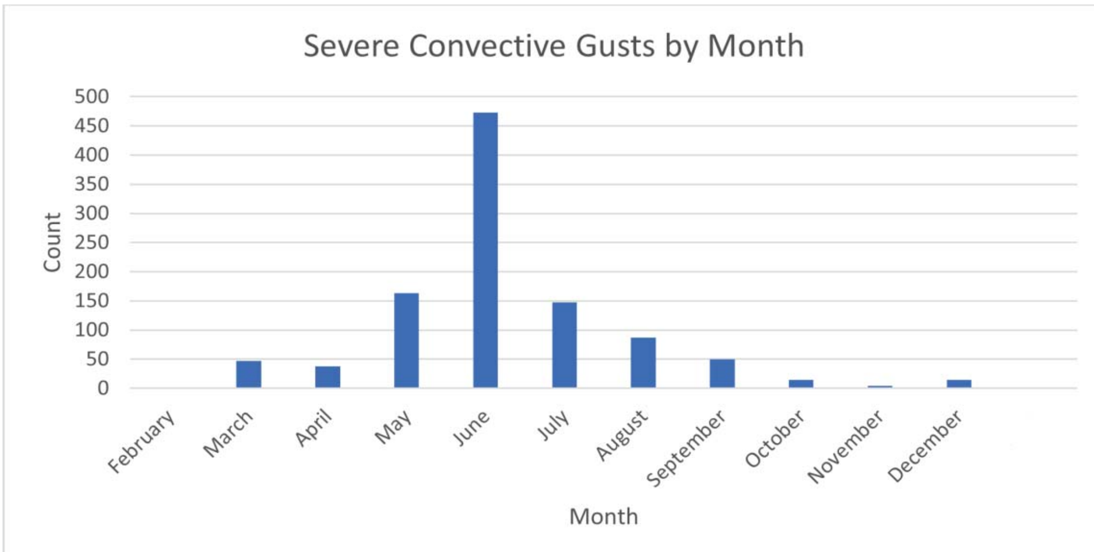

Figure 19: Severe convective gusts by month

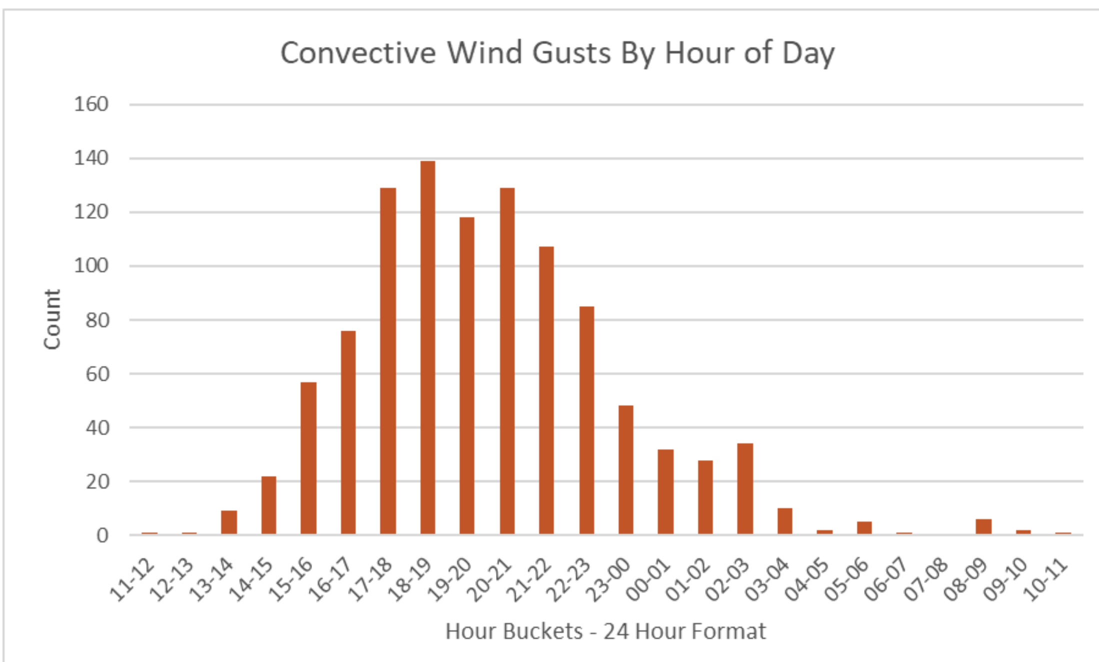

Figure 20: Convective gusts by hour of day. Times displayed in 24-hour format beginning at the 11 am – 12 PM hour.

These results closely match those shown in Lombardo and Zickar (2019). As shown in Figure 21 (Lombardo and Zickar (2019) Figure 2), the results of their study and this study find supporting evidence of an increase in convective activity in the spring with a peak in the summer months, as well as peak convection occurring during the mid to late afternoon when these regions experience peak heating from the sun. Although the Lubbock CWA experiences a peak earlier than what is shown in Lombardo and Zickar (2019), this is something to be expected as prime convective environments migrate seasonally. Considering the Lombardo and Zickar (2019) analysis was performed on a national scale, it is encouraging to see this similar trend on an extremely local scale using data with a much higher spatial resolution.

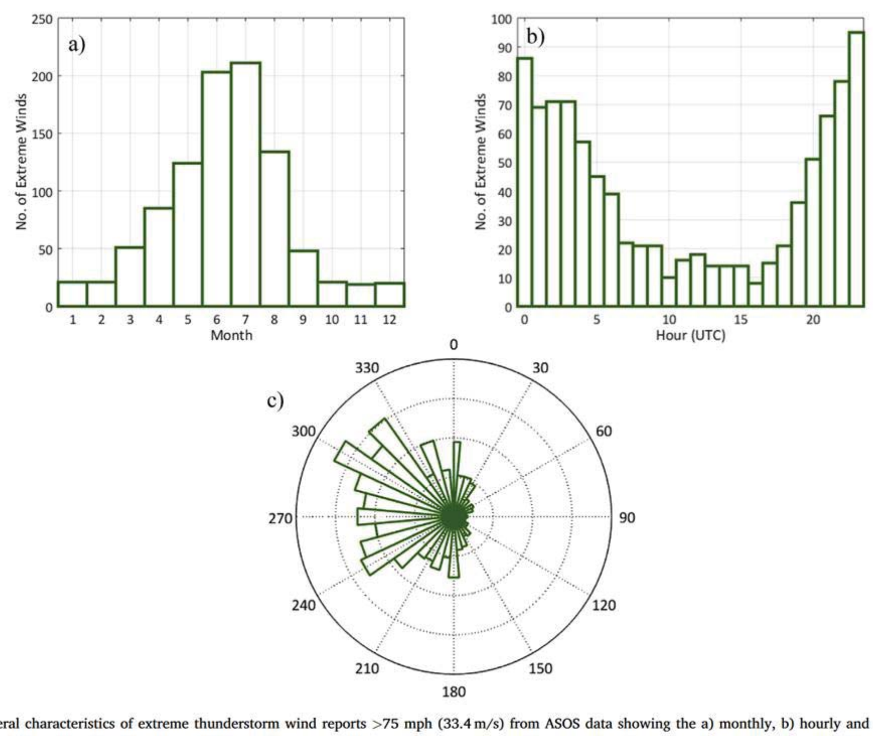

Fig. 2. General characteristics of extreme thunderstorm wind reports >75 mph (33.4 m/s) from ASOS data showing the a) monthly, b) hourly and c) directional distributions.

Figure 21: Lombardo and Zickar (2019), "Characteristics of measured extreme thunderstorm near-surface wind gusts in the United States". Chart a represents the number of extreme wind events by month. Chart b represents the number of extreme wind events by hour of day.

DAMAGE REPORT ANALYSIS:

To begin looking at the classifications of severe events to see which may have caused damage throughout Lubbock County, the data was filtered to only show events recorded by station 33. Adding more than one station would have allowed for a larger event count but overlapping 25-mile buffer zones and conflicting convective types would have been a potential issue for the methods used in this study. Keeping to one station's events, which has a buffer zone that encapsulates the entirety of Lubbock County, was the simplest way to proceed with this portion of the study while maximizing the probability of observing damage.

Over the 15-year period, severe gusts were measured from five events resulting in nine individual severe wind gusts available for storm damage analysis. Because of the natural delay in reporting, damage reports were counted for these events if they were delivered to the NWS either the day of the event or the following day.

Of the five events, only two had any recorded and vetted damage reports found on the Damage Assessment Toolkit. The Damage and Assessment toolkit differs from both the SPC and NCEI databases in that it houses a record of surveyed damage across the area, which has been vetted for quality control by the NWS. For this reason, it was chosen to ultimately provide the data points for the discussion below, while the SPC and NCEI databases were consulted as backups if data did not exist in the toolkit.

Both of the systems which produced this damage were classed as organized linear. With the majority of reported damage, the first date was 7/6/2005, with 74 recorded events across the county and a 10-meter, 3-second severe wind gust reading exceeding the severe gust threshold at 27.54 m s^{-1}. The second event, which was longer-lived, produced severe gusts for four consecutive 5-minute intervals on 6/6/2013. The max gust during this period was 33.19 m s^{-1}. The wind directions for these events were different, with the first event having a wind direction from the northwest while the second event had a wind direction from the west. This difference in wind direction is, however, not entirely surprising as most organized linear convection types contained a westerly component to their wind direction. Of the five events, three produced seven of the nine severe gusts. These seven severe gusts contained a westerly component, while the remaining two had an associated easterly component.

CONCLUSION:

The study began by asking two broad questions: could WTM data be used to develop a regional severe wind climatology that, when compared, reflects findings discussed in larger-scale national studies, and could the information be used to develop a verified and comprehensive severe wind climatology of the region? In short, the results are mixed.

Developing the severe wind climatology of the Lubbock CWA brought on unique challenges which had to be addressed. Many of the difficulties posed were related to the small size of the study area itself. The goal when the research began was to mimic, as close as possible, the national scaled studies to see if their methodology could be transposed or if greater flexibility was needed. Although classification was attempted using similar definitions defined in both Smith et al. (2012) and Schoen and Ashley (2011), it was found that what systems did move through the area required new defining criteria more specific to the regional weather patterns. Because of this, fewer classification categories were used, which simplified the classification process but at the cost of differentiating between, for example, a regular linear system or a bow echo within a linear system. Although it would not have been a challenge to include additional subcategories into the study, the details it would have brought forth would have been negligible at best. These subcategory events occurred far too infrequently to gain insight into their behaviors within such a small region.

Similarly, developing maps, such as kernel density maps or more advanced statistical point analysis maps, failed to reveal any details because there was not enough spatial dispersion of points to distinguishable differences in the data. Most points would experience the same convection type, particularly during large-scale events while smaller events were drastically under-sampled leading to a dataset heavily biased toward large-scale events. Only occasionally would small events traverse the area, but oftentimes they would slip between mesonet stations remaining unsampled.

Eliminating the bias brought on by large convective systems is difficult to do, but doing an event analysis coupled with the gust analysis revealed the highest producer of wind gusts is not the most common in the region. The analysis also shows that the Lubbock CWA is not 13.5 times more likely to experience a severe wind gust from an organized linear system. This number likely sits closer to four times more likely without considering the fact that supercells are still extremely under-sampled. Similar studies in the future should consider doing both analyses to compare outcomes. Adding more mesonet stations may help to sample smaller events but this will ultimately increase large event gust counts as well making this solution counterintuitive.

The spatial extent of the study is also why it is difficult to produce a meaningful comparison to its larger-scale inspirations. Convective events can be both local, in such cases as a supercell, or span multiple states, such as quasi-linear convective systems.

Given that synoptic drivers are likely the leading forcing mechanisms responsible for convection within this region, a more extensive study area with mesonet coverage is needed. The extent of synoptically driven convection is far too large for a single county warning area to account for. This could require multiple mesonet from different partners across several neighboring states. Doing this would bring forth its challenges, like accounting for differences in equipment, sampling intervals, spatial distribution, and a host of other complications; however, the benefits of such a study could be quite telling.

This study does achieve its primary goal of developing a verified severe wind climatology for the Lubbock CWA. The study shows that:

- A majority of severe gusts occur when the 5-minute average winds have a westerly component to them, primarily from the west or northwest. These severe gusts accounted for 57% of observed recordings.
- The number of severe gusts peaks in June, with more than double the occurrence of severe gusts recorded in May or July (the next two most active months).
- A majority of the severe gusts occur within the first 4.5 m s^{-1} of a wind gust meeting the severe velocity threshold. These severe gusts account for about 80% of the severe gusts observed.
- Extreme wind gusts (classified as winds with velocities greater than or equal to 33.4 m s^{-1}) occur very rarely and account for about 5.5% of all gusts.
- The highest producer of severe wind gusts is an organized linear system, producing 38% of all gusts recorded during the study period even though it is not the most common convective mode in this region.
- The most common convective mode is organized cellular, accounting for about 30% of all convective events.

The study also achieves its other primary goal of showing similar results to evidence found in national studies when developing a regional climatology, particularly Smith et al. (2012), Lombardo and Zickar (2019), and Kelly et al. (1985). The study reflects a seasonal increase in severe convective wind events in the south-central portion of the CONUS during the spring/early summer season until conditions more favorable for convective development migrate northward through the great plains and into southern Canada. The study also reflects evidence of diurnal patterns as the atmosphere's dynamics are influenced by the added energy from the sun. This study also reflects findings in Brotzge et al. (2011) where evidence suggests an increase in convective activity after 12 PM.

Although a damage analysis was performed, this analysis did not develop into the telling story which the research had initially intended to do. Problems with the number of reports across a large, sparsely populated region hindered the collection of damage information from reports by non-NWS personnel. Compounding this was the lack of spatial data included in reports generated by the public, particularly when reviewing reports on the SPC and NCEI websites. The NWS manages a wonderful resource of collected damage reports from NWS damage surveys on the Damage Analysis Toolkit website but lacks, at least in the events viewed for this research, any input not done by a survey of damage done by the NWS itself. This lack of information could be due to the age of the systems that crossed our analysis path, or the Damage Analysis Toolkit is only used for NWS surveys.

The damage analysis highlights that more effort needs to be put into garnering public input for generating reports, including spatial data. These reports need a resource similar to the Damage Analysis Toolkit or to be included as their own layer on the toolkit itself. Furthermore, more effort should focus on spreading the knowledge of the mPing report app developed in partnership with the National Severe Storms Lab (NSSL), the University of Oklahoma, and the Cooperative Institute of Mesoscale Meteorological Studies (NOAA/NSSL mPing (2014)) . Given the saturation of smartphones throughout society, storm reports from mPing could easily outpace all other forms of reporting within months.

This study also shows that valuable climatological information can be derived from mesonet sites sampling the lowest parts of our atmosphere. Flexibility in the parameters of a study to fit your area is critical, as this research shows, but beneficial information can be mined and put to use. As the WTM continues to collect data and more years pass, repeat studies should be done utilizing its entire expanse to see how the data may change. Adding an additional 15 years to create an average climatological record could drastically change the results of this study or further solidify the patterns seen within. As researchers develop the collective understanding of severe surface-level winds, mesonets may yet prove to be a vital link in determining the correlation and causation of our living space within the dynamic atmosphere.

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