THE SPATIAL DISTRIBUTION OF CONTIGUOUS UNITED STATES THUNDERSTORM RELATED SHORT-FUSE SEVERE WEATHER WARNINGS

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THE SPATIAL DISTRIBUTION OF CONTIGUOUS UNITED STATES

THUNDERSTORM RELATED SHORT-FUSE

SEVERE WEATHER WARNINGS

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ABSTRACT

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by

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August 2012

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The purpose of this research is to define the spatial distribution of short-fuse severe weather warnings as they relate to population density within the Contiguous United States (CONUS). Using Geographic Information Science and statistical techniques, the overall spatial pattern of National Weather Service (NWS) warning issuance was determined along with correlations to population distribution. Four basic short-fuse warning types were studied; severe thunderstorm county-based warnings, severe thunderstorm storm (polygon) based warnings, tornado county-based warnings, and tornado storm-based warnings. Severe weather warning and ambient population data were obtained from United States Government sources and were spatially joined to the United States Geological Survey's 7.5 minute, 1:24,000 (1:25,000 metric) Quadrangle Series. Counts of the number of warnings issued and population density for each Quadrangle in the CONUS were statistically compared to find correlations between the two data types. The direction of the center of mean warning distribution was compared to the geographic center of National Weather Service County Warning Areas to determine if a directional bias exists. This study finds that a spatial relationship to population exists for three warnings types: severe thunderstorm storm-based warnings, tornado county-based warnings and tornado storm-based warnings. Population bias statistical evidence is most prevalent for severe storm-based warnings. This study also finds that the spatial distribution of warnings has shifted with the transition to storm-based warnings from the central part of the Nation to the southeastern United States. The annual frequency of county-based severe and tornado warnings was highest for the Central Plains, where severe storm-based warnings were issued for distinctly defined county warning areas mainly in the south and southeastern United States. Tornado storm-based warnings were issued more frequently in the Deep South, southeast, and Gulf Coast areas. Several National Weather Service Weather Forecast Offices showed a tendency to have a high frequency of warnings when compared to neighboring NWS offices. Directional distribution varied drastically between weather forecast offices, but the overall tendency was for warnings to be issued to the south of the geographic center of National Weather Service County Warning Areas. Several weather forecast offices showed a tendency to issue more warnings in the up-range direction associated with climatological storm movement. Results from this study indicated that human influence is the main factor that contributes to warning frequency and spatial distribution.

CHAPTER I

SHORT-FUSE SEVERE WARNING SPATIAL DISTRIBUTION AND BIAS

A. Introduction

The research idea for this dissertation dates back to when the author was working as a broadcast meteorologist at a television station located in central Texas. The author observed that, when severe weather was approaching populated areas within the stations coverage zone, the local weathercasters would be in a highly vigilant "all hands on deck" mode. This often meant breaking into programming to alert viewers of the approaching danger. The approaching storms would be monitored closely, and the news department would often gear up to cover possible resulting damage or life threatening situations. As the storms moved into the most populated parts of the area, broadcast coverage would often go "wall to wall," meaning programming would be interrupted for an indefinite period of time.

Then something interesting would happen. After the storms passed the cities and populated zones in the viewing area, normal programming would resume, and station personnel would be allowed to take a break, or go home. The storms would often be just as severe after they passed the urban areas and moved "down range," but on-air coverage would be reduced. This process basically resulted in a situation where the urban and most population parts of the television coverage area would receive the most warnings and alerts. Lesser populated and rural regions were often under-warned.

The thought occurred to the author that perhaps this same process occurred with forecasters at the National Weather Service who are responsible for issuing official severe weather warnings in the United States. Similar to television stations, local National Weather Service Weather Forecast Offices are often located in the most populated parts of their coverage area. National Weather Service (NWS) personnel deal with reports and information requests from the public, which are more numerous in populated areas. The forecasters at the NWS work closely with local television stations (television weathercasters are referred to as “Media Partners” by the NWS), and often receive reports and feedback in severe weather situations. Therefore, it makes sense that NWS forecasters deal with the same professional pressures to pay more attention to severe weather events that affect populated areas.

This idea was reinforced when the author attended the 2011 National Severe Weather Workshop in Norman, Oklahoma. During a presentation by a staff member from the local NWS Weather Forecast Office, a local Emergency Manager raised his hand, was recognized, and made a statement. This public servant was from a community located about 32 kilometers (20 miles) to the east of the Norman and Oklahoma City urban areas (a location that is considered “down-range” based on normal storm movement in the area). His statement was to the effect of, “Everyone in this room knows that you issue more warnings and are more focused on the storms as they move into Oklahoma City, but you ignore the storm after they’ve passed through and moved into our area.” Several Emergency Managers in attendance echoed the concern over the under-warning issue for rural areas in Oklahoma. The National Weather Service representative giving the presentation did not have a response.

B. Purpose and Research Questions

The purpose of this study is to define the spatial and temporal distributions of thunderstorm-related short-fuse severe weather warnings and severe weather reports as they relate to non-meteorological factors outside of actual severe weather climatology. In other words, this dissertation seeks to determine if the National Weather Service issues more warnings for populated areas compared to lesser populated or rural regions, and if more warnings are issued "up-range," or in the direction of approaching storms. This study addresses short-fuse severe weather warnings issued by the National Weather Service within the 15-year-time period between January 1, 1996 and December 31, 2010.

This study seeks to define the spatial and temporal distribution of short-fuse severe weather warnings as they relate to factors outside of actual severe weather events. This study will focus on factors related directly to the locations of the National Weather Service County Warning Areas (CWA) and Weather Forecast Offices (WFO). To facilitate description of these distributions, three basic research questions are asked:

1. Do short-fuse severe warnings show a spatial relationship to population density for the entire Contiguous United States (CONUS)?

2. Do NWS County Warning Areas have different warning and severe weather reporting rates based on the location of the CWA and/or the ambient population of the CWA?

3. What is the difference in the number of warnings "up range" and "downrange" of densely populated urban areas and the associated WFO (high priority targets)? In other words, is there a directional emphasis on warning issuance?

The spatial and temporal distribution of short-fuse severe weather warnings is likely because of several technical and human factors outside of the actual location of severe weather events. The most significant technical limitations are related to gaps in the coverage of the WSR-88D NEXRAD radar network. The main human factor that will be addressed in this study is population bias. Although research has shown that factors including pressure placed on the forecaster by broadcast media and local emergency management, the fear of the warning forecasters to issue false alarms, and the "severe weather culture" of the region or community where the Weather Forecast Office is located may have influences on warning forecast, these factors are beyond the scope of this study.

C. Short-Fused Severe Weather

Short-fuse severe weather refers to weather events that occur within a climatologically short temporal time frame (Branick 2007). Short-fuse weather events develop rapidly and often last less than a few hours. This duration can be contrasted with the long-fuse event of a hurricane which can last for several weeks to a month, as is evidenced by Hurricane Ginger in 1971, which lasted for more than 27 days, and Hurricane John, which lasted for 31 days (Riley 2009).

Short-fuse severe weather events are generally associated with thunderstorms, and therefore are spatially small in scale when compared to tropical severe weather events (Meyers and Etkin 2000; Kunkel, et al. 1999). Severe weather events that can be directly related to thunderstorms are damaging winds, hail, and lightning. Tornadoes are generated from thunderstorms, and are typically the shortest events in the temporal scale. Although non-thunderstorm related situations can lead to flash floods (such as the failure of levees and dams, the sudden release of water from ice blockage, and tropical storm related rainfall), the majority of flash flooding is due to very heavy rain associated with slow moving thunderstorms (Smith, et al. 2001; NOAA/NWS 1992).

Because thunderstorms generate short-fuse severe weather hazards, several of these hazards can happen simultaneously within the same severe weather event. An example is the May 5, 1995 storm event which occurred in the Texas counties of Tarrant and Dallas (Hill 1996). This event started as a large thunderstorm moving from west to east into the city of Fort Worth during the early evening hours. The storm matured into a softball-size hail-producing "super-storm" as it moved into the most populated areas of the city, injuring 109 people. The storm continued to move east into Dallas County and the city of Dallas, where the storm transformed into a heavy rain producer. The torrential rains caused flash flooding which resulted in 18 deaths and 23 injuries (NCDC 2009). In the two hours that it took for the storm to move across the Fort Worth/Dallas area, 19 people died and 132 were injured. The estimated 1.1 to 2 billion dollars in hail and flood damage caused by the storm make it the costliest single thunderstorm in United States history (The Weather Channel 2009; Changnon and Burroughs 2003).

D. Short-Fuse Severe Weather Warnings

Short-fuse severe weather warnings issued by the National Weather Service include severe thunderstorm, tornado, and flash flood warnings (NWS 1996). Warnings are based on criteria that relate to the severity of the event. For a severe thunderstorm warning, the NWS criteria is a radar indicated or observed storm producing winds of 93.34 km/h (58 mph) or greater and/or hail of 2.54 cm (1 inch, changed in 2010 from 1.905 cm (0.75 inch)) in diameter or larger (NWS 2008). It is worth noting that lightning is not taken into account during the warning process. For a tornado warning, there must be radar indications that a thunderstorm is producing the rotation necessary for tornado formation, or there must be eyewitness verification that a tornado is occurring. For flash flood warnings, there must be indications from monitoring gauges or eyewitness reports that a flash flood is occurring, although warnings can be issued based on radar estimates of rainfall. Flash flood warnings will often take into account the amount of saturation as it relates to potential runoff in a particular location (Carpenter, et al. 1999).

Since the modernization and restructuring of the National Weather Service in the mid-1990's, short-fuse severe weather warnings are issued at a local NWS office termed the Weather Forecast Office or WFO (Friday 1994). One hundred and sixteen WFOs exist in the contiguous United States; each with a warning area of responsibility termed the County Warning Area or CWA. The staff of the WFO uses data from the WSR-88D Doppler radar network and interpretive computer algorithms, along with visual observations from storm spotters, reports from the general public, and data from weather stations (Stensrud, et al. 2009). To a limited extent, the forecasters will utilize satellite imagery, although the long temporal scale makes this information less useful for analyzing short-term storms as opposed to long-fuse weather events such as hurricanes.

Prior to October 1, 2007, all short-fuse severe warnings were issued for entire counties (Sutter and Erickson 2010). Beginning in 2005 the National Weather Service began issuing experimental warnings based on individual storms in an effort to reduce over-warning for severe weather events (NOAA 2007). These experimental warnings were issued for areas represented graphically by polygons and were often much smaller than comparable warnings for entire counties, and reduced area coverage by 70%-75%

(Jacks and Ferree 2007). Based on the success of the experimental storm-based warnings, the NWS switched to the polygon warning system in 2007.

Short-fuse severe weather warnings issued by the National Weather Service do not necessarily reflect nature. In other words, short-fuse severe warnings and reports are spatially and temporally non-homogeneous. Figure 1.1 shows an area normalized map of total county-based severe thunderstorm warnings for the contiguous United States. Although this map compares favorably overall to the spatial patterns of thunderstorms as defined by Changnon (2003), apparent “hot spots” are present within the boundaries of NWS County Warning Areas.

On the surface, Figure 1.1 might indicate that certain regions, and especially those surrounding densely populated urban areas are prone to experience a great number of severe weather events, but this is not necessarily the case. Although research indicates that urban areas can have the effect of initiating thunderstorm development (Changnon 2001); this effect is found to be related to surface heating and airmass instability as opposed to frontally produced severe thunderstorms (Stallins and Bentley 2006). In addition, storms which are moving toward cities often change direction and move around the urban area (Bornstein and Lin 2000). Additional research has shown that storm enhancement occurs in a general easterly direction from urban centers (Changnon 2001; Shepherd, Pierce and Negri 2002). These studies indicate that warnings favoring urban areas cannot be explained by the urban influence on atmospheric conditions alone. Although research by Medlin and Croft (1998) demonstrates how topography can influence the generation of thunderstorms, physiographic influences on severe weather development are beyond the scope of this study.

Perhaps then, a greater bias exists within the spatial distribution of National Weather Service Weather Forecast Offices. Figure 1.2 (*A*) shows the distribution of severe thunderstorm warnings issued in 2009, compared to National Weather Service County Warning Areas. It can be seen that the spatial extent of the warnings are within the boundaries of specific CWAs. For example, the Columbia, South Carolina (CAE) CWA exhibits an unusually high number of warnings when compared to surrounding CWAs. This trend is not isolated to one year, as can be seen in the map of severe thunderstorm warnings for 2010 (Figure 1.2 (*B*)). This indicates that certain National Weather Service Weather Forecast Offices issue a greater number of warnings compared to other offices during similar severe weather situations.

National Weather Service severe weather forecasters are evaluated based on the number of false warnings (or false alarms) that they issue (NWS 2009). This evaluation is done by the means of a calculation referred to as the false alarm rate (FAR). The FAR is principally calculated based on the number of warnings issued compared to the number of warnings that are verified. Another method by which warning forecasters are judged is defined by Schaefer (1990) as the critical success index (CSI), which takes into account severe weather events that are not warned for, and the probability of detection (POD) for these events. The NWS works to reduce the FAR and improve the CSI through means of training courses for warning forecasters (NWS 2009).

The staff of certain WFOs may also actively seek to verify warnings by searching for severe weather reports and damage, which then become part of the National Climatic Data Center’s Storm Event Database. Barnes et al. (2007) suggest that NWS officials will look for reports that verify warnings that were issued, and are less likely to seek evidence of severe weather events that occurred, but were not warned for. This is especially true for non-tornadic severe weather events as is supported by Doswell, Brooks and Kay (2005). For the warning forecasters, false alarms can have undesirable financial consequences independent of losses from storm damage. Sutter and Erickson (2010) studied the monetary loss from time spent under tornado warnings outside of the loss from storm damage, and found that storm-based warnings may reduce the cost by up to $1.9 billion. Prior to the advent of storm-based warnings, Sutter and Erickson estimated the annual average loss at $2.7 billion. Smith (2003) gives an example of an over-warned tornado event in Wichita, Kansas, where it is estimated that close to $1,000,000 was lost in revenue during the hour that the tornado warning was in effect. Figures 3 and 4 show the distribution of severe wind reports that seem to favor specific CWAs.

Barnes et al. (2007) argue that the judging of forecasters based on the FAR can result in incidence of not warning for severe weather events that actually occur. They reason that the lack of reliable observations in rural areas can lead to warnings not being issued for less populated counties. It is also argued that NWS officials will actively seek to verify warnings that were issued, but are less likely to look for reports or evidence of severe weather events that occurred, but were not warned for.

Figure 1.3 shows severe thunderstorm warnings for 2009 centered on the Norman, Oklahoma CWA. It can be seen that a greater number of warnings occur to the west of the populated areas of the Oklahoma City metro, with a decrease in the number of warnings to the east. The general movement of severe weather systems and associated tornadoes in this region is generally from west to east (Suckling and Ashley 2006). The distribution of warnings in Oklahoma suggests either a decrease in the intensity of the severe weather event after it has passed over the populated urban area, or a tendency of the Weather Forecast Office to warn for storms approaching the metro as opposed to storms moving out of the area. One possible explanation for this directional distribution is the desire of the WFO to provide greater lead times to prepare densely populated areas for the approaching severe weather event (Scharfenberg, et al. 2011). Once the storm has passed the urban areas and WFO, there may be the tendency for the staff of the WFO to relax and not give the event as high of a priority, or shift focus to incoming severe weather systems that will have a greater impact on populated areas.

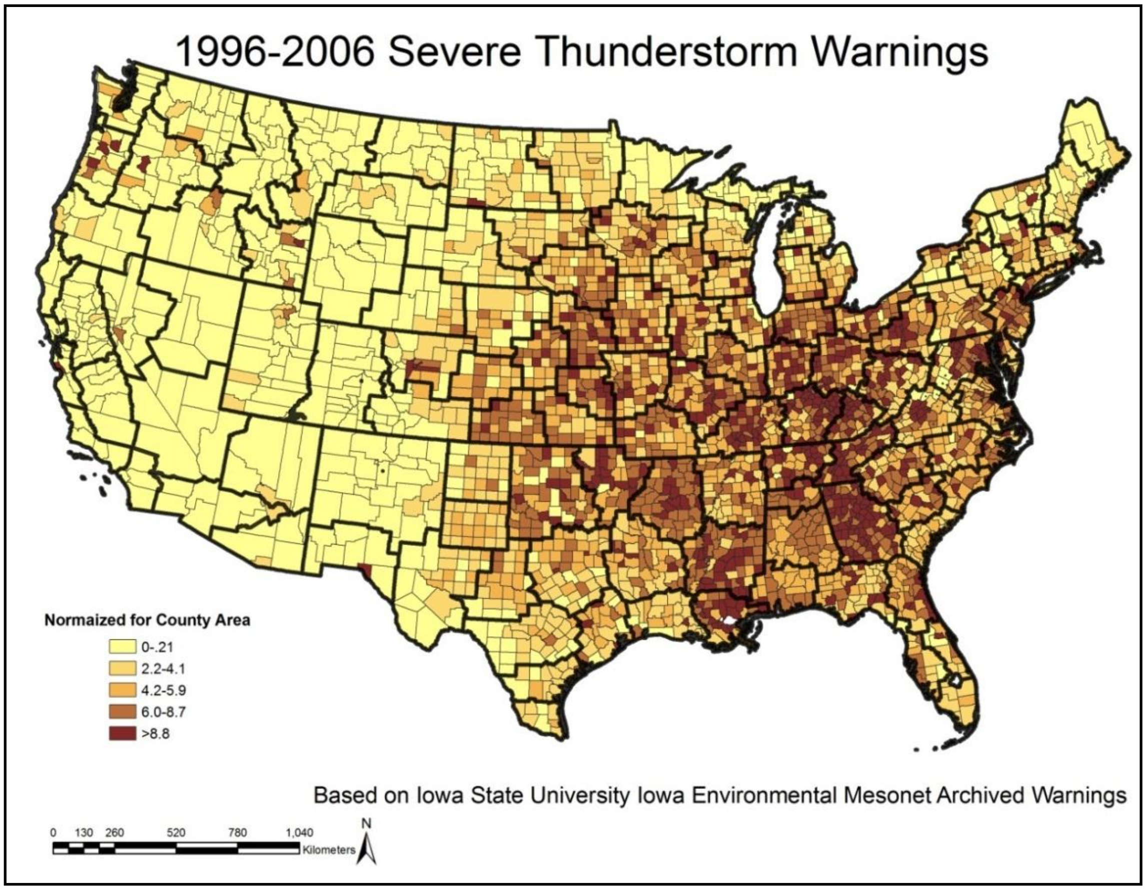

Figure 1.1. Total number of county based severe thunderstorm warnings issued by the National Weather Service between January 1996 and December 2006.

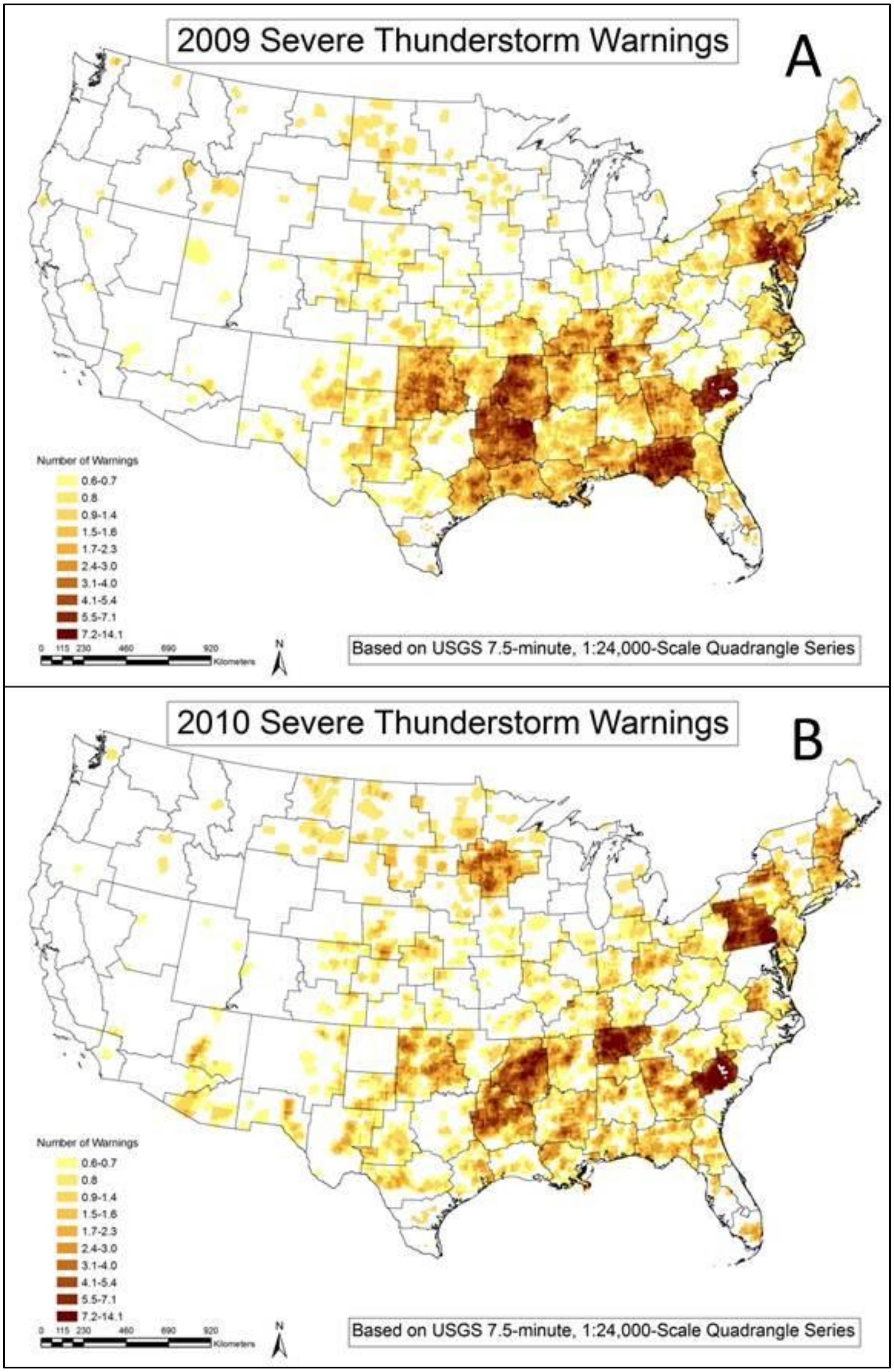

Figure 1.2. Spatial distribution of severe thunderstorm warnings in the Contiguous United States. Storm based severe warnings issued in 2009 are depicted in *A*, and storm based severe warnings issued in 2010 are depicted in *B*. The boundary lines indicate National Weather Service County Warning Areas.

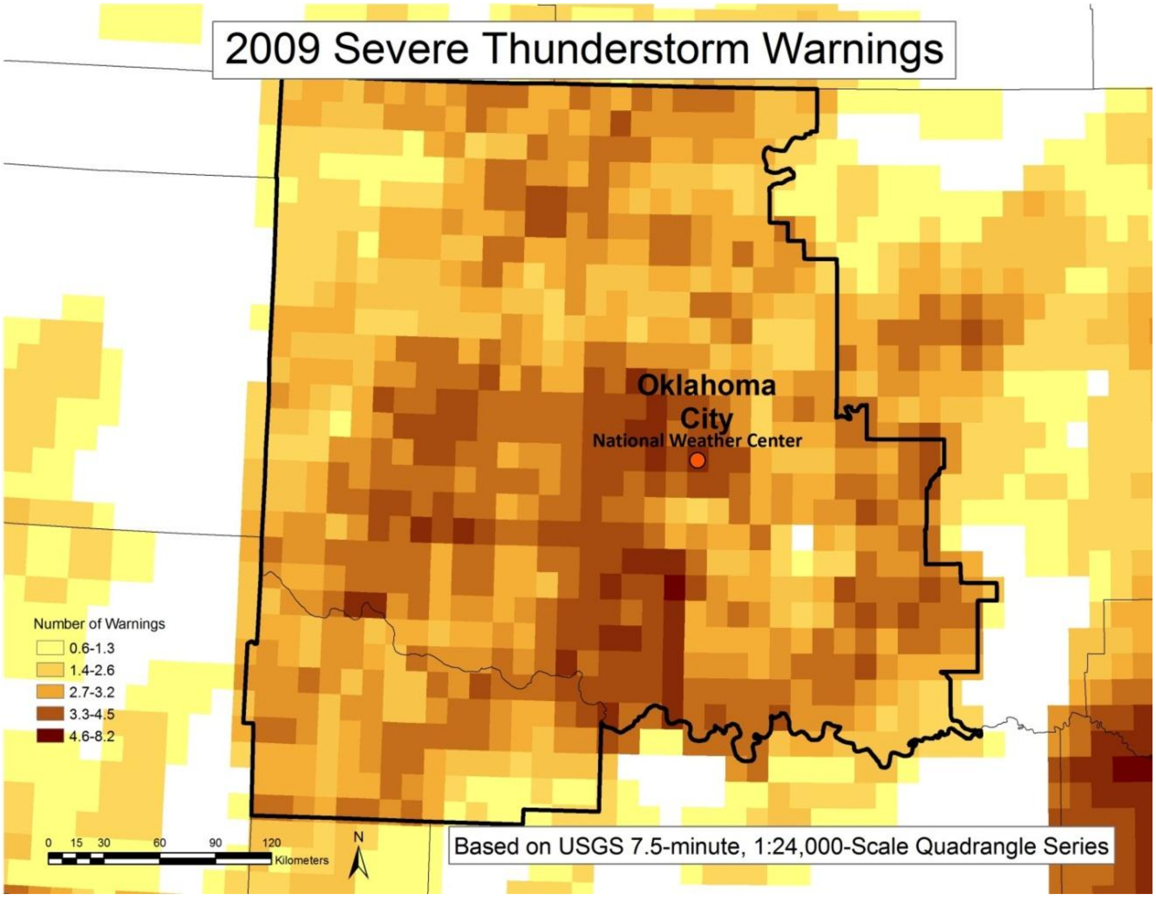

Figure 1.3. 2009 storm-based severe thunderstorm warnings for the Norman, Oklahoma (OUN) County Warning Area. This map not only shows a greater number of warnings issued for the CWA, but also a tendency for a greater number of warnings to be issued for areas to the west of the Oklahoma City metro.

E. Summary

Previous research has shown that the increase in the population of the United States correlates with increases in the number of severe weather reports. The spatial distribution of these reports has become non-homogeneous, and tends to be more frequent in densely populated areas. This leads to the perception that urban areas are more likely to be affected by severe weather phenomenon, and this is likely reflected in the distribution of warnings. However; a stronger argument can be made that the strength of the severe weather warning system is defined by the false alarm rate. In seeking to verify short-fuse warnings, National Weather Service Weather Forecast Offices conduct damage surveys and log severe weather reports which become part of the Storm Event Database. Results from this study are expected to show that the distribution of severe weather warnings is highly related to individual NWS WFOs, thus severe weather reports used to verify warnings are also related to WFOs. This would indicate that any severe weather climatology based on the Storm Event Database will contain biases, and future researchers basing studies on these data need to take the errors into account.

CHAPTER II

POSSIBLE FACTORS AFFECTING SHORT-FUSE WARNING SPATIAL DISTRIBUTION

A. Introduction

The spatial and temporal distribution of short-fuse severe weather warnings is likely because of several technical and human factors outside of the actual location of severe weather events. The most significant technical limitations are related to gaps in the coverage of the WSR-88D NEXRAD radar network. Human factors in the warning process include population bias, pressure placed on the forecaster by broadcast media and local emergency management, the fear of the warning forecasters to issue false alarms, and the "severe weather culture" of the region or community where the Weather Forecast Office is located.

B. Gaps in NEXRAD Radar Network Coverage

The WSR-88D radar network (NEXRAD) was developed in the 1980's and was fully operational and in use by the National Weather Service, Federal Aviation Administration and United States Department of Defense in 1997 (Whiton, et al. 1998). The NEXRAD system was the primary technological development that brought about the mid-90s modernization of the NWS. When compared to older radar technology in use prior to 1995, the WSR-88D radar system was a vast improvement and allowed for increased lead times when forecasting for short-fuse severe weather events (Bieringer and Ray 1996). The system led to an increase in the probability of detecting severe local storms and reducing the number of false alarm warnings (Crum, Saffle, and Wilson 1998). In addition the system was upgradeable, with numerous improvements to hardware and software implemented during the operational lifespan.

No system is perfect, and the NEXRAD network is no exception. Each individual radar in the network covers large areas, with many coverage domains overlapping; however, numerous areas in the contiguous United States are not covered (Maddox, et al. 2002). Within coverage domains there is variation in the radar signal because of radar beam broadening, variation in coverage height because of Earth curvature, and beam blockage because of terrain effects (Junyent, et al. 2010). In addition, temporal resolution is affected by the time it takes the radar system to scan each level of the atmosphere.

C. Population Bias

The primary human based explanation for inconsistency in the issuance of warnings is population bias (Barrett 2008). Acting on a purely scientific basis, the warning forecaster would issue warnings based on the strength of the storm, without regard for the population density of a certain county, thus producing a relatively uniform distribution of warning across the entire County Warning Area (CWA). However, National Weather Service (NWS) forecasters issue more warnings for populated areas. This may be because of several factors, including a greater number of observations and severe weather reports for populated areas, the desire of the warning forecasters to protect the maximum number of lives and property, and the greater likelihood that the severe weather event warned for will be confirmed by the denser population (Barnes, et al. 2007). Of particular interest is the possibility that there is pressure placed on the forecasters to appease the population, even when a storm is not at the severe threshold, thus leading to over-warning, and a greater number of false alarms.

Work by Hales (1993) shows several biases in severe thunderstorm reporting across the United States, the most prominent of which are population related. Aguirre et al. (1994) show that weak tornado reports increase substantially with increasing population. Research by Weiss and Vescio (1998) indicates a non-meteorological trend in the reporting of tornadic events that is related to population. Doswell, Brooks and Kay (2005) show that non-homogeneous reports are stronger for non-tornadic severe thunderstorms. Frisbie (2006) illustrates a temporal increase in the number of severe weather reports across the western portion of the United States, and shows a correlation between population growth and the increase in reports.

Ray et al. (2003) demonstrate that the spatial bias of tornado reports is related to population centers and radar location. Ray et al. postulate that population centers become areas in and near where it is most likely that a severe weather event will be observed.

Pietrycha and Fox (2004) document the number of storm spotters in the vicinity of the densely populated Amarillo, Texas, area during a severe weather outbreak in 2003. During this event, rural areas were not represented by real time weather reports, and there was difficulty within the National Weather Service office in the issuance of severe weather warnings because of the lack of storm spotter coverage in the less populated counties.

Schaefer and Edwards (1999) demonstrate the increase in the number of severe weather events reported over time. The authors attribute the increase to new weather observing technologies (including NEXRAD), changes in societal factors, and enhancement in communications. Schaefer and Edwards also found a correlation between an increase in urban population and a decrease in rural population with the spatial reports of severe weather events. The authors also point to problems with hail and wind reports, in that the observations typically come from individual locations, therefore little is known about the actual total area that is being or has been affected. Schaefer and Edwards specifically attribute the linear increase in tornado reports not only to population increase but also to heightened public awareness of tornado hazards.

Research by Trapp et al. (2006) on the value of using wind reports to determine severe thunderstorm event intensity indicates that not only is increasing population responsible for an increase in the number of severe wind reports but so is improved public severe storm education and awareness. Trapp et al. also suggest that NWS policy regarding the use of wind gust in the final severe weather report is also a factor in the spatial and temporal location of the reports.

Research by Barrett (2008) indicates that, not only is there a population bias in the reporting of severe thunderstorm events but also in the issuance of severe thunderstorm warnings by the National Weather Service (NWS). Barrett found that NWS warning forecasters in Texas issue more warnings for highly populated counties. This research also found that forecasters favored certain counties outside of the densely populated areas, indicating the possibility that the forecaster warns for counties where there is a greater likelihood that the storm will be reported and confirmed. The study also found that the greater the distance from the NWS office, the less likely that a warning will be issued.

Aguirre et al. (1993) ran a statistical test on tornado reports from 1950 through 1990 compared to various demographic data. The authors found that tornados are more frequent in urban counties compared to rural counties, and tornadoes occur more frequently after previous tornado events for the same county.

Kunkel, et al. (1999) studied temporal trends on the effect of severe weather events on society. The authors found that the number of thunderstorm-related catastrophes have increased in a linear trend since 1950 because of increase in population and urbanization. This study also notes that the number of tornado observations has increased in a linear correlation with population growth.

In contrast to the increasing number of weather events being reported, the number of severe weather-related fatalities has decreased with the modern industrial age. In a study conducted by Brooks and Doswell (2002), it was revealed that the number of tornado related fatalities generally decreased each year since 1945. However, the authors showed that the number of deaths for individuals living in mobile homes increased over the same time period. Brooks and Doswell also found that the number of deaths from individual tornados decreased across the entire population of the United States.

Closely related to pure population bias is the role of storm spotters. When looking at the arrangement of the NWS short-fuse warning structure, it becomes apparent that bias is introduced by the storm spotter and public report pieces of the system (Barrett 2008). If there are more “eyes” to see a storm in a populated area, then there is a greater likelihood that the storm will be reported. In an article by Doswell et al. (1999), it is shown that storm spotters have become an important part of the warning system for the NWS. The authors found that the number of storm spotters has increased since the first warning forecast issued by the NWS but this increase has happened in mostly populated regions. The study also acknowledges errors in severe storm reporting related to poor observations because of lack of training, and visibility issues resulting from terrain and distance. The authors estimate that up to 30% of reports may contain errors. Barnes, Brotzge, and Erickson (2010) acknowledge that, even among NWS trained storm spotters, expertise is unidentified and inconsistent.

The reporting of severe weather affects the diurnal distribution of short-fuse warnings because of the limiting factors of visibility during the nighttime hours. Nocturnal events are particularly dangerous, not only because of limitations in visually identifying tornado events but also because the majority of the population is asleep. Ashley (2007) found that during the time period of 1985 to 2005, 42.5% of all tornado fatalities in the contiguous United States occurred during the nighttime hours, compared to 25.8% of all reported nocturnal tornadoes.

Although this study will not seek to determine physiographic influences on storm initiation and strength, visibility limits because of landscape will be addressed. Terrain elevation and forest cover affect the consistency of severe weather reports (Ashley 2007). Tornadoes are much more likely to be seen and tracked across the relatively flat and non-forested landscape of the Central Plans, contrasting the challenges which face severe weather observers in the forested and topographically varied regions in the southeastern US. Compounding the visibility problem in the Southeast is the fact that the forested regions of Mississippi and Alabama also have a high occurrence of nocturnal tornadoes (Kis and Straka 2010).

D. The Role of Local Broadcast Television

Although warnings are issued by the National Weather Service, there are many studies that demonstrate how the majority of the population receives their primary severe weather information from broadcast television. Balluz et.al. (2000) conducted a survey after a tornado event in Arkansas, and found that the majority of respondents were informed of the issued tornado warning by local television stations. A survey conducted after the 1999 Oklahoma City tornado showed that 89% of the sampled population received warning information from television (Hammer and Schmidlin 2002). In a study by Sherman-Morris (2005), it was found that the overwhelming majority (93.6%) of respondents to a survey conducted in Memphis, Tennessee, learn of the threat of severe weather from local television stations. In severe weather perception surveys conducted in Denver, Colorado and Austin, Texas, Hayden et al. (2007) found that local television stations were the most significant source for acquiring severe weather information.

Cruz Inoa (2009) found that residents in San Juan, Puerto Rico, not only received the majority of their severe weather warning information from television but also gave greater credibility to a particular television weather-caster. Sherman-Morris (2007) found that the relationship viewers develop with their local weather-caster has an affect on how they respond to severe weather warnings. The study found that certain weather-casters have a greater influence on shelter seeking behavior.

Since 1995, the NWS has taken proactive measures to disseminate not only warnings but real time information about the status of warnings to television broadcasters

(Borden 2005). Borden describes how the NWS uses an internet based instant message system to communicate with local television stations during severe weather events. Information is passed between the NWS and the media. Television weather-casters provide the NWS warning forecasters with information from in-house weather systems and radar, and pass along severe weather reports from viewers. Borden demonstrates the importance the NWS places in its relationship with the media, and the need for timely dissemination of severe weather information to the majority of the population.

Kasperson and Kasperson (1996) demonstrate how mass media plays a vital role in the social amplification of risk. Television and print media often cover potential risk discerningly, choosing to cover potential events that are rare, while downplaying more common risk. This has the potential to lead to misconceptions about the seriousness of the risk, and can play into the "cry wolf" effect of human response to severe weather warnings.

Leiss (1996) argues that persuasive communication is not enough when it comes to the end result of actions taken by the population in response to the risk. Trust is the most important factor, and can only be gained from the demonstrations of accurate risk forecast over the long term.

Viscusi and Zeckhauser (1996) state that warnings must be tailored to the cognitive abilities of the end users in order to be effective. Too much information or information that is beyond the ability of the general population can lead to unsuccessful hazard warnings.

Stewart (2007) developed a method to relate verbal descriptions of weather to human perception of the atmospheric environment. This study works outside of normal quantitative weather descriptions, and instead uses English language adjectives to describe various weather conditions. The research was conducted using a survey method, and results indicate that correct verbal communication of severe or extreme weather events is more important than proper linguistics for common events. The study finds that proper verbal communication has a noticeable impact on overall severe weather perception.

Local television stations will often conduct campaigns for severe weather awareness. In addition to providing a useful source for the community to learn about and prepare for severe weather hazards, local TV stations also gain potential viewers. Therefore the severe weather awareness campaign becomes a marketing campaign (or branding promotion) for the station (Willi 2008). For TV stations, covering extreme weather events makes for good entertainment (Ungar 1999, Graham 2008). As demonstrated by Lowry et al. (2003) and Meyrowitz (1985), public perception of events is influenced by virtual experience through television, and these perceptions do not necessarily reflect the reality of the event. Broadcast meteorologists in effect control the preponderance of the public’s perception of a severe weather event, and have a vested interest in the location of short-fuse severe weather warnings.

E. False Alarms and “The Cry Wolf” Effect

Breznitz (1984) conducted a psychological laboratory study on the impact of false alarms on human perception of warning systems and hazard danger, and formed several ideas on the "cry wolf" effect. The author claims that modern attempts to warn for short-fuse, or "surprise" events, leads to more overall warnings, and therefore more false warnings. Breznitz's view is that, the greater the number of false alarms, the greater the loss of the credibility of the warning system. The author also notes the differences in warnings issued for events where extrinsic evidence of the hazard are available to the person receiving the warning (e.g., television radar images of a severe storm), and events where no extrinsic information is available. False extrinsic warnings are less susceptible to the loss of credibility of the warning system, because of the fact that the receiver of the warning can see that the false alarm as a result of the nature of the event, and not the fault of the warning system. Breznitz also asserts that true alarms augment both the positive perception of the warning system and the danger of the hazard, whereas false alarms diminish the integrity of only one of these two perceptions. Another postulation by Breznitz is that the number of consecutive false alarms correlates with loss of trust in the warning system; whereas, the number of consecutive true alarms correlates with the gaining of trust in the same system.

National Weather Service severe weather forecasters are evaluated based on the number of false warnings (or false alarms) that they issue (NWS 2009). This evaluation is done by the means of a calculation referred to as the false alarm rate (FAR). The FAR is basically calculated based on the number of warnings issued compared to the number of warnings that are verified. Another method by which warning forecasters are judged is defined by Schaefer (1990) as the critical success index (CSI), which takes into account severe weather events that are not warned for, and the probability of detection (POD) for these events. The NWS works to reduce the FAR and improve the CSI through means of training courses for warning forecasters (NWS 2009).

Barnes et al. (2007) argues that the judging of forecasters based on the FAR can result in incidents of not warning for severe weather events that actually occur. Barnes reasons that the lack of reliable observations in rural areas can lead to warnings not being issued for less populated counties. It is also argued that NWS officials will actively seek to verify warnings that were issued, and are less likely to look for reports or evidence of severe weather events that occurred but were not warned for.

Issuing a short-fuse warning can have undesirable financial consequences independent of losses from storm damage. Smith (2003) defined two types of false alarms and calculated the monetary loss from a severe weather false alarm event. The author divided the false alarms into categories of false warnings because of the limitations of meteorological science (unavoidable false alarms), and false alarms that are issued for areas not directly affected by the approaching hazards (unnecessary false alarms or over-warning). Smith gives an example of an over-warned tornado event in Wichita, Kansas, where it is estimated that close to $1,000,000 was lost in revenue during the hour that the tornado warning was in effect. Sutter and Erickson (2010) studied the monetary loss from time spent under tornado warnings outside of the loss from storm damage. The authors found that storm based warnings may reduce the cost by up to $1.9 billion. Prior to the advent of storm based warnings, Sutter and Erickson estimated the annual average loss at $2.7 billion.

Atwood and Major (1998) studied a false alarm for an earthquake warning, in which survey respondents indicated that they were less likely to give the same importance to future earthquake warnings. This research also showed that mass media coverage of the false warning heightened the false alarm effect.

A study conducted in Austin, Texas, found evidence contrary to the “cry wolf effect” in relation to tornado warnings. In the survey conducted by Schultz et al. (2007), it was established that a small percentage (13.8%) of the sampled population would pay less attention to future warnings after "one or two" false warnings. This finding is echoed by Monfredo and Tiefenbacher (2003), in that only one respondent from a survey conducted after a tornadic event thought that there were too many false alarms. It must be noted that these results are based on survey questions that ask about the impact of just a few false alarm events, and do not take into account numerous or consecutive scenarios.

F. Severe Weather Culture

Although the proposed research in this paper does not seek to study shelter seeking behavior relating to short-fuse severe weather warnings, the "severe weather culture" of National Weather Service County Warning Areas will be addressed. Place perception study is an approach of humanistic cultural geography (Myers et al. 2003). It deals with human understanding and reaction to community cultural environments. Place perception plays an important role in defining the severe weather culture of regions and communities. These perceptions define how the community prefers to be warned of severe weather threats and what actions it takes as a whole during an event.

Pennell (2009) conducted a survey study comparing the severe weather perception of residents of two United States cities based on past severe weather experiences. Both cities were within regions of the country which experience a high frequency of severe weather events; however, there was a contrast in previous severe weather events. Abilene, Texas, had not experienced a major weather event in recent history, contrasting Huntsville, Alabama, which had experienced several tornado outbreaks since the 1970's. Pennell found that the severe weather culture in Huntsville was strong when compared to Abilene. The author suggests that the previous storm experiences as well as greater severe weather coverage by local television stations and other media enhances the awareness and preparedness of the city.

As an example of how place perception affects the way in which the population prefers to receive information about severe weather warnings, research by Hayden et al. (2007) found that surveyed residents of Denver, Colorado, prefer to be warned of severe weather by sirens, whereas residents of Austin, Texas, prefer to obtain their warnings through television. The authors suggest that demographic and cultural factors of specific areas need to be addressed in order to determine the best warning method.

Certain demographic characteristics of the population can lead to different perceptions and reactions to weather risk. Mileti (1993) states that there are several factors that influence personal response to natural hazards warnings, including demographics and length of community residence. Balluz et al. (2000) demonstrate that education is a factor that can determine whether the population will respond to tornado warnings. Schmidlin et al. (2009) found that a surveyed sample of mobile home residents is more likely to take shelter if the residents have a high school education and/or children living in the household. Liu et al. (1996) found that persons with more than a high school education were six times more likely to take a tornado warning seriously and seek shelter. Semenza et al. (2008) conducted research in Portland, Oregon, and Houston, Texas, on public perception during hot weather and high air pollution events, and found that females react more to hazardous environmental clues when compared to males. The same study found other differences with regard to population demographics but these results were not consistent for the two cities.

In a pilot study by Cruz Inoa (2009), it was found that socio-economic and social characteristics influence reaction to short fuse severe weather warnings. A focus group indicated that the ethnic background of the receiver of the warning had an effect on actions taken during severe weather events. The prominent differences in these actions dealt with shelter seeking behavior. Cruz Inoa postulates that certain ethnic groups have a stronger social network than others, and these networks provide support for seeking safety during severe weather events. Cruz Inoa's hypothesis is supported by earlier research by Aguirre et al. (1991), who found that persons who are part of a strong social network are more likely to take notice of tornado warnings and seek shelter.

Donner (2003) developed a model to test the theory that demographic and organizational features of communities impact their resilience to tornado events. Donner discovered that areas with a large population of single mother households and elderly residents experience a higher death rate compared to tracts with a low proportion of single mothers and elderly. The author's results indicate that the Hispanic population is more resilient to tornado disasters when compared to other ethnic groups. The research indicated that there is a statistically significant number of deaths in time periods outside of the normal climatological tornado season. Donner also found that tornado watches do not significantly reduce tornado morbidity. Donner theorizes that the population that has immigrated into a region is not familiar with the area's "disaster culture," and therefore has a higher risk of morbidity because of tornadic events.

Bray and Shackley (2004) show the effects of public experience with weather events and how they affect belief systems. The authors constructed a model that relates direct experience with weather events and indirect experience from sources such as media reports, and correlated the results to belief formation. The direct weather experience of warming temperatures was shown to have a negative effect on the belief that temperature will continue to rise because the modeled population perceives the warmer temperatures as the norm. The authors also show that continued warnings by the media lead to saturation, where further "reports" have a negative effect on the risk belief system.

Knez et al. (2009) constructed a conceptual model to show the influence of several psychological factors on human response to weather variables and place perception. The authors found significant influences of weather conditions, age of individual and environmental awareness on place perception.

Mitchell (2000) argues that certain memories of disasters act as benchmarks for policy making. The author postulates that, although the memory of most major catastrophic events is lost or almost completely forgotten by the majority of the population over time, certain events are retained in the collective consciousness and become part of the sense of place. Mitchell contends that the memories are not totally lost, and can be restored when new, similar events, occur.

CHAPTER III

DATA AND METHODOLOGY

A. Introduction

The research approach for this study will be to test the relationships between various extraneous factors and short-fuse severe weather warnings. This study will also examine the associated severe weather reports from the Storm Event Database which are used for NWS verification. The methods described here will be performed using the ESRI ArcGIS 9 geographic information system. Because the data are spatial in origin, this study relies heavily on the GIS techniques of spatial layering and joining of spatial data. Statistical correlation tests are also used extensively in this study.

B. Data

This study covers the time period between January 1, 1996 and December 31, 2010. This stretch of time represents the 15-year-period after the modernization of the National Weather Service and associated implementation of forecasting technologies including the NEXRAD radar network. The October 1, 2007, change from county-based warnings to storm-based warnings occurs during this study period and allows for a spatial and temporal comparison of county-based and storm-based warning methods. Because 2007 is a transitional year, data from that year have been left out of this study.

Four types of short-fuse warnings were analyzed in this study. Severe county-based warnings (SCBW) are severe thunderstorm warnings that were issued between January 1, 1996 and December 31, 2006. Severe storm-based warnings (SSBW) are severe thunderstorm warnings issued between January 1, 2008 and December 31, 2010. Tornado county-based warnings (TCBW) are tornado warnings that were issued between January 1, 1996 and December 31, 2006. Tornado storm-based warnings (TSBW) are tornado warnings that were issued between January 1, 2008 and December 31, 2010. These data have been averaged to provide the mean number of warnings that were issued for each year and month for all 116 National Weather Service Weather Forecast Offices.

The smaller sample size relative to the short three year time period of the presence of storm-based warnings should be kept in mind when analyzing the results of this study. Because of the GIS gridding method used in this study, the number of storm-based warnings was also affected by the drastic decrease in the amount of area covered by single polygon warnings.

All data used in the spatial analysis for this study were converted to the Global Coordinate System North American Datum 1983 and projected in USA Contiguous Lambert Conformal Conic using ESRI ArcGIS. The main data types and sources used in this study are listed in Table 3.1. With the exception of Severe Weather Warnings from Iowa State University, all data are from United States government sources.

Table 3.1. Data types used in study and sources where data were obtained.

Data Type	Source
1:24,000 Quadrangle Series	US Geological Survey
Severe Weather Warnings	Iowa State University, National Climatic Data Center
WSR-88D NEXRAD Archive	National Climatic Data Center
Population	Oak Ridge National Laboratory, US Census Bureau
County Warning Area Boundaries	Storm Prediction Center

C. Spatial Grid

A consistent method of spatial representation of both county- and storm-based short-fuse warnings was developed for this study. Because of the extreme variations in polygon and county size, a uniform grid covering the contiguous United States is necessary. The use of a grid system also allows for the possibility of data smoothing using a Gaussian low-pass filter. This study used GIS spatial joining techniques to merge data of interest to the United States Geological Survey's (USGS) 7.5 minute, 1:24,000 (1:25,000 metric) Quadrangle Series. An example of this merging, or joining, of data is shown in Figure 3.1, where storm-based warning polygons are joined to each quad cell. In effect, each quadrangle becomes a cell in a grid system that covers the contiguous United States, and will be referred to as the quad grid. The 7.5 minute quadrangles represent a spatial area comparable to the extent of damage caused by individual storms. Although variation exists in the area of the quadrangles (ranging from 176 km^2 (68 square miles) in the Florida Keys to 126 km^2 (48.5 square miles) in the extreme northern part of Minnesota), this variation is minor when compared to the pronounced areal differences of counties and polygons. Because of the small variation in quad cell size, there is no need for the data to be spatially normalized for cell size. The use of the USGS

Quadrangle series also allows this study to be easily reproduced, and has the added benefit of providing specific physiographic details for use in future studies.

Although data is not adjusted for the area of the quad cells, spatial adjustment was performed for several of the analysis techniques that follow. Area adjustment of National Weather Service County Warning Areas and National Climatic Data Center climate regions was accomplished by dividing the average number of warnings by the measured geographic area (in square meters). This resulting number was then multiplied by 100,000,000,000, resulting in the area adjusted frequency or average number of yearly and monthly warnings. It should be noted when area adjusted results are presented that these data are not the actual average number of warnings for a given location.

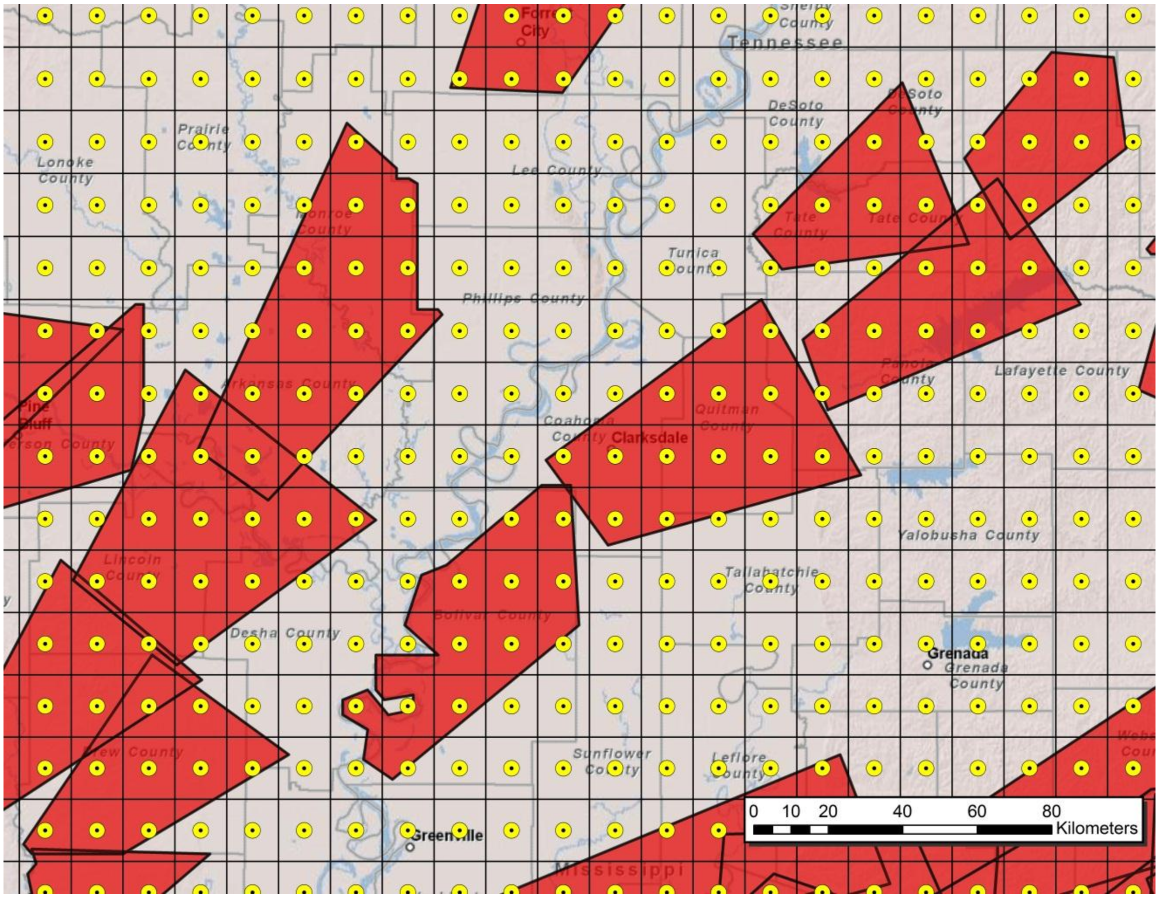

Figure 3.1. Example of the method used to merge warning data with the USGS 7.5 Minute Quadrangle Series. The red polygons represent tornado warnings. A warning is counted for the grid cell when the polygon or county covers the central point (yellow dot) of the grid.

D. Adjustments of Data

This study looks at influences outside of actual severe storm occurrences which affect the spatial distribution of short-fuse severe weather warnings. In order to "level the playing field" of the CONUS, two factors must be accounted for; severe weather climatology and gaps in NEXRAD coverage.

1. Severe Weather Climatology

First, the known severe weather climatology of the 48 states is taken into account. Because of the geography of the North American continent, severe weather is more frequent in certain regions. For example, far fewer thunderstorm-related severe weather events occur west of the Rocky Mountains. It is necessary for the short-fuse warning record to be normalized to the frequency of actual events. As noted earlier, the NCDC Storm Event Database is likely a poor representation of the spatial extent of actual events (Trapp, et al. 2006).

For this study, variations in severe weather frequency are taken into account using climate regions. The National Weather Service divides the Contiguous United States into four regions as shown in Figure 3.2. These regions are much too large to represent general severe weather climatology accurately. A better representation of severe weather is found by using climate regions as defined by the National Climatic Data Center (Enloe 2011). Figure 3.3 shows the NCDC division of the United States into nine climate regions.

A map of National Weather Service County Warning Areas grouped by National Climatic Data Center climate region was devised by using a GIS spatial overlay technique (Figure 3.4). A county warning area boundary layer was overlain over the National Climatic Data Center state boundary map. The grouping of the county warning areas into climate regions was determined by the majority of the CWA area that lies within a state's border. For example, the greatest part of the El Paso (EPZ) County Warning Area lies within the state of New Mexico, which is in the Southwest Climate Region. These climate groupings were then used to compare warnings amongst the county warning areas by similar expected severe weather climatology.

The frequency of warnings and reports was calculated for each climate region and associated CWAs and adjusted for area as noted previously. Warning counts were-based on the number of warnings issued by the associated WFO, averaged by year and month. This allows for a direct numerical comparison between CWAs.

2. Gaps in NEXRAD Radar Coverage

Second, gaps in the NEXRAD radar coverage may explain short-fuse warning distribution in under-warned areas. A NEXRAD network coverage GIS layer of the contiguous United States relevant to the time scale of this study was produced. Radar coverage data was obtained directly from the National Weather Service Radar Operations Center. These data contained coverage-based on radar beam elevation in space because of Earth curvature. These data also indicated areas were terrain blockage is a factor in radar coverage. The data were converted to the USGS 1:24,000 grid using GIS joining techniques, resulting in a map where coverage is divided into three sectors (Figure 3.5). Basically, a NEXRAD coverage of 0 means that there is no coverage, a coverage of 1 means that there is no coverage below 3048 meters, and a coverage of 2 indicates that coverage is almost perfect, with coverage at least below 1829 meters. This GIS layer was then spatially correlated with short-fuse warning distributions to determine locations where the lack of accurate radar coverage may be linked to under-warned severe weather events.

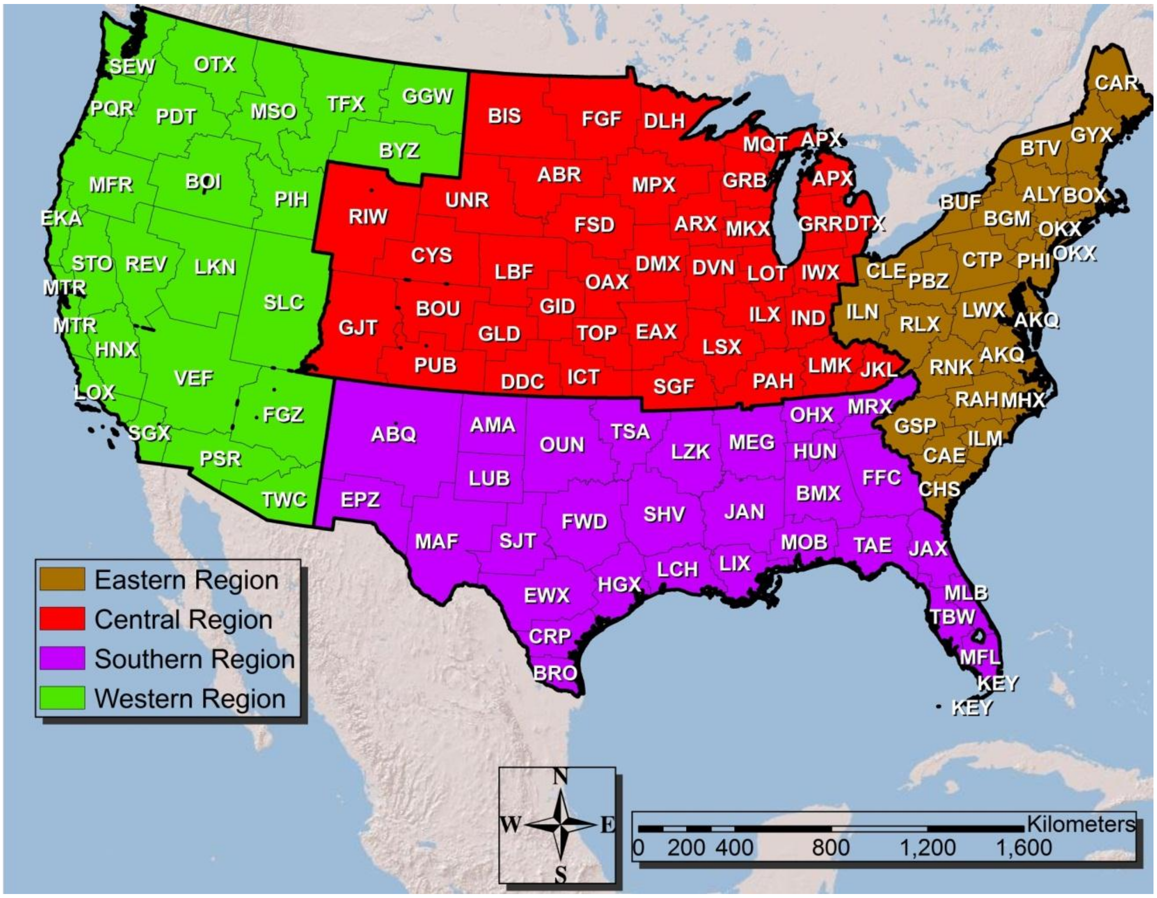

Figure 3.2. The four region division of the Contiguous United States as defined by the National Weather Service.

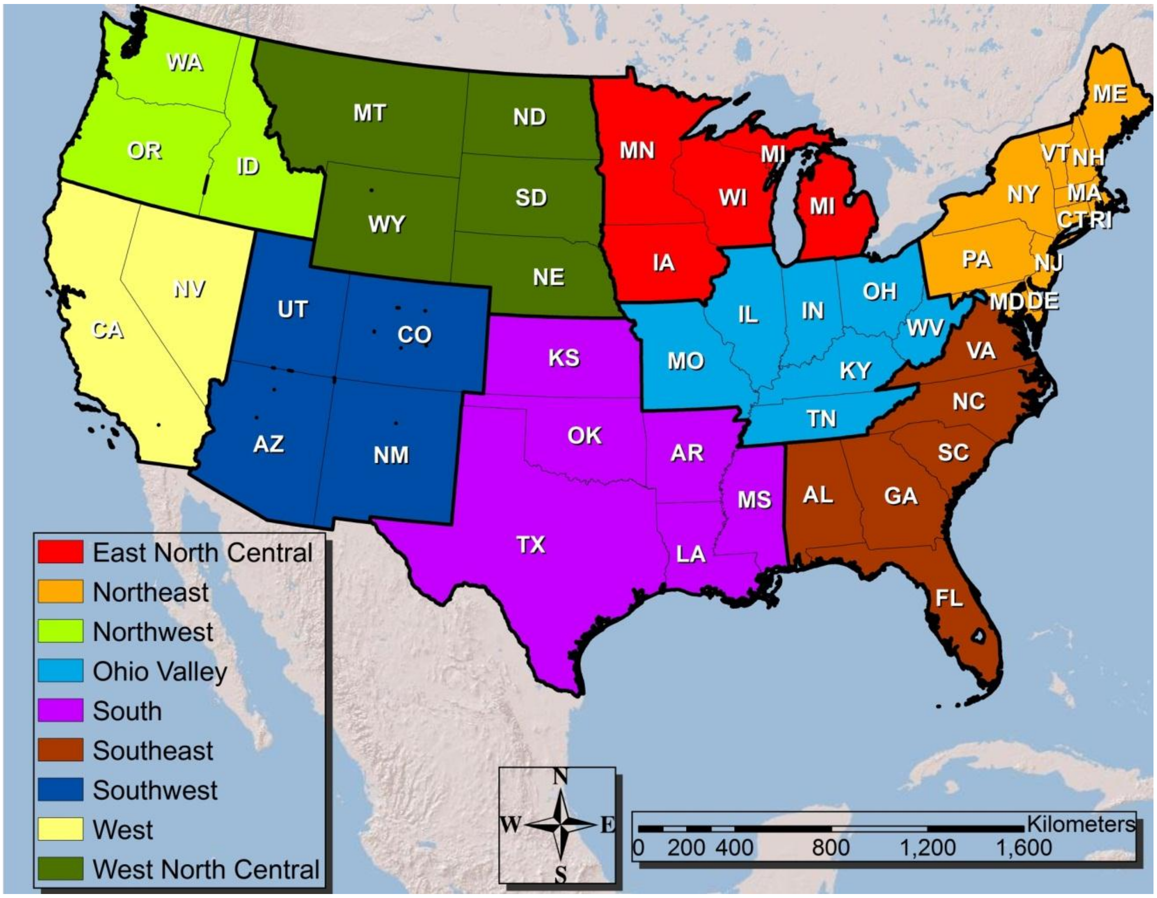

Figure 3.3. The nine climate regions of the Contiguous United States as defined by the National Climatic Data Center (Enloe 2011).

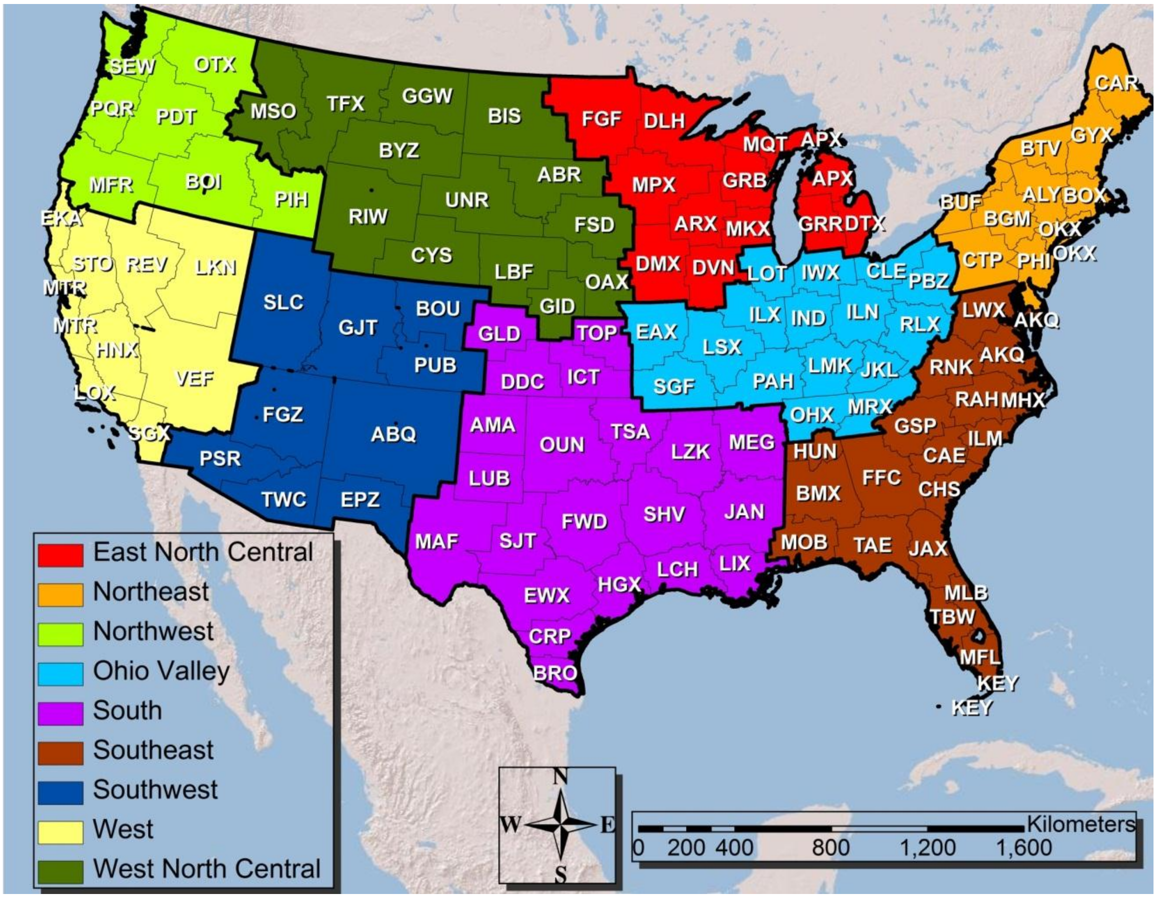

Figure 3.4. The derived National Weather Service County Warning Area climate region classification-based on the National Climatic Data Center climate regions.

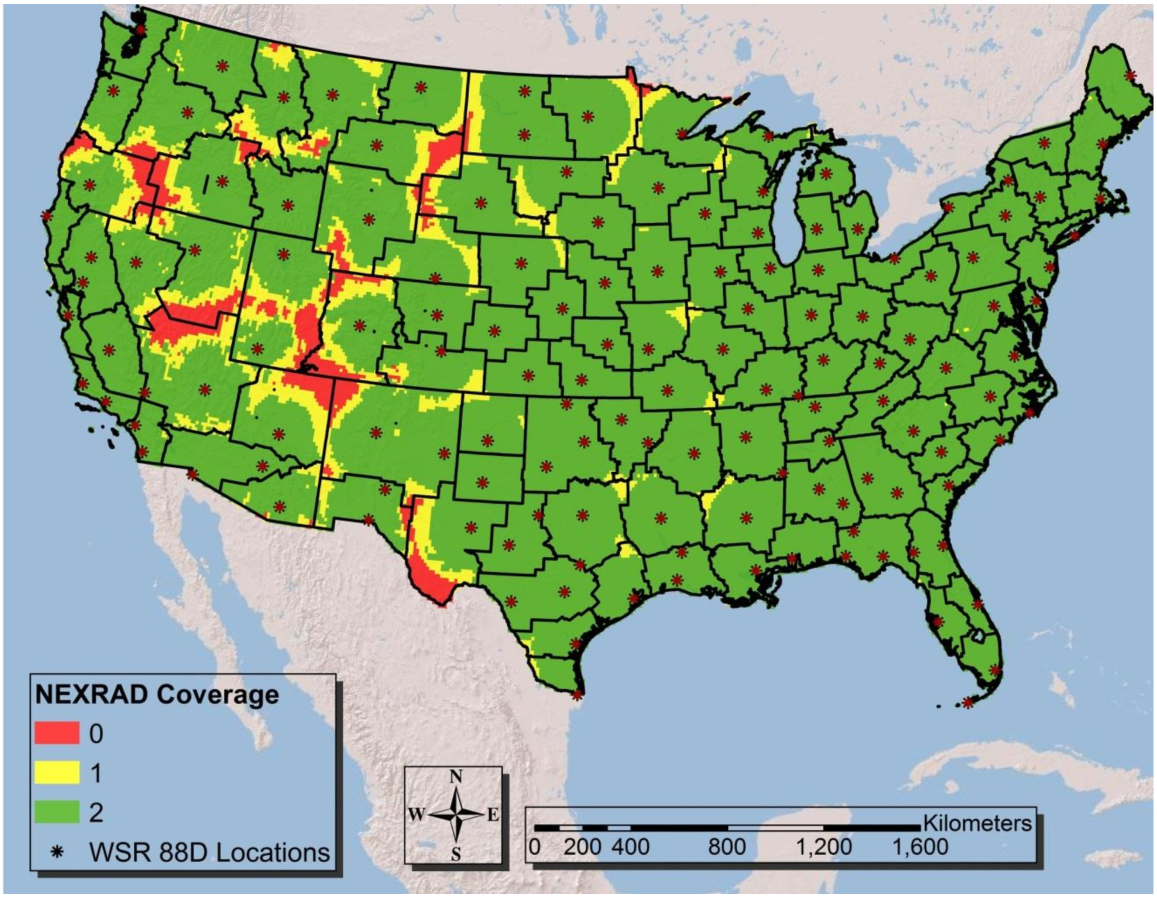

Figure 3.5. NEXRAD coverage-based on data obtained from the National Weather Service Radar Operations Center. NEXRAD Coverage 0 = No Coverage or Terrain Blockage, NEXRAD Coverage 1 = No Radar Coverage below 3048 meters (10,000 ft), NEXRAD Coverage 2 = Radar Coverage below at least 1828.8 meters (6,000 ft).

E. Spatial Distribution

The spatial distributions of the warning types were determined using GIS mapping techniques. Maps-based on the USGS quad cells were produced representing each warning type. These maps were produced on different data scales-based on the types of warnings. For example, far fewer storm-based warnings were issued annually and monthly compared to county-based warnings. For consistency, maps for both severe thunderstorm warning and tornado warning types were produced on the same data scale.

GIS smoothing techniques were used to provide a more consistent visual representation of the data. Kernel density smoothing was used on the CONUS scale. This GIS technique is-based on fitting a smoothed surface on the map-based on the warning "density" of each grid cell. This smoothing technique is-based on the quadratic kernel function (Silverman 1986). The resulting output produced units in square meters, but the main use of the smoothing function is to help in the description of the spatial distribution of warnings. The resulting kernel density unit values have little practical importance.

F. Distance and Direction

Because directional bias will occur within individual County Warning Areas, the determination of directional bias will be-based on the geographic center of the CWA and the physical location within each CWA of the WFO. This selection is because most Weather Forecast Offices are located in or near large metropolitan areas, and is-based on the idea that a warning forecaster is more likely to issue a warning for a storm that is approaching his or her immediate physical location. The directional distribution and distance was determined by GIS analysis of the center of distribution for each warning type. The latitude and longitude of each warning types where then compared to the latitude and longitude of the center of the county warning area and physical location of the WFO for each county warning area to determine distance and direction. Distance was determined using the Spherical Law of Cosines which states:

$$d = (\text{acos}\ (\sin(\text{lat1}))(\sin(\text{lat2})) + (\cos(\text{lat1}))(\cos(\text{lat2}))(\cos(\text{long2} - \text{long1}))\ \text{R}$$

Where R is the Earth's radius or 6371 km (Veness 2012).

Direction was determined using a navigational bearing formula which states:

$$ATAN\left[\frac{cos(L_1)\ sin(L_2) - sin(L_1)\ cos(L_2)\ cos(\Delta\ Long)}{sin(\Delta\ Long)\ cos(L_2)}\right]$$

Where L_1 = Latitude 1, L_2 = Latitude 2, and ΔLong = Longitude 2 – Longitude 1. This formula results in an azimuthal direction in degrees.

The directional distributions of warnings were also defined for each CWA in the CONUS-based on the One Standard Deviation Ellipse Test. This test results in a GIS layer which will show the distance and location of the most number of warnings and exhibits any directional trend of warning issuance within the CWA. The ellipse layer can then be compared to the geographic center of the CWA and the location of the WFO to determine what direction and distance the WFO is predisposed to warn for.

A distance performance rank was developed-based on the idea that a WFO is performing well if it is issuing warnings close to the county warning area geographic center, and is performing poorly if more warnings are issued near the physical location of the WFO. Distance performance rank was determined by the following calculation:

Distance Performance Rank = (Adjusted Distance to Center Rank) + (Difference in Distance to Center and Distance to WFO Rank)

This results in a ranking scheme in which the best performing WFOs have the highest rankings. It should be noted that this ranking system is influenced by the location of the WFO in relation to the geographic center, and is used in this study only as a general guide to warning performance.

G. Population and County Warning Areas

Scharfenberg et al. (2011) suggest the use of 1 km resolution ambient population data to provide an estimate of population exposure to weather hazards in an effort to increase warning efficiency. These LandScan data (Figure 3.6) are maintained by the Oak Ridge National Laboratory (ORNL), and represent the finest resolution global population density data available (ORNL 2011). The data were developed by combining census data, satellite imagery, terrain, proximity to roads, and other data sets to produce a representation of the population averaged over 24 hours, and an ambient hour-by-hour population approximation. This dataset provides the opportunity to estimate the population that was actually affected during the times that short-fuse warnings were in effect.

The LandScan data was spatially joined to the quad grid layer, thus giving the ambient population present in each quad cell during the event in question. Figure 3.7 shows the results of the GIS spatial join of the USGS 7.5 Minute Quadrangle Series with the LandScan ambient population data.

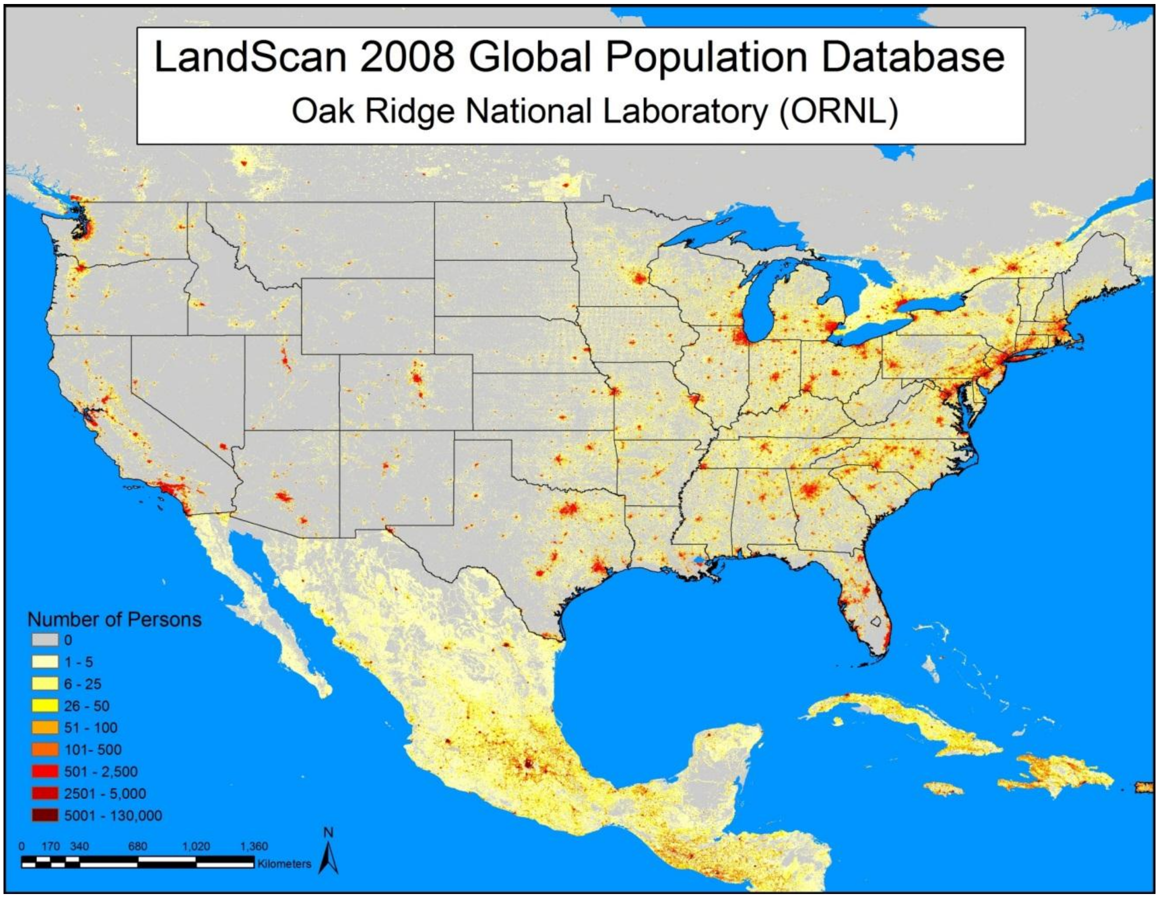

Figure 3.6. LandScan ambient population data for North America (ORNL 2011).

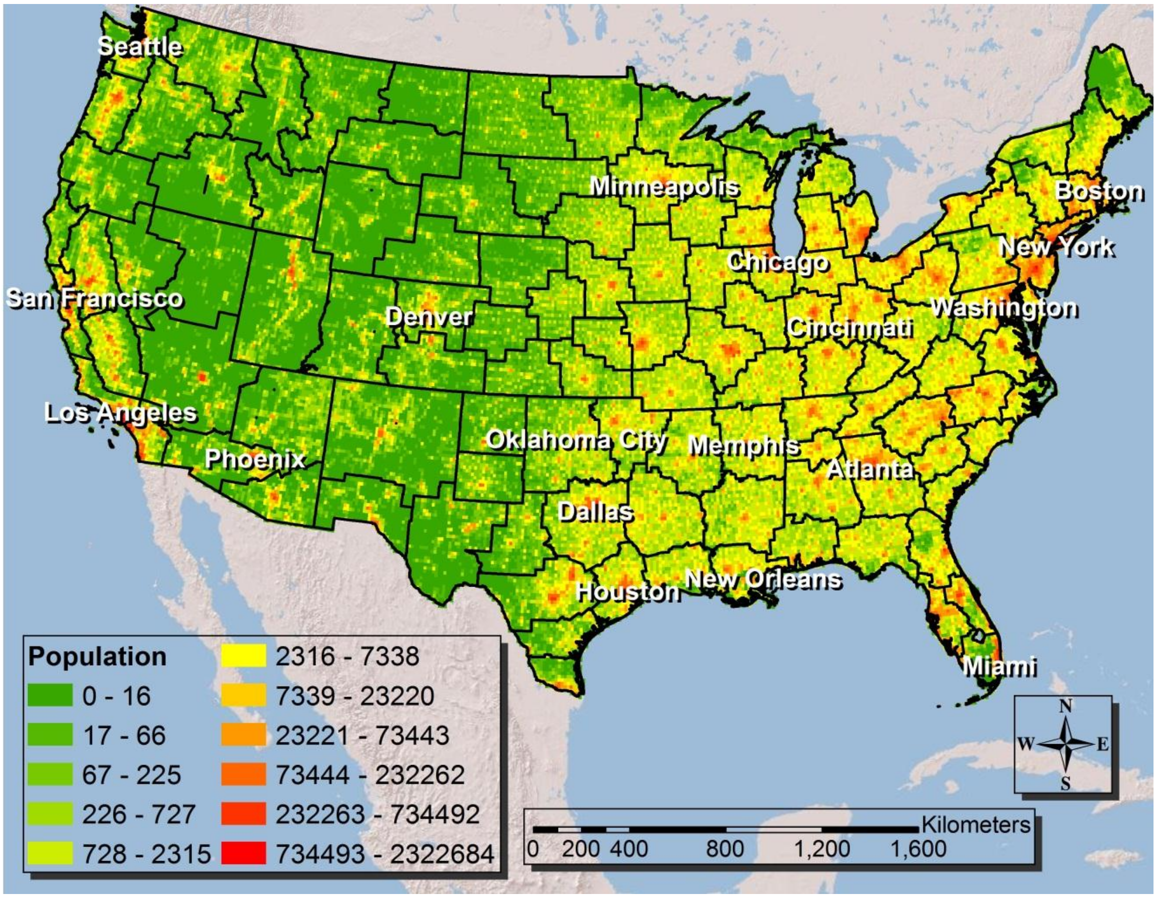

Figure 3.7. Results of the spatial join of LandScan Ambient population data with USGS quad cells.

H. Population Groups

Using methods devised by Dobur (2005), the population density warning for each quad cell was divided into five groups defined by standard deviation and quartile. The quad cells with the highest population density were grouped-based on values that are one standard deviation from the mean overall population density. The remaining four groups were assembled-based on the remaining quartile. This method essentially produces urban and rural groupings from the population quad cell layer. The frequency of short-fuse warnings and event reports were then compared for each group. This method does not produce an exact number which can be interpreted to show correlation or population bias. Instead, graphs representing the population group warning frequency are subjectively evaluated for the presence of a "stair step" pattern, where Population Group 1 has the highest frequency of warnings, gradually decreasing through the population groups. In this population bias pattern, Population Group 5 will always have the lowest number of average warnings.

I. Statistical Techniques

Two main statistical tests were used to determine the relationship between warnings and population: The Pearson Product-Moment Correlation and Spearman's Rank-Order Correlation. Both of these tests do not require the data to be of the same type or exist on the same scale. The Pearson correlation test is used extensively in this study to determine the strength of association between warnings and population. The Spearman rank order correlation was chosen for certain analysis in this study because it is less sensitive to outliers in the data than the Pearson correlation test (Daniel 1990). Because most of the data that was being analyzed contained Spearman ties, the formula for the Spearman correlation coefficient (Spearman's Rho) correcting for ties was used. This version of the Spearman formula is:

$$\rho = \frac{\Sigma_i (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\Sigma_i (x_i - \bar{x})^2 \Sigma_i (y_i - \bar{y})^2}}$$

Where i is the paired score.

Difficulty exists in determining practical statistical significance for this study. Because of very large sample sizes (53711 quad cells for the CONUS area), many of the correlation results show a statistical significance, and a critical value cannot be determined. The challenge then is to determine a practical significance for such a large sample size. After analyzing the resulting values of the correlation statistical test, it was determined that practical significance exists for Pearson and Spearman correlation results greater than 0.3. The alpha level for statistical significance when the entire grid cell population is tested for the CONUS, climate regions and county warning areas was set at 0.1% ($\alpha = 0.001$). When testing between the population density of county warning areas, the alpha was set at 5% ($\alpha = 0.05$) because of the much smaller sample size.

CHAPTER IV

SHORT-FUSE WARNING RESULTS AND DESCRIPTIVE DATA

A. Introduction

The first section of this chapter will describe the results of the warning spatial distribution and population analysis of the Contiguous United States (CONUS). The next nine sections will present results of warning and severe report frequency distribution, population, and directional distribution from the individual climate regions. It should be noted that far fewer storm-based warnings were issued when compared to county-based warnings because of the reduction in warning coverage area which is inherent to the polygon drawn warning system. Evidence of this is found in the area adjusted (normalized) annual average numbers of warnings. The average number of annual severe county-based warnings was 16.06 compared to 1.36 severe storm-based warnings, a difference of 14.7. An annual average of 2.45 tornado county-based warnings was issued compared to 0.37 tornado storm-based warnings, a difference of 2.08. The county- and storm-based warning data depicted in the maps and graphs in this chapter are not on the same scale. Scaled data are illustrated in the warning maps in Appendix A.

B. Contiguous United States

A significant part of the following analysis is-based on correlation results. Both the standard Pearson correlation coefficient and the Spearman correlation (Rho) are used throughout the study. Because of the large sample sizes (53,711 quad cells for the CONUS area), many of the correlation results show a statistical significance, but very few appear to show a practical significance. Therefore, these results are interpreted by comparing the correlation values between warning types, months, and population groups.

1. NEXRAD Radar Coverage

Results of the radar analysis indicate that a greater proportion of county-based warnings were issued for areas with sparse NEXRAD coverage when compared to annual average storm-based warnings (Figure 4.1). The greatest correlation of NEXRAD coverage with warning type exists with severe storm-based warnings (Table 4.1). Tornado county-based warnings show a higher correlation than tornado storm-based warnings.

Table 4.1. Correlation results for NEXRAD coverage for the CONUS.

Test	Correlation	Z-Value	P-Value	Rho	Rho Z-Value	Rho P-Value
SVR CBW	0.023	5.31	<.001	0.150	34.68	<.001
SVR SBW	0.055	12.86	<.001	0.235	54.55	<.001
TOR CBW	0.050	11.50	<.001	0.213	49.29	<.001
TOR SBW	0.018	4.22	<.001	0.159	36.79	<.001

All monthly warning types, with the exception of severe storm-based warnings, were issued more often for the “perfect” (2) NEXRAD coverage area. During August and September, more severe county-based warnings were issued for the “1” NEXRAD coverage area (Figure 4.2). During September, low coverage “0” areas received more warnings than the “2” coverage areas. This may be because of a greater number of severe weather events during the late summer months for the southwestern United States which has significant gaps in NEXRAD coverage.

2. Spatial Distribution

Figure 4.3 shows the spatial distribution of severe county-based warnings as depicted by kernel density analysis. It is apparent from this map that the majority of severe thunderstorm warnings were issued for the Great Plains region of the nation. Large areas of high kernel density returns are seen in the Phoenix, Arizona, region as well as in the northern part of Nebraska in the vicinity of Cherry County, and are likely artifacts of large counties which are found in those areas. Warnings were also more prevalent in urban areas, as is indicated by the hotspots in Jackson, Mississippi, and Nashville, Tennessee.

Kernel density analysis results for severe storm-based warnings indicate that, not only were far fewer annual warnings issued, but also that the general spatial pattern of warning issuance has shifted (Figure 4.4). The general spatial pattern shows warning distribution favored the southeastern part of the Nation, with more warnings also seen in the densely populated northeast. Very few warnings were issued to the west of the Continental Divide. Hot spots of warnings were seen in the Little Rock, Shreveport, Nashville, State College, and Columbia CWAs. Of note is the unusually extreme kernel cluster in the Columbia (CAE) CWA.

The overall pattern for tornado county-based warnings shows most warnings were centered on the Central Plains with hot spots in the western part of the Boulder (BOU) CWA, and near Houston, Texas (Figure 4.5). Numerous warnings were issued from near New Orleans, Louisiana, to the southeastern part of the Jackson (JAN) CWA. Another area of tornado warning activity is seen in the southern part of the Chicago (LOT) and northern part of the Lincoln Central Illinois (ILX) CWAs. Of note are the lack of warnings in the Fort Worth (FWD) and Peachtree City (FFC) CWAs, both of which contain major urban areas. Tornado warnings were very rare west of the Continental Divide, although numerous warnings were issued by the Flagstaff (FGZ) WFO.

Although the scales of the kernel density maps for tornado warnings are different (far fewer average storm-based warnings were issued), a shift in the spatial distribution from the central part of the nation to the southeast is apparent (Figure 4.6). Hot spots are seen in the Lake Charles (LCH), Shreveport (SHV), Springfield (SGF), and Birmingham (BMX) CWAs. Numerous warnings were issued for the eastern part of the Boulder (BOU) CWA. Very few warnings were issued for the western part of the nation.

Kernel density maps depicting monthly averages of each warning type are found in Appendix B. The spatial extent of severe county-based warnings was greatest in the month of May. Numerous warnings were issued for the Rocky Mountain region and areas just to the east in the month of June. Warnings in the desert southwest were most prevalent from July to October, with the Gulf Coast region receiving the most warnings during the late fall and winter months. The same general pattern is seen for severe storm-based warnings, although June warnings in the vicinity of the Rocky Mountains were not as prevalent as seen in the county-based warning maps. Hot spots of storm-based warning activity are seen in the months of June and December for the CAE CWA.

Similar to county-based severe warnings, tornado county-based warnings exhibit the greatest spatial extent in the month of May. Warnings were distributed in the Rocky Mountain region in June, and migrated into the north central part of the nation in July.

Numerous county-based warnings were issued along the southeastern seaboard and eastern Gulf Coast during September, with most warnings issued for the central Gulf Coast region from October through December. In contrast to county-based warnings, the greatest spatial extent of storm-based warnings occurred during the month of April. June storm-based warnings were spread to a greater extent to the east of the Rocky Mountains into the central plains. A migration of tornado warnings into the northern part of the nation was seen through the summer months, with warnings along the Gulf Coast experienced in the Fall and Winter. Unlike county-based tornado warnings, far fewer storm-based warnings were issued from the southeast coast during the month of August.

3. Distance and Direction

The resulting maps from the GIS directional distribution analysis contain directional ellipsoids which are-based on the distribution at one standard deviation from the mean. This produces a map in which the directional ellipses tend to mimic the geographic outline of the individual CWAs. The ellipse results should only be used as a rough guide to directional distribution. A better indication of directional distribution is found by comparing points representing the mean centers of distributions.

Figure 4.7 is a map of the directional distribution of severe thunderstorm warnings in relation to the geographic center of the 111 County Warning Areas. The average directional distribution from geographic center of CWAs for all types of severe thunderstorm warnings is 185.26 azimuth degrees.

Figure 4.8 and Figure 4.9 show the directional distribution of severe county-based warnings and severe storm-based warnings. The azimuth direction from CWA geographic center to county-based severe warnings is 187.26° and 183.26° for storm-based severe warnings. The distance results indicate a tendency for storm-based warnings to be issued further away from the center of the CWAs. The adjusted distance is 5.76 km for county-based warnings and 9.49 km for storm-based warnings.

The directional distributions of all tornado warnings are shown in Figure 4.10. The average directional distribution from the CWA centers is 161.59 azimuth degrees, indicating a tendency for tornado warnings to be issued to the south-southeast. The adjusted distance of the CWAs centers to tornado warning center is 9.52 km. County- and storm-based directional distributions are shown in Figure 4.11 and Figure 4.12. The azimuth direction from CWA geographic center to tornado-based severe warnings is 167.39° and 155.80° for storm-based tornado warnings. The adjusted distance from CWA centers is 8.42 km for county-based warnings and 10.63 km for storm-based warnings. This indicates a tendency for storm-based warnings to be issued in a more southeasterly direction and at a greater distance from CWA center.

The average azimuthal directional distribution from CWA centers for all county-based warnings is almost due south at 177.3°. For storm-based warnings the direction moves a few degrees to the southeast at 169.53°. The distance from storm-based warning center compared to county base center increases, with an average increase of 15.27 km (2.97 adjusted for CWA area). This shows a tendency for storm-based warnings to be issued further away from the geographic center of the CWAs.

The average directional distribution for all 111 CWAs in the CONUS for all warnings types is 173.43°, demonstrating an overall tendency for WFOs to issue warnings to the south of the geographic center of CWAs. Warnings also tend to be issued almost exactly due south of physical location of the WFOs. The azimuthal calculations of warning direction from WFOs produce an average of 183.36°. Average distance from geographic center is 51.88 km (8.57 km adjusted).

4. Population

When determining the influence of population density on the issuance of warnings, it is useful to first compare the correlation results for each warning type. Table 4.2 shows the Pearson and Spearman Rho correlation statistics for population and average annual number of warnings. In these results the Rho values have been corrected for ties. All of the results are statistically significant. The most significant practical correlation occurs with severe storm-based warnings, followed by tornado county-based warnings, severe county-based warnings, and finally tornado storm-based warnings. Rho values indicate that the highest population correlation occurs with storm-based warnings, although tornado types are close in Rho correlation value. It should be noted that because of the relative rarity of tornado warnings during the 3-year-period of record of the storm-based warnings, the sample size is limited.

Table 4.2. Correlation results for population and warning type for the CONUS.

Test	Correlation	Z-Value	P-Value	Rho	Z-Value	P-Value
SVR CBW	0.023	5.309	<.001	0.116	26.915	<.001
SVR SBW	0.055	12.858	<.001	0.391	90.688	<.001
TOR CBW	0.05	11.504	<.001	0.260	60.335	<.001
TOR SBW	0.018	4.221	<.001	0.262	60.748	<.001

Figure 4.13 shows the population groups derived for the CONUS. On this scale the densely populated group one includes urban areas with populations above 30,000 per

quad area. This population density includes parts of the nation which are not normally considered dense urban areas and should be noted in the results. The densest population occurs in the eastern part of the nation, from the Great Lakes to the northeastern seaboard. The lowest population density occurs across the desert southwest, middle Rocky Mountains, and Great Basin regions of the country.

Figure 4.14 is a bar graph of the results from the annual severe county-based warning population group analysis. Theoretically, population bias would be indicated by a “stair step” appearance of the chart, where Population Group 1 would have the highest frequency of average annual warnings and frequency values gradually decrease down to the lowest values in Population Group 5 (Dobur 2005). This graph indicates that, although more warnings are issued for Population Group 1, overall the warnings across population groups appear to be evenly distributed. Table 4.3 indicates that the only statistically significant correlations for population and warnings exist in Population Group 5; however, the correlation value remains relatively low. Population group values for individual months are shown in Figure 4.15 and show that the greatest population bias occurs during the month of May. However, correlation values for May are low at 0.0533 (P <.001). More warnings are issued for the lesser populated groups 4 and 5 during the summer months of June, July and August with a statistically significant negative population correlation of -0.0281 (P <.001) indicated for the month of June.

Table 4.3. Correlation results for severe county-based warning population groups.

Test	Correlation	Count	Z-Value	P-Value
SVR CBW G1	0.017	2008	0.739	0.4599
SVR CBW G2	0.025	11423	2.674	0.0075
SVR CBW G3	-0.016	13450	-1.872	0.0612
SVR CBW G4	-0.018	13573	-2.125	0.0336
SVR CBW G5	0.165	13257	19.162	<.001

Severe storm-based warnings show a significant tendency to be issued for populated areas. The bar graph of average annual warnings for population group indicate that far fewer warnings are issued for the lesser populated groups 4 and 5, whereas group 2 receives the greatest number of warnings (Figure 4.16). Table 4.4 indicates that population correlation results remain relatively low but statistically significant for population groups 3, 4 and 5. Figure 4.17 shows that Population Group 2 receives the most warning during the winter and spring severe weather months, and Population Group 1 dominates from summer through September. The highest correlation values occur during the summer months of July (0.06, $P<.001$) and August (0.0674, $P<.001$).

Table 4.4. Correlation results for severe storm-based warning population groups.

Test	Correlation	Count	Z-Value	P-Value
SVR SBW G1	-0.068	2008	-3.033	0.0024
SVR SBW G2	0.018	11423	1.97	0.0488
SVR SBW G3	0.108	13450	12.531	<.001
SVR SBW G4	0.12	13573	14.002	<.001
SVR SBW G5	0.068	13257	7.798	<.001

Average annual tornado county-based warnings also demonstrate an inclination to be issued for populated areas compared to rural regions. The greatest number of average annual tornado county-based warnings is issued for population group 1, with the lowest number issued for population group 5 (Figure 4.18). This indicates a substantial population bias; however, the population correlation remain low for the entire CONUS population, with only groups 4 and 5 showings a statistically significant correlation (Table 4.5). The monthly peak occurs in May when groups 3 and 4 dominate in the average number of warnings received (Figure 4.19). Warnings for group 5 remained low throughout the year. Group 1 received the most number of warnings from September through December.

Table 4.5. Correlation results for tornado county-based warning population groups.

Test	Correlation	Count	Z-Value	P-Value
TOR CBW G1	0.025	2008	1.113	0.2656
TOR CBW G2	-0.003	11423	-0.291	0.7711
TOR CBW G3	0.023	13450	2.694	0.0083
TOR CBW G4	0.034	13573	3.919	<.001
TOR CBW G5	0.196	13257	22.845	<.001

With the exception of group 1, the population group graph for annual average tornado storm-based warnings shows a stair-step pattern (Figure 4.20). Of the five population groups, groups 3, 4 and 5 show a statistically significant correlation (Table 4.6). The monthly peak of tornado warnings occurs in April, where group 2 dominates in the average number of warnings received (Figure 4.21). It is of interest that group 4 shows a peak in June, whereas average numbers for group 5 remain relatively low during that month.

Table 4.6. Correlation results for tornado storm-based warning population groups.

Test	Correlation	Count	Z-Value	P-Value
TOR SBW G1	-0.060	2008	-2.698	0.0070
TOR SBW G2	-0.007	11423	-0.737	0.4614
TOR SBW G3	0.056	13450	6.550	<.001
TOR SBW G4	0.044	13573	5.104	<.001
TOR SBW G5	0.120	13257	13.939	<.001

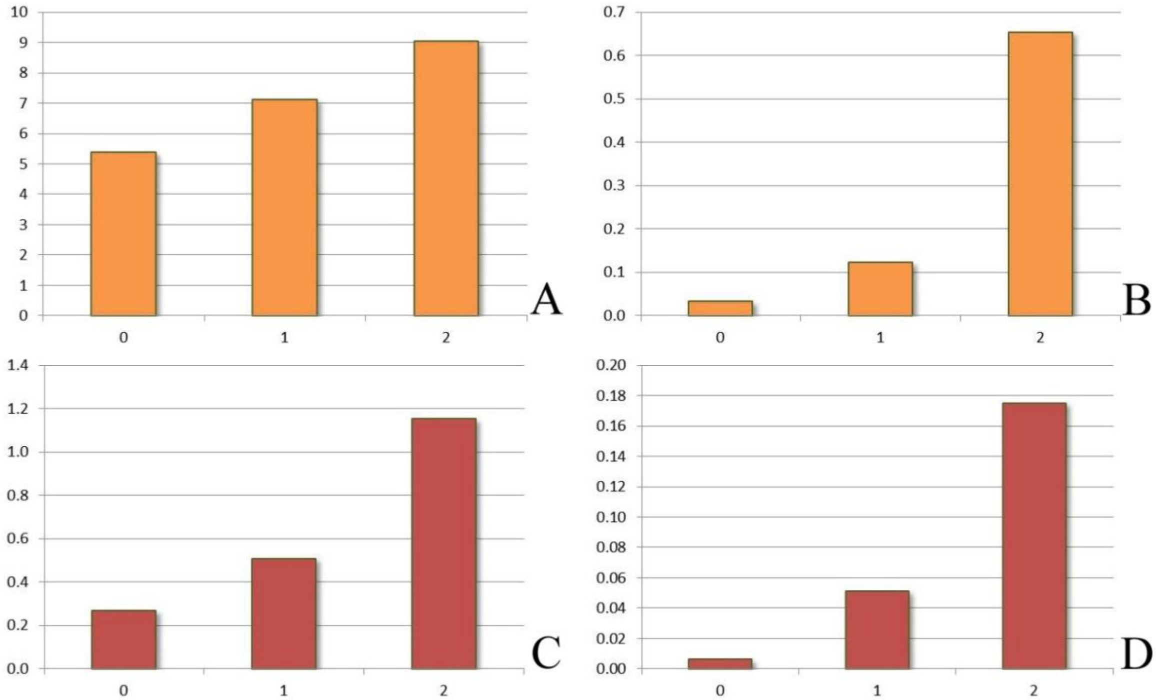

Figure 4.1. Annual average frequency of severe county-based warnings (*A*), severe storm-based warnings (*B*), tornado county-based warnings (*C*), and tornado storm-based warnings (*D*) by NEXRAD coverage area.

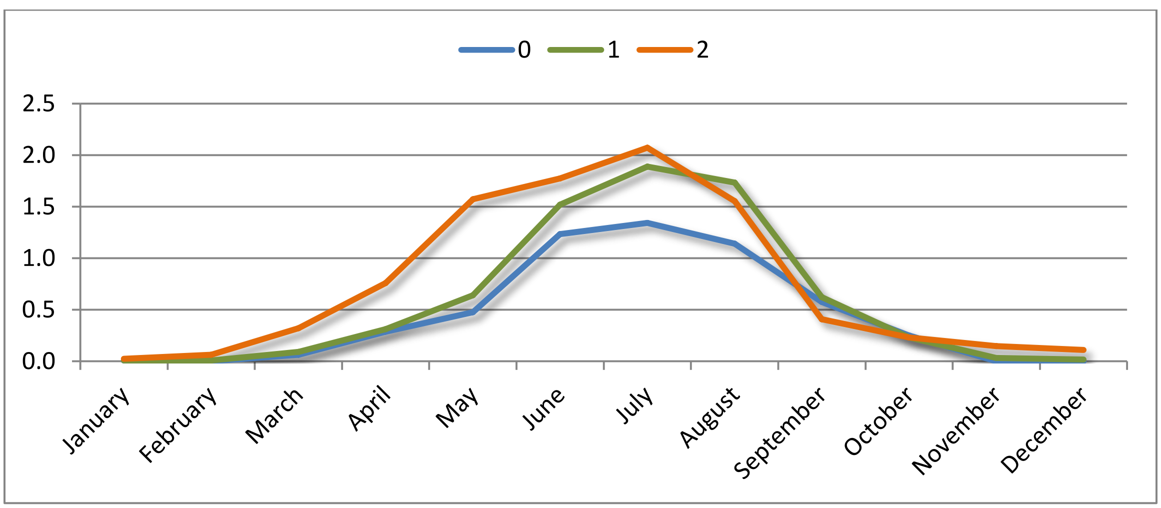

Figure 4.2. Monthly average severe county-based warnings by NEXRAD coverage area.

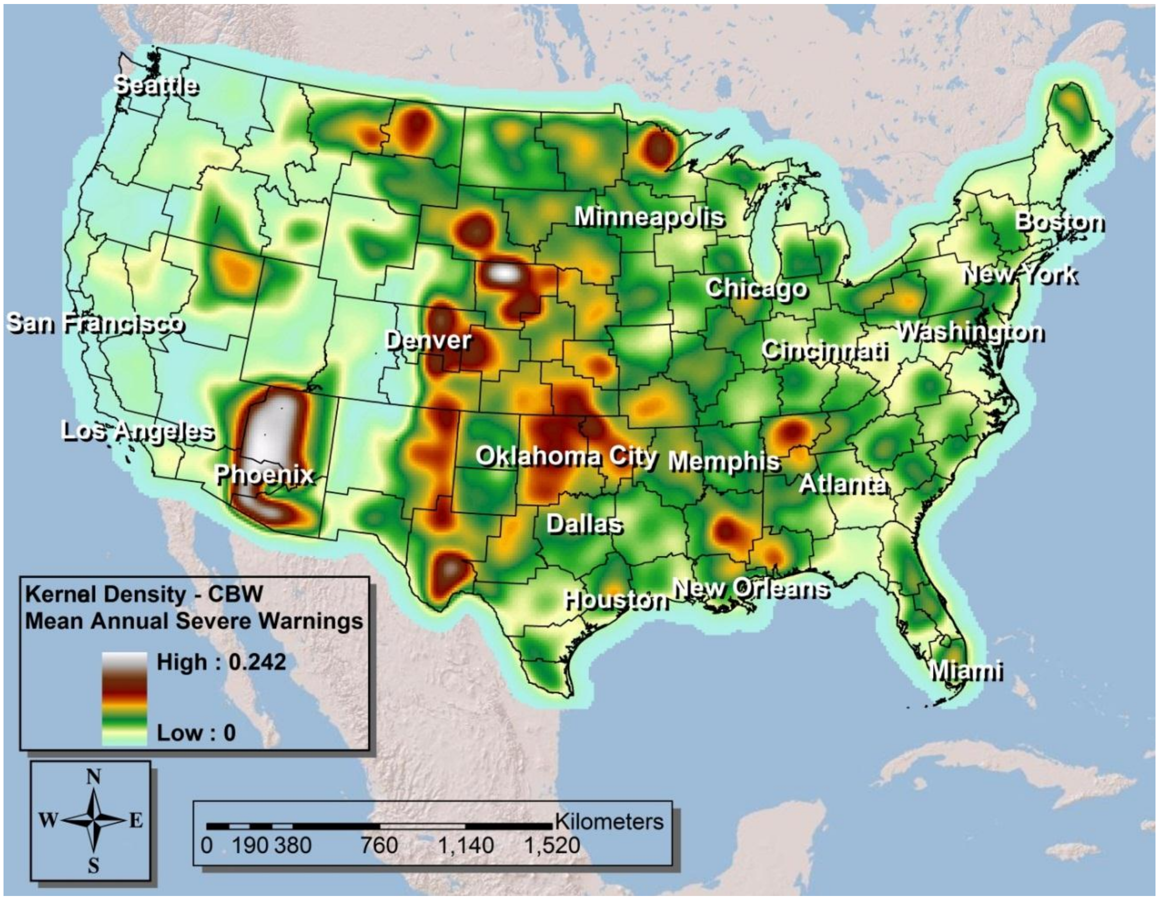

Figure 4.3. Results of the severe county-based warning kernel density analysis.

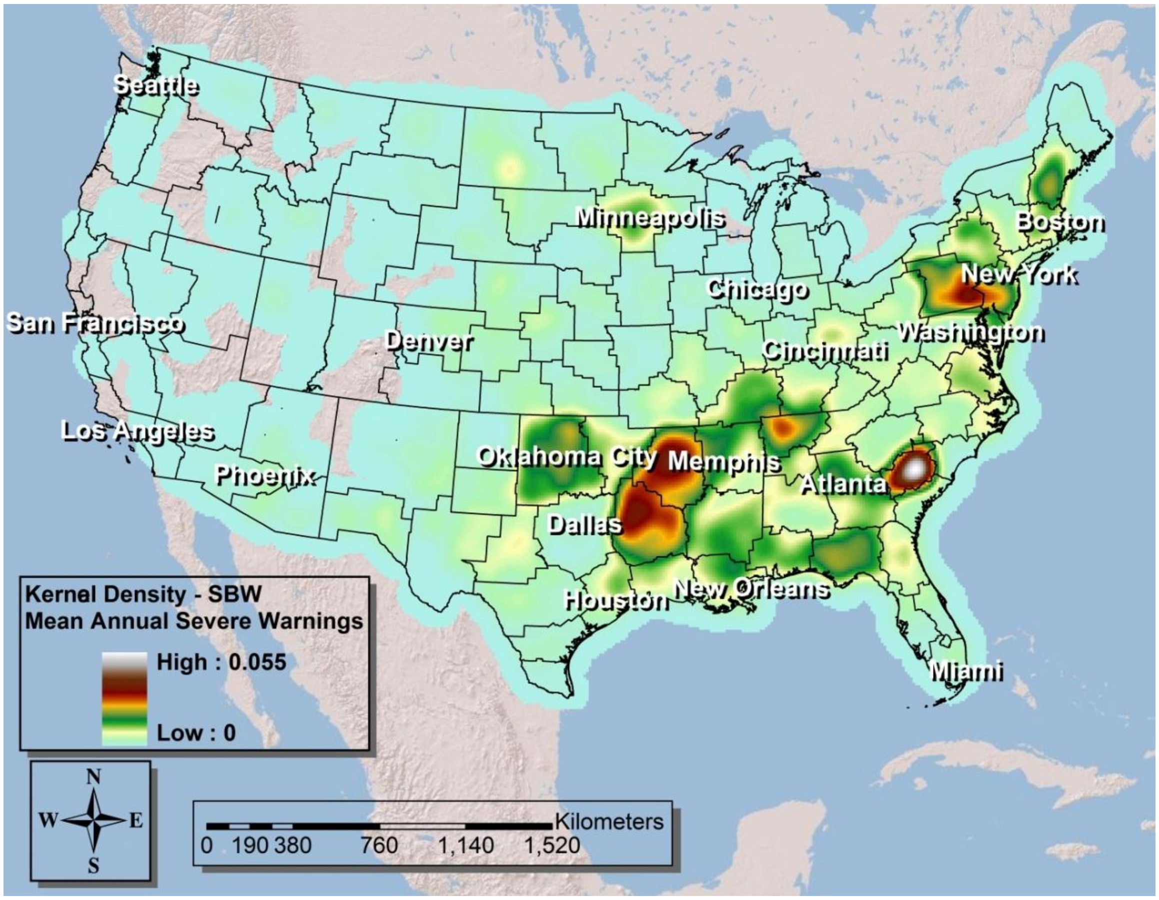

Figure 4.4. Results of the severe storm-based warning kernel density analysis.

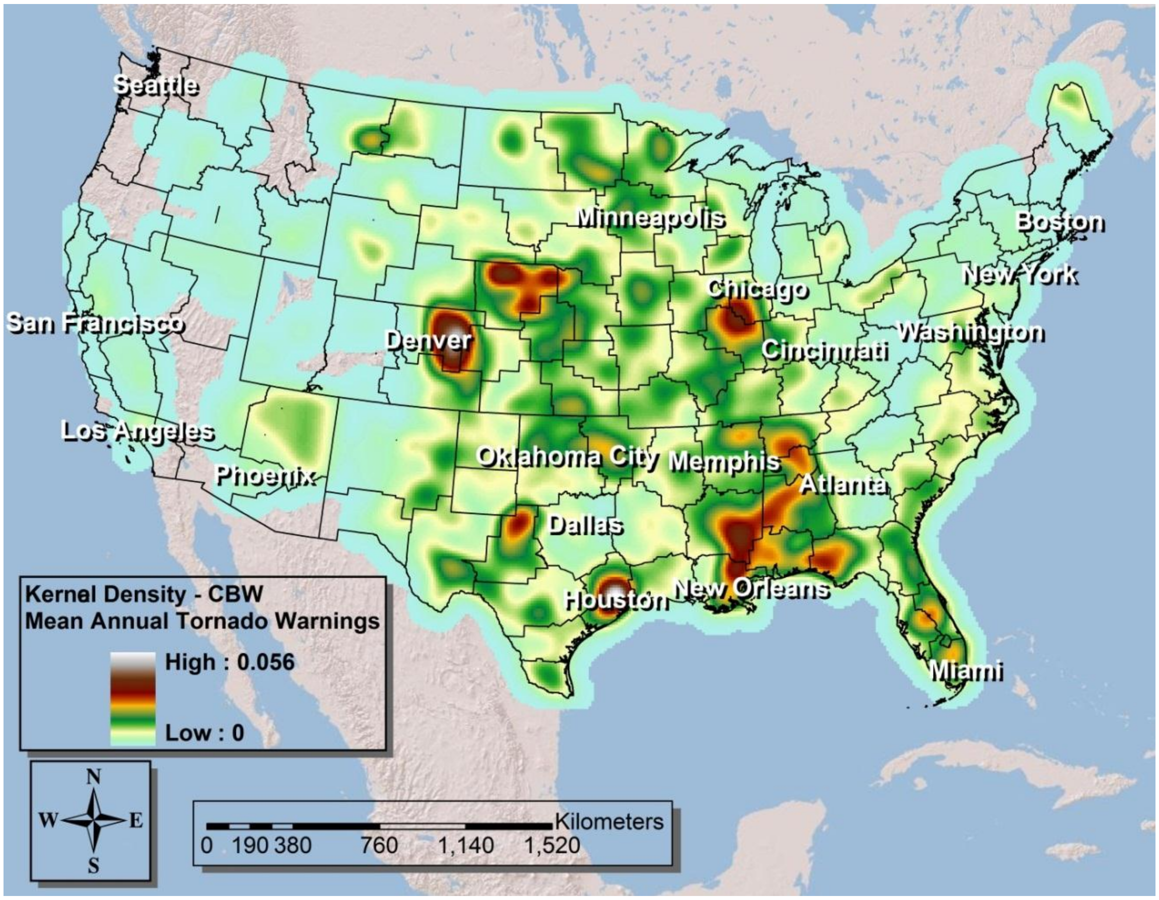

Figure 4.5. Results of the tornado county-based warning kernel density analysis.

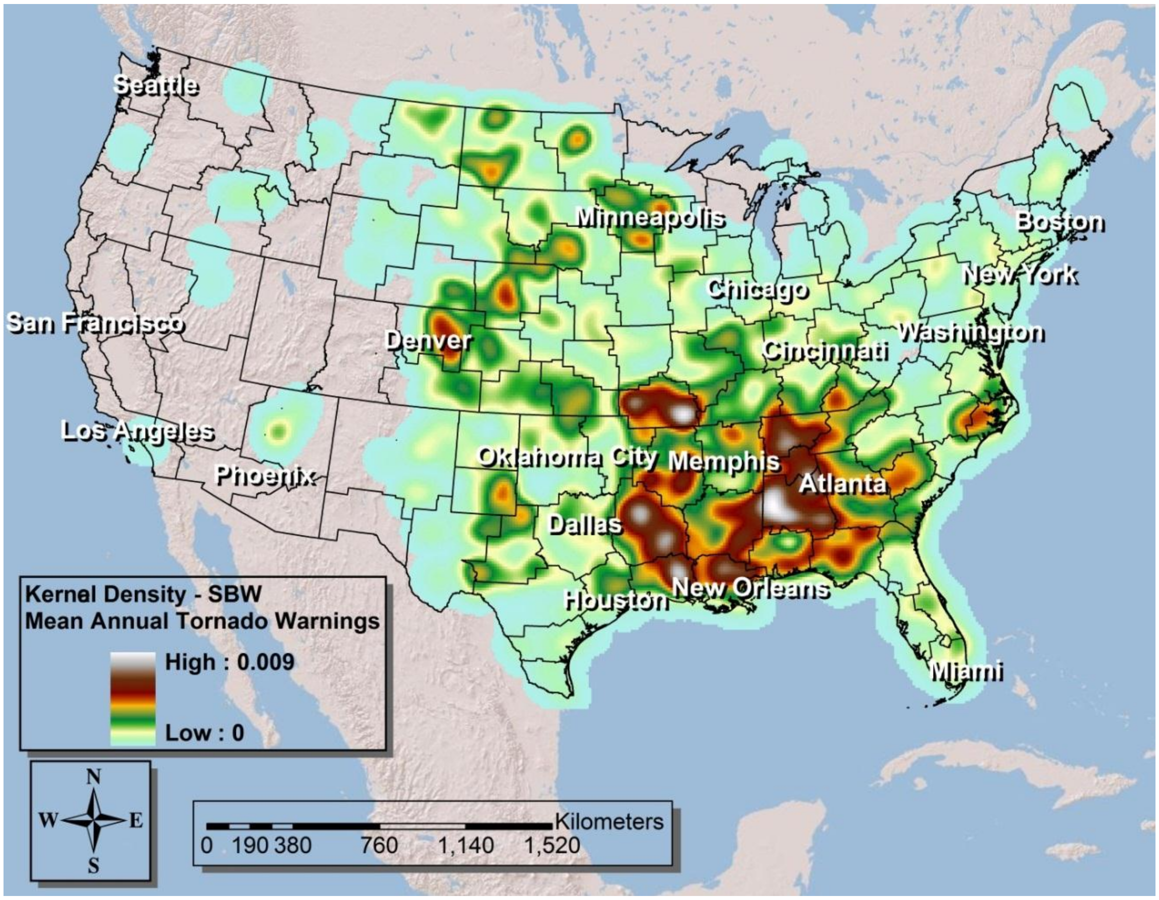

Figure 4.6. Results of the tornado storm-based warning kernel density analysis.

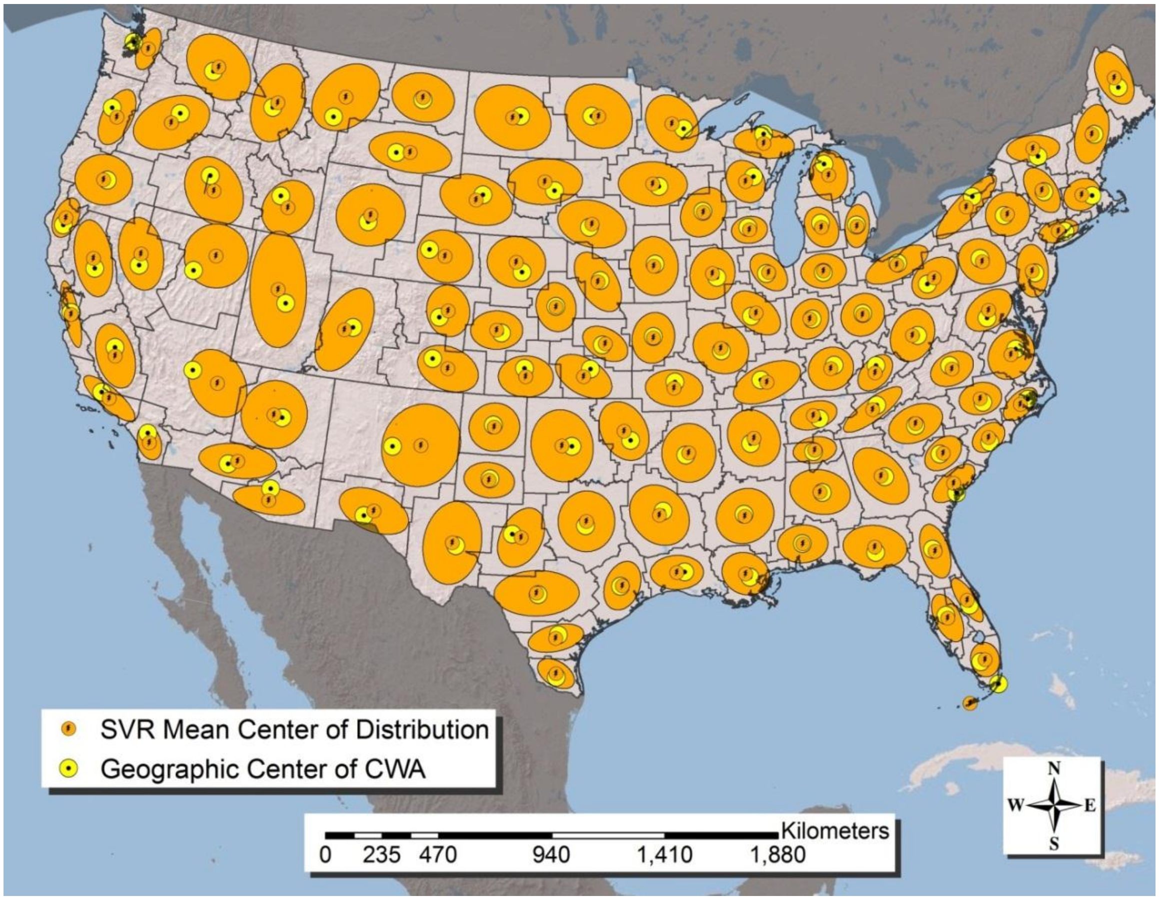

Figure 4.7. Results of the severe thunderstorm warning directional distribution analysis.

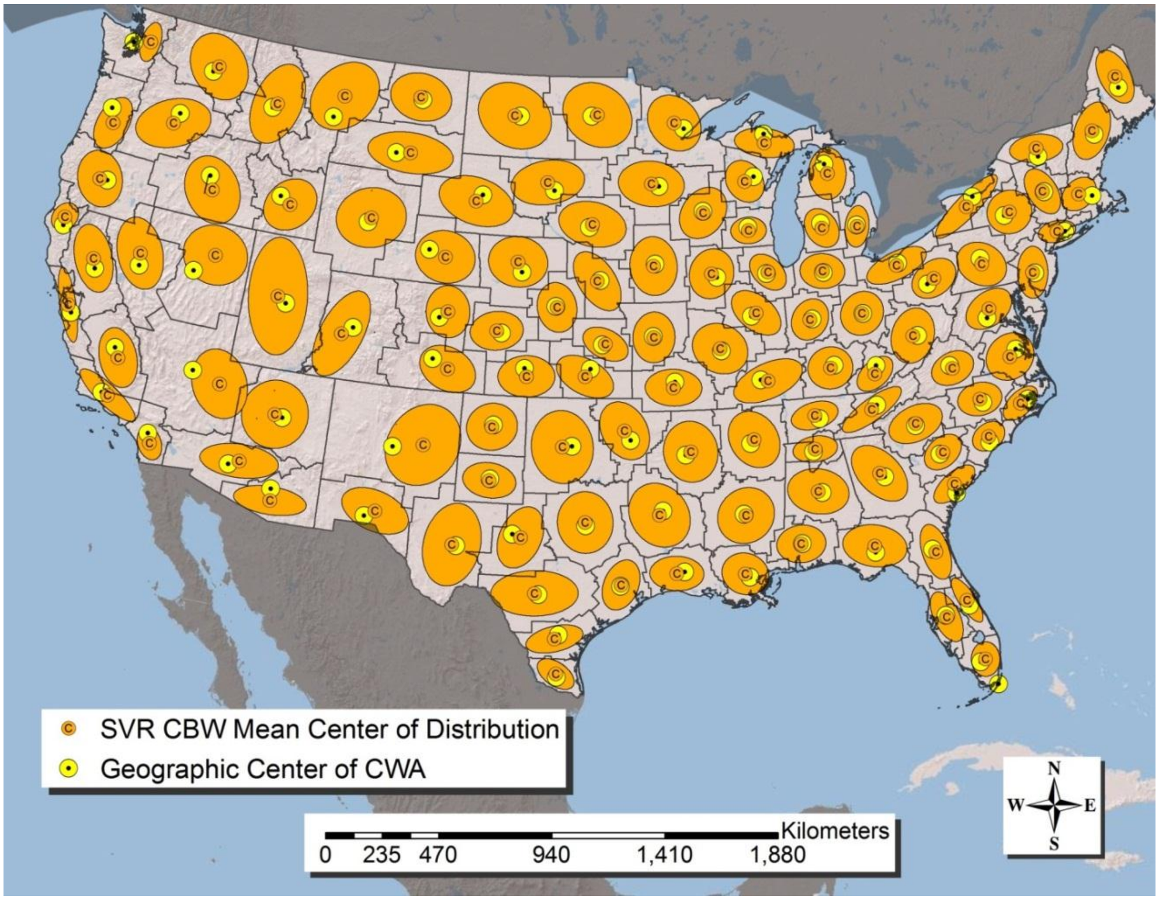

Figure 4.8. Results of the severe county-based warning directional distribution analysis.

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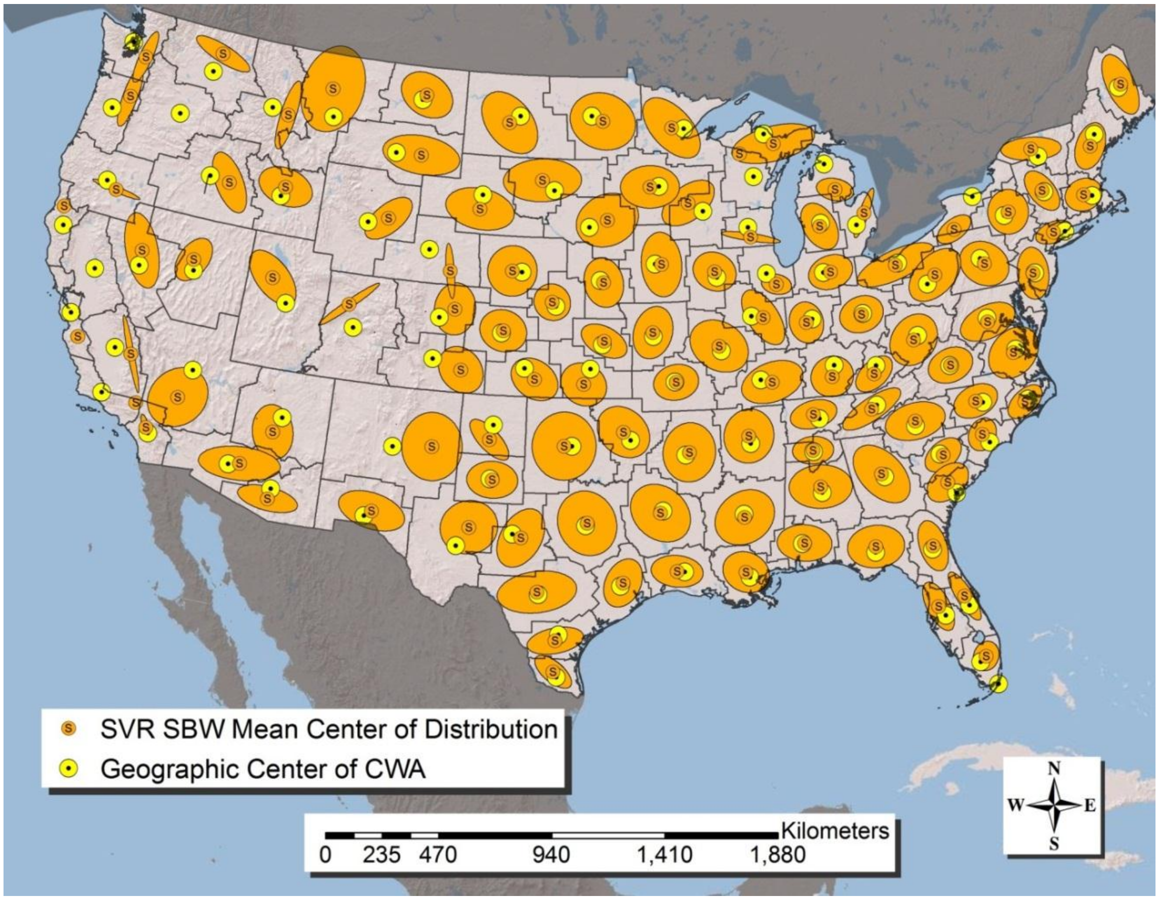


Figure 4.9. Results of the severe storm-based warning directional distribution analysis.

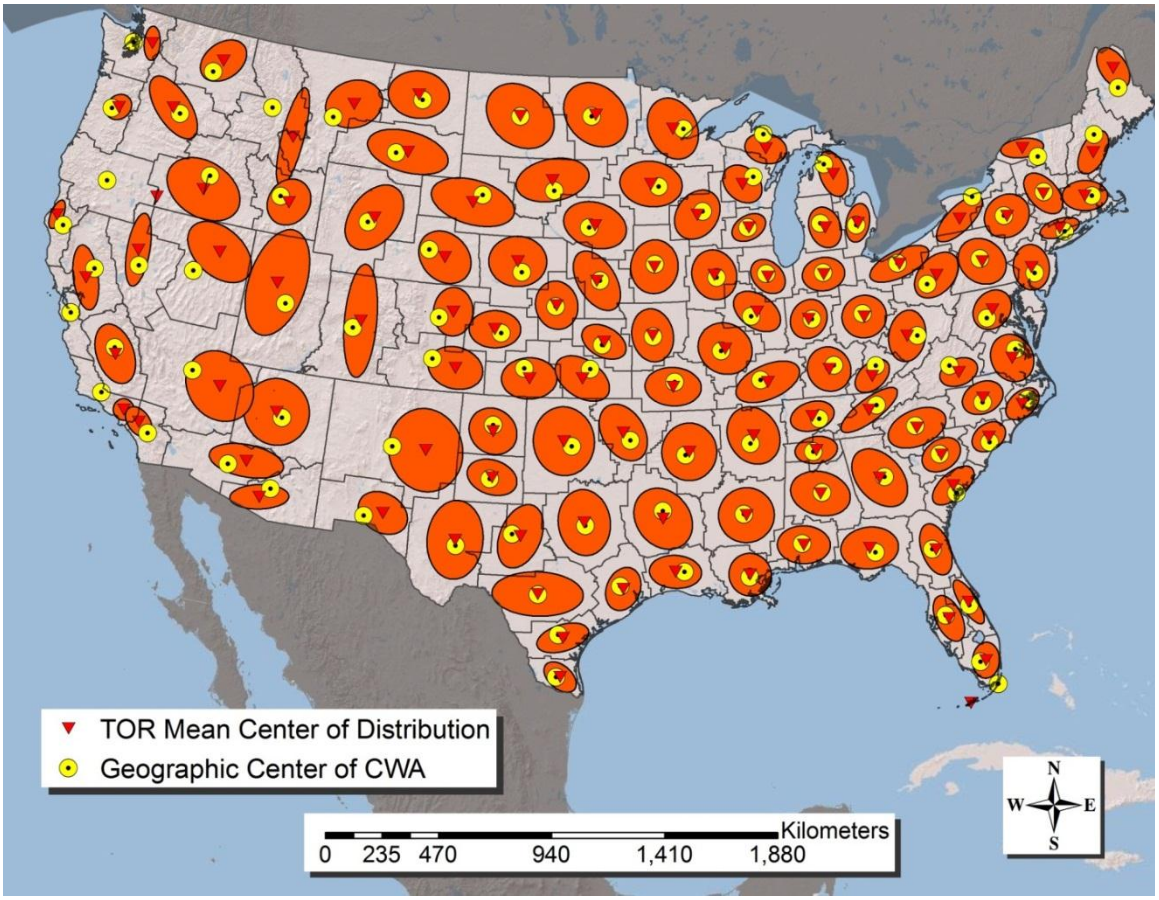


Figure 4.10. Results of the tornado warning directional distribution analysis.

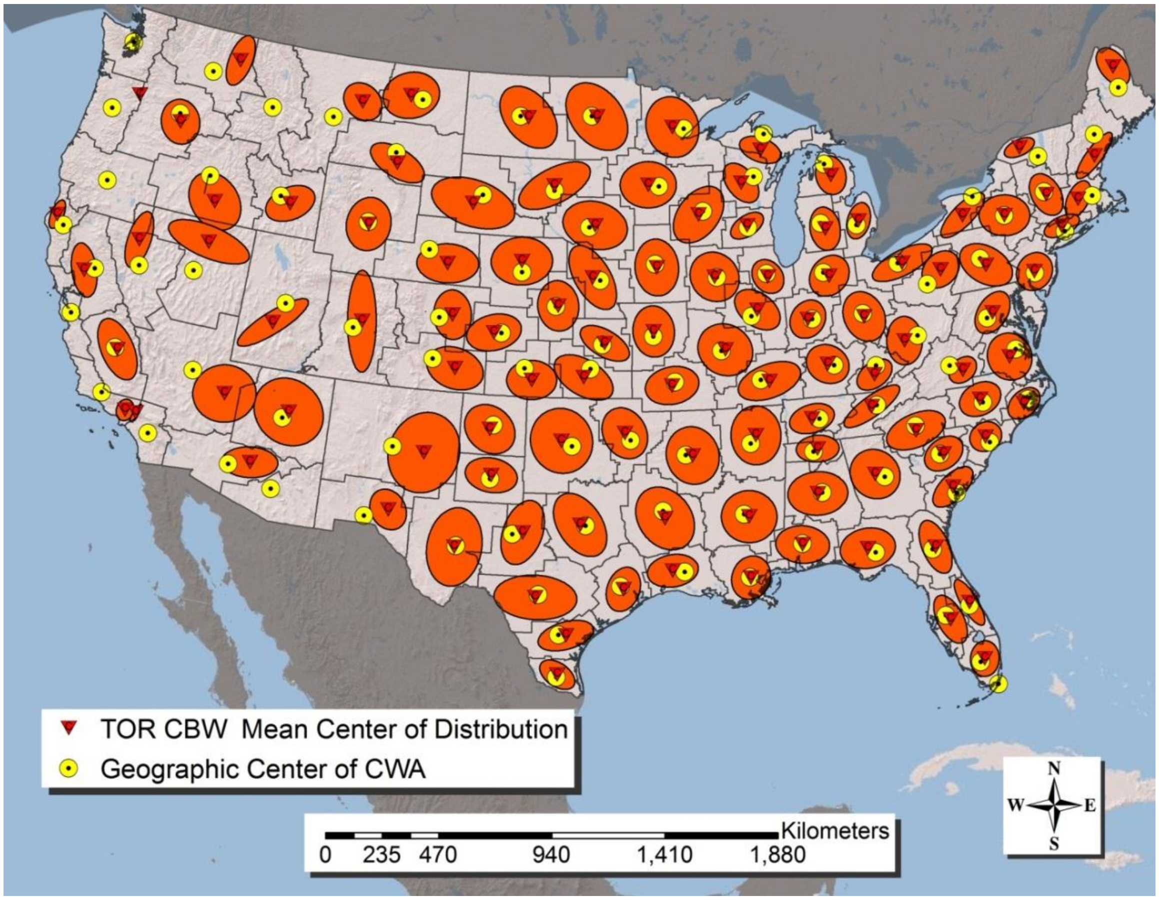


Figure 4.11. Results of the tornado county-based warning directional distribution analysis.

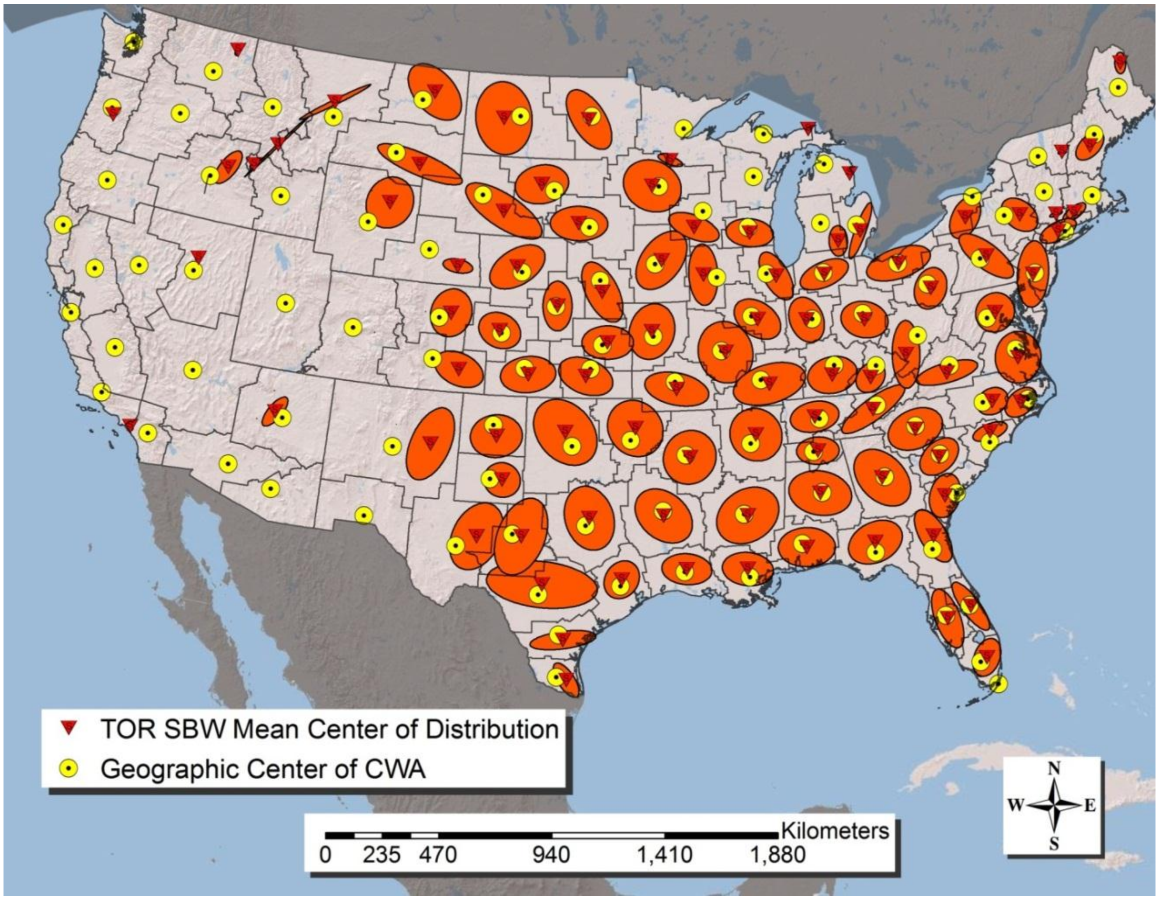


Figure 4.12. Results of the tornado storm-based warning directional distribution analysis.

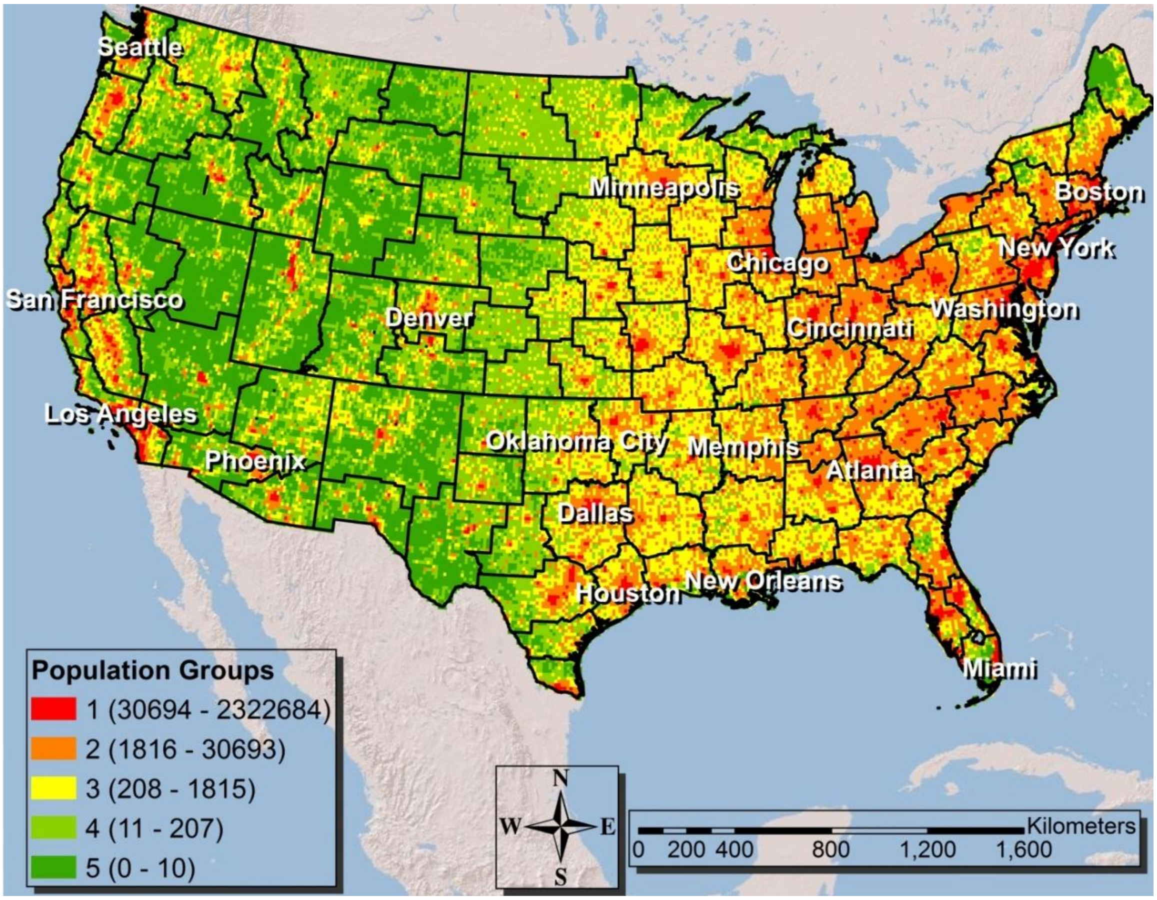


Figure 4.13. Population group distribution within the CONUS.

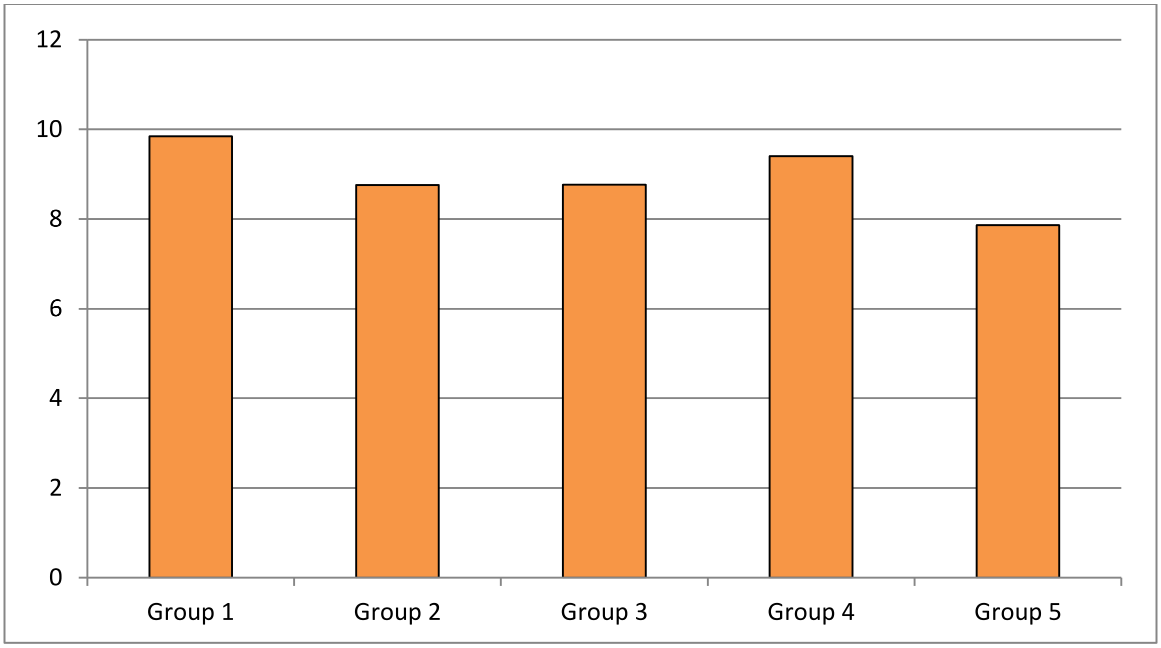


Figure 4.14. Severe county-based warning population group analysis.

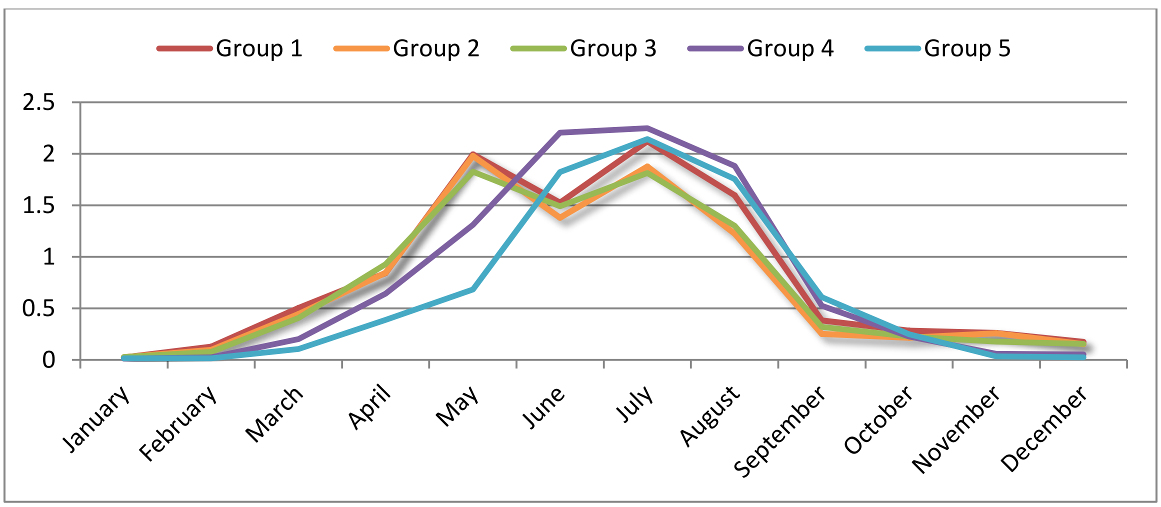


Figure 4.15. Monthly county-based warning population group analysis.

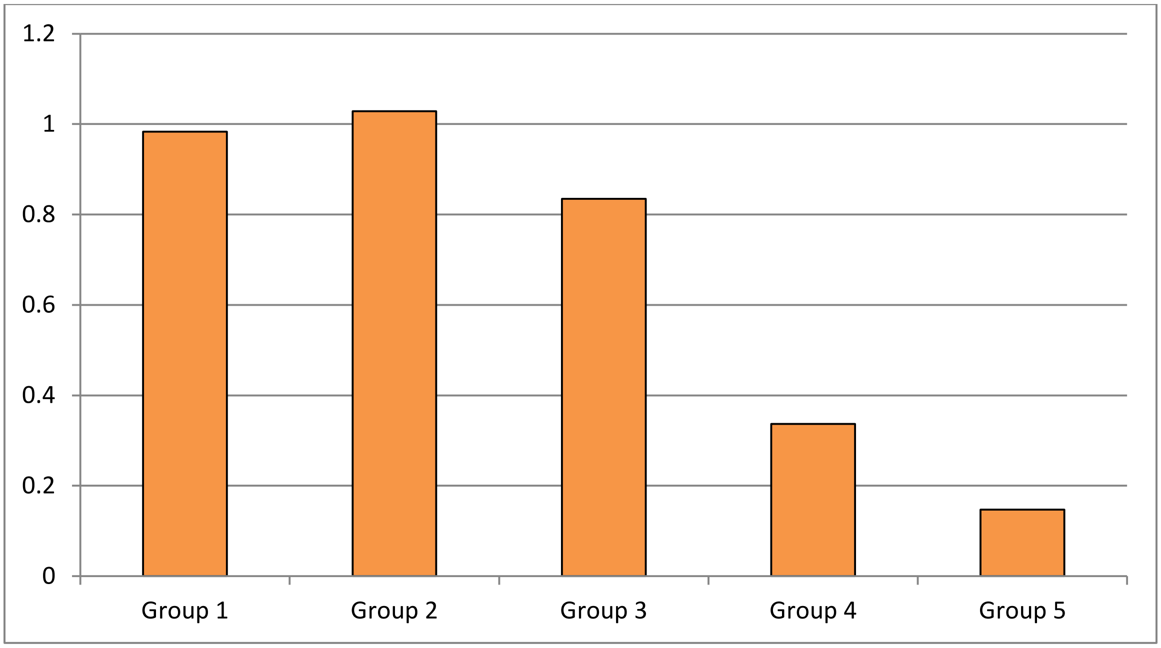


Figure 4.16. Severe storm-based warning population group analysis.

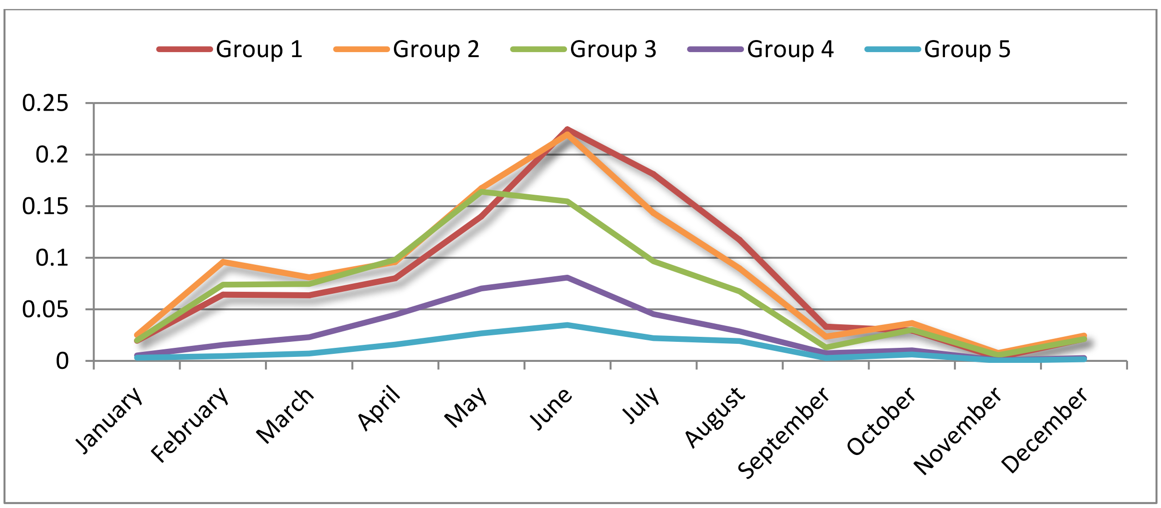


Figure 4.17. Monthly severe storm-based warning population group analysis.

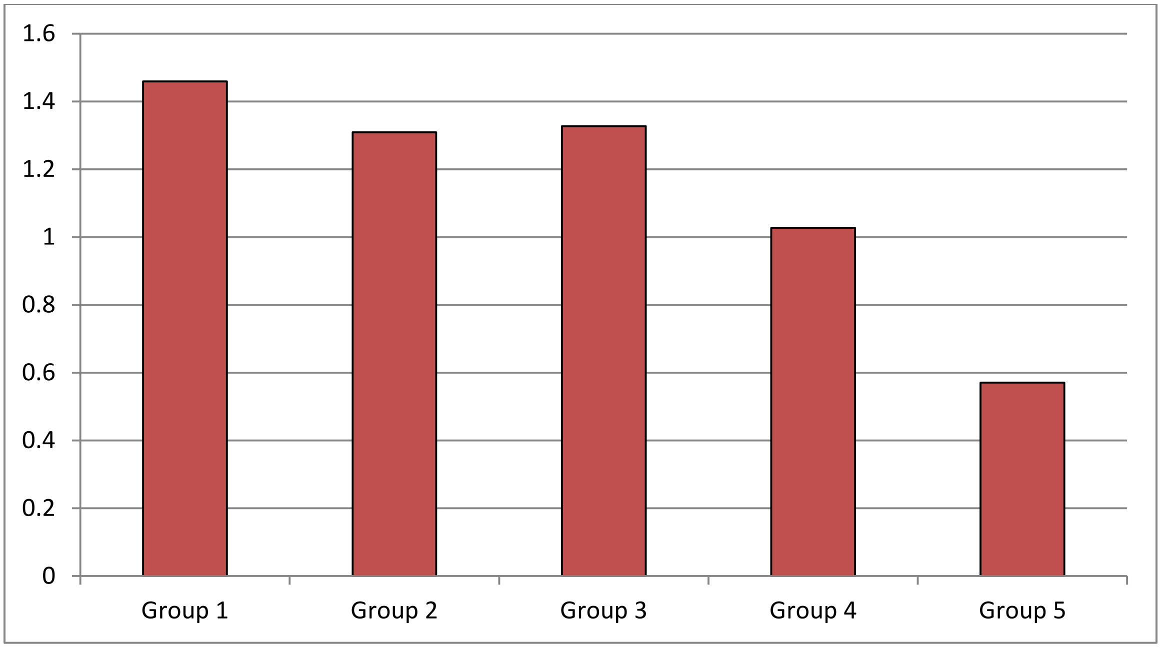


Figure 4.18. Tornado county-based warning population group analysis.

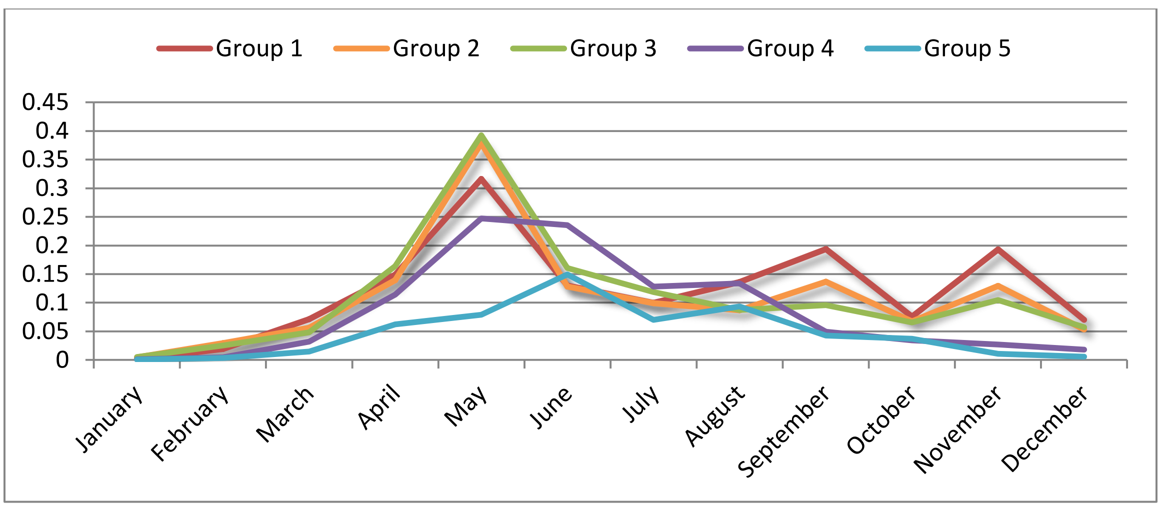


Figure 4.19. Monthly tornado county-based warning population group analysis.

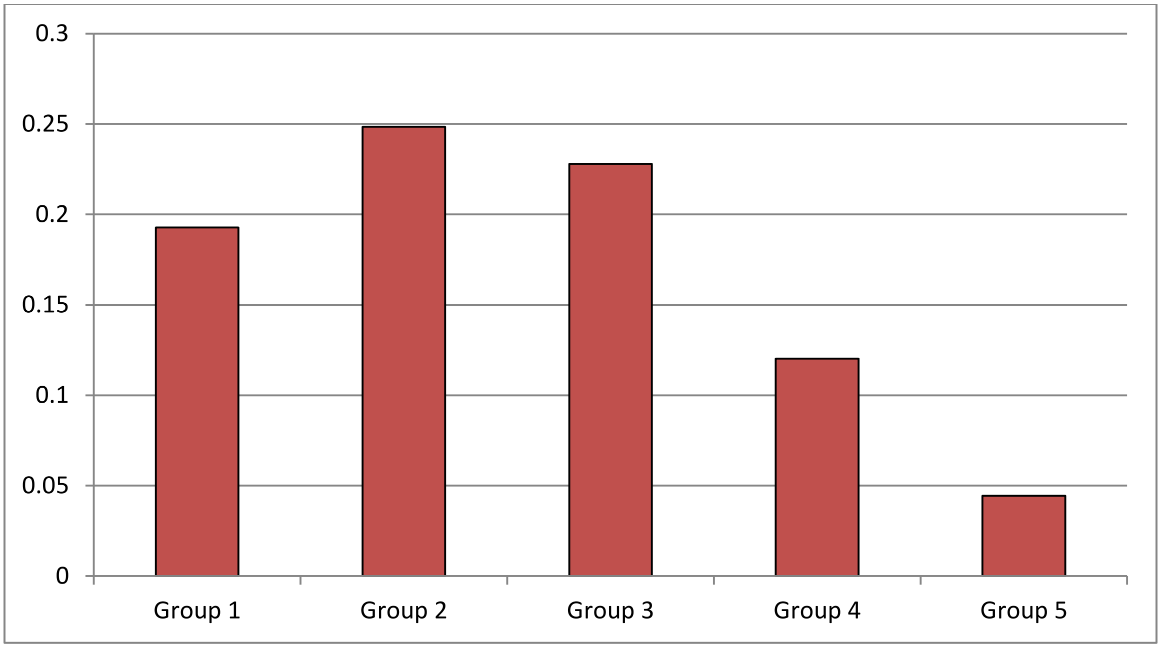


Figure 4.20. Tornado storm-based warning population group analysis.

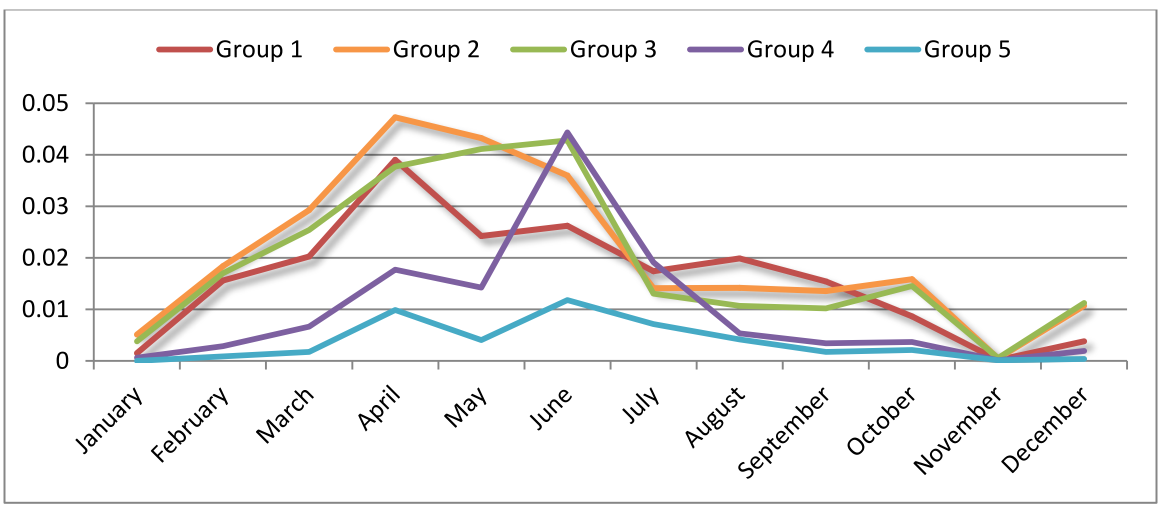


Figure 4.21. Monthly tornado storm-based warning population group analysis.

C. East North Central Climate Region

The total population for East North Central Climate Region is 23,524,667 with an average population density between WFOs of 46.15 persons per km². This region is characterized by the large metropolitan areas of Detroit, Milwaukee, and Minneapolis-St. Paul. By far, the WFO with the highest population density is Detroit/Pontiac (DTX), followed by Milwaukee/Sullivan (MKX) (Figure 4.22). Grand Forks, ND, (FGF), has the lowest population density followed by Marquette, MI (MQT), and Duluth, MN, (DLH). The total number of grid cells (sample size) within the region is 4,723. A table listing the acronym and name of each WFO in this region can be found in Appendix C.

The total number of severe thunderstorm warnings issued for the East North Central Climate Region was 23,311 which ranks fifth among the nine regions. The total number of severe county-based warnings was 23,047 ranking fifth. The total number of severe storm-based warnings was 264 which ranks sixth. A total of 3,128 tornado warnings were issued, 3,067 of which were county-based and 61 of which were storm-based. This region ranks fifth in total tornado warnings, fifth in tornado county-based warnings, and fourth in tornado storm-based warnings.

Milwaukee/Sullivan (MKX) and Detroit Pontiac (DTX) issued the greatest adjusted annual average number of severe county-based warnings (Figure 4.23(*A*)). The Twin Cities (MPX) WFO issued the greatest number of severe storm-based warnings follow by Grand Rapids (GRR), with warnings being relatively low for the remaining CWAs (Figure 4.23 (*B*)). By far the greatest number of tornado county-based warnings were issued by the MKX WFO, with the Quad Cities (DVN) and Detroit Pontiac almost tied for a distant second place (Figure 4.23 (*C*)). The Twin Cities CWA received the greatest number of tornado storm-based warnings, followed by Milwaukee/Sullivan (Figure 4.23 (*D*)).

1. NEXRAD Radar Coverage

NEXRAD coverage for the East North Central region is extensive with very few gaps. Slightly more than 1 percent of the area was lacking radar coverage during the time period of this study (Figure 4.24). Table 4.7 shows that correlation results are relatively low for all warning types, with the highest Z-values calculated for tornado county-based warnings. These results indicate that radar coverage is not a significant factor affecting warning issuance for this climate region.

Table 4.7. Correlation results for NEXRAD coverage for the East North Central Climate Region.

Test	Correlation	Z-Value	P-Value
Population	0.06	4.401	<.001
SVR CBW	0.032	2.336	0.0195
SVR SBW	0.033	2.421	0.0155
TOR CBW	0.096	7.048	<.001
TOR SBW	0.051	3.738	0.0002

2. Distance and Direction

The East North Central Climate Region ranks tied for fifth with the South region in distance performance in overall severe and tornado warnings issued. The adjusted average distance from the geographic center of the CWAs to center of warning distribution is 9.98 km. The mean adjusted distance from location of WFOs to warning center is 11.07 km. The average directional distribution has an azimuth of 196.92°, indicating a tendency for warnings to be issued to the south-southeast of the center of the County Warning Areas. The warning directional distribution from the location of the Weather Forecast Offices registers an azimuth direction of 208.64° (SSW).

The East North Central Climate Region average severe county-based warning azimuthal direction from the CWA centers is 205.36° (SSW). The average warning direction from the WFO locations is 248.09° (WSW). The average distance from the warning center of distribution to the center of the CWAs is 24.18 km (5.13 km adjusted). This region ranks fourth in minimum distance to center of CWAs among all Climate Regions. The average distance from warning center to WFO location is 34.78 km (6.81 km adjusted). The minimum distance ranking for warning center to WFO location is third. The DMX WFO ranks first in distance performance, whereas APX ranks last (Table 4.8).

Table 4.8. Distance performance ranks for the East North Central Climate Region.

WFO	SCBW	SSBW	TCBW	TSBW
APX	12	12	11.5	10
ARX	5.5	4	4.5	6
DLH	9	8	8.5	8
DMX	1	2.5	7	3.5
DTX	2.5	6.5	4.5	8
DVN	7	9	2	5
FGF	4	2.5	3	1
GRB	5.5	6.5	6	NA
GRR	10	1	10	8
MKX	2.5	10	1	2
MPX	8	5	8.5	3.5
MQT	11	11	11.5	11

The mean severe storm-based warning direction from the CWA centers is 203.69° (SSW). The average warning direction from the WFO locations is 192.42° (S). The average distance from the warning center of distribution to the center of the CWAs is 54.85 km (11.91 km adjusted). This region ranks seventh in minimum distance to center of CWAs among all Climate Regions. The average distance from warning center to WFO location is 60.79 km (12.72 km adjusted). The minimum distance ranking for warning center to WFO location is sixth. The GRR WFO ranks first in distance performance, whereas APX ranks last.

The average tornado county-based warning direction from the CWA centers is 203.74° (SSW). The average warning direction from the WFO locations is 220.44° (SW). The average distance from the warning center of distribution to the center of the CWAs is 33.06 km (6.86 km adjusted). This region ranks fifth in minimum distance to center of CWAs among all Climate Regions. The average distance from warning center to WFO location is 44.46 km (9.48 km adjusted). The minimum distance ranking for warning center to WFO location is fifth. The MKX WFO ranks first in distance performance, whereas APX and MQT are tied for the last place rank.

The mean tornado storm-based warning direction from the CWA centers is 174.91° (S). The average warning direction from the WFO locations is 173.64° (S). The average distance from the center of the warning center of distribution to the center of the CWAs is 73.84 km (16.03 km adjusted). This region ranks eighth in minimum distance to center of CWAs among all Climate Regions. The average distance from warning center to WFO location is 73.38 km (15.25 km adjusted). The minimum distance ranking for warning center to WFO location is seventh. The FGF WFO ranks first in distance performance, whereas MQT ranks last.

3. Population

Figure 4.25 shows the results of mapping the derived population groups for the East North Central region. The most significant areas of Population 1 density are in the Detroit, Michigan, and Minneapolis/St. Paul, Minnesota, areas. The lowest population density is found along the Canadian border and northern Great Lakes region.

Figure 4.26 presents the results of the population group analysis in bar graph form. The majority of severe county-based warnings were issued for Population Group 1, although warnings are also numerous for Population Groups 4 and 5 (Figure 4.26 (*A*)). Figure 4.26 (*B*) for severe storm-based warnings is more indicative of a population bias with a "stair-step" like pattern where Population Group 1 received the greatest number of warnings and Population Group 5 received the least. No population bias seems to exist in Figure 4.26 (*C*) for tornado county-based warnings, where Population Group 4 has the most average annual number of warnings. A "stair-step" population bias pattern is seen in Figure 4.26 (*D*) for tornado storm-based warnings. These results suggest that population bias for the East North Central Climate region does not exist for severe warnings, but is likely for tornado warnings.

Table 4.9 shows population correlation results for the entire East North Central Climate Region, and indicates that there is very low correlation between warnings and overall population. Correlation values between the population density of individual WFO county warning areas and both types of county-based warnings are significant. The strongest correlation exists between county-based warnings and WFO density.

Table 4.9. Population correlation results for the East North Central Climate Region. *Significant correlation results are in **bold** listed with Z-Values and P-Values (α = 0.001 for overall population and α = 0.05 for WFO population density).

Test	Correlation	Z-Value	P-Value	Rho	Z-Value	P-Value
SCBW/Population	0.033	2.371	0.0177	0.001	0.058	0.9537
SCBW/WFO Pop Density	**0.754**	**2.949**	**0.0032**	0.566	1.879	0.0603
SSBW/Population	0.043	3.122	0.002	**0.100**	**7.273**	**<.001**
SSBW/WFO Pop Density	0.052	0.157	0.875	0.238	0.789	0.4300
TCBW/Population	-0.030	-2.216	0.0267	**0.085**	**6.219**	**<.001**
TCBW/WFO Pop Density	**0.583**	**2.002**	**0.0452**	**0.734**	**2.435**	**0.0149**
TSBW/Population	0.033	2.437	0.0148	**0.108**	**7.846**	**<.001**
TSBW/WFO Pop Density	0.329	1.026	0.3048	0.462	1.531	0.1258

Table 4.10 shows population correlation values for all WFOs in the East North Central region. The greatest likelihood for correlation between population and severe county- and storm-based warnings exists with the Quad Cities (DVN) WFO. Severe county-based warnings and tornado county-based warnings are statistically significant for the Des Moines (DMX) WFO. Tornado county-based warnings are statistically significant for Grand Forks (FGF) and severe county-based warnings are statistically significant for the Grand Rapids (GRR). There appears to be little evidence of population correlation with any of the remaining WFOs in the East North Central Region.

Table 4.10. WFO population correlations for the East North Central Climate Region. *Significant correlation results are in **bold** listed with P-Values (α = 0.001).

WFO	SCBW	P-Value	SSBW	P-Value	TCBW	P-Value	TSBW	P-Value
APX	0.164	0.0016	0.030	0.5608	0.087	0.0963	-0.033	0.5318
ARX	-0.123	0.0147	-0.022	0.6714	-0.070	0.1675	0.002	0.9730
DLH	0.065	0.0822	0.027	0.4735	0.085	0.0221	0.021	0.5694
DMX	**0.197**	**<.001**	-0.044	0.3056	**0.147**	**0.0005**	0.065	0.1272
DVN	**0.242**	**<.001**	**0.211**	**<.001**	-0.020	0.6788	-0.040	0.4109
FGF	0.102	0.0024	0.016	0.6285	**0.133**	**<.001**	0.049	0.1448
GRB	0.039	0.4760	-0.047	0.3951	0.054	0.3315	--	>.9999
GRR	**0.215**	**0.0004**	0.015	0.8102	-0.034	0.5796	0.013	0.8380
MKX	-0.040	0.5661	0.010	0.8895	**-0.223**	**0.0013**	0.045	0.5204
MPX	0.042	0.3123	0.025	0.5437	-0.092	0.0281	0.039	0.3479
MQT	0.153	0.0030	-0.023	0.6538	0.097	0.0603	-0.028	0.5823

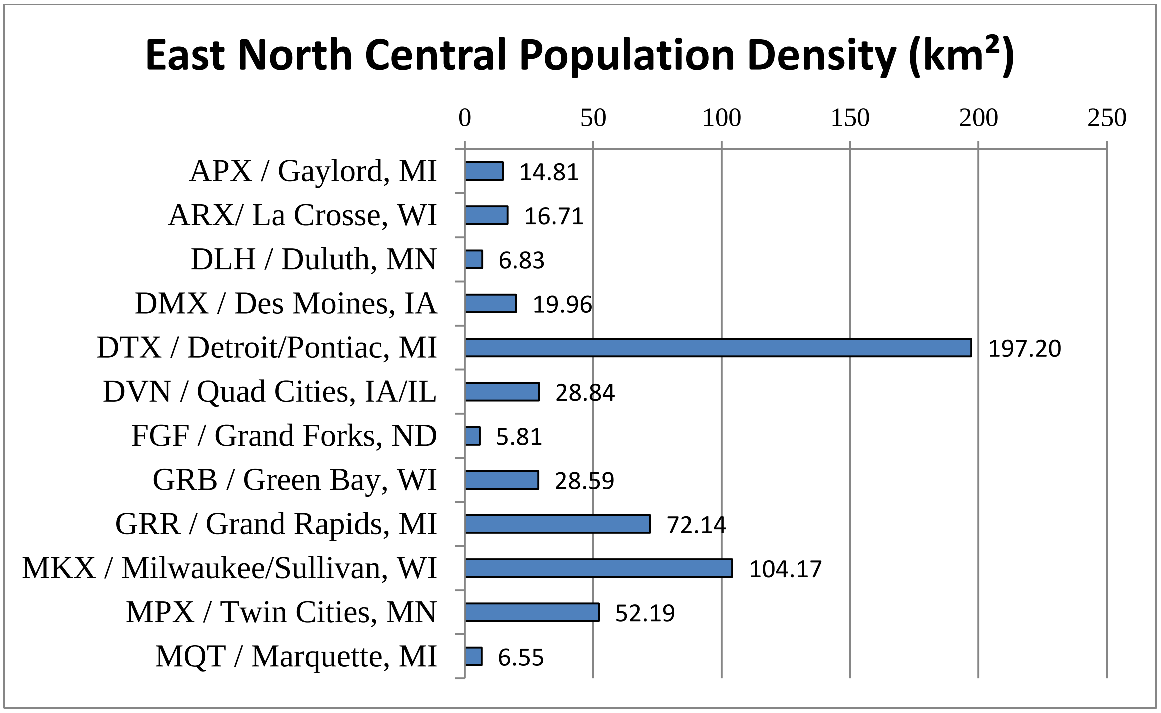


Figure 4.22. WFO population density for the East North Central Climate Region.

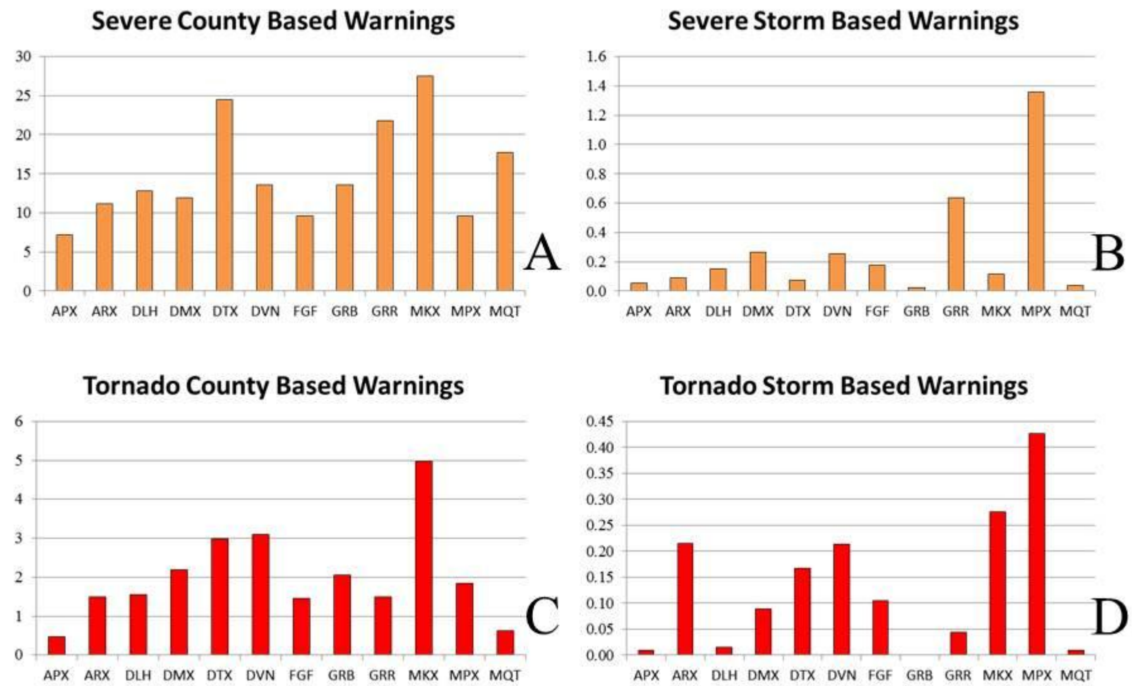


Figure 4.23. Area adjusted annual average warnings by National Weather Service Weather Forecast Office. Average severe county-based warnings (*A*), severe storm-based warnings (*B*), tornado county-based warnings (*C*), and tornado storm-based warnings (*D*) are depicted for the East North Central Climate Region.

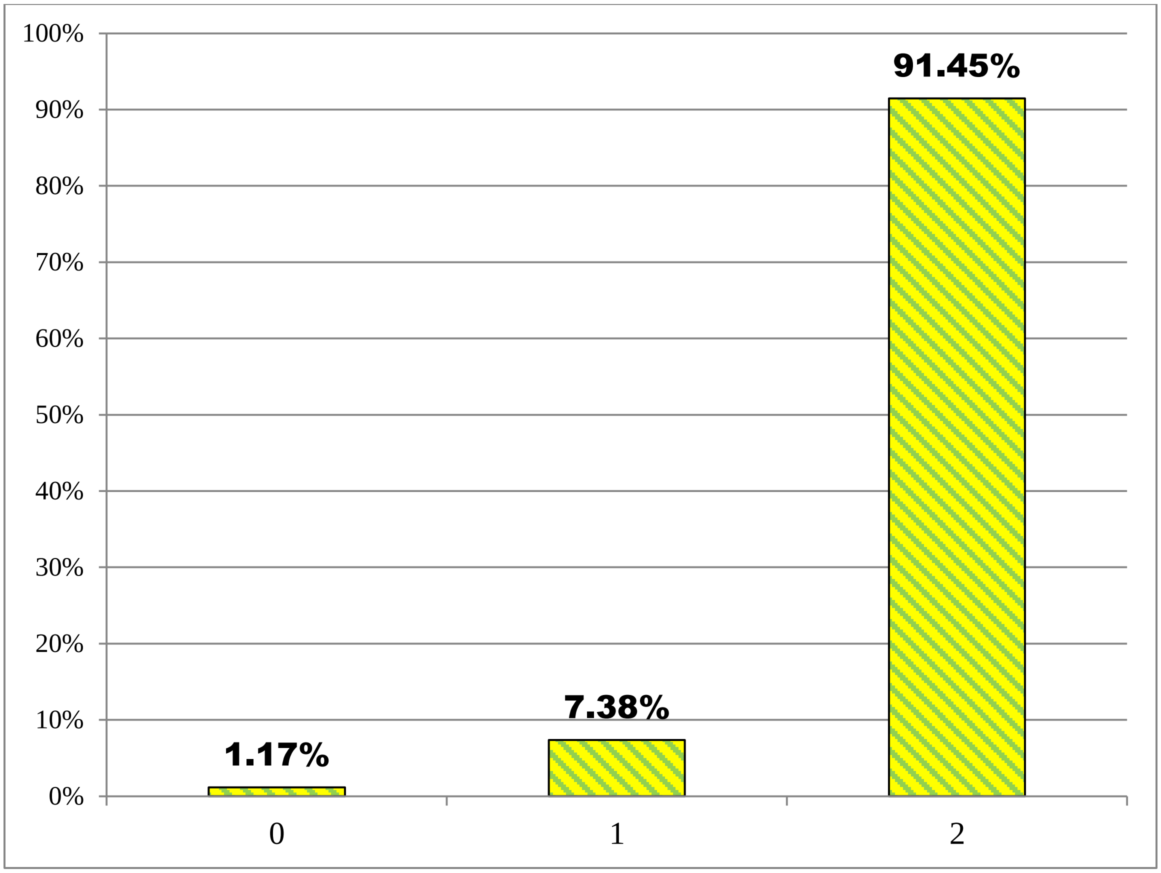


Figure 4.24. NEXRAD radar coverage for the East North Central Climate Region.

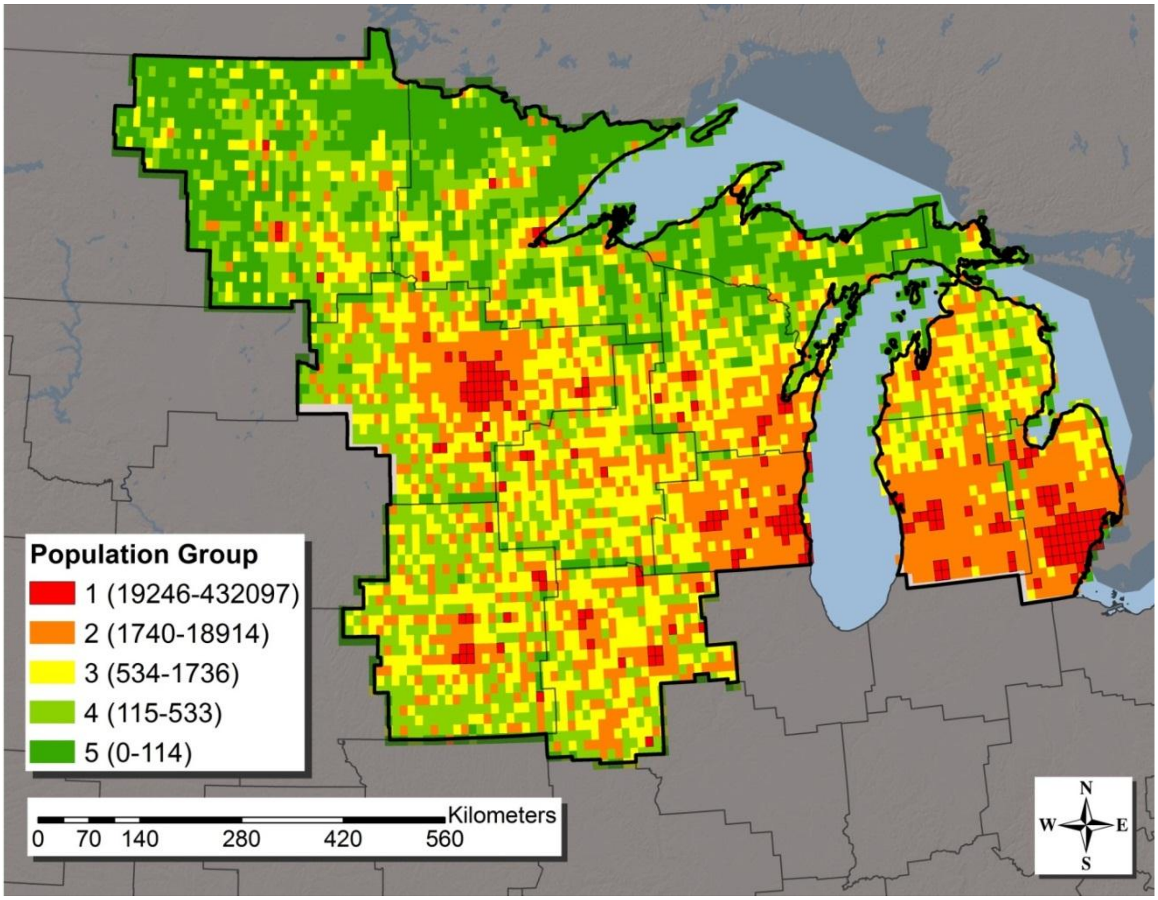


Figure 4.25. Population group distribution within the East North Central Climate Region.

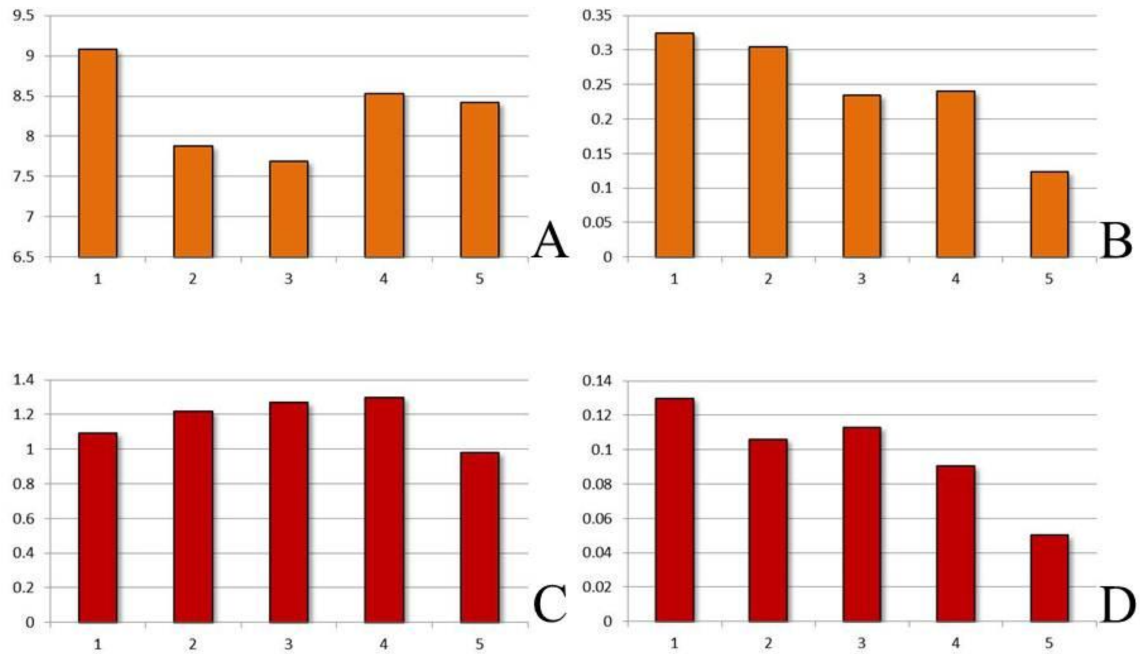


Figure 4.26. Results of the population group analysis for the four warning types. Average severe county-based warnings (A), severe storm-based warnings (B), tornado county-based warnings (C), and tornado storm-based warnings (D) are depicted for the East North Central Climate Region.

D. Northeast Climate Region

With a total population of 54,110,834 and an average WFO population density of 206.10 persons per km^2, the Northeast Climate Region is the most densely populated Climate Region in the CONUS. This region includes the major metropolitan areas of New York City, Philadelphia, and Boston. The New York, NY (OKX) WFO has the greatest population density of all the WFOs in the CONUS at 1091.55 persons per km^2 (Figure 4.27). This is in sharp contrast of Caribou, ME (CAR), which has a very low population density of 5.54 persons per km^2. The total number of grid cells (sample size) within the region is 3,132. A table listing the acronym and name of each WFO in this region can be found in Appendix C.

The total number of severe thunderstorm warnings issued for the Northeast Climate Region was 16,718 which ranks sixth among the nine regions. The total number of severe county-based warnings was 15,533 ranking sixth. The total number of severe storm-based warnings was 1,185, which ranks fourth. A total of 743 tornado warnings were issued, 698 of which were county-based and 45 of which were storm-based. This region ranks seventh in total tornado warnings, seventh in tornado county-based warnings, and sixth in tornado storm-based warnings.

Figure 4.28 (*A*) shows that the greatest number of severe county-based warnings were issued by the New York (OKX) WFO, followed by Philadelphia (PHI). The Philadelphia and State College (CTP) WFOs issued the greatest number of severe storm-based warnings, with very few warnings being issued for Burlington (BTV) and Caribou (CAR) (Figure 4.28 (*B*)). The highest annual average numbers of tornado county-based warnings were issued in the densely populated New York and Philadelphia CWAs, as well as the sparsely populated Caribou warning area (Figure 4.28 (*C*)). New York was dominant in the number of tornado storm-based warnings issued (Figure 4.28 (*D*)).

1. NEXRAD Radar Coverage

Figure 4.29 shows that NEXRAD radar coverage for the Northeast Climate Regions is nearly total with almost 99 percent perfect coverage. Correlations between all warning types are weak, with only severe warnings indicating a statistical significance (Table 4.11).

Table 4.11. Correlation results for NEXRAD coverage for the Northeast Climate Region.

Test	Correlation	Z-Value	P-Value
Population	0.023	1.273	0.2029
SVR CBW	0.09	5.057	<.001
SVR SBW	0.084	4.709	<.001
TOR CBW	0.03	1.692	0.0906
TOR SBW	0.036	2.032	0.0421

2. Distance and Direction

The Northeast Climate Region ranks eighth in distance performance in overall severe and tornado warnings issued. The adjusted average distance from the geographic center of the CWAs to center of warning distribution is 13.07 km. The mean adjusted distance from location of WFOs to warning center is 17.63 km. The average directional distribution has an azimuth of 198.24°, indicating a tendency for warnings to be issued to the south-southwest of the center of the County Warning Areas. The warning directional distribution from the location of the Weather Forecast Offices registers an azimuth direction of 219.44° (SW).

The Northeast Climate Region mean severe county-based warning azimuthal direction from the CWA centers is 197.10° (SSW). The average warning direction from the WFO locations is 230.05° (SW). The average distance from the warning center of distribution to the center of the CWAs is 29.81 km (8.70 km adjusted). This region ranks eighth in minimum distance to center of CWAs among all Climate Regions. The average distance from warning center to WFO location is 34.78 km (16.44 km adjusted). The minimum distance ranking for warning center to WFO location is last at ninth place. The PHI and GYX WFOs are tied for first place ranking in distance performance, whereas BGM ranks last (Table 4.12).

Table 4.12. Distance performance ranks for the Northeast Climate Region.

WFO	SCBW	SSBW	TCBW	TSBW
ALY	3	3	5	7
BGM	10	8.5	2.5	5
BOX	4.5	5.5	5	6
BTV	7.5	7	7	8.5
BUF	9	10	10	10
CAR	6	1.5	8.5	8.5
CTP	7.5	5.5	5	2.5
GYX	1.5	8.5	8.5	4
OKX	4.5	4	2.5	2.5
PHI	1.5	1.5	1	1

The mean severe storm-based warning azimuthal direction from the CWA centers is 218.12° (SW). The average warning direction from the WFO locations is 228.11°

(SW). The average distance from the warning center of distribution to the center of the CWAs is 41.33 km (12.44 km adjusted). This region ranks eighth in minimum distance to center of CWAs among all Climate Regions. The average distance from warning center to WFO location is 59.91 km (17.98 km adjusted). The minimum distance ranking for warning center to WFO location is eighth. The CAR and PHI WFOs are tied for first place ranking in distance performance, whereas BUF ranks last.

The average tornado county-based warning azimuthal direction from the CWA centers is 211.24° (SSW). The average warning direction from the WFO locations is 230.77° (SW). The average distance from the warning center of distribution to the center of the CWAs is 49.50 km (12.92 km adjusted). This region ranks eighth in minimum distance to center of CWAs among all Climate Regions. The average distance from warning center to WFO location is 53.95 km (16.11 km adjusted). The minimum distance ranking for warning center to WFO location is last at ninth place. The PHI WFO ranks first in distance performance, whereas BUF ranks last.

The mean tornado storm-based warning azimuthal direction from the CWA centers is 166.50° (SSE). The average warning direction from the WFO locations is 188.84° (S). The average distance from the warning center of distribution to the center of the CWAs is 68.69 km (18.21 km adjusted). This region ranks last place at ninth in minimum distance to center of CWAs among all Climate Regions. The average distance from warning center to WFO location is 67.68 km (20.00 km adjusted). The minimum distance ranking for warning center to WFO location is eighth. The PHI WFO ranks first in distance performance, whereas BUF ranks last.

3. Population

The population group map for the Northeast Climate Region (Figure 4.30) demonstrates the effect of the densely populated urban areas of New York City, Philadelphia, and Boston on the spatial distribution of the population groups. The resulting map shows that the bulk of Population Group 1 lies along the east and southeast Atlantic coast area. Most of Population Group 5 is in the northern part of the region, especially in the rural areas of Maine.

Figure 4.31 (*A*) indicates a "stair step" population bias for severe county-based warnings, with the exception of Population Group 5. This is likely because of spatial bias which is introduced by large counties in the sparsely populated areas in northern Maine. Figure 4.31 (*B*) shows a possible population bias by demonstrating that the highest severe storm-based warning frequency is found in Population Groups 1 and 2, with the lowest number of warnings having been issued for Population Group 5. Tornado county-based warnings demonstrate no population bias with warnings having been issued almost evenly across the population groups, with the exception of Population Group 5, which may again be an indication of the effect of large county size (Figure 4.31 (*C*). Figure 4.31 (*D*) exhibits a population bias, with far more tornado storm-based warnings having been issued for Population Group 1 and the least for Population Group 5.

Table 4.13 indicates a practical and statistical relationship between severe county-based warnings and WFO population density, but no correlation is evident for this warning type and overall population. The results of the Spearman's Rho test establish that severe storm-based warnings show a robust relationship between both overall population and WFO population density. Rho results indicate a weak correlation for tornado county-based warnings and population. The strongest correlations exist between tornado storm-based warnings and WFO population density, with weak results indicated for overall population relationship.

Table 4.13. Population correlation results for the Northeast Climate Region. *Significant correlation results are in **bold** listed with Z-Values and P-Values (α = 0.001 for overall population and α = 0.05 for WFO population density).

Test	Correlation	Z-Value	P-Value	Rho	Z-Value	P-Value
SCBW/Population	-0.006	-0.344	0.7311	0.056	3.139	0.0017
SCBW/WFO Pop Density	**0.795**	**2.874**	**0.0041**	0.406	1.218	0.2232
SSBW/Population	**0.06**	**3.336**	**0.0008**	**0.396**	**22.161**	**<.001**
SSBW/WFO Pop Density	0.39	1.091	0.2753	**0.709**	**2.127**	**0.0334**
TCBW/Population	-0.027	-1.488	0.1367	**0.077**	**4.284**	**<.001**
TCBW/WFO Pop Density	0.406	1.14	0.2541	0.212	0.636	0.5245
TSBW/Population	0.052	2.896	0.0038	**0.153**	**8.557**	**<.001**
TSBW/WFO Pop Density	**0.913**	**4.091**	**<.001**	**0.721**	**2.164**	**0.0305**

The strongest correlations for the individual WFOs in the Northeast Climate Region exist for the State College (CTP) WFO, where all results show statistical significance (Table 4.14). The strongest relationship exists for the State College WFO and severe storm-based warnings. The Gray/Portland (GYX) WFO shows a correlation with severe storm-based warnings and weaker correlation with tornado county-based warnings. Philadelphia (PHI) demonstrates a correlation with severe storm-based warnings.

Table 4.14. WFO population correlations for the Northeast Climate Region. *Significant correlation results are in **bold** listed with P-Values (α = 0.001).

WFO	SCBW	P-Value	SSBW	P-Value	TCBW	P-Value	TSBW	P-Value
ALY	0.182	0.003	0.033	0.5961	0.14	0.0228	-0.007	0.905
BGM	-0.061	0.2469	0.1	0.0593	0.015	0.7839	-0.067	0.2091
BOX	0.073	0.2183	0.214	0.0002	-0.075	0.2051	0.076	0.1973
BTV	0.088	0.1403	0.054	0.362	-0.037	0.5323	-0.031	0.6062
BUF	0.005	0.9358	-0.079	0.1994	0.012	0.8442	-0.058	0.3498
CAR	0.036	0.4616	-0.05	0.3091	-0.019	0.7045	-0.02	0.6869
CTP	**0.276**	**<.001**	**0.411**	**<.001**	**0.276**	**<.001**	**0.176**	**0.001**
GYX	**-0.159**	**0.001**	**0.282**	**<.001**	**0.176**	**0.0003**	0.013	0.7965
OKX	-0.091	0.2516	-0.09	0.2577	-0.135	0.087	-0.009	0.9067
PHI	0.115	0.0399	**0.213**	**0.0001**	0.002	0.9678	0.088	0.1185

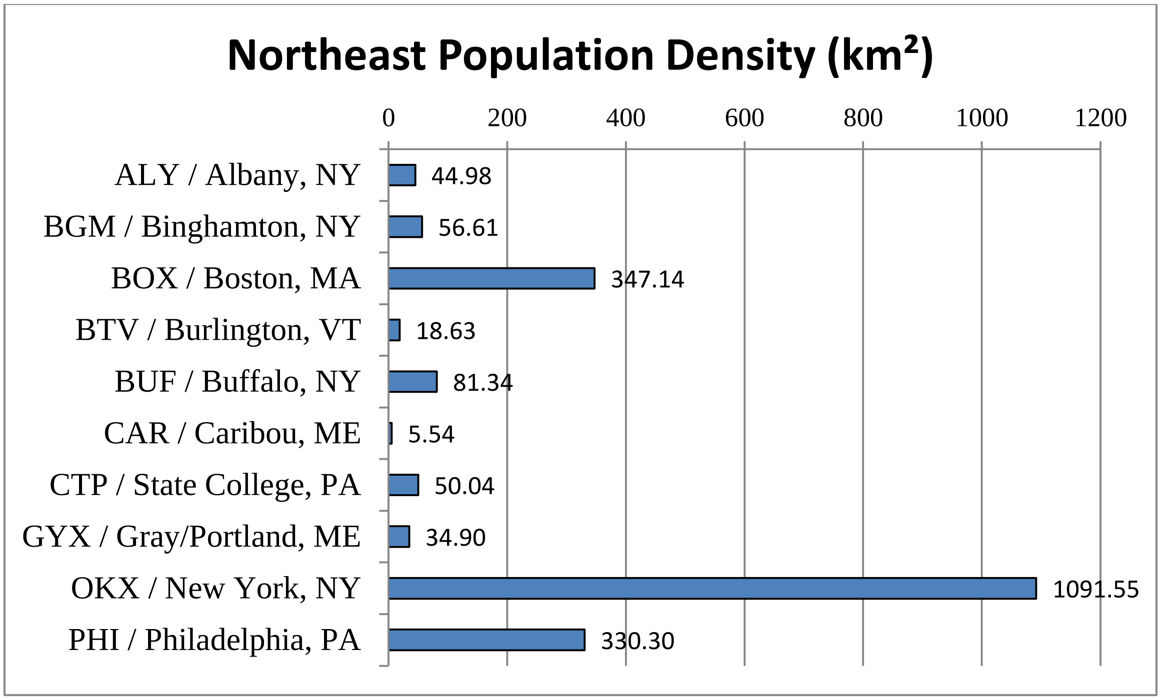


Figure 4.27. WFO population density for the Northeast Climate Region.

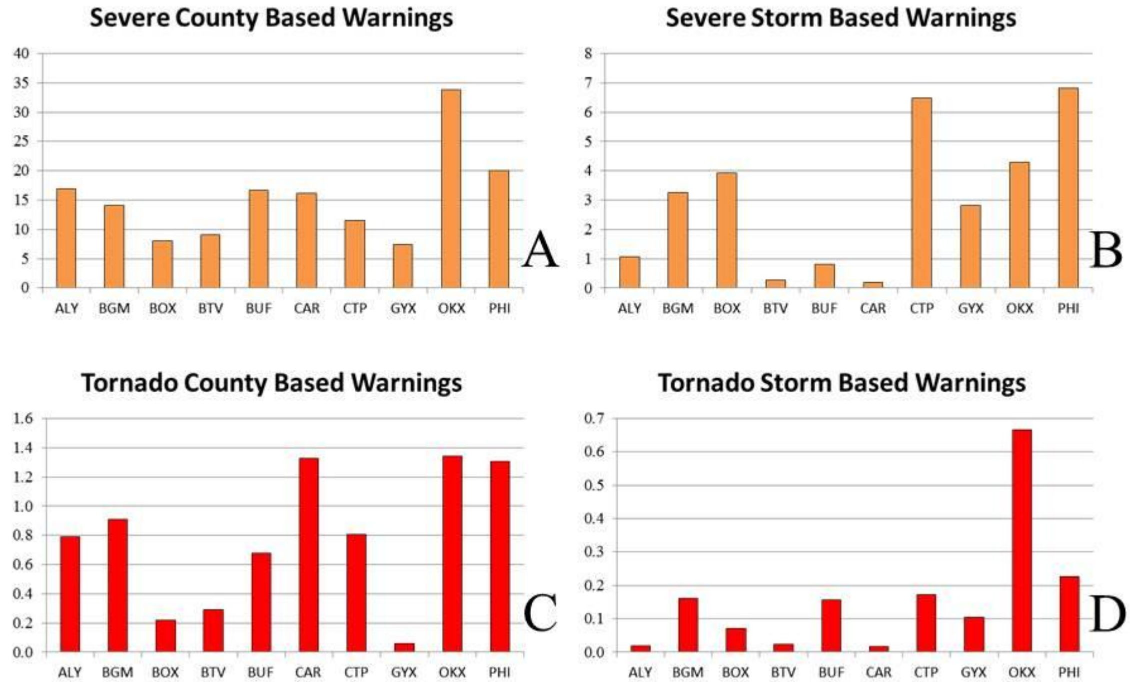


Figure 4.28. Area adjusted annual average warnings by National Weather Service Weather Forecast Office. Average severe county-based warnings (*A*), severe storm-based warnings (*B*), tornado county-based warnings (*C*), and tornado storm-based warnings (*D*) are depicted for the Northeast Climate Region.

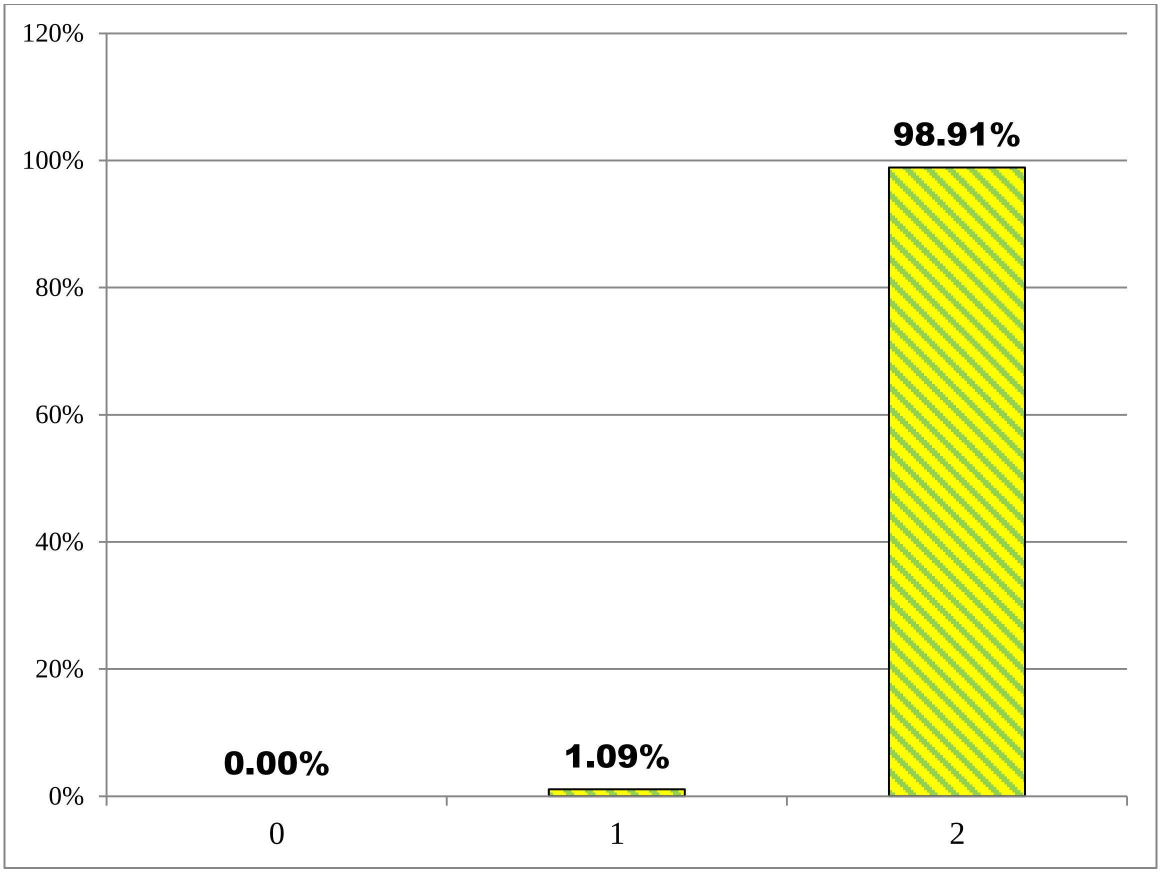


Figure 4.29. NEXRAD radar coverage for the Northeast Climate Region.

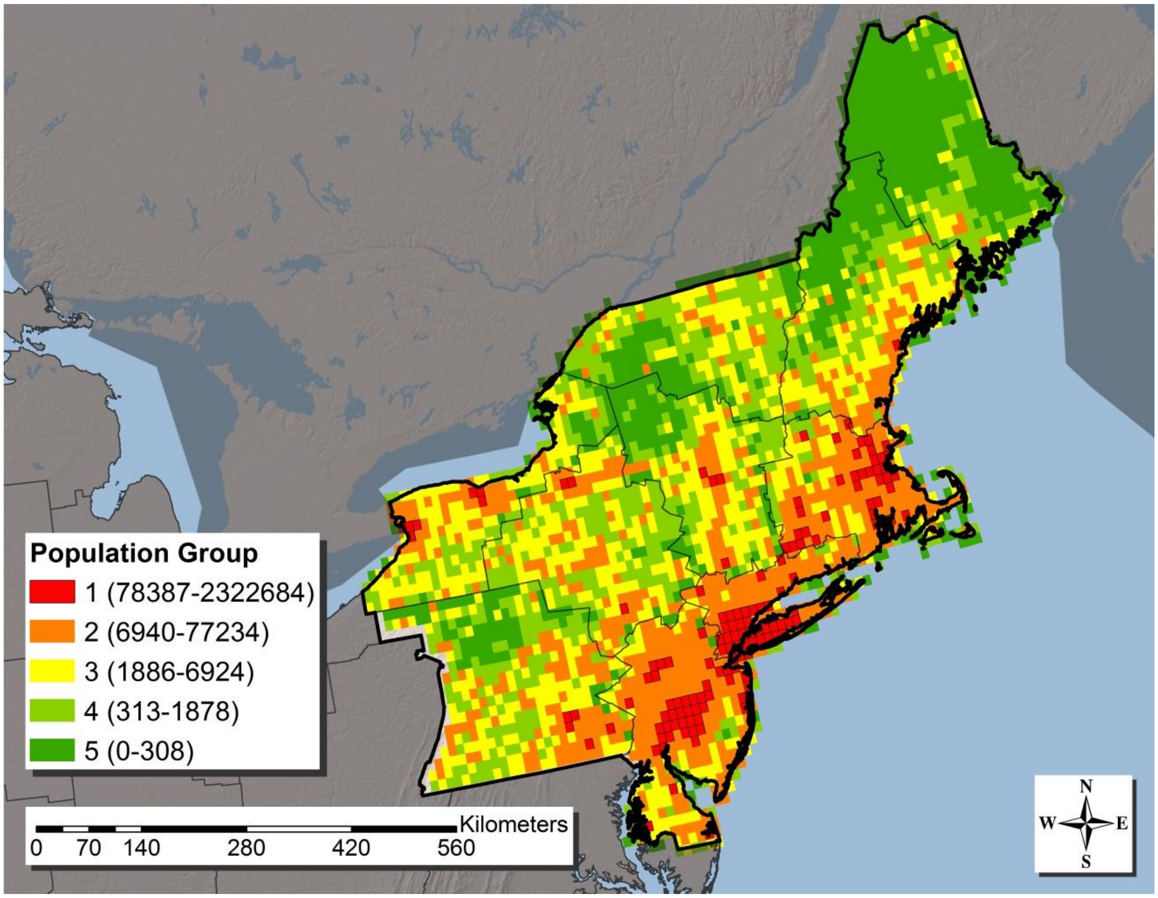


Figure 4.30. Population group distribution within the Northeast Climate Region.

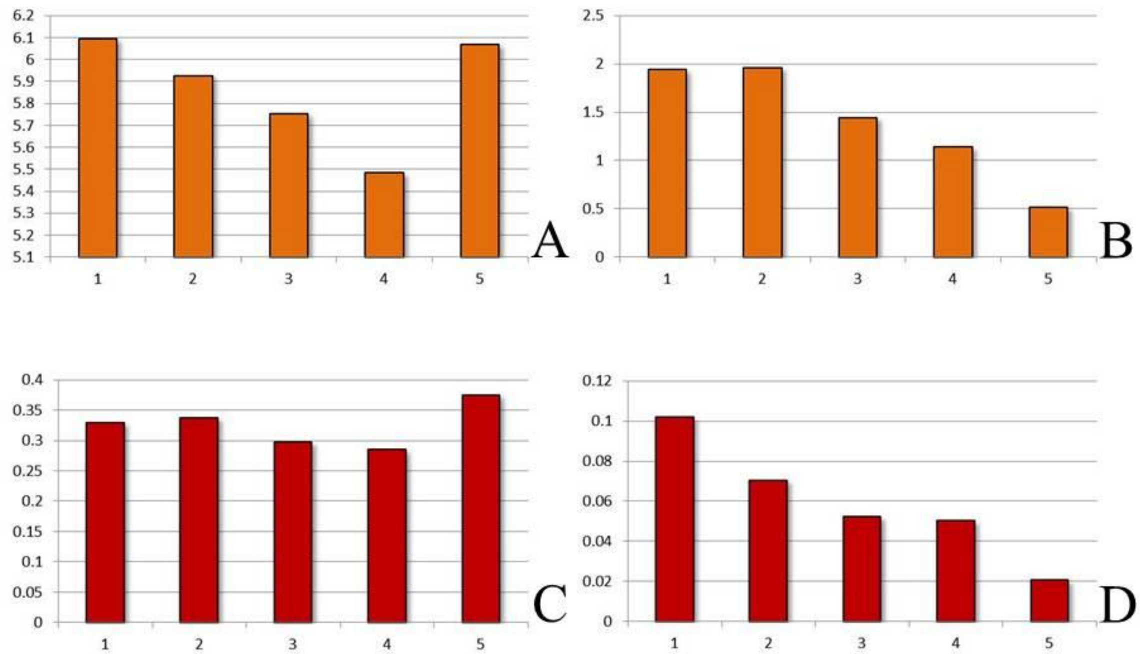


Figure 4.31. Results of the population group analysis for the four warning types. Average severe county-based warnings (A), severe storm-based warnings (B), tornado county-based warnings (C), and tornado storm-based warnings (D) are depicted for the Northeast Climate Region.

E. Northwest Climate Region

The Northwest Climate Region has a total population of 11,755,951 and an average WFO population density of 25.66 persons per km². This region contains the metropolitan areas of Seattle, Washington, and Portland, Oregon. The county warning area with the densest population is Seattle (SEW), at 83 persons per square kilometer (Figure 4.32). The Portland (PQR) WFO has the second highest population density. The remaining county warning areas are sparsely populated, with an average population density of 7.54 persons per km². The total number of grid cells (sample size) within the region is 4,724. The Northwest Climate Region has the least number of WFOs. A table listing the acronym and name of each WFO in this region can be found in Appendix C.

The total number of severe thunderstorm warnings issued for the Northwest Climate Region was 2,289 which ranks eighth among the nine regions. The total number of severe county-based warnings was 2,253 ranking eighth. The total number of severe storm-based warnings was 36 which ranks eighth. 90 tornado warnings were issued, 88 of which were county-based and 2 of which were storm-based. The Northwest region has the least amount of total and county-based tornado warnings and is tied for the least amount of storm-based warnings with the West region.

The Pocatello (PIH) CWA received the greatest annual average number of severe county-based warnings, followed by Boise (BOI) (Figure 4.33 (*A*)). Seattle (SEW) received the most severe storm-based warnings, with the Pendleton (PDT) issuing none during the time period of study (Figure 4.33 (*B*)). By far, the most tornado warnings of all types were issued by the Pocatello WFO (Figure 4.33 (*C-D*)).

1. NEXRAD Radar Coverage

Because of terrain blockage and lack of a dense network of radar locations, radar coverage is somewhat sparse in the Northwest Climate Region. Almost 7.5% percent of the area lacks radar coverage, with only 81.5% receiving perfect coverage (Figure 4.34). This region shows some evidence of radar correlation to warnings. Table 4.15 shows statistical significance for severe and tornado county-based warnings as well as severe storm-based warnings.

Table 4.15. Correlation results for NEXRAD coverage for the Northwest Climate Region.

Test	Correlation	Z-Value	P-Value
Population	0.053	3.672	<.001
SVR CBW	0.166	11.528	<.001
SVR SBW	0.104	7.149	<.001
TOR CBW	0.144	9.993	<.001
TOR SBW	0.006	0.382	0.7022

2. Distance and Direction

The Northwest Climate Region ranks second in distance performance in overall severe and tornado warnings issued. The adjusted average distance from the geographic center of the CWAs to center of warning distribution is 9.48 km. The mean adjusted distance from location of WFOs to warning center is 9.28 km. The average directional distribution has an azimuth of 115.15°, indicating a tendency for warnings to be issued to the east-southeast of the center of the County Warning Areas. The warning directional distribution from the location of the Weather Forecast Offices registers an azimuth direction of 171.66° (S).

The Northwest Climate Region mean severe county-based warning azimuthal direction from the CWA centers is 145.39° (SE). The average warning direction from the WFO locations is 195.04° (SSW). The average distance from the warning center of distribution to the center of the CWAs is 51.67 km (6.67 km adjusted). This region ranks seventh in minimum distance to center of CWAs among all Climate Regions. The average distance from warning center to WFO location is 53.36 km (6.82 km adjusted). The minimum distance ranking for warning center to WFO location is fourth. The MFR and PDT WFOs are tied for first place in distance performance, whereas SEW ranks last (Table 4.16).

Table 4.16. Distance performance ranks for the Northwest Climate Region.

WFO	SCBW	SSBW	TCBW	TSBW
BOI	5	3.5	2.5	3
MFR	1.5	2	--	--
OTX	3	3.5	4	4
PDT	1.5	--	1	--
PIH	6	1	2.5	2
PQR	4	6	5	1
SEW	7	5	--	--

The mean severe storm-based warning azimuthal direction from the CWA centers is 69.43° (ENE). The average warning direction from the WFO locations is 182.61° (S). The average distance from the warning center of distribution to the center of the CWAs is 72.28 km (9.39 km adjusted). This region ranks sixth in minimum distance to center of

CWAs among all Climate Regions. The average distance from warning center to WFO location is 67.31 km (8.47 km adjusted). The minimum distance ranking for warning center to WFO location is second. The PIH WFO ranks first in distance performance, whereas PQR ranks last.

The average tornado county-based warning azimuthal direction from the CWA centers is 108.20° (ESE). The average warning direction from the WFO locations is 174.89° (S). The average distance from the warning center of distribution to the center of the CWAs is 89.12 km (10.46 km adjusted). This region ranks seventh in minimum distance to center of CWAs among all Climate Regions. The average distance from warning center to WFO location is 67.72 km (7.62 km adjusted). The minimum distance ranking for warning center to WFO location is second. The PDT WFO ranks first in distance performance, whereas PQR ranks last.

The mean tornado storm-based warning azimuthal direction from the CWA centers is 137.57° (SE). The average warning direction from the WFO locations is 134.08° (SE). The average distance from the warning center of distribution to the center of the CWAs is 103.68 km (11.42 km adjusted). This region ranks sixth in minimum distance to center of CWAs among all Climate Regions. The average distance from warning center to WFO location is 116.78 km (14.22 km adjusted). The minimum distance ranking for warning center to WFO location is sixth. The PQR WFO ranks first in distance performance, whereas OTX ranks last.

3. Population

The Seattle and Portland metro areas represent the majority of the Population Group 1 areas for the Northwest Climate Region (Figure 4.35). Other Population Group 5 areas are found near Boise and Spokane. Most of the Population Group 5 areas are found in the southern part of the climate region. It is of interest to note that each Population Group 5 cell contains no people.

Figure 4.36 (*A*) indicates that there is no population bias for severe county-based warnings as it shows a reverse "stair step" pattern. Possible population bias is shown in Figure 4.36 (*B*), where Population Group 1 had the highest frequency of severe storm-based warnings, with the fewest warnings issued for groups 4 and 5. No indication of tornado warning population bias exists in Figure 4.36 (*C*-*D*).

Table 4.17 shows that, although several correlation test show statistical significance, none show evidence of strong correlation. Most of the resulting values are negative, indicating a negative correlation.

Table 4.17. Population correlation results for the Northwest Climate Region. *Significant correlation results are in **bold** listed with Z-Values and P-Values (α = 0.001 for overall population and α = 0.05 for WFO population density).

Test	Correlation	Z-Value	P-Value	Rho	Z-Value	P-Value
SCBW/Population	**-0.059**	**-4.047**	**<.001**	**-0.179**	**-12.279**	**<.001**
SCBW/WFO Pop Density	-0.519	-1.149	0.2507	-0.607	-1.487	0.137
SSBW/Population	0.002	0.123	0.9018	**0.053**	**3.652**	**0.0003**
SSBW/WFO Pop Density	0.635	1.499	0.134	0.357	0.875	0.3817
TCBW/Population	-0.027	-1.842	0.0655	**-0.048**	**-3.318**	**0.0009**
TCBW/WFO Pop Density	-0.494	-1.084	0.2785	-0.45	-1.103	0.2698
TSBW/Population	-0.014	-0.955	0.3397	**0.053**	**3.652**	**0.0003**
TSBW/WFO Pop Density	-0.293	-0.603	0.5468	-0.408	-0.999	0.318

Results of the correlation test for the individual WFOs in the Northwest Climate Region show that there is little chance of relationships between warnings and population for this region. The only significant results are indicated for the Boise (BOI) WFO, where severe storm-based warnings show a statistical significance.

Table 4.18. WFO population correlations for the Northwest Climate Region. *Significant correlation results are in **bold** listed with P-Values (α = 0.001).

WFO	SCBW	P-Value	SSBW	P-Value	TCBW	P-Value	TSBW	P-Value
BOI	0.03	0.3536	**0.225**	**<.001**	0.01	0.7429	-0.014	0.6521
MFR	0.056	0.14	0.093	0.0151	--	>.9999	--	>.9999
OTX	0.108	0.0017	0.022	0.5228	0.102	0.0031	-0.003	0.9233
PDT	-0.067	0.0689	--	>.9999	-0.044	0.2387	--	>.9999
PIH	0.096	0.0211	-0.014	0.731	0.113	0.0068	-0.026	0.5352
PQR	-0.011	0.8176	-0.056	0.2296	-0.017	0.7099	-0.021	0.6539
SEW	0.14	0.0032	-0.083	0.081	--	>.9999	--	>.9999

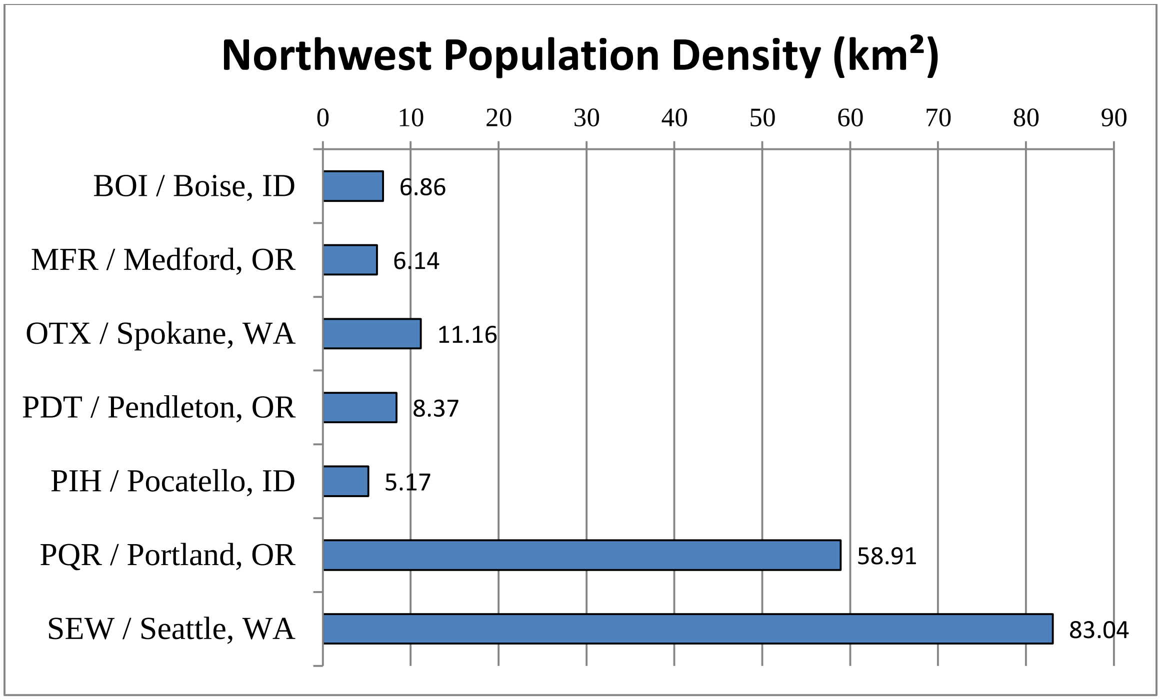


Figure 4.32. WFO population density for the Northwest Climate Region.

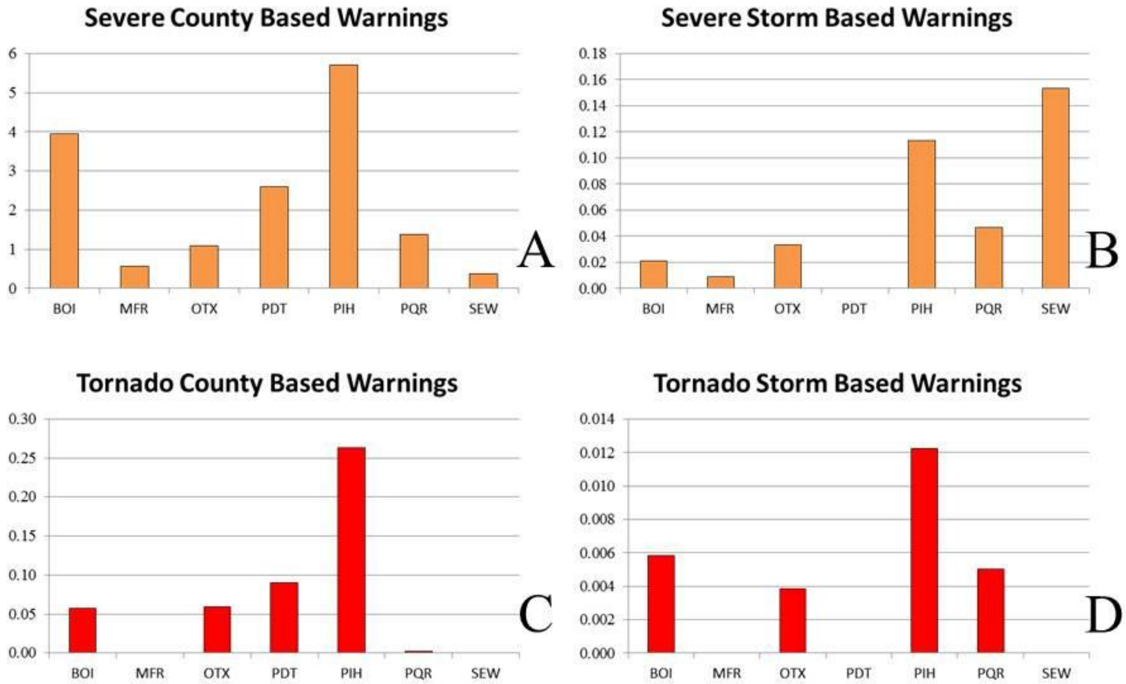


Figure 4.33. Area adjusted annual average warnings by National Weather Service Weather Forecast Office. Average severe county-based warnings (*A*), severe storm-based warnings (*B*), tornado county-based warnings (*C*), and tornado storm-based warnings (*D*) are depicted for the Northwest Climate Region.

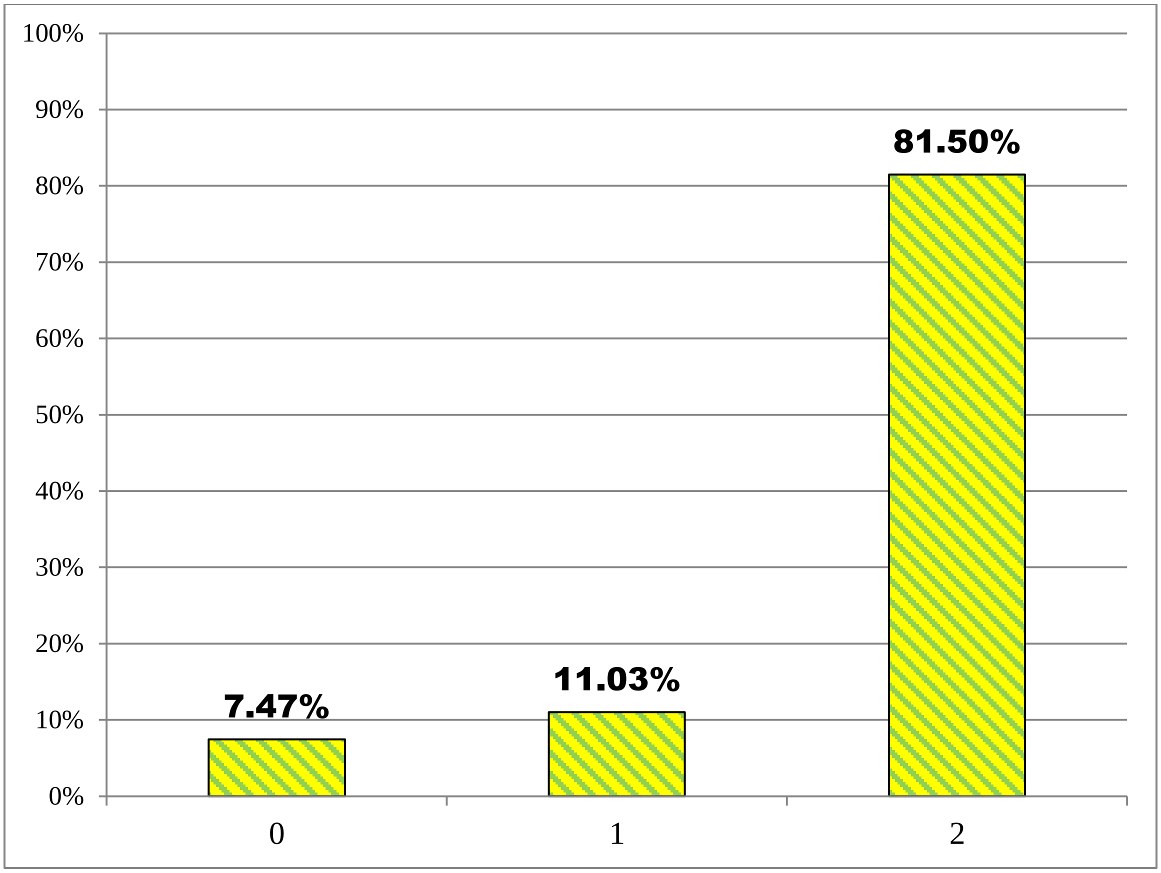


Figure 4.34. NEXRAD radar coverage for the Northwest Climate Region.

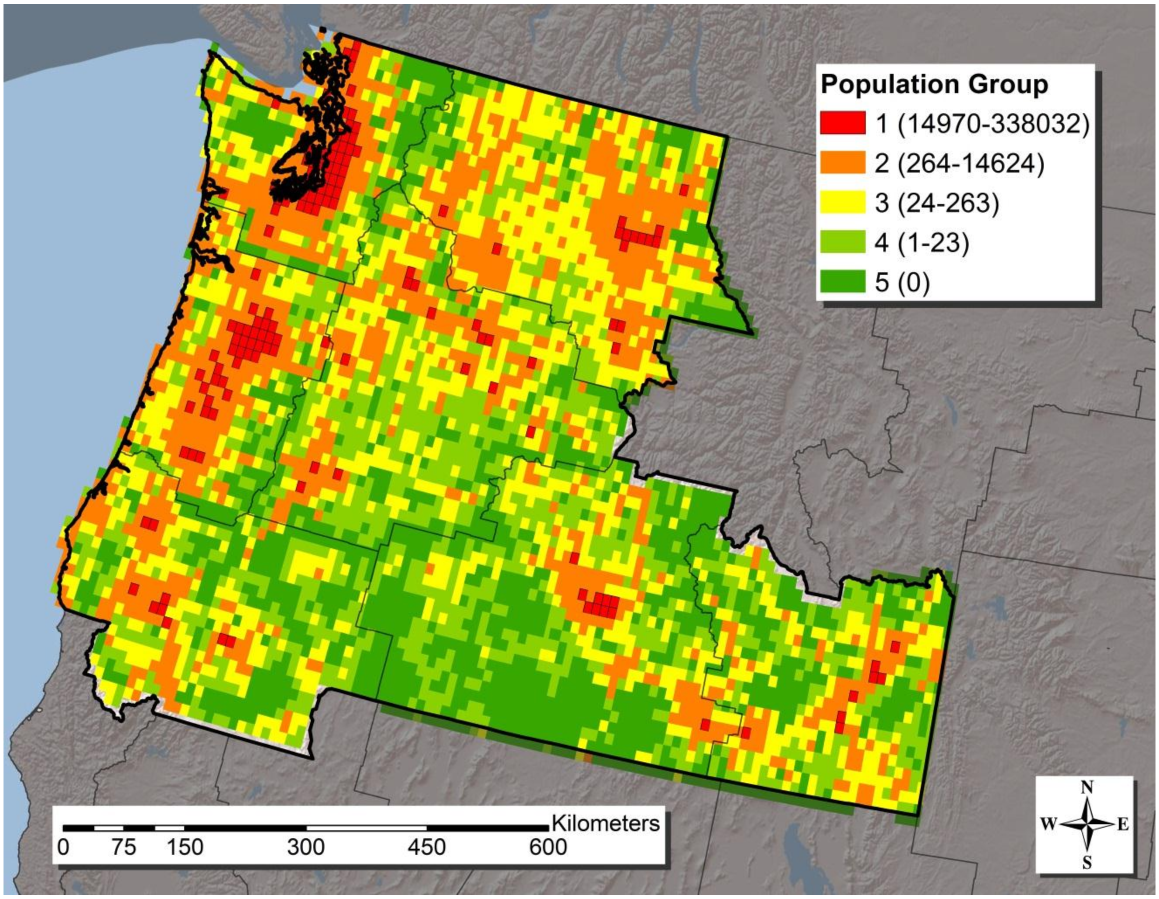


Figure 4.35. Population group distribution within the Northwest Climate Region.

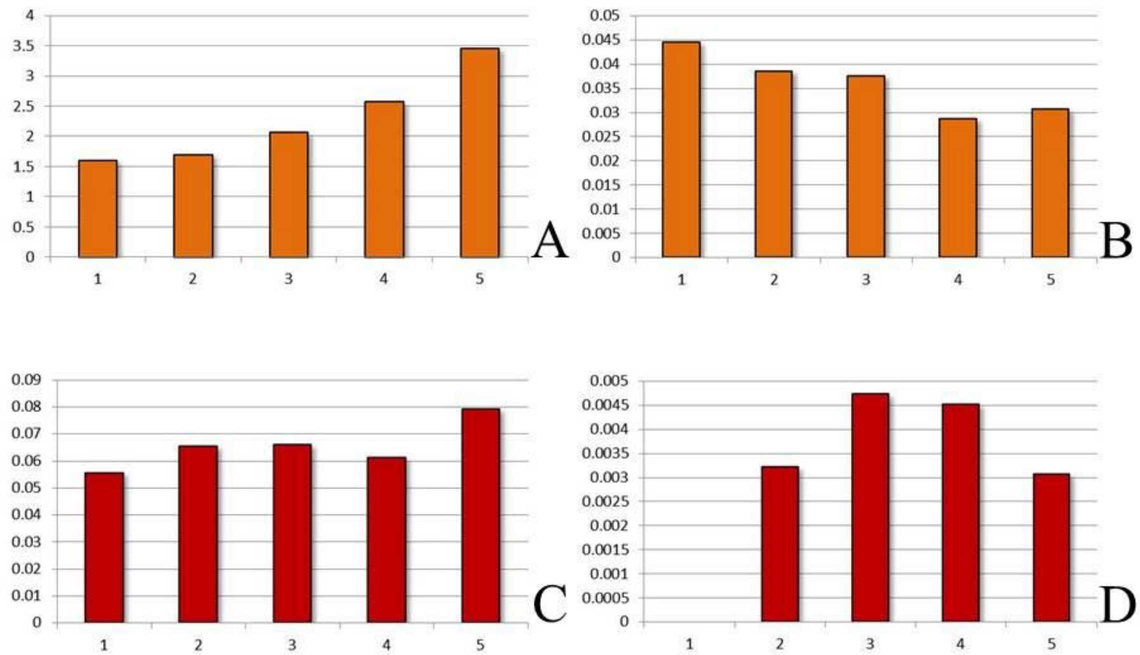


Figure 4.36. Results of the population group analysis for the four warning types. Average severe county-based warnings (A), severe storm-based warnings (B), tornado county-based warnings (C), and tornado storm-based warnings (D) are depicted for the Northwest Climate Region.

F. Ohio Valley Climate Region

The Ohio Valley has a total population of 53,885,870 and an average WFO population density of 73.39 persons per km^2. This region contains the major metropolitan area of Chicago, Illinois, as well as the cities of Cleveland, Ohio, St. Louis, Missouri, and Pittsburgh, Pennsylvania. Figure 4.37 shows that, by far, the most densely populated county warning area is Chicago (LOT), followed by Cleveland (CLE), and Wilmington, Ohio (ILN). The least populated CWA is Springfield (SGF). The total number of grid cells (sample size) within the region is 5,246. A table listing the acronym and name of each WFO in this region can be found in Appendix C.

The total number of severe thunderstorm warnings issued for the Ohio Valley Climate Region was 54,507, which ranks second among the nine regions. The total number of severe county-based warnings was 53,287, ranking second. The total number of severe storm-based warnings was 1,220, which ranks third. 6,702 tornado warnings were issued, 6,518 of which were county-based and 184 of which were storm-based. This region ranks third in all types of tornado warnings issued.

The Nashville (OHX) WFO issued the greatest numbers of annual average severe warnings of both types. Figure 4.38 (*A*-*B*) shows a decrease in the general issuance of severe storm-based warnings across all of the WFOs in the climate region. Nashville, Chicago (LOT), and Central Illinois/Lincoln (ILX) issued the most number of tornado county-based warnings (Figure 4.38 (*C*)). Figure 4.38 (*D*) shows that Nashville issued the greatest number of tornado storm-based warnings, follow by Jackson (JKL) and Springfield (SGF).

1. NEXRAD Radar Coverage

Figure 4.39 shows that the Ohio Valley does not suffer from a lack of NEXRAD radar coverage. Coverage is nearly total with almost 99 percent perfect coverage. Correlations between all warning types are weak. (Table 4.19).

Table 4.19. Correlation results for NEXRAD coverage for the Ohio Valley Climate Region.

Test	Correlation	Z-Value	P-Value
Population	0.033	2.420	0.0155
SVR CBW	0.065	4.690	<.001
SVR SBW	0.036	2.611	0.009
TOR CBW	0.058	4.182	<.001
TOR SBW	-0.054	-3.932	<.001

2. Distance and Direction

The Ohio Valley Climate Region ranks tied for third with the Southwest Climate Region in distance performance in overall severe and tornado warnings issued. The adjusted average distance from the geographic center of the CWAs to center of warning distribution is 5.95 km. The mean adjusted distance from location of WFOs to warning center is 8.35 km. The average directional distribution has an azimuth of 188.86° indicating a tendency for warnings to be issued to the south-southwest of the center of the County Warning Areas. The warning directional distribution from the location of the Weather Forecast Offices registers an azimuth direction of 153.48° (SSE).

The Ohio Valley Climate Region mean severe county-based warning azimuthal direction from the CWA centers is 204.57° (SSW). The average warning direction from the WFO locations is 161.36° (SSE). The average distance from the warning center of distribution to the center of the CWAs is 18.39 km (3.98 km adjusted). This region ranks third in minimum distance to center of CWAs among all Climate Regions. The average distance from warning center to WFO location is 30.53 km (6.53 km adjusted). The minimum distance ranking for warning center to WFO location is second. The EAX WFO ranks first in distance performance, whereas PBZ ranks last (Table 4.20).

Table 4.20. Distance performance ranks for the Ohio Valley Climate Region.

WFO	SCBW	SSBW	TCBW	TSBW
CLE	4	4.5	5	1.5
EAX	1	1	1	1.5
ILN	2	4.5	8	12.5
ILX	10	10	14	9
IND	6.5	9	8	11
IWX	3	7	8	3
JKL	11	12.5	12.5	12.5
LMK	5	6	10.5	7
LOT	6.5	15	2	15
LSX	9	8	6	7
MRX	8	3	3	5
OHX	14	12.5	10.5	7
PAH	14	14	12.5	14
PBZ	16	16	16	4
RLX	12	11	15	16
SGF	14	2	4	10

The mean severe storm-based warning azimuthal direction from the CWA centers is 199.87° (SSW). The average warning direction from the WFO locations is 160.57° (SSE). The average distance from the warning center of distribution to the center of the CWAs is 30.98 km (6.81 km adjusted). This region ranks second in minimum distance to center of CWAs among all Climate Regions. The average distance from warning center to WFO location is 44.10 km (9.50 km adjusted). The minimum distance ranking for warning center to WFO location is fourth. The EAX WFO ranks first in distance performance, whereas PBZ ranks last.

The average tornado county-based warning azimuthal direction from the CWA centers is 162.86° (SSE). The average warning direction from the WFO locations is 139.16° (SE). The average distance from the warning center of distribution to the center of the CWAs is 30.14 km (6.38 km adjusted). This region ranks third in minimum distance to center of CWAs among all Climate Regions. The average distance from warning center to WFO location is 37.39 km (8.12 km adjusted). The minimum distance ranking for warning center to WFO location is third. The EAX WFO ranks first in distance performance, whereas PBZ ranks last.

The mean tornado storm-based warning azimuthal direction from the CWA centers is 188.16° (S). The average warning direction from the WFO locations is 152.84° (SSE). The average distance from the warning center of distribution to the center of the CWAs is 24.18 km (6.64 km adjusted). This region ranks second in minimum distance to center of CWAs among all Climate Regions. The average distance from warning center to WFO location is 43.05 km (9.25 km adjusted). The minimum distance ranking for warning center to WFO location is second. The CLE and EAX WFOs are tied for first place rank in distance performance, whereas RLX ranks last.

3. Population

The map for population group distribution for the Ohio Valley Climate Region shows pockets of Population Group 1 indicating urban centers. These group 1 areas include Chicago, Cleveland, St. Louis, Pittsburgh, and Indianapolis. The majority of the

Population Group 5 areas are found in the western region in the vicinity of highly ruralized parts of the Central Plains.

The only possible population bias for the population groups is indicated by the graph for severe county-based warnings (Figure 4.41 (*A*)). The highest frequency of severe storm-based warnings was for Population Groups 2, 3, and 4 (Figure 4.51 (*B*)). Tornado county-based warnings were issued more frequently for Population Groups 1 and 5 (Figure 4.51 (*C*)). Population Group 1 received the fewest number of tornado storm-based warnings, whereas Population Group 5 received the greatest (Figure 4.51 (*D*)).

For the Ohio Valley Climate Region, results of the correlation tests show the only relationship exists between overall population and severe county-based warnings (Table 4.21). However; resulting correlation values are very low. The remaining statistically significant results show negative correlations.

Table 4.21. Population correlation results for the Ohio Valley Climate Region. *Significant correlation results are in **bold** listed with Z-Values and P-Values (α = 0.001 for overall population and α = 0.05 for WFO population density).

Test	Correlation	Z-Value	P-Value	Rho	Z-Value	P-Value
SCBW/Population	**0.157**	**11.446**	**<.001**	**0.137**	**9.946**	**<.001**
SCBW/WFO Pop Density	0.304	1.132	0.2575	0.165	0.638	0.5235
SSBW/Population	-0.032	-2.348	0.0189	-0.020	-1.425	0.1542
SSBW/WFO Pop Density	-0.242	-0.89	0.3733	-0.400	-1.549	0.1213
TCBW/Population	0.043	3.113	0.0019	**-0.049**	**-3.57**	**0.0004**
TCBW/WFO Pop Density	0.305	1.137	0.2555	0.015	0.057	0.9546
TSBW/Population	**-0.045**	**-3.267**	**0.0011**	**-0.051**	**-3.687**	**0.0002**
TSBW/WFO Pop Density	-0.323	-1.208	0.227	-0.391	-1.515	0.1298

Table 4.22 shows that several of the WFOs in the Ohio Valley Climate Region demonstrate a relationship between severe county-based warnings and population. The strongest correlation exist for severe county-based warnings and population for the Nashville (OHX) and Cleveland (CLE) WFOs. Nashville also demonstrates a strong correlation for severe storm-based warnings. Correlation for tornado warnings are not statistically significant, with the only possible relationship existing for county-based warnings issued by the St. Louis (LSX) WFO.

Table 4.22. WFO population correlations for the Ohio Valley Climate Region. *Significant correlation results are in **bold** listed with P-Values (α = 0.001).

WFO	SCBW	P-Value	SSBW	P-Value	TCBW	P-Value	TSBW	P-Value
CLE	**0.306**	**<.001**	-0.085	0.133	-0.052	0.3552	0.092	0.1042
EAX	**0.242**	**<.001**	-0.006	0.9104	-0.038	0.4497	-0.075	0.1419
ILN	**0.192**	**0.0002**	**0.22**	**<.001**	**-0.167**	**0.0014**	-0.071	0.1764
ILX	**0.241**	**<.001**	0.006	0.9182	0.145	0.0076	-0.046	0.4023
IND	0.09	0.143	-0.136	0.0262	0.136	0.0254	-0.094	0.1264
IWX	0.164	0.0038	-0.156	0.0058	-0.024	0.6735	-0.003	0.9562
JKL	0.111	0.1394	-0.03	0.6935	0.171	0.0218	0.071	0.3429
LMK	0.081	0.1413	**-0.213**	**<.001**	0.153	0.0056	-0.021	0.7051
LOT	**0.278**	**<.001**	**-0.265**	**<.001**	0.024	0.7036	-0.058	0.3575
LSX	**0.166**	**0.0002**	-0.009	0.8306	**0.15**	**0.0006**	0.002	0.9711
MRX	**0.277**	**<.001**	0.097	0.1281	0.014	0.8254	0.007	0.9102
OHX	**0.431**	**<.001**	**0.408**	**<.001**	-0.026	0.6902	0.071	0.2791
PAH	0.009	0.8561	0.065	0.1959	0.057	0.2591	0.116	0.0206
PBZ	**0.297**	**<.001**	-0.149	0.0079	0.155	0.0057	0.101	0.073
RLX	0.069	0.1646	-0.069	0.1623	0.043	0.3874	-0.076	0.1241
SGF	**0.217**	**<.001**	0.018	0.7206	0.047	0.3607	-0.041	0.4199

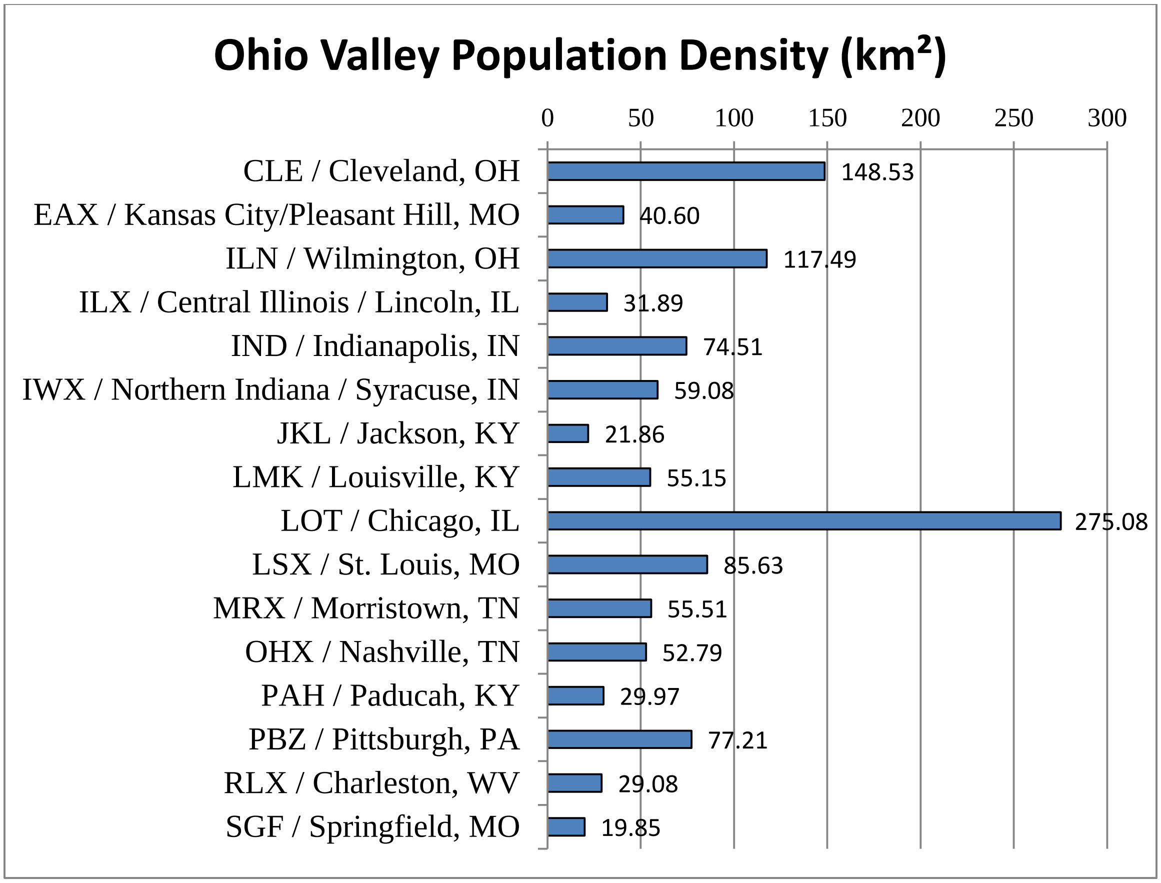


Figure 4.37. WFO population density for the Ohio Valley Climate Region.

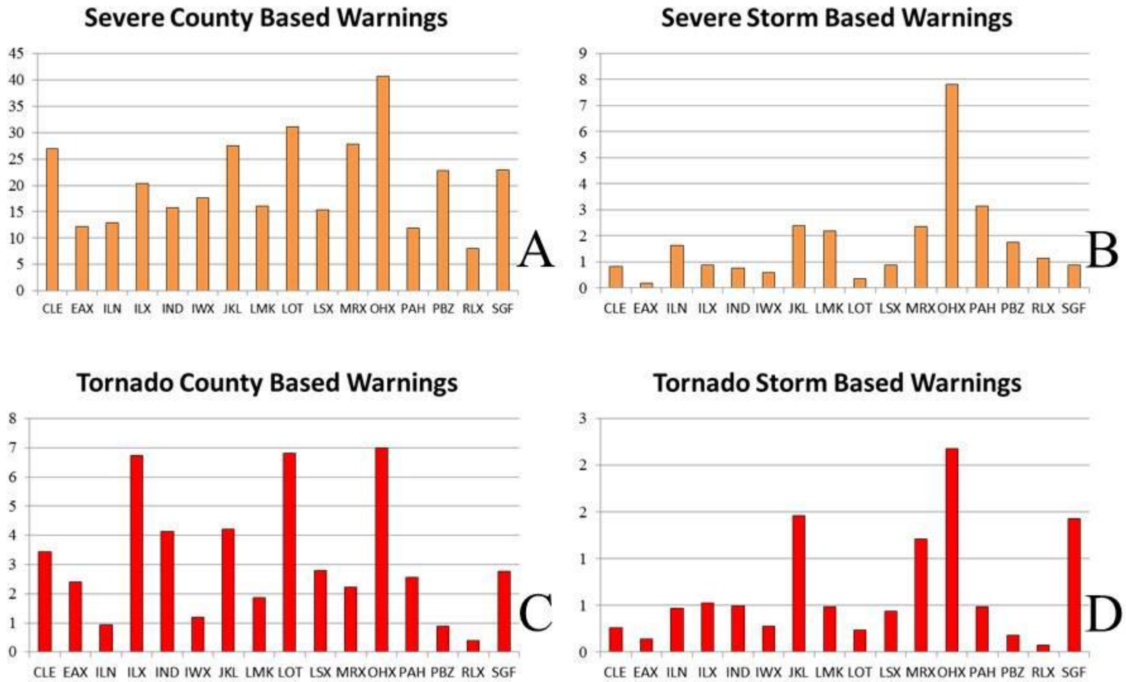


Figure 4.38. Area adjusted annual average warnings by National Weather Service Weather Forecast Office. Average severe county-based warnings (*A*), severe storm-based warnings (*B*), tornado county-based warnings (*C*), and tornado storm-based warnings (*D*) are depicted for the Ohio Valley Climate Region.

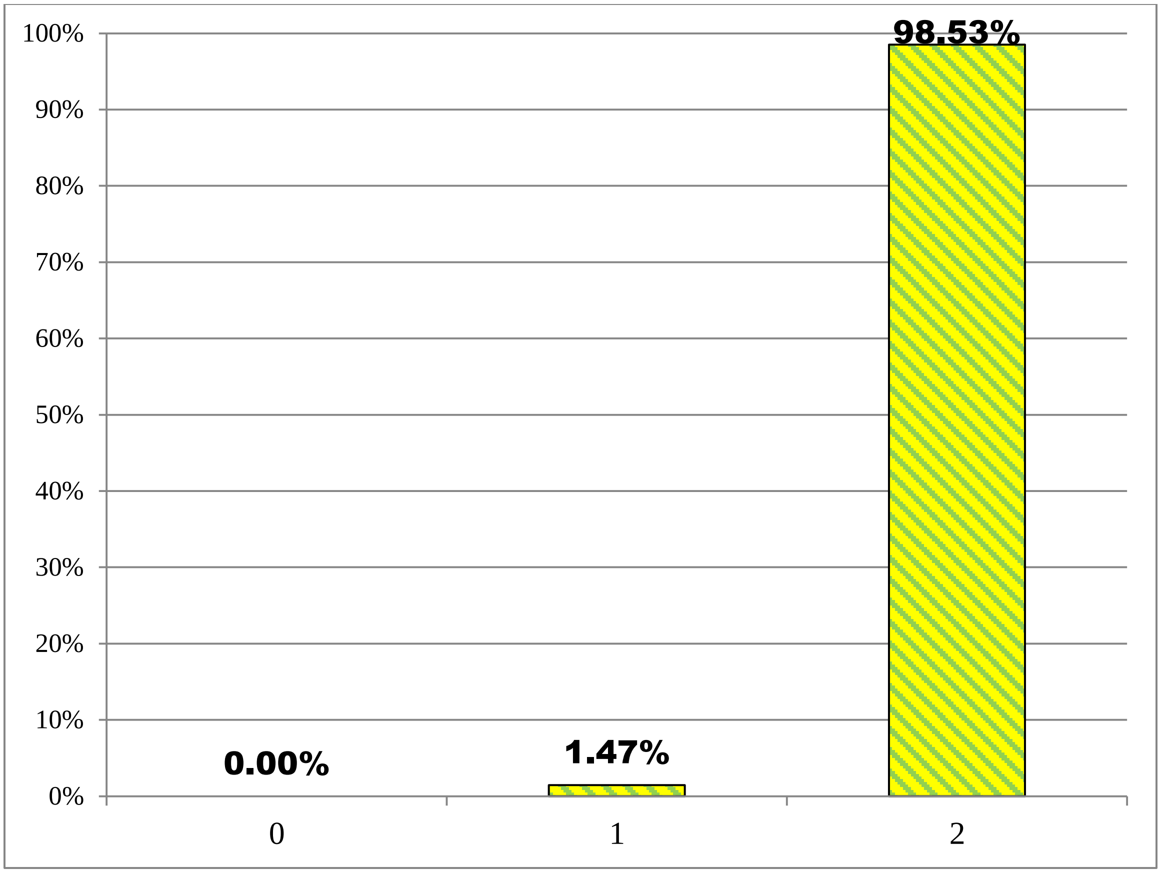


Figure 4.39. NEXRAD radar coverage for the Ohio Valley Climate Region.

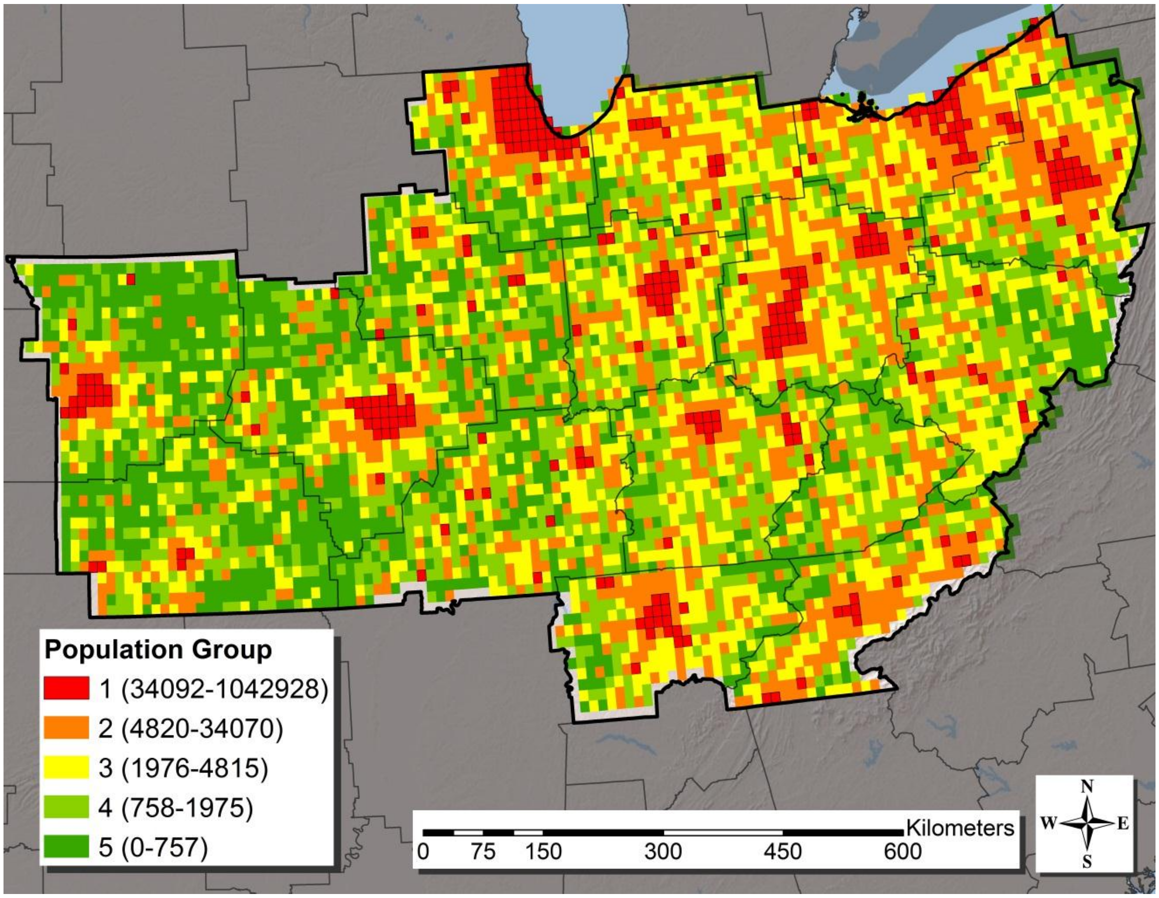


Figure 4.40. Population group distribution within the Ohio Valley Climate Region.

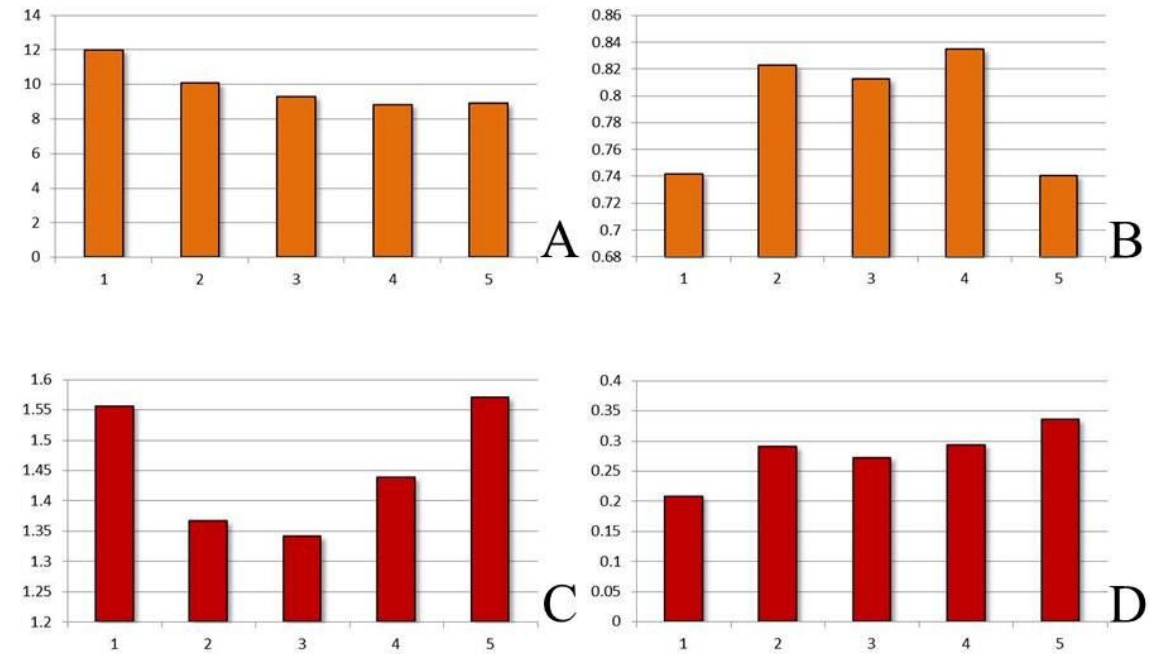


Figure 4.41. Results of the population group analysis for the four warning types. Average severe county-based warnings (A), severe storm-based warnings (B), tornado county-based warnings (C), and tornado storm-based warnings (D) are depicted for the Ohio Valley Climate Region.

G. South Climate Region

The total population of the South Climate Region is 40,774,667, with an average WFO population density of 28.67 persons per km². This region includes the metropolitan areas in Texas (Houston, Dallas, San Antonio) as well as New Orleans, Louisiana, and Oklahoma City, Oklahoma. Figure 4.42 shows that The Houston/Galveston (HGX) WFO has the highest population density, followed by Fort Worth (FWD). Several of the county warning areas have a very low population density, including Goodland (GLD) and Dodge City (DDC). The South region has a population density difference of 114.41 persons per km². The total number of grid cells (sample size) within the region is 9,411. The South Climate Region is the largest in area of the nine regions and contains the greatest number of WFOs. A table listing the acronym and name of each WFO in this region can be found in Appendix C.

The most warnings of all types were issued for the South region among the nine Climate Regions. The total number of severe thunderstorm warnings issued for the South Climate Region was 90,051. The total number of severe county-based warnings was 86,734. The total number of severe storm-based warnings was 3,317. A total of 12,634 tornado warnings were issued, 12.107 of which were county-based and 60 of which were storm-based.

The most severe county-based warnings were issued by the Brownsville (BRO) WFO followed by Topeka (TOP) (Figure 4.43 (*A*)). The greatest numbers of annual average severe storm-based warnings were issued by the Little Rock (LZK) and Shreveport (SHV) WFOs (Figure 4.43 (*B*)). Tornado county-based warnings were more frequently issued by the Brownsville and Houston (HGX) WFOs, whereas tornado storm-based warnings were issued more frequently for the Lake Charles (LCH) and New Orleans/Baton Rouge (LIX) county warning areas, indicating a tendency for more tornado warnings to be issued near the Gulf Coast area (Figure 4.43 (*C*-*D*)).

1. NEXRAD Radar Coverage

Some gaps exist in the NEXRAD coverage for the South region. Figure 4.44 shows that almost two percent of the area is lacking coverage, whereas almost four percent only has substantial coverage above 3048 meters. Correlation tests results indicate some correlation for severe and tornado storm-based warnings (Table 5.23). No correlations exist for severe county-based warnings.

Table 4.23. Correlation results for NEXRAD coverage for the South Climate Region.

Test	Correlation	*Z*-Value	P-Value
Population	0.039	3.791	0.0002
SVR CBW	-0.02	-2.188	0.0286
SVR SBW	0.144	14.082	<.001
TOR CBW	0.113	11.02	<.001
TOR SBW	0.127	12.415	<.001

2. Distance and Direction

The South Climate Region ranks fifth (tied with the East North Central region), in distance performance for overall severe and tornado warnings issued. The adjusted average distance from the geographic center of the CWAs to center of warning distribution is 4.72 km. The mean adjusted distance from location of WFOs to warning center is 9.54 km. The average directional distribution has an azimuth of 170.14°, indicating a tendency for warnings to be issued to the south of the center of the County

Warning Areas. The warning directional distribution from the location of the Weather Forecast Offices registers an azimuth direction of 191.83° (SSW).

The South Climate Region mean severe county-based warning azimuthal direction from the CWA centers is 210.13° (SSW). The average warning direction from the WFO locations is 209.51° (SSW). The average distance from the warning center of distribution to the center of the CWAs is 22.45 km (3.56 km adjusted). This region ranks first in minimum distance to center of CWAs among all Climate Regions. The average distance from warning center to WFO location 54.80 km (9.75 km adjusted). The minimum distance ranking for warning center to WFO location is eighth. The HGX WFO ranks first in distance performance, whereas ICT ranks last (Table 4.24).

Table 4.24. Distance performance ranks for the South Climate Region.

WFO	SCBW	SSBW	TCBW	TSBW
AMA	4.5	19	9	20
BRO	7.5	10	6.5	13
CRP	10	7.5	11.5	11.5
DDC	20	20	21	17
EWX	4.5	1	1	4
FWD	6	2	8	8.5
GLD	17	5	18.5	3
HGX	1	4	6.5	2
ICT	21	21	20	18.5
JAN	9	11.5	10	5
LCH	19	15.5	18.5	1
LIX	12.5	11.5	4.5	18.5
LUB	2.5	3	4.5	15
LZK	15.5	13	16	6.5
MAF	2.5	18	2	21
MEG	12.5	15.5	16	14
OUN	11	9	11.5	8.5
SHV	14	7.5	16	10
SJT	15.5	14	13	11.5
TOP	7.5	6	3	6.5
TSA	18	17	14	16

The average severe storm-based warning azimuthal direction from the CWA centers is 180.53° (S). The average warning direction from the WFO locations is 211.37° (SSW). The average distance from the warning center of distribution to the center of the CWAs is 32.13 km (5.06 km adjusted). This region ranks third in minimum distance to center of CWAs among all Climate Regions. The average distance from warning center to WFO location is 51.12 km (9.83 km adjusted). The minimum distance ranking for warning center to WFO location is eighth. The EWX WFO ranks first in distance performance, whereas ICT ranks last.

The mean tornado county-based warning azimuthal direction from the CWA centers is 163.13° (SSE). The average warning direction from the WFO locations is 179.67° (S). The average distance from the warning center of distribution to the center of the CWAs is 28.55 km (4.45 km adjusted). This region ranks first in minimum distance to center of CWAs among all Climate Regions. The average distance from warning center to WFO location is 54.74 km (9.49 km adjusted). The minimum distance ranking for warning center to WFO location is sixth. The EWX WFO ranks first in distance performance, whereas DDC ranks last.

The mean tornado storm-based warning azimuthal direction from the CWA centers is 126.79° (SE). The average warning direction from the WFO locations is 166.76° (SSE). The average distance from the warning center of distribution to the center of the CWAs is 37.19 km (5.81 km adjusted). This region ranks first in minimum distance to center of CWAs among all Climate Regions. The average distance from warning center to WFO location is 52.67 km (9.07 km adjusted). The minimum distance ranking for warning center to WFO location is fourth. The LCH WFO ranks first in distance performance, whereas MAF ranks last.

3. Population

Figure 4.45 shows that Population Group 1 zones in the South Climate Region are found in the urban areas of Houston, Dallas/Fort Worth, San Antonio, and New Orleans, with smaller pockets found near moderately sized urban areas. The majority of Population Group 5 areas are found in the western part of the climate region, especially in the desert areas of western Texas.

All of the graphs representing warnings issued for population groups indicate the possibility of a population bias for the South Climate Region. The weakest possible population bias exists in Figure 4.46 (*A*), where the majority of severe county-based warnings were issued for Population Group 1, but the remaining four population groups received similar numbers of warnings. Although Population Group 1 received fewer severe storm-based warnings than groups 2 and 3, the overall pattern for severe storm-based warnings is “stair step” with the least number of warnings issued for Population Group 5 (Figure 4.46 (*B*)). The strongest case can be made for population bias for tornado county-based warnings-based on Figure 4.46 (*C*), where Population Group 1 received the greatest proportion of warnings. Figure 4.46 (*D*) for tornado storm-based warnings shows a pattern that is very similar to severe storm-based warnings where Population Groups 4 and 5 received the fewest numbers of warnings.

The most significant correlations for the South Climate region exist between tornado county-based warnings and WFO population density (Table 4.25). Tornado county-based warnings and overall population are also significant for both standard correlation and Spearman’s Rho. Severe and tornado storm-based warnings show correlation with overall population. Although severe county-based warnings demonstrate a statistical significance with overall population, the low correlation values suggest it is not a practical relationship.

Table 4.25. Population correlation results for the South Climate Region. *Significant correlation results are in **bold** listed with Z-Values and P-Values (α = 0.001 for overall population and α = 0.05 for WFO population density).

Test	Correlation	Z-Value	P-Value	Rho	Z-Value	P-Value
SCBW/Population	**0.083**	**8.111**	**<.001**	-0.007	-0.661	0.5086
SCBW/WFO Pop Density	-0.046	-0.195	0.8453	-0.194	-0.865	0.3868
SSBW/Population	0.029	2.77	0.0056	**0.329**	**31.955**	**<.001**
SSBW/WFO Pop Density	0.141	0.601	0.5478	0.294	1.313	0.1893
TCBW/Population	**0.216**	**21.252**	**<.001**	**0.117**	**11.398**	**<.001**
TCBW/WFO Pop Density	**0.544**	**2.587**	**0.0097**	0.191	0.854	0.3932
TSBW/Population	0.031	3.042	0.0023	**0.228**	**22.077**	**<.001**
TSBW/WFO Pop Density	0.096	0.41	0.682	0.13	0.581	0.5614

Table 4.26 demonstrates that there are several WFOs which exhibit correlations across the warning types for the South Climate Region. The strongest correlation values exist for tornado county-based warnings, severe county-based warnings, and severe storm-based warnings for the Houston (HGX) WFO. Correlation values are also robust for severe county-based warnings for the Fort Worth (FWD) WFO.

Table 4.26. WFO population correlations for the South Climate Region. *Significant correlation results are in **bold** listed with P-Values (α = 0.001).

WFO	SCBW	P-Value	SSBW	P-Value	TCBW	P-Value	TSBW	P-Value
AMA	**0.211**	**<.001**	**0.22**	**<.001**	0.106	0.0311	0.076	0.1209
BRO	0.232	0.0017	-0.027	0.7243	0.231	0.0017	0.185	0.0126
CRP	-0.013	0.8404	0.043	0.4998	0.138	0.0303	0.058	0.3673
DDC	0.053	0.2994	-0.052	0.3104	-0.011	0.8367	-0.005	0.9246
EWX	0.104	0.0148	-0.053	0.2179	0.117	0.0061	0.043	0.3166
FWD	**0.455**	**<.001**	-0.036	0.3807	**0.19**	**<.001**	0.089	0.0300
GLD	-0.014	0.7922	-0.082	0.1105	-0.058	0.2589	-0.006	0.9062
HGX	**0.560**	**<.001**	**0.337**	**<.001**	**0.614**	**<.001**	0.149	0.0063
ICT	**0.212**	**<.001**	-0.024	0.6434	0.016	0.7599	-0.026	0.6218
JAN	**0.279**	**<.001**	0.021	0.6201	0.122	0.0038	-0.059	0.1613
LCH	0.013	0.8233	0.108	0.0591	-0.077	0.1796	0.112	0.0497
LIX	0.082	0.1282	0.141	0.009	0.066	0.2215	0.024	0.6555
LUB	0.052	0.3534	-0.126	0.0246	-0.056	0.3192	0.041	0.4691
LZK	**0.208**	**<.001**	**0.256**	**<.001**	**0.171**	**<.001**	-0.040	0.3418
MAF	0.019	0.591	**0.143**	**<.001**	-0.042	0.2311	0.000	0.9893
MEG	**0.31**	**<.001**	**0.159**	**0.0003**	-0.077	0.0862	0.026	0.5587
OUN	0.063	0.0802	0.092	0.0106	**0.123**	**0.0006**	**0.119**	**0.0009**
SHV	0.096	0.0199	0.067	0.1059	0.049	0.2312	0.049	0.2315
SJT	**0.155**	**0.0011**	0.096	0.0441	0.105	0.0278	-0.010	0.8421
TOP	0.165	0.0062	**0.232**	**0.0001**	0.126	0.0379	0.070	0.252
TSA	0.019	0.6886	0.038	0.4278	0.142	0.0026	0.058	0.2213

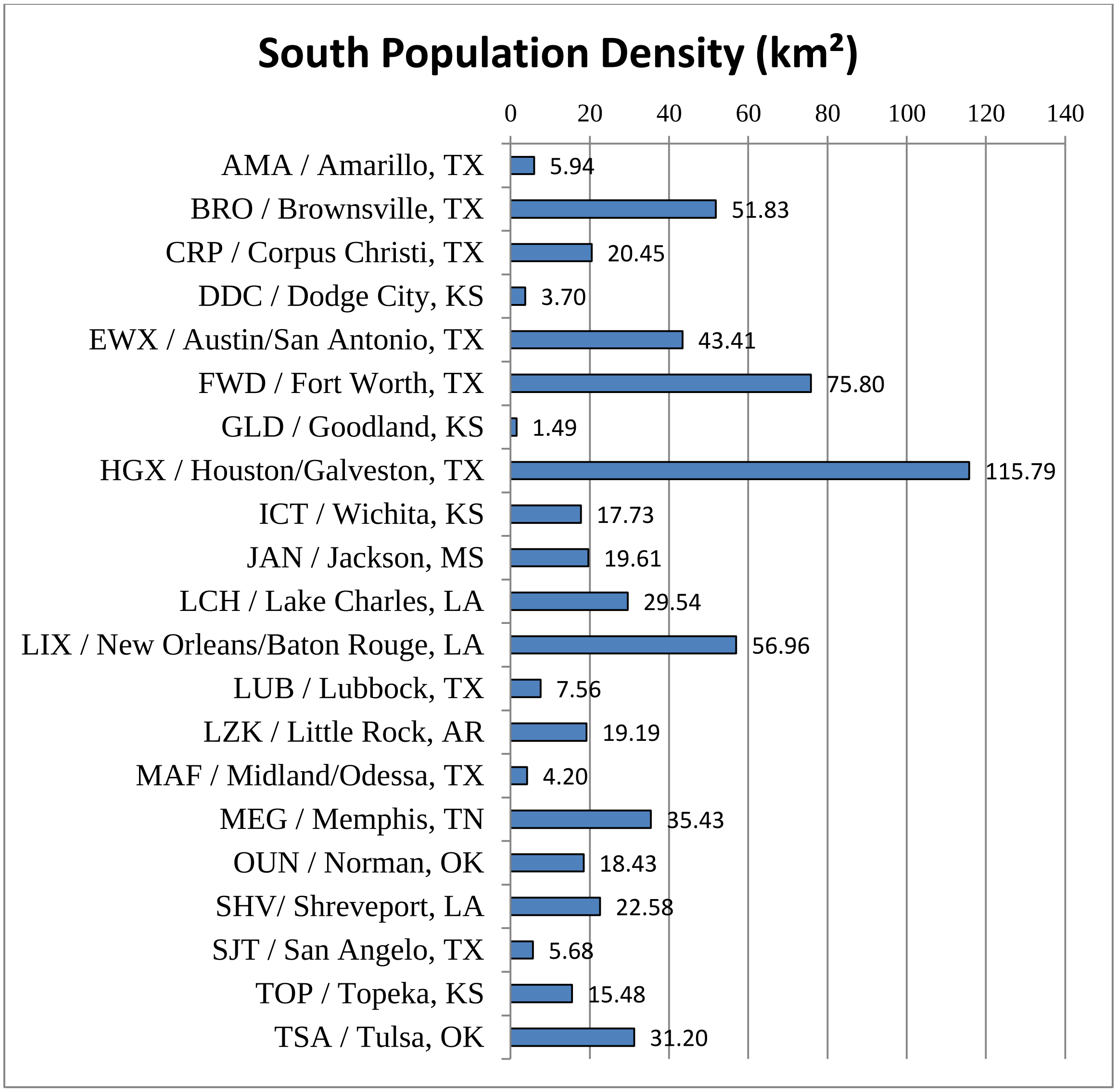


Figure 4.42. WFO population density for the South Climate Region.

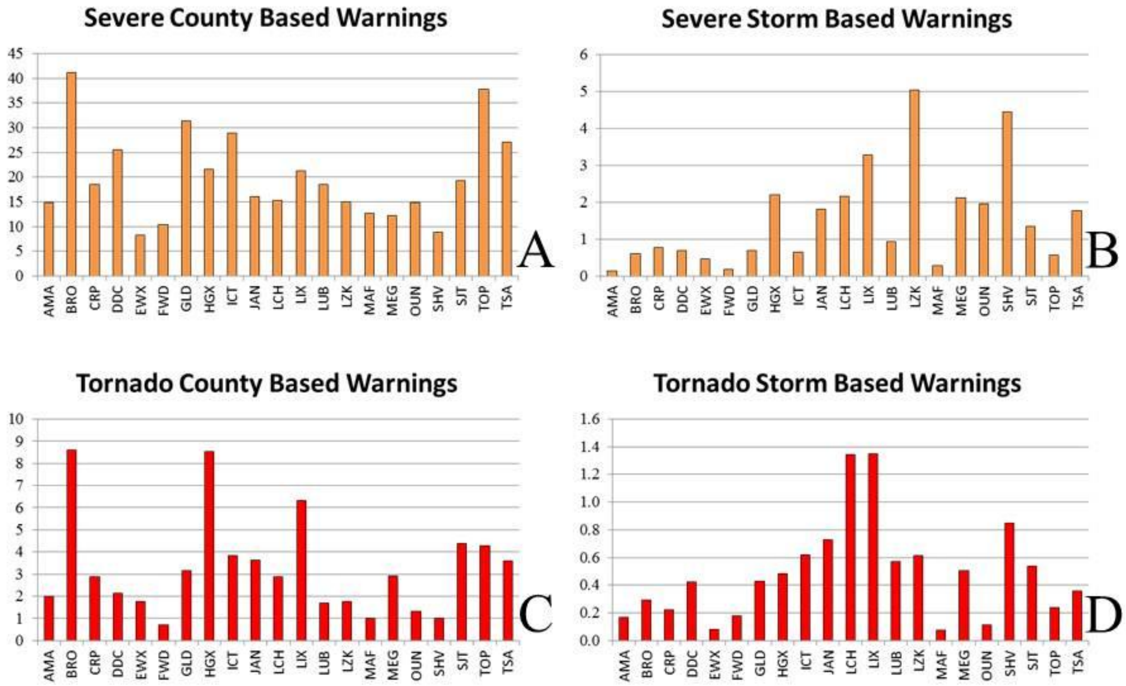


Figure 4.43. Area adjusted annual average warnings by National Weather Service Weather Forecast Office. Average severe county-based warnings (*A*), severe storm-based warnings (*B*), tornado county-based warnings (*C*), and tornado storm-based warnings (*D*) are depicted for the South Climate Region.

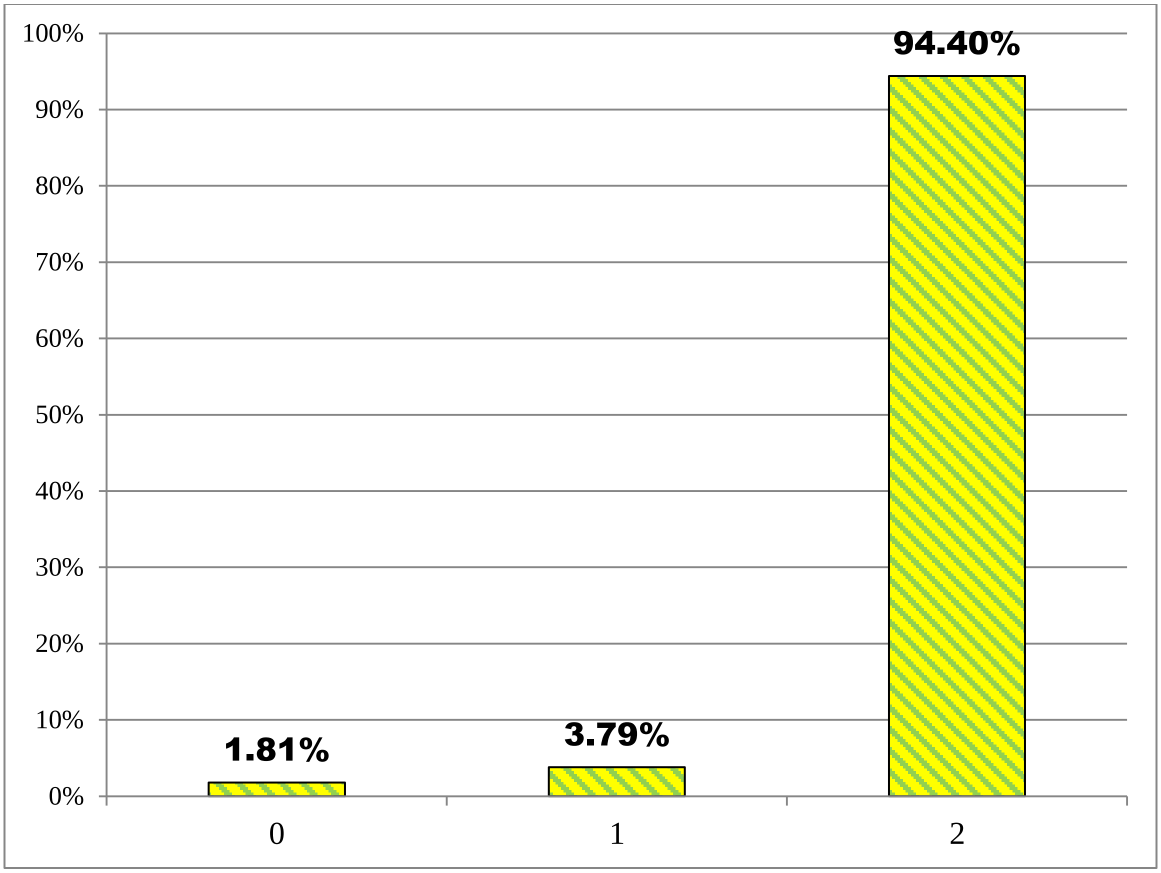


Figure 4.44. NEXRAD radar coverage for the South Climate Region.

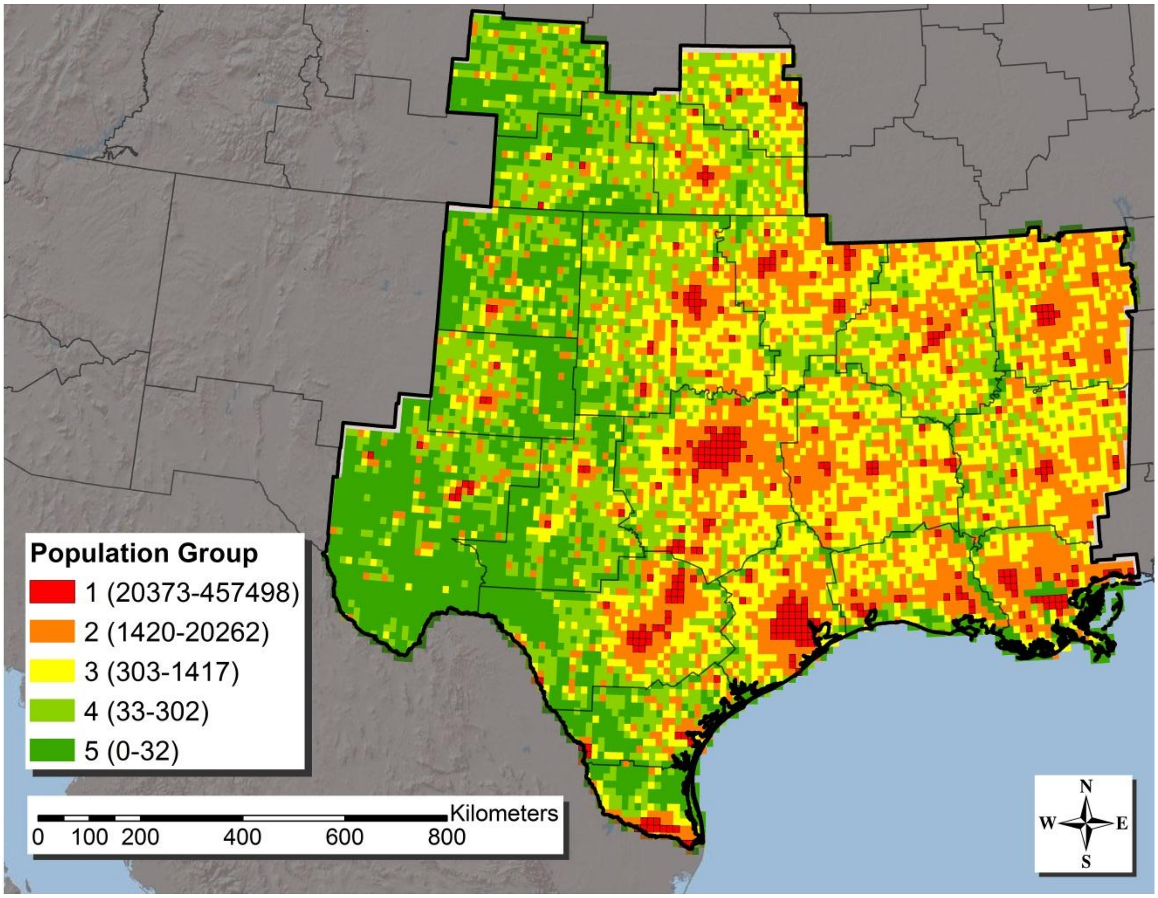


Figure 4.45. Population group distribution within the South Climate Region.

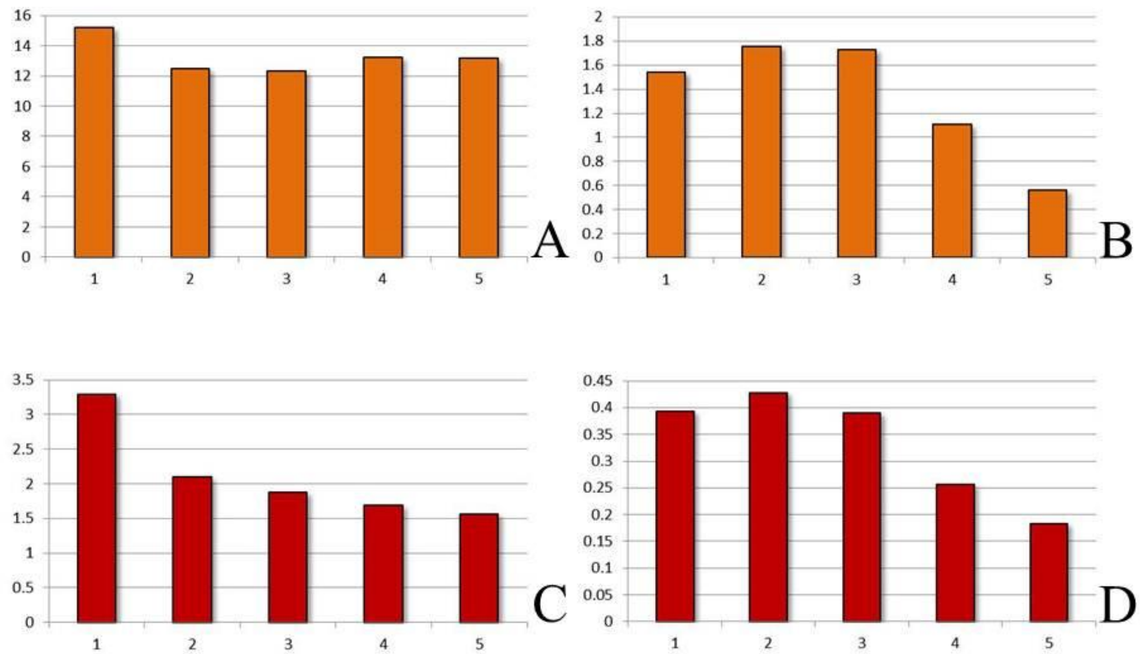


Figure 4.46. Results of the population group analysis for the four warning types. Average severe county-based warnings (A), severe storm-based warnings (B), tornado county-based warnings (C), and tornado storm-based warnings (D) are depicted for the South Climate Region.

H. Southeast Climate Region

The Southeast Climate Region has a total population of 59,316,957, and an average WFO population density of 82.03 persons per km^2, making it the third most population dense of all the regions. This region includes Miami, Florida, Washington, DC, and Atlanta, Georgia. The South Florida/Miami (MFL) and Baltimore/Washington (LWX) are the most population dense WFOs in the region (Figure 4.47). Compared to the other climate regions, there are very few county warning areas with low population density, the lowest of which is Tallahassee (TAE). The total number of grid cells (sample size) within the region is 5,217. A table listing the acronym and name of each WFO in this region can be found in Appendix C.

The total number of severe thunderstorm warnings issued for the Southeast Climate Region was 52,387, which ranks third among the nine regions. The total number of severe county-based warnings was 49,967, ranking second. The total number of severe storm-based warnings was 2,420, which ranks third. A total of 7,916, tornado warnings were issued, 7,562 of which were county-based and 60 of which were storm-based. This region ranks second for all types of tornado warnings issued.

The Huntsville (HUN) WFO issued the most severe county-based warnings followed by South Florida/Miami (MFL) and Melbourne (MLB) (Figure 4.48 (*A*)). Figure 4.48 (*B*) shows that an unusually large average number of severe storm-based warnings were issued for the Columbia (CAE) county warning area, making this WFO an extreme outlier among the offices in the area for this warning type. The Huntsville WFO issued the most tornado county and storm-based warnings (Figure 4.48 (*C*-*D*)).

1. NEXRAD Radar Coverage

The Southeast region has the most complete NEXRAD coverage of all the climate regions, with almost total coverage above 1,829 meters (Figure 4.49). Table 4.27 indicates that there is no correlation between NEXRAD coverage and the issuance of severe weather warnings.

Table 4.27. Correlation results for NEXRAD coverage for the Southeast Climate Region.

Test	Correlation	Z-Value	P-Value
Population	0.007	0.509	0.6111
SVR CBW	0.035	2.562	0.0104
SVR SBW	0.02	1.434	0.1516
TOR CBW	0.03	2.148	0.0317
TOR SBW	0.022	1.578	0.1146

2. Distance and Direction

The Southeast Climate Region ranks seventh in distance performance in overall severe and tornado warnings issued. The adjusted average distance from the geographic center of the CWAs to center of warning distribution is 6.78 km. The mean adjusted distance from location of WFOs to warning center is 13.33 km. The average directional distribution has an azimuth of 179.40°, indicating a tendency for warnings to be issued to the south of the center of the County Warning Areas. The warning directional distribution from the location of the Weather Forecast Offices registers an azimuth direction of 203.42° (SSW).

The Southeast Climate Region mean severe county-based warning azimuthal direction from the CWA centers is 188.05° (S). The average warning direction from the WFO locations is 205.03° (SSW). The average distance from the warning center of distribution to the center of the CWAs is 21.44 km (5.96 km adjusted). This region ranks sixth in minimum distance to center of CWAs among all Climate Regions. The average distance from warning center to WFO location is 43.07 km (12.29 km adjusted). The minimum distance ranking for warning center to WFO location is seventh. The MOB WFO ranks first in distance performance, whereas AKQ ranks last (Table 4.28).

Table 4.28. Distance performance ranks for the Southeast Climate Region.

WFO	SCBW	SSBW	TCBW	TSBW
AKQ	18	16	17	16.5
BMX	8	15	4	5.5
CAE	16	18	13.5	5.5
CHS	11.5	12	8	10
FFC	6	6.5	12	1.5
GSP	3	9	10	7
HUN	14.5	2.5	18	16.5
ILM	5	8	8	10
JAX	8	4.5	3	14
LWX	17	6.5	15	16.5
MFL	10	10	5	12.5
MHX	14.5	4.5	13.5	10
MLB	11.5	12	2	1.5
MOB	1	1	1	3
RAH	13	17	6	16.5
RNK	4	2.5	16	12.5
TAE	8	12	8	8
TBW	2	14	11	4

The average severe storm-based warning azimuthal direction from the CWA centers is 202.63° (SSW). The average warning direction from the WFO locations is 203.28° (SSW). The average distance from the warning center of distribution to the center of the CWAs is 23.91km 7.00 km adjusted). This region ranks fourth in minimum distance to center of CWAs among all Climate Regions. The average distance from warning center to WFO location is 53.84 km (15.39 km adjusted). The minimum distance ranking for warning center to WFO location is seventh. The MOB WFO ranks first in distance performance, whereas CAE ranks last.

The mean tornado county-based warning azimuthal direction from the CWA centers is 182.98° (S). The average warning direction from the WFO locations is 208.29° (SSW). The average distance from the warning center of distribution to the center of the CWAs is 25.42 km (6.47 km adjusted). This region ranks fourth in minimum distance to center of CWAs among all Climate Regions. The average distance from warning center to WFO location is 44.67 km (12.48 km adjusted). The minimum distance ranking for warning center to WFO location is seventh. The MOB WFO ranks first in distance performance, whereas HUN ranks last.

The mean tornado storm-based warning azimuthal direction from the CWA centers is 143.96° (SE). The average warning direction from the WFO locations is 197.08° (SSW). The average distance from the warning center of distribution to the center of the CWAs is 28.26 km (7.68 km adjusted). This region ranks third in minimum distance to center of CWAs among all Climate Regions. The average distance from warning center to WFO location is 46.68 km (13.15 km adjusted). The minimum distance ranking for warning center to WFO location is fifth. The FFC and MLB WFOs tie for first place in distance performance, whereas APX ranks last.

3. Population

The population group spatial distribution for the Southeast Climate Region is shown in Figure 4.50, and indicates that Population Group 1 areas are located near Miami, Atlanta, Washington/Baltimore, and the central parts of Florida. The largest region of Population Group 5 cells are located in the south Florida Everglades.

County-based warnings demonstrate the possibility of a population bias-based on the graphs represented in Figure 4.51 (*A* and *C*). In both cases, the most warnings were issued for Population Group 1. Severe county-based warnings exhibit the "stair step" pattern with Population Group 5 receiving the fewest numbers of warnings. Although tornado county-based warnings show the highest frequency for Population Group 1, the remaining population groups are in a reverse "stair step" pattern. Storm-based warnings for the region demonstrate similar patterns, where the greatest number of both severe and tornado warnings were issued for Population Groups 4 and 5 (Figure 4.51 (*B* and *D*)).

Overall correlation values are low for the Southeast Climate Region. Statistical significance exists for severe county-based warnings and overall population, although actual correlation results are somewhat minor in value (Table 4.29). Tornado county-based warnings and overall population shows statistical significance, but no practical correlation exist.

Table 4.29. Population correlation results for the Southeast Climate Region. *Significant correlation results are in **bold** listed with Z-Values and P-Values (α = 0.001 for overall population and α = 0.05 for WFO population density).

Test	Correlation	Z-Value	P-Value	Rho	Z-Value	P-Value
SCBW/Population	**0.183**	**13.377**	**<.001**	**0.172**	**12.422**	**<.001**
SCBW/WFO Pop Density	0.165	0.666	0.5055	0.088	0.372	0.7098
SSBW/Population	-0.033	-2.42	0.0155	0.008	0.572	0.5675
SSBW/WFO Pop Density	-0.317	-1.315	0.1884	-0.439	-1.861	0.0628
TCBW/Population	**0.058**	**4.219**	**<.001**	0.006	0.408	0.6831
TCBW/WFO Pop Density	0.207	0.841	0.4004	-0.004	-0.015	0.9881
TSBW/Population	-0.043	-3.09	0.002	0.023	1.696	0.0899
TSBW/WFO Pop Density	-0.348	-1.455	0.1458	-0.342	-1.451	0.1467

Eight of the WFOs in the Southeast Climate Region demonstrate a statistical correlation with severe county-based warnings (Table 4.30). The strongest correlation exists for the Peachtree City (FFC) WFO which covers the Atlanta, Georgia, metro area. Tampa Bay Area (TBW) has the strongest correlation with severe storm-based warnings. Three WFOs demonstrate correlation with tornado county-based warnings, of which the Jacksonville (JAX) WFO is the strongest. Only the Newport/Morehead City (MHX) WFO shows a correlation with tornado storm-based warnings.

Table 4.30. WFO population correlations for the Southeast Climate Region. *Significant correlation results are in **bold** listed with P-Values (α = 0.001).

WFO	SCBW	P-Value	SSBW	P-Value	TCBW	P-Value	TSBW	P-Value
AKQ	0.024	0.6356	0.069	0.1813	0.100	0.0516	0.111	0.0300
BMX	**0.208**	**<.001**	**0.276**	**<.001**	**0.206**	**<.001**	-0.040	0.4063
CAE	0.241	0.0002	0.191	0.0035	-0.029	0.6581	0.008	0.9000
CHS	0.175	0.0092	-0.045	0.5114	0.212	0.0015	0.095	0.1614
FFC	**0.410**	**<.001**	0.131	0.0033	**0.237**	**<.001**	-0.009	0.8452
GSP	**0.304**	**<.001**	0.017	0.7467	0.164	0.0018	-0.063	0.2353
HUN	0.180	0.0125	0.006	0.9364	0.139	0.0537	0.220	0.0021
ILM	0.030	0.6915	-0.102	0.1816	-0.063	0.4089	-0.061	0.4289
JAX	**0.298**	**<.001**	-0.062	0.3112	**0.283**	**<.001**	0.035	0.5673
LWX	**0.289**	**<.001**	-0.123	0.0165	0.102	0.0476	-0.034	0.5034
MFL	**0.290**	**<.001**	0.146	0.0526	0.185	0.0137	0.021	0.7863
MHX	**0.248**	**0.0005**	**0.256**	**0.0003**	0.217	0.0023	**0.246**	**0.0005**
MLB	0.209	0.0096	0.007	0.936	0.006	0.9411	0.187	0.0206
MOB	0.117	0.03	0.050	0.353	0.104	0.0541	0.034	0.5229
RAH	0.173	0.0063	**-0.214**	**0.0007**	0.126	0.049	0.09	0.1615
RNK	0.091	0.1305	-0.097	0.1046	0.035	0.5576	-0.018	0.7591
TAE	0.059	0.2131	**0.221**	**<.001**	0.026	0.5786	0.066	0.1634
TBW	**0.248**	**<.001**	**0.317**	**<.001**	0.061	0.3493	0.0430	0.5080

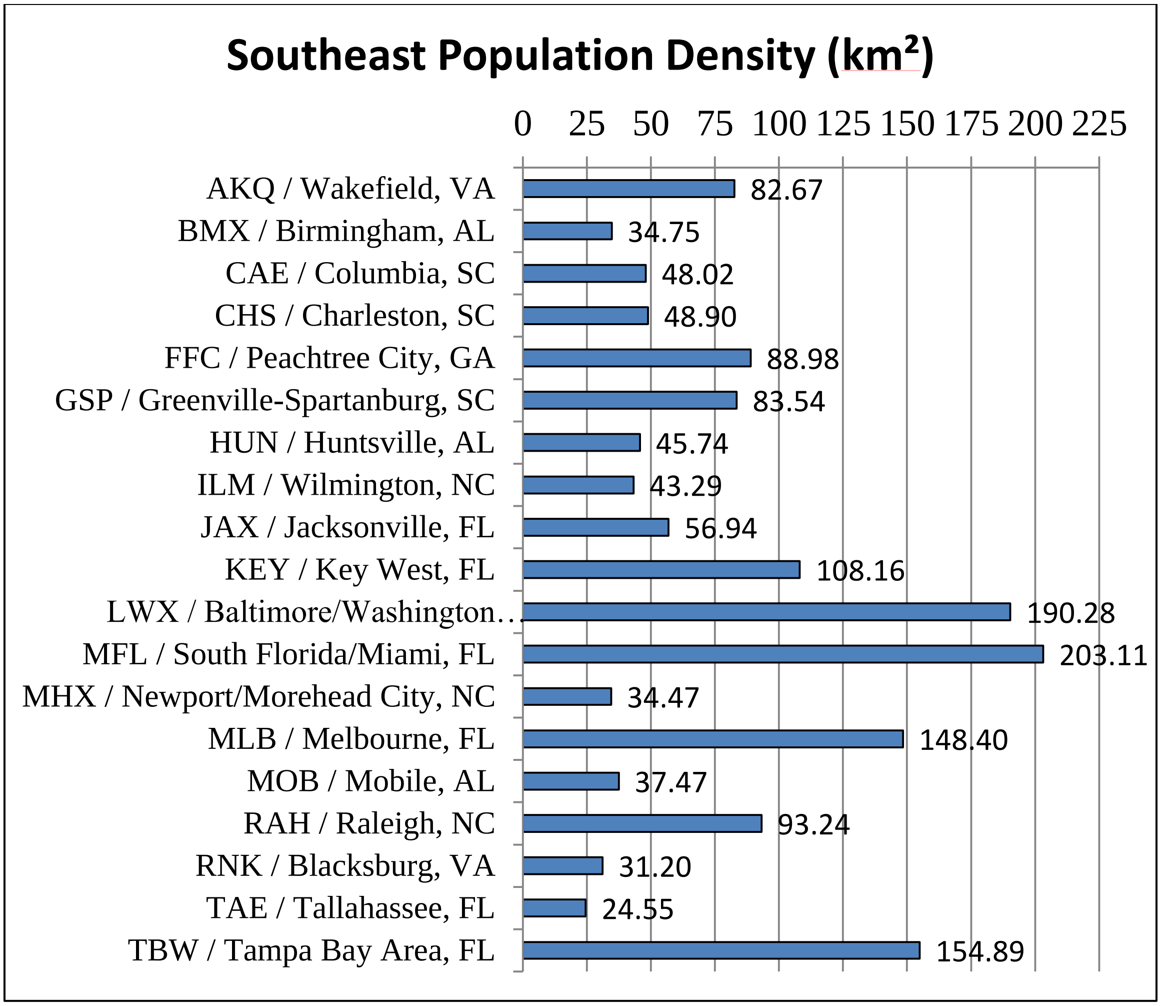


Figure 4.47. WFO population density for the Southeast Climate Region.

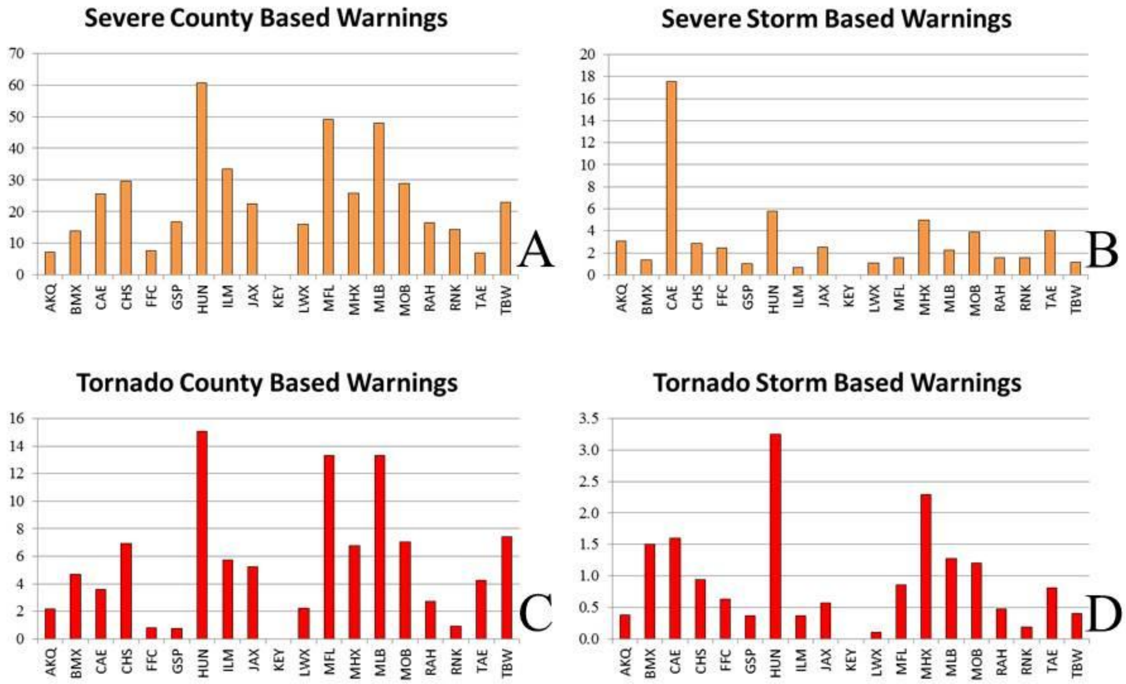


Figure 4.48. Area adjusted annual average warnings by National Weather Service Weather Forecast Office. Average severe county-based warnings (*A*), severe storm-based warnings (*B*), tornado county-based warnings (*C*), and tornado storm-based warnings (*D*) are depicted for the Southeast Climate Region.

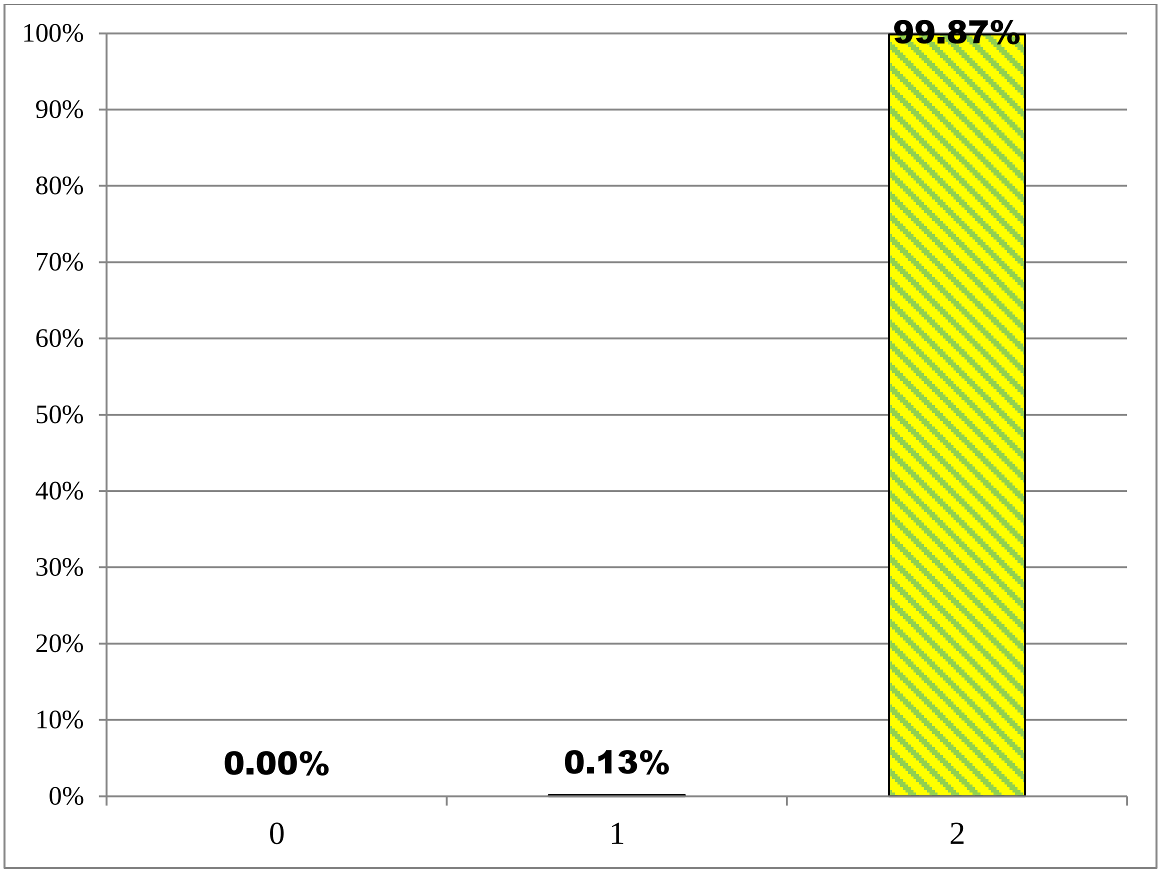


Figure 4.49. NEXRAD radar coverage for the Southeast Climate Region.

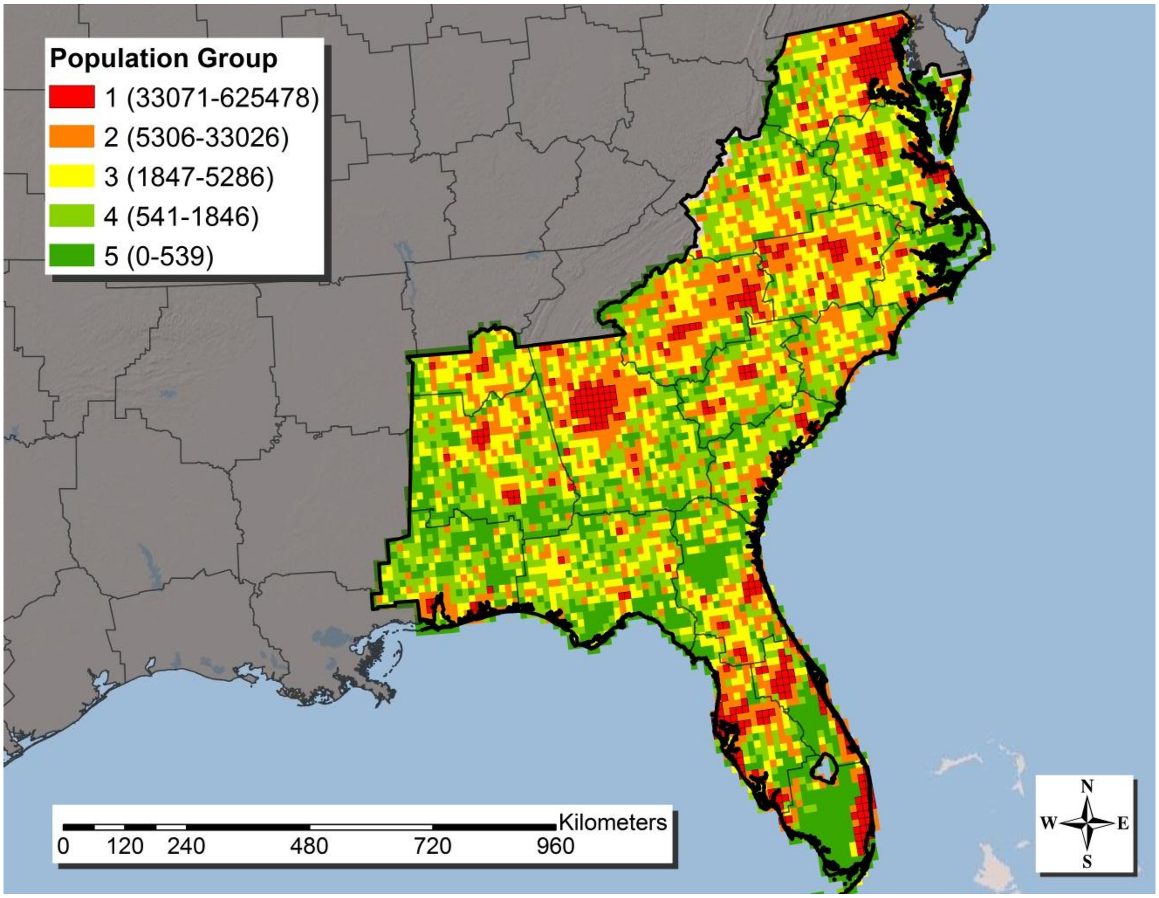


Figure 4.50. Population group distribution within the Southeast Climate Region.

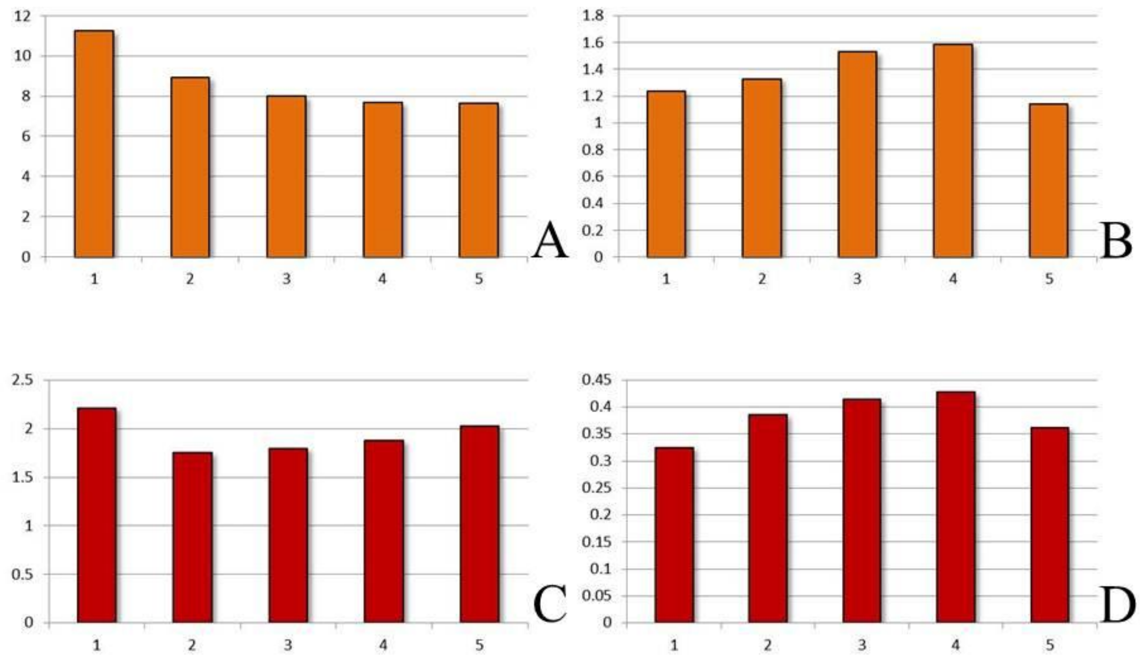


Figure 4.51. Results of the population group analysis for the four warning types. Average severe county-based warnings (A), severe storm-based warnings (B), tornado county-based warnings (C), and tornado storm-based warnings (D) are depicted for the Southeast Climate Region.

I. Southwest Climate Region

The Southwest Climate Region has a total population of 16,667,320 and an average WFO population density of 19.37 persons per km². This region has the second lowest population density of all the regions. Figure 4.52 shows that the Phoenix (PSR) WFO has the highest population density followed by Boulder (BOU). The total number of grid cells (sample size) within the region is 7,033. A table listing the acronym and name of each WFO in this region can be found in Appendix C.

The total number of severe thunderstorm warnings issued for the Southwest Climate Region was 10,659. The total number of severe county-based warnings was 10,415, and the total number of severe storm-based warnings issued was 309. This region ranks seventh for all severe warnings. A total of 1,106 tornado warnings were issued, 1,068 of which were county-based and 38 of which were storm-based. This region ranks sixth in total tornado warnings, sixth in tornado county-based warnings, and seventh in tornado storm-based warnings.

The greatest number of average annual severe county-based warnings were issued by the Tucson (TWC) WFO (Figure 4.53 (*A*)). Figure 4.53 (*B*) shows that the El Paso EPZ and Boulder CWAs received the greatest average numbers of severe storm-based warnings. The Boulder WFO by far issues the most tornado county and storm-based warnings (Figure 4.53 (*C-D*)).

1. NEXRAD Radar Coverage

Radar coverage in the Southwest region is limited by topography and the spatial distribution of radar sites. More than nine percent of the area has no radar coverage with only 73.4 percent having coverage above 1829 meters (Figure 4.54). All correlation tests showed statistical significance, with severe storm-based warnings indicating the greatest possibility of correlation between storm issuance and radar coverage (Table 4.31).

Table 4.31. Correlation results for NEXRAD coverage for the Southwest Climate Region.

Test	Correlation	Z-Value	P-Value
Population	0.06	5.061	<.001
SVR CBW	0.151	12.797	<.001
SVR SBW	0.203	17.221	<.001
TOR CBW	0.111	9.384	<.001
TOR SBW	0.117	9.837	<.001

2. Distance and Direction

The Southwest Climate Region ranks tied for third with the Ohio Valley region in distance performance for overall severe and tornado warnings issued. The adjusted average distance from the geographic center of the CWAs to center of warning distribution is 7.11 km. The mean adjusted distance from location of WFOs to warning center is 8.77 km. The average directional distribution has an azimuth of 134.85° indicating a tendency for warnings to be issued to the southeast of the center of the County Warning Areas. The warning directional distribution from the location of the Weather Forecast Offices registers an azimuth direction of 208.64° (SSW).

The Southwest Climate Region mean severe county-based warning azimuthal direction from the CWA centers is 152.92° (SSE). The average warning direction from the WFO locations is 146.66° (SSE). The average distance from the warning center of distribution to the center of the CWAs is 58.52 km (4.44 km adjusted). This region ranks fifth in minimum distance to center of CWAs among all Climate Regions. The average distance from warning center to WFO location is 80.30 km (6.99 km adjusted). The minimum distance ranking for warning center to WFO location is fifth. The SLC WFO ranks first in distance performance, whereas TWC ranks last (Table 4.32).

Table 4.32. Distance performance ranks for the Southwest Climate Region.

WFO	SCBW	SSBW	TCBW	TSBW
ABQ	3.5	4.5	4	1.5
BOU	2	4.5	3	1.5
EPZ	7	1.5	8	--
FGZ	6	3	1	3
GJT	3.5	7.5	5	--
PSR	5	1.5	7	--
PUB	8	9	6	4
SLC	1	6	2	--
TWC	9	7.5	--	--

The average severe storm-based warning azimuthal direction from the CWA centers is 159.32° (SSE). The average warning direction from the WFO locations is 170.95° (S). The average distance from the warning center of distribution to the center of the CWAs is 87.06 km (7.62 km adjusted). This region ranks fifth in minimum distance to center of CWAs among all Climate Regions. The average distance from warning center to WFO location is 95.82 km (8.56 km adjusted). The minimum distance ranking for warning center to WFO location is third. The EPZ and PSR WFOs tie for first place rank in distance performance, whereas PUB ranks last.

The mean tornado county-based warning azimuthal direction from the CWA centers is 88.93° (E). The average warning direction from the WFO locations is 117.89°

(ESE). The average distance from the warning center of distribution to the center of the CWAs is 83.01 km (7.61 km adjusted). This region ranks sixth in minimum distance to center of CWAs among all Climate Regions. The average distance from warning center to WFO location is 111.81 km (9.29 km adjusted). The minimum distance ranking for warning center to WFO location is fourth. The FGZ WFO ranks first in distance performance, whereas EPZ ranks last.

The mean tornado storm-based warning azimuthal direction from the CWA centers is 138.24° (SE). The average warning direction from the WFO locations is 85.54° (E). The average distance from the warning center of distribution to the center of the CWAs is 92.27 km (7.78 km adjusted). This region ranks fourth in minimum distance to center of CWAs among all Climate Regions. The average distance from warning center to WFO location is 118.77 km (10.25 km adjusted). The minimum distance ranking for warning center to WFO location is fourth. The ABQ and BOU WFOs tie for first place rank in distance performance, whereas PUB ranks last.

3. Population

In the Southwest Climate Region, Population Group 1 cells are found in the Phoenix, Denver, Salt Lake City, El Paso, and Albuquerque areas (Figure 4.55). Population Group 5 areas are found throughout the climate region, with the largest area located in the northwest corner. Population Group 5 is sparsely populated with 0-1 persons in each quad cell.

For both types of severe warnings Population Group 1 had the highest frequency of warnings issued (Figure 4.56 (*A*-*B*)). Severe county-based warning frequency was relatively even for the remaining population groups. Population Group 5 received the least number of severe storm-based warnings. Although Population Group 5 received the least number of tornado county-based warnings, both Population Groups 3 and 4 had a higher warning frequency than Group 1 (Figure 4.56 (*C*)). Tornado storm-based warnings show the greatest possibility for population bias with a “stair step” pattern (with the exception of Population Group 2) indicated, and the warnings most frequent for Population Group 1 and far less frequent for Group 5 (Figure 4.56 (*D*)).

The correlation tests values for the Southwest climate region are low and do not indicate a relationship between population and warning issuance. Figure 4.33 demonstrates that, although several tests show statistical significance, the correlation values are not of the magnitude to conclude that a practical correlation exists. The strongest possible correlation exists between tornado county-based warnings and overall population as indicated by Rho values.

Table 4.33. Population correlation results for the Southwest Climate Region. *Significant correlation results are in **bold** listed with Z-Values and P-Values (α = 0.001 for overall population and α = 0.05 for WFO population density).

Test	Correlation	Z-Value	P-Value	Rho	Z-Value	P-Value
SCBW/Population	**0.087**	**7.338**	**<.001**	0.016	1.383	0.1666
SCBW/WFO Pop Density	0.407	1.058	0.2902	0.367	1.037	0.2997
SSBW/Population	**0.086**	**7.248**	**<.001**	**0.074**	**6.224**	**<.001**
SSBW/WFO Pop Density	0.417	1.087	0.277	0.633	1.791	0.0732
TCBW/Population	0.017	1.462	0.1438	**0.101**	**8.455**	**<.001**
TCBW/WFO Pop Density	0.424	1.107	0.2682	0.017	0.047	0.9624
TSBW/Population	0.026	2.146	0.0318	**0.098**	**8.234**	**<.001**
TSBW/WFO Pop Density	0.438	1.149	0.2504	-0.091	-0.258	0.7963

The greatest possibility for correlation among the nine WFOs in this region exists with the Phoenix (PSR) WFO. The highest correlation results for this WFO are for severe storm-based warnings (Table 4.34). Flagstaff (FGZ) also shows a correlation possibility for this warning type. None of the WFOs in the Southwest climate region show a correlation with tornado storm-based warnings.

Table 4.34. WFO population correlations for the Southwest Climate Region. *Significant correlation results are in **bold** listed with P-Values (α = 0.001).

WFO	SCBW	P-Value	SSBW	P-Value	TCBW	P-Value	TSBW	P-Value
ABQ	-0.036	0.1781	0.015	0.5657	-0.041	0.1171	-0.032	0.2233
BOU	0.002	0.9661	-0.085	0.0422	-0.042	0.3165	0.019	0.6574
EPZ	0.049	0.2822	0.052	0.2522	-0.002	0.9637	--	>.9999
FGZ	0.055	0.1061	**0.240**	**<.001**	-0.058	0.0851	0.122	0.0003
GJT	-0.017	0.6055	-0.034	0.3107	-0.001	0.9699	--	>.9999
PSR	**0.220**	**<.001**	**0.405**	**<.001**	**0.224**	**<.001**	--	>.9999
PUB	**0.229**	**<.001**	-0.045	0.2686	**0.138**	**0.0008**	-0.043	0.2962
SLC	0.015	0.5961	-0.045	0.1225	-0.037	0.2033	--	>.9999
TWC	0.142	0.0034	-0.011	0.8143	--	>.9999	--	>.9999

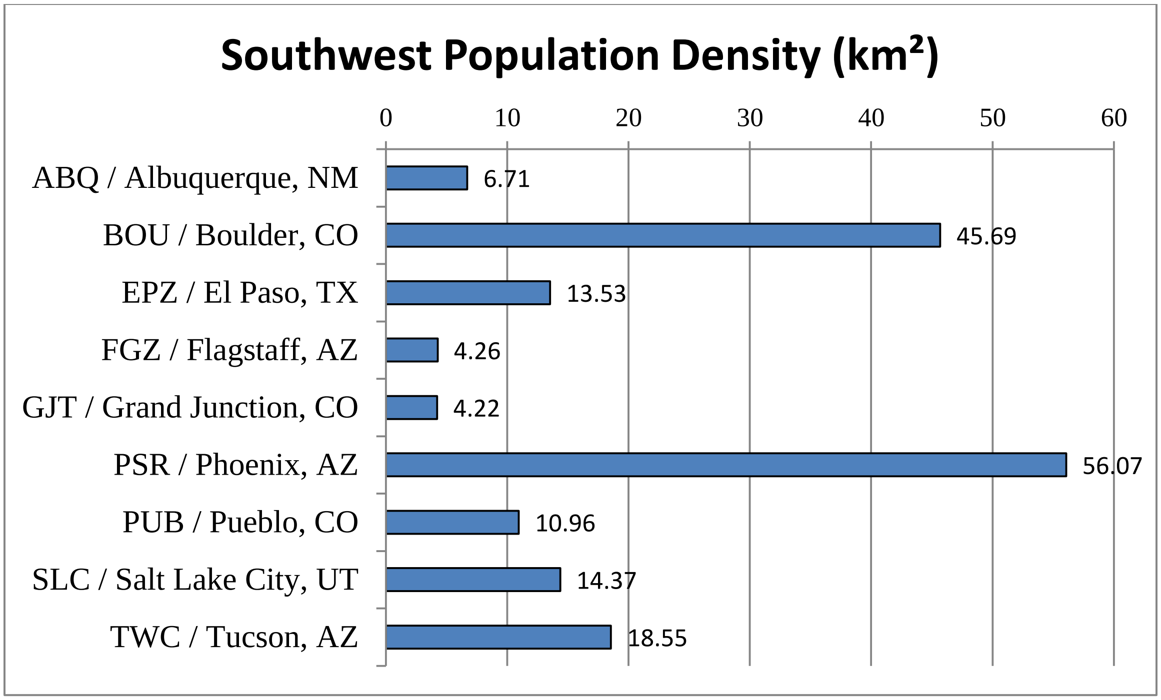


Figure 4.52. WFO population density for the Southwest Climate Region.

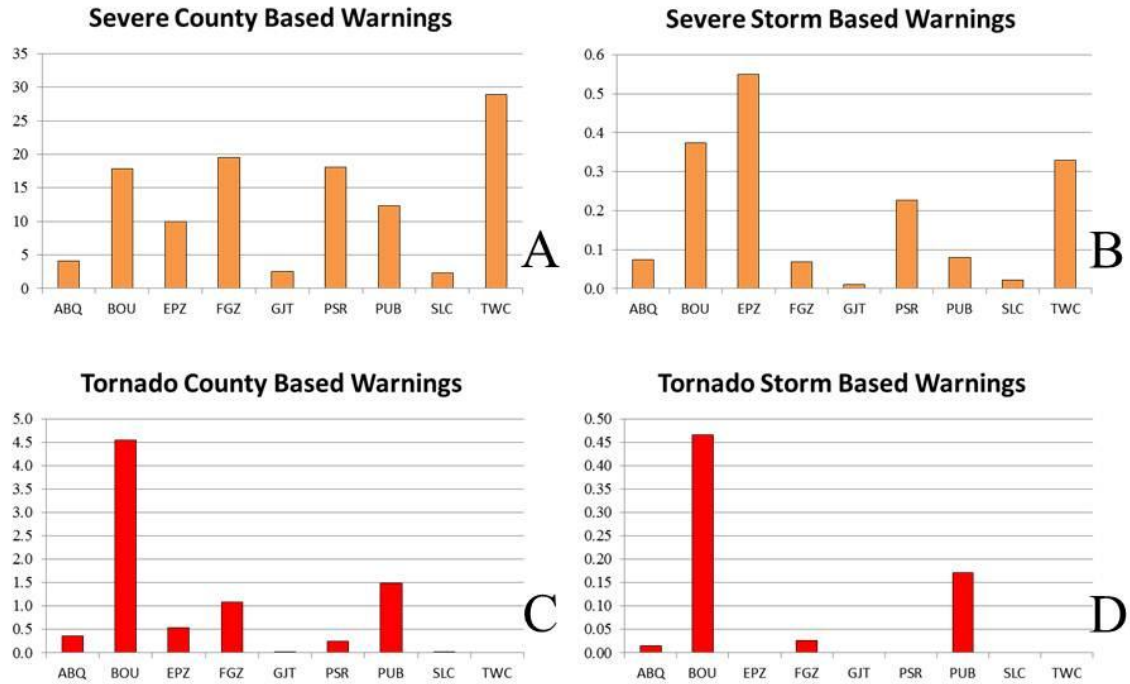


Figure 4.53. Area adjusted annual average warnings by National Weather Service Weather Forecast Office. Average severe county-based warnings (*A*), severe storm-based warnings (*B*), tornado county-based warnings (*C*), and tornado storm-based warnings (*D*) are depicted for the Southwest Climate Region.

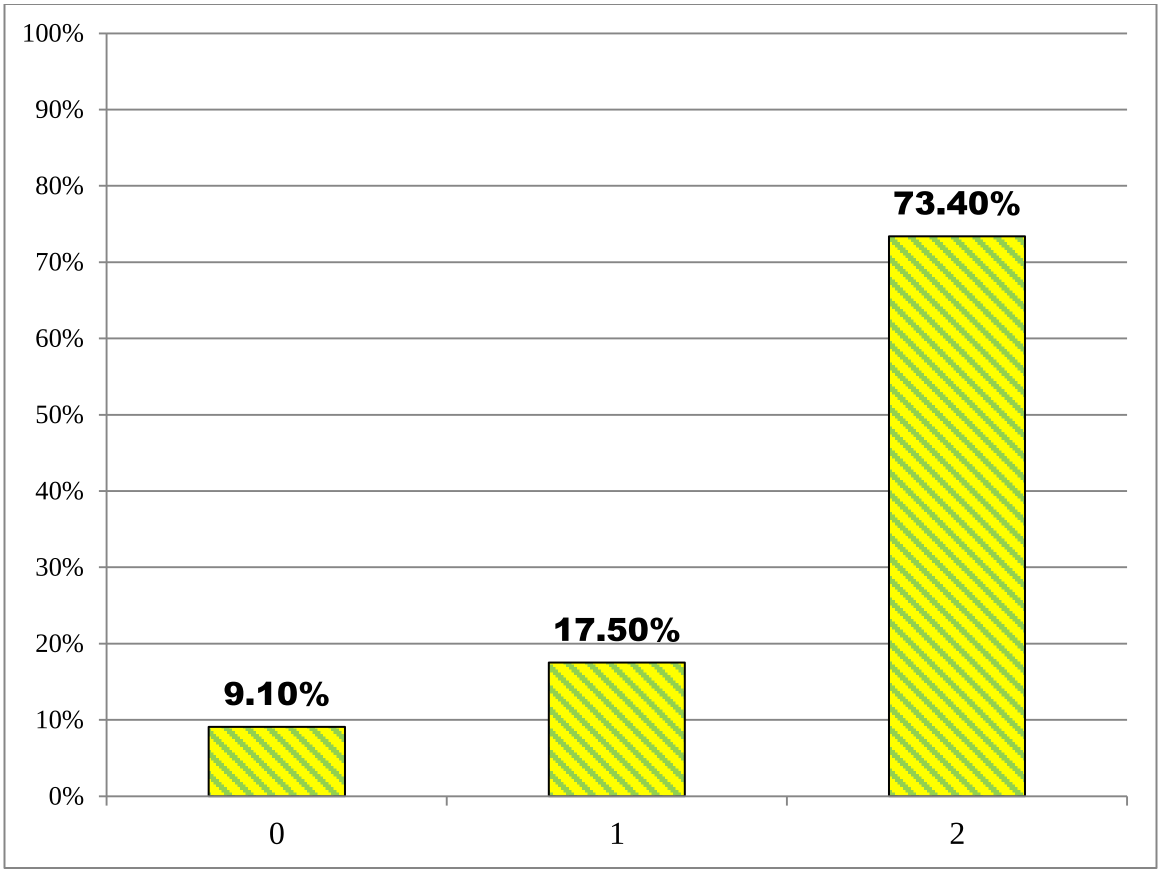


Figure 4.54. NEXRAD radar coverage for the Southwest Climate Region.

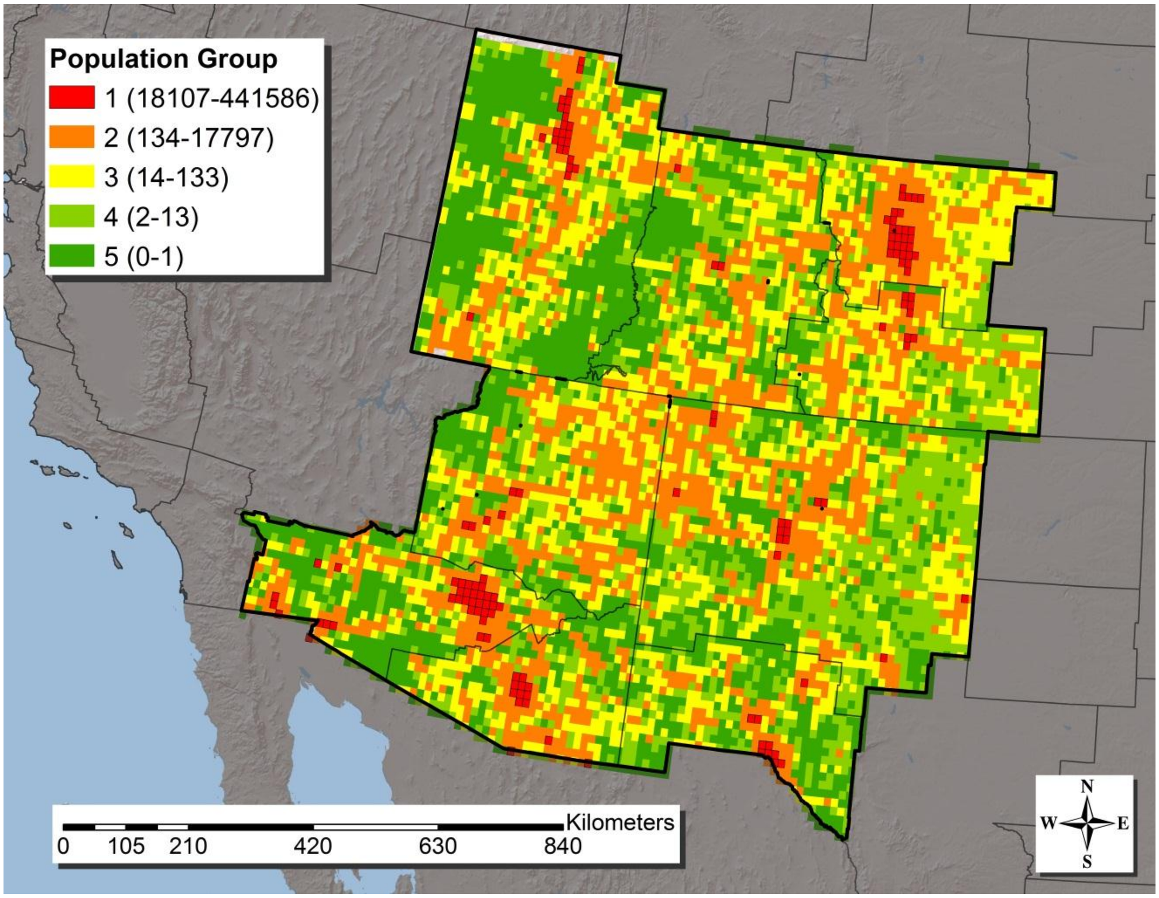


Figure 4.55. Population group distribution within the Southwest Climate Region.

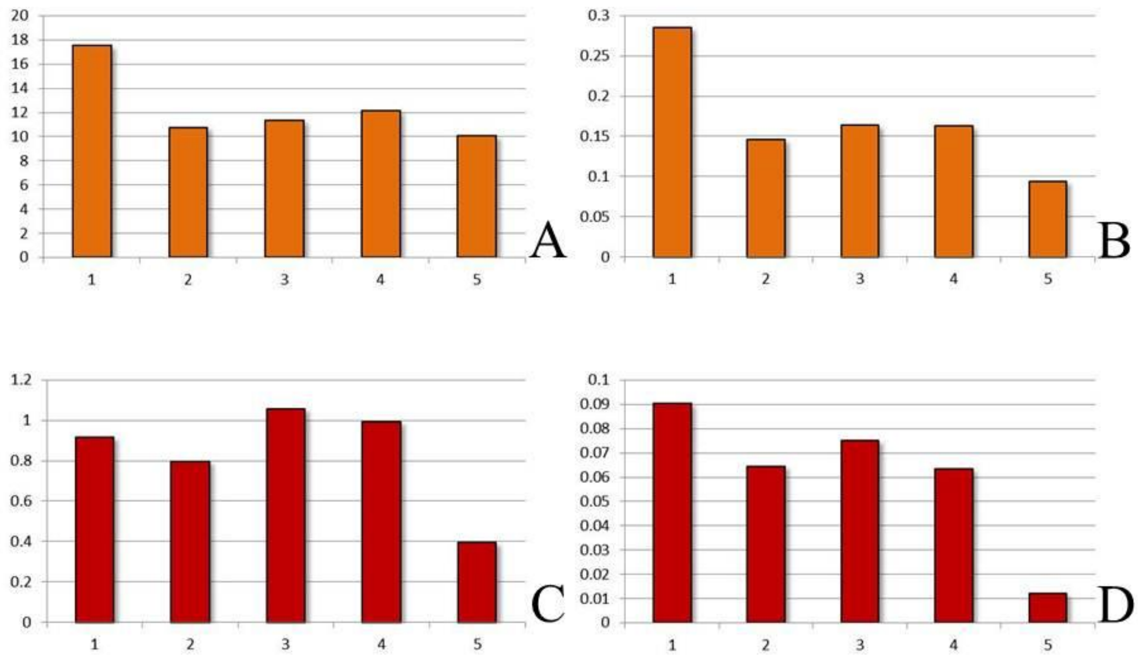


Figure 4.56. Results of the population group analysis for the four warning types. Average severe county-based warnings (A), severe storm-based warnings (B), tornado county-based warnings (C), and tornado storm-based warnings (D) are depicted for the Southwest Climate Region.

J. West Climate Region

The West climate region has a total population of 37,436,579 and an average WFO population density of 112.39 persons per km², the second highest density among all climate regions. This high population density is likely because of the densely populated California major metropolitan area of Los Angeles, and the urban centers of San Francisco and San Diego. The difference between the most densely populated county warning area and the least populated is 325.41 persons per km². Figure 4.57 shows the most populated county warning area is Los Angelas/Oxnard (LOX) followed by San Diego (SGX) and San Francisco/Monterey Bay (MTR). The total number of grid cells (sample size) within the region is 4,548. A table listing the acronym and name of each WFO in this region can be found in Appendix C.

The total number of severe thunderstorm warnings issued for the West Climate Region was 1,450. The total number of severe county-based warnings was 1,423. The total number of severe storm-based warnings was 27. This region had the least amount of all types of severe warnings issued among the nine regions. 101 tornado warnings were issued, 99 of which were county-based and 2 of which were storm-based. This region ranks eighth in total tornado warnings and eighth in tornado county-based warnings. The West region is tied for the least number of warnings issued with the Northwest Climate Region in tornado storm-based warnings.

The San Diego (SGX) CWA received the greatest number of average annual severe county-based warnings, with the Eureka (EKA) issuing the most severe storm-based warnings (Figure 4.58 (*A*-*B*)). Figure 4.58 (*C*) shows that Los Angeles/Oxnard (LOX) received the most tornado county-based warnings. Adjusted mean tornado storm-based warnings were only issued by the San Diego (SGX) and Elko (LKN) WFOs (Figure 4.58 (*D*)).

1. NEXRAD Coverage

Significant gaps appear in the NEXRAD radar coverage of the West region because of radar spatial distribution and topographic influences. Almost eight percent of the area is without radar coverage, with under 80 percent receiving coverage above 1828 meters (Figure 4.59). Radar correlations are statistically significant for both types of county-based warnings, but correlation values remain relatively low (Table 4.35).

Table 4.35. Correlation results for NEXRAD coverage for the West Climate Region.

Test	Correlation	Z-Value	P-Value
Population	0.084	5.688	<.001
SVR CBW	0.144	9.793	<.001
SVR SBW	0.034	2.324	0.0201
TOR CBW	0.156	10.615	<.001
TOR SBW	0.023	1.525	0.1273

2. Distance and Direction

The West Climate Region ranks tied for eighth with the Northeast Climate Region in distance performance for overall severe and tornado warnings issued. The adjusted average distance from the geographic center of the CWAs to center of warning distribution is 14.28 km. The mean adjusted distance from location of WFOs to warning center is 16.86 km. The average directional distribution has an azimuth of 198.46°, indicating a tendency for warnings to be issued to the south-southwest of the center of the

County Warning Areas. The warning directional distribution from the location of the Weather Forecast Offices registers an azimuth direction of 192.53° (SSW).

The West Climate Region mean severe county-based warning azimuthal direction from the CWA centers is 213.57° (SSW). The average warning direction from the WFO locations is 179.45° (S). The average distance from the warning center of distribution to the center of the CWAs is 56.80 km (8.73 km adjusted). This region ranks last place at ninth in minimum distance to center of CWAs among all Climate Regions. The average distance from warning center to WFO location is 63.98 km (13.66 km adjusted). The minimum distance ranking for warning center to WFO location is eighth. The REV and STO WFOs tie for first place rank in distance performance, whereas SGX ranks last (Table 4.36).

Table 4.36. Distance performance ranks for the West Climate Region.

WFO	SCBW	SSBW	TCBW	TSBW
EKA	6	6	7	--
HNX	5	4.5	1	--
LKN	8	1	6	1.5
LOX	3.5	7	8	--
MTR	3.5	8	--	--
REV	1.5	2.5	3.5	--
SGX	9	2.5	3.5	1.5
STO	1.5	--	2	--
VEF	7	4.5	5	--

The average severe storm-based warning azimuthal direction from the CWA centers is 239.16° (SW). The average warning direction from the WFO locations is 143.15° (SE). The average distance from the warning center of distribution to the center of the CWAs is 83.10 km (18.34 km adjusted). This region ranks last place at ninth in minimum distance to center of CWAs among all Climate Regions. The average distance from warning center to WFO location is 91.12 km (18.15 km adjusted). The minimum distance ranking for warning center to WFO location is last place at ninth. The LKN WFO ranks first in distance performance, whereas MTR ranks last.

The mean tornado county-based warning azimuthal direction from the CWA centers is 197.01° (SSW). The average warning direction from the WFO locations is 167.65° (SSE). The average distance from the warning center of distribution to the center of the CWAs is 91.50 km (15.77 km adjusted). This region ranks last place at ninth in minimum distance to center of CWAs among all Climate Regions. The average distance from warning center to WFO location is 80.49 km (15.27 km adjusted). The minimum distance ranking for warning center to WFO location is eighth. The HNX WFO ranks first in distance performance, whereas LOX ranks last.

The mean tornado storm-based warning azimuthal direction from the CWA centers is 144.11° (SE). The average warning direction from the WFO locations is 279.87° (W). The average distance from the warning center of distribution to the center of the CWAs is 65.85 km (14.27 km adjusted). This region ranks seventh in minimum distance to center of CWAs among all Climate Regions. The average distance from warning center to WFO location is 94.87 km (20.38 km adjusted). The minimum distance ranking for warning center to WFO location is last place at ninth. Because of a low sample size only two WFOs (LKN and SGX) are ranked in distance performance, with the same rank of 1.5 calculated for both.

3. Population

The highest population density for the West Climate Region is along the Pacific coast of California. This is indicated on the Population Group map in Figure 4.60, where Population Group 1 is located in the Los Angeles, San Diego, and San Francisco urban areas. Another pocket of Population Group 1 cells is located in the Las Vegas Area. By far the least populated areas represented by Population Group 5 are found in the eastern two-third of the climate region, in the desert areas of eastern California and Nevada. This region represents the most extreme variation in population groups, where there is zero population represented in Population Group 5 cells.

Results of the population group graphs indicate that the only possible population bias exists with tornado warnings. Figures 4.61 (*A*-*B*) show that the lowest frequency of both types of severe warnings was for Population Group 1. Tornado county-based warnings show an almost perfect “stair step” pattern (Figure 4.61 (C)). Despite the very small sample size for tornado storm-based warnings, by far the highest frequency of the warnings occurred in Population Group 1 grid cells.

In the West Climate Region, only tornado storm-based warnings demonstrate a possible connection to overall population-based on correlation results (Table 4.37). The remaining results, although some show a statistical significance, have correlation values that are too low to conclude a possible relationship.

Table 4.37. Population correlation results for the West Climate Region. *Significant correlation results are in **bold** listed with Z-Values and P-Values (α = 0.001 for overall population and α = 0.05 for WFO population density).

Test	Correlation	Z-Value	P-Value	Rho	Z-Value	P-Value
SCBW/Population	**-0.058**	**-3.900**	**<.001**	**-0.083**	**-5.584**	**<.001**
SCBW/WFO Pop Density	0.218	0.544	0.5866	-0.233	-0.66	0.5093
SSBW/Population	-0.026	-1.744	0.0812	-0.003	-0.206	0.837
SSBW/WFO Pop Density	-0.05	-0.124	0.9016	-0.133	-0.377	0.7061
TCBW/Population	**0.158**	**10.772**	**<.001**	**0.111**	**7.485**	**<.001**
TCBW/WFO Pop Density	0.408	1.063	0.288	0.300	0.849	0.3961
TSBW/Population	**0.207**	**14.181**	**<.001**	**0.048**	**3.267**	**0.0011**
TSBW/WFO Pop Density	0.537	1.471	0.1414	-0.023	-0.065	0.9485

Results of the correlation test for the individual WFOs in the West Climate Region show that the Los Angeles/Oxnard (LOX) WFO shows a correlation with severe county-based warnings and tornado county-based warnings (Table 4.38). The San Diego (SGX) WFO shows a correlation with tornado storm-based warnings. The Sacramento (STO) WFO has a statistically significant but low correlation result for tornado county-based warnings. The remaining results do not pass the significance test. Because of the relative rarity of tornado storm-based warnings to have been issued for this climate region, correlation values were calculated for the only two of the WFOs that have issued these types of warnings.

Table 4.38. WFO population correlations for the West Climate Region. *Significant correlation results are in **bold** listed with P-Values (α = 0.001).

WFO	SCBW	P-Value	SSBW	P-Value	TCBW	P-Value	TSBW	P-Value
EKA	-0.088	0.1966	-0.022	0.7478	0.027	0.6963	--	>.9999
HNX	0.079	0.0960	-0.048	0.3123	0.016	0.7322	--	>.9999
LKN	0.06	0.0700	0.051	0.1252	0.067	0.0439	-0.004	0.8956
LOX	**0.374**	**<.001**	-0.033	0.6406	**0.458**	**<.001**	--	>.9999
MTR	-0.025	0.7361	-0.055	0.4461	--	>.9999	--	>.9999
REV	0.089	0.0278	-0.001	0.9726	0.113	0.0050	--	>.9999
SGX	-0.042	0.5505	-0.023	0.7496	-0.091	0.1968	**0.569**	**<.001**
STO	-0.022	0.5987	--	>.9999	**0.210**	**<.001**	--	>.9999
VEF	0.065	0.0251	-0.01	0.7354	-0.024	0.3996	--	>.9999

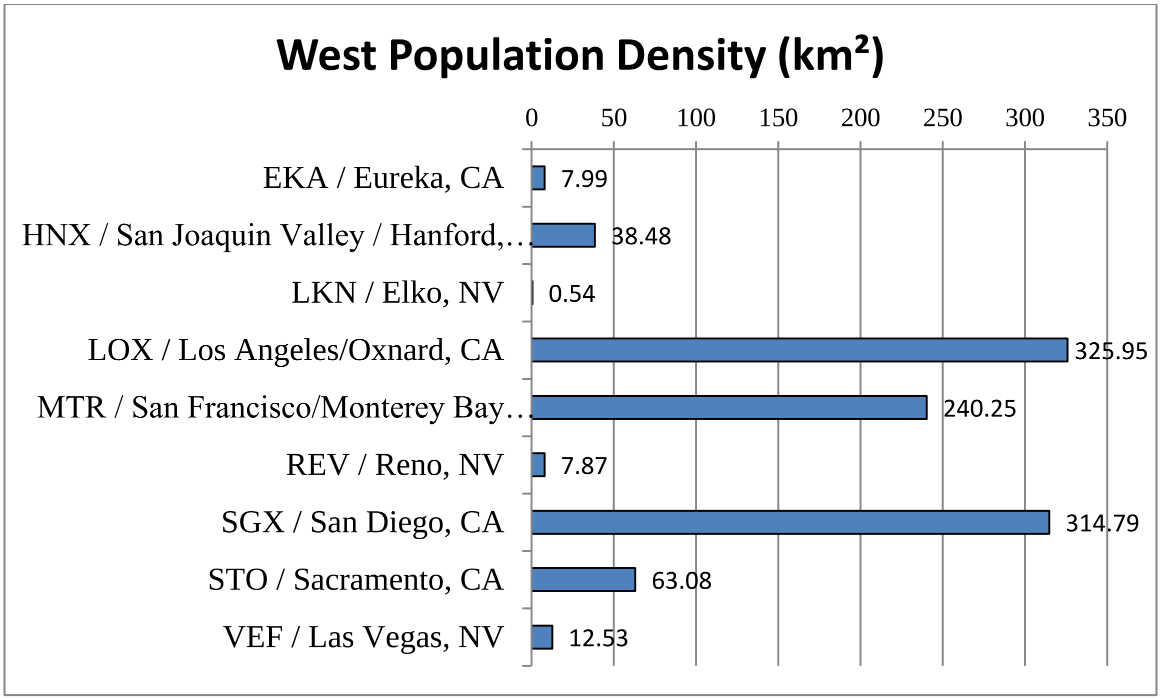


Figure 4.57. WFO population density for the West Climate Region.

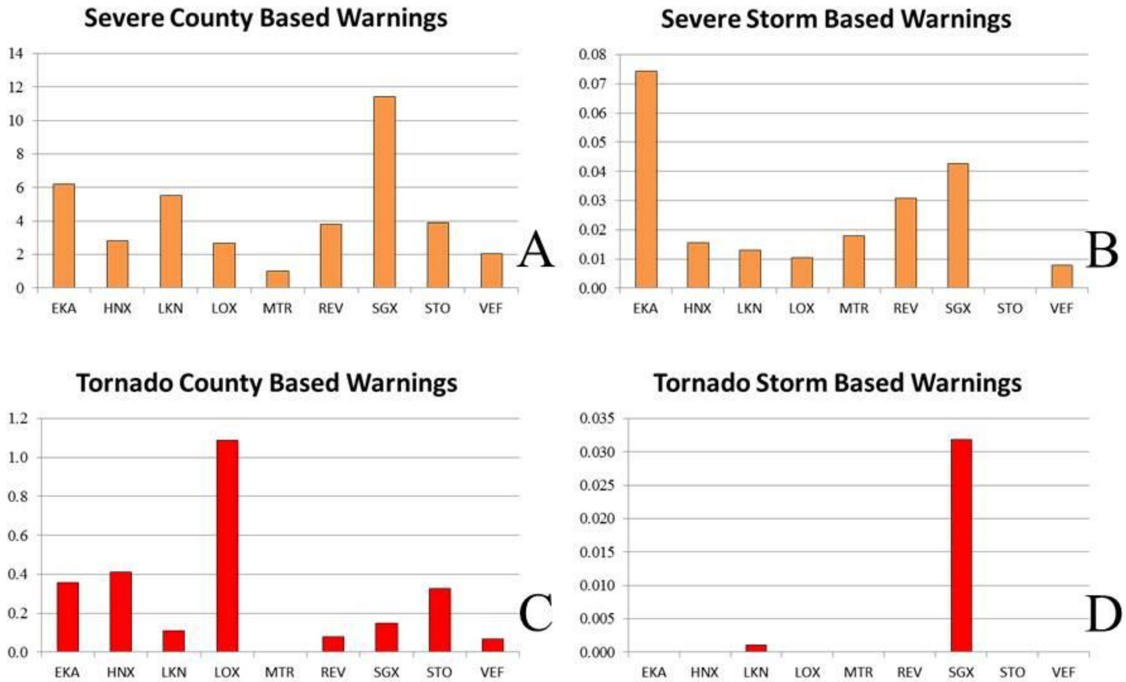


Figure 4.58. Area adjusted annual average warnings by National Weather Service Weather Forecast Office. Average severe county-based warnings (*A*), severe storm-based warnings (*B*), tornado county-based warnings (*C*), and tornado storm-based warnings (*D*) are depicted for the West Climate Region.

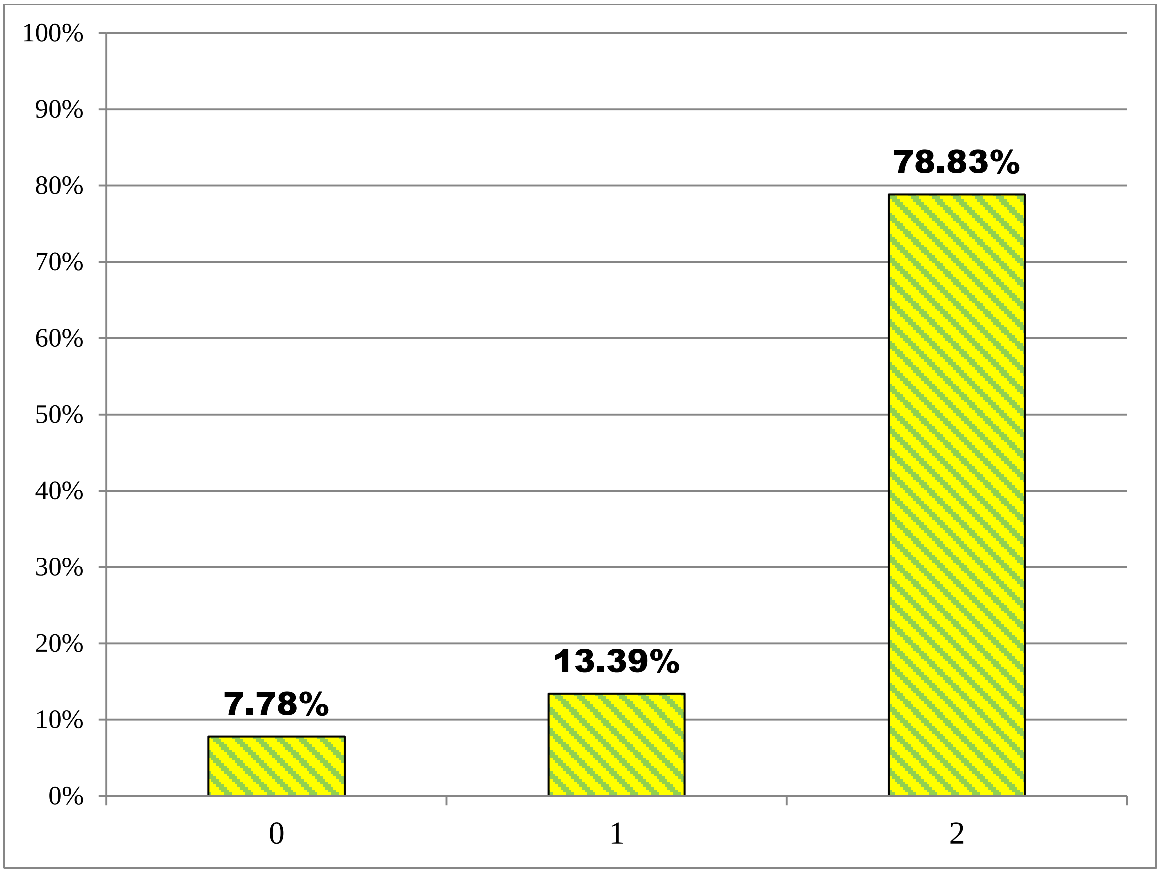


Figure 4.59. NEXRAD radar coverage for the West Climate Region.

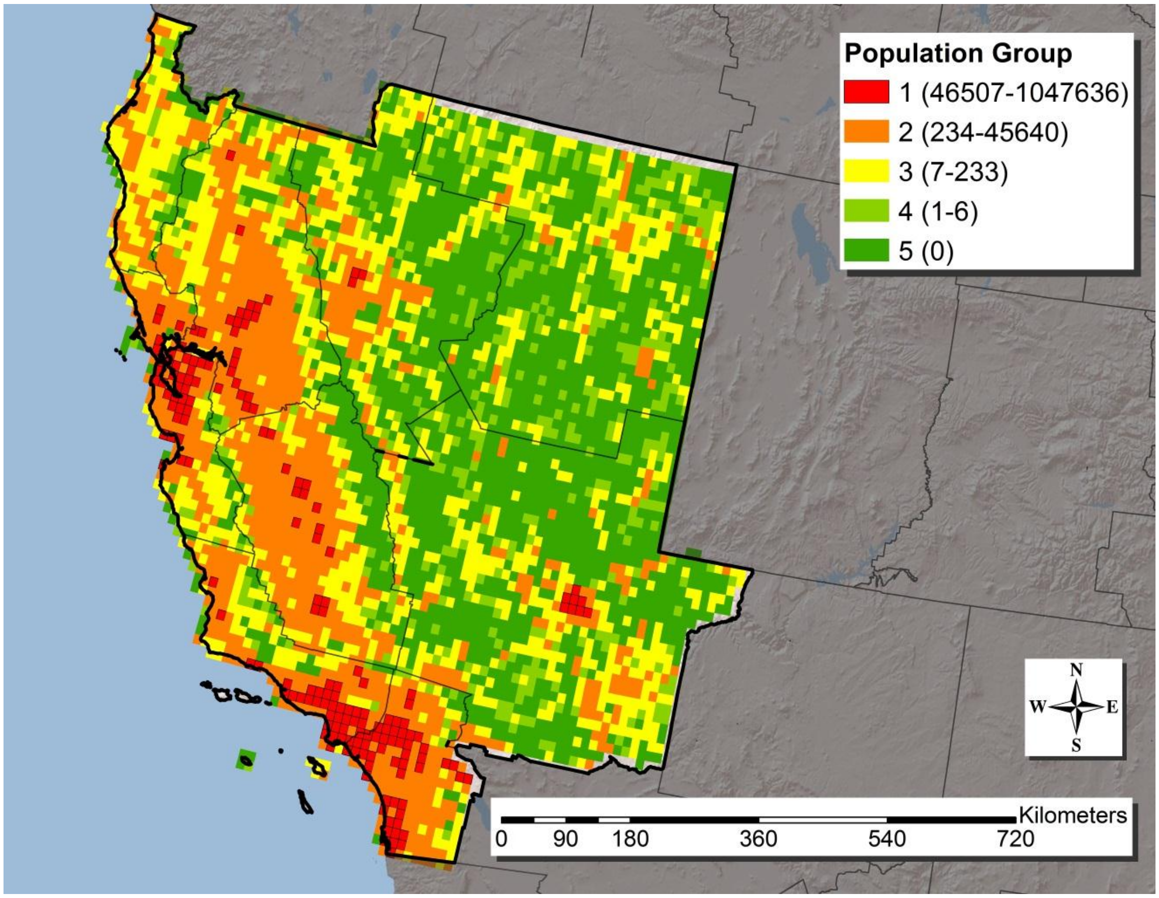


Figure 4.60. Population group distribution within the West Climate Region.

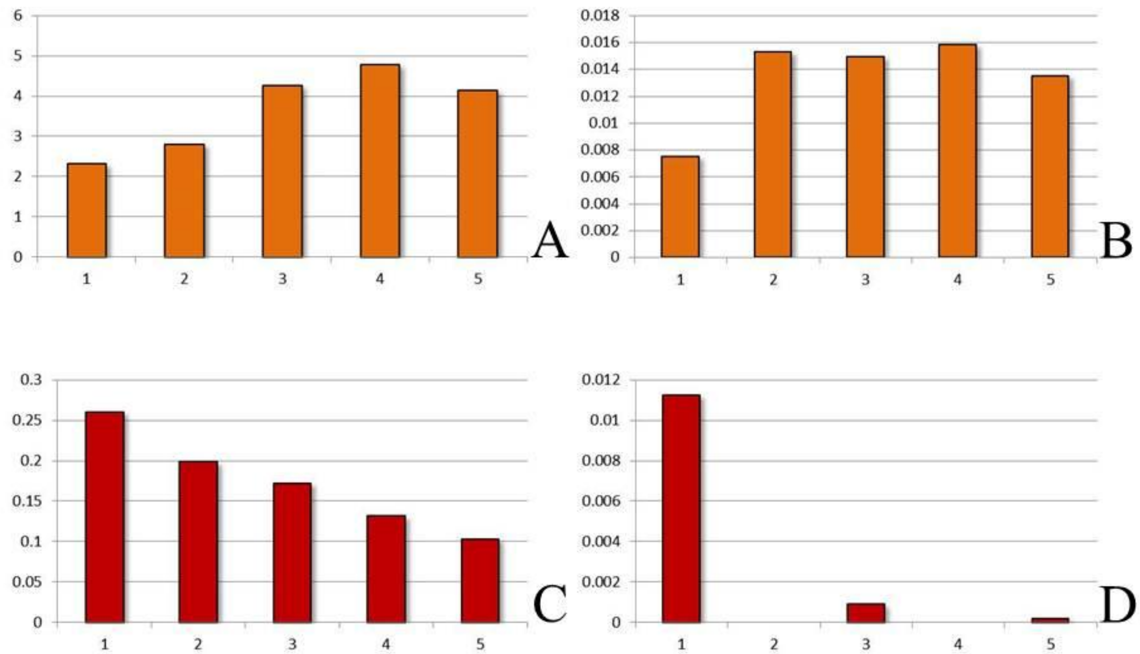


Figure 4.61. Results of the population group analysis for the four warning types. Average severe county-based warnings (A), severe storm-based warnings (B), tornado county-based warnings (C), and tornado storm-based warnings (D) are depicted for the West Climate Region.

K. West North Central Climate Region

The total population of the West North Central Climate Region is 5,036,480 with an average WFO population density of 5.05 persons per km². This region has the lowest population density of all the climate regions. Figure 4.62 shows that the most densely populated county warning area is Omaha/Valley (OAX), with the least populated being Glasgow (GGW). The total number of grid cells (sample size) within the region is 9,068. A table listing the acronym and name of each WFO in this region can be found in Appendix C.

The total number of severe thunderstorm warnings issued for the West North Central Climate Region was 28,664, which ranks fourth among the nine regions. The total number of severe county-based warnings was 28,355, ranking fourth. The total number of severe storm-based warnings was 309 which ranks fifth. 3,564 tornado warnings were issued, 3,504 of which were county-based and 60 of which were storm-based. This region ranks fourth in total tornado warnings, fourth in tornado county-based warnings, and fifth in tornado storm-based warnings.

The most annual average number of severe county-based warnings were issued for the Hastings (GID), North Platte (LBF), and Omaha/Valley (OAX) county warning areas (Figure 4.63 (*A*)). The Hastings WFO issued the most severe storm and tornado county-based warnings (Figure 4.63 (*B*-*C*)). Figure 4.63 (*D*) shows that North Platte and Sioux Falls (FSD) issued the most tornado storm-based warnings. Missoula (MSO) received the least annual average number of warnings of all types.

1. NEXRAD Radar Coverage

Figure 4.64 shows the NEXRAD coverage for the West North Central Climate Region. Although most of the region has perfect coverage at 1829 km and above, almost 4 percent of the total area has no radar coverage. The highest NEXRAD correlation values occur with county-based warnings, with the lowest correlation between NEXRAD coverage and tornado storm-based warnings (Table 4.39). There is no correlation between population and radar coverage.

Table 4.39. NEXRAD Correlation results for coverage in the West North Central Climate Region.

Test	Correlation	Z-Value	P-Value
Population	0.03	2.849	0.0044
SVR CBW	0.177	16.99	<.001
SVR SBW	0.089	8.534	<.001
TOR CBW	0.186	17.966	<.001
TOR SBW	0.086	8.246	<.001

2. Distance and Direction

The West North Central Climate Region ranks first in distance performance in overall severe and tornado warnings issued. The adjusted average distance from the geographic center of the CWAs to center of warning distribution is 5.79 km. The mean adjusted distance from location of WFOs to warning center is 7.60 km. The average directional distribution has an azimuth of 178.82°, indicating a tendency for warnings to be issued to the south of the center of the County Warning Areas. The warning directional distribution from the location of the Weather Forecast Offices registers an azimuth direction of 178.97° (S).

The West North Central Climate Region mean severe county-based warning azimuthal direction from the CWA centers is 168.26° (SSE). The average warning direction from the WFO locations is 180.52° (S). The average distance from the warning center of distribution to the center of the CWAs is 36.43 km (3.68 km adjusted). This region ranks second in minimum distance to center of CWAs among all Climate Regions. The average distance from warning center to WFO location is 58.53 km (6.48 km adjusted). The minimum distance ranking for warning center to WFO location is first. The GID WFO ranks first in distance performance, whereas TFX ranks last (Table 4.40).

Table 4.40. Distance performance ranks for the West North Central Climate Region.

WFO	SCBW	SSBW	TCBW	TSBW
ABR	7.5	6.5	1	3
BIS	3	3	4.5	4.5
BYZ	5.5	6.5	4.5	6
CYS	12	13	12	13
FSD	9.5	11.5	8	4.5
GGW	2	2	9	7.5
GID	1	1	2	1.5
LBF	5.5	4	6	1.5
MSO	9.5	9.5	--	10.5
OAX	4	5	7	12
RIW	7.5	8	3	9
TFX	13	11.5	11	7.5
UNR	11	9.5	10	10.5

The mean severe storm-based warning azimuthal direction from the CWA centers is 176.63° (S). The average warning direction from the WFO locations is 192.52°

(SSW). The average distance from the warning center of distribution to the center of the CWAs is 66.70 km (6.82 km adjusted). This region ranks third in minimum distance to center of CWAs among all Climate Regions. The average distance from warning center to WFO location is 65.18 km (6.91 km adjusted). The minimum distance ranking for warning center to WFO location is first. The GID WFO ranks first in distance performance, whereas CYS ranks last.

The average tornado county-based warning azimuthal direction from the CWA centers is 188.45° (S). The average warning direction from the WFO locations is 164.20° (SSE). The average distance from the warning center of distribution to the center of the CWAs is 46.32 km (4.82 km adjusted). This region ranks second in minimum distance to center of CWAs among all Climate Regions. The average distance from warning center to WFO location is 62.50 km (6.87 km adjusted). The minimum distance ranking for warning center to WFO location is first. The ABR WFO ranks first in distance performance, whereas CYS ranks last.

The mean tornado storm-based warning azimuthal direction from the CWA centers is 181.96° (S). The average warning direction from the WFO locations is 178.65° (S). The average distance from the warning center of distribution to the center of the CWAs is 77.84 km (7.85 km adjusted). This region ranks fifth in minimum distance to center of CWAs among all Climate Regions. The average distance from warning center to WFO location is 97.38 km (10.15 km adjusted). The minimum distance ranking for warning center to WFO location is third. The GID and LBF WFOs tie for first place in distance performance, whereas OAX ranks last.

3. Population

The population group distribution map (Figure 4.65) for the West North Central Climate Region shows that Population Group 1 areas are widely dispersed and are located near moderately sized cities. The Omaha, Nebraska, area has the highest population density in the region, with large areas of Population Group 2 cells in the vicinity. Population Group 5 cells are found in the southwest and western sections of the climate region.

The West North Central climate region population group analysis indicates that there is population bias likely across all warnings types. Severe county-based warnings (Figure 4.66 (*A*)) were issued the most frequently for Population Group 1 and least frequently for Population Group 5. Figure 4.66 (*B*) shows a “stair step” pattern for severe storm-based warnings, although there is little variation in the warnings issued for Population Groups 1-3. A greater population bias is possible for tornado county-based warnings, where far more warnings were issued for Population Groups 1 and 2, and the number of warnings drastically decreases through the remaining population groups (Figure 4.66 (*C*)). Tornado storm-based warnings were issued most frequently for Population Group 3, although there is little variation in frequency between groups 1-3 (Figure 4.66 (*D*)). For all warning types, Population Group 5 received proportionally far fewer warnings.

For the West North Central Climate Region, Spearman’s Rho values shown in Table 4.41 demonstrate statistical and possible practical significance for severe county-based warnings and overall population, as well as tornado county-based warnings and overall population. The remaining results show some statistical significance but very little likelihood of practical significance.

Table 4.41. Population correlation results for the West North Central Climate Region. *Significant correlation results are in **bold** listed with Z-Values and P-Values (α = 0.001 for overall population and α = 0.05 for WFO population density).

Test	Correlation	Z-Value	P-Value	Rho	Z-Value	P-Value
SCBW/Population	**0.053**	**5.062**	**<.001**	**0.239**	**22.779**	**<.001**
SCBW/WFO Pop Density	0.485	1.673	0.0943	-0.233	-0.66	0.5093
SSBW/Population	**0.035**	**3.331**	**0.0009**	**0.180**	**17.148**	**<.001**
SSBW/WFO Pop Density	0.314	1.029	0.3036	-0.133	-0.377	0.7061
TCBW/Population	0.031	2.97	0.003	**0.274**	**26.12**	**<.001**
TCBW/WFO Pop Density	0.451	1.535	0.1248	0.3	0.849	0.3961
TSBW/Population	**0.039**	**3.715**	**0.0002**	**0.170**	**16.144**	**<.001**
TSBW/WFO Pop Density	0.375	1.248	0.212	-0.023	-0.065	0.9485

Of the 13 WFOs in the West North Central Climate Region, only three have resulting correlation values that indicate a possible relationship between warning issuance and population. It should be noted however, that these values are rather low. Table 4.42 points to significant values for the Sioux Falls (FSD) WFO for severe county and storm-based warnings, as well as tornado storm-based warnings. Rapid City (UNR) has statistically significant results for severe county-based warnings and tornado storm-based warnings, and Missoula (MSO) shows significance for severe county-based warnings.

Table 4.42. WFO population correlations for the West North Central Climate Region. *Significant correlation results are in **bold** listed with P-Values (α = 0.001).

WFO	SCBW	P-Value	SSBW	P-Value	TCBW	P-Value	TSBW	P-Value
FSD	**0.182**	**<.001**	**0.189**	**0.0004**	--	>.9999	**0.203**	**<.001**
UNR	**0.139**	**0.0002**	0.068	0.0337	0.12	0.0045	**0.176**	**0.001**
MSO	**0.121**	**0.0004**	0.075	0.0459	0.087	0.0272	0.095	0.015
BIS	0.092	0.0043	0.073	0.132	0.091	0.0282	0.06	0.0867
CYS	0.107	0.0061	0.042	0.277	0.048	0.1332	0.057	0.1738
OAX	0.101	0.0369	0.002	0.9695	0.029	0.4927	0.034	0.3737
RIW	0.035	0.2786	-0.008	0.8359	0.004	0.9136	0.008	0.8054
LBF	0.041	0.3219	-0.01	0.8149	-0.011	0.7792	0.000	0.9969
BYZ	0.02	0.5705	-0.014	0.6775	-0.017	0.6372	-0.005	0.8715
TFX	-0.004	0.9037	-0.018	0.6668	-0.034	0.2958	-0.011	0.7515
ABR	-0.015	0.7221	-0.019	0.5599	-0.055	0.255	-0.022	0.5518
GID	-0.038	0.4868	-0.035	0.2874	-0.092	0.0865	-0.047	0.2561
GGW	-0.05	0.1874	-0.044	0.2092	-0.077	0.0452	-0.071	0.0938

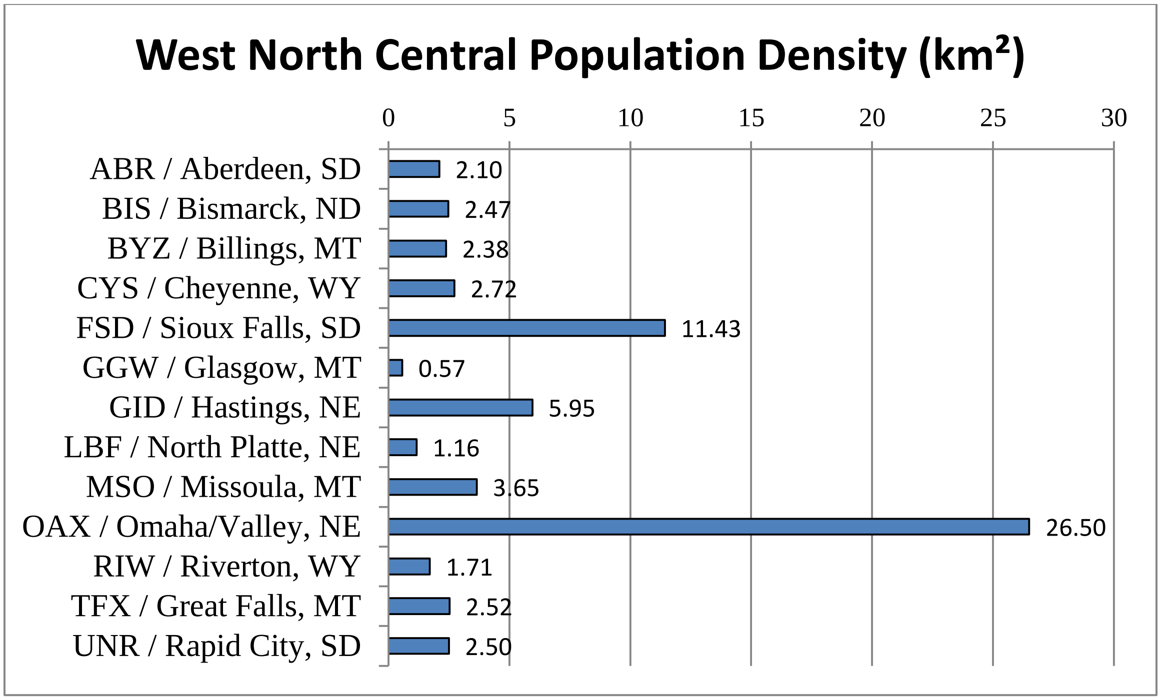


Figure 4.62. WFO population density for the West North Central Climate Region.

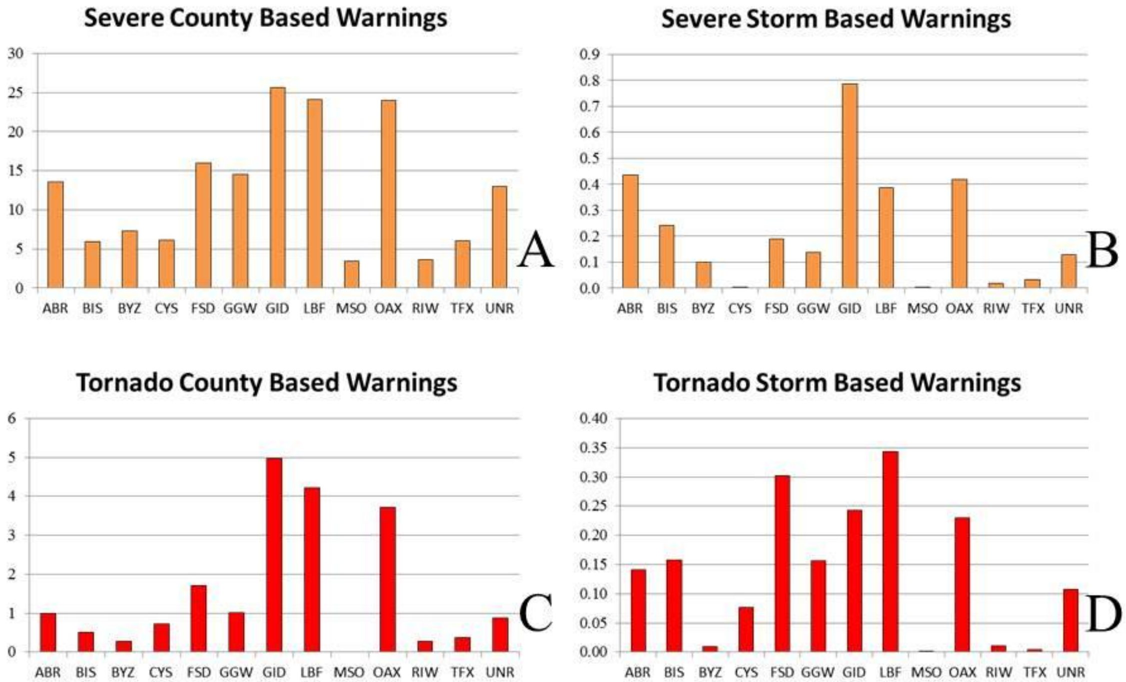


Figure 4.63. Area adjusted annual average warnings by National Weather Service Weather Forecast Office. Average severe county-based warnings (*A*), severe storm-based warnings (*B*), tornado county-based warnings (*C*), and tornado storm-based warnings (*D*) are depicted for the West North Central Climate Region.

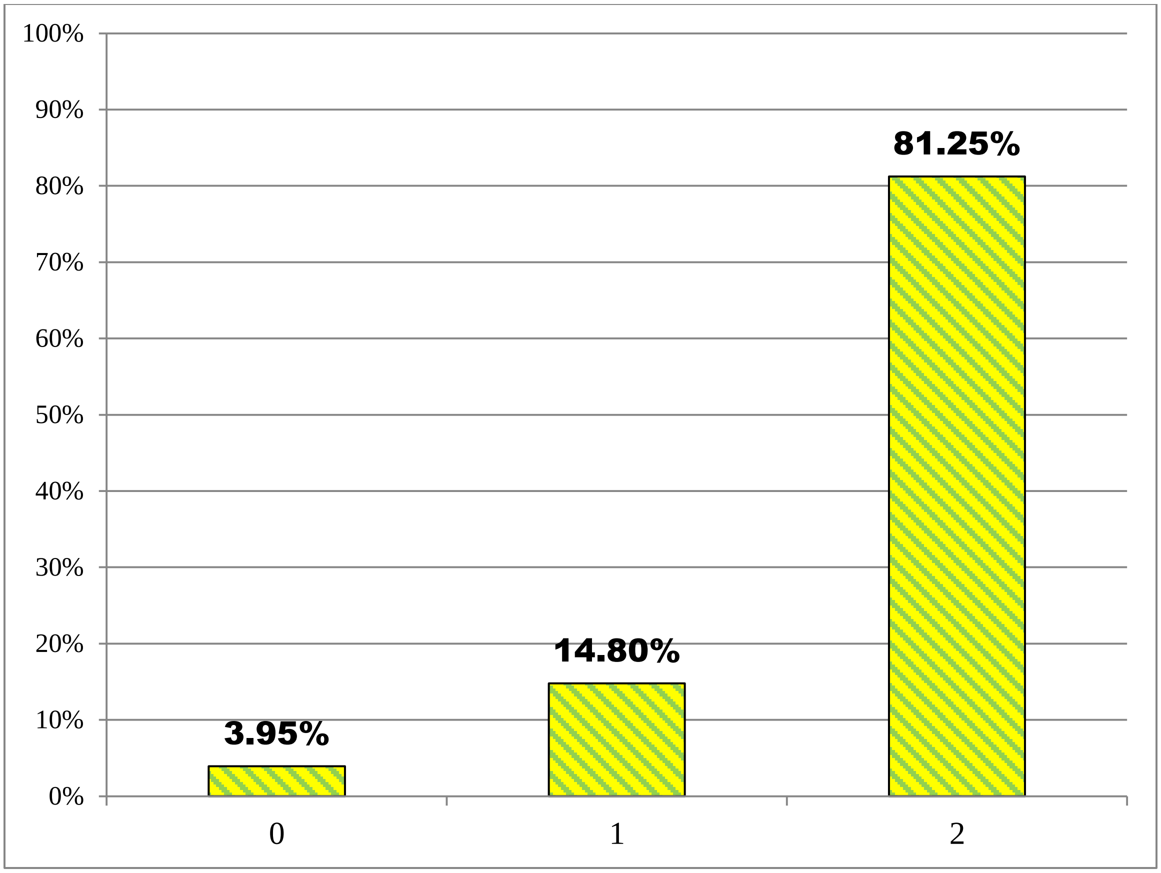


Figure 4.64. NEXRAD radar coverage for the West North Central Climate Region.

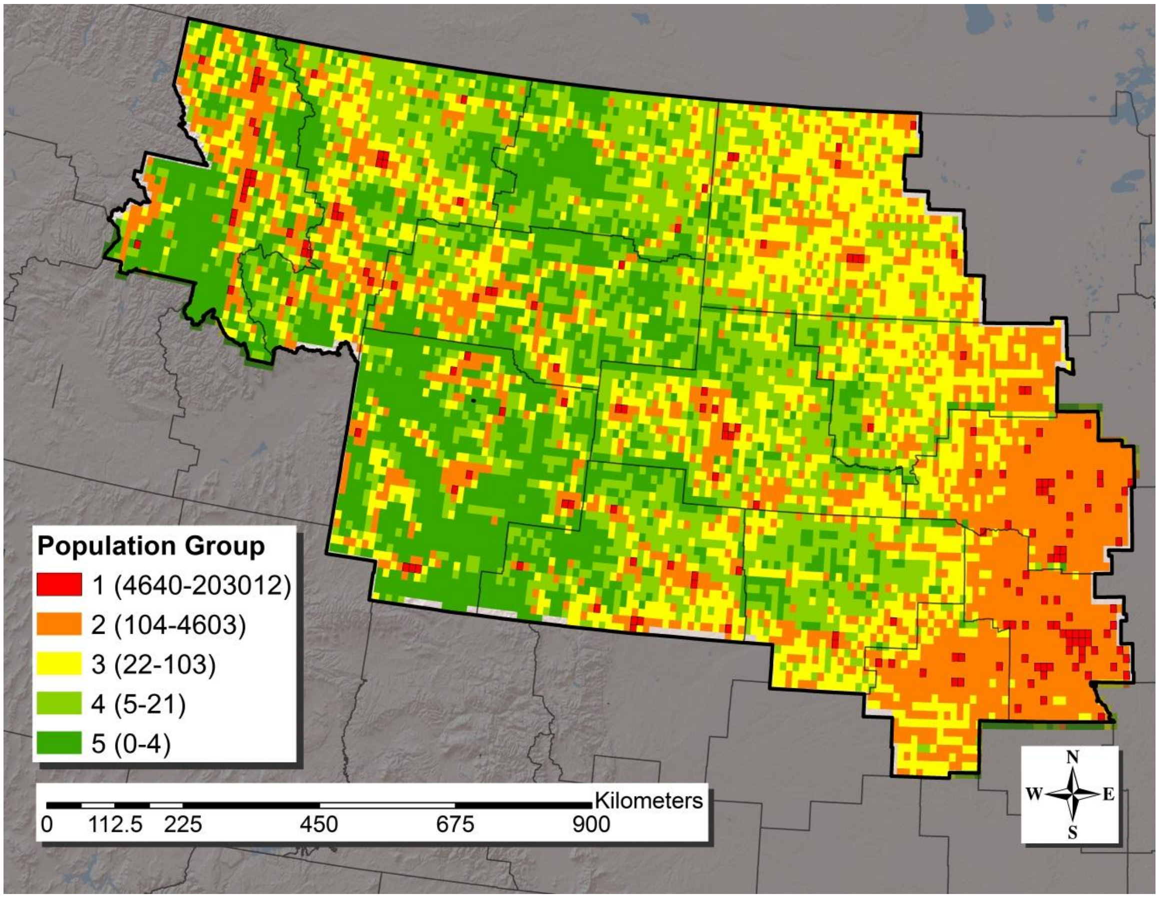


Figure 4.65. Population group distribution within the West North Central Climate Region.

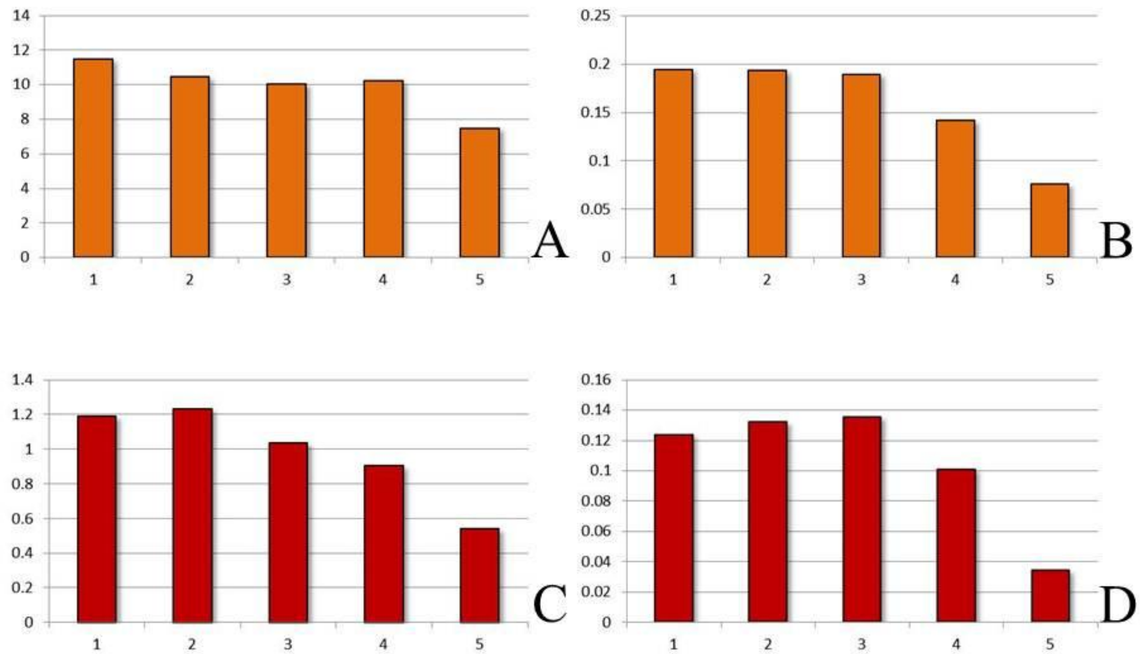


Figure 4.66. Results of the population group analysis for the four warning types. Average severe county-based warnings (A), severe storm-based warnings (B), tornado county-based warnings (C), and tornado storm-based warnings (D) are depicted for the West North Central Climate Region.

L. Summary

The results presented in this chapter show that the spatial distribution of warnings has shifted with the transition to storm-based warnings from the central part of the Nation to the southeastern United States. The annual frequency of county-based severe and tornado warnings was highest for the Central Plains. Severe storm-based warnings were issued for distinctly defined county warning areas, mainly in the south and southeastern United States. Tornado storm-based warnings were issued more frequently in the Deep South, southeast, and Gulf Coast areas.

The Southeast Climate Region has the highest overall population, whereas the Northeast Climate Region has the highest CWA population density. Table 4.43 shows that NEXRAD radar coverage is extensive in the most populated Climate Regions, but is lacking in lesser populated regions generally west of the Continental Divide. The greatest areal coverage of warnings (warning counts) occurred in the South Climate Region. The least number of warnings occurred in the West Climate Region.

Table 4.43. Summary of population counts, NEXRAD radar coverage, and warning counts for the Climate Regions. Regions are ordered by total population.

Region	Population	NEXRAD Coverage	SCBW	SSBW	TCBW	TSBW	Total warnings
SE	59,316,957	100%	49967	2420	7562	60	60009
NE	54,110,834	99%	15533	1185	698	45	17461
OV	53,885,870	99%	53287	1220	6518	184	61209
S	40,774,667	94%	86734	3317	12107	60	102218
W	37,436,579	79%	1423	27	99	2	1551
ENC	23,524,667	91%	23047	264	3067	61	26439
SW	16,667,320	73%	10415	309	1068	38	11830
NW	11,755,951	82%	2253	36	88	2	2379
WNC	5,036,480	81%	28355	309	3504	60	32228

The average direction from the geographic center of the CWAs to the center of the spatial distribution of all types of warnings is shown in Table 4.44. The predominant warning direction was south of the center of the CWAs. The WFOs in the Southwest and Northwest Climate Regions displayed a tendency to issue warnings in a more eastwardly direction. This table also shows the average area adjusted distance of warnings from the geographic center of the CWAs. The greatest distance from center occurs in the West Climate Region. Surprisingly, the Northeast Climate Region displayed the second greatest distance despite the much smaller size of the county warning areas in this region. The South Climate Region showed the greatest tendency for WFOs to issue warnings close to the geographic center of the CWAs.

Table 4.44. Climate Region and CONUS average azimuth direction and adjusted distance from the geographic center of CWAs to the center of warning distribution for all warnings.

Region	Direction	Adjusted Distance (km)
CONUS	185° South	8.58
SE	179° South	6.78
NE	198° South-Southwest	13.07
OV	189° South	5.95
S	170° South	4.72
W	198° South-Southwest	14.28
ENC	197° South-Southwest	9.98
SW	135° Southeast	7.11
NW	115° East-Southeast	9.48
WNC	179° South	5.79

Results of population analysis show that severe thunderstorm storm-based warnings were the most likely to be issued-based on population distribution. Subjective population group analysis indicates that six of the nine Climate Regions and the CONUS showed a tendency to issue more storm-based warnings for populated areas (Table 4.45). The population groups within the CONUS indicate that only severe county-based warnings were not issued-based on population. Results of statistical correlation tests with practical significance above 0.3 indicate that severe storm-based warnings were issued-based on population for the CONUS, Northeast Climate Region, and South Climate Region. When practical significance is dropped to 0.2, the CONUS displayed a tendency to issue warnings-based on population for both types of tornado warnings, supporting the results of the population group analysis.

Table 4.45. Summary of results from the population group and statistical analysis of warnings compared to population. Yes indicates that a relationship exists between population and warning issuance. Regions are ordered by total population. *PG = Population Group analysis. Stat = Statistical analysis. Results that show practical significance at a level > 0.3 are in **bold**. Results that show practical significance at a level > 0.2 are in *italic*.

Region	SCBW PG	SSBW PG	TCBW PG	TSBW PG	SCBW Stat	SSBW Stat	TCBW Stat	TSBW Stat
CONUS	No	Yes	Yes	Yes	No	**Yes**	*Yes*	*Yes*
SE	Yes	No	No	No	No	No	No	No
NE	No	Yes	No	Yes	No	**Yes**	No	No
OV	Yes	No	No	No	No	No	No	No
S	No	Yes	Yes	Yes	No	**Yes**	No	*Yes*
W	No	No	Yes	Yes	No	No	No	*Yes*
ENC	No	Yes	No	Yes	No	No	No	No
SW	Yes	Yes	No	Yes	No	No	No	No
NW	No	Yes	No	No	No	No	No	No
WNC	Yes	Yes	Yes	Yes	*Yes*	No	*Yes*	No

Through a variety of methods, this chapter has detailed the spatial relationships of short-fuse warnings and factors outside of actual storm genesis, strength and movement. The results presented here show the overall spatial pattern for both county and storm-based short-fuse severe weather warnings, and establish potential relationships to population density. Conclusions-based on these results are presented in Chapter V.

CHAPTER V

DISCUSSION AND CONCLUSIONS

A. Introduction

This chapter seeks to clarify the results presented in Chapter IV and answer the research questions posed in Chapter I.

B. NEXRAD Radar Coverage

Across the Contiguous United States, this study shows that radar coverage is not a significant factor in the overall issuance of warnings types, although average warnings were issued more frequently for areas with perfect radar coverage. NEXRAD coverage is compromised in the Northwest, Southwest, West, and West North Central Climate Regions. It should be noted that these are regions of the United States which received the fewest numbers of warnings. There is not significant statistical evidence to show that radar coverage is related to warning frequency and distribution in these regions. Based on the results from this study, NEXRAD coverage cannot account for the spatial distribution of short-fuse severe weather warnings. This statement is especially true for the part of the Contiguous United States east of the Continental Divide.

C. Research Question 1 – Warning Spatial Relationships to Population Density

The first research question in this study is related to the relationship between the spatial distribution of short-fuse warnings and population density. This question states:

Do short-fuse severe warnings show a spatial relationship to population density for the entire Contiguous United States (CONUS)?

Subjective population group analysis for the Contiguous United States shows that a spatial relationship to population exists for three warnings types: severe storm-based warnings, tornado county-based warnings and tornado storm-based warnings. Population bias evidence is most prevalent for severe storm-based warnings with six of the nine climate regions showing a “stair step” pattern. Five climate regions demonstrate population bias evidence for tornado storm-based warnings. Both types of county-based warnings only show evidence among three of the regions. Of the nine regions, the South Climate Region shows the strongest evidence for population bias for all warning types except severe county-based warnings. The West North Central Climate Region shows evidence of population bias for all warning types.

Based on Spearman’s Rho values, severe storm-based warnings show the greatest likelihood of being related to overall population distribution both annually and monthly. However; only two of the nine climate regions show an annual Rho value for this warning type which is above 0.3, the Northeast Climate Region at 0.396 (P-Value = <.001), and the South Climate Region at 0.329 (P-Value = <.001).

The spatial distribution of warnings has shifted from the central part of the Nation to the southeastern United States. The annual frequency of county-based severe and tornado warnings was highest for the Central Plains. Severe storm-based warnings were issued for distinctly defined county warning areas, mainly in the south and southeastern United States. Tornado storm-based warnings were issued more frequently in the Deep South, southeast, and Gulf Coast areas.

D. Research Question 2 – CWA Reporting Rates

The second question relates to the 116 individual National Weather Service Weather Forecast Offices and associated county warning areas. This question states:

Do NWS County Warning Areas have different warning rates-based on the location of the CWA and/or the ambient population of the CWA?

The influence of location is addressed by dividing the CWAs into nine distinct climate regions. To get an idea of the frequency of warnings for each climate region, it is useful to determine how each climate groups ranks by warning type. Table 5.1 shows the area adjusted warning rankings for the climate groups. The warning frequency between county and storm-based warnings for both severe and tornado warnings are remarkably similar for most Climate Regions, indicating an overall consistency for WFOs to issue proportionally similar numbers of warnings for both warning types. Warnings of all types were issued most frequently for the Southeast Climate Region. Warnings were least frequent in the Northwest and West climate regions. Only the Northeast Climate Region shows a ranking difference greater than one rank for severe thunderstorm warnings (from a fourth place rank for county-based warnings to a second place rank for storm-based warnings). The East North Central region increased to a sixth place rank for tornado storm-based warnings, whereas the Northeast Climate Region dropped to fourth place, with the remaining regions showing very little variation.

Table 5.1. Average annual warnings by climate region and associated ranks. The data have been normalized for climate region area.

Climate Region	SCBW	Rank	SSBW	Rank	TCBW	Rank	TSBW	Rank
ENC	15.07	5	0.27	5	2.02	4	0.13	6
NE	15.35	4	2.99	2	0.77	7	0.16	4
NW	2.23	9	0.05	8	0.07	9	0.00	8
OV	20.63	2	1.74	3	3.14	3	0.65	2
S	19.98	3	1.53	4	3.26	2	0.48	3
SE	23.45	1	3.12	1	5.42	1	0.91	1
SW	12.84	6	0.19	7	0.92	6	0.08	7
W	4.37	8	0.02	9	0.29	8	0.00	9
WNC	12.55	7	0.22	6	1.51	5	0.14	5

Overall top ten ranks for all 116 WFOs for all warning types are shown in Table 5.2. Seven of the ten are located in the Southeast Climate Region, including Huntsville (HUN), which ranks first among all WFOs. Nashville ranks second; the highest of all WFOs in the Ohio Valley Climate Region. The New Orleans/Baton Rouge WFO is the only South Climate Region WFO in the top ten, with most of its warnings issued as tornado storm-based.

Table 5.2. Top ten WFO ranks for average annual warnings by warning type. The data have been normalized for CWA area.

WFO	Climate Region	SCBW Rank	SSBW Rank	TCBW Rank	TSBW Rank	Rank All Warnings
HUN	SE	1	5	1	1	1
OHX	OV	5	2	8	3	2
MLB	SE	3	23	2	10	3
MHX	SE	20	7	11	2	4
MOB	SE	14	12	7	12	5
CHS	SE	11	17	9	13	6
MFL	SE	2	34	3	14	7
CAE	SE	22	1	30	4	8
LIX	S	33	13	13	8	9
JKL	OV	17	21	24	6	10

The Southeast Climate Region has four of the top ten WFOs for average severe county-based warnings, including the top three (Table 5.3). Three of the top ten are from the South Climate Region, including Brownsville (BRO). Nashville (OHX) ranks fifth, the highest of the two Ohio Valley Climate Region WFOs. New York (OKX), which is the most densely populated WFO of the 116, ranks seventh. Four of the top ten WFOs which issue the most severe storm-based warnings are from the Southeast Climate Region (Table 5.4). The Columbia (CAE) WFO issued a disproportionate average annual number of warnings, and ranks first among all WFOs. Nashville (OHX) is ranked second, and is the only WFO from the Ohio Valley Climate Region. Three of the top ten WFOs are from the Northeast Climate Region, including New York (OKX). The Huntsville WFO receives its lowest ranking for severe storm-based warnings. Of the WFOs that received the most warnings of all types, only three WFOs appear in the top ten for severe storm-based warnings; Huntsville, Nashville, and New York.

Table 5.3. Top ten WFO ranks for average annual severe county-based warnings. The data have been normalized for CWA area.

WFO	Climate Region	SCBW	Rank
HUN	SE	60.77	1
MFL	SE	49.29	2
MLB	SE	47.90	3
BRO	S	41.15	4
OHX	OV	40.68	5
TOP	S	37.72	6
OKX	NE	33.76	7
ILM	SE	33.50	8
GLD	S	31.44	9
LOT	OV	31.10	10

Table 5.4. Top ten WFO ranks for average annual severe storm-based warnings. The data have been normalized for CWA area.

WFO	Region	SSBW	Rank
CAE	SE	17.50	1
OHX	OV	7.82	2
PHI	NE	6.81	3
CTP	NE	6.48	4
HUN	SE	5.82	5
LZK	S	5.04	6
MHX	SE	4.95	7
SHV	S	4.45	8
OKX	NE	4.29	9
TAE	SE	4.02	10

For both types of tornado warnings, only three of the nine climate regions have WFOs which rank in the top ten; the Southeast, South, and Ohio Valley. Six of the top ten tornado county-based warning issuers are from the Southeast Climate Region, including the top three (Table 5.5). The Houston WFO (HGX) ranks in the top ten for this warning type. Two Ohio Valley Climate Region WFOs are in the top ten, including

Nashville (OHX). The Southeast Climate Region has the most WFOs representatives in the tornado storm-based rankings, including Hunstville (HUN) once again in first place (Table 5.6). Nashville (OHX) moves up four spots to third, and is the highest ranked Ohio Valley WFO. Only three WFO appear in both the county and storm-based rankings; Huntsville, Nashville, and Melbourne (MLB).

Table 5.5. Top ten WFO ranks for average annual tornado county-based warnings. The data have been normalized for CWA area.

WFO	Region	TCBW	Rank
HUN	SE	15.07	1
MLB	SE	13.33	2
MFL	SE	13.30	3
BRO	S	8.59	4
HGX	S	8.55	5
TBW	SE	7.41	6
MOB	SE	7.06	7
OHX	OV	6.98	8
CHS	SE	6.91	9
LOT	OV	6.80	10

Table 5.6. Top ten WFO ranks for average annual tornado storm-based warnings. The data have been normalized for CWA area.

WFO	Region	TSBW	Rank
HUN	SE	3.24	1
MHX	SE	2.29	2
OHX	OV	2.18	3
CAE	SE	1.60	4
BMX	SE	1.50	5
JKL	OV	1.46	6
SGF	OV	1.43	7
LIX	S	1.35	8
LCH	S	1.35	9
MLB	SE	1.27	10

National Weather Service Weather Forecast Offices that demonstrate likely warning and population correlations are shown in Table 5.7. The Houston (HGX) WFO shows strong correlation with both types of county-based warnings. The Fort Worth (FWD) WFO also shows a significant correlation to severe county-based warnings. The population of the Nashville (OHX) WFO is correlated with both types of severe warnings. Los Angeles (LOX) shows correlation to both types of county-based warnings. The San Diego (SGX) WFO demonstrates a correlation to tornado storm-based warnings, although this calculation is-based on a very small sample size.

Table 5.7. WFO population correlation values above 0.300. All tests results have a P-Value <.001 ($\alpha = 0.001$).

WFO	Region	SCBW	SSBW	TCBW	TSBW
CTP	NE	--	0.411	--	--
CLE	OV	0.306	--	--	--
OHX	OV	0.431	0.408	--	--
FWD	S	0.455	--	--	--
HGX	S	0.560	0.337	0.614	--
FFC	SE	0.410	--	--	--
GSP	SE	0.304	--	--	--
TBW	SE	--	0.317	--	--
PSR	SW	--	0.405	--	--
LOX	W	0.374	--	0.458	--
SGX	W	--	--	--	0.569

Based on these results, it can be concluded that Weather Forecast Offices do have different warning rates-based on the location of the CWA and/or the ambient population of the CWA. Warnings are most likely to be issued by WFOs in the Southeast Climate Region. The WFO with the highest warning frequency (Hunstville) shows no strong statistical relation to warning rate and ambient population, but this result may be because of the CWAs small area size and the normalization method. The Nashville WFO likely issues severe thunderstorm warnings-based on population distribution and ranks in the top ten for all warning types for WFO warning frequency. Houston shows the strongest evidence for population and warning correlation across warning types. Houston ranks in the top ten for tornado storm-based warnings issued and has the most significant population correlation result for this type of warning. Although it is located in an area of the United States which climatologically receives less severe weather, the densely populated New York WFO is in the top ten for both types of severe thunderstorm warnings.

Additional evidence for variations in warning frequency by WFO is found by comparing WFOs which have high warning rates to their neighboring CWAs. There should be no reason meteorologically that CWAs in the same general regions have drastic variations in severe weather. Table 5.8 compares the Hunstville WFO to immediately surrounding county warning areas. The Nashville WFO, which boarders Huntsville to the immediate north, is the only neighboring office which issued warnings at a similar rate to Huntsville.

Table 5.8. Annual average warning ranking for Huntsville (HUN) and bordering WFOs.

WFO	SCBW	SSBW	TCBW	TSBW
HUN	1	5	1	1
MEG	71	27	35	26
BMX	62	36	18	5
FFC	87	20	77	19
MRX	15	22	44	11
OHX	5	2	8	3

E. Research Question 3 – Directional Distribution of Short-Fuse Warnings

The third research question deals with the directional distribution and distance of warning issuance-based on the geographic center of the County Warning Areas and the location of individual Weather Forecast Offices within each County Warning Area. This question states:

What is the difference in the number of warnings "up range" and "downrange" of densely populated urban areas and the associated WFO (high priority targets)? In other words, is there a directional emphasis on warning issuance?

It was expected that warning direction would mimic the general direction of storm movement. This hypothesis is-based on the fact that in the climate regions that received the most severe weather, general storm movement is from west to east. This means that the "up range" zone for warning distribution would be to the west for the majority of the CWAs in the Ohio Valley, South, and Southeast climate regions. Directional distribution for the entire CONUS was expected to show a general pattern that favors the issuance of storms to the west, but the average would be affected by normal severe weather movement for each region and CWA.

Average direction of the center of warning distribution for the entire CONUS occurred generally south of the geographic centers of county warning areas, but this direction varies by climate region. Table 5.9 shows the directional distribution for each warning type as they relate to the geographic center of the CWAs. The average direction for all warning types is generally south for the three regions that exhibit the highest warning frequencies. The Northwest and Southwest climate regions show a tendency for warnings to be issued in a general southeasterly direction.

Table 5.9. Climate group average azimuth direction in degrees as measured from the geographic center of CWAs to the mean center of warning distribution.

Climate Region	SCBW	SSBW	TCBW	TSBW	Average
ENC	205	204	204	167	195
NE	197	218	211	166	198
NW	145	69	108	138	115
OV	205	200	163	188	189
S	210	181	163	127	170
SE	188	203	183	144	179
SW	153	159	89	138	135
W	214	239	197	197	212
WNC	168	177	188	182	179

This study found that certain WFOs issued more warnings that favored the "up range" areas of their CWAs. Table 5.10 shows the directional distribution for these CWAs. The average direction for all warning types for these CWAs is to the west-southwest. With the exceptions of Raleigh (RAH), Wakefield (AKQ) and Wilmington (ILN), all WFOs in Table 5.10 show a consistent tendency to issue warnings in a general westerly direction from the mean geographic center. Tornado storm-based warnings show the most variation in direction. The Huntsville (HUN) WFO did not show an inclination to issue warnings in a particular direction, despite being the WFO with the highest warning frequency. Likewise, the Houston (HGX) WFO which showed the greatest probability of having a population bias did not exhibit a consistent directional distribution.

Table 5.10. Significant WFO average azimuth direction in degrees as measured from the geographic center of the CWAs to the mean center of warning distribution.

WFO	Climate Region	SCBW Dir	SSBW Dir	TCBW Dir	TSBW Dir	Average
OUN	S	263	269	296	334	291
ICT	S	215	203	218	212	212
MRX	OV	232	236	261	225	239
LMK	OV	239	195	288	196	229
IND	OV	266	245	275	270	264
ILN	OV	265	237	163	173	210
OHX	OV	308	312	276	297	298
BMX	SE	293	353	264	260	292
AKQ	SE	229	223	231	175	214
MHX	SE	252	237	233	256	244
RAH	SE	326	289	328	96	260

Distance results indicate that warning distance from the geographic centers of the CWAs and locations of the WFOs varies significantly between WFOs. This is most likely because of the variation in areal size of the CWAs, despite attempts to normalize for geographic area. On notable result is a tendency for storm-based warnings to be issued at a further distance from the center of the CWAs when compared to county-based warnings. This may be because of the relatively short temporal sample period for storm-based warnings compared to county-based warnings.

F. WFO Outliers

It is useful to analyze what is documented about the warning performance of several of the WFOs which showed a high warning frequency and/or population bias. -based on the results of this dissertation, the Nashville, Huntsville, Houston, and Columbia weather forecast offices were shown to be outliers. Investigation of publically available NOAA/NWS publications and WFO websites provides an insight into the severe weather culture of the Nashville and Huntsville WFOs. Information about warning performance for the Houston and Columbia WFOs is lacking or unavailable.

The Nashville (OHX) WFO had a very high warning frequency and showed a tendency to issue more warnings for populated areas. It is interesting to note that this office has received numerous awards from the United States Department of Commerce (DOC) for excellence in service related to severe weather events (NWS OHX 2010). These awards included three Bronze Medal Awards for tornado outbreaks. The WFO received an award in 1998 for “providing timely and accurate severe weather warning services during the April 16, 1998 tornado outbreak in middle Tennessee.” Another award was conferred in 2007 for “exceeding tornado lead times and providing life-saving warning services during the April 7, 2006 tornado outbreak in Middle Tennessee.” An award was given to the WFO in 2010 for a storm-based polygon warning event where the office provided “proactive and life-saving service.” It is interesting to note that publically available internal National Weather Service assessments of warning performance for the office do not document cases of excessive over-warning.

The Nashville office has also been critically scrutinized by NOAA however. In a NOAA Service Assessment (an internal government report-based on investigations of WFO performance during severe weather events), it was found that the Nashville WFO was lacking in communication and thus coordination with immediately surrounding WFOs during a major tornado outbreak (NOAA 2009). This report implies that the Nashville WFO was “going it alone,” and working in isolation despite the regional spatial scale of the severe weather event. In another Service Assessment related to a major flood event in the Nashville area, it was found that the numerous warnings issued by the WFO were confusing and lead to warning fatigue by the general public (NOAA 2011).

The Huntsville (HUN) WFO issued the most warnings of types except for severe storm-based warnings. This WFO has also received numerous Department of Commerce and professional weather association awards, not only for the WFO as a whole, but also for individual office staff members (NWS HUN 2012). This office demonstrates a rich history of outstanding performance among National Weather Service WFOs, with Department of Commerce Awards dating back to 1974. This office has received six DOC Bronze Medal Awards, and one Silver Medal, as well as two Operational Achievement Awards presented by the National Weather Association. Seven of these WFO recognitions were given during the time period of study for this dissertation. Seven Isaac Cline Awards (given for operational excellence) were awarded to individual staff members. The NOAA administrator award was conferred to the Huntsville Meteorologist in Charge in 2006 for “the successful Polygon Warning Initiative, which demonstrated the value of targeting the most specific area possible to receive severe weather warnings, thereby reducing the number of false alarms to the public.” It should be noted that this WFO issued these storm-based warnings to test the polygon warning system before it went operational nationally and official warnings issued by the office during this time period were county-based (DOC 2007). -based on the numerous awards and lack of evidence for over-warning in publically released NOAA/NWS documents, it is apparent that this office was viewed as being an exceptional performer by the National Weather Service.

The Houston (HGX) WFO displayed the greatest tendency to issue more warnings for populated areas. The severe weather climatology of the Houston area and southeast Texas is heavily influenced by tropical weather systems (Bomar 1994). Many of the warnings (including county-based tornado warnings) were issued during tropical weather events such as tropical storms or hurricanes. The matching of specific warnings to associated storm events is beyond the scope of this dissertation, but future research that breaks down the warnings by type of severe weather event would be useful in interpreting this office's tendency to issue warnings for urban areas.

The Columbia (CAE) WFO demonstrated a disproportionate tendency to issue storm-based severe thunderstorm warnings. Documentation does not exist that indicates that this office has a propensity to over-warn. An investigation of office culture and warning procedures for this WFO may shed light on the high warning frequency.

G. Further Studies

This dissertation did not attempt to define the false alarm rate or predisposition of WFO to over-warn. Future research should attempt to spatially associate actual severe weather events with warning issuance for individual WFOs. Although the National Weather Service keeps track of over-warned and missed events as well as false alarms, methods used in this dissertation can be applied to provide a better overall spatial representation of these measures. It should be noted, however, that previous studies have found that severe weather reports from the National Climatic Data Center serve as poor characterizations of actual storm events and associated damage (Trapp et al. 2006). In addition, the Storm Event Database is used by NWS Weather Forecast Offices to verify warnings (Waters 2007). Because this analysis focuses on spatial distributions related to locations of Weather Forecast Offices, the database provides the opportunity to study the possibility that certain offices actively seek to provide reports to validate warnings.

This study shows that warning frequency and distribution varies drastically by County Warning Area. Results from this dissertation point to human factors in the warning system being the root cause for these discrepancies. This conclusion is supported by a study conducted by the National Weather Service Warning Decision Training Branch (Morris and Quoetone 2011). In this study National Weather Service personnel were asked to perform root cause analysis (RCA) for historical severe weather events which affected their WFOs. Results found that, overwhelmingly (65% for hail events, 61% tornado for events, 60% severe for wind events) human factors were responsible for missed tornado and severe thunderstorm warnings. Of the human factors, communication failures and interpretation of spotter reports were the greatest contributing factors. This study implies that not only is the working environment within the WFO vitally important to the warning process but also the relationship the office has with local storm spotters, emergency managers, and broadcast media outlets.

In his book Authors of the Storm: Meteorologist and the Culture of Prediction, Gary Alan Fine spent time interviewing and observing the staff and operations of several WFOs (Fine 2007). From his observations, Fine found that forecast and warnings are heavily influenced by social factors as well as the culture of the local office. Fine’s book supports the theory that human influence is the main factor that contributes to warning frequency and spatial distribution. These findings may help to explain the warning frequencies and distributions found in this dissertation.

1. Future Research Questions

Based on the findings of this dissertation and supporting studies, future research should focus on the following:

a. ***<u>External Human Factors</u>***

Is there a correlation of the strength of the local spotter network/weather savvy community to warning frequency and distribution?

Does local broadcast media (especially television) severe weather coverage and marketing strategies have an influence on the warning decision making process of severe weather forecasters at WFOs?

How does the strength of the involvement of local emergency management factor into the warning process for local WFOs?

b. ***<u>Internal Human Factors</u>***

How does the culture within WFOs differ from office to office and what effect does it have on the warning system?

What distractions do forecasters deal with during severe weather events and to what extent do the distractions affect the warning process?

What is the experience level of forecasters and management at the various WFOs and how does this experience correlate to warning frequency and distribution?

How does workload and fatigue affect the warning forecasters and to what extent is it an issue at the various WFOs?

How much do individual forecasters know about the geographic intricacies of their CWAs and to what extent does this knowledge affect their warning decisions?

How much severe weather training do forecasters receive at the various WFOs and does this training take into account radar use distractions, knowledge of the CWA, and fatigue?

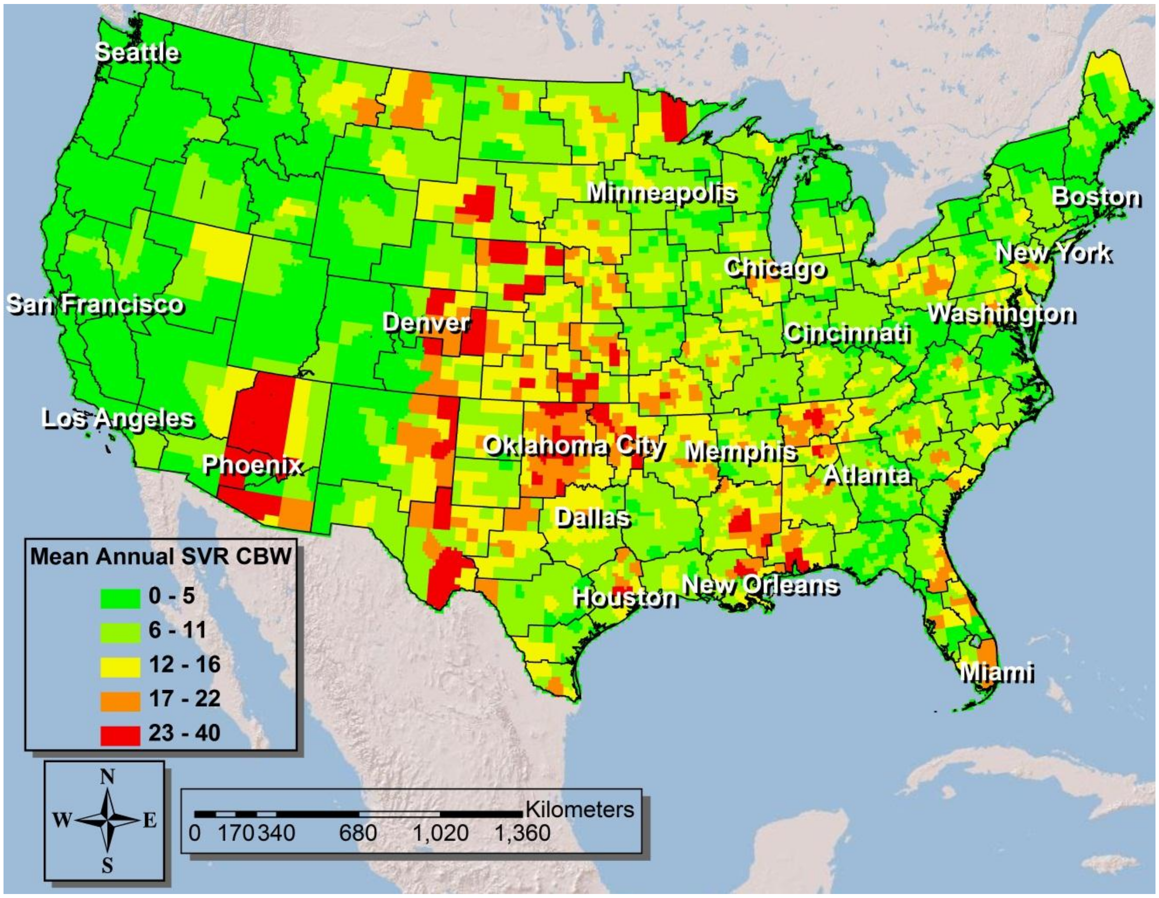
These research questions and the possibility of investigating the influence of topography, urbanization, and land cover using the spatial joining techniques developed for this dissertation provide ample opportunity for future studies. It is expected that results from this dissertation and possible future studies will be of great help in the strengthening of the National Weather Service short-fuse warning system.

H. Conclusion

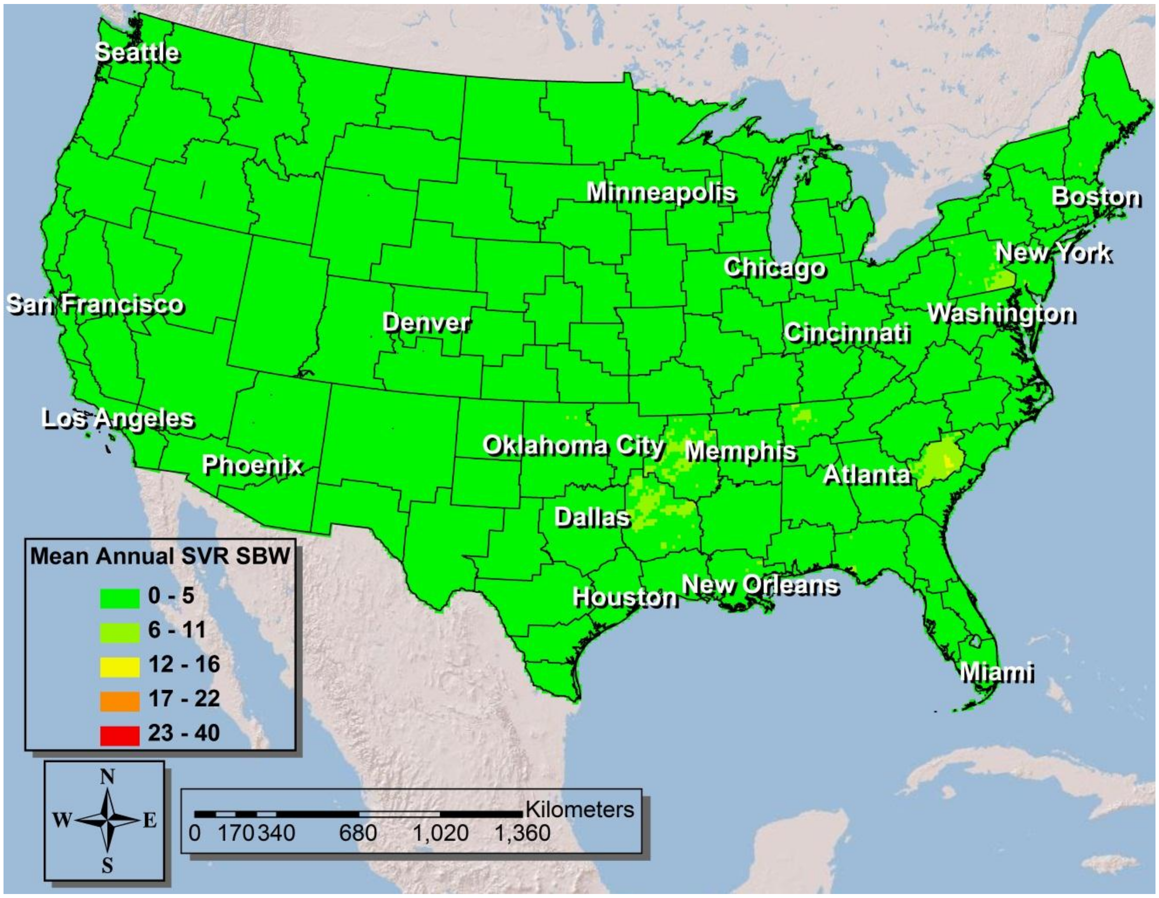
This study has shown that short-fuse severe weather warnings are not issued on an "even playing field." Warning frequency varies by National Weather Service County Warning Area and is sometimes driven by population density. National Weather Service Weather Forecast Offices strive to protect life and property, and in seeking this goal some offices tend to give more warning to urban and populated areas. This in itself may not be negative. It is expected that the staff of the individual WFOs know their community needs and have an understanding of the locations of "high priority" targets in their area. The challenge comes in leveling the playing field, and providing consistent warnings for regions with similar severe weather climatology. Results from this dissertation can help the National Weather Service identify undesirable differences in warning performance between WFOs, and thus help improve the short-fuse warning system and possibly weather forecast products in general.

APPENDIX A

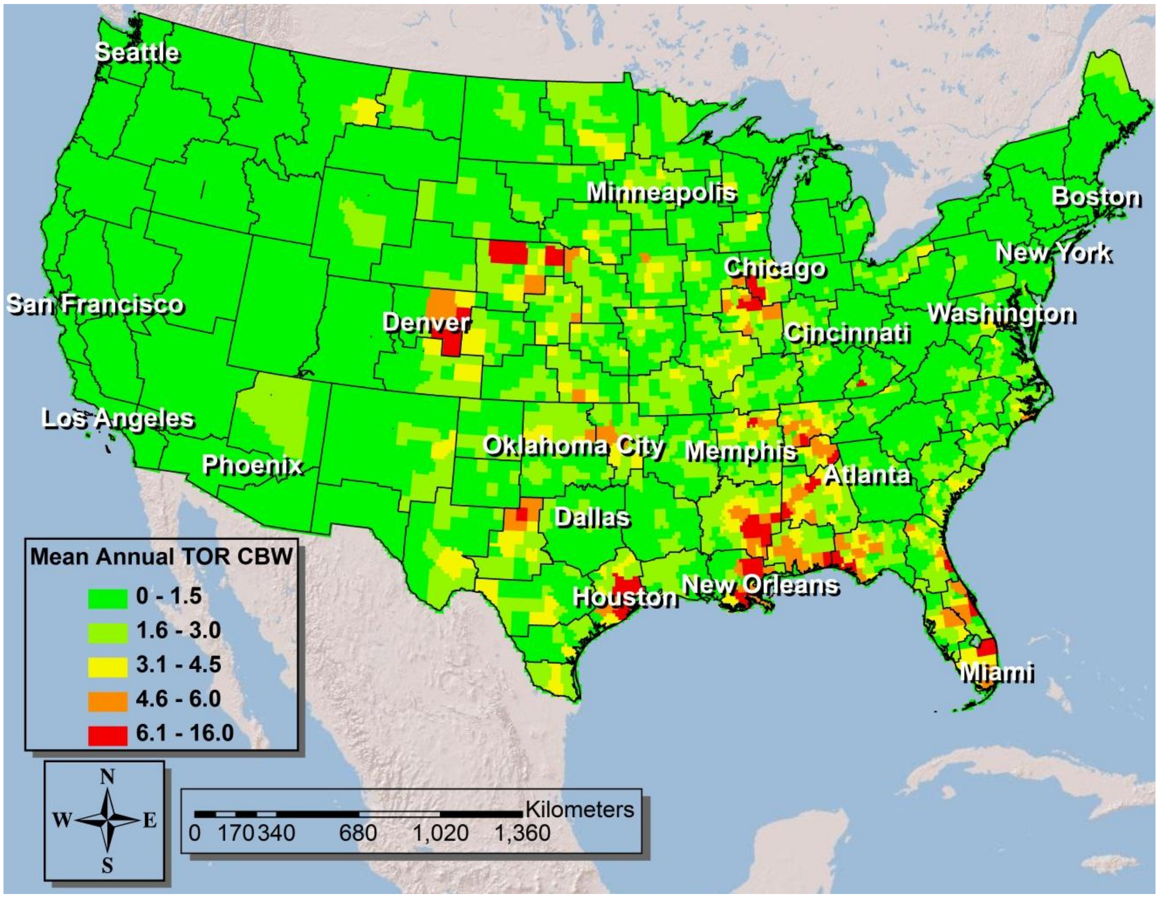
WARNING DISTRIBUTION MAPS FOR THE CONTIGUOUS UNITED STATES



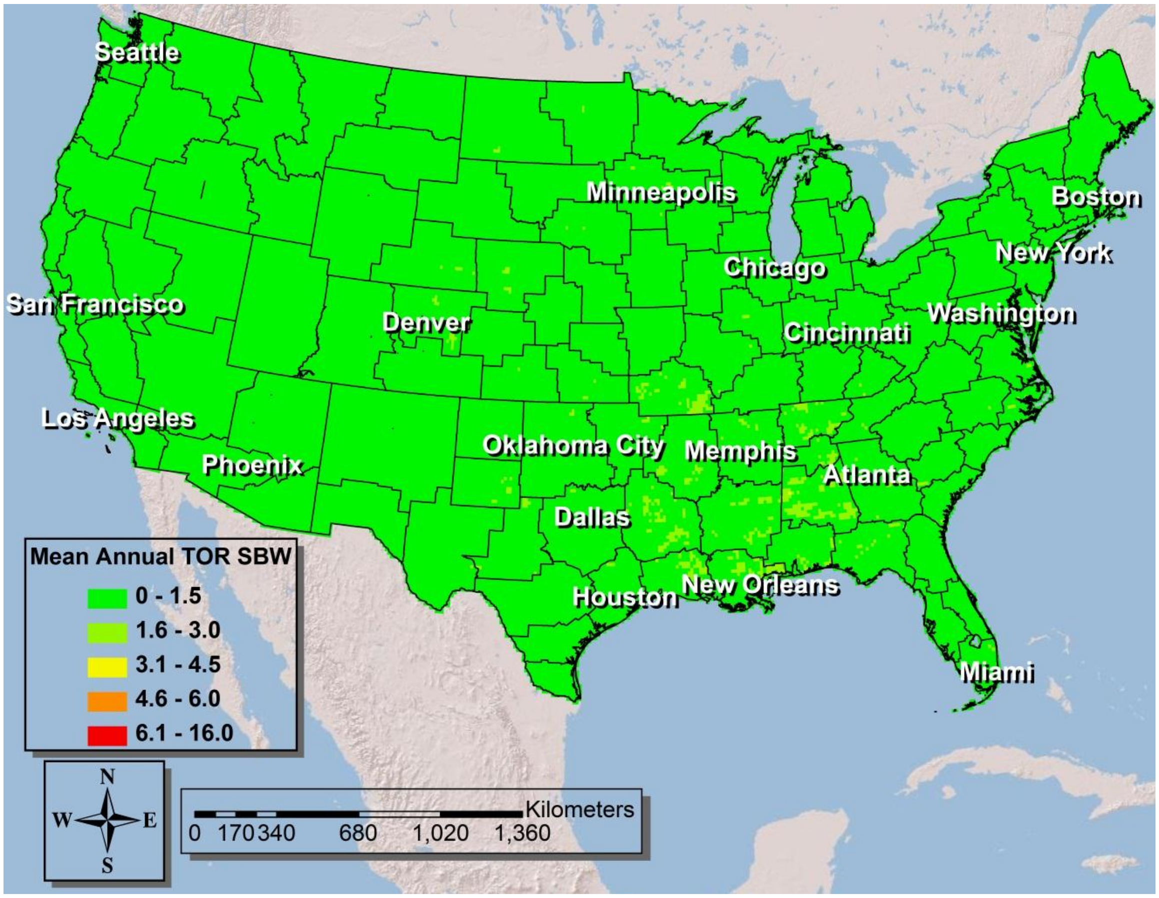
Mean annual severe thunderstorm county-based warnings-based on the United States Geological Survey's (USGS) 7.5 minute, 1:24,000 (1:25,000 metric) Quadrangle Series. The time period represented by these data is from 1996 to 2006.



Mean annual severe thunderstorm storm-based warnings-based on the United States Geological Survey's (USGS) 7.5 minute, 1:24,000 (1:25,000 metric) Quadrangle Series. The time period represented by these data is from 2007 to 2010.



Mean annual tornado county-based warnings-based on the United States Geological Survey's (USGS) 7.5 minute, 1:24,000 (1:25,000 metric) Quadrangle Series. The time period represented by these data is from 1996 to 2006.

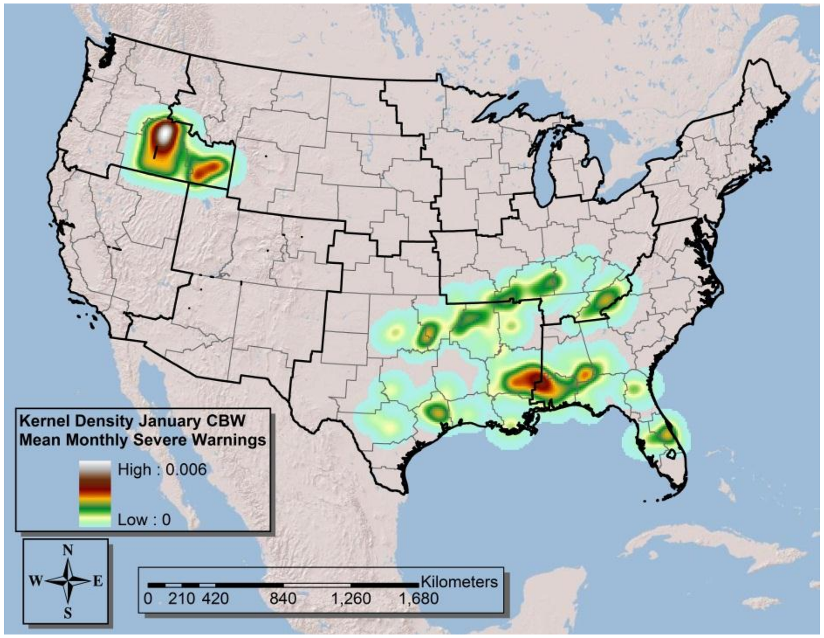


Mean annual tornado storm-based warnings-based on the United States Geological Survey's (USGS) 7.5 minute, 1:24,000 (1:25,000 metric) Quadrangle Series. The time period represented by these data is from 2007 to 2010.

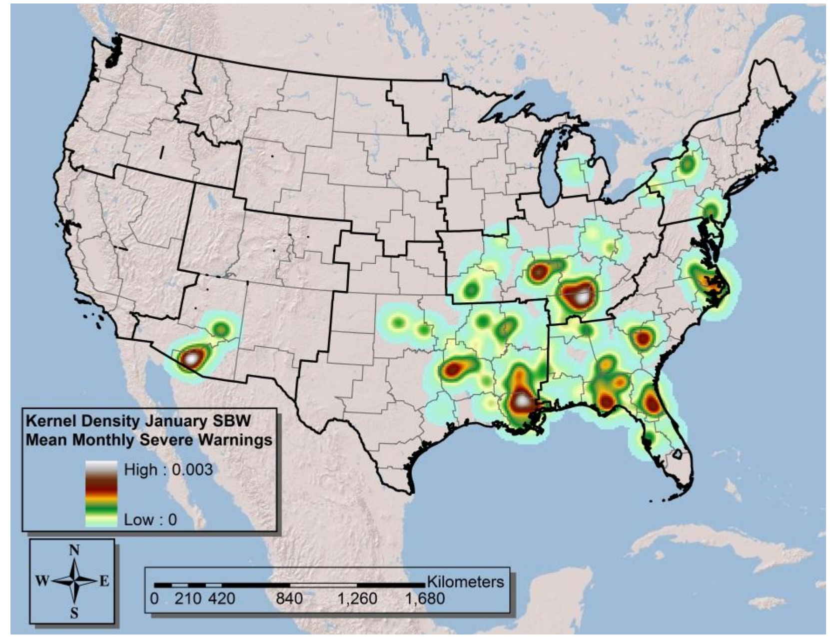
APPENDIX B

KERNEL DENSITY MAPS DEPICTING MONTHLY AVERAGES OF

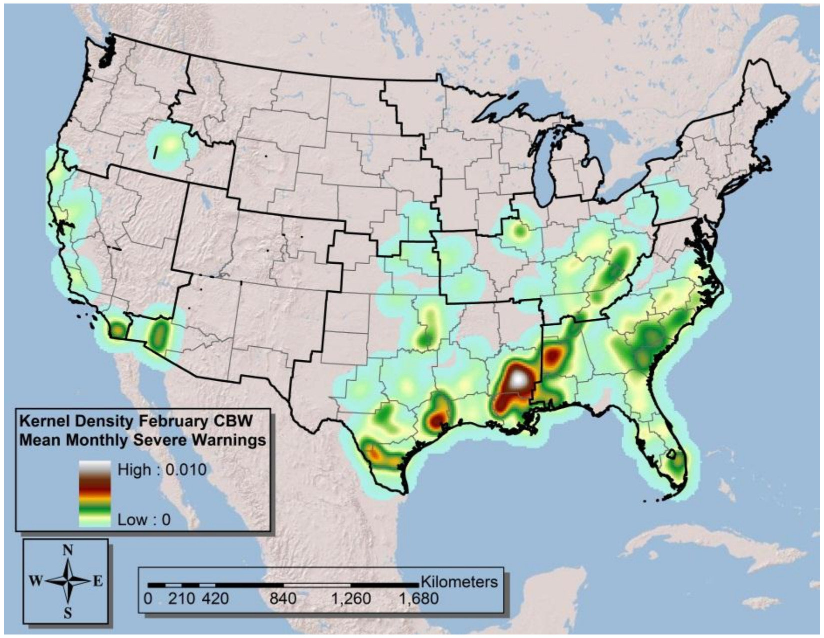
WARNINGS FOR THE CONTIGUOUS UNITED STATES



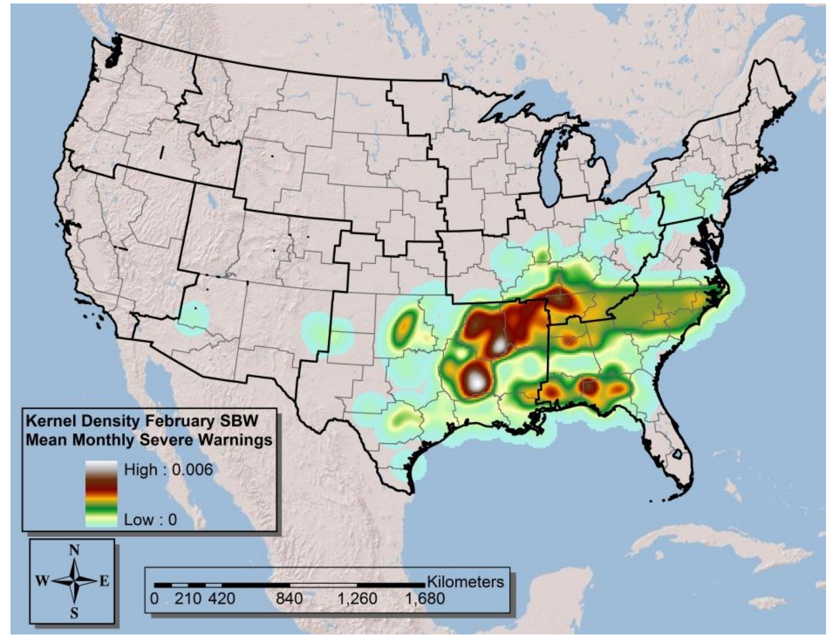
Kernel density analysis for severe thunderstorm county-based warnings for the month of January.



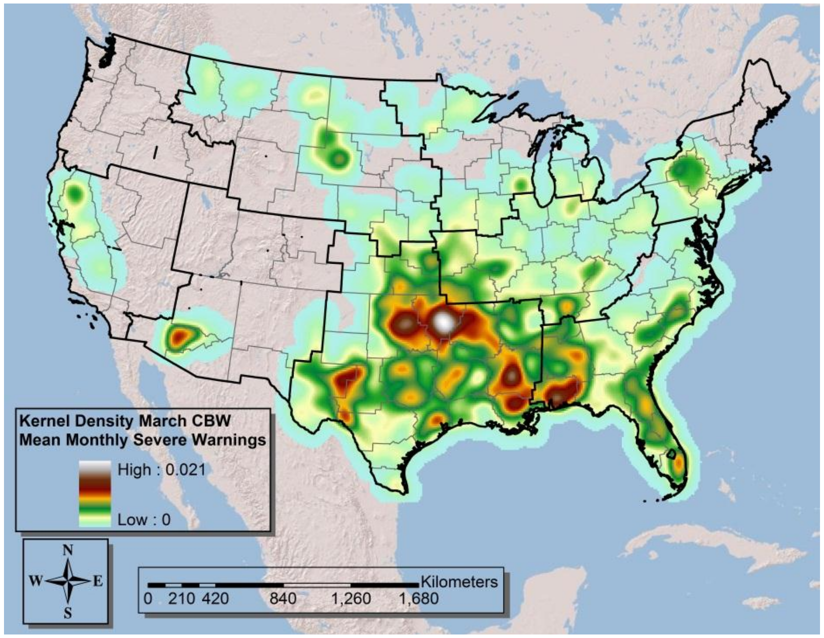
Kernel density analysis for severe thunderstorm storm-based warnings for the month of January.



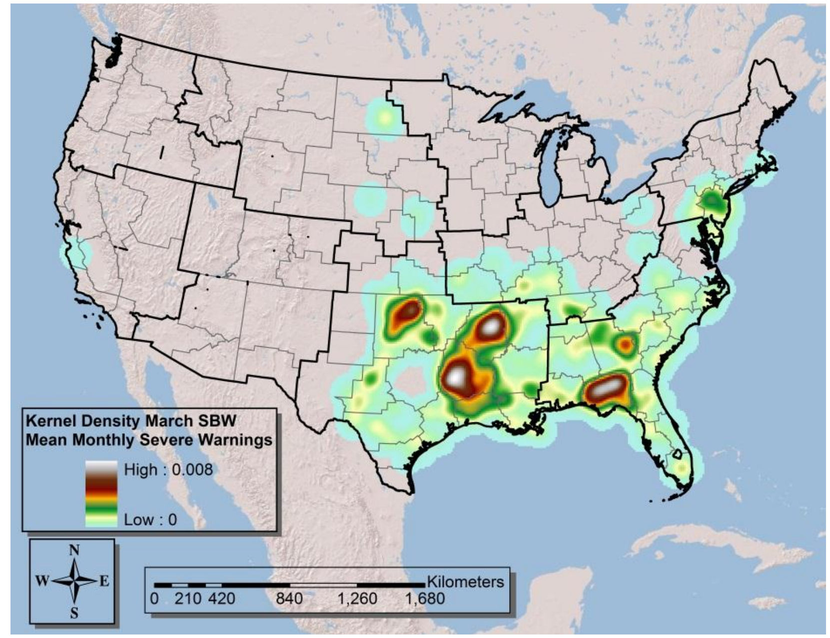
Kernel density analysis for severe thunderstorm county-based warnings for the month of February.



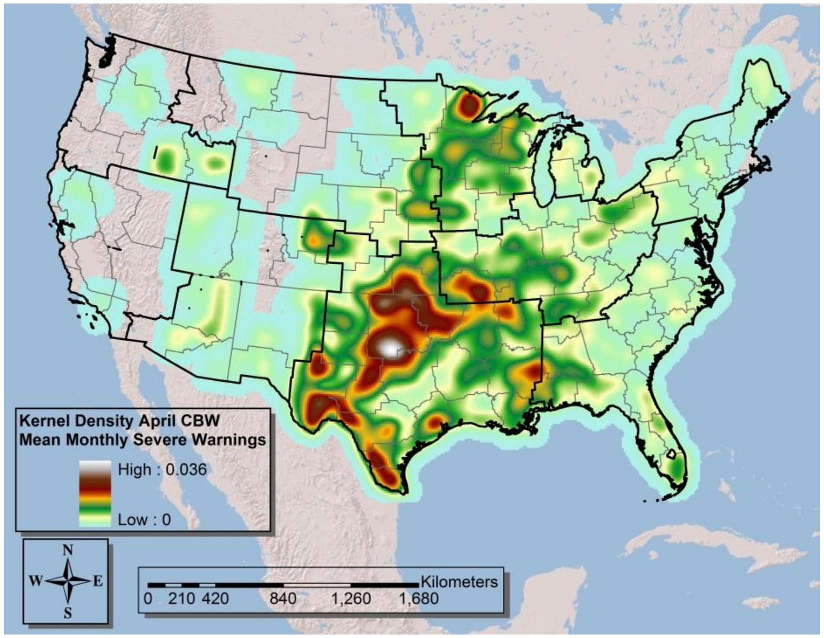
Kernel density analysis for severe thunderstorm storm-based warnings for the month of February



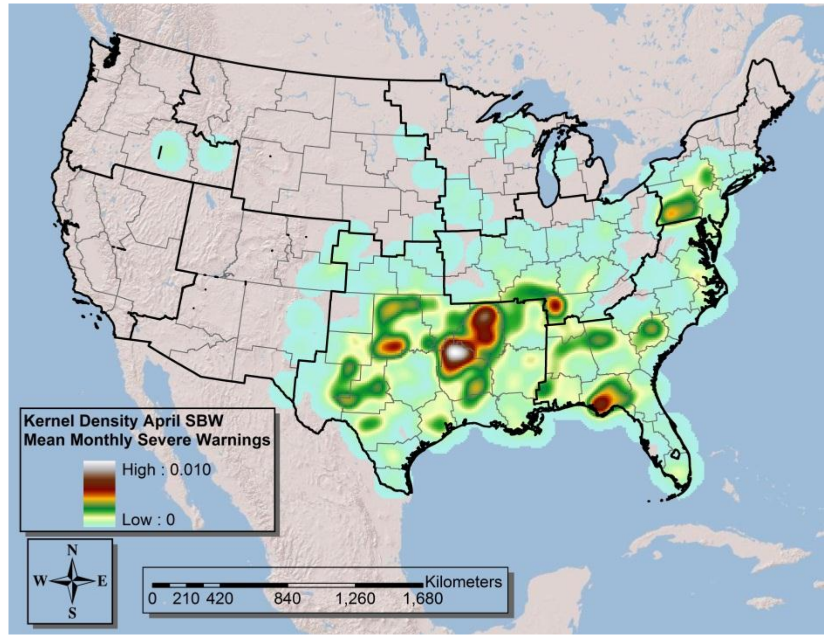
Kernel density analysis for severe thunderstorm county-based warnings for the month of March.



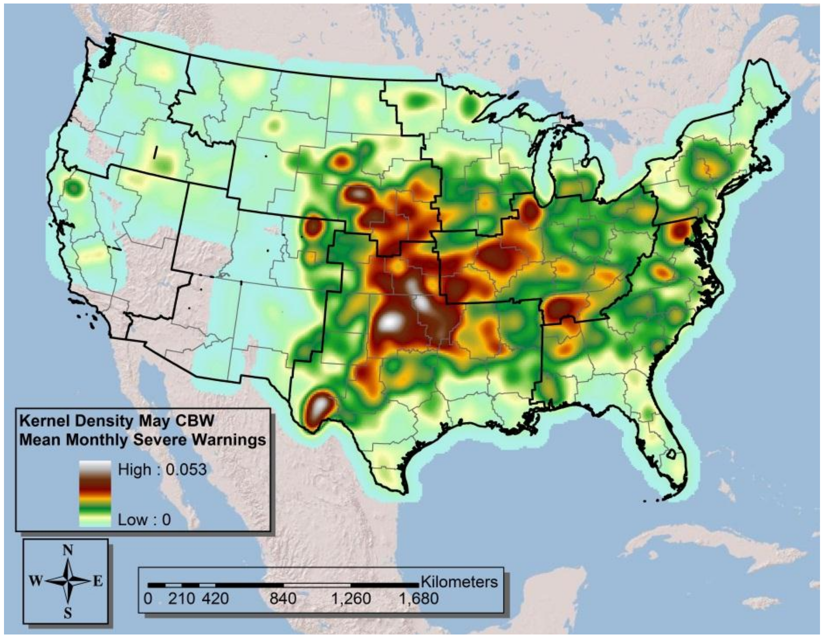
Kernel density analysis for severe thunderstorm storm-based warnings for the month of March.



Kernel density analysis for severe thunderstorm county-based warnings for the month of April.



Kernel density analysis for severe thunderstorm storm-based warnings for the month of April.



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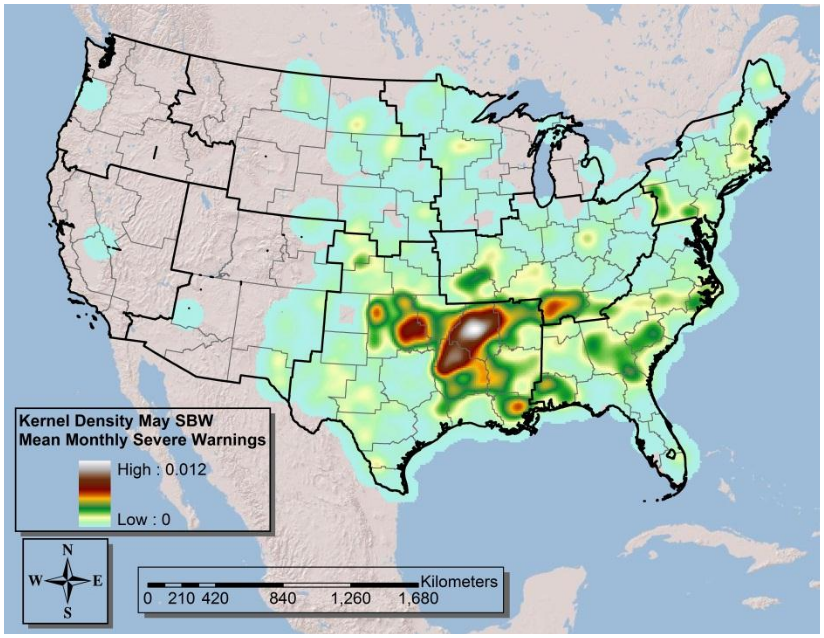

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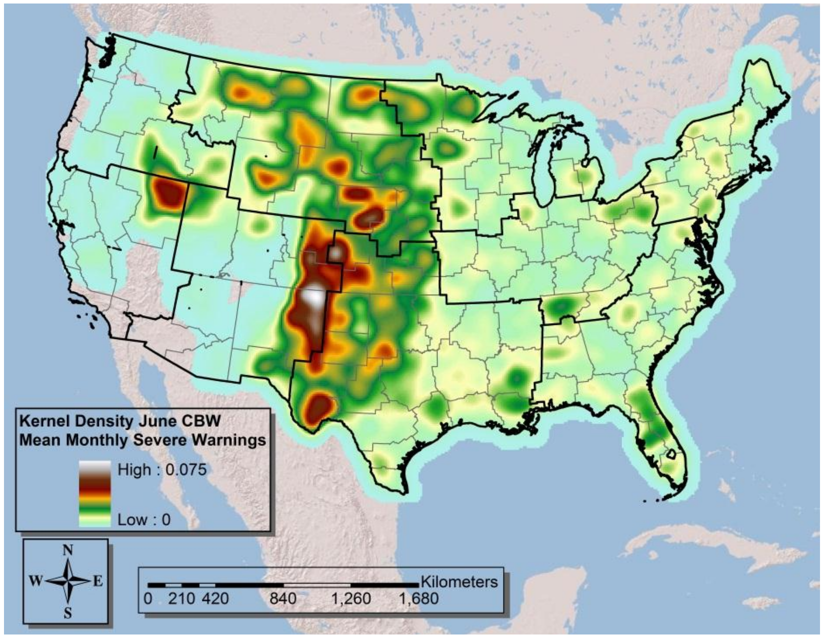

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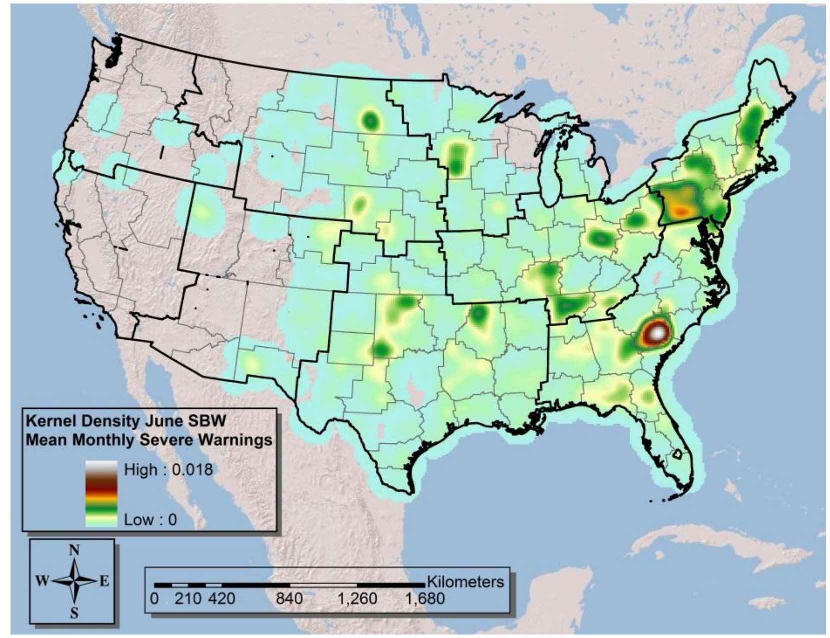

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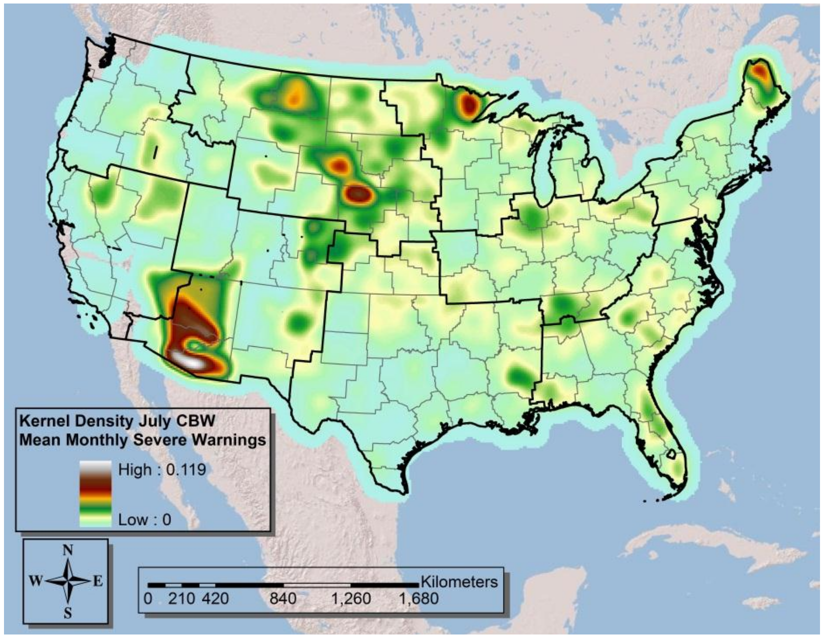

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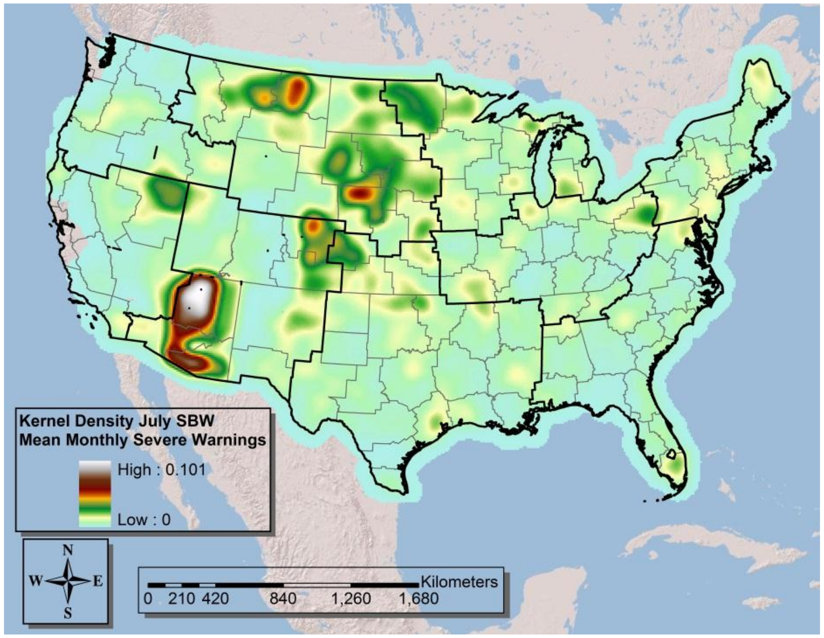

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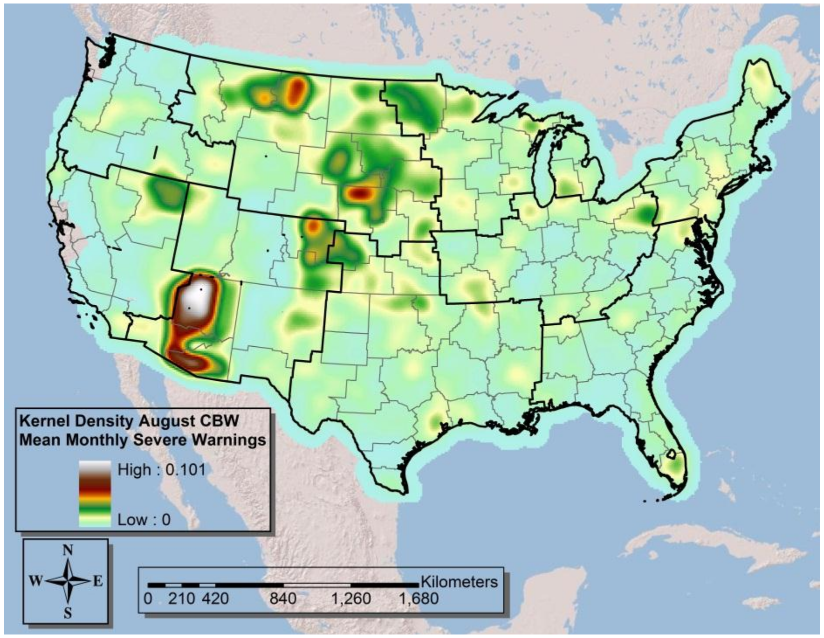

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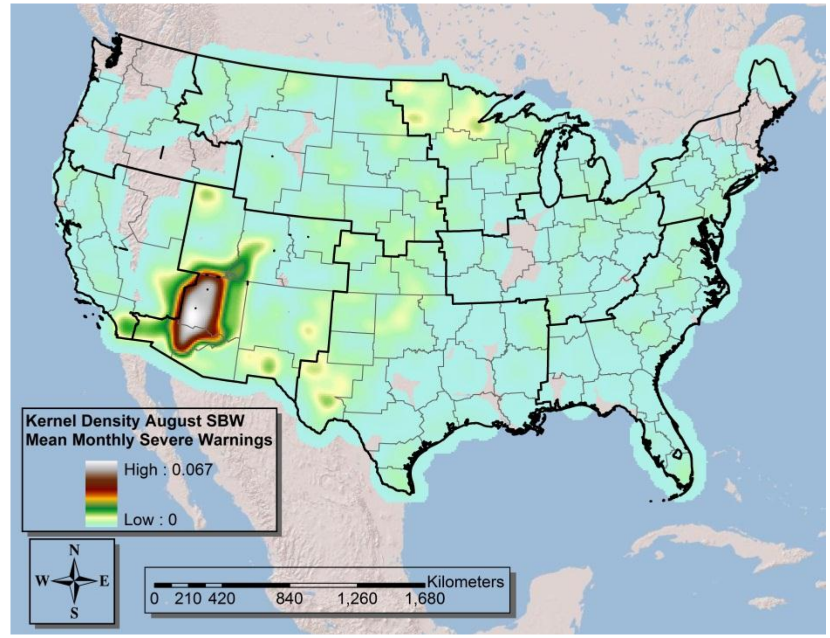

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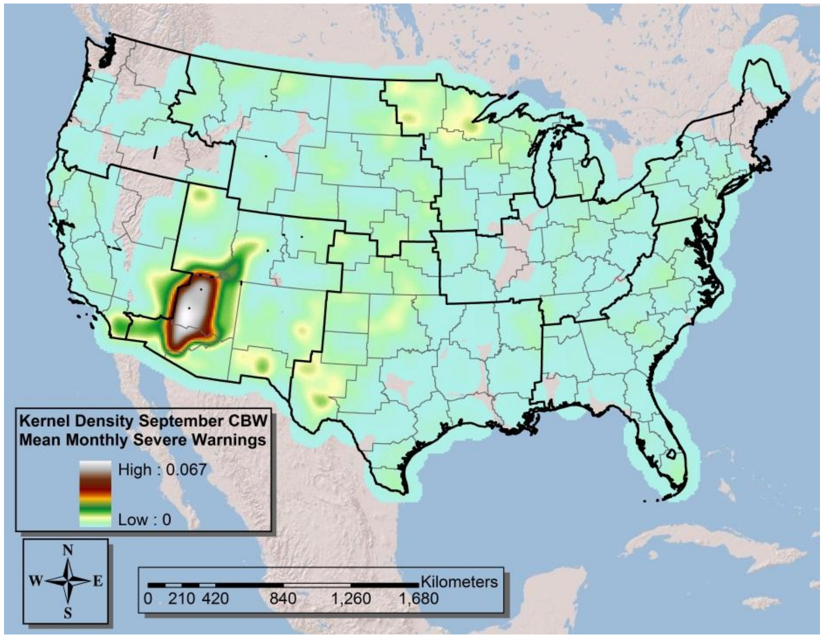

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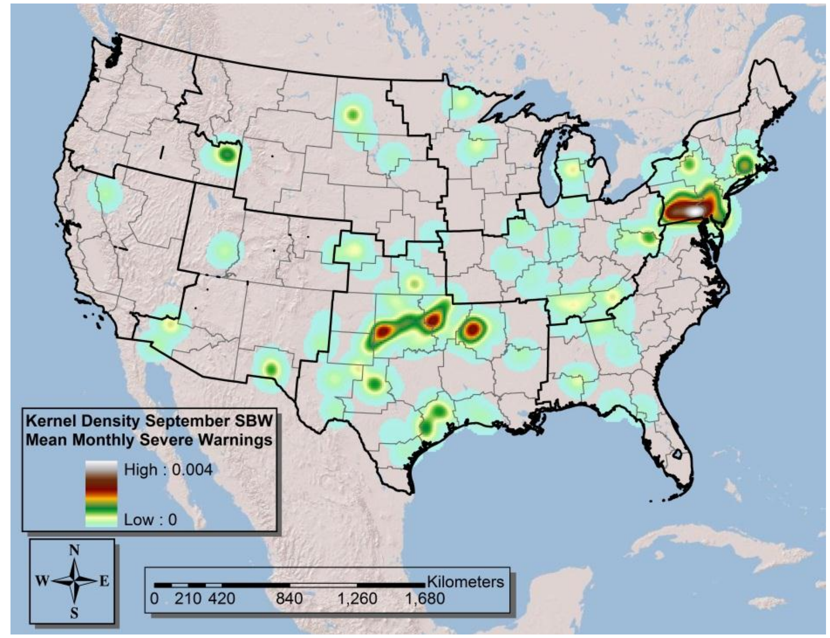

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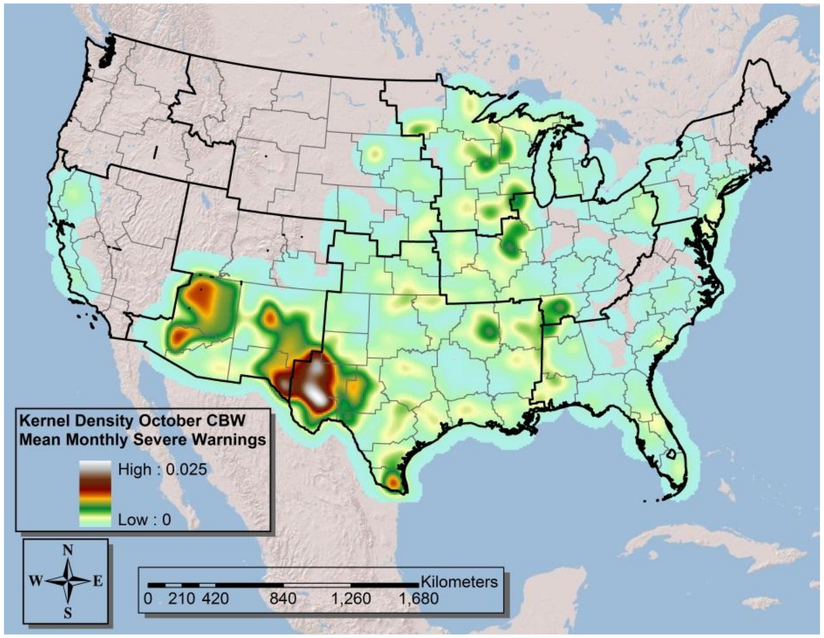

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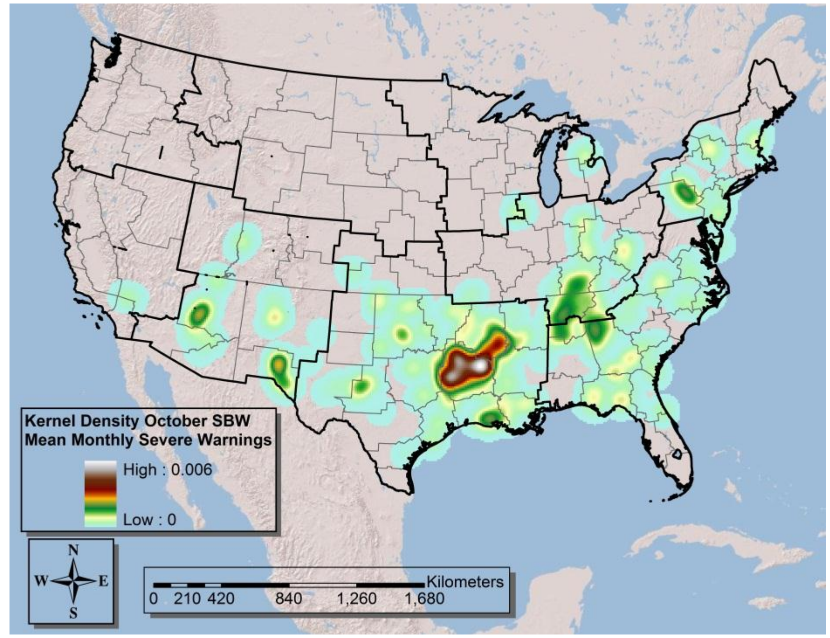

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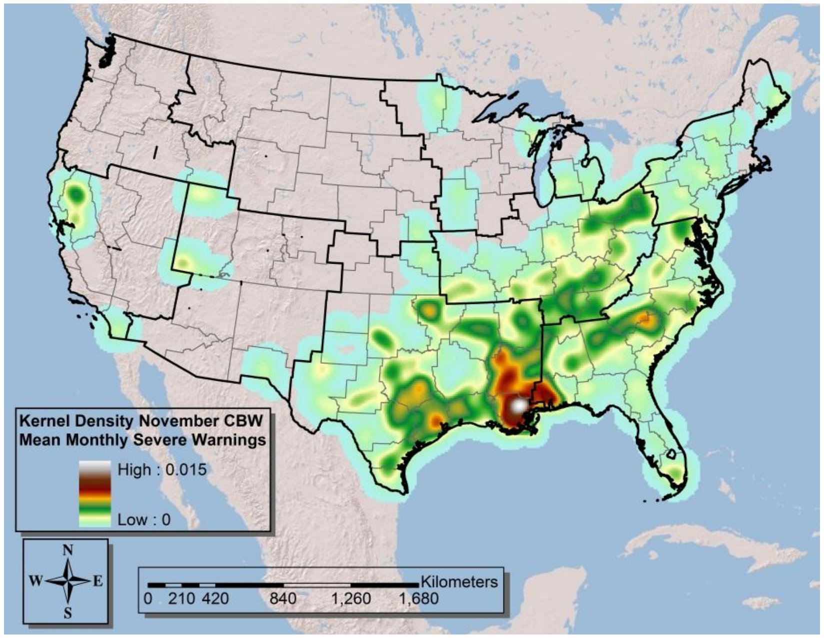

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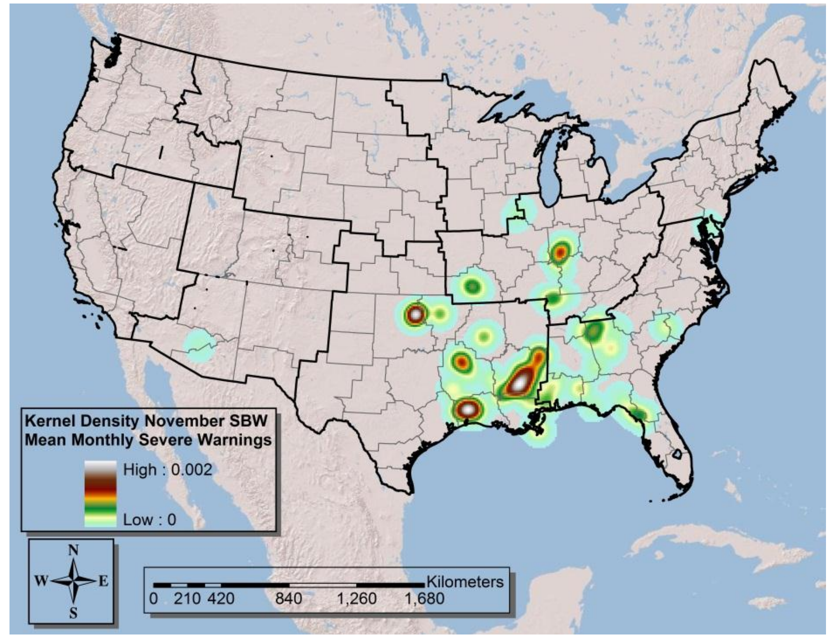

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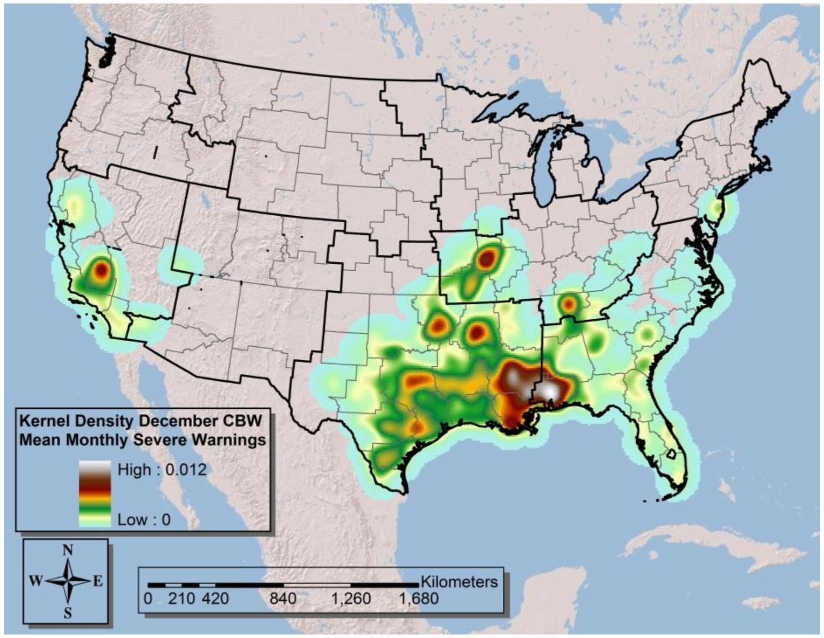

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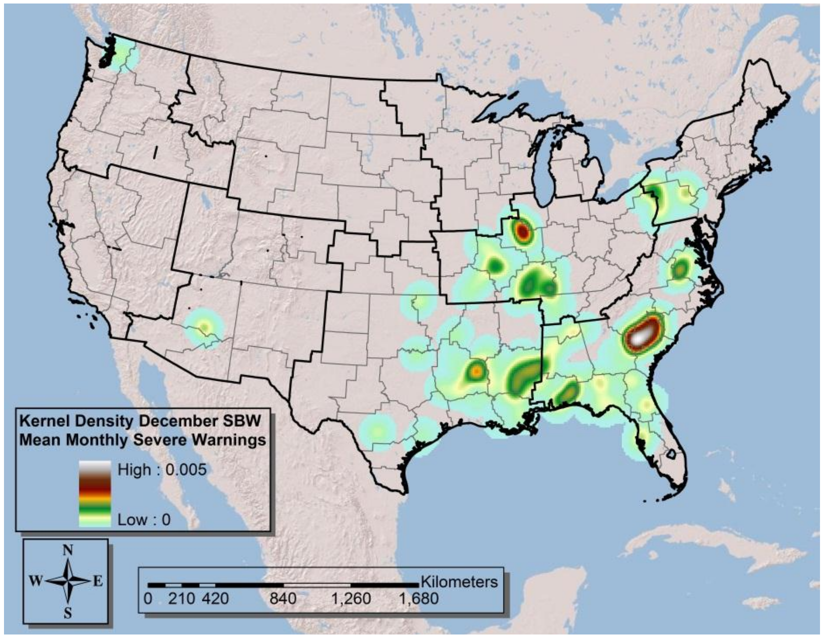

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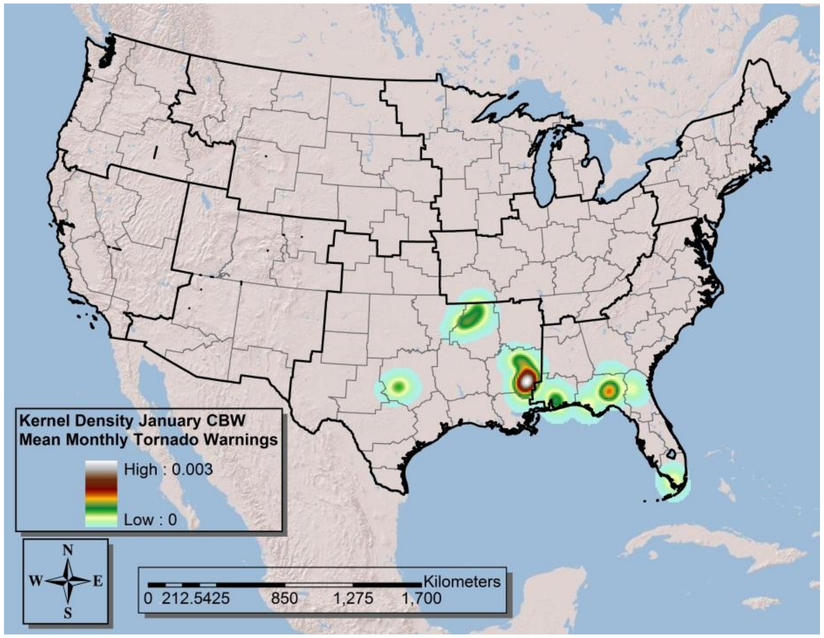
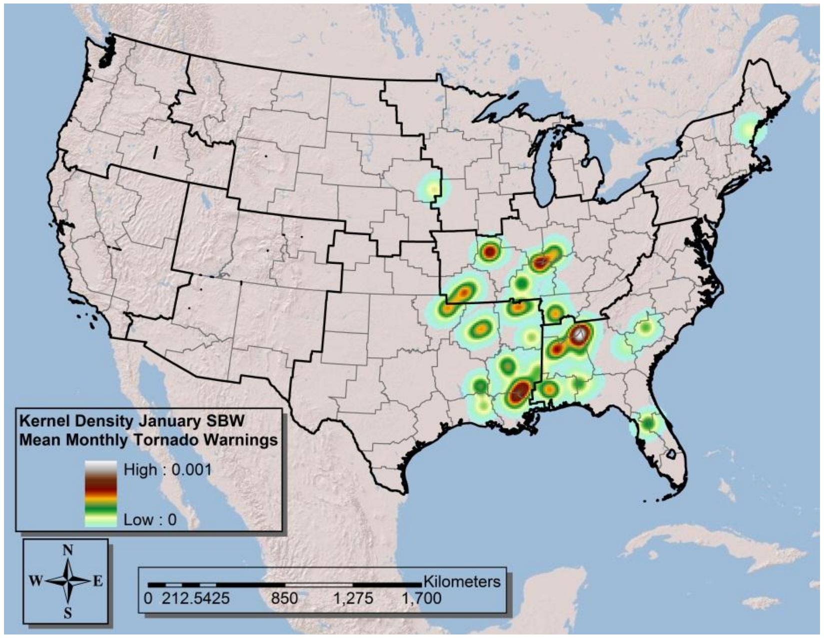
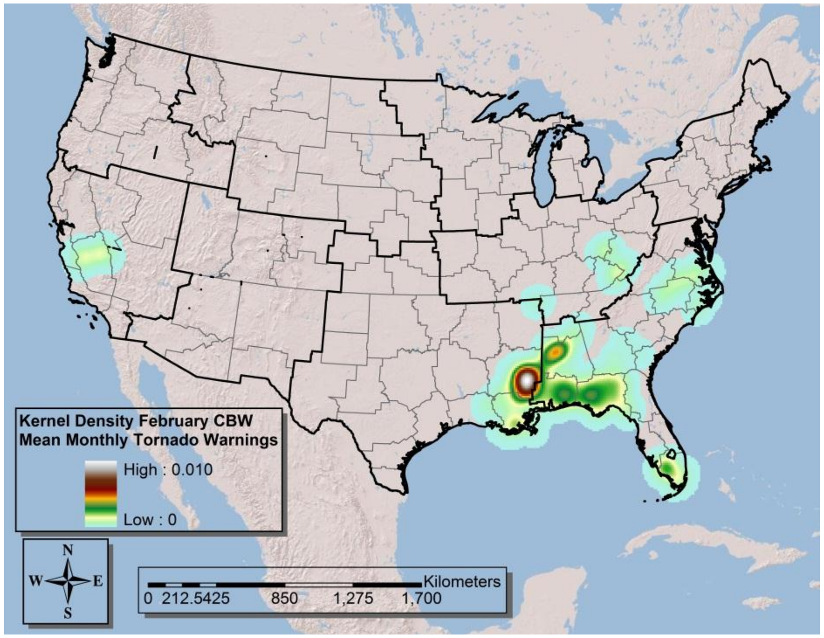


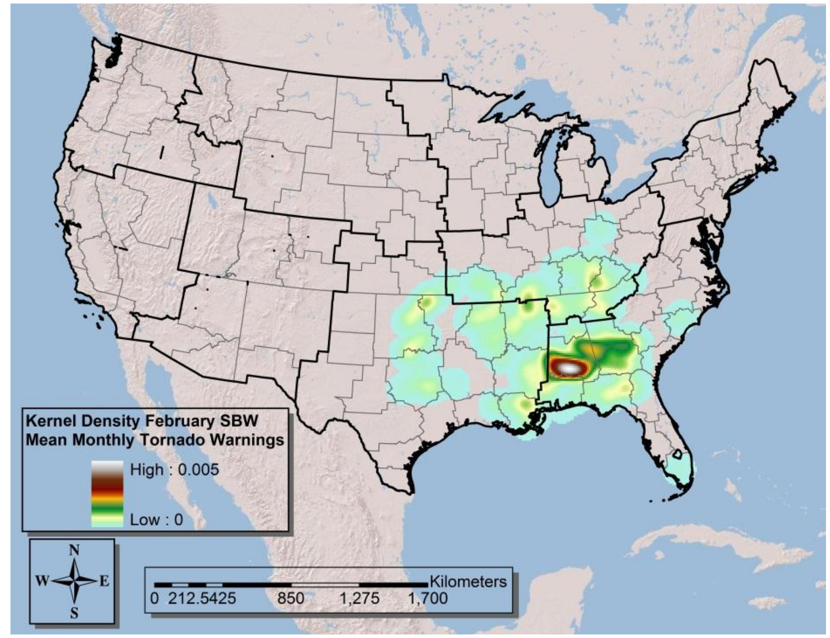
Kernel density analysis for tornado county-based warnings for the month of January.



Kernel density analysis for tornado storm-based warnings for the month of January.



Kernel density analysis for tornado county-based warnings for the month of February.



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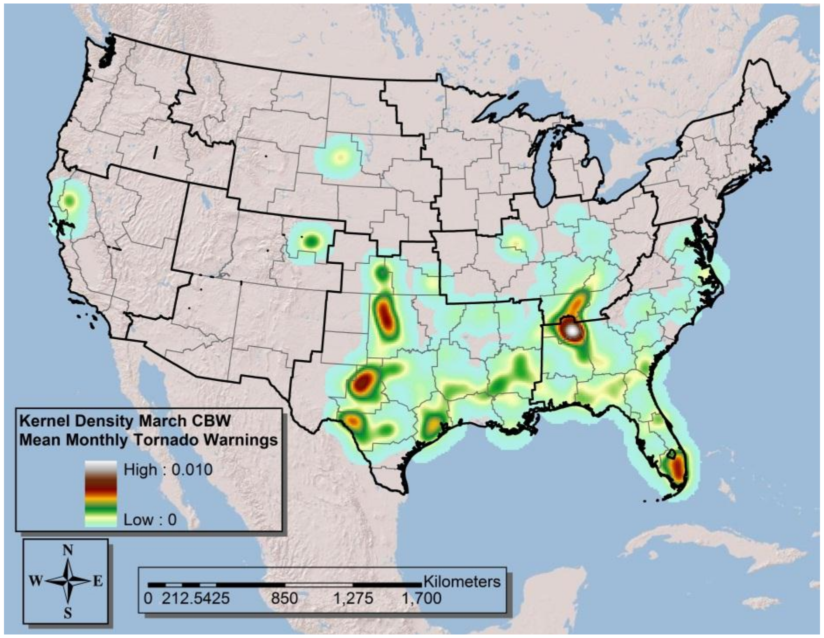
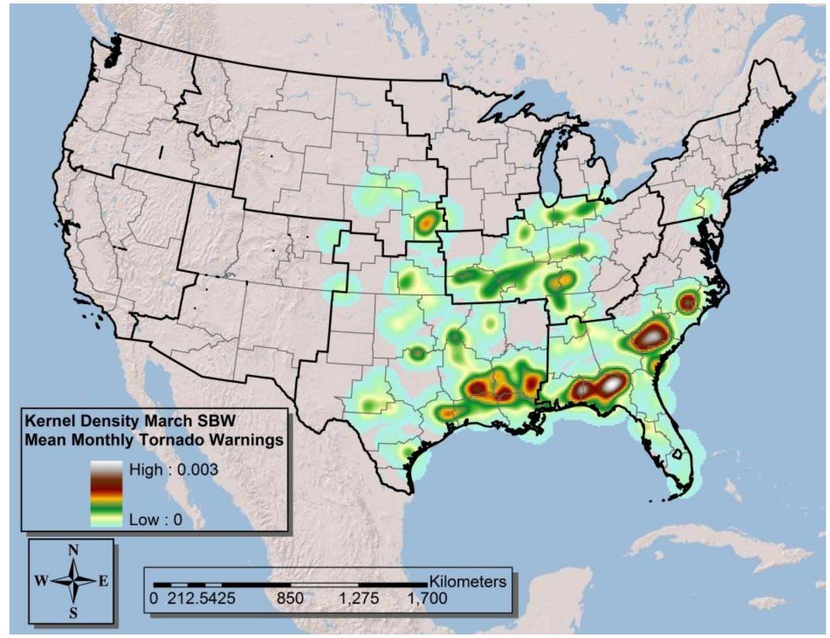
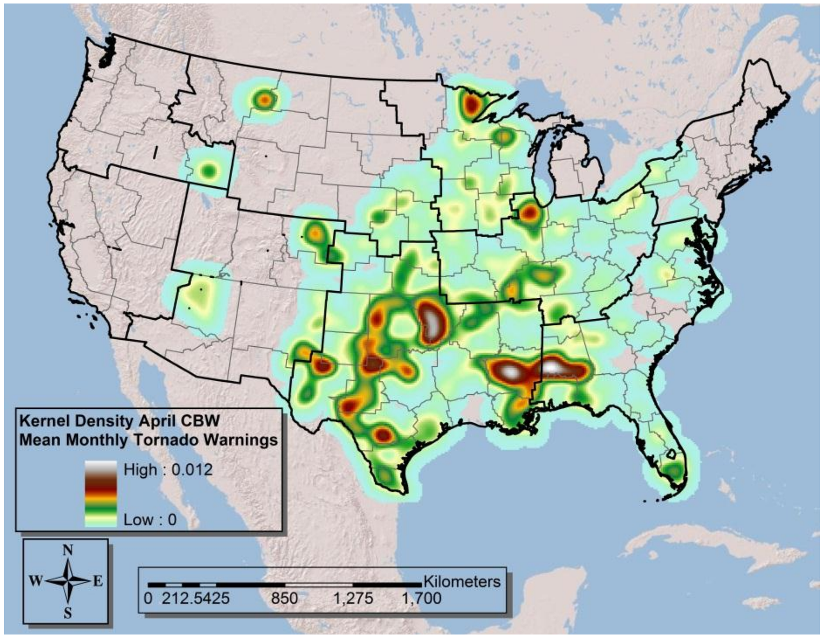


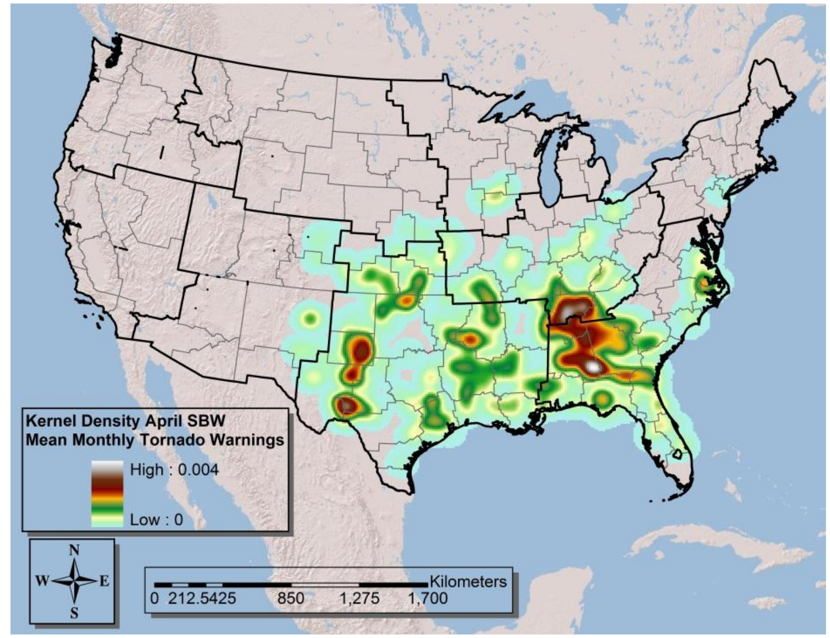
Kernel density analysis for tornado county-based warnings for the month of March.



Kernel density analysis for tornado storm-based warnings for the month of March.



Kernel density analysis for tornado county-based warnings for the month of April.



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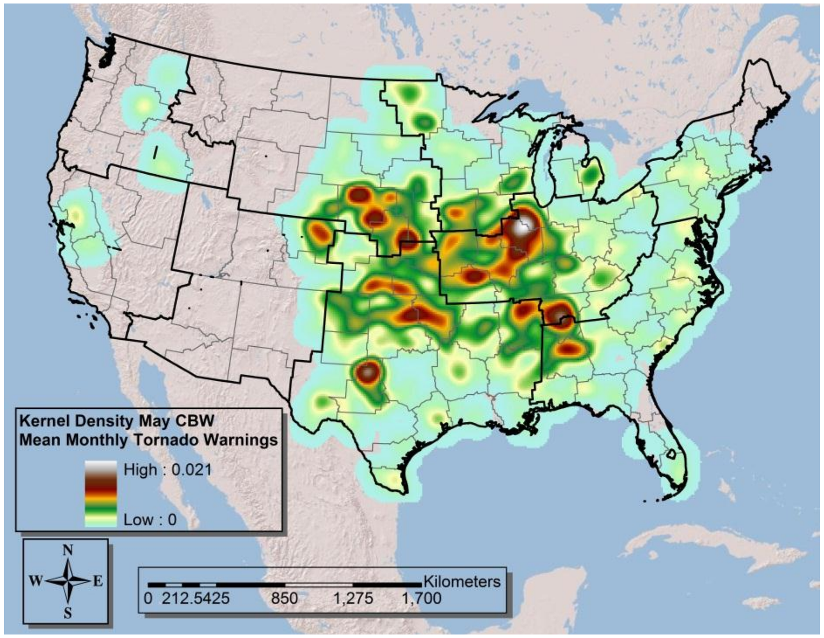
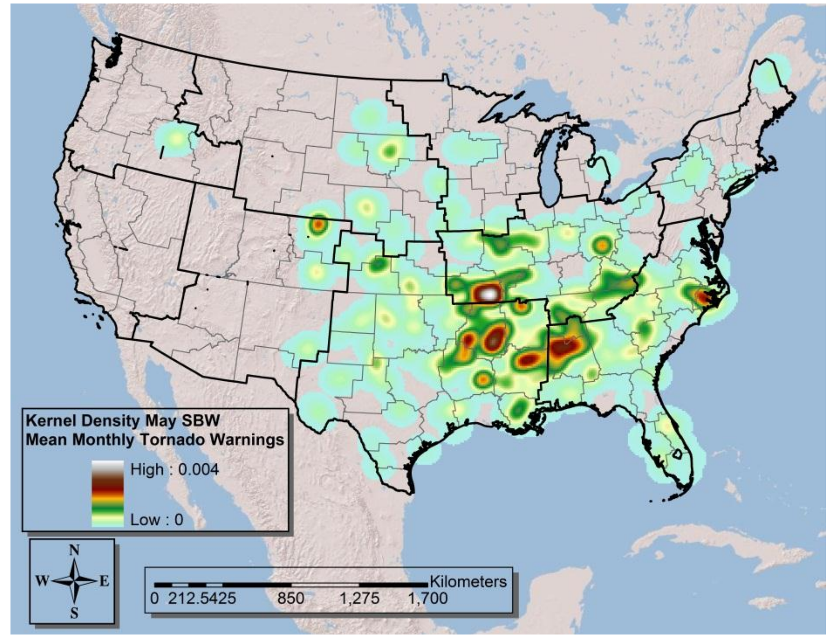


Kernel density analysis for tornado county-based warnings for the month of May.



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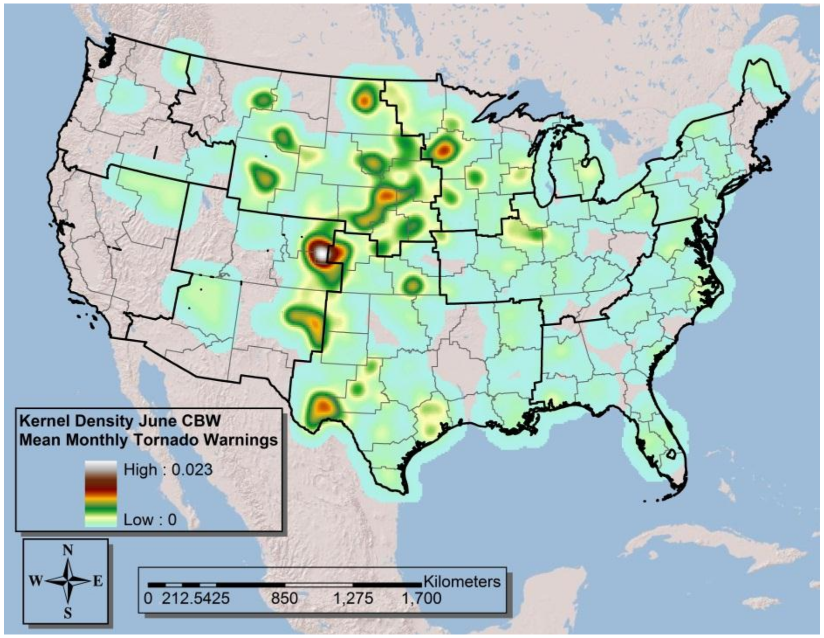
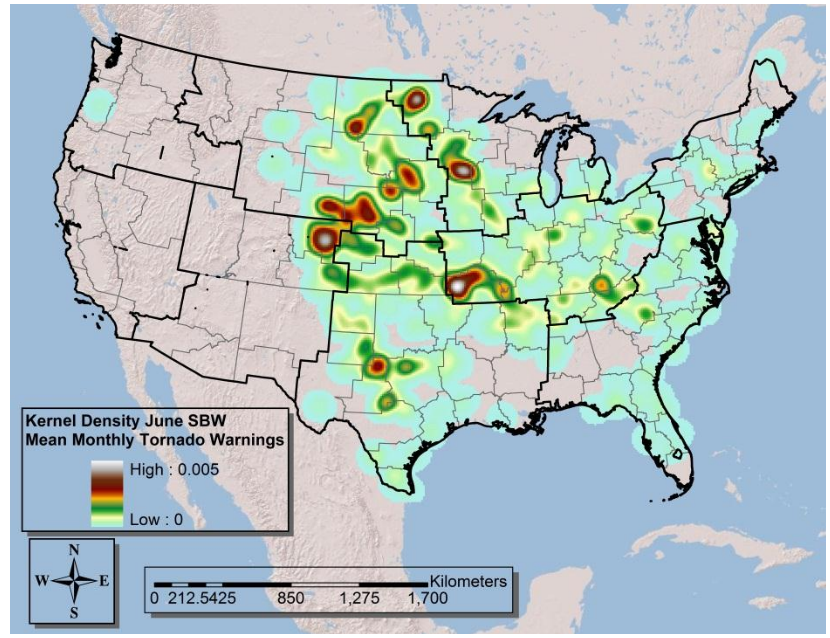


Kernel density analysis for tornado county-based warnings for the month of June.



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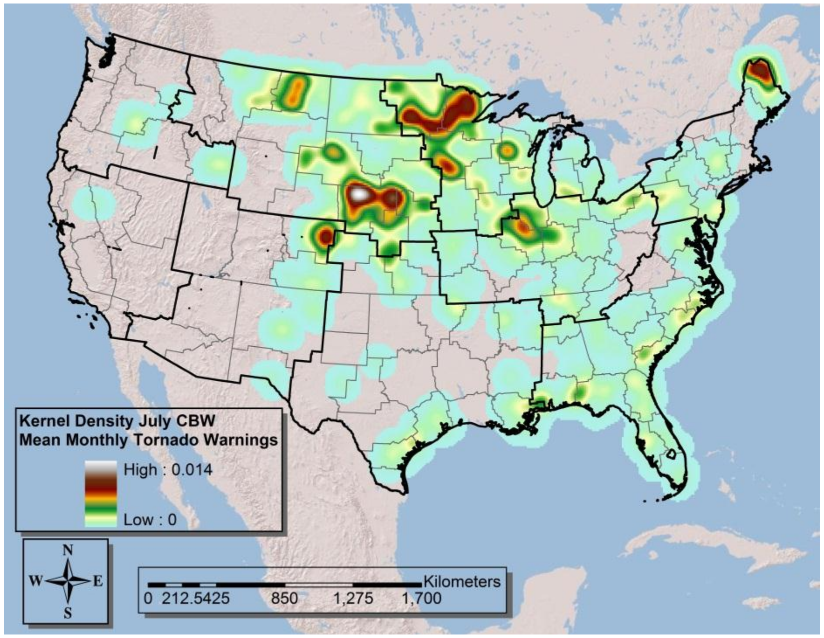
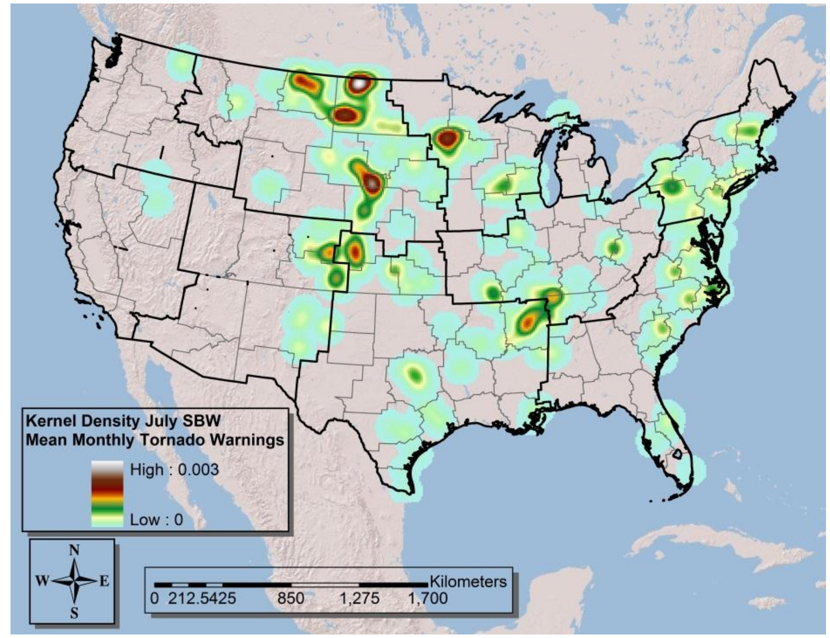


Kernel density analysis for tornado county-based warnings for the month of July.



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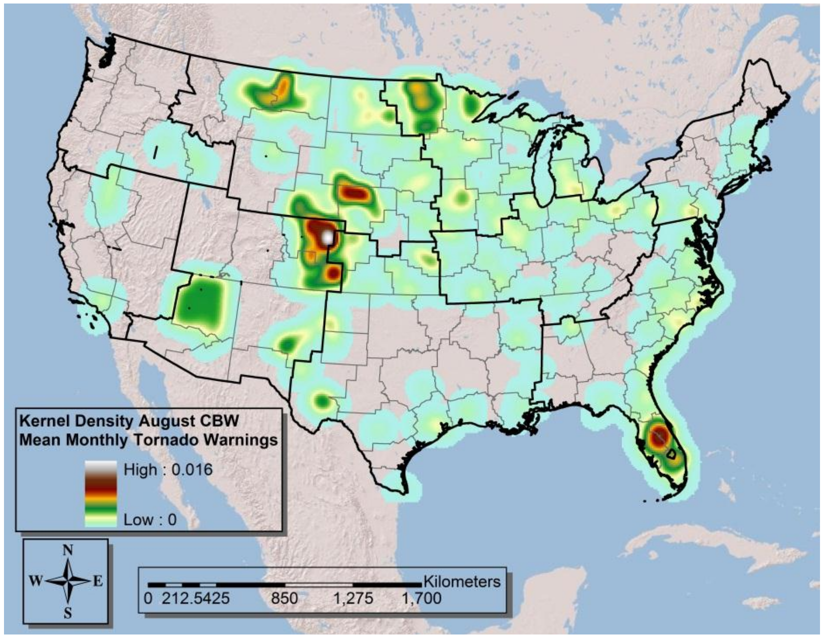
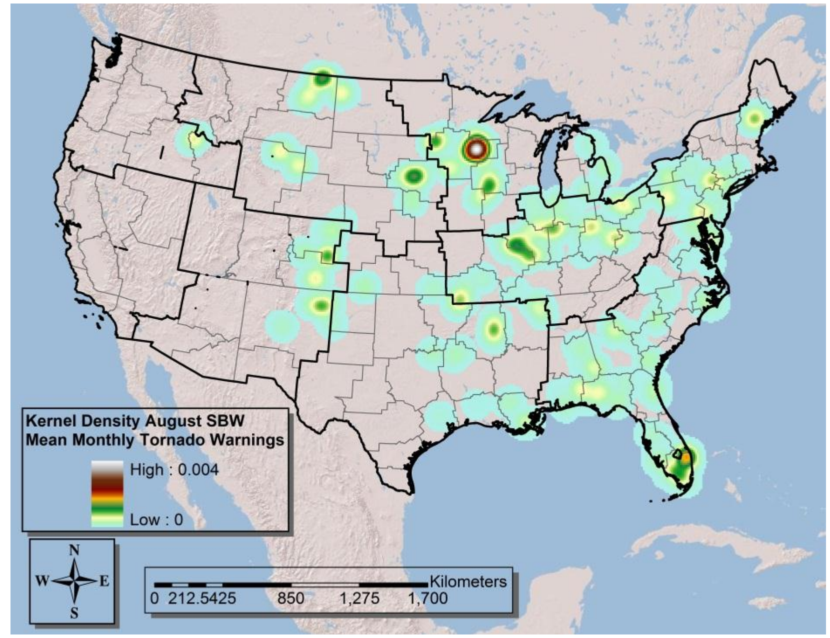


Kernel density analysis for tornado county-based warnings for the month of August.



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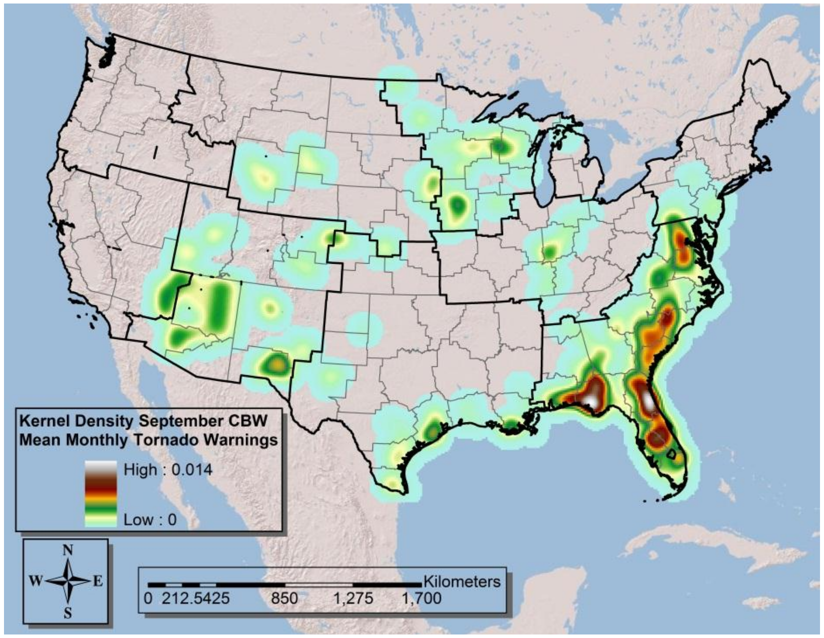

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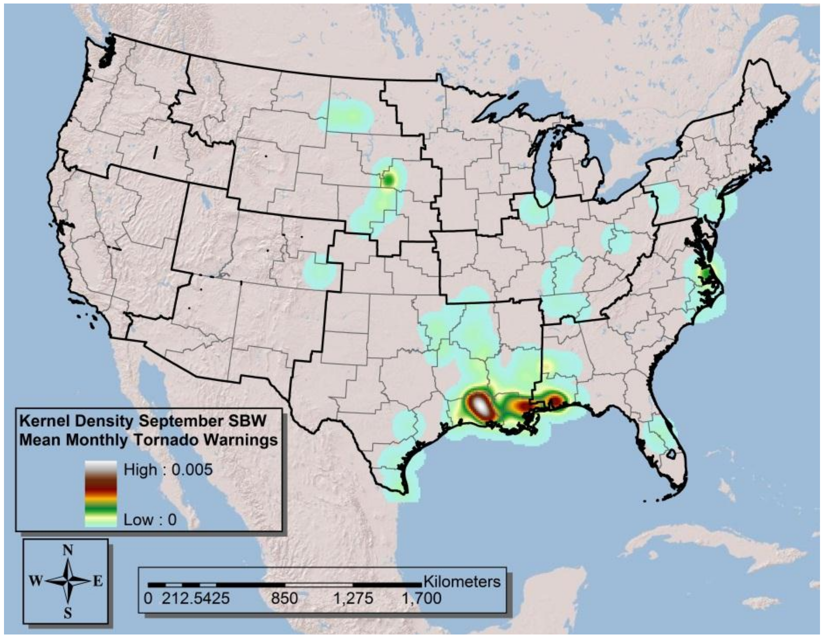

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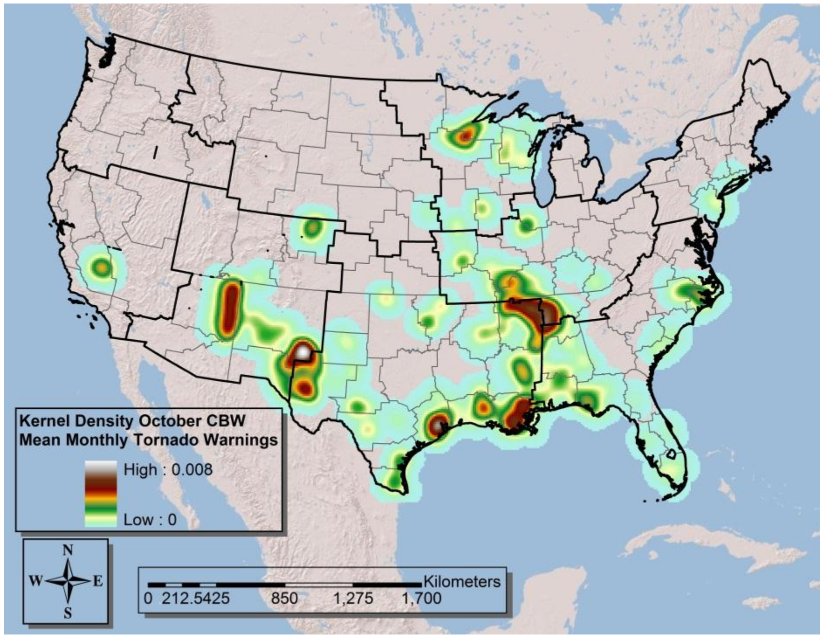
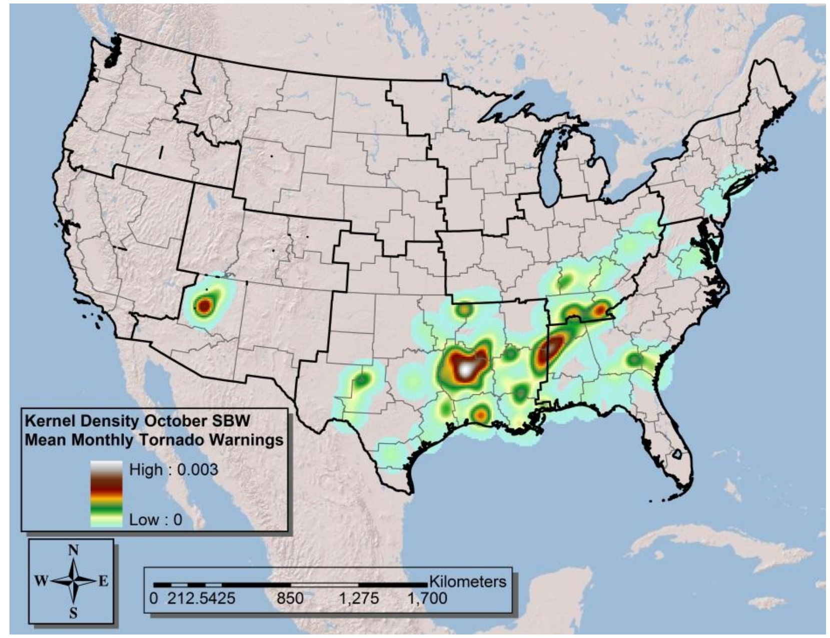


Kernel density analysis for tornado county-based warnings for the month of October.



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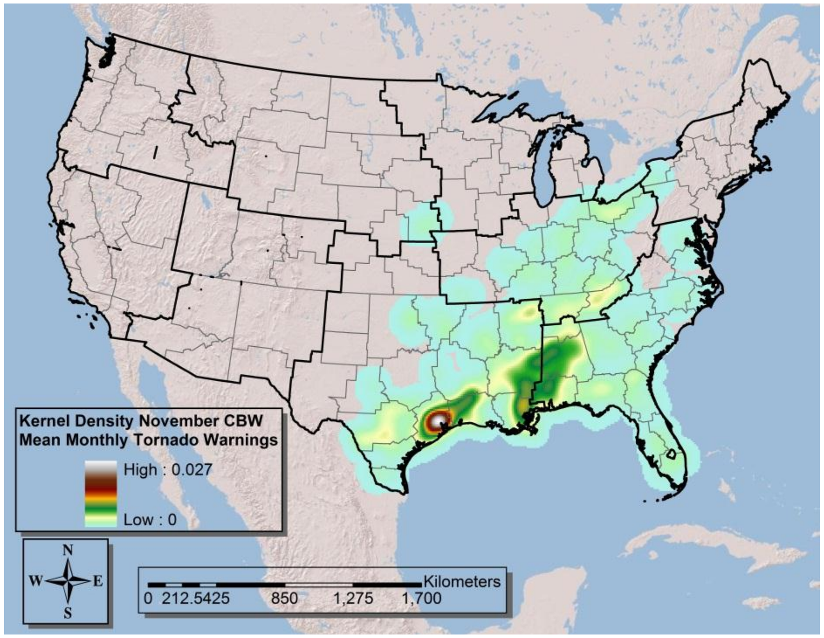

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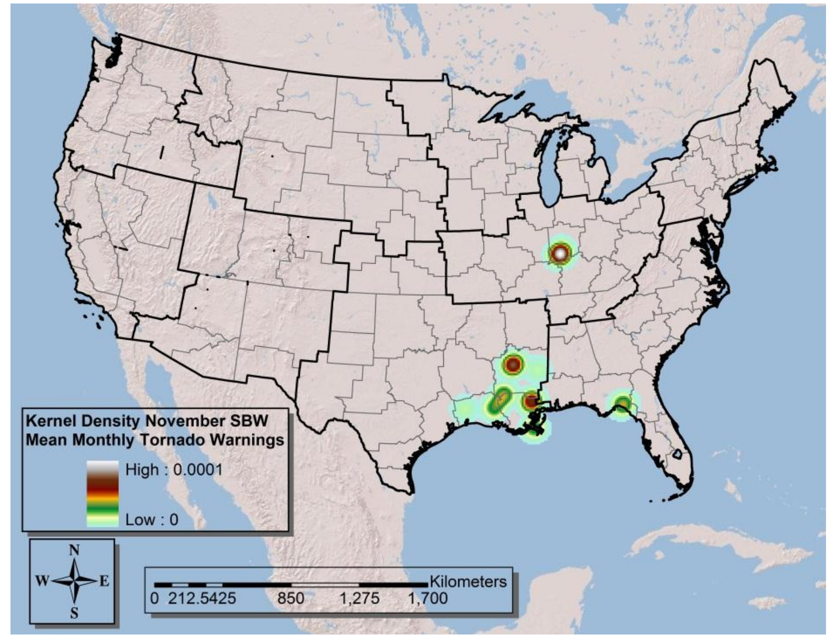
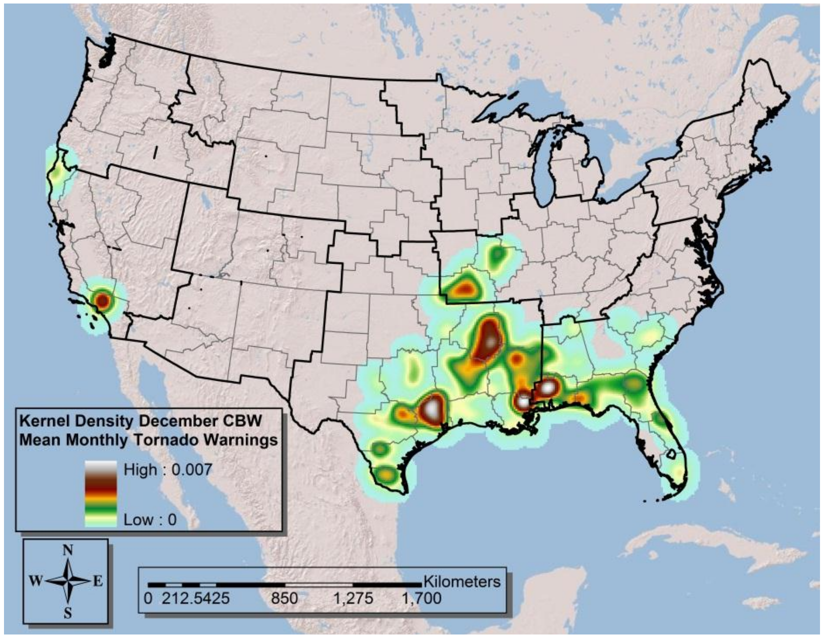
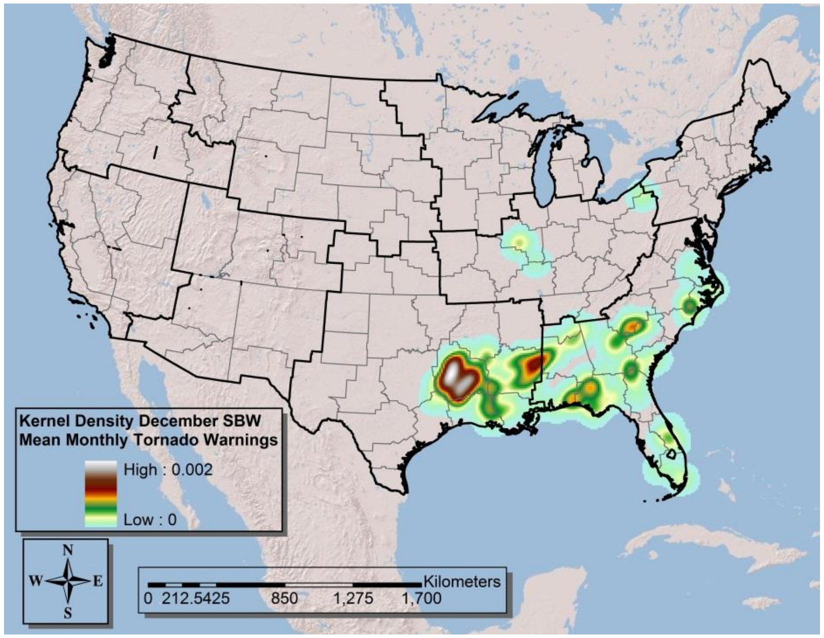


Kernel density analysis for tornado storm-based warnings for the month of November.



Kernel density analysis for tornado county-based warnings for the month of December.



Kernel density analysis for tornado storm-based warnings for the month of December.

APPENDIX C

TABLES LISTING THE ACRONYMS AND NAMES OF THE WEATHER FORECAST OFFICES BY CLIMATE REGION

National Weather Service Weather Forecast Offices (WFO) acronyms and names for the East North Central Climate Region.

WFO	WFO Name
APX	Gaylord, MI
ARX	La Crosse, WI
DLH	Duluth, MN
DMX	Des Moines, IA
DTX	Detroit/Pontiac, MI
DVN	Quad Cities, IA/IL
FGF	Grand Forks, ND
GRB	Green Bay, WI
GRR	Grand Rapids, MI
MKX	Milwaukee/Sullivan, WI
MPX	Twin Cities, MN
MQT	Marquette, MI

National Weather Service Weather Forecast Offices (WFO) acronyms and names for the Northeast Climate Region.

WFO	WFO Name
ALY	Albany, NY
BGM	Binghamton, NY
BOX	Boston, MA
BTV	Burlington, VT
BUF	Buffalo, NY
CAR	Caribou, ME
CTP	State College, PA
GYX	Gray/Portland, ME
OKX	New York, NY
PHI	Philadelphia, PA

National Weather Service Weather Forecast Offices (WFO) acronyms and names for the Northwest Climate Region.

WFO	WFO Name
BOI	Boise, ID
MFR	Medford, OR
OTX	Spokane, WA
PDT	Pendleton, OR
PIH	Pocatello, ID
PQR	Portland, OR
SEW	Seattle, WA

National Weather Service Weather Forecast Offices (WFO) acronyms and names for the Ohio Valley Climate Region.

WFO	WFO Name
CLE	Cleveland, OH
EAX	Kansas City/Pleasant Hill, MO
ILN	Wilmington, OH
ILX	Central Illinois / Lincoln, IL
IND	Indianapolis, IN
IWX	Northern Indiana / Syracuse, IN
JKL	Jackson, KY
LMK	Louisville, KY
LOT	Chicago, IL
LSX	St. Louis, MO
MRX	Morristown, TN
OHX	Nashville, TN
PAH	Paducah, KY
PBZ	Pittsburgh, PA
RLX	Charleston, WV
SGF	Springfield, MO

National Weather Service Weather Forecast Offices (WFO) acronyms and names for the South Climate Region.

WFO	WFO Name
AMA	Amarillo, TX
BRO	Brownsville, TX
CRP	Corpus Christi, TX
DDC	Dodge City, KS
EWX	Austin/San Antonio, TX
FWD	Fort Worth, TX
GLD	Goodland, KS
HGX	Houston/Galveston, TX
ICT	Wichita, KS
JAN	Jackson, MS
LCH	Lake Charles, LA
LIX	New Orleans/Baton Rouge, LA
LUB	Lubbock, TX
LZK	Little Rock, AR
MAF	Midland/Odessa, TX
MEG	Memphis, TN
OUN	Norman, OK
SHV	Shreveport, LA
SJT	San Angelo, TX
TOP	Topeka, KS
TSA	Tulsa, OK

National Weather Service Weather Forecast Offices (WFO) acronyms and names for the Southeast Climate Region.

WFO	WFO Name
AKQ	Wakefield, VA
BMX	Birmingham, AL
CAE	Columbia, SC
CHS	Charleston, SC
FFC	Peachtree City, GA
GSP	Greenville-Spartanburg, SC
HUN	Huntsville, AL
ILM	Wilmington, NC
JAX	Jacksonville, FL
KEY	Key West, FL
LWX	Baltimore/Washington Sterling, VA
MFL	South Florida/Miami, FL
MHX	Newport/Morehead City, NC
MLB	Melbourne, FL
MOB	Mobile, AL
RAH	Raleigh, NC
RNK	Blacksburg, VA
TAE	Tallahassee, FL
TBW	Tampa Bay Area, FL

National Weather Service Weather Forecast Offices (WFO) acronyms and names for the Southwest Climate Region.

WFO	WFO Name
ABQ	Albuquerque, NM
BOU	Boulder, CO
EPZ	El Paso, TX
FGZ	Flagstaff, AZ
GJT	Grand Junction, CO
PSR	Phoenix, AZ
PUB	Pueblo, CO
SLC	Salt Lake City, UT
TWC	Tucson, AZ

National Weather Service Weather Forecast Offices (WFO) acronyms and names for the West Climate Region.

WFO	WFO Name
EKA	Eureka, CA
HNX	San Joaquin Valley / Hanford, CA
LKN	Elko, NV
LOX	Los Angeles/Oxnard, CA
MTR	San Francisco/Monterey Bay Area, CA
REV	Reno, NV
SGX	San Diego, CA
STO	Sacramento, CA
VEF	Las Vegas, NV

National Weather Service Weather Forecast Offices (WFO) acronyms and names for the West North Central Climate Region.

WFO	WFO Name
ABR	Aberdeen, SD
BIS	Bismarck, ND
BYZ	Billings, MT
CYS	Cheyenne, WY
FSD	Sioux Falls, SD
GGW	Glasgow, MT
GID	Hastings, NE
LBF	North Platte, NE
MSO	Missoula, MT
OAX	Omaha/Valley, NE
RIW	Riverton, WY
TFX	Great Falls, MT
UNR	Rapid City, SD

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VITA

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