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Bias in Severe Thunderstorm and Tornado Warnings Issued by the National Weather Service in the Doppler Radar Era: A Spatial-Temporal Evaluation

Gary S. Votaw

BIAS IN SEVERE THUNDERSTORM AND TORNADO WARNINGS ISSUED BY THE NATIONAL WEATHER SERVICE IN THE DOPPLER RADAR ERA: A SPATIAL-TEMPORAL EVALUATION

by

Gary S. Votaw
Bachelor of Arts, Western Illinois University, 1995

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This thesis, submitted by Gary S. Votaw in partial fulfillment of the requirements for the Degree of Master of Science from the University of North Dakota, has been read by the Faculty Advisory Committee under whom the work has been done and is hereby approved.

Paul Todhunter
Chairperson

Brad Rundquist

Mark Askelson

This thesis meets the standards for appearance, conforms to the style and format requirements of the Graduate School of the University of North Dakota, and is hereby approved.

Joseph N. Benoit
Dean of the Graduate School

April 28, 2006
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Date 4/27/06

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ABSTRACT

A climatology of severe thunderstorm (damaging wind and/or hail) and tornadoes in the United States has established the location of the areas of highest frequency of occurrence. This climatology was attained through analysis of a basic data source, that of observed events, which carries many associated biases. Among these biases is the requirement that someone be on hand to witness the event no matter what time of the day or night, the assumption that the observer had sufficient visibility to see the event clearly, and whether there was something available on location to damage. In this study I use an alternate database consisting of the number of county severe thunderstorm warnings and tornado warnings issued by the National Weather Service, primarily for the 1995-2004 time window, between the Rocky Mountains and Appalachian Mountains. Because this alternative climatology is based upon the much improved technology available using Doppler radar, it is believed to have fewer and more quantifiable biases for the spatial analysis of severe weather distribution. There are two suspected areas of bias in this alternative data source: 1) population density; and 2) distance a county is from the nearest radar transmitter. The numbers could also vary spatially according to which Weather Service Office (WFO) issued the warning. Regression analysis and statistical tests were used to quantify bias to produce a spatial distribution that is complimentary to the climatology based upon reported events. The primary goal of the study was to identify and quantify the biases, and then develop a spatial pattern that is representative of the actual severe weather threat. Results indicate that bias is frequent and highly variable

according to WFO but could not be accurately quantified. The difference in issuance frequency of warnings between those offices which is based on much subjectivity appears more dominant than the biases. The resultant distribution of severe thunderstorm warnings is similar to one that uses reported events. The distribution of tornado warnings remains skewed by the differences between WFOs and is not likely to be representative of the actual tornado threat.

CHAPTER I

INTRODUCTION

Much research has been done to determine the frequency of occurrences and spatial distribution of severe thunderstorms (high winds and large hail) and tornadoes in the United States. Studies show that the location of highest frequency of occurrence for these events extends through the Great Plains region from north-central Texas north-northeast toward Omaha, Nebraska, especially if the definition is narrowed to include only extreme occurrences. This is the area where cool and/or dry air frequently and strongly contrasts with warm and humid air just to the east or south, producing a potentially potent environment for developing severe thunderstorms and tornadoes in conjunction with related vertical stability factors and winds aloft. Consensus regarding this climatology was achieved through analysis of the same basic source of data, that of observed events. By far the largest, most reliable and complete data source for severe thunderstorms is currently maintained in the United States National Weather Service (NWS) verification database and *Storm Data* program and it is sometimes supplemented or compared to records of insurance claims. Brooks *et al.*'s (2003a) study of the spatial distribution of the data is currently the most respected in regards to the location of the highest severe thunderstorm and tornado threat. But the distribution of severe weather events has varied dramatically over the years, especially since 1980 as the numbers of reported events have increased and the reporting process has become more efficient.

The severe thunderstorm and tornado climatology is based on reports of property or crop damage, direct instrument measurements, or by personal injury or loss of life. It contains a myriad of biases, most notably those resulting from the effects of population density and its associated and resultant infrastructure variations. After all, if no one is on location to observe the event how would it be reported? Other biases in the data include those associated with nighttime occurrence (low visibility and the period when most people sleep), unequal or insufficient training for weather observers and subjectivity in reports that results, how proactive the staff in a local Weather Forecast Office (WFO) might be in soliciting reports, varying building codes, and associated subjectivity in damage assessment. In order to improve our understanding of where severe thunderstorms and tornadoes occur, researchers have removed or compensated for known biases in the data (Ray *et al.*, 2003), accepted the climatology, mindful of the inherent biases (Doswell and Burgess, 1988), or filtered the data to exclude questionable entries (Kelly *et al.*, 1978).

After deciding which way to treat this observational data, one must decide what must be done to see accurate spatial patterns in the data. Many methods in forming patterns from the data normally require so much smoothing of data that detail at a level as small as a county is lost (Brooks *et al.*, 2003a). Filling in large gaps between reports with estimates require assumptions based on what might be reported if those areas were populated and someday might be, a risky way to determine hazard threat. Not only is this database of reports suspect in many ways, it is simply undesirable to look for another way to study it that has not already been done. I sought an alternate database that was substantially different and had fewer biases, especially regarding population density. The

Modernization and Restructuring (MAR) of the NWS included a joint effort by the Departments of Commerce, Defense, and Transportation to develop a Doppler weather radar network that was deployed in the 1990s. NWS Meteorologists who use these radars are required to issue severe weather warnings throughout the United States, 24 hours a day and 7 days a week, whether or not anyone will notice the inclement weather or be hurt by it, thus removing the potential population and nighttime biases. These radars were designed with much improved technology to detect high wind (including those in tornadoes) and hail, with better range capability compared to the previous radar system. A complete database of reported events and issued warnings from 1986 through 2004 between the Rocky Mountains and Appalachian Mountains, and extending through Florida, was used for this study of severe weather. This database is regarded to have no biases due to nighttime factors or possible damage, and no bias associated with gathering severe weather reports.

In this study I will determine the extent of biases in warnings and attempt to remove them. I will then develop a spatial pattern that may be more representative of the actual severe weather threat, and is complimentary to one derived from a database of reported events. Specific questions to answer include: 1) is there bias associated with either population density or with a storm's distance from the radar?; 2) do individual WFOs show differences in the number of issued warnings compared to neighboring offices, and could these differences be interpreted as a bias?; and 3) what is the spatial pattern of severe weather based on this new source, and how does it compare to earlier climatology?

Although the author of this study is an employee of the National Weather Service this study has not been authorized by this employer. The analysis and data interpretation included herein are those of the author and do not necessarily represent those of the National Weather Service.

CHAPTER II

LITERATURE REVIEW

The National Weather Service and Severe Local Storms

The NWS is charged with the task of issuing official public warnings concerning hazardous weather in the United States, including those for severe thunderstorms and tornadoes, floods and flash floods, high winds and various winter hazards (NWS Directive NWSI 10-511, 2003). Official NWS definitions of severe thunderstorms and tornadoes in the United States, sometimes referred to as severe local storms, have remained constant since 1970 (Galway, 1989). A WFO issues a severe thunderstorm warning when radar or satellite data indicate that such a storm exists and/or reliable spotter reports are received of wind gusts equal to or in excess of 50 knots (58 mph) and/or hail of at least 0.75 inch (penny) diameter or larger. A tornado warning is similarly issued when radar or satellite is suggestive of a tornado and/or reliable spotter reports of a tornado are received (NWS Directive NWSI 10-511, 2003).

Using an approach sometimes referred to as "ready, set, go," the NWS begins to advise the public, media, and state and county emergency managers, law enforcement personnel, and the public with a convective outlook. This first step is performed by the Storm Prediction Center (SPC) in Norman, OK, and is issued up to three days in advance of suspected severe weather across the continental United States (NWS Directive NWSI 10-512, 2005). As atmospheric conditions become favorable for severe thunderstorms

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Warning verification in the NWS has gone hand-in-hand with its SKYWARN program. These volunteer weather spotters collaborate with the NWS in helping it locate severe weather which in turn helps warn other people in its path (Doswell *et al.*, 1999). Other methods of verification in the 1950s through 1980s included official weather observers at airports and on-site damage assessment. Remote wind sensors have, since the 1980s, taken a larger role in warning verification. But weather spotters, public reports, and damage to crops and other property are still the primary means of verifying occurrences.

Causes and Climatology

Severe thunderstorms and tornadoes happen over much of Earth's surface. Primary causes of severe thunderstorms include large instability in the atmosphere, having warm and moist air within the surface boundary layer or just above it in the case non-tornadic severe thunderstorms, however, has lagged somewhat behind research done on tornadic storms. While the SPC maintains a database for both types of storms, the National Severe Storms Laboratory (NSSL) in Norman, OK (co-located with SPC) has been directed to develop such a climatology. This database was used to produce Figures 1-3 (http://www.nssl.noaa.gov/hazard) in a spatial format for the "total" threat (the mean number of days per year with one or more events within 25 miles of a point) for any severe thunderstorm wind (58 mph or more), severe hail (0.75 inch in diameter or larger), or tornado as defined for NWS warning of criteria (NWS Directive NWSI 10-512, 2005).

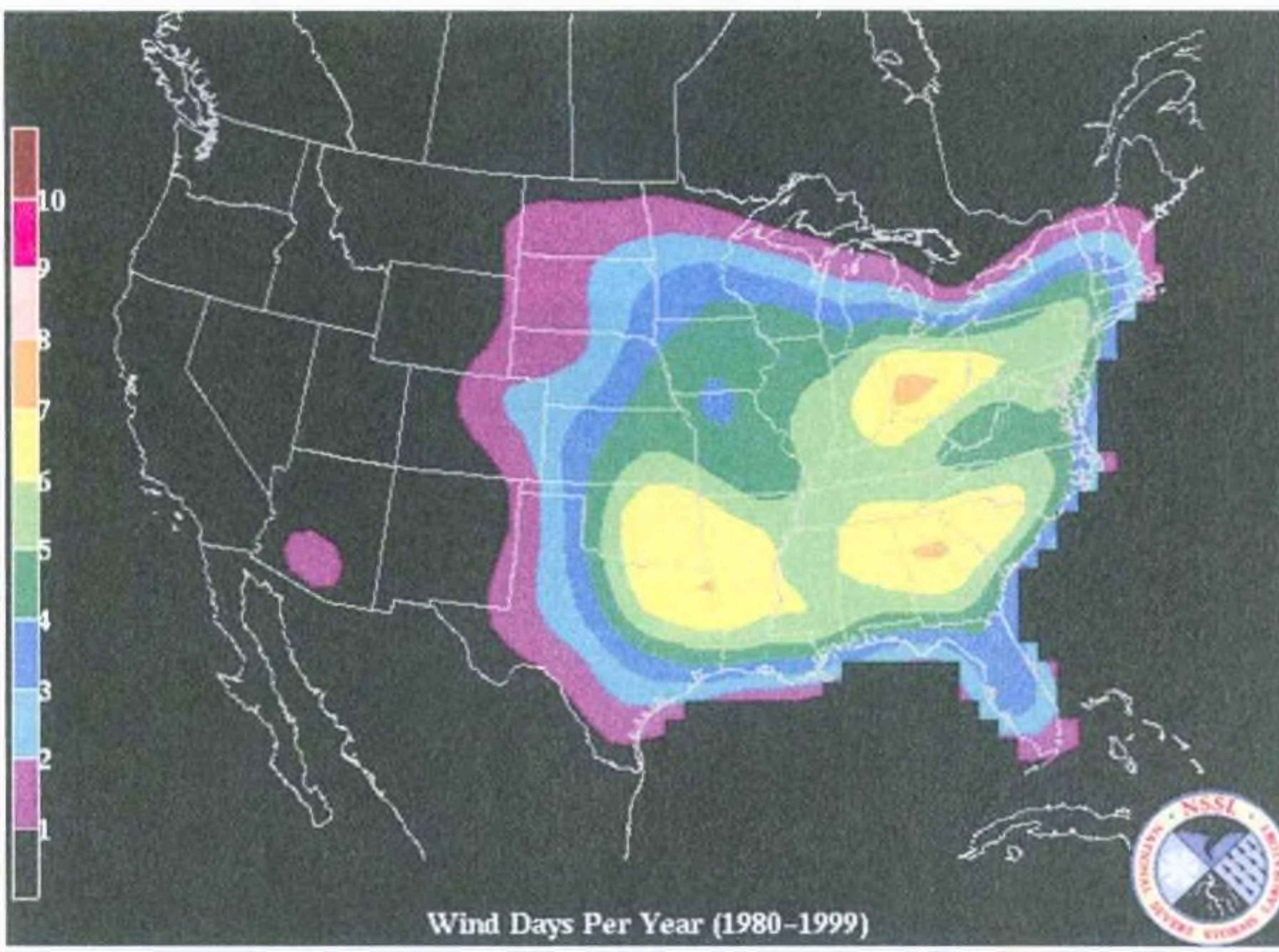

Figure 1. Severe Thunderstorm Wind Days per Year, 1980-1999).

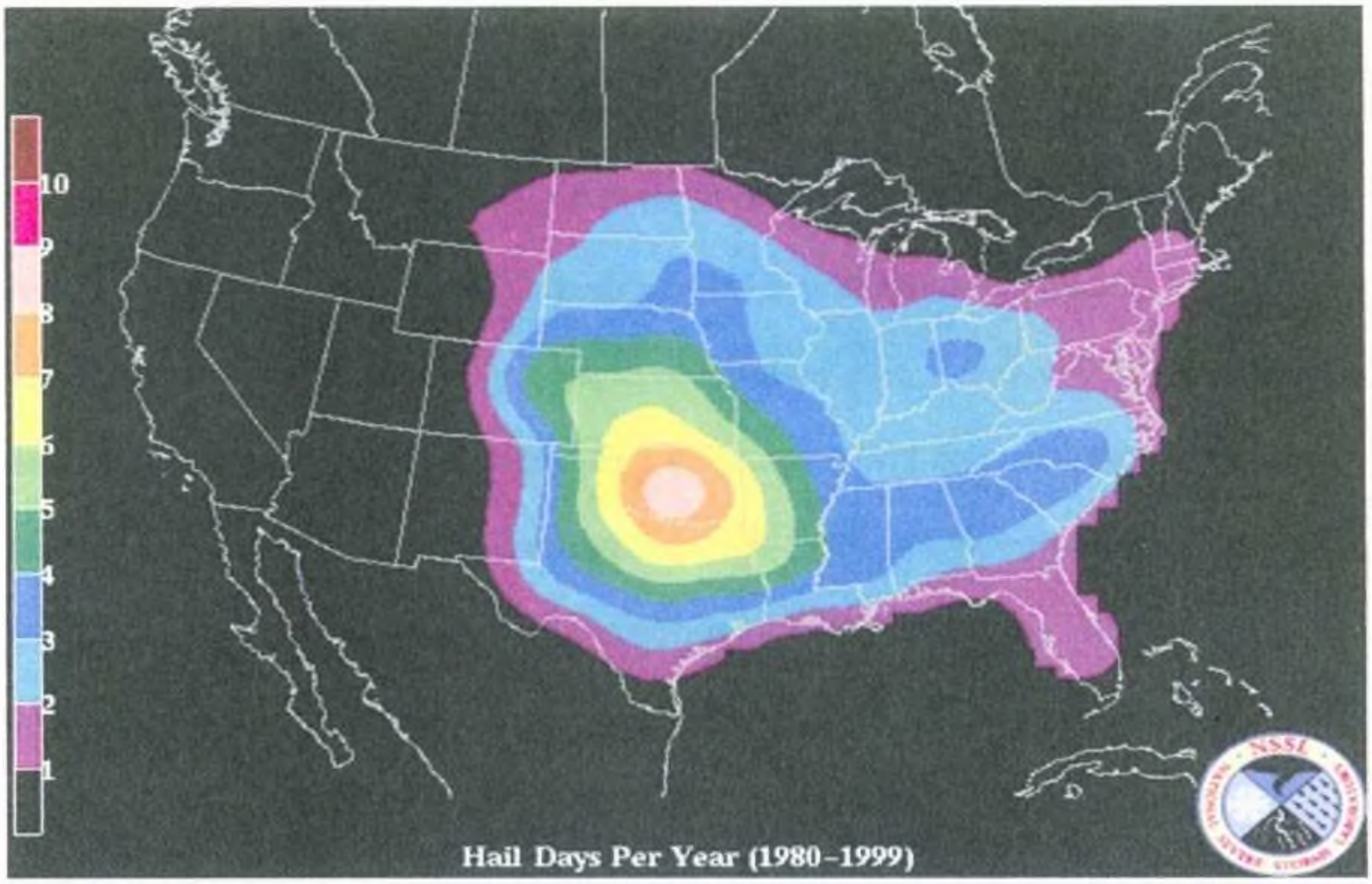

Figure 2. Severe Thunderstorm Hail Days per Year, 1980-1999).

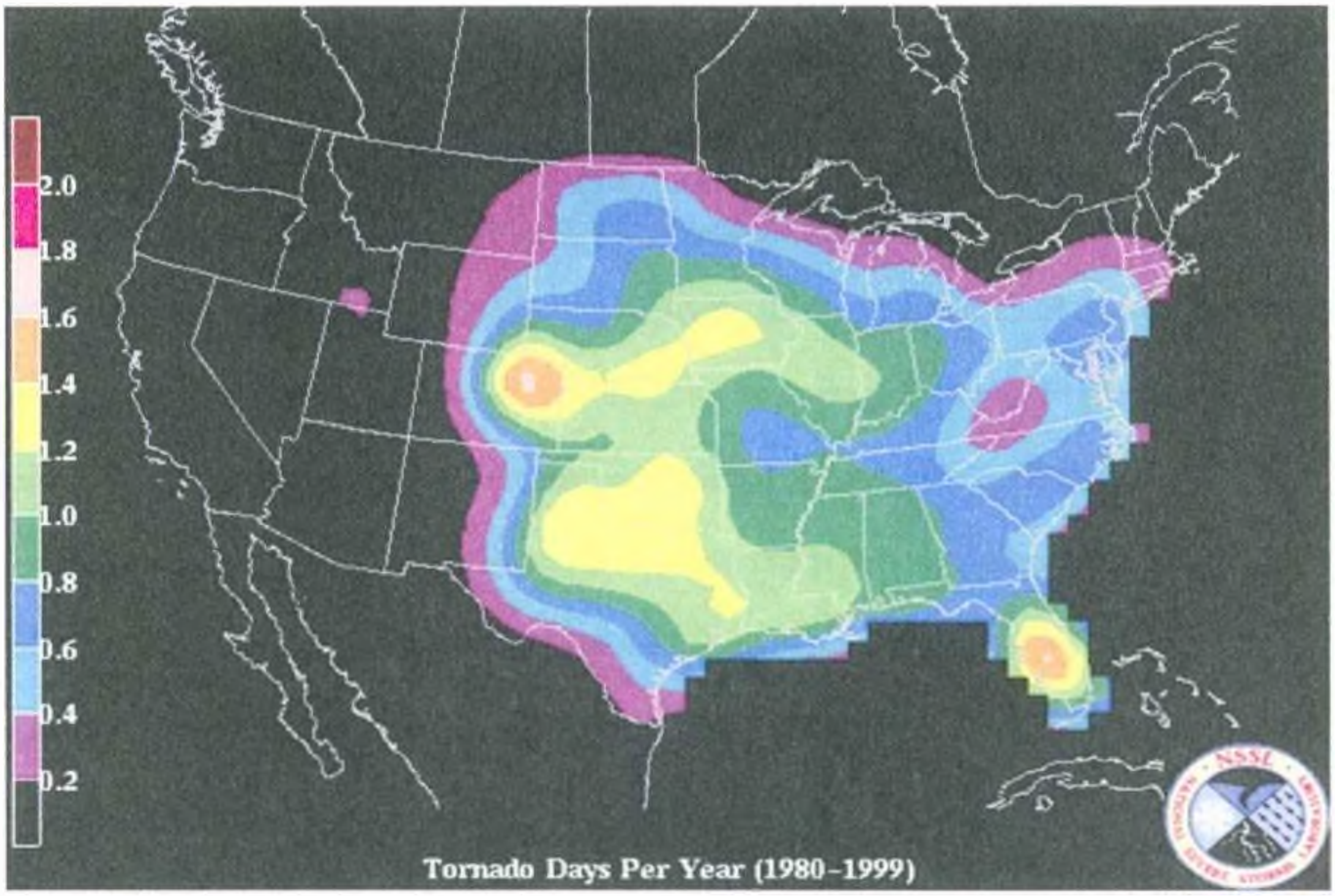

Figure 3. Tornado Days per Year, 1980-1999).

Problems for Climatologies Based on Past Events

A climatology based on past events has numerous limitations. A large grid size (80 km either side of a point or about 5 times larger than an average sized county in the central U.S.) was used in Figure 1, which resulted in poor spatial resolution. As in all climatologies based on recorded events, there are many other inherent problems and one must settle on an acceptable balance. Higher population will normally result in a higher probability of an event being reported (Kelly *et al.*, 1985), but we may not then infer that we can accurately extrapolate how many reports would have been received had there been more population. Other associated factors such as variable highway distribution and amount of urbanization, some people having (or not having) available communication, distance to a reporting station, day of the week, activity level of the people on location, and education of the populous complicate the matter. The net result of these demographic factors on the data is quite complex and most likely nonlinear (Kelly *et al.*, 1985). Additional problems include low visibility at night, blockage of visibility by terrain, trees and low clouds (especially in the eastern U.S.), lack of appropriate measuring devices, lack of a local spotter network, incorrectly identified causes, incorrect identification of a tornado, and subjectivity of storm damage surveys. Some storms or tornadoes are properly observed but are not reported since the observer felt no responsibility to report it, or did not know it should be reported (Kelly *et al.*, 1985). Efforts have been made to adjust the numbers of known reports for some of these limitations (Ray *et al.*, 2003), but may easily introduce a new bias when choosing which of those factors not to consider.

The number reports of hail of at least 0.75 inch diameter rose from an annual average of 1,100 in the late 1970s to almost 2,500 in the early 1980s (Schaefer *et al.*, 2004). Reports included in *Storm Data*, the national database of severe events, have increased by nearly an order of magnitude during the last 30 years due, in part, to implementation of the national warning verification program, increased training for trained storm spotters, deployment of the WSR-88D radar network, population increases and associated redistribution, and an overall increased awareness of weather hazards by media and government agencies (Weiss *et al.*, 2004). Hail climatologies have been developed at all scales from city to national levels and is usually based on the use of either *Storm Data*, crop-hail insurance losses or property damage records (Changnon, 1977).

Concannon *et al.* (2000) state that if the climatology of tornadoes is redefined with strong criteria then the data are more reliable since these tornadoes are larger, more visible, have longer damage paths and cause the most damage. A strong tornado is defined as one with wind speeds of at least 113 mph, or F2 on the Fujita scale (Fujita, 1987; de Villiers, 1997). The same may be said about severe thunderstorms since stronger wind and larger hail is less likely to occur unnoticed. Strong severe thunderstorms cause wind of at least 65 knots (75 mph) and/or hail in excess of 2 inches in diameter. These events are less likely to occur without leaving a record of structural or crop damage or loss of life (Kelly *et al.*, 1985; Concannon *et al.*, 2000). Better definition and confidence in such a climatology is possible, but using such narrow criteria results in ignoring the majority of potentially severe and damaging occurrences. For example, tornadoes classified as strong comprise only 30% of the total number, and violent ones

(>207 mph, F4 or stronger) only 2% (Concannon *et al.*, 2000). Wind and hail reports in excess of these criteria have comprised only 30% and 18% respectively (Kelly *et al.*, 1985). Thus, in order to have high confidence in our climatology dataset we might have to not consider more than two-thirds of those events that are considered potentially damaging.

Population Bias

Population density is one possible bias to account for when considering a climatology of reported tornadoes or other severe events. Newark (1983) estimated that a minimum threshold of 1.5 persons/km^2 is necessary to observe and report more than half of actual tornadoes. King (1997) concurred that this minimum threshold would be less than 6.0 persons/km^2. That study concluded that the effect of high population density may be removed by excluding the population of all incorporated cities and towns (generally more than 1,000 persons) in this southwestern Ontario region, using only rural population and combining townships of similar population density. This would be an extremely difficult task in a much larger or complex area. Other studies support a causal relationship between population density and number of tornado reports (Changnon, 1982; Snider, 1977). While they find that the signal toward population bias is strong, Elsom and Meaden (1982) found that metropolitan London experiences fewer tornadoes than its suburbs. However, Schaefer and Galway (1982) found that the effect of population density is surprisingly small. These studies suggest what population density might result in a significant percentage of tornadoes to be reported, but a population density will be sought in this study of warnings that would result in the inclusion of nearly all tornadoes.

Distance Bias

Ideally, weather radars would sense conditions as close to the ground as possible. A funnel cloud or a 100 mph wind that is aloft is not usually perceived by people on the ground as particularly dangerous to them unless it reaches the ground. But a radar beam that is tangential to the Earth's surface at the radar location (0° elevation angle) will largely sense "ground clutter" (trees, buildings, etc.) instead of the weather phenomenon of interest. The lowest elevation angle for the center of a radar beam employed by NWS radars (the degree to which a beam is tilted away from a plane tangential to the Earth's surface) is 0.5°. This tilt is necessary to lift the beam away from too much contact with ground based objects that might interfere with the radar's ability to remotely sense a thunderstorm. This elevated angle causes the beam to increase in height with greater distance from the transmitter. This problem is aggravated by the natural curvature of the Earth, which curves downward relative to the tangential plane with increasing distance. At a distance of 60 km at 0.5° the radar beam center is about 600 m above ground level, at 107 km (the mean distance of the counties studied here) it is 1450 m above the radar, or higher than the visible part of most tornadoes. Beam width is another factor that limits severe weather detection through poorer resolution of small-scale flows (like tornadoes) at greater distances since linear beam width is a function of angular beam width and range from the radar. The Doppler radar has a beam width of 1.0°, which limits its practical range limit for all but the widest of tornadoes to 60 km (Vasiloff, 2001). So with increasing distance from the radar comes greater uncertainty, meaning that visual sightings of tornadoes become even more critical. Damaging wind and large hail from severe thunderstorms are also hard to detect at greater distances since the radar can "see" less detail in fewer slices through a thunderstorm at these ranges. Figure 4 shows that while ten slices of radar data can be obtained through a thunderstorm 40 nautical miles (nmi) from the radar that has a top of 45 thousand feet above the radar, only three slices are possible through a similar storm at 120 nmi.

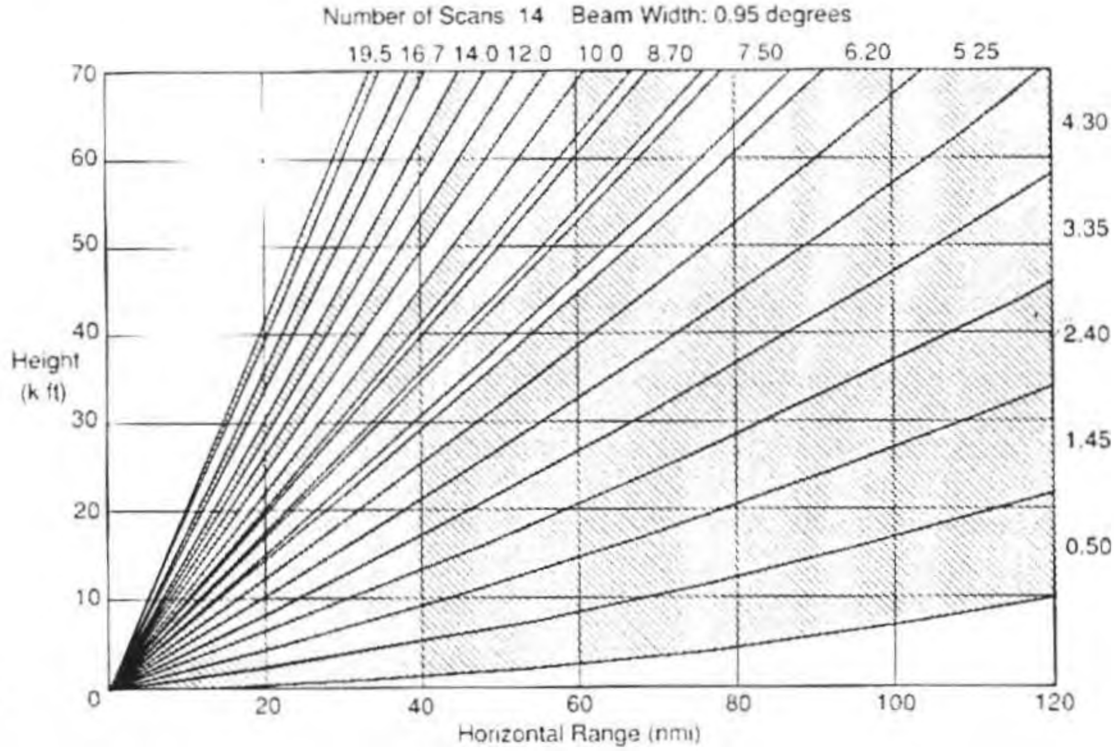

Figure 5-1
Precipitation/Severe Weather Scan
Volume Coverage Pattern 11

Figure 4. Volume Coverage Pattern (VCP) 11, from University Center for Atmospheric Research (UCAR).

Possible Ground Effects

Many studies address how increased wind shear and storm relative helicity (SRH), in addition to other parameters, increase the likelihood of tornadoes (Davies-Jones *et al.*, 1990; Cortinas and Stensrud, 1994, Stensrud *et al.*, 1997). A few suggest that the increasing roughness of the ground and objects on it may be a factor for decreasing the frequency of tornadoes reaching the ground (Dessens, 1972; Snider, 1977) by changing the low level wind shear that contributes to rotation and updraft in a thunderstorm. Pryor and Kurzhal (1997) used land use categories from the U.S. Geological Survey (USGS) and found that urban and forested areas had the greatest surface roughness in Indiana, while the greatest frequency of tornadoes was determined to be on the relatively treeless and flat plains area of the state. Dessens (1972) found in laboratory simulations that with increased roughness of the surface vertical speed shear decreased and turbulence increased in the lowest layer. He did not, however, address the issue of possible directional wind shear.

Some studies use classification of land use/land cover to determine variations in diurnal temperature range (Gallo *et al.*, 1996). Daily maximum temperatures were determined to be lower when a forested region is converted to cropland (Bonan, 2001) (though it increased low level moisture through evapotranspiration). This could also affect temperature contrast across boundary layer environments or change stability factors. Other studies reflect on increased convective precipitation activity over various ground surfaces (including cropland, or irrigated crops) that may artificially change low level moisture or heat thus changing air mass contrast across boundaries (Segal *et al.*, 1989; 1995). Also, convection was found to increase just downstream from urban environments larger than 3 million in population (Changnon, 2001). Oklahoma's winter wheat belt was found to modify the surface boundary layer at the mesoscale level, with anomalously high dew points during the growing season (November and April) and anomalously warm air temperature in July after harvest (McPherson, 2004).

New Technology

Through the 1980s detection of severe local storms had been frequently hampered by using radars based on 1940s and 1950s technology. In 1988 the U.S. Congress authorized the modernization and restructuring of the NWS, which included a new network of Doppler radars and restructuring of weather service offices with updated equipment. In 1994, the Assistant Administrator for Weather Services of the National Oceanic and Atmospheric Administration (NOAA) testified before the U.S. Congress for the continued modernization of the NWS and that tornado warnings using the older radars were usually being issued only when visual sightings had been reported (United States, 1994). This next generation radar (NEXRAD, later referred to as WSR-88D) network is a joint agency program of the National Weather Service (NWS), the Federal Aviation Administration (FAA), and Department of Defense (DOD). The deployment of these radars took the majority of the 1990s, but the last of 166 was deployed in 1997 (Crum *et al.*, 1998). The assistant administrator also made the following comments in favor their deployment: "Historically, severe weather events as a whole have had a bias toward areas of larger population. This was related to the number and aggressiveness of trained spotter networks available to provide ground truth reports of severe weather." and "With the introduction of the WSR-88D, we feel that there is no population bias where the radar is being used operationally." While being questioned on an extra radar site being necessary at Huntsville, AL, and the possibility of a range bias owing to this area being too far from a radar without one, he stated that Huntsville "lies well within Doppler range of the planned sites near Nashville, about 103 miles north; Columbus AFB, about 114 miles southwest; Birmingham, about 109 miles south southwest, and Fort Campbell, about 140 miles north" (United States, 1994). For detection of severe local storms for warning purposes, radar data are needed as close to the ground as possible to infer what weather events may be occurring on the ground. But Maddox *et al.* (2002) determined that availability of radar data to support the warning mission of the NWS is very limited below 2 km above ground level (AGL) over much of the contiguous United States and is worse below 1 km AGL (Figure 5).

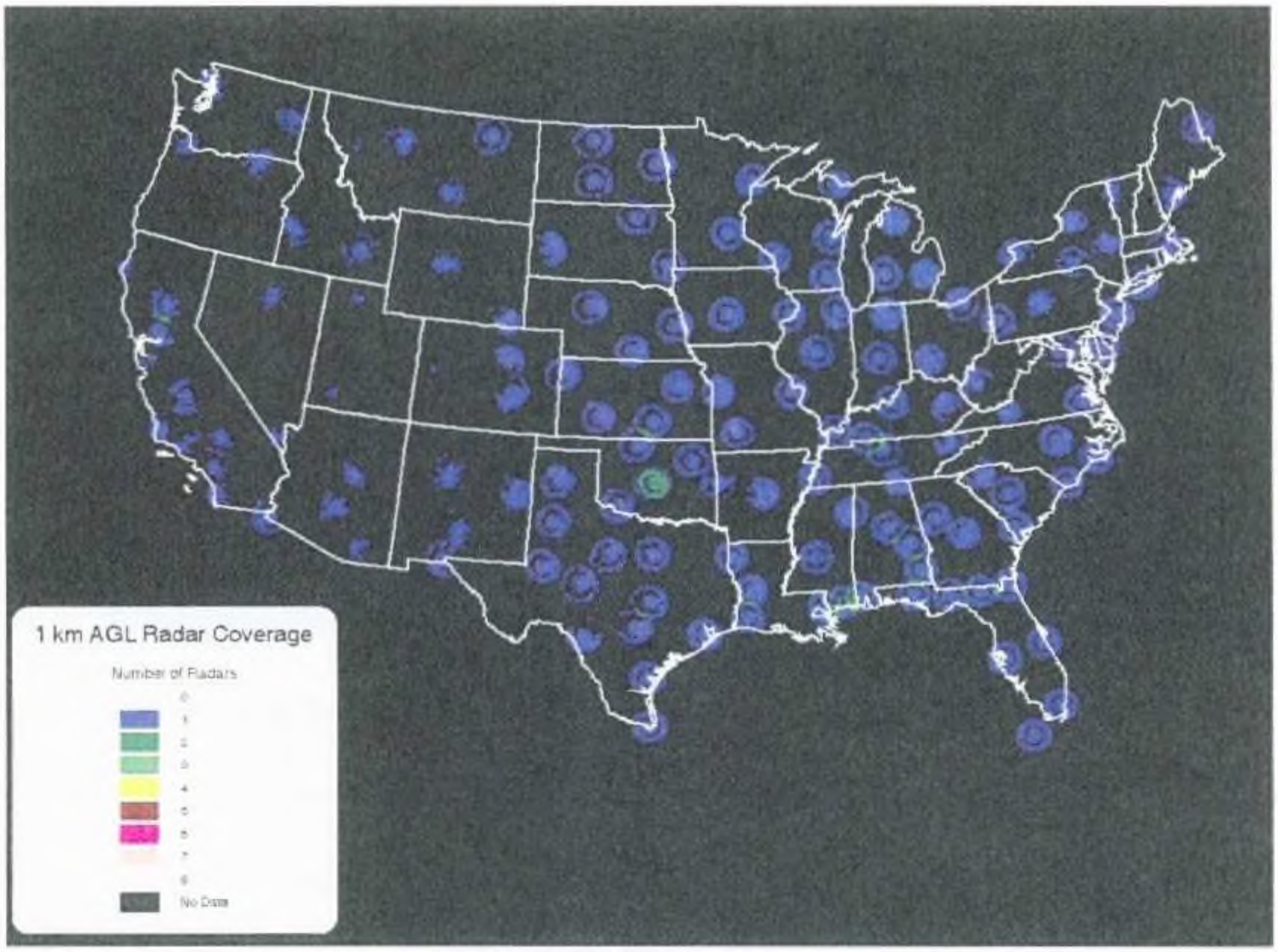

Figure 5. WSR-88D Effective Radar Coverage at a Height of 1 km AGL, from Zhang, J. and the Cooperative Institute for Mesoscale Meteorological Studies (http://www.cimms.ou.edu/~jzhang/radcov/US_lamb.radcov_1kmagl.jpg).

Verification of Warnings

The NWS uses several indices to verify their warnings and gage success in issuing the optimal number, location, and type of each kind of warning (NWS Directive 10-1601, 2003). Probability of Detection (POD) is a numerical fraction between 0 and 1 calculated by dividing the number of correctly forecast events (A) by the number of actual events (A + B), where B is the number of events observed but not forecast:

$$POD = A / (A + B).$$

False Alarm Ratio (FAR) is a numerical fraction between 0 and 1 equal to the number of false alarm warnings (C) divided by the total number of warnings (A + C):

$$FAR = C / (A + C).$$

The Critical Success Index (CSI) is the ratio of correct warnings (A) to the number of events (A + B) plus the number of incorrect warnings (C), with the best possible score being 1:

$$CSI = A / (A + B + C).$$

Every WFO seeks to correctly identify and then warn for the maximum number of severe thunderstorms in their area of responsibility (POD) while not over-warning (FAR), which may lead to ambivalence by the public and possible loss of economic productivity. A high CSI achieves the dual objectives of correctly warning for all actual severe events and not over-warning for incorrect events. Though it is not expressed explicitly, it is implied in the NWS mission statement and operations manual that a high POD is sought even if the price is a higher FAR than desired. The priorities as outlined in the NWS operations manual are: 1) protection of life; 2) protection of property; and 3) promotion of the Nation's welfare and economy (NWS Operations Manual, 2006). CSI can be somewhat misleading as the best measure of success since it implies that high POD is as equally desired by the NWS as low FAR.

It is very likely that there is no "correct" number of warnings that a WFO should issue even though the definitions of severe thunderstorms and tornadoes are constant throughout the nation. People typically respond to issued warnings differently by region. Sims and Baumann (1972) indicated that people in Alabama were more likely than people in Illinois to die from a tornado even if they had been adequately warned, while other factors were kept constant. The Alabama residents were less likely than those in Illinois to respond to a warning by seeking shelter because they believed that "it would be their time" if it resulted in their death. People in Illinois tended more to believe that their destinies were in their own hands and would prepare for and then respond to warnings by seeking shelter. Thus, the warning itself carries a different meaning depending on the user. Perhaps false alarms also carry greater significance in one region versus another, leading to greater justified caution by warning meteorologists to evaluate the consequences of a false alarm. This may lead to waiting until they feel more confident about the threat, and fewer warnings. Roulston and Smith (2004) point out that when forecasters issue nonprobabilistic forecasts (binary), such as the severe thunderstorm and tornado warnings, they also make implicit assumptions about the cost to loss ratios and the tolerance of the users. They conclude that a higher false alarm ratio may be acceptable in low cost to loss ratios, relatively high frequency events, and for users who have a moderate intolerance to false alarms, factors not considered in FAR scores within the NWS.

In still other regions the definition of a thunderstorm that is actually severe may be different. For example, a storm that drops 0.25 inch diameter hail but accumulating five inches deep may not be more than an inconvenience in a forested or urban area, and does not meet criteria for issuance of a warning. But the same occurrence on a field of crops may prove disastrous. Verification as practiced by the NWS requires exact criteria to be met, yet incorporates much subjectivity over whe[illegible]y were met (i.e. a visual estimation that the wind gust was 58 mph and not 57 m[illegible]

CHAPTER III

STUDY AREA

The area in the United States between the Rocky Mountains to the Appalachian Mountains and extending from the border of Canada to the Gulf of Mexico was selected for this study (Figure 6). It is the region in the world most affected by severe thunderstorms, contains the most complete data set in the world for severe weather events, and possesses relatively even terrain. The study area extends south to the Rio Grande Valley and through Florida, and north to the Canadian international border. Nearly bisecting this area is the Mississippi River from which terrain gradually rises towards the north, east, and west directions. Exceptions include the Ozark Mountains, primarily in Arkansas and southern Missouri, with only a few peaks exceeding 600 m, and the Black Hills which rise 1200 m from the surrounding plains. The High Plains gradually rise westward towards the Rocky Mountains and eventually approach 2000 m before reaching the foothills, but there is isolated higher terrain on these plains that may contribute to localized maxima in severe weather. On the eastern side are the Appalachian Mountains that generally rise to a ridge averaging almost 1000 m with a few peaks exceeding 2000 m. A major water body affecting this area is the Gulf of Mexico, which is the region's most significant source of moisture for convective storms. The relatively cool water of the Great Lakes usually helps to cool air in the boundary layer near and immediately downwind of the lakes, which helps to moderate storms to less than a severe level.

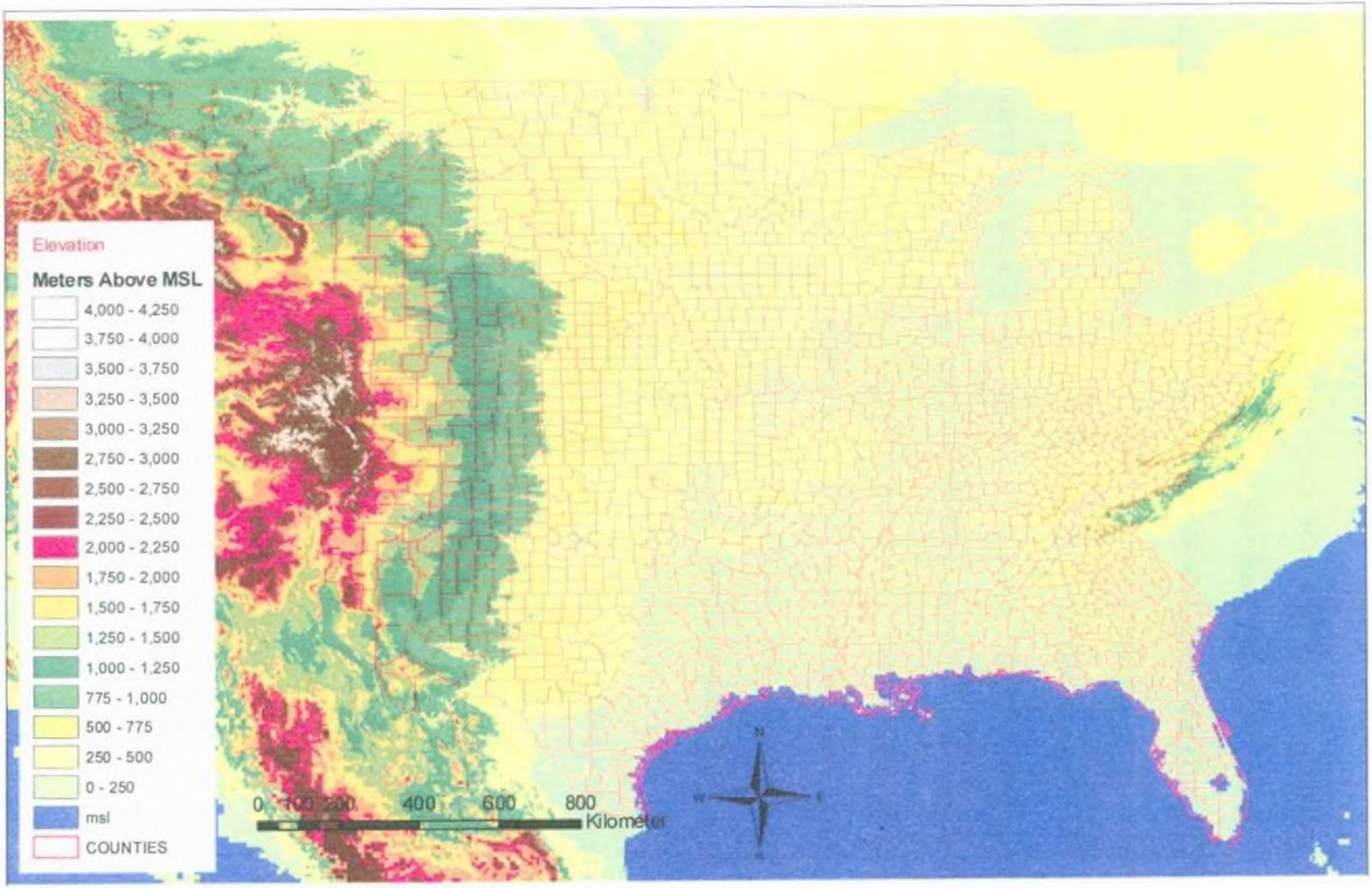

Figure 6. Topographic Map of the Study Area.

Due to the results of initial mapping efforts for the spatial distribution of warnings, the study area was expanded to include Georgia and Florida. It was later decided to not extend northward along the East Coast due to time constraints and increasing population density tending to skew the data making regression more difficult. Moreover, the study area was not extended into the western states due to extremely large counties there and highly variable topography tending to dominate the spatial pattern. The study area comprises 2,267 counties in 29 states. Figure 7 shows the county warning areas (CWA) for 63 WFOs completely contained in this region, while including parts of 13 others. The CWAs are labeled with their responsible WFO (see Appendix A for a complete listing of WFO 3-letter identifiers). However, the counties within the CWA of WFO Huntsville, Alabama (HUN), which did not open until 2003, were treated as belonging to Nashville, Tennessee (OHX, 3 counties) and Birmingham, Alabama (BMX, 11 counties), the offices to which they belonged before the Huntsville office opened. Those were the offices with responsibility for the counties for the majority of the study period. Also, the three counties belonging to the Weather Service Office in Williston, North Dakota were treated as belonging to Bismarck, North Dakota (BIS).

Figure 7. Area of Study and County Warnings Areas (CWA).

CHAPTER IV

DATA

Initial collection of data for the quantity of reported severe weather events and numbers of issued warnings was done by accessing the NWS verification website and manually copying output numbers (https://verification.nws.noaa.gov). At the time of this writing, access to this web site was restricted due to its technological inability to handle the expected traffic volume and required a password. Severe thunderstorm warnings were compiled into one data set while tornado warnings were collected into a second. A thunderstorm containing a tornado is also regarded to be a severe thunderstorm and has potential to produce damaging wind and large hail, so the tornado warning data are a subset of the larger severe thunderstorm warning data set. Recorded information included the number of events and warnings in each county from 1986-2004 and also for the 1995-2004 period. County scores for probability of detection (POD), false alarm ratio (FAR) and critical success index (CSI) were recorded from the website before and since the commission year of the radar closest to the county. The WSR-88D radar network became more than half commissioned by the end of 1995 and was completed by 1997. Since the radars were in unofficial use even before their commission dates, for the study of spatial distribution of the number of warnings the network was treated as complete in 1995. The distance each county is from the nearest radar was determined manually by using the NWS Advanced Weather Interactive Processing System (AWIPS) computer system. Radar names, locations, and their commission dates were copied from the NWS Operations Support Facility web site (http://www.roc.noaa.gov). WFO locations and their county assignments were accessed through NWS Directives at the NWS website (http://www.nws.noaa.gov/directives).

County data regarding population, county federal information processing standard (FIPS) codes, and county size in square miles were recorded directly from the 2000 U.S. Census available at the U.S. Census Bureau web site (http://www.census.goy). All data was converted to metric units.

This research focuses primarily on the 1995-2004 time period during which there were 213,761 severe thunderstorm warnings and 30,639 tornado warnings, for 244,400 total warnings issued in the 2,267 counties of interest. Five primary variables were used in analysis: 1) number of severe thunderstorm warnings issued in each county, divided by aerial county size (dependent variable); 2) number of tornado warnings issued in each county, divided by aerial county size (dependent); 3) population density in each county (independent); 4) distance the center of a county is from the nearest WSR-88D radar after completion of the network (independent); and 5) the 75 WFOs issuing the warnings (independent). Table 1 shows the descriptive statistics for the raw data for the four quantitative variables.

Among the assumptions of regression analysis are that the variables have a normal distribution while having a linear relationship between them. Failure of the linearity assumption results in multicollinear variables which is when the effects of supposedly independent variables cannot be disentangled. The population density variable is highly skewed while being extremely leptokurtic which caused it to be untransformable to a normal distribution. The distance variable is quite platykurtic and

Table 1. Descriptive Statistics of Variables.

	Severe Thunderstorm Warnings	Tornado Warnings	Population Density	Distance to Radar
Counties (n)	2267	2267	2267	2267
Mean	65.23	7.86	44.85	107.00
Standard Deviation	35.67	5.92	128.72	48.57
Standard Error	0.75	0.12	2.70	1.02
C.I. of Mean	1.47	0.24	5.30	2.00
Range	553.62	56.27	2195.34	325.9
Max	554.53	56.27	2195.38	326.8
Min	0.91	0.00	0.04	1.85
25%	41.49	3.52	6.54	72.23
Median	60.49	6.61	14.67	105.56
75%	82.39	10.68	33.20	138.90
Skew	2.46	1.51	8.69	0.33
Kurtosis	20.85	4.57	102.31	0.09
K_S Distance	0.07	0.09	0.36	0.03
Sum	147878.0	17826.6	101686.0	242563.8
Sum of Squares	12530198.3	219521.3	42105948.9	31298988.8

also very difficult to transform. The two dependent variables could be transformed to a normal distribution only if the α level reduced to 0.01. Deletion of outliers and modification of some of the more extreme values was examined but did not result in normality for any variable. Doing so appeared to cause a critical loss of explainable variance since some of the extremely high values in the dependent variables were paired with extremely high values in the independent variables. Since regression is more robust to violations of assumptions especially in large data sets (Tate, 1992; Mertler and Vannatta, 2005), regression was tried anyway but only R^2 values of less than 0.12 were attainable for the severe thunderstorm warning data set and 0.03 for the tornado warning set, both of which failed constant variance tests.

Better success was achieved if the sets were broken into smaller groups based on CWA, or groups of several CWAs. The dependent variables were then transformable to normal (α=0.01) by using a square root transform function. Exceptions included the severe set at Pittsburgh, Pennsylvania (PBZ), where a reciprocal transform function was required, and for the combined CWAs of St. Louis, Missouri (LSX) and Central Illinois, Illinois (ILX), where a logarithmic transform was used. Population density remained untransformable even at the more local level so both independent variables were accepted for regression as they were and the robust quality of regression was relied upon. But passing the normality and constant variance tests remained included in the requirements to determine which equations explain the variance.

The independent variables (population density and distance from radar) are somewhat correlated themselves, which may reduce the potential R values obtainable through regression. Figure 8 and the exponential regression equation (R^2=0.148) calculated using Excel show that radars tend to be located closer to population centers (with the scale of population density having been truncated above 100 persons/km^2). The Spearman Rank Order Correlation value for the relationship between these two variables is 0.356. However, mindful of this tendency, no county data was flagged by SigmaStat as being multicollinear, so no adjustments were made regarding this issue.

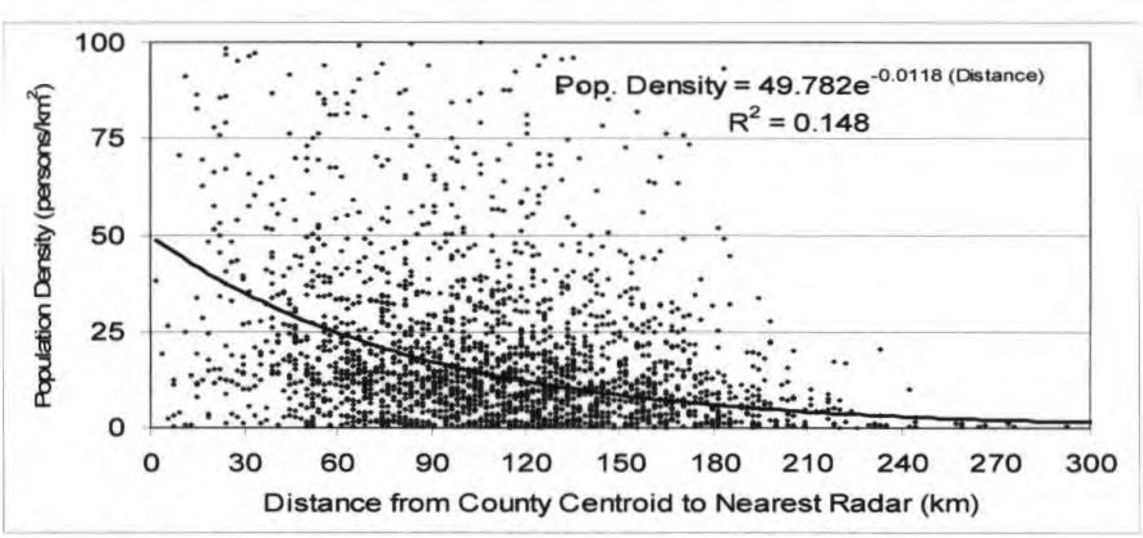

Figure 8. Scatterplot of County Population Density vs. County Distance From the Nearest Radar.

CHAPTER V

METHODS

Microsoft Excel was used extensively for data maintenance and generation of analysis results through this program's ability to use arithmetic equations, its ability to generate some of the initial regression analysis, and its compatibility for copying data into GIS software. All raw numbers of events and warnings recorded in individual counties were divided by their aerial county size to correlate them and then multiplied by 1,000 to convert their values to a per 1,000 km^2 basis for easier interpretation. These became the dependent variables.

Quality control of the data was done using several computer programs. Excel was used to total the numbers of events and warnings in each state from the verification website, and then data were checked to ensure that the resulting totals matched those on the web site. MapViewer (5.0) and ArcView GIS (9.0) were used to quality control radar names and locations, WFO names and locations, and distance from the nearest radar by using FIPS codes to plot them on a generated map to verify their correct location assignments. Maps were generated in ArcView GIS.

To answer the first primary research question of potential population bias and distance from radar bias, regression analysis was used to partition their different aspects and determine the degree of dominance for each in prediction of the dependent variables. The null hypothesis was that there is no difference (H_0: $\mu_1 = \mu_2$), or that regression equations involving the two independent variables do not significantly predict where warnings are issued. SigmaStat statistical software was used to transform data, derive regression equations, and conduct t-tests and Mann-Whitney tests. This software utilizes the Kolmogorov-Smirnov test to determine normality of the data. Regression was performed by deriving the best equation for each CWA(s), whether it was linear, multiple-linear, non-linear, logarithmic, polynomial, or exponential. Determination of which regression equation to use was done by determining which solution achieved the highest R^2(adj) score while passing the normality and constant variance tests, reaching a $\rho \leq 0.05$ value in the ANOVA F-test, and attaining a power rating ≥ 0.8 (Agresti and Finlay, 1997; Mertler and Vannatta, 2005). If no equation was found that met all of these criteria for a given WFO(s) then no equation was used in adjustment of its dependent variables; and bias was assumed to be immeasurable. The successful equations show how much the two variables contribute to the variance of warning distribution. It was thought that in most cases the majority of variance would be explainable by natural atmospheric conditions and any local topographic anomalies (such as more stability available very near the Great Lakes thus leading to fewer severe storms there). Very high R and R^2(adj) scores were not expected.

Regression and t-tests were the statistical tests of choice due to their robust qualities in dealing with data that in some instances could not pass the normality or constant variance tests. Regression was also chosen for its ability to quantify relative influence by independent variables.

When deriving equations for individual WFOs, usually both the population density and distance independent variables were included. But, using one variable produced a better score in some cases. Roughly a 15:1 ratio (Stevens, 1992) was used between the minimum number of counties included and the number of independent variables utilized. Using that ratio, it was possible to derive an individual equation for only 32 of the 75 CWAs. Other CWAs were combined with others in close proximity to increase the number of counties (n) used in regression, especially if scores improved when doing so or when it helped to normalize input data. The 75 CWAs were then reduced to 49 groups, each with their own regression equation and scores (see Appendix B for WFO groupings, equation lists with coefficients, F-test results and power ratings).

After regression was complete, the actual values of population density and distance from radar were removed from the equation of each county, and replaced with constants. This was intended to produce a spatial pattern that would be equally correlated across this large area with no differences due to these variables. Studies show that population densities between 1.5 and 6.0 persons/km^2 would result in at least half of all tornadoes being reported (Newark, 1983; King, 1997). While this article studies warnings rather than reports, it stands to reason that a significantly higher population density would result in nearly all tornadoes being reported, and eventually that value flat-lining at some maximum figure. Figures 9 and 10 are scatter plots of the dependent variables versus the independent variables with regression lines computed using Excel. Each of the dependent variables tends to rise logarithmically with population density but decrease linearly according to distance.

For this study the population density value chosen to substitute in regression equations in both data sets was 44.9 persons/km^2. This value was chosen because warnings begin to flat-line above this level and because it is the mean observed value for all counties. Using higher values sometimes resulted in over-inflation of numbers when

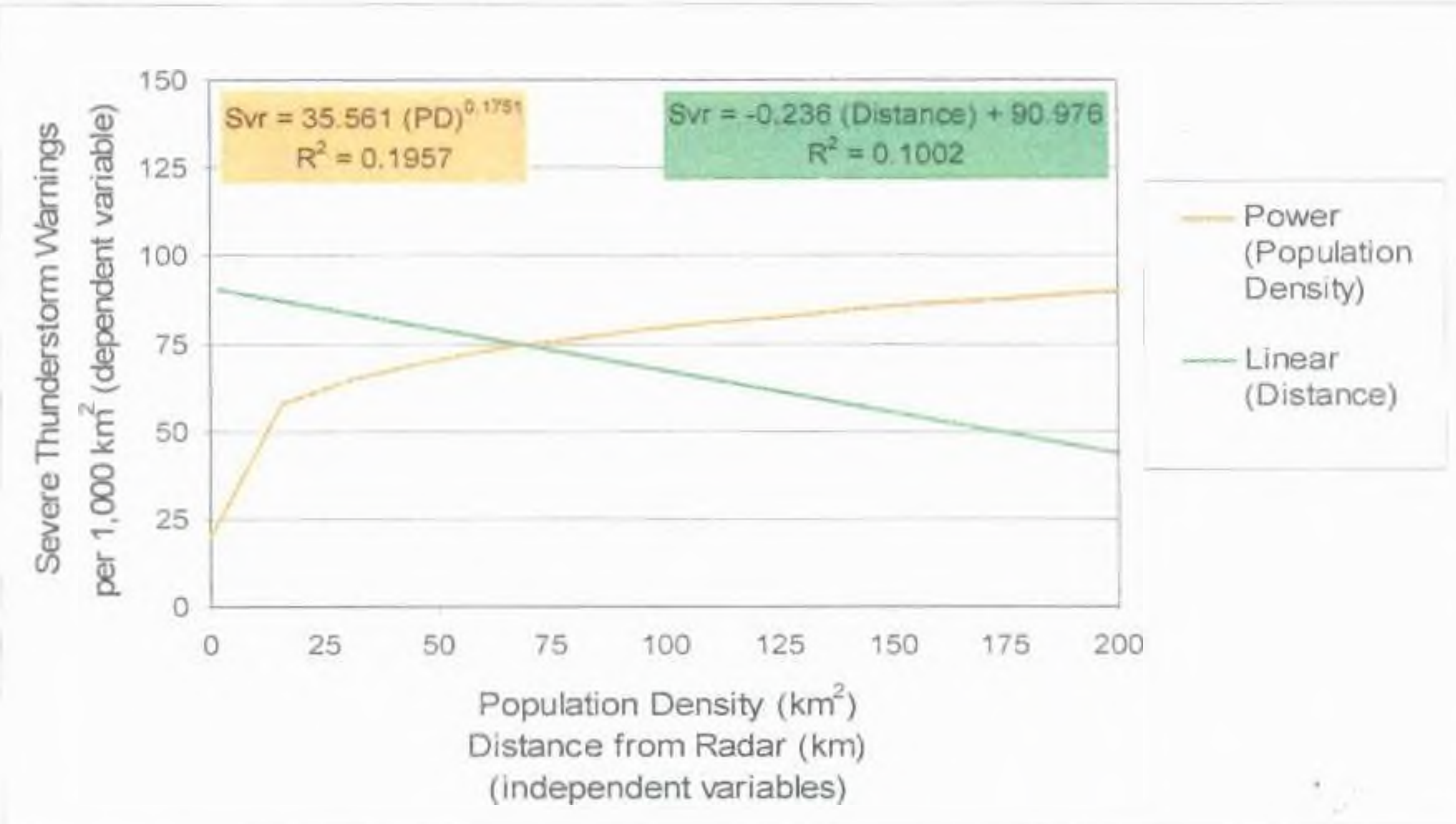

Figure 9. Regression Trends for the Number of County Severe Thunderstorm Warnings Issued per 1,000 km^2 vs. Population Density of the County and its Distance from Radar.

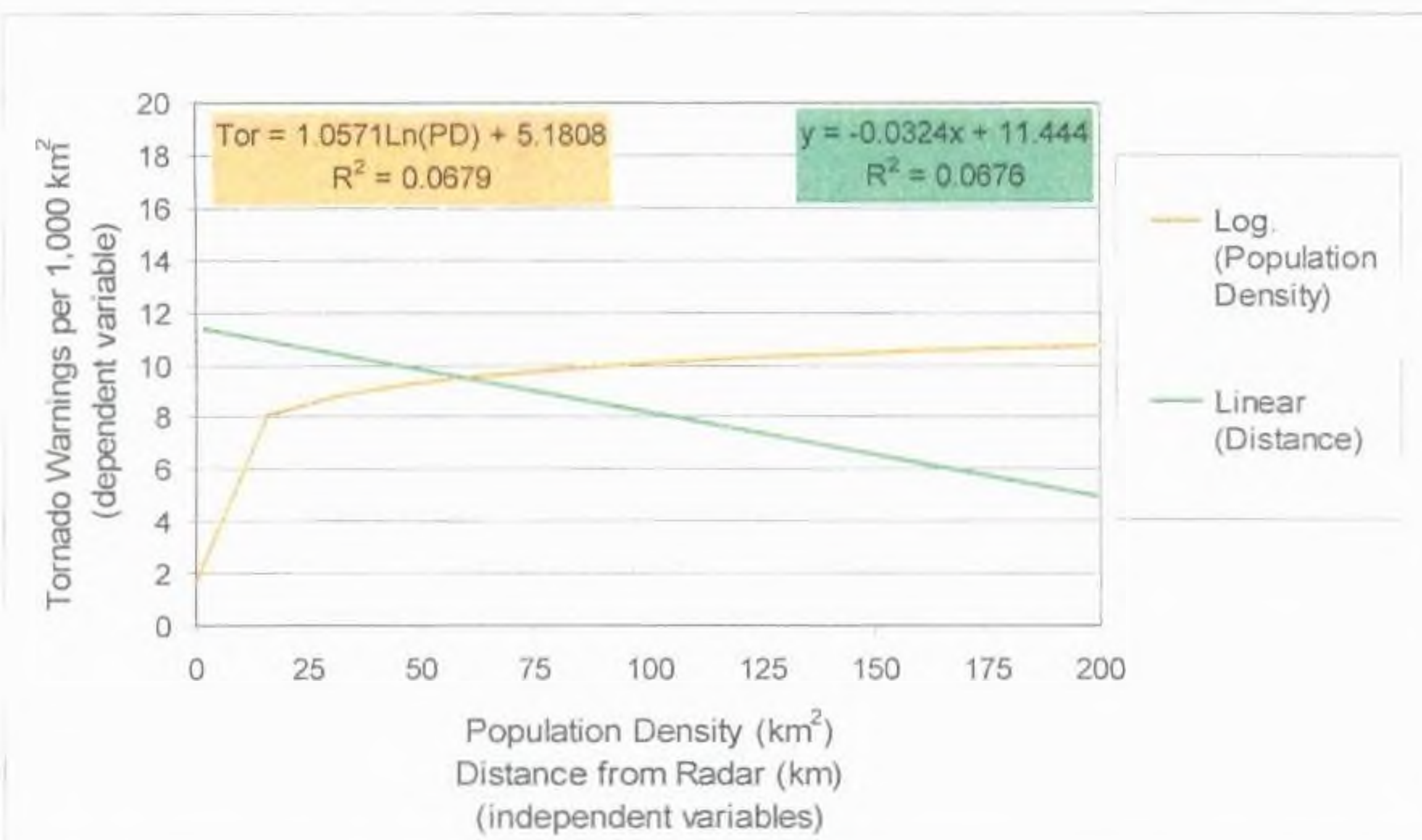

Figure 10. Regression Trends for the Number of County Tornado Warnings Issued per 1,000 km^2 vs. Population Density of the County and its Distance from Radar.

either population density input values used to derive an equation were very much different than this value or a high order polynomial equation fit the data best.

For distance from radar, Vasiloff (2001) stated that tornado algorithms are not effective beyond 60 km for detecting all but the largest tornadoes. However, somewhat greater distance from the radar is sometimes useful for sensing higher levels of a thunderstorm to maximize the number of useful slices the radar can obtain in a storm. With these thoughts in mind, Figures 9 and 10 show that a trade-off is made to select 60 km to use as the best distance to substitute for actual values in the regression equations.

Figure 11 is a graphic example of how the regression and adjustment were done for the number of tornado warnings in Golden Valley County, North Dakota. A scatter plot was created for the counties in the Bismarck (BIS) area, with the best regression line placed over it (in this case a linear regression line with the only independent variable being distance from radar). The square root of the actual value per 1,000 km^2 was 1.5 with a distance from radar of 266.7 km. Moving along the regression line, the distance was reduced to 60 km while holding the residual constant. A new value of 2.63 was then reached and squared again to remove the effect of the transform function. This results in a new value of 6.92 tornado warnings per 1,000 km^2.

A similar regression procedure involving both independent variables was done for every county in each data set. Once regression is finished it is expected that the number of county warnings per 1,000 km^2 at each data point would reflect the number that might have been issued if every county had a population density of 44.9 persons/km^2 and its county centroid been 60 km from the radar station.

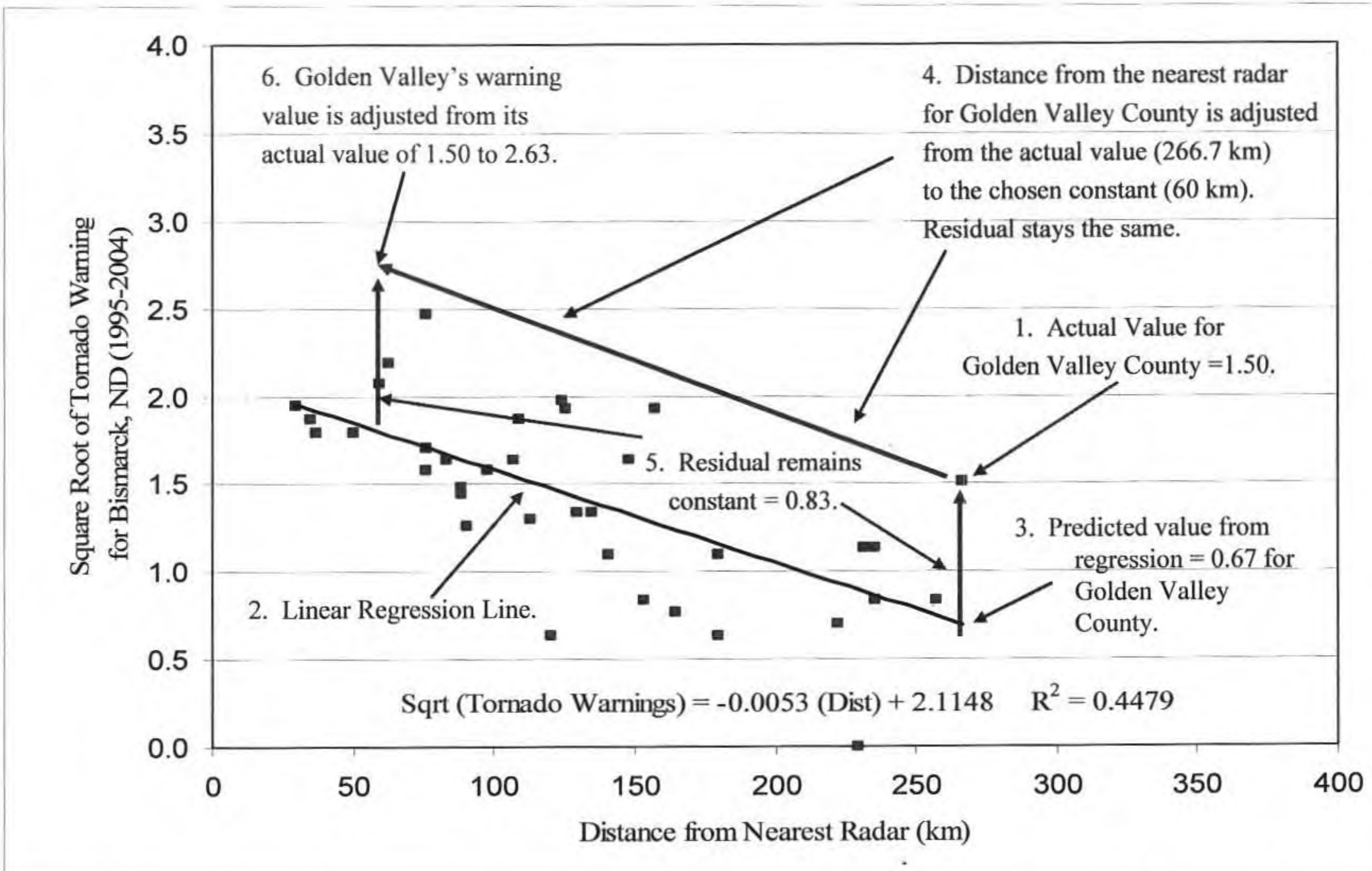

Figure 11. Example of how an adjustment was made to the number tornado warnings in Golden Valley County, ND through Regression.

After much of the population density and distance biases have been removed, it seems likely that the remaining variance not due to spatial differences in atmospheric or topographic conditions would be the result of subjective practices by meteorologists in WFOs. Such differences between CWAs could not be labelled as a "bias" even if the numbers of one CWA were vastly different from the other CWAs around it. As discussed earlier, the dynamics of warning responses are too variable according to the user. Determination of a "correct" number of warnings that should have been issued must involve a great deal of subjective judgment. It is for the issuers of those warnings to determine whether they should change how frequently to "pull the trigger" in the warning process and warn to obtain a maximum effective response from their users.

The second primary research question, the possibility of significant differences between quantities of warnings between adjacent WFOs/CWAs (categorical independent variable), was addressed individually for each CWA. To the individual warning meteorologist it is useful to know if their office issues a significantly different number of warnings than its neighbors, and by how much. Since these data are at a nominal level they were not included in regression, but done afterward using t-tests (Mann-Whitney tests when either the normality or equal variance tests failed). In these tests, after any identified biases had been removed, values from all available counties of a CWA were compared against all counties contained within all CWAs adjacent (sharing a common border) to the CWA being tested. Using the Eastern North Dakota WFO/CWA as an example (Figure 12), counties in the area shown in white (the tested CWA) is considered one group and tested against all counties shown in gray (BIS, ABR, MPX, and DLH), the second group. The null hypothesis in these tests is that there is no difference between the

Figure 12. Eastern North Dakota, ND County Warning Forecast Area (CWA) and Surrounding CWAs.

CWA being tested and the group of CWAs surrounding it (H_0: $\mu_1 = \mu_2$). The most stringent criteria possible was sought for these tests to reduce the probability of a Type I error so the most extreme alpha requirement to reject the null hypothesis was chosen ($\alpha = 0.01$) while attaining a power rating of at least 0.8 (Agresti and Finlay, 1997). If the test determined that the numbers were not different (did not reject the null), then it was assumed that the WFO did not issue warnings with a statistically different frequency than its neighbors and no adjustment was made. If the test determined that there is a difference (null is rejected) then it is concluded that an adjustment is necessary. A percentage would be sought to multiply the warning numbers in the tested CWA so that a re-test involving the new multiplied numbers would determine that the null could not be rejected. The resultant numbers became the finally adjusted number of warnings in each county.

CHAPTER VI

RESULTS

Initial Spatial Distribution Plots

Spatial distributions of the reported severe thunderstorm and tornado events, and distributions of severe thunderstorm and tornado warnings are shown in Figures 13-16. Although these data encompass a slightly different time period than Figures 1-3 (1986-2004 vs. 1980-1999), have a county format rather than the 80 km x 80 km grid format in Figures 1-3, and have not been smoothed, they do show similarities. While Figure 13 is a composite image representing both severe thunderstorm wind and hail, one must visually combine Figures 1 and 2 to compare them. But a broad maximum area is apparent, extending from northeast Texas, Kansas and Oklahoma eastward to at least Georgia, and northeastward to Ohio. Figure 13 is obviously noisy resulting from the use of a county format without adjustments for bias and can be compared to Figures 1 and 2 only in a general sense. The largest difference in Figure 13 versus Figures 1 and 2 is more reported events in Kansas than farther south into Oklahoma. A comparison of Figures 3 and 15 is slightly easier. The relative maximum for tornadoes in northeast Colorado and the minimum encompassing most of Missouri in Figure 15 are similar to the pattern in Figure 3. But there are many other maxima in Figure 15 that likely reflect unadjusted differences in reporting procedures and other biases discussed earlier. Some of these maxima are near the center of CWAs, such as for Des Moines, Iowa (DMX), Central

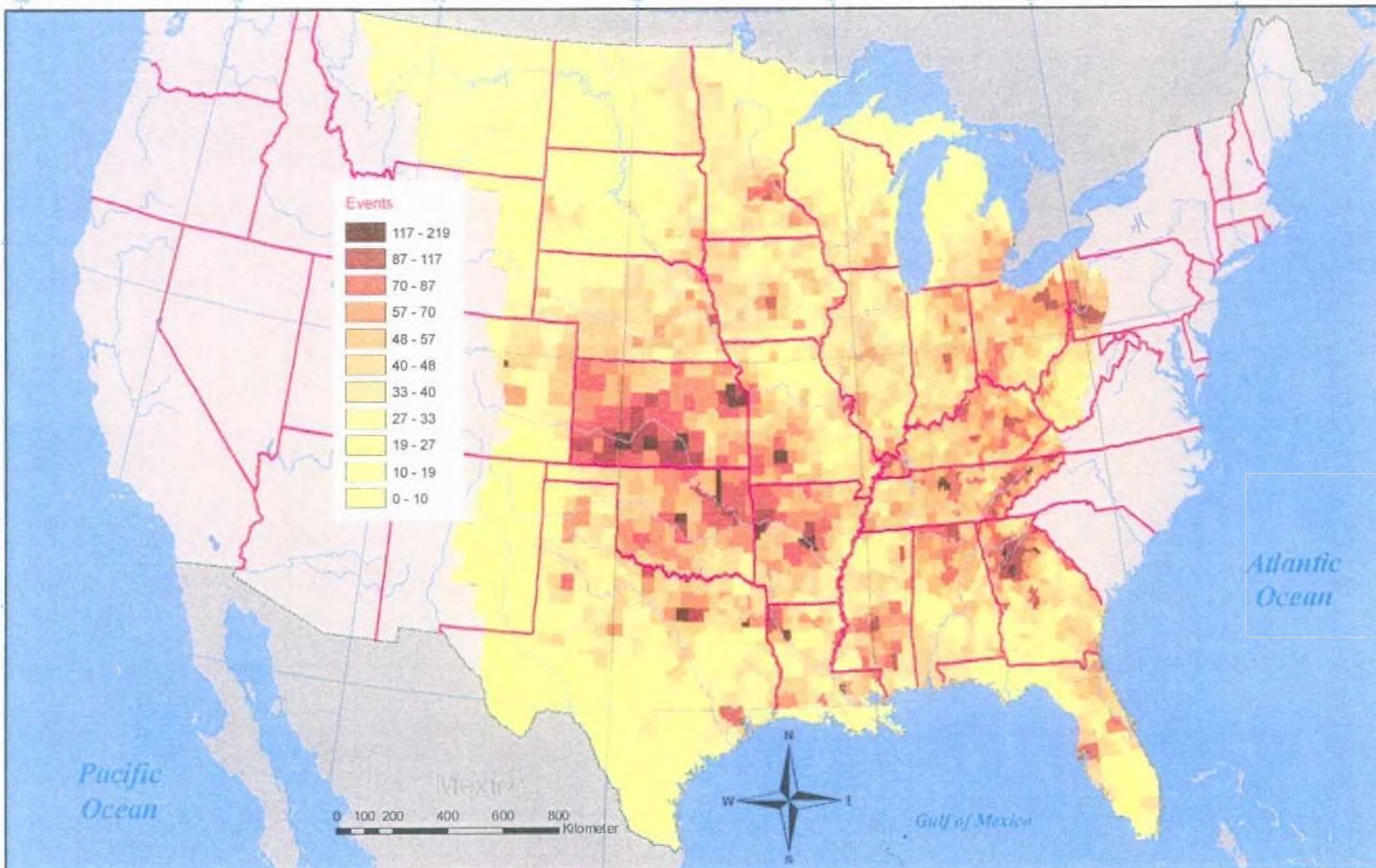

Figure 13. Reported Severe Thunderstorm Events per 1,000 km² (1995-2004).

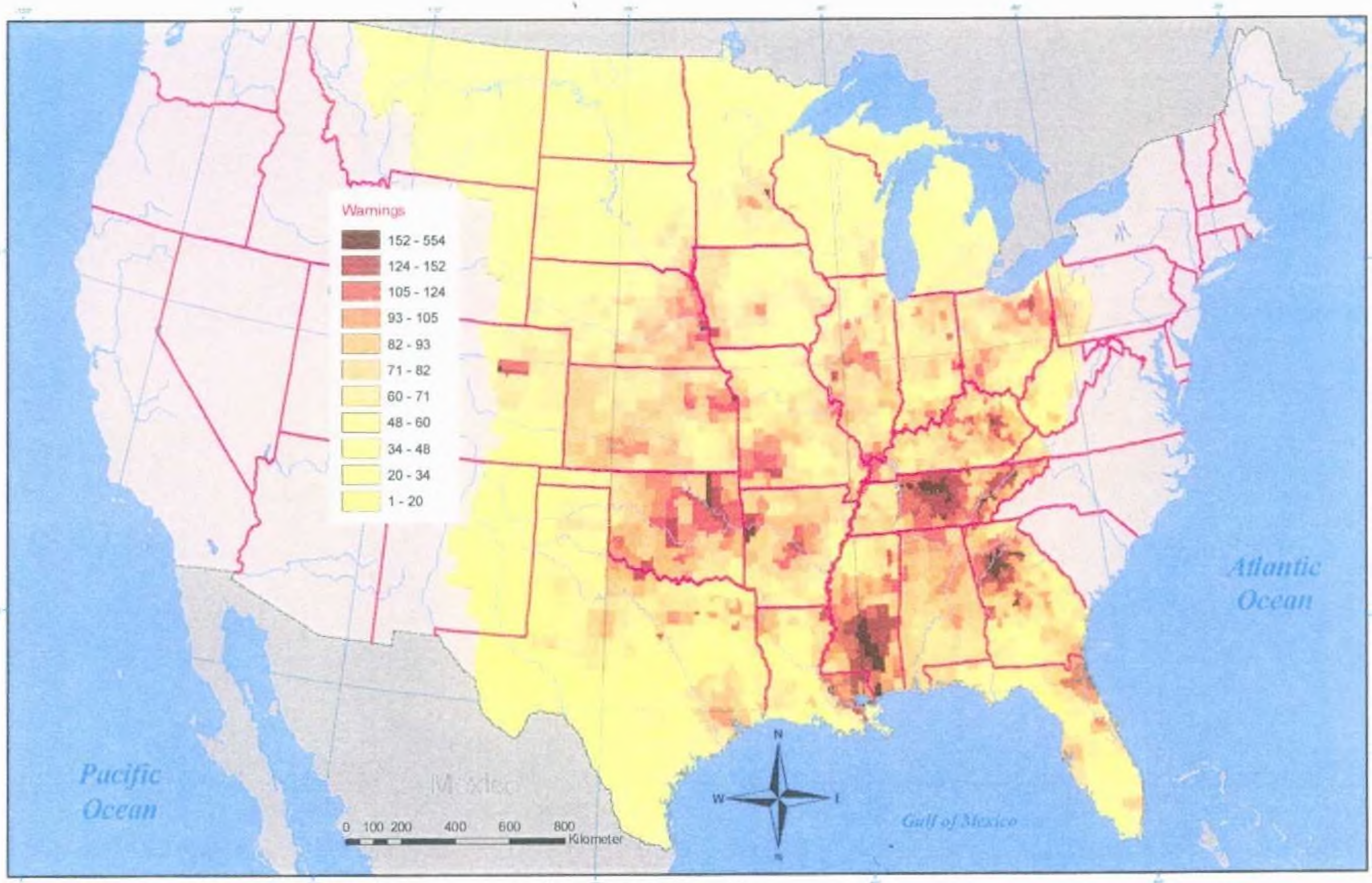

Figure 14. Severe Thunderstorm Warnings per 1,000 km² (1995-2004).

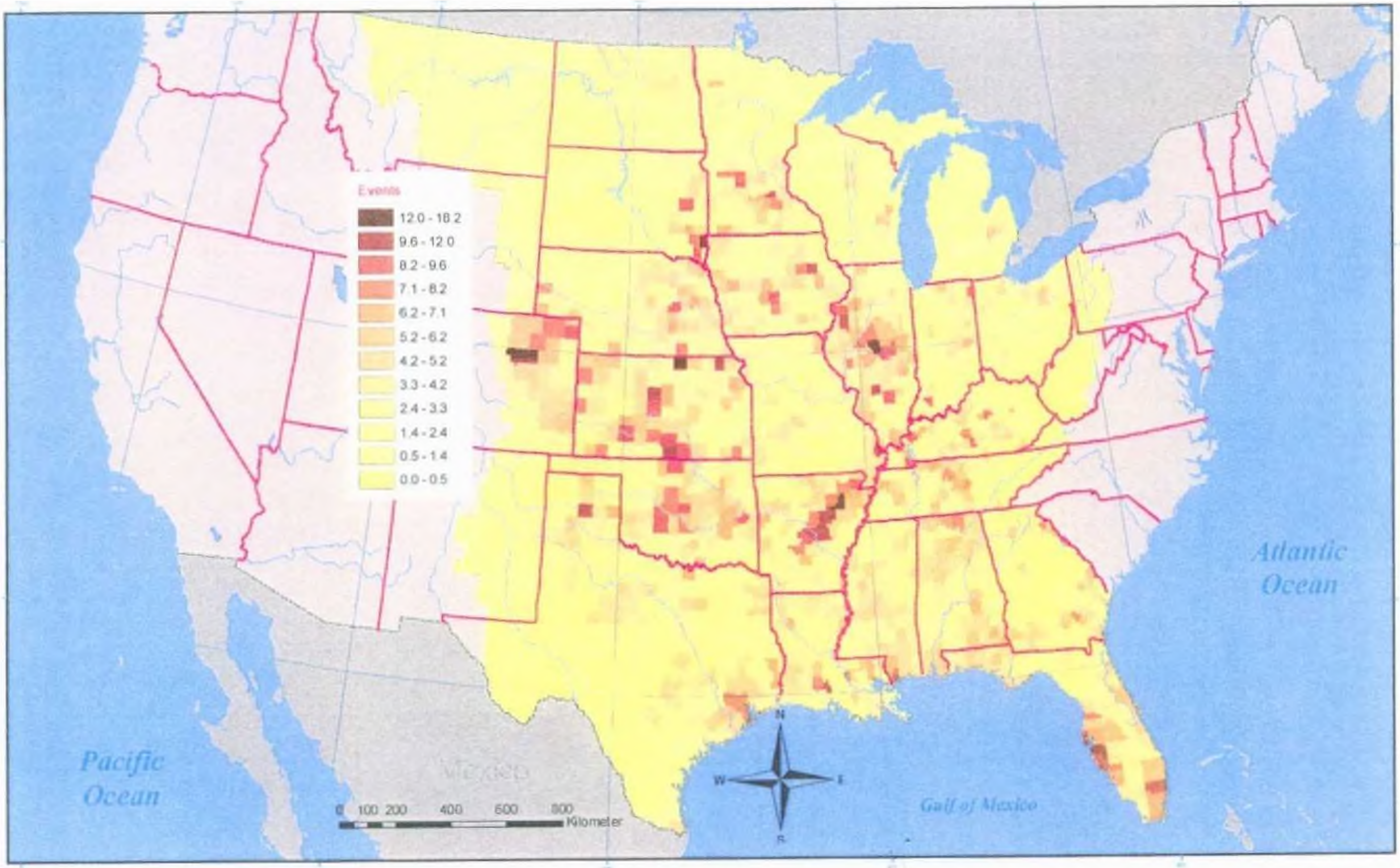

Figure 15. Reported Tornado Events per 1,000 km² (1995-2004).

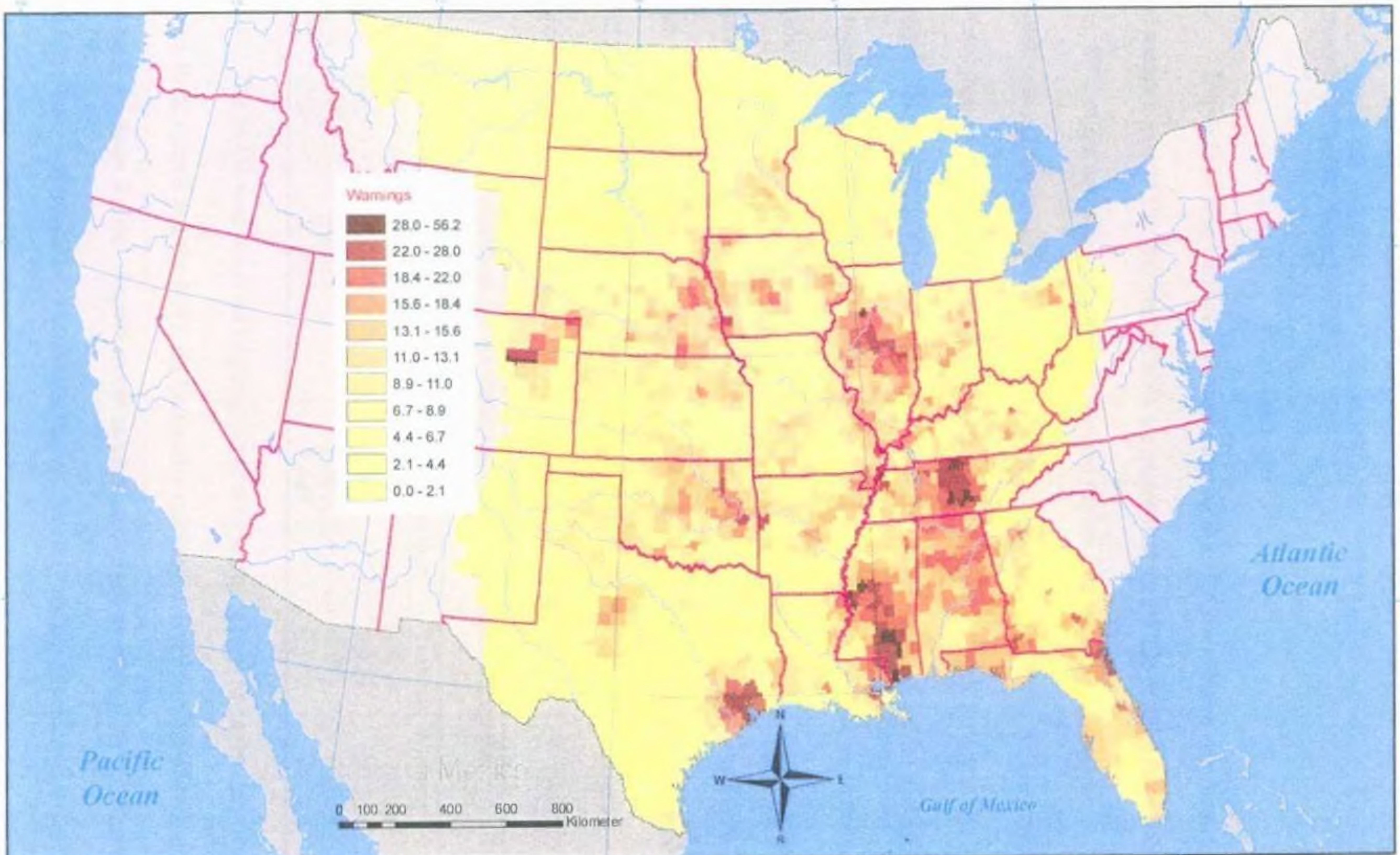

Figure 16. Tornado Warnings per 1,000 km2 (1995-2004).

Illinois, Illinois (ILX), Nashville, Tennessee (OHX), Jackson, Mississippi (JAN) and Houston/Galveston, Texas (HGX).

POD, FAR and CSI Scores

Improvement in verification scores during the 1990s and since commissioning of the radars is one of the few quantifiable measures that justify the MAR of the NWS. In fact, 89% of the counties in this study showed higher POD scores for severe thunderstorm (and tornado) warnings after commissioning the closest radar to each county than by using the older radars, and 81% showed lower FAR scores in the later period. The overall POD, FAR and CSI scores for the area studied before and after commission dates are shown in Table 2. Scores for the later period are certainly an improvement over the earlier period. Of course, there is much room for improvement, especially regarding false alarms for tornadoes. The greatest progress is with POD, rising from 0.429 to 0.711 for tornado warnings. And though it is not shown here, the average lead time in these warnings (warning issuance time before the recorded tornado touchdown) increased from 6.5 to 11.8 minutes.

Table 2. Verification Scores Before and Since Commissioning the Counties' Closest Radar.

	Severe Thunderstorm/Tornado Warnings		Tornado Warnings	
	Before	After	Before	After
POD	0.682	0.842	0.429	0.711
FAR	0.537	0.463	0.751	0.758
CSI	0.381	0.488	0.187	0.220

The MAR was and is an ongoing process of learning how to detect and warn for severe local storms and the NWS is continually working to improve identification and warning for these storms. Improvement in verification scores during the 1990s was a gradual trend, with much of it occurring during the early part of the decade, even before

1990, and it appears to have reached a plateau in the 21st Century and even possibly decreased then due to a higher FAR (Figures 17 and 18).

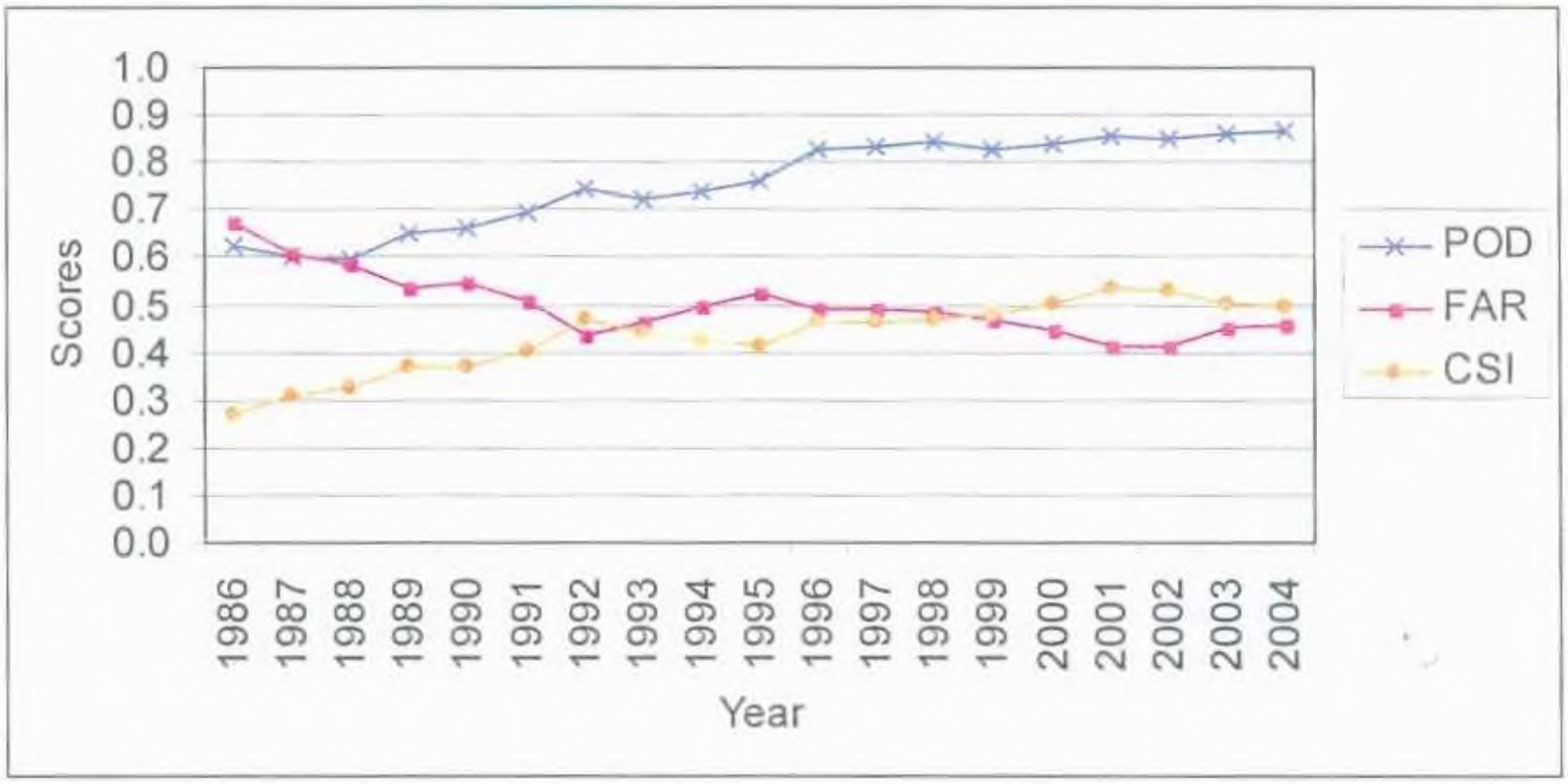

Figure 17. Yearly NWS Verification Scores for Severe Thunderstorm Warnings.

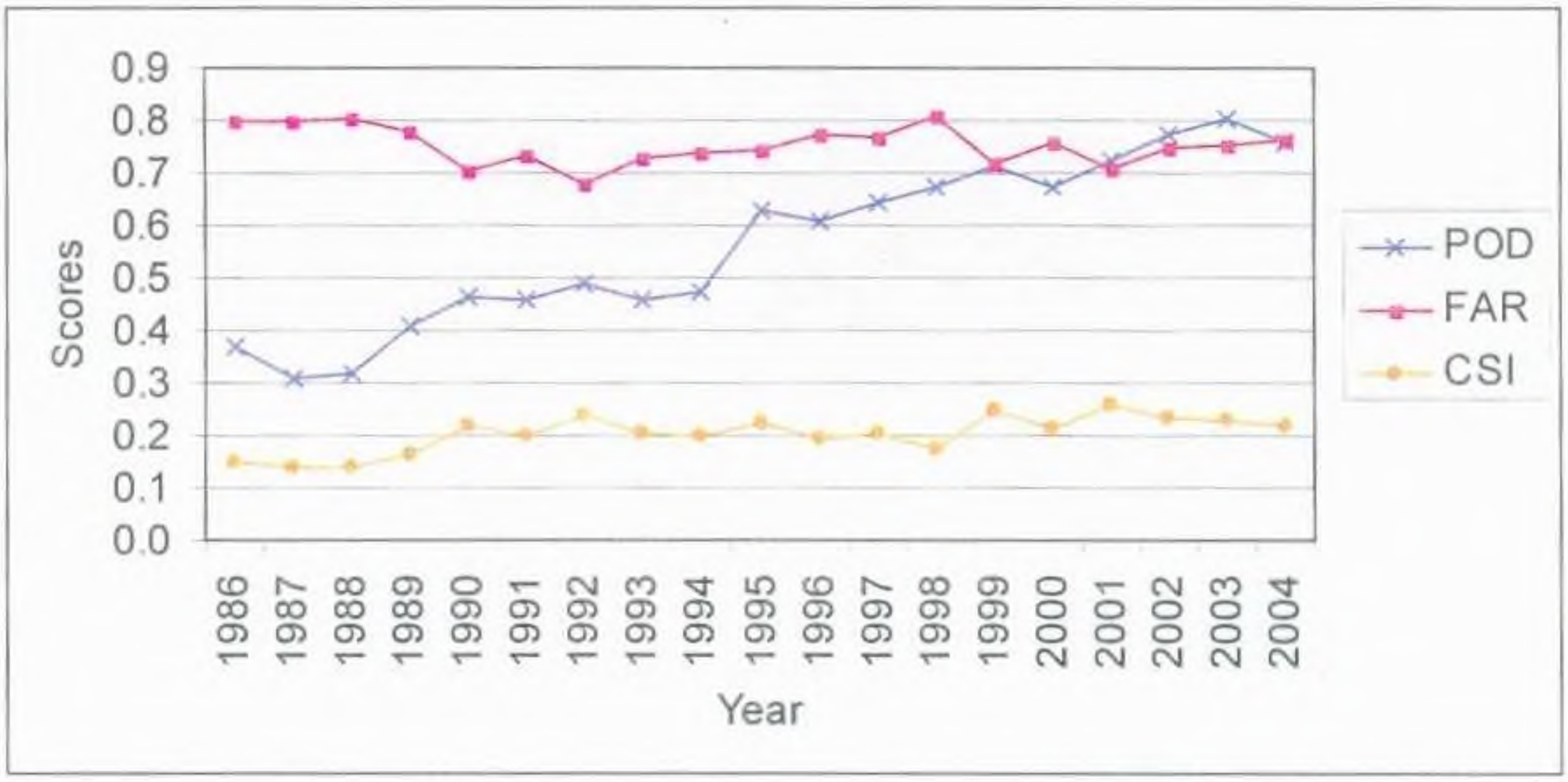

Figure 18. Yearly NWS Verification Scores for Tornado Warnings.

Figure 19 is a map of POD scores for severe thunderstorm warnings before the commission dates (which range from September, 1992 to May, 1998) of the closest radar to each county and Figure 20 is the same distribution pertaining to after those dates. FAR

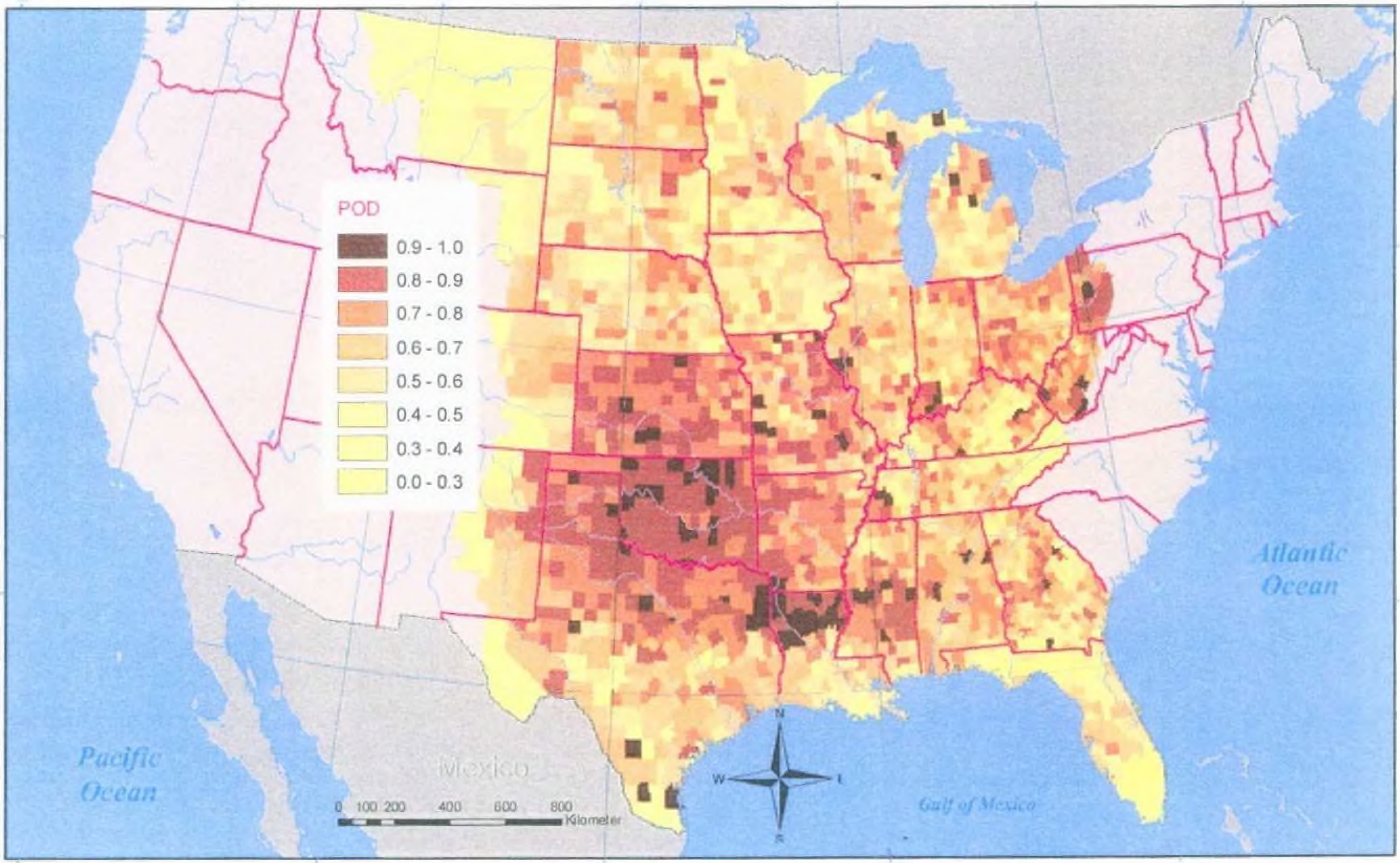

Figure 19. POD Scores for Severe Thunderstorm Warnings Before Commission Date of the Radar Closest to the Counties Shown.

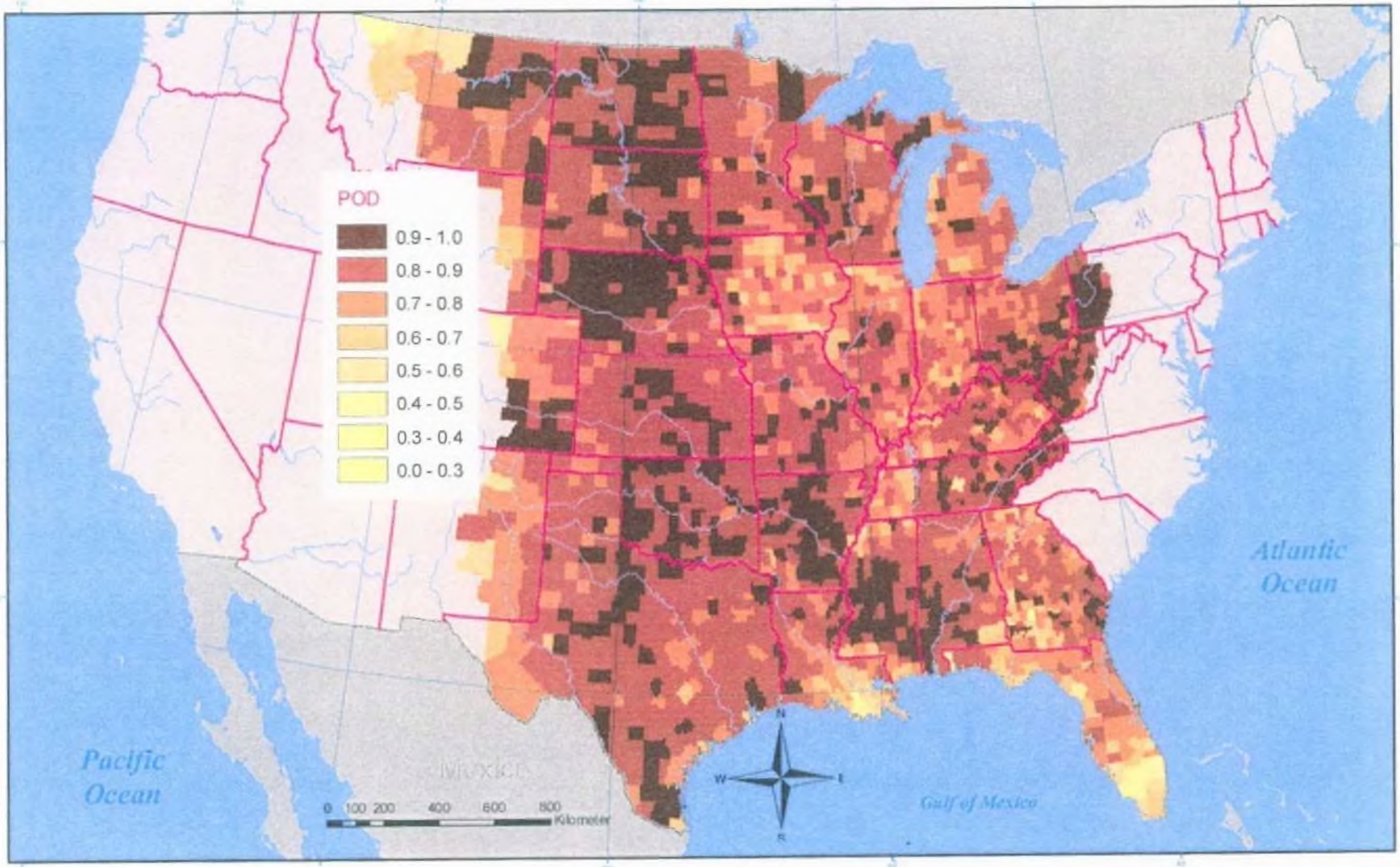

Figure 20. POD Scores for Severe Thunderstorm Warnings After Commission Date of the Radar Closest to the Counties Shown.

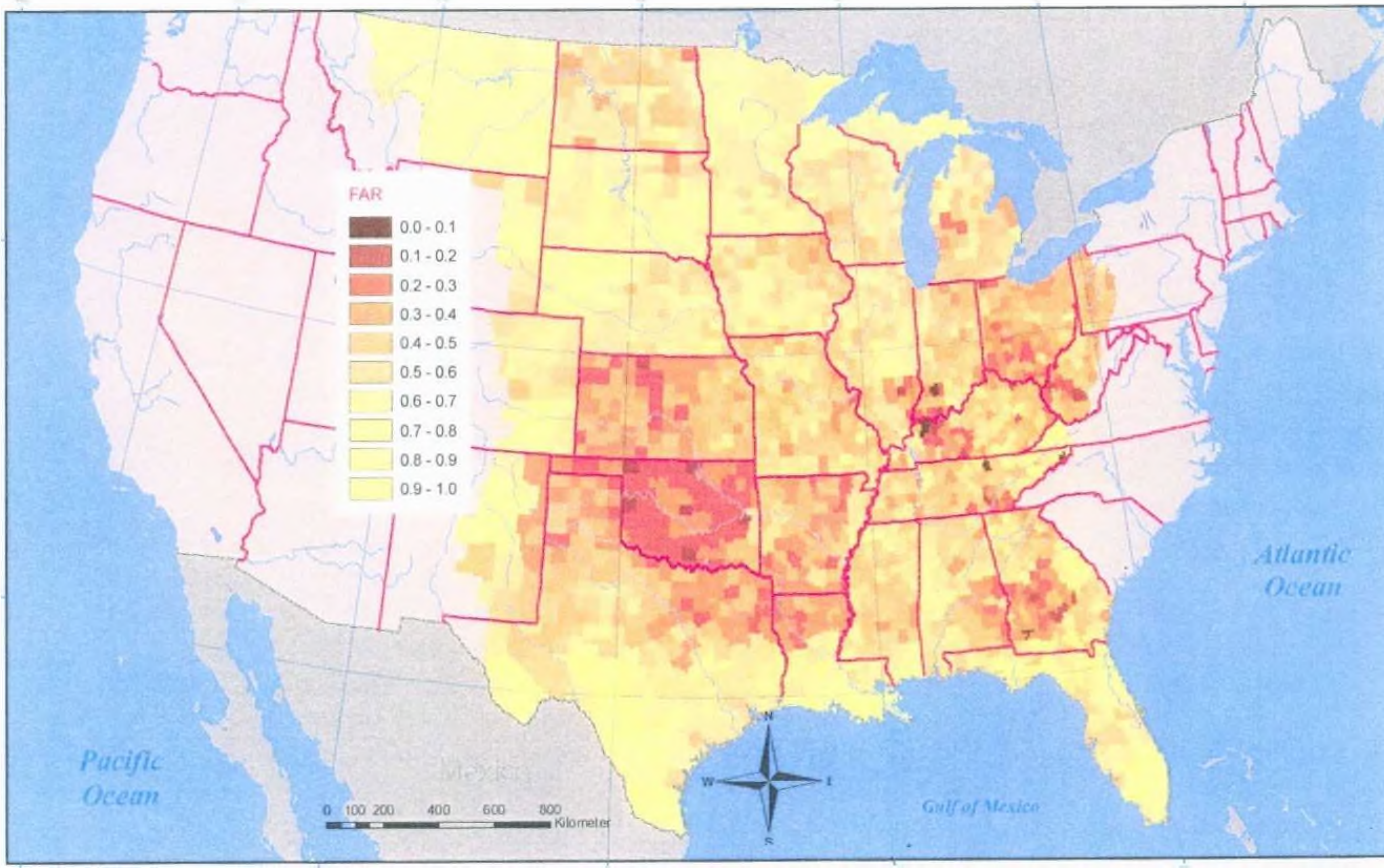

Figure 21. FAR Scores for Severe Thunderstorm Warnings Before Commission Date of the Radar Closest to the Counties Shown.

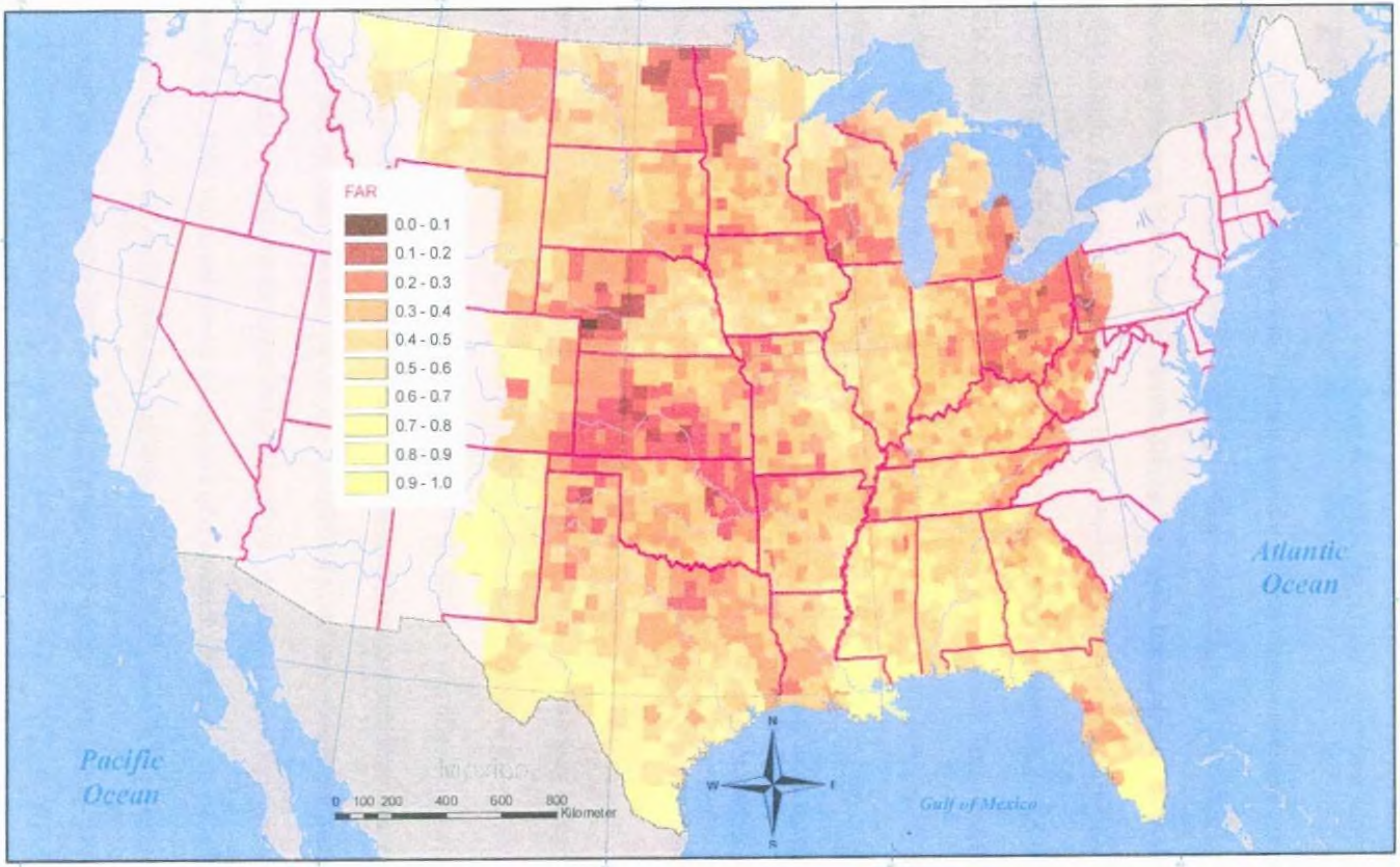

Figure 22. FAR Scores for Severe Thunderstorm Warnings After Commission Date of the Radar Closest to the Counties Shown.

scores for severe thunderstorm warnings for the same two periods are shown in Figures 21 and 22.

POD and FAR scores since commission of the radars show impressive overall improvement. In particular, both scores improved the most across the north portion including Montana, North Dakota, South Dakota, Nebraska, Iowa, Minnesota, Wisconsin and Michigan. Other areas of significant improvement include counties where local offices are responsible and doing exceptionally well, including Knoxville, Tennessee (MRX) and Lake Charles, Louisiana (LCH) and a few offices in south Texas and north Florida. Pockets of low POD and high FAR relative to overall trends remained after radar commissioning but their causes were not determined.

There are significant large areas where the use of Doppler radar has not helped improve scores as much in comparison to earlier radars. Most notably, they are in north Texas, Kansas, Oklahoma, and many counties covered by Shreveport, Louisiana (SHV) and the Weather Service Office (until 1995) in Evansville, Indiana (http://www.crh.noaa.gov/pah/history.php). Very good scores were already being achieved in those areas before arrival of the Doppler radar. The skill of the people issuing warnings and verifying them prior to the WSR-88D era was often times excellent and sometimes underestimated; they knew their radars and severe thunderstorms well.

There are other possible factors that contributed to the improved scores in the Doppler radar era, beyond the improved performance. As stated earlier, the reported events since 1980 increased almost by an order of magnitude. Since it is very likely that this number of severe events was also happening prior to MAR, then POD scores before 1995 were likely artificially high due to many unreported events (since a greater number of unwarned events would lower POD). Procedures in a weather office before and after the MAR are very different. Improvement in verification scores after the MAR are partly due to a more pro-active approach, frequently requiring road trips by meteorologists to investigate areas to look for signs of unreported but recent severe weather (such as broken tree limbs or crop damage). Verifying meteorologists may also access telephone numbers in rural directories and call homes and businesses where people may have experienced the severe weather. This remains a rather thorny issue for large areas of the nation since unsolicited phone calls sometimes draw anger from the person called. Many other offices continue to wait to hear of severe reports from a second hand source. Before the MAR, parts of the warning process that required more personal attention and more time are: 1) composition of the warning message (was less automated); and 2) reading of the warnings on NOAA Weather Radio (was done manually versus using synthetic voices today).

Regression for Bias in Severe Thunderstorm Warnings

The 75 CWAs were reduced to 49 areas and multiple regression was performed for each. With this reduction regression results greatly improved overall, but showed a wide variation in scores. Table 3 summarizes the R^2 and R^2(adj) values of derived equations for each area. Satisfactory equations were not found that met the predetermined criteria for 13 of the CWA(s) and the numbers for those CWA(s) were left unchanged. Among the other 36 areas where valid equations were derived, the mean scores were $R^2 = 0.418$ and $R^2(adj) = 0.383$.

Once the equations were derived, the population density and distance from radar variables for each county were replaced with a constant. The population density for each

Table 3. Regression Scores for Identifying Bias in Warnings (# = equation not used).				
WFO(s)	Severe Thunderstorm Warnings		Tornado Warnings	
	R^2	R^2(adj)	R^2	R^2(adj)
ABQ+BOU+PUB	0.688	0.670	0.330	0.246
ABR	0.334	0.308	0.441	0.397
AMA+LUB	0.404	0.377	0.175	0.156
APX+MQT	0.329	0.291	0.391	0.317
ARX	# 0.120	# 0.087	# 0.079	# 0.005
BIS	# 0.131	# 0.105	0.460	0.444
BMX	0.311	0.297	# 0.101	# 0.082
BRO+CRP+EWX	0.200	0.153	0.239	0.225
BYZ+TFX	# 0.238	# 0.174	# 0.131	# 0.059
CAE+CHS+GSP+JAX	0.248	0.201	# 0.092	# 0.035
CLE	# 0.204	# 0.112	# 0.046	# 0.012
CYS+GGW+UNR	0.437	0.395	0.367	0.320
DDC+GID+GLD+LBF	0.197	0.181	0.119	0.111
DLH+GRB	0.451	0.421	0.239	0.219
DMX	0.308	0.294	0.206	0.190
DTX+GRR	0.369	0.335	0.205	0.163
DVN	0.400	0.343	0.224	0.151
EAX	0.680	0.664	# 0.089	# 0.068
FFC	0.592	0.583	0.116	0.107
FGF	# 0.066	# 0.038	# 0.045	# 0.016
FSD	0.357	0.326	0.294	0.260
FWD	0.220	0.202	0.161	0.142
HGX+LCH	0.245	0.189	0.337	0.289
ICT+TOP	0.351	0.323	0.201	0.128
ILN	# 0.103	# 0.067	# 0.060	# 0.022
ILX+LSX	0.490	0.484	# 0.064	# 0.052
IND	0.198	0.153	0.216	0.149
IWX	# 0.041	# 0.014	# 0.055	# 0.028
JAN	0.313	0.288	# 0.052	# 0.035
JKL+RNK	# 0.123	# 0.068	# 0.094	# 0.066
LIX+MOB	# 0.123	# 0.106	0.158	0.123
LMK	0.251	0.210	0.167	0.105
LOT+MKX	# 0.058	# 0.036	# 0.083	# 0.061
LZK	0.479	0.454	0.449	0.379
MAF+SJT	0.335	0.291	# 0.175	# 0.101
MEG	# 0.094	# 0.078	# 0.001	# 0.000
MFL+MLB+TBW	0.798	0.759	0.754	0.706
MPX	0.606	0.572	0.373	0.303
MRX	# 0.167	# 0.119	# 0.015	# 0.000
OAX	0.711	0.655	0.323	0.192
OHX	# 0.077	# 0.030	# 0.112	# 0.067
OUN	0.499	0.437	0.334	0.268

Table 3 (cont.). Regression Scores for Identifying Bias in Warnings (# = equation not used).

WFO(s)	Severe Thunderstorm Warnings		Tornado Warnings	
	R^2	R^2(adj)	R^2	R^2(adj)
PAH	0.443	0.401	0.168	0.138
PBZ	0.543	0.478	# 0.221	# 0.110
RLX	0.333	0.269	# 0.075	# 0.054
SGF	0.754	0.731	0.535	0.508
SHV	0.406	0.335	# 0.145	# 0.126
TAE	0.177	0.140	0.200	0.165
TSA	0.603	0.576	0.349	0.304

county was replaced with a constant value of 44.9 people/km^2 and the actual distance from radar in each county was replaced with 60 km. Recalculation of the equations with constant values for every county resulted in the distribution displayed in Figure 23. Differences across many CWA boundaries appear to have been enhanced such as around Glasgow, Montana (GGW), Nashville, Tennessee (OHX), Atlanta, Georgia (FFC), Springfield, Missouri (SGF), Oklahoma City, Oklahoma (OUN), and around the combined area for Amarillo, TX and Lubbock, TX (which were combined for regression). These contrasts should be expected if the two sources of bias have been removed.

Regression for Bias in Tornado Warnings

The same regionalization as for the larger data set was performed for tornado warnings to improve regression scores. Again the results varied greatly. Table 3 also summarizes R^2 and R^2(adj) values for this subset. No equation was found to pass all required tests for 20 of these CWA(s). Equations for the remaining 29 CWA(s) achieved mean scores of $R^2 = 0.294$ and $R^2(adj) = 0.248$. Again, once equations were derived the population density and distance from radar variables were removed and replaced with the same constants as were used for the larger severe thunderstorm warning data. This was

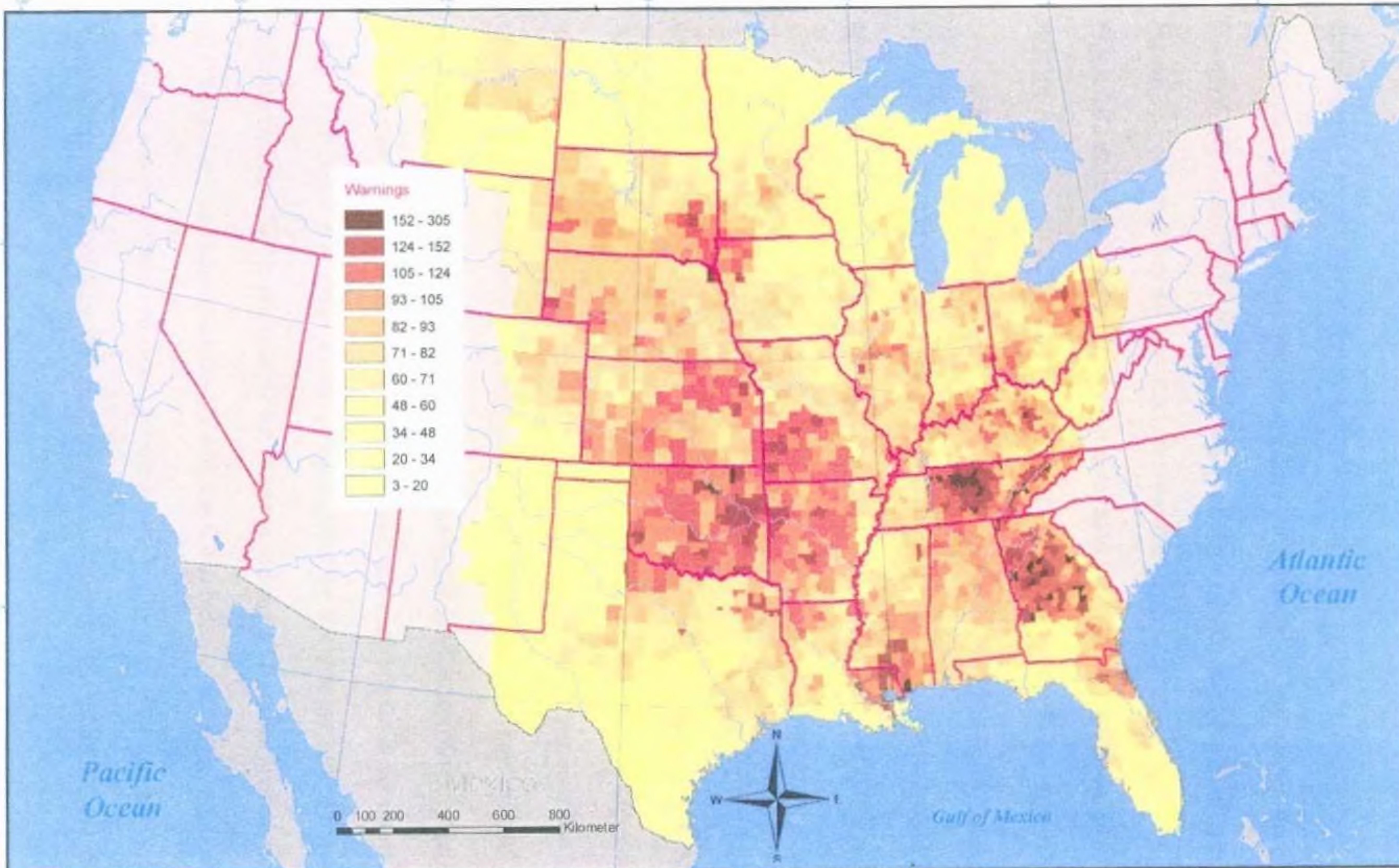

Figure 23. Severe Thunderstorm Warnings per 1,000 km² after Regression and Substitution of Variables for Constants.

done for every county for which the equation was derived. Figure 24 shows the distribution of tornado warnings after recalculation of the equations for every county. Differences across CWA boundaries again appear enhanced for a few areas such as Glasgow, Montana (GGW) and Nashville, Tennessee (OHX) but not nearly as often as in Figure 23. The tendency for maxima to be near the center of many CWAs noted in Figure 16 remains in Figure 24 though it decreased for Houston/Galveston, Texas (HGX).

As Figures 25 and 26 show, regression scores vary widely according to CWA(s). CWA(s) where valid equations were not found, and presumably no detectable bias was present, are shown in white.

T-tests and Mann-Whitney Tests for WFO/CWAs

Differences between CWAs in the number of warnings issued cannot be considered a bias since it carries a high level of subjectivity from varied sources such as interpretation of radar displays to perception by the user for the meaning of a warning and what their response action should be. There is the possibility that an office issuing an unusually high or low number of warnings is more correct than all other offices surrounding them. But to construct a more meaningful distribution of warnings that may be comparable to a distribution of reported events, some adjustment is necessary.

For each CWA, either a t-test or Mann-Whitney test was performed between all counties that an office is responsible for in one group and all counties contained within all CWAs that share a common border with the CWA being tested in the other group. The t-test was preferred in all cases, but the Mann-Whitney test was frequently required, usually because the constant variance test failed. The input values were those obtained

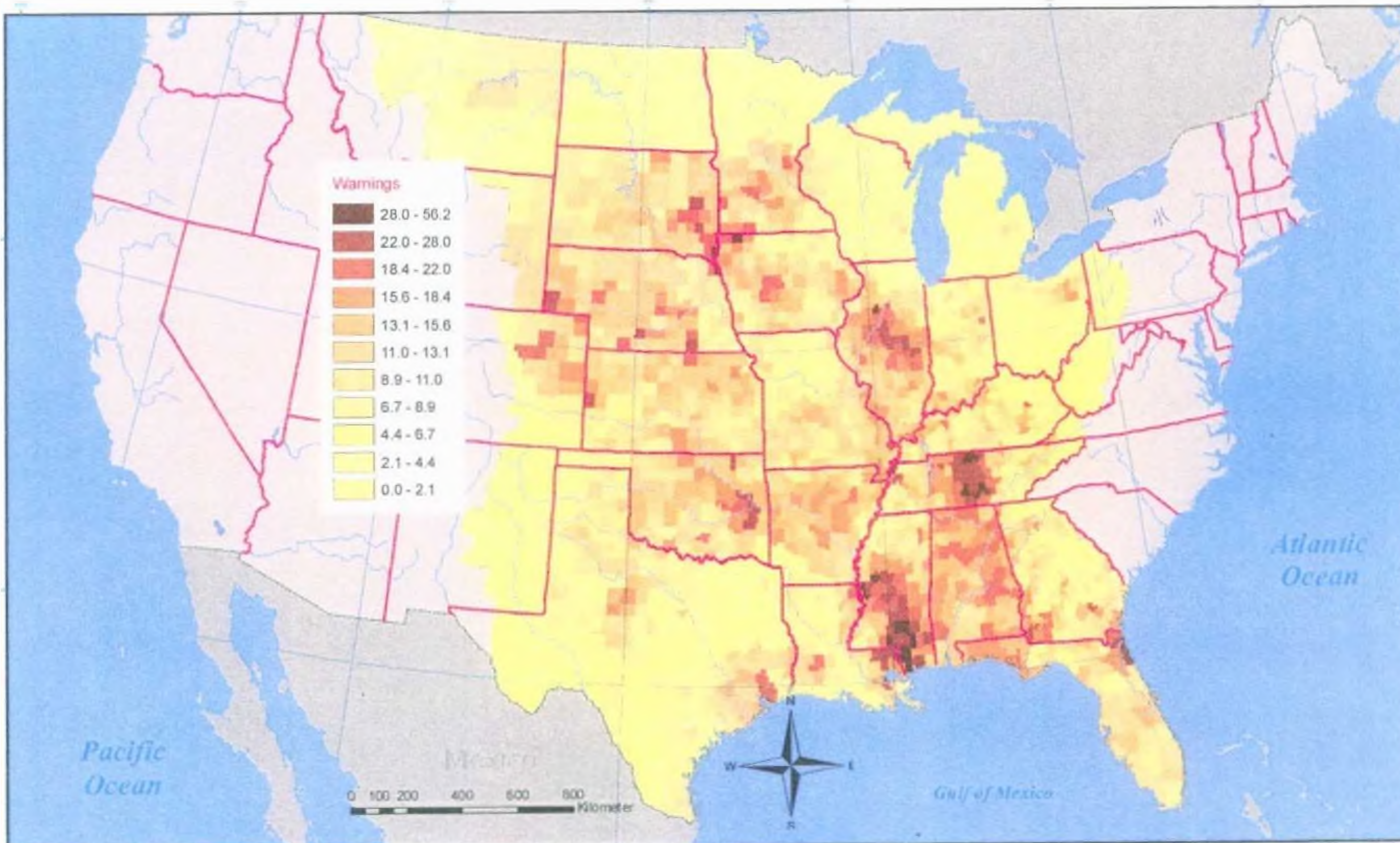

Figure 24. Tornado Warnings per 1,000 km^2 after Regression and Substitution of Variables for Constants.

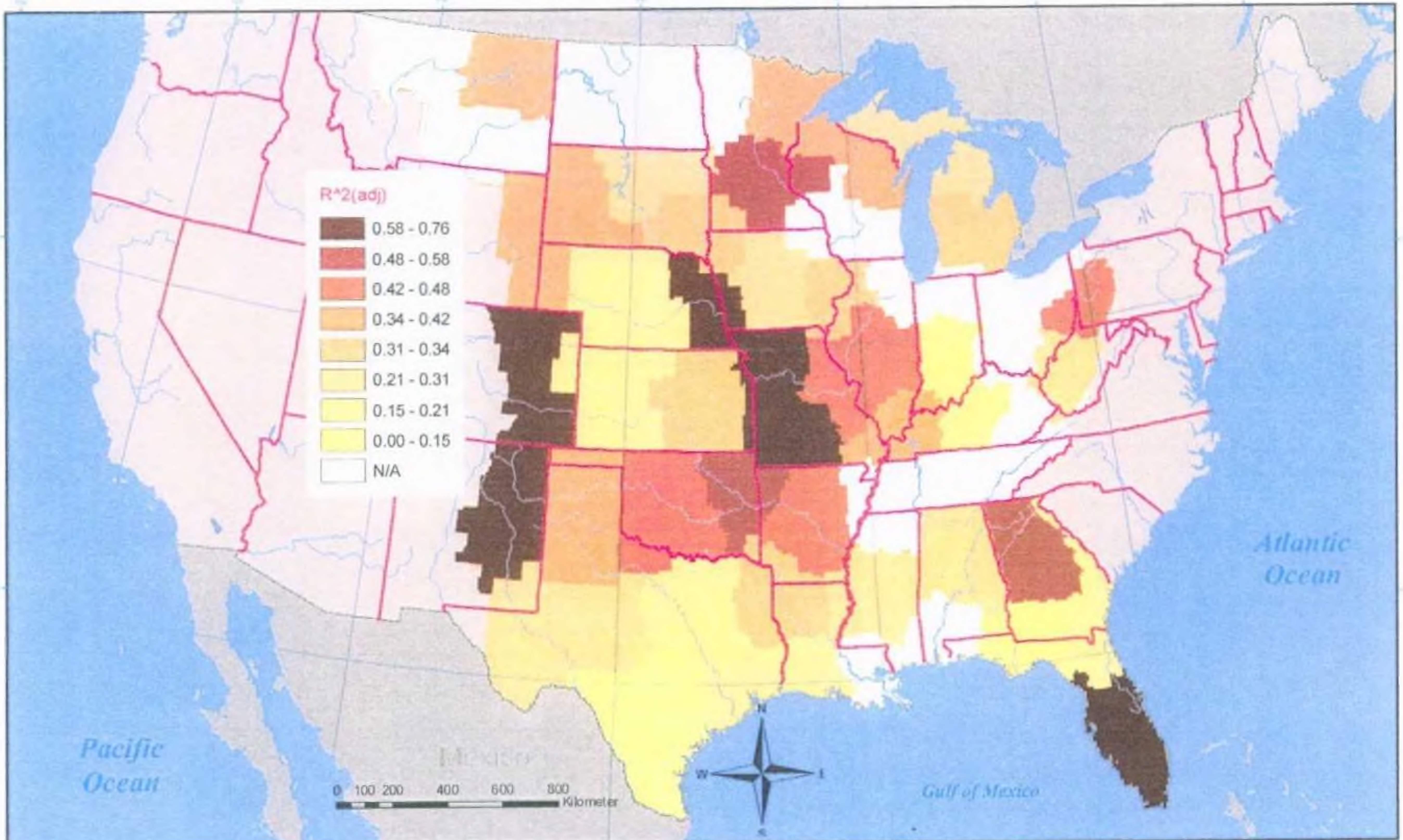

Figure 25. Regression R^2 Scores for Severe Thunderstorm Warnings.

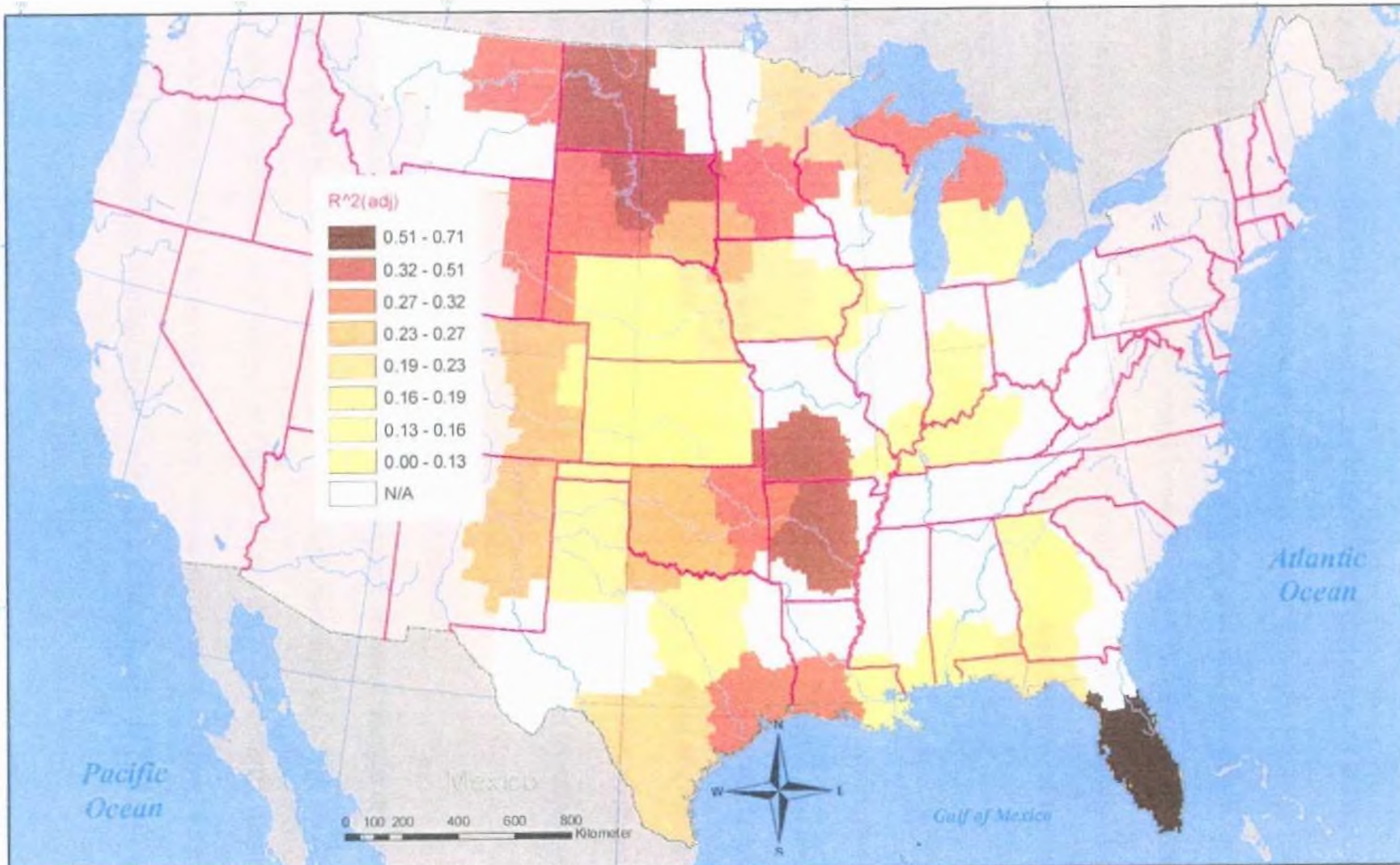

Figure 26. Regression R^2 Scores for Tornado Warnings.

after removal of the two sources of bias (population density and distance from nearest radar). However, if the CWA does not have other CWAs bordering it on at least three sides (within the study area), then no test was performed. The CWAs where no test was performed are those for Great Falls, Montana (TFX), Brownsville, Texas (BRO), Marquette, Michigan (MQT), North Central Lower Michigan, Michigan (APX), Miami, Florida (MFL), Greesnboro/Spartanburg, South Carolina (GSP) and Roanoke, Virginia (RNK). In all, 38 t-tests and 98 Mann-Whitney tests determined differences between CWAs. Table 4 summarizes the results of these tests with the data set of severe thunderstorm warnings and also for the subset of tornado warnings. A ratio multiplier is shown for each CWA that when applied to its input warning numbers, would result in the null hypothesis (that CWAs are not different) to be marginally accepted in a re-test. A ratio multiplier higher than one indicates that more warnings would have had to be issued during 1995-2004 in that CWA in order for the total to not be different from those associated with neighboring CWAs. The resultant multiplier was applied to the numbers of warnings after regression and then recorded as the final adjustment to county warning numbers.

Final Analysis Results

Population bias and distance from radar bias were removed through regression and differences between CWAs were removed through statistical tests. The resulting final spatial distributions are displayed in Figures 27 and 28. Their overall patterns show minor changes, with the numbers of warnings increasing relative to Figures 14 and 16. The severe thunderstorm warning data set resembles the distribution in Figures 1 and 2

Table 4. Results of T-tests and Mann-Whitney Tests. TT=t-test. MW = Mann-Whitney.						
	Severe Thunderstorm Warnings			Tornado Warnings		
WFO	Test	Fail to Reject the Null?	Ratio Multiplier Required to Reject	Test	Fail to Reject the Null?	Ratio Multiplier Required to Reject
ABQ	TT	N	1.37	MW	N	1.78
ABR	MW	Y	1.00	MW	Y	1.00
AMA	MW	N	1.23	MW	N	1.00
APX	N/A			N/A		
ARX	MW	N	1.15	MW	N	1.30
BIS	MW	N	1.60	MW	N	1.40
BMX	MW	N	1.09	MW	N	0.97
BOU	MW	Y	1.00	TT	Y	1.00
BRO	N/A			N/A		
BYZ	MW	N	1.98	MW	N	1.79
CAE	TT	Y	1.00	MW	Y	1.00
CHS	TT	N	1.25	MW	Y	1.00
CLE	TT	Y	1.00	MW	N	0.53
CRP	TT	N	1.15	MW	Y	1.00
CYS	TT	Y	1.00	TT	Y	1.00
DDC	MW	N	0.97	MW	Y	1.00
DLH	TT	N	1.05	MW	Y	1.00
DMX	MW	N	1.03	MW	Y	1.00
DTX	MW	Y	1.00	MW	Y	1.00
DVN	MW	N	1.02	MW	Y	1.00
EAX	MW	Y	1.00	TT	N	1.81
EWX	MW	N	1.25	MW	N	1.28
FFC	MW	N	0.72	TT	N	1.10
FGF	MW	Y	1.00	MW	Y	1.00
FSD	MW	N	0.90	TT	Y	1.00
FWD	MW	N	1.03	MW	N	1.30
GGW	MW	Y	1.00	TT	Y	1.00
GID	MW	Y	1.00	TT	Y	1.00
GLD	MW	Y	1.00	TT	Y	1.00
GRB	TT	Y	1.00	MW	Y	1.00
GRR	MW	Y	1.00	TT	Y	1.00
GSP	N/A					
HGX	TT	Y	1.00	MW	N	0.54
ICT	MW	N	1.03	TT	Y	1.00
ILN	MW	Y	1.00	MW	N	1.34
ILX	TT	N	1.00	MW	N	0.61
IND	MW	N	1.21	MW	Y	1.00
IWX	MW	Y	1.00	MW	Y	1.00
JAN	MW	N	0.63	MW	N	0.67
JAX	MW	Y	1.00	TT	Y	1.00
JKL	MW	Y	1.00	MW	Y	1.00

Table 4 (cont.). Results of T-tests and Mann-Whitney Tests. TT = t-test. MW = Mann-Whitney.

	Severe Thunderstorm Warnings			Tornado Warnings		
WFO	Test	Fail to Reject the Null?	Ratio Multiplier Required to Reject	Test	Fail to Reject the Null?	Ratio Multiplier Required to Reject
LBF	TT	Y	1.00	TT	Y	1.00
LCH	MW	N	1.53	MW	N	1.13
LIX	TT	Y	1.00	TT	Y	1.00
LMK	TT	Y	1.00	TT	Y	1.00
LOT	TT	Y	1.00	MW	N	1.04
LSX	MW	Y	1.00	MW	Y	1.00
LUB	MW	Y	1.00	MW	N	1.11
LZK	TT	Y	1.00	TT	Y	1.00
MAF	MW	N	0.97	MW	N	0.76
MEG	MW	N	1.37	MW	N	1.20
MFL	N/A			N/A		
MKX	TT	Y	1.00	MW	Y	1.00
MLB	TT	Y	1.00	TT	Y	1.00
MOB	TT	Y	1.00	TT	Y	1.00
MPX	MW	N	0.94	TT	Y	1.00
MQT	N/A			N/A		
MRX	TT	Y	1.00	MW	N	1.02
OAX	TT	Y	1.00	TT	Y	1.00
OHX	MW	N	0.62	MW	N	0.55
OUN	MW	N	0.86	MW	N	0.95
PAH	TT	Y	1.00	MW	Y	1.00
PBZ	TT	Y	1.00	MW	N	1.29
PUB	TT	Y	1.00	MW	Y	1.00
RNK	N/A			N/A		
RLX	MW	N	1.54	TT	Y	1.00
SGF	MW	N	0.88	TT	Y	1.00
SHV	MW	N	1.15	MW	N	1.64
SJT	TT	Y	1.00	MW	N	0.54
TAE	MW	N	2.02	TT	Y	1.00
TBW	MW	N	0.90	TT	Y	1.00
TFX	N/A			N/A		
TOP	MW	N	0.96	TT	Y	1.00
TSA	MW	N	0.75	TT	N	0.82
UNR	MW	Y	1.00	TT	Y	1.00

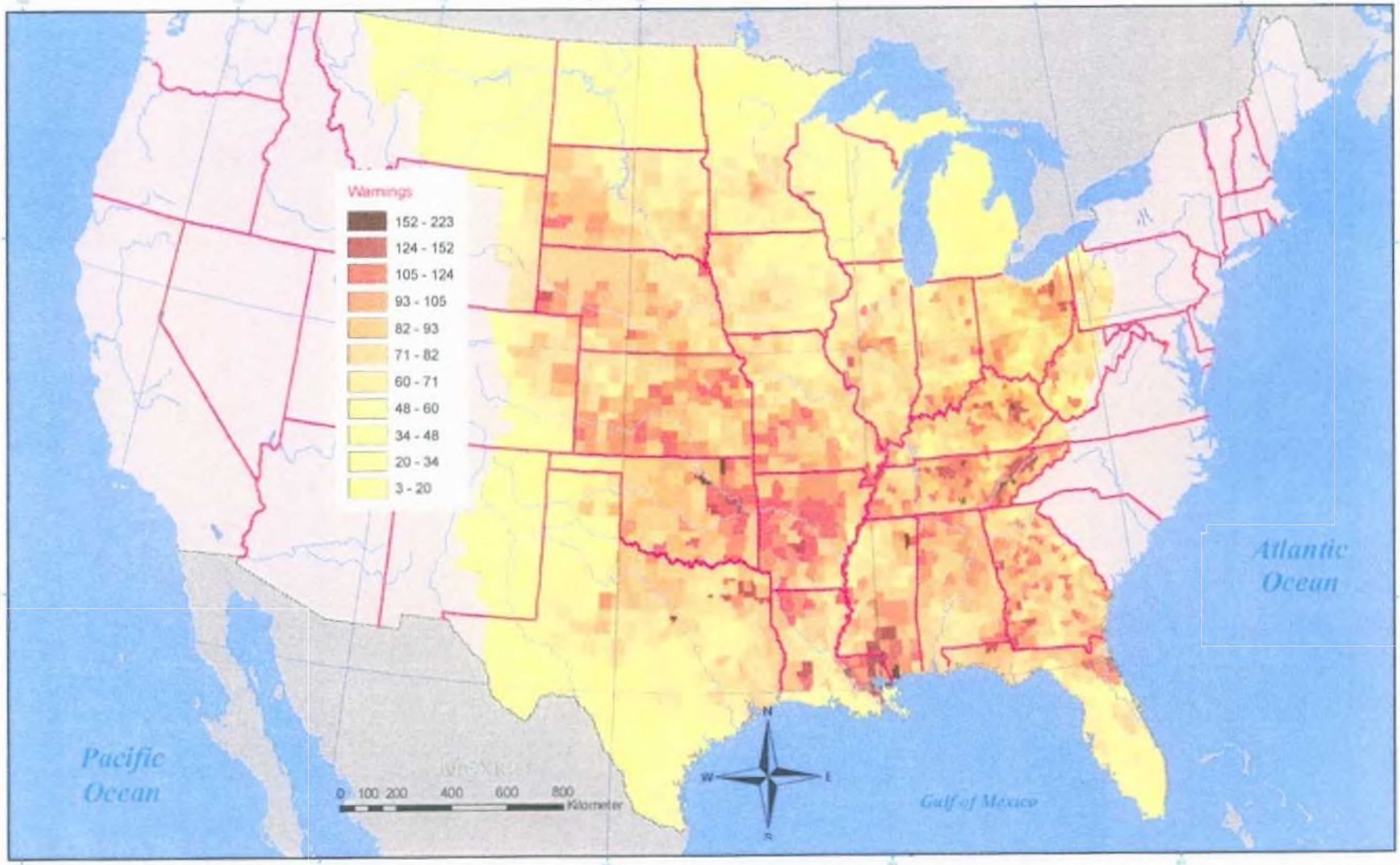

Figure 27. Severe Thunderstorm Warnings, After Final Adjustments.

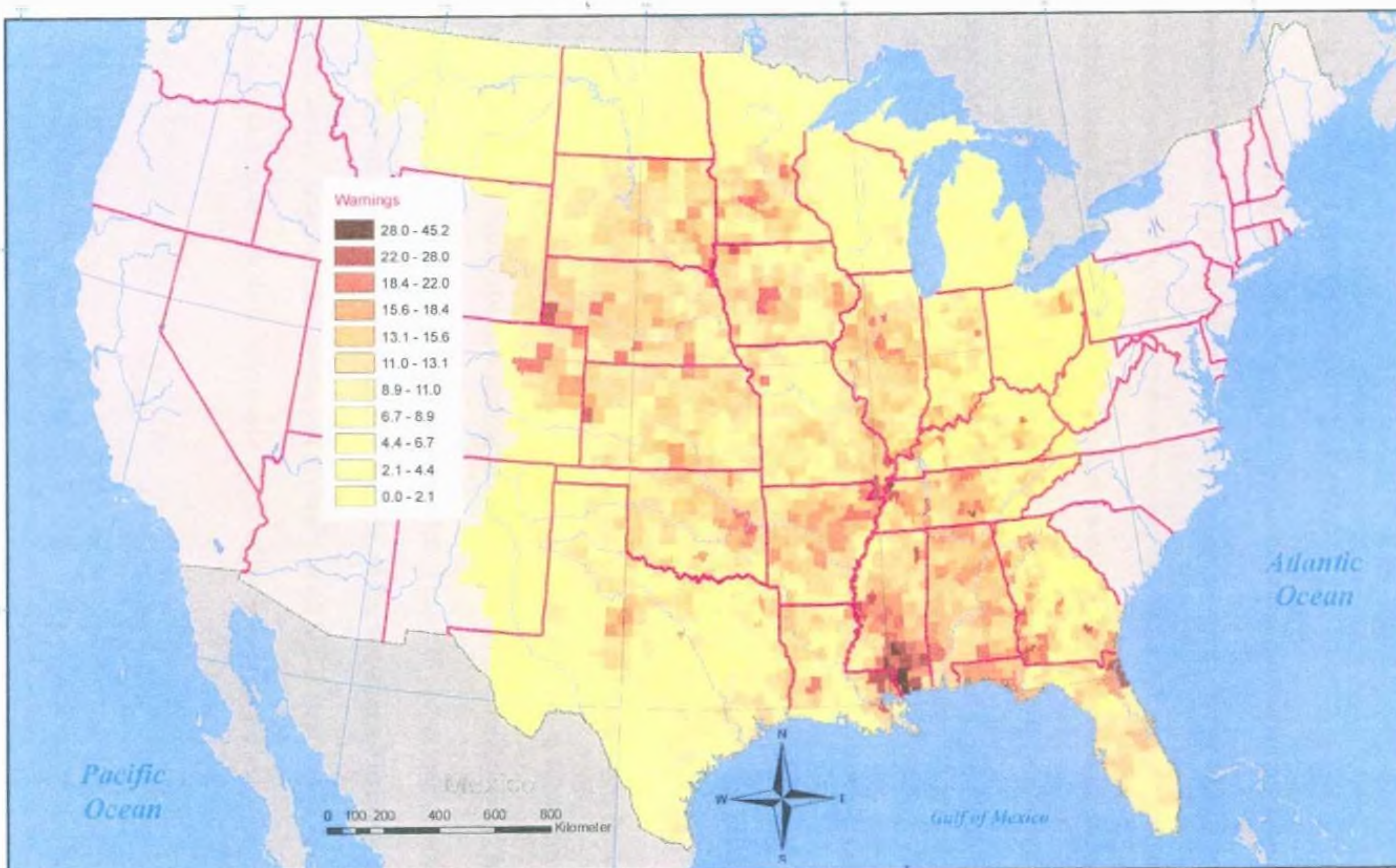

Figure 28. Tornado Warnings, After Final Adjustments.

except for higher numbers but the tornado warning data subset (Figure 28) continues to look very different from reported events (Figure 3).

After all adjustments, the data set containing severe thunderstorm warnings appears comparable to the one based on recorded events alone. In Figure 27 there is an overall maximum of warnings issued over eastern Oklahoma, Arkansas and extending into southeast Kansas, and another maximum for eastern Tennessee and extending towards Atlanta, Georgia. In addition, there is a ridge of high values extending from Kentucky towards western Pennsylvania. These features are similar to those in Figures 1 and 2 except those figures based on events reach farther into north Texas. However, reported events in the 1995-2004 period (Figure 13) were higher in Kansas than areas farther south so the difference is valid. This distribution of severe thunderstorm warnings adds validation to climatologies based on reported events and suggests that hazard risk from these storms has been well identified.

The data set with only tornado warnings, even with biases from population density and distance from radar removed, does not compare as well to actual events. Though the minimum of issued warnings in Figure 28 exists in Missouri as in Figure 3, little else compare favorably between these figures. Figure 28 shows major maxima in southern Mississippi, northeast Arkansas, near the Alabama-Georgia-Florida tri-state region, around Jacksonville, Florida, and generally much higher than would be expected in South Dakota and southern Minnesota. None of these findings are indicated in Figure 3.

What About the Remaining Significant Differences Between Tornado Reports and Tornado Warnings?

A remaining question is whether the shift from highest reported tornado occurrences on the central and southern plains to a high number of tornado warnings in and near Mississippi and Alabama is a product of under-warning on the plains, or over-warning in Mississippi-Alabama? Or, do more tornadoes actually occur in those states farther east? The high density of trees along with the very low clouds associated with thunderstorm across the Mid-South may cause visual sightings to be much more difficult than on the treeless Great Plains, and densely wooded areas may escape easily noticeable damage from weak tornadoes.

To further address this issue, FAR scores for tornado warnings alone were obtained for the 1995-2004 period and their distribution are shown in Figure 29. This image is rather noisy and difficult to assess, so the neighborhood statistic option in ArcView GIS was utilized. This tool computes an output grid in which the value at each location is a function of the input cells within a specified neighborhood of the location. For this image settings were set at 10 units in a radius around data points to produce Figure 30. This essentially smoothed the data and shows that false alarms are dramatically higher over the eastern portion of the region. Such high FAR covering the east leads to low confidence in the shift of high tornado frequency in that direction relative to the distribution of tornado events (Figures 3 and 15 vs. Figures 16 and 28). Notice that FAR rises quite rapidly east of the boundary between the Plains and the more forested areas of Minnesota, extreme eastern Iowa and southern Missouri.

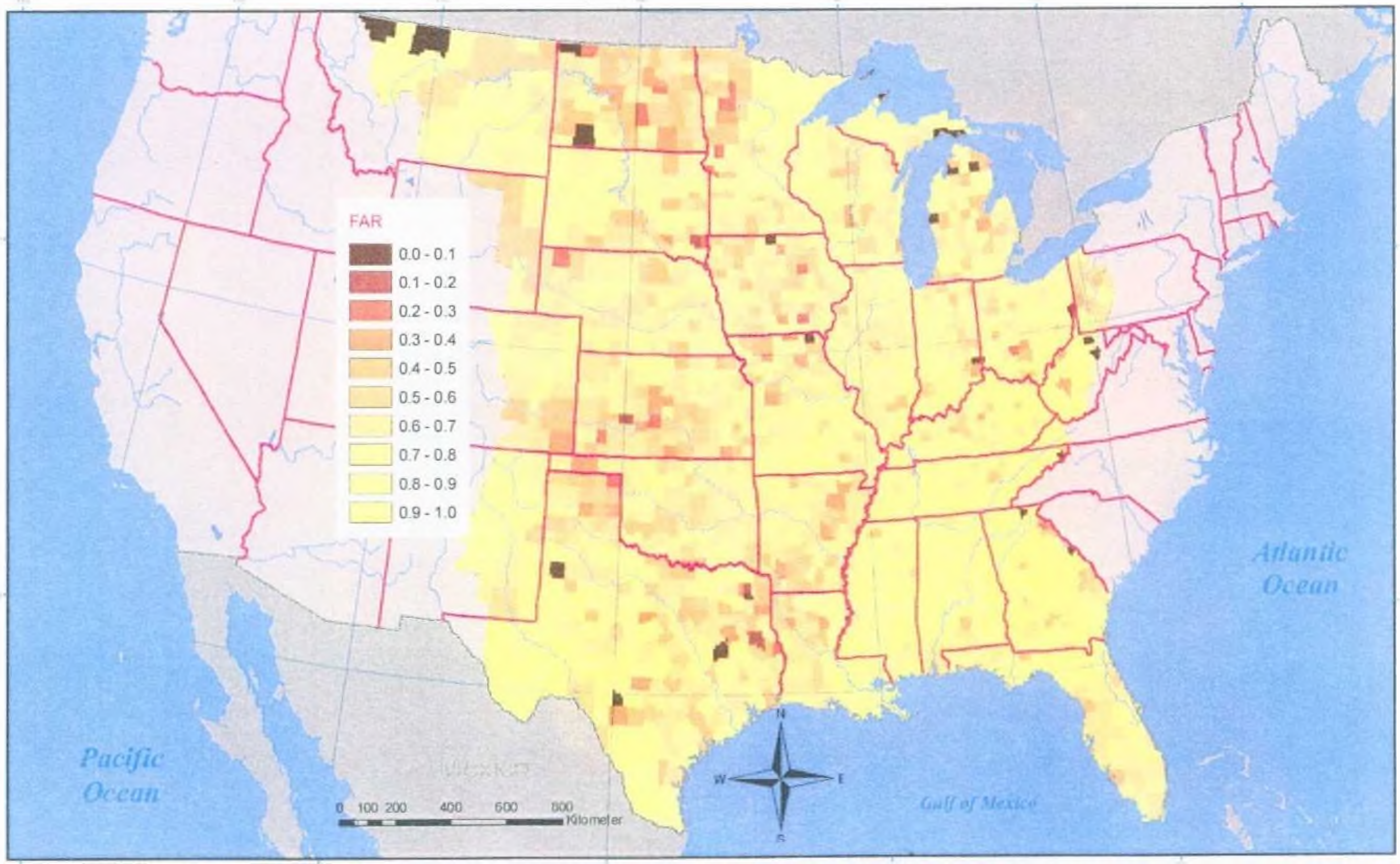

Figure 29. FAR Scores for Tornado Warnings (1995-2004).

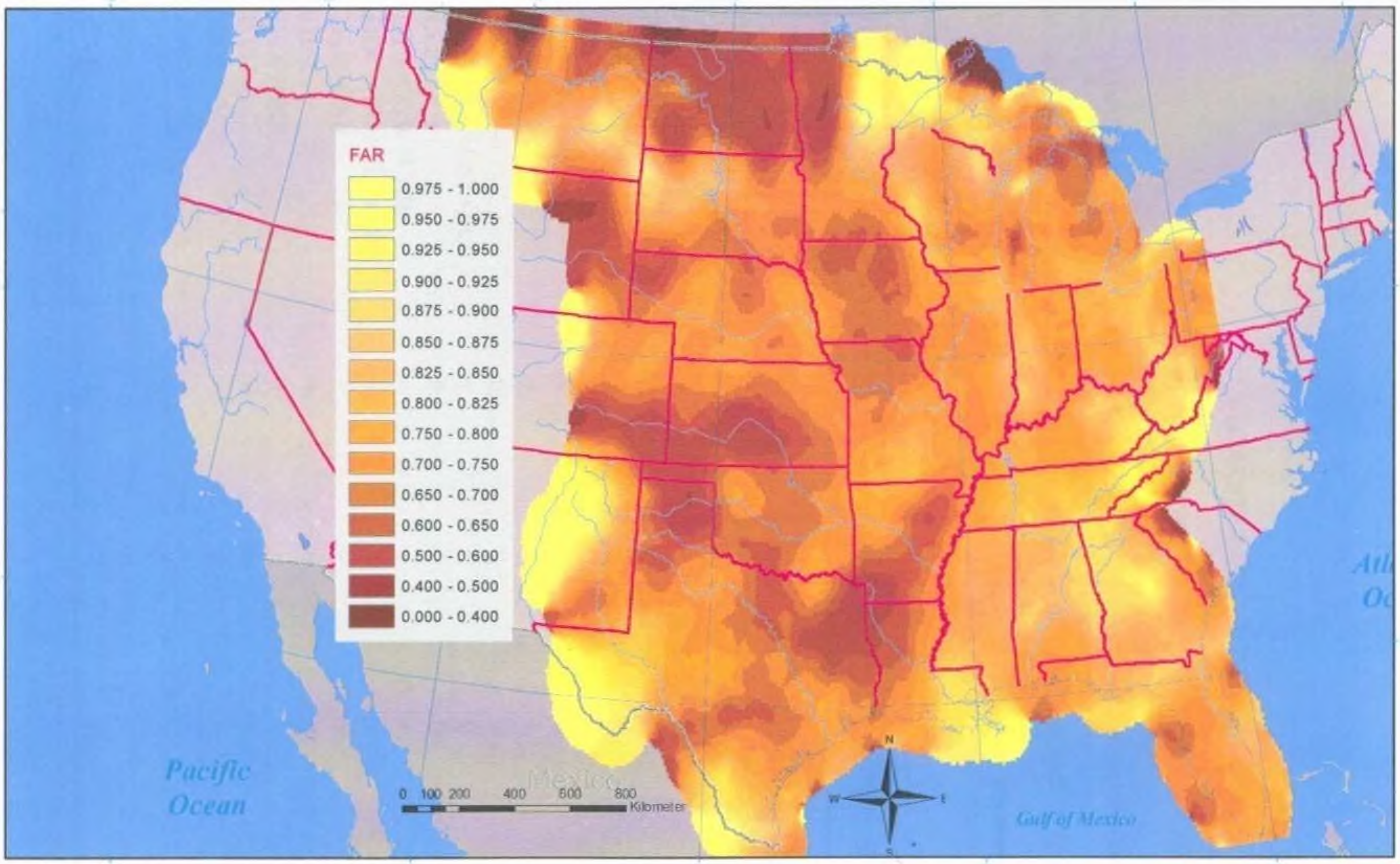

Figure 30. Neighborhood Statistics Modification of FAR Scores (1995-2004)

CHAPTER VII

REGRESSION TRENDS AND DISCUSSION

Table 5 shows the tendencies that each WFO/CWA or combination of offices had for issuing warnings as a function of population density and distance to radar station. A plus (minus) indicates that as the variable increased (decreased) there was a trend to issue more (fewer) warnings.

Table 5. Tendencies of WFO/CWA to Issue Warnings with Increasing Values in the Independent Variables.

WFO(s)	Severe Thunderstorm		Tornado	
	Population Density	Distance	Population Density	Distance
ABQ+BOU+PUB	+	0	+	-
ABR	+	0	+	-
AMA+LUB	+	-	0	-
APX+MQT	+	-	+	-
ARX	0	0	0	0
BIS	0	0	0	-
BMX	+	0	0	0
BRO+CRP+EWX	+	0	+	0
BYZ+TFX	0	0	0	0
CAE+CHS+GSP+JAX	+	0	0	0
CLE	0	0	0	0
CYS+GGW+UNR	+	+	+	+
DDC+GID+GLD+LBF	+	+	+	0
DLH+GRB	+	-	+	0
DMX	+	0	+	0
DTX+GRR	+	-	+	-
DVN	+	+	+	+
EAX	+	0	0	0
FFC	+	+	+	0
FGF	0	0	0	0
FSD	-	0	-	0
FWD	+	0	+	0

Table 5 (cont.). Tendencies of WFO/CWA to issue warnings with increasing values in the independent variables.				
WFO(s)	SevereThunderstorm		Tornado	
	Population Density	Distance	Population Density	Distance
HGX+LCH	+	+	+	+
ICT+TOP	+	0	+	-
ILN	0	0	0	0
ILX+LSX	+	0	0	0
IND	+	0	+	+
IWX	0	0	0	0
JAN	+	-	0	0
JKL+RNK	0	0	0	0
LIX+MOB	0	0	+	-
LMK	+	0	+	-
LOT+MKX	0	0	0	0
LZK	+	0	+	-
MAF+SJT	+	0	0	0
MEG	0	0	0	0
MFL+MLB+TBW	+	-	+	+
MPX	+	0	+	-
MRX	0	0	0	0
OAX	-	-	-	-
OHX	0	0	0	0
OUN	+	-	-	-
PAH	-	-	0	+
PBZ	+	-	0	0
RLX	-	-	0	0
SGF	+	-	0	+
SHV	+	-	0	0
TAE	0	-	0	-
TSA	+	-	+	-

In most cases for severe thunderstorm warnings (31 out of 35) when a trend was detected, increasing values of population density suggest that more warnings would be predicted (positive correlation), while increasing distance values usually (15 out of 20) result in fewer predicted warnings (negative correlation).

For the tornado warnings, 21 out of 24 areas indicated that increasing population density would result in more predicted warnings (positive correlation), while increasing distance values usually (15 out of 22) result in fewer predicted warnings (negative correlation.

Both data sets show that the unintended tendency of most warning meteorologists is to issue warnings more often when population density is high and the storm is close to the radar. The warning has a higher likelihood of verifying where population is higher which increases the meteorologist's confidence in issuing it. Meanwhile he or she is usually more confident about issuing one when the storm is relatively close to the radar since more information from the radar about the storm is then available. But a minority of meteorologists apparently issue warnings more often when in doubt of the conditions, a better safe than sorry viewpoint. Lower population density (and thus fewer spotters giving ground truth reports) and lower vertical and horizontal resolutions available at greater distance from the radar transmitter lead to such doubt.

There are a few areas where this form of regression was not effective in identifying bias, and no equation was found to satisfy the criteria set forth. The area including WFOs at Billings, Montana and Great Falls, Montana is one such location. The population density in these CWAs is highest in the western portion of their counties, yet a higher number of severe thunderstorms and tornadoes typically occur in their eastern counties due to higher moisture availability and the presence of fewer mountains to disrupt the supporting wind flow patterns to develop storms. Higher population density seems to imply fewer warnings issued for this area, which is reflected in the equations derived. But the reasoning is faulty; more events and warnings actually do occur in their eastern counties where population density is lower.

The area containing the Chicago, Illinois (LOT) and Milwaukee, Wisconsin (MKX) metroplexes and the large population along the Lake Michigan shore between the two, probably experience fewer severe storms than farther inland due to their proximity to Lake Michigan. It is a false conclusion (as shown in the regression equations for both data sets) that higher population near the lake results in fewer warnings. It is not a bias, but a real occurrence with an underlying physical reason.

A comparison of the warnings distributions after regression was applied (Figures 23 and 24) shows that bias correction does not significantly alter the pattern from those noted in Figures 14 and 16, although the numbers do increase. Table 6 compares the gross number of warnings issued to the hypothetical number with little or no bias. These numbers were derived by multiplying the values after regression by the county areas, dividing by 1,000, and adding all county values, which is the reverse procedure of producing the original dependent variables. Regression suggests that without the two sources of bias there would be an approximate 16% increase in warnings issued in both data sets. But these are very likely low estimates of how many warnings should be issued since: 1) only 44.9 people/km^2 was used as a constant in the equations, and 2) warnings tend to continue to increase with higher population density (Fig. 9 and 10).

Table 6. Actual Warnings Issued and Hypothetical Warnings after Regression (1995-2004).

	Issued	After Regression
Severe Thunderstorm Warnings	244,400	282,741
Tornado Warnings	30,639	35,507

One possible area of bias for tornado warnings that was not included for regression in this study is that of ground effects. Pryor and Kurzhal (1993) found in regression that surface roughness is a significant predictor (after county size and county population) of the number of reported tornadoes in Indiana. They concluded that high surface roughness played a role in fewer reported tornadoes over southwest Indiana which correlates in Figure 30 to a relative maximum of FAR over the same area of that state. They also concluded that surface roughness explained 6% of the variance of tornado reports during their period of study.

Warning meteorologists do not usually account for this variable when considering whether a tornado might reach the ground. Atmospheric conditions favorable for tornado development and a radar signature indicating a tornado vortex usually cause enough concern to issue a warning. But forest and/or rugged terrain causing friction for low-level winds may be a significant factor in decreasing the chance of a developing tornado from reaching the surface. Table 7 shows a ratio of issued tornado warnings to reported tornadoes within the study area. Though there are some highly forested states that have low ratios, the 11 states that have ratios of 3.0 or higher are eastern states having forest covering a high percentage of their land. This west-east gradient is a new trend as ratios during 1986-1994 were much more random. But as the Assistant Administrator for Weather Services pointed out tornado warnings before Doppler radar were usually issued only after visual sightings of tornadoes were received and not necessarily based on radar interpretation.

Table 7. Ratio of Issued Tornado Warnings to Reported Tornadoes in the Area of Study, by State (1995-2004).

Alabama	4.3	Kansas	1.7	Montana	2.1	South Dakota	1.9
Arkansas	2.0	Kentucky	3.3	Nebraska	2.6	Tennessee	4.9
Colorado	2.0	Louisiana	3.0	New Mexico	2.4	Texas	2.2
Florida	2.1	Michigan	2.1	North Dakota	1.5	Virginia	7.0
Georgia	4.4	Minnesota	2.2	Ohio	3.2	West Virginia	5.4
Illinois	2.5	Mississippi	4.5	Oklahoma	2.3	Wisconsin	2.5
Indiana	3.0	Missouri	3.0	Pennsylvania	2.1	Wyoming	1.9
Iowa	2.1						

Pryor and Kurzhal (1993) obtained the amount of land use in each category from the U. S. Geological Survey, multiplied each amount by the natural logarithm of the assigned roughness and then aggregated to arrive at an average value in each Indiana county. This would be quite labor intensive if done for the counties of this study, but would likely be worth the time in future efforts.

CHAPTER VIII

CONCLUSIONS

The regression trends seen in this study are prevalent enough to conclude that during the 1995-2004 period, at most WFOs population density continued to be a significant bias for radar meteorologists to deal with, and distance from radar was a significant bias at almost half of the WFOs. These biases were much stronger in some parts of the nation; however, the magnitude of each source of bias at the WFOs was not obtainable through this method.

To answer the first research question about possible bias associated with population density or distance from radar, regression indicated that population density was a significant predictor for where severe thunderstorm warnings were issued in 71% of the 49 areas studied, and for tornado warnings in 59%. Bias for distance from radar was slightly less prevalent, being a significant predictor for 49% of the areas issuing severe thunderstorm warnings and for 45% issuing tornado warnings.

The second primary question to answer regarded whether counties in individual CWAs show significant differences as compared to counties in their neighboring CWAs. T-tests and Mann-Whitney tests indicated that for severe thunderstorm warnings, 31 out of 68 CWAs were significantly different, 13 of those by greater than 20%. For tornado warnings, 26 out of 68 CWAs showed differences, 14 of them by more than 20%. But these differences could not be considered a bias since there is too much subjectivity involved to determine how many warnings is a correct number to issue.

The spatial pattern of severe weather was examined and compared to earlier climatology. The distribution of severe thunderstorms warnings, after removal of bias and differences between CWAs, compared well with a distribution of reported events. But the pattern of tornado warnings differed much from events, with several probable causes. Subjectivity in the decision to issue a tornado warning is greater than for a severe thunderstorm warning and the processes which cause an existing tornado vortex in a thunderstorm to reach the ground are poorly understood. Yet the warning meteorologist cannot wait for the funnel cloud or tornado to be spotted and reported to issue a warning. As a result false alarms continue too high, especially in the east, to consider a spatial distribution of tornado warnings to be highly valued for use in hazard risk assessment. More conventional studies of reported tornadoes currently paint a more likely picture of where the greater threats are.

More research is needed on why false alarms are so prevalent in tornado warnings. Most current efforts are directed at what can be determined from radar images or from atmospheric conditions. Surface roughness may be a very significant factor to explain why many thunderstorms that look tornadic on radar do not result in tornadoes reaching the ground, especially in those thunderstorms where the support for developing funnel clouds and tornadoes are weak. Dessens (1972) showed how decreasing vertical wind shear increased turbulence in the lowest layer which may keep a funnel cloud from dipping to the surface. But other factors complicate the matter and must be considered, such as whether these warnings are simply harder to verify in the east due to trees, hills, rain or low clouds which sometimes obscure the view of a tornado.

Future study might do well to look further at what impact frictional effects have on these phenomena. It is possible that inclusion of surface roughness in regression as Pryor and Kurzhal (1993) did would improve the distribution of the tornado warnings in this study. If it were, any percentage of warnings that regression would identify as explainable by surface effects might simply be removed from the warning totals since these would represent false alarm warnings.

APPENDICES

APPENDIX A

WFO STATION ID LIST

ABQ - Albuquerque, NM
ABR - Aberdeen, SD
AMA - Amarillo, TX
APX - North Central Lower Michigan, MI
ARX - La Crosse, WI
BIS - Bismarck, ND
BMX - Birmingham, AL
BOU - Denver/Boulder, CO
BRO - Brownsville, TX
BYZ - Billings, MT
CAE - Columbia, SC
CHS - Charleston, SC
CLE - Cleveland, OH
CRP - Corpus Christi, TX
CYS - Cheyenne, WY
DDC - Dodge City, KS
DLH - Duluth, MN
DMX - Des Moines, IA
DTX - Detroit, MI
DVN - Quad Cities, IA
EAX - Kansas City/Pleasant Hill, MO
EWX - Austin/San Antonio, TX
FFC - Atlanta, GA
FGF - Eastern North Dakota, ND
FSD - Sioux Falls, SD
FWD - Dallas/Fort Worth, TX
GGW - Glasgow, MT
GID - Hastings, NE
GLD - Goodland, KS
GRB - Green Bay, WI
GRR - Grand Rapids, MI
GSP - Greenville/Spartanburg, SC
HGX - Houston/Galveston, TX
HUN - Huntsville, AL
ICT - Wichita, KS
ILN - Cincinnati, OH
ILX - Central Illinois, IL
IND - Indianapolis, IN
IWX - Northern Indiana, IN
JAN - Jackson, MS
JAX - Jacksonville, FL
JKL - Jackson, KY
LBF - North Platte, NE
LCH - Lake Charles, LA
LIX - New Orleans/Baton Rouge, LA
LMK - Louisville, KY
LOT - Chicago, IL
LSX - St. Louis, MO
LUB - Lubbock, TX
LZK - Little Rock, AR
MAF - Midland/Odessa, TX
MEG - Memphis, TN
MFL - Miami, FL
MKX - Milwaukee, WI
MLB - Melbourne, FL
MOB - Mobile, AL
MPX - Minneapolis, MN
MQT - Marquette, MI
MRX - Knoxville/Tri-Cities, TN
OAX - Omaha, NE
OHX - Nashville, TN
OUN - Oklahoma City, OK
PAH - Paducah, KY
PBZ - Pittsburgh, PA
PUB - Pueblo, CO
RLX - Charleston, WV
RNK - Roanoke, WV
SGF - Springfield, MO
SHV - Shreveport, LA
SJT - San Angelo, TX
TAE - Tallahassee, FL
TBW - Tampa Bay Area, FL
TFX - Great Falls, MT
TOP - Topeka, KS
TSA - Tulsa, OK
UNR - Rapid City, SD

APPENDIX B

EQUATION LIST

Regression Equations Derived for Severe Thunderstorm Warnings and Tornado Warnings, F test results and power rating. x=population density, y=distance from radar. #=equation not used in recalculation for spatial distribution.

WFO(s)	n value	Equation	First Six Coefficients (to nearest hundredth)						Constant	F test	Pwr
			a	b	d	e	f	g	c		
ABQ+BOU+PUB	37	$a*x^{b}+c$	0.08	0.71					5.31	F(2,34)=37.47ρ<0.01	1.00
ABR	28	a*ln(x)+b	0.47						5.77	F(1,26)=13.02ρ<0.01	0.91
AMA+LUB	47	a*ln(x)+b*y+c	0.39	-0.01					6.81	F(2,44)=14.91ρ<0.01	1.00
APX+MQT	38	a*ln(x)+b*y+c	0.44	-0.01					4.00	F2,35)=8.576 ρ<0.01	0.97
ARX	28	# a*x+c	0.01						6.08	F(1,26)=3.56 ρ=0.07	0.44
BIS	36	# a*x+c	0.00						5.00	F(1,34)=5.11 ρ=0.03	0.59
BMX	49	a*x+c	0.01						2.13	F(1,34)=28.92 ρ<0.01	1.00
BRO+CRP+EWX	56	$a*x^{3}+b*x^{2}+d*x+e$	0.00	-0.00	0.03				5.14	F(3,52)=4.32 ρ<0.01	0.94
BYZ+TFX	27	# a*ln(x)+b*y+c	-0.25	-0.01					4.82	F(2,24)=3.75 ρ=0.04	0.74
CAE+CHS+GSP+JAX	52	$a*x^{3}+b*x^{2}+d*x+c$	0.00	-0.00	0.05				7.37	F(3,48)=5.27 ρ<0.01	0.97
CLE	30	# $a*x^{7}+b*x^{6}+d*x^{5}+c$	-0.00	0.00	-0.00				8.74	F(3,26)=2.22 ρ=0.11	0.72
CYS+GGW+UNR	44	$a*x^{b}+d*\ln(y)+c$	2.54	0.26	0.44				0.31	F(3,40)=10.36 ρ<0.01	1.00
DDC+GID+GLD+LBF	102	a*ln(x)+b*ln(y)+c	0.41	0.00					7.44	F(2,99)=12.14 ρ<0.01	1.00
DLH+GRB	40	a*ln(x)+b*y+c	0.57	-0.01					4.64	F(2,37)=15.17 ρ<0.01	1.00
DMX	51	a*x+c	0.01						6.73	F(1,49)=21.80 ρ<0.01	0.99
DTX+GRR	40	a*ln(x)+b*ln(y)+c	0.65	-0.73					6.64	F(2,37)=10.82 ρ<0.01	0.99
DVN	36	$a*x+b*y^{2}+d*y+c$	0.01	-0.00	0.02				5.81	F(3,32)=7.01 ρ<0.01	0.99
EAX	44	$a*x^{b}+c$	2.07	0.23					3.55	F(2,41)=43.78 ρ<0.01	1.00
FFC	96	a*ln(x)+b*y+c	1.07	-0.01					6.60	F(2,93)=67.37 ρ<0.01	1.00
FGF	35	# a*ln(y)+c	0.38						4.13	F(1,33)=2.32 ρ=0.14	0.32
FSD	45	$a*x^{2}+b*x+c$	-0.00	0.16					6.51	F(2,42)=11.64 ρ<0.01	0.99
FWD	46	a*ln(x)+c	0.53						5.81	F(1,44)=12.38 ρ=0.01	0.92
HGX+LCH	45	$a*\ln(x)+b*y^{2}+d*y+c$	0.54	-0.00	0.04				3.69	F(3,41)=4.43 ρ<0.01	0.94
ICT+TOP	49	$a*x^{2}+b*x+c$	-0.00	0.05					7.71	F(2,46)=12.48 ρ<0.01	1.00
ILN	52	# a*ln(x)+b*ln(y)+c	0.34	0.43					5.45	F(2,49)=2.828 ρ=0.69	0.65
ILX+LSX	81	a*x+b	0.00						1.85	F(1,79)=75.92 ρ<0.01	1.00
IND	39	$a*x^{b}+c$	0.15	0.41					6.80	F(2,36)=4.43 ρ=0.02	0.82
IWX	37	# a*ln(y)+c	-0.43						10.05	F(1,35)=1.51 ρ=0.23	0.22
JAN	58	a*ln(x)+b*ln(y)+c	0.86	-0.98					12.63	F(2,55)=12.53 ρ<0.01	1.00

(Cont.) Regression Equations Derived for Severe Thunderstorm Warnings and Tornado Warnings, F test results and power rating. x=population density, y=distance from radar. #=equation not used in recalculations for spatial distribution.

WFO(s)	n value	Equation	First Six Coefficients (to nearest hundredth) a	b	d	e	f	g	Constant c	F test	Pwr
JKL+RNK	36	# a*ln(x)+b*ln(y)+c	-0.88	-1.11					16.55	$F(2,32)=2.24\ \rho=0.12$	0.54
LIX+MOB	51	# a*ln(x)+b	0.53						7.53	$F(1,49)=6.90\ \rho=0.01$	0.72
LMK	59	$a*x^3+b*x^2+d*x+c$	0.00	-0.00	0.03				8.30	$F(3,55)=6.14\ \rho<0.01$	0.99
LOT+MKX	43	# a*x+c	-0.00						7.35	$F(1,41)=2.55\ \rho=0.12$	0.35
LZK	45	$a*x^2+b*x+c$	-0.00	0.05					8.14	$F(2,42)=19.27\ \rho<0.01$	1.00
MAF+SJT	50	$a*x^3+b*x^2+c*x+d$	0.00	-0.02	0.44				5.28	$F(3,46)=7.71\ \rho<0.01$	1.00
MEG	56	# a*ln(x)+b	0.55						6.30	$F(1,54)=5.63\ \rho=0.02$	0.64
MEG	56	# a*ln(x)+b	0.55						6.30	$F(1,54)=5.63\ \rho=0.02$	0.64
MFL+MLB+TBW	32	$a*x^2+b*x+d*y^3+e*y^2+f*y+g$	-0.00	0.01	0.00	-0.00	0.09		3.66	$F(5,26)=20.50\ \rho<0.01$	1.00
MPX	51	$a*x^4+b*x^3+d*x^2+e*x+c$	-0.00	0.00	-0.00	0.04			6.31	$F(4,46)=17.70\ \rho<0.01$	1.00
MRX	38	# $a*x^2+b*x+c$	-0.00	0.03					9.18	$F(2,35)=17.75\ \rho=0.04$	0.73
OAX	38	$a*x^5+b*x^4+d*x^3+e*x^2+f*x+g*y+c$	0.00	-0.00	0.00	-0.01	0.31	-0.01	8.05	$F(6,31)=12.69\ \rho<0.01$	1.00
OHX	42	# a*ln(x)+b*y+c	0.35	-0.01					11.02	$F(2,39)=1.63\ \rho=0.21$	0.43
OUN	56	$a*x^3+b*x^2+d*x+e*y^3+f*y^2+g*y+c$	0.00	-0.00	0.02	-0.00	0.00	-0.01	10.03	$F(6,49)=8.13\ \rho<0.01$	1.00
PAH	58	$a*x^2+b*x+d*y^2+e*y+c$	0.00	-0.01	0.00	-0.03			10.88	$F(4,53)=10.56\ \rho<0.01$	1.00
PBZ	33	$a*x^3+b*x^2+d*y^2+e*y+c$	0.00	-0.00	-0.00	0.00			0.01	$F(4,28)=8.32\ \rho<0.01$	1.00
RLX	46	$a*x^3+b*x^2+d*x+e*y+c$	0.00	-0.00	0.07	-0.01			6.43	$F(4,42)=5.24\ \rho=0.02$	0.99
SGF	37	$a*x^2+b*x+d*y+c$	-0.00	0.03	-0.02				10.73	$F(3,33)=33.69\ \rho<0.01$	1.00
SHV	48	$a*x^4+b*x^3+d*x^2+e*x+f*y+c$	-0.00	0.00	-0.01	0.21	-0.01		6.17	$F(5,42)=5.74\ \rho<0.01$	1.00
TAE	48	$a*y^2+b*y+c$	-0.00	0.01					6.58	$F(2,45)=4.84\ \rho=0.01$	0.85
TSA	32	a*x+b*y+c	0.01	-0.02					11.82	$F(2,29)=22.07\ \rho<0.01$	1.00

APPENDIX B (CONT.)

EQUATION LIST

Regression Equations Derived for Tornado Warnings, F test results and power rating.
x=population density, y=distance from radar. #=equation not used in recalculation for spatial distribution.

WFO (s)	n value	Equation	First Six Coefficients (to nearest hundredth)						Constant	F test	Power
			a	b	d	e	f	g	c		
ABQ+BOU+PUB	37	$a*x+b*y^3+c*y^2+d*y+c$	0.00	-0.00	0.00	-0.01			1.92	$F(4,32)=3.94$ $\rho=0.01$	0.97
ABR	28	$a*\ln(x)+b*y+c$	0.35	-0.00					2.01	$F(2,25)=9.87$ $\rho<0.01$	0.98
AMA+LUB	47	$a*x+c$	-0.01						2.76	$F(1,45)=9.53$ $\rho<0.01$	0.84
APX+MQT	38	$a*x^3+b*x^2+d*x+e*y+c$	0.00	-0.01	0.20	-0.00			0.39	$F(4,33)=5.29$ $\rho<0.01$	0.99
ARX	28	# $a*\ln(x)+b*\ln(y)+c$	0.35	0.27					-0.09	$F(2,25)=1.07$ $\rho=0.36$	0.30
BIS	36	$a*x+c$	0.01						2.13	$F(1,34)=28.92$ $\rho<0.01$	1.00
BMX	49	# $a*x+c$	0.00						3.92	$F(1,47)=5.29$ $\rho=0.03$	0.61
BRO+CRP+EWX	56	$a*\ln(x)+b$	0.18						1.61	$F(1,54)=16.96$ $\rho<0.01$	0.97
BYZ+TFX	27	# $a*x^2+b*x+c$	0.01	-0.12					0.87	$F(2,24)=1.81$ $\rho=0.19$	0.46
CAE+CHS+GSP+JAX	52	# $a*x^3+b*x^2+d*x+c$	0.00	-0.00	0.01				2.82	$F(3,48)=1.62$ $\rho=0.20$	0.59
CLE	30	# $a*x+c$	-0.00						3.04	$F(1,28)=1.34$ $\rho=0.26$	0.20
CYS+GGW+UNR	44	$a*x^b+d*\ln(y)+c$	1.65	0.20	0.33				-1.75	$F(3,40)=7.74$ $\rho<0.01$	0.99
DDC+GID+GLD+LBF	102	$a*\ln(x)+b$	0.23						2.47	$F(1,100)=13.56$ $\rho<0.01$	0.95
DLH+GRB	40	$a*\ln(x)+b$	0.24						0.80	$F(1,38)=11.94$ $\rho=0.01$	0.90
DMX	51	$a*\ln(x)+b$	0.42						1.64	$F(1,49)=12.70$ $\rho<0.01$	0.92
DTX+GRR	40	$a*\ln(x)+b*z+c$	0.26	-0.00					0.87	$F(2,37)=4.78$ $\rho=0.01$	0.85
DVN	36	$a*x+b*y^2+d*y+c$	0.00	-0.00	0.02				2.28	$F(3,32)=3.08$ $\rho=0.04$	0.84
EAX	44	# $a*\ln(x)+b$	0.13						1.88	$F(1,42)=4.12$ $\rho=0.05$	0.51
FFC	96	$a*\ln(x)+b$	0.25						1.59	$F(1,94)=12.37$ $\rho<0.01$	0.93
FGF	35	# $a*x+b$	0.02						1.90	$F(1,33)=1.54$ $\rho=0.22$	0.23
FSD	45	$a*x^2+b*x+c$	-0.00	0.09					1.92	$F(2,42)=8.74$ $\rho<0.01$	0.98
FWD	46	$a*\ln(x)+c$	0.17						1.54	$F(1,44)=8.46$ $\rho<0.01$	0.80
HGX+LCH	45	$a*\ln(x)+b*y^2+d*y+c$	0.39	-0.00	0.03				0.20	$F(3,41)=6.96$ $\rho<0.01$	0.99
ICT+TOP	49	$a*x^2+b*x+d*y^5+e*z^3+c$	-0.00	0.02	0.00	-0.00			2.89	$F(4,44)=2.77$ $\rho=0.04$	0.91
ILN	52	# $a*\ln(x)+b*\ln(y)+c$	0.06	-0.18					2.53	$F(2,49)=1.57$ $\rho=0.22$	0.42
ILX+LSX	81	# $a*\ln(x)+b$	0.20						3.02	$F(1,79)=5.39$ $\rho=0.02$	0.63
IND	39	$a*\ln(x)+b*z^c+d$	0.25	0.00	2.99				1.71	$F(3,35)=3.21$ $\rho=0.04$	0.86
IWX	37	# $a*\ln(y)+c$	-0.35						4.13	$F(1,35)=2.05$ $\rho=0.16$	0.29
JAN	58	# $a*x+c$	0.01						3.95	$F(1,56)=3.07$ $\rho=0.08$	0.41

(Cont.) Regression Equations Derived for Tornado Warnings, F test results and power rating.
x=population density, y=distance from radar. #=equation not used in recalculation for spatial distribution.

WFO (s)	n value	Equation	First Six Coefficients (to nearest hundredth)						Constant	F test	Power
			a	b	d	e	f	g	c		
JKL+RNK	36	# $a*\ln(y)+c$	-0.43						4.49	$F(1,33)=3.41\ \rho=0.07$	0.43
LIX+MOB	51	$a*\ln(x)+b*\ln(y)+c$	0.33	-0.24					3.57	$F(2,48)=4.52\ \rho=0.02$	0.83
LOT+MKX	43	# $a*\ln(x)+b$	-0.15						2.96	$F(1,41)=3.72\ \rho=0.06$	0.47
MAF+SJT	50	# $a*x^3+b*x^2+d*x+e*\ln(y)+c$	0.00	-0.01	0.20	-0.26			3.18	$F(4,45)=2.38\ \rho=0.07$	0.86
MEG	56	# $a*\ln(x)+b*\ln(y)+c$	0.09	-0.05					2.58	$F(2,53)=0.16\ \rho=0.85$	0.08
MFL+MLB+TBW	32	$a*x^2+b*x+d*y^3+e*y^2+f*y+c$	-0.00	0.00	0.00	-0.00	0.04		1.49	$F(5,26)=15.92\ \rho<0.01$	1.00
MPX	51	$a*x^4+b*x^3+d*x^2+e*x+f*y+c$	-0.00	0.00	-0.00	0.03	-0.00		2.41	$F(5,45)=5.35\ \rho<0.01$	1.00
MRX	38	# $a*\ln(x)+b*\ln(y)+c$	-0.08	0.00					2.69	$F(2,35)=0.27\ \rho=0.77$	0.11
OAX	38	$a*x^5+b*x^4+d*x^3+e*x^2+f*x+g*\ln(y)+c$	0.00	-0.00	0.00	-0.01	0.19	-0.27	3.77	$F(6,31)=2.46\ \rho=0.05$	0.97
OHX	42	# $a*\ln(x)+b*\ln(y)+c$	0.24	-0.37					5.35	$F(2,39)=2.47\ \rho=0.10$	0.59
OUN	56	$a*x^4+b*x^3+d*x^2+e*x+f*y+c$	-0.00	0.00	-0.00	0.05	-0.01		3.23	$F(5,50)=5.03\ \rho<0.01$	1.00
PAH	58	$a*y^2+b*y+c$	-0.00	0.01					2.99	$F(2,55)=5.57\ \rho<0.01$	0.90
PBZ	33	# $a*x^4+b*x^3+d*x^2+e*x+c$	0.00	-0.00	0.00	-0.05			2.07	$F(4,28)=1.99\ \rho=0.12$	0.80
RLX	46	# $a*y+c$	-0.01						1.89	$F(1,45)=3.63\ \rho=0.06$	0.46
SGF	37	$a*y^2+b*z+c$	-0.00	0.01					2.68	$F(2,34)=19.57\ \rho<0.01$	1.00
SHV	48	# $a*\ln(y)+c$	-0.37						3.85	$F(1,46)=7.78\ \rho<0.01$	0.77
TAE	48	$a*y^2+b*y+c$	-0.00	0.02					2.69	$F(2,45)=5.64\ \rho<0.01$	0.90
TSA	32	$a*x+b*y+c$	0.00	-0.01					4.11	$F(2,29)=7.76\ \rho<0.01$	0.96

REFERENCES

Agresti, A. and Finlay, B., 1997: Statistical Methods for the Social Sciences (3rd ed.), Upper Saddle River, NJ: Prentice Hall.

Altinger de Schwarzkopf, M. L., and Rosso, L. C., 1982: Severe Storms and Tornadoes in Argentina. Preprints, *12th Conference on Severe Local Storms*, San Antonio, TX, American Meteorological Society, 59-62.

Bonan, G. B., 2001: Observational Evidence for Reduction of Daily Maximum Temperature by Croplands in the Midwest United States. *Journal of Climate*, 14: 2430-2442.

Brooks, H. E., Doswell III, C. A., and Kay, M. P., 2003a: Climatological Estimates of Local Daily Tornado Probability for the United States. *Weather and Forecasting*, 18: 626-640.

Brooks, H. E., Lee, J. W., and Craven, J. P., 2003b: The Spatial Distribution of Severe Thunderstorm and Tornado Environments from Global Reanalysis Data. *Atmospheric Research*, 67-68: 73-94. (last accessed 22 March, 2006).

Changnon, S. A., 1977: The Scales of Hail. *Journal of Applied Meteorology*, 16: 626-648.

Changnon. S. A., 1982: Trends in Tornado Frequencies, Preprints, *12th Conference on Severe Local Storms*, San Antonio, TX, American Meteorological Society, 42-44.

Changnon, S. A., 2001: Assessment of Historical Thunderstorm Data for Urban Effects: The Chicago Case. *Climatic Change*, 49: 161-169.

Concannon, P. R., Brooks, H. E., and Doswell III, C. A., 2000: Climatological Risk of Strong and Violent Tornadoes in the United States. Preprints, *2nd Symposium on Environmental Applications*, Long Beach, CA, USA, American Meteorological Society.

Cortinas, J. V., Stensrud, D. J., 1994: The Mesoscale Features Associated with Severe Convective Weather, Preprints, Preprints, *10th Conference on Numerical Weather Prediction*, Portland, OR, American Meteorological Society, 606-608.

Crum, T. D., Saffle, R. E., and Wilson, J. W., 1998: An Update on the NEXRAD Program and Future WSR-88D Support to Operations.

deVilliers, N. A., 1997: Severe Weather Statistics for the Warning Area of the Modernized Weather Forecast Offices at Little Rock, Arkansas. NOAA Technical Memorandum NWS SR-182. 1997. http://www.srh.noaa.gov/ssd/techmemo/tm182.htm (last accessed 22 March, 2006).

Davies-Jones, R., Burgess, D., and Foster M., 1990: Test of helicity as a tornado forecast parameter. Preprints, *16th Conf. Severe Local Storms*, Kananaskis Park, Alberta, American Meteorological Society, 588-592.

Dessens, Jr., J., 1972: Influence of Ground Roughness on Tornadoes: A Laboratory Simulation. *Journal of Applied Meteorology*, 11: 72-75.

Dessens, J. and Snow, J. T., 1989: Tornadoes in France. *Weather and Forecasting*. 4: 110-132.

Doswell III, C. A. and Burgess, D. W., 1988: On Some Issued of United States Tornado Climatology. *Monthly Weather Review*, 116: 495-501.

Doswell III, C. A., Moller, A. R., and Brooks, H. E., 1999: Storm Spotting and Public Awareness since the First Tornado Forecasts of 1948. *Weather and Forecasting*, 14: 544-557.

Elsom, D., and Meaden, G., 1982: Suppression and Dissipation of Weak Tornadoes in Metropolitan Areas: A Case Study of Greater London. *Monthly Weather Review*, 110: 745-756.

ESRI Inc.®, ArcMap 9.0, 2004.

Federal Meteorological Handbook No. 11, Doppler Radar Meteorological Observations, Part B., 1990. Page 3-19. U.S. Dept. of Commerce, National Oceanic and Atmospheric Administration.

Forecast Systems Laboratory, 2005. U.S. Dept. of Commerce, National Oceanic and Atmospheric Administration. Advanced Weather Interactive Processing System, Two Dimensional Display.

Fujita, T. F., 1987: U.S. Tornadoes, Part 1, 70-Year Statistics, *University of Chicago Press*, Chicago.

Gallo, K. P., Easterling, D. R., and Peterson, T. C., 1996: The Influence of Land Use/Land Cover on Climatological Values of the Diurnal Temperature Range. *Journal of Climate*, 9: 2941-2944.

Galway, J. G., 1989: History: The Evolution of Severe Thunderstorm Criteria within the Weather Service. *Weather and Forecasting*, 4: 585-592.

Golden Software Inc.®, MapViewer 5.0, 2002.

Grazulis, T. P., 1991: Significant Tornadoes, 1880-1989. Volume I: Discussion and Analysis. Environmental Films: 526 pp.

Kelly, D. L., Schaefer, J. T., McNulty, R. P., and Doswell III, C. A., 1978: An Augmented Climatology. *Monthly Weather Review*, 106: 1172-1183.

Kelly, D. L., Schaefer, J. T., and Doswell III, C. A., 1985: Climatology of Nontornadic Severe Thunderstorm Events in the United States. *Monthly Weather Review*, 113: 1997-2014.

King, P., 1997: On the Absence of Population Bias in the Tornado Climatology of Southwestern Ontario. *Weather and Forecasting*, 12: 939-946.

Maddox, R. A., Zhang, J., Gourley, J. J., and Howard, K. W., 2002: Weather Radar Coverage over the Contiguous United States. *Weather and Forecasting*. 17: 927-934.

McPherson, R., 2004: The Impact of Oklahoma's Winter Wheat Crop on the Mesoscale Environment. *Monthly Weather Review*, 132: 405-421.

Meaden, G. T., 1976. Tornadoes in Britain: their intensities and distribution in space and time. *Journal of Meteorology*, 1: 242-251.

Mertler, C. A., and Vannatta, R. A., 2005: Advanced and Multivariate Statistical Methods (3rd ed.). Glendale, CA: Pyrczak Publishing

Minor, J. E., and Peterson, R. E., 1979: Characteristics of Australian Tornadoes. *11th Conference on Severe Local Storms*, Kansas City, MO. American Meteorological Society, 208-215.

National Severe Storms Laboratory, Severe Thunderstorm and Tornado Climatological Graphics. 2003:
http://www.nssl.noaa.gov/hazard/img/ttor8099.gif (last accessed 22 March, 2006).
http://www.nssl.noaa.gov/hazard/img/twin8099.gif (last accessed 22 March, 2006).
http://www.nssl.noaa.gov/hazard/img/thai8099.gif (last accessed 22 March, 2006).

National Weather Service Directives 10-511, 10-512, and 10-1601, 2003:
http://www.nws.noaa.gov/directives/010/pd01005011b.pdf (last accessed 22 March, 2006).
http://www.nws.noaa.gov/directives/010/pd01005012b.pdf (last accessed 22 March, 2006).
http://www.nws.noaa.gov/directives/010/pd01016001a.pdf (last accessed 22 March, 2006).

National Weather Service, Paducah, Kentucky, 2006: Paducah WFO history: http://www.crh.noaa.gov/pah/history.php (last accessed 8 April, 2006).

National Weather Service Operations Manual, Part A, Chapter 2, Section 2. 2006: http://www.weather.gov/wsom/manual/archives/NA027045.HTML (last accessed 22 March, 2006).

National Weather Service Radar Operations Center, 2006: http://www.roc.noaa.gov/ssb/queries/siteid/advanced.asp (last accessed 22 March, 2006).

National Weather Service, 2005: Shapefiles for CONUS Digital Terrain and County Warning Area Boundaries, 2005.
http://www.nws.noaa.gov/geodata (last accessed 22 March, 2006).

National Weather Service Verification Data. 2005: https://verification.nws.noaa.gov (last accessed 22 March, 2006).

National Weather Service WSR-88D STEPS Operation Plan, Section 4.1.3. 2006: http://www.mmm.ucar.edu/pdas/Ops-plan.images/ops-plan.vcp11.html (last accessed 22 March, 2006).

Newark, M. J., 1983: Tornadoes in Canada for the period 1950 to 1979. Canadian Climate Centre Publication [Available from AES Library, 4905 Dufferin St., Downsview, ON M3H 5T4, Canada].

Pryor, S. C., and Kurzhal, T., 1997: A Tornado Climatology for Indiana. *Physical Geography*, 18: 525-543.

Ray, P. S., Bieringer, P., Niu, X., and Whissel, B., 2003: An Improved Estimate of Tornado Occurrence in the Central Plains of the United States. *Monthly Weather Review*, 131: 1026-1031.

Roulston, M. S., and Smith, L. A., 2004: The Boy Who Cried Wolf Revisited: The Impact of False Alarm Intolerance on Cost-Loss Scenarios. *Weather and Forecasting*, 19: 391-397.

Schaefer, J. T., and Galway, J. G., 1982: Population Biases in Tornado Climatology. Preprint, *12th Conference on Severe Local Storms*, San Antonio, Texas. American Meteorological Society, Boston.

Schaefer, J. T., Levit, J. J., Weiss, S. J., and McCarthy, D. W., 2004: The Frequency of Large Hail over the Contiguous United States. *14th Conference on Applied Climatology*. http://ams.confex.com/ams/pdfpapers/69834.pdf (last accessed 30 March, 2006).

Segal, M., Garratt, J. R., Pielke, R. A., Schreiber, W. E., Rodi, A., Kallos, G. and Weaver, J., 1989: The Impact of Crop Areas in Northeast Colorado on Midsummer Mesoscale Thermal Circulations. Monthly Weather Review, 117: 809-825.

Segal, M., Arritt, R. W., and Clark, C., 1995: Scaling Evaluation of the Effect of Surface Characteristics on Potential for Deep Convection over Uniform Terrain. *Monthly Weather Review*, 123: 383-400.

Sims, J. H., and Baumann, D., 1972: The Tornado Threat: Coping Styles of North and South. *Science* 176 (4042): 1386-1392.

SPSS Inc.®, SigmaStat for Windows 2.03, 1997.

Snider, C. R., 1977: Notes and Correspondence, A Look at Michigan Tornado Statistics. *Monthly Weather Review*, 115: 1341-1342.

Snow, J. T., and Wyatt, A. L., 1997: Back to Basics: The Tornado, Nature's Most Violent Wind: Part I-World-wide Occurrence and Categorisation. *Weather*, 52: 298-304.

Snow, J. T., and Wyatt, A. L., 1998: Back to Basics: The Tornado, Nature's Most Violent Wind: Part 2-Formation and Current Research. *Weather*, 53: 66-72.

Stensrud, D. J., Cortinas Jr., J. V., Brooks, H. E., 1997: Discriminating between Tornadic and Nontornadic Thunderstorms Using Mesoscale Model Output. *Weather and Forecasting*, 12: 613-632.

Stevens, J., 1992: Applied Multivariate Statistics for the Social Sciences (2nd ed.), Hillsdale, NJ: Lawrence Erlbaum Associates.

Tate, R. 1992: General Linear Model Applications. Unpublished manuscript, Florida State Univeristy.

Vasiloff, S. V., 2001: Improving Tornado Warnings with the Federal Aviation Administration's Terminal Doppler Weather Radar. *Bulletin of the American Meteorological Society*, 82: 861-874.

Weiss, S. J., Hart, J. A., and Janish, P. R., 2004: An Examination of Severe Thunderstorm Wind Report Climatology: 1970-1999. *21st Conference on Severe Local Storms*: http://ams.confex.com/ams/pdfview.cgi?username=47494 (last accessed 22 March, 2006).

U.S. Census Bureau county population density and area sizes from 2000 U.S. Census. 2003: http://www.census.gov (last accessed 1 May, 2004).

United States, 1994: NEXRAD, Tornado Warnings, and National Weather Modernization: hearing before the Subcommittee on Space of the Committee on Science, Space, and Technology, U.S. House of Representatives, One Hundred Third Congress, Second session.

The University Center for Atmospheric Research (UCAR), 2006: National Weather Service WSR-88D STEP Operations Plan, Section 4.1.3, Volume Coverage Pattern 11 Schematic. http://www.mmm.ucar.edu/pdas/Ops-plan.images/ops-plan.vcp11.html (last accessed 22 March, 2006).

Zhang, J., 2006: Two-Dimensional Effective Radar Coverage at a Constant Height Above Ground Level. Cooperative Institute for Mesoscale Meteorological Studies. http://www.cimms.ou.edu/~jzhang/radcov/US_lamb.radcov_1kmagl.jpg (last accessed 22 March, 2006).