THE INFLUENCE OF URBANIZATION ON TORNADO DEVELOPMENT IN THE CENTRAL UNITED STATES: A CASE STUDY OF 30 METROPOLITAN STATISTICAL AREAS

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Abstract of Thesis

The Influence of Urbanization on Tornado Development in the Central United States: A Case Study of 30 Metropolitan Statistical Areas

Despite the vast amount of research into the urban effect on weather and climate, very little is known about the effect on severe weather events such as tornadoes. As the population of the United States becomes increasingly urban, it is imperative to understand exactly how urbanization can affect such processes. To fill this void in urban meteorology research, this study analyzed urbanization changes in 30 Metropolitan Statistical Areas in the Central United States over a period of 30 years, comparing those changes to tornado occurrences. While the results indicate there is a direct relationship between the size of an urban area and the number of tornado events observed, no relationship exists between urban expansion and tornado events occurring within the urban boundaries. Future work on the subject should incorporate the potential urban effect on downwind locations.

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CHAPTER I: Introduction

In March of 2008, an intense tornado struck the downtown area of Atlanta, Georgia, causing millions of dollars in damages and affecting the lives of thousands of people. In the past, tornadoes striking urban areas have been rare (simply because cities do not take up as much geographic space as rural areas), so rare that there is a widely-believed myth regarding tornadoes avoiding urban locations. A recent study funded by NASA, however, shows that the likelihood of an urban area being struck by a tornado is increasing (Bauerlein, 2009). This conclusion seems logical- after all, as the area of urbanized land increases it becomes a bigger geographic target, thus increasing its chance of being hit by a storm. However, other meteorological factors, such as the Urban Heat Island Effect (UHIE), may be involved that are increasing the vulnerability of these locations. This study will determine if urban expansion increases the likelihood of tornado development.

History of Urbanization

For the first time in history, the majority of humans live in an urban setting. In the last 50 years alone the number of city dwellers worldwide has risen by 30%; and with urban populations increasing by 67 million per year, that percentage will continue to increase. By 2030, it is estimated that the urban population will reach five billion people (UN, 2002).

In the United States, population has increased from four million in 1800 to just over 300 million today. Urban population is a thousand times larger than it was in 1800, and today nearly two-thirds of the American population are urban residents (EPA,

2009A). In geographic area, however, these densely populated locations collectively occupy less than two percent of the entire landmass of the country (NOAA, 2004). Despite the small area they encompass, urban landscapes can have a wide range of effects on the natural environment.

As populations increase, undeveloped land is typically converted into areas for commercial and residential use (EPA, 2009A). In this respect, as the population of the United States becomes increasingly urban, large changes are brought to the natural landscape. Land cover types are changed from their natural vegetative state into collections of steel and concrete and other impervious surfaces typically found in cities and towns (Silva et al., 2009).

In the past few decades, many areas of the country have seen disproportionate increases in urbanized land compared to population growth. In the 1980s and 1990s, for example, the population increased only half as fast as the amount of developed land. Specifically, urban land in the US grew by 48%, or by 35 million acres. During the same time, however, the population only grew 25%, or by 58 million people (EPA, 2009A).

With more land being converted for urban use than the population increases require, the effects on the environment are compounded (EPA, 2009A). Deforestation, loss in biodiversity, and increases in greenhouse-gas emissions are just a few of the environmental changes caused by urbanization. Ninety percent of worldwide anthropogenic carbon emissions come from cities, and environmental changes caused by humans are generally acknowledged to increase the frequency and effects of droughts, floods, and other extreme weather events (Aguirre et al., 1993; Sviriejeva-Hopkins et al., 2004). Considering the number of people now living in urban areas and the amount of

resources they demand, urban populations have a very strong influence on global environmental change as a whole (Grimmond, 2007).

Urban areas also affect environmental conditions on a smaller regional or local scale (Grimmond, 2007). Human-built landscapes can have substantial impacts on the energy budget and water cycle of an area, while the transformation away from vegetation reduces evaporation and increases the heat storage capacity of the landscape (Golden, 2003). Another notable impact is that urban environments can disrupt weather patterns around them. Impervious surfaces used to create buildings and pavements absorb and store more heat energy than natural vegetation. This process, combined with the heat generated from technological emissions (such as air conditioning units, vehicles, and industrial machinery) can change the thermal properties of the atmosphere. The result is a distinctive 'urban climate' that differs from the surrounding rural area (Silva et al., 2009).

Considering the drastic increase in urban land during the past half-century, the study of urban meteorology has recently become an important scientific topic. Because of the number of people potentially affected, urban populations are far more likely to suffer prolonged effects from severe weather events or weather extremes than rural populations. Heavy rains within a densely-populated area can flood homes and businesses, snow and ice can impact traffic systems, and storms with high winds or lightning can down power lines and cut electricity to thousands (NOAA, 2004). For these reasons, it is imperative to understand how urban environments might influence or even completely change the weather around them.

Technological advances in remote sensing and Geographic Information System (GIS) applications allow for sub-regional observations of urban areas and can record small

changes in the landscape. Also, the ever-increasing reliability and complexity of weather and climate models allow for more accurate predictions of weather events (NOAA, 2004). Combined, these scientific advancements allow for the in-depth research of urban meteorology; specifically how severe weather events might be influenced by an urban landscape. While some of the basic meteorological effects urban areas have on weather conditions are well understood, the urban influence on isolated severe weather events has been largely ignored. The goal of this project is to determine if there has been a historical relationship between urban expansion in the United States and the occurrence of severe weather events such as tornadoes.

CHAPTER II: How does urbanization affect local climate?

When large tracts of natural land are modified for anthropogenic use, the effects on the surrounding natural environment, including the local climate, can be drastic. The collective term for how urban areas influence the climate and weather around them is known as UHIE. UHIE constitutes a wide range of meteorological effects, even if the name implies only a temperature increase. The temperature change in an urban area is simply the most documented effect of development; cities are almost always warmer than the surrounding rural area (Grimmond, 2007). However, secondary effects include changes in wind patterns, amounts of clouds and fog, humidity, and precipitation (AMA, 1992; Silva et al., 2009).

The idea that the urbanization of natural landscapes alters localized climate has been widely researched in the past few decades. As far back as the 1950's, when the post-war economic boom saw a large increase in the built environment, scientists were analyzing how climate might be modified by anthropogenic land use. Much of the earliest work came from H.E. Landsberg, who published 40 years of research that discussed the climate of cities. He outlined the most important factors of urban expansion that affect the climate: the increase in impervious surfaces, the absorption and retention of heat, and especially the increase in pollution. In numerous research articles, the first of which was published in 1955, Landsberg was the first to note how excess pollution affected a wide range of meteorological factors, including temperature (Landsberg, 1955, 1970, 1981).

Tiedemann (1986), Ebert (1988), and Jager and Barry (1990) expanded upon Landsberg's ideas and verified his initial assumptions. They found that cities in general,

in comparison to rural areas, have: 1) higher levels of particulate matter; 2) less radiation from the sun reaching the surface; 3) less visibility due to clouds, smog, and fog; 4) higher levels of precipitation; 5) higher temperatures; 6) less humidity; and 7) lower wind speeds.

Temperature Difference

The tendency of a city to experience warmer temperatures than rural areas is a result of five different factors: 1) increased heat storage; 2) reduced evaporation, 3) increased net radiation; 4) reduced convection; and 5) increased anthropogenic heat.

1. **Increased heat storage.** The main cause of a temperature increase in an urban setting comes from the materials used to construct the city (Grimmond, 2007). Impervious surfaces such as concrete have different thermal properties than the vegetation, soil, water, and rock found in a natural landscape. Materials with high thermal diffusivity (when heat is absorbed more deeply into the layers of a material) keep temperatures relatively constant for a longer period of time. Low thermal diffusivity implies that heat is absorbed only in the outer layers, allowing for temperatures to change more rapidly. Man-made materials have much higher thermal diffusivity levels than natural vegetation, and therefore increase the surrounding air temperature (see Figure 2.1 for a list of various materials and their thermal diffusivity values). On a clear and sunny summer day, for example, these exposed surfaces could become as much as 50 to 70 °F warmer than the air above them. The vegetation that typically dominates a rural landscape does not retain as much heat, and as a result remains close to air temperature (Luvall and Quattrochi, 2006).

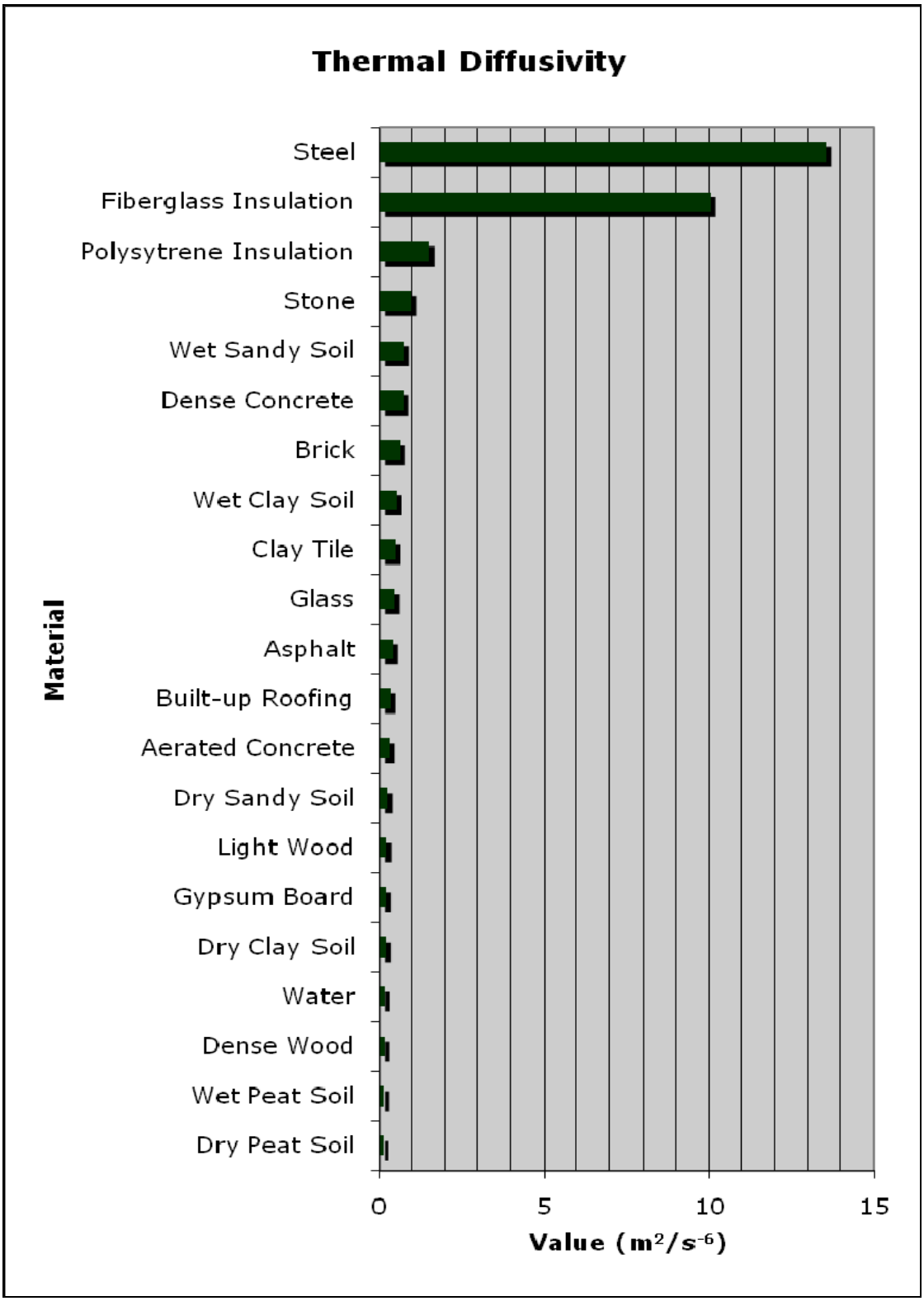

Figure 1.1: Thermal Diffusivity Values of Various Materials (from Gartland 2008)

While man-made materials usually have high thermal diffusivity values, each different type of material has its own unique property that contributes to the variability of the heat island effect even within the same urban area. For this reason, temperatures can fluctuate measurably across small distances; there can be a difference between a residential neighborhood and an industrial area, an apartment complex and a business office, or even from one side of a street to the other (Grimmond, 2007).

2. **Reduced Evaporation.** While adding impervious surfaces can increase temperature, removing the natural vegetation enhances the effect. Under normal circumstances, a large portion of the surface energy balance is devoted to the process of evaporation (Gartland, 2008). Vegetation is largely responsible for releasing this energy through the process of evapotranspiration, which cools the surrounding air (EPA, 2009B). Most cities do not replace vegetation lost through urban expansion, so the effect on temperature is enhanced when vegetation is lost and impervious surfaces replace it (Grimmond, 2007). With less vegetation to release energy through evaporation, urban areas store more energy during the day and slowly release the energy at night (Gartland, 2008).

3. **Increased net radiation**. Most materials found in urban landscapes absorb more incoming solar radiation than reflect it. By lowering the overall solar reflectance, urban areas generally increase the net radiation (Gartland, 2008). Similarly, most man-made materials have low emittance values, meaning they do not radiate heat well. Concrete and metal surfaces have both low albedo and low emittance, meaning they absorb far more energy than reflect and also release the stored energy slowly (thus

retaining the energy longer). Combined, these factors lead to an increase in net radiation within an urban landscape (Gartland, 2008).

Aside from the reflectance and emittance values, the difference in net radiation between urban and rural can also be attributed to higher air pollution and the shape of urban constructions. First, heat energy is typically released from a surface in all directions. In an urban area, because of the shape of the landscape, this means that energy released from the ground has a good chance of being recaptured by the side of a building instead of being released back into the atmosphere. Second, air pollution serves to increase net radiation by absorbing radiation in the atmosphere. Excess radiation leads to higher temperatures in the atmosphere (Landsberg, 1981). In addition, while it does block some radiation from reaching the surface, excess pollution in the atmosphere also blocks outgoing reflected radiation. This effectively traps the radiation close to the surface and keeps the temperature warmer (EPA, 2007).

4. **Reduced Convection.** Heat islands are strongest during clear weather with little wind (Landsberg, 1981; Gartland, 2008). The more wind action present, the quicker the convection of energy occurs from the surface to the air. When the wind speeds are low, however, more heat energy is stored and the release of heat is slower (Gartland, 2008).

5. **Increased anthropogenic heat.** The heat emitted from electrical appliances, industrial units, factories, and automobiles (all of which are far more numerous in urban areas than rural) increase the ambient temperature of cities (AMA, 1992). There has been a steady increase in energy consumption in the U.S. since 1950, with a 25% increase occurring between 1980 and 2000 alone. Much of this increase has been attributed to the

more widespread use of air conditioning units in the summer time, which has led to a greater increase in anthropogenic heat emissions in the summer months (Gartland, 2008).

While all of the above reasons increase temperature in an urban setting, the actual temperature *difference* between a city and the surrounding rural region depends on many different factors including the size of the city, season, and time of day (Gartland, 2008). First, the size of the city and the temperature difference is directly proportional (i.e. as size increases, so does the difference). A city of one million people can be, on average, as much as 6 °F warmer, while a city of 100,000 people might only be 1-2 °F warmer (EPA 2009B). The size and density of the buildings is also important, as taller and more dense buildings will further increase the temperature (Oke, 1981; Voogt and Oke, 1991).

The season and time of day also affects the temperature difference. Heat islands tend to be more pronounced in the winter than the summer because of the greater difference between the temperature of the air and the temperature of the urban materials. The air temperature difference between urban and rural locations can be increased by as much as 10 ° F during colder months. Regarding time of day, the heat island is weakest during the morning hours (when all the stored energy in the urban area has been exhausted and has not yet had time to rebuild) but slowly increases throughout the day (EPA, 2009B). While the warmest overall temperatures are usually felt during the late afternoon, the greatest difference between urban and rural locations is typically recorded two to three hours after sunset (EPA, 2009B; Grimmond, 2007). At this time, the energy absorbed by the urban materials during the day is slowly being released into the atmosphere, keeping the temperatures warmer. Temperatures in the rural areas, however, steadily drop after the sun sets and there is no stored energy available. On a clear night

with little wind, the temperature differential can be increased by as much as 22 ° F between urban and rural locations (Grimmond, 2007).

Wind

Urban influences extend beyond temperature to affect other meteorological factors, such as wind. Because of the roughness of the surface (due to buildings), friction is greater in urban areas than in rural (AMA, 1992). Increased friction reduces wind speeds because the buildings effectively block straight-line winds. By acting as a barrier, buildings can slow wind speeds up to 60% (Landsberg, 1981). The decrease contributes to the warmer temperatures, as air is not circulated as well in urban locations. However, it is important to note that under the right circumstances, wind speed can actually increase inside a city. In a location that has many tall buildings densely aggregated into a small area, a tunneling effect might be produced that increases wind speeds at the base of the buildings (NOAA, 2004; Gartland, 2008). This increase is temporary and site-specific, so it generally does not have a large effect on average wind speeds throughout the entire city.

The effects of urbanization are not restricted only to surface level winds, but also to upper-level wind patterns as well. First, uneven heating that occurs between the surface (which heats up quickly during the day, especially during the summertime) and the upper atmosphere leads to convective winds, which eventually cause instability in the urban boundary layer (the area that marks the highest level of land surface influence). And second, extremely large urban areas can create enough friction to influence movement of air in the upper-level of the atmosphere. The jet stream, a strong wind pattern that extends around the globe, has been documented to alter its course when it

passes over New York City- the friction created by the buildings is strong enough to actually split the jet stream and divert the halves around the city (NOAA, 2004).

Precipitation

Similar to temperature and wind, precipitation is affected by the urban landscape. Changes in the surface wind patterns around cities can lead to converging air masses in the upper atmosphere. These convergence zones help form different weather fronts, which in turn leads to more clouds and increased precipitation (AMA, 1992). Also, having an excessive amount of aerosols or other particulate matter in the atmosphere can encourage cloud development by providing the necessary condensation nuclei needed for cloud droplets to form. Eventually, these pollution-induced clouds will create precipitation (Kaufman et al., 2005). And lastly, cities are more likely to produce convective lifting, which is a major source of precipitation. The enhanced urban convection is especially noticeable in the summer months, as the contrast (combined with the already warm air of summer) leads to stronger convective uplift and therefore more precipitation than in the surrounding rural regions. Combined, these urban effects can cause cities to record between 10-20% more rainfall per year than nearby rural areas (AMA, 1992).

Urban areas can clearly have a large effect on the weather around them. Research into UHIE has shown that by changing from a natural to a built environment, cities are capable of altering a variety of meteorological factors, ranging from temperature to wind to precipitation levels. Because most research has focused on general weather patterns and trends, little is known about how urbanization might influence specific weather events (such as severe thunderstorms or tornadoes). This project attempts to fill that

particular void in urban meteorology research by studying how an increase in urbanization affects the frequency of such storms.

CHAPTER III*:* Urban Influences on Thunderstorm and Tornado Development

While the urban effects on climate in general are relatively well-understood and documented, research looking into urban influence on specific meteorological events such as thunderstorms or tornadoes has been less thorough. In order to understand exactly how cities might affect severe weather events, it must first be understood how such events form under normal conditions.

Thunderstorms

Thunderstorms are weather events that include lightning and thunder, while heavy rain, strong winds, and even hail are possible side effects. They usually form when instability is created after warm, humid air rises. Uneven heating of the earth's surface is the most common cause of instability, and alone can form air-mass thunderstorms that are usually short-lived and weak (Lutgens and Tarbuck, 2010; Pidwirny, 2006).

Typical air-mass storms follow a three-step process: 1) the cumulus stage (when updrafts cause the cloud to grow from cumulus to cumulonimbus); 2) the mature stage (downdrafts form to balance out the updrafts, leading to heavy rain); and 3) the dissipating stage (updrafts gradually weaken and disappear, removing the moisture supply and ending the thunderstorm). But when uneven heating at the earth's surface combines with diverging wind aloft, more severe storms form. Diverging air in higher levels of the atmosphere pulls air upward, creating more instability. These conditions create a supercell, the strongest type of severe thunderstorm, and one far more likely to produce damaging hail and wind than an air mass storm. (Lutgens and Tarbuck, 2010).

Only about 2,000 of the 10,000 thunderstorms that occur in the United States each year are classified as supercells. The key difference between an air-mass thunderstorm and a supercell is the movement of the updrafts. In a supercell, diverging wind conditions aloft cause the updrafts to rotate. In order to remain stable, supercells require large amounts of heat energy coming from the surface as well as moisture off of which to feed (Lutgens and Tarbuck, 2010; Pidwimy, 2006).

A temperature inversion above the surface also plays a key role in supercell formation. An inversion, a very stable atmospheric condition that restricts vertical motion, prohibits the formation of smaller storms by allowing one very large storm to form. The inversion stops the air at the surface from mixing with the air above, and at first stalls the storm formation process. But as surface heating throughout the day increases the temperature at the ground and increases convective motion, eventually the inversion breaks down. The unstable air reacts violently by producing a much stronger storm than would otherwise have appeared (Lutgens and Tarbuck, 2010).

Supercell thunderstorms can produce devastating micro-scale events in the form of torrential rainfall, large hail, dangerous lightning, and in the most severe cases, even tornadoes (Trapp et al., 2007). Because they require such precise conditions, certain times and geographic locations are more likely to experience these extreme weather events than others (see Figure 3.1). In the United States, tornado season begins in the early spring throughout the southeastern and south-central states, and then expands to include the southern plains and north-central regions by early summer.

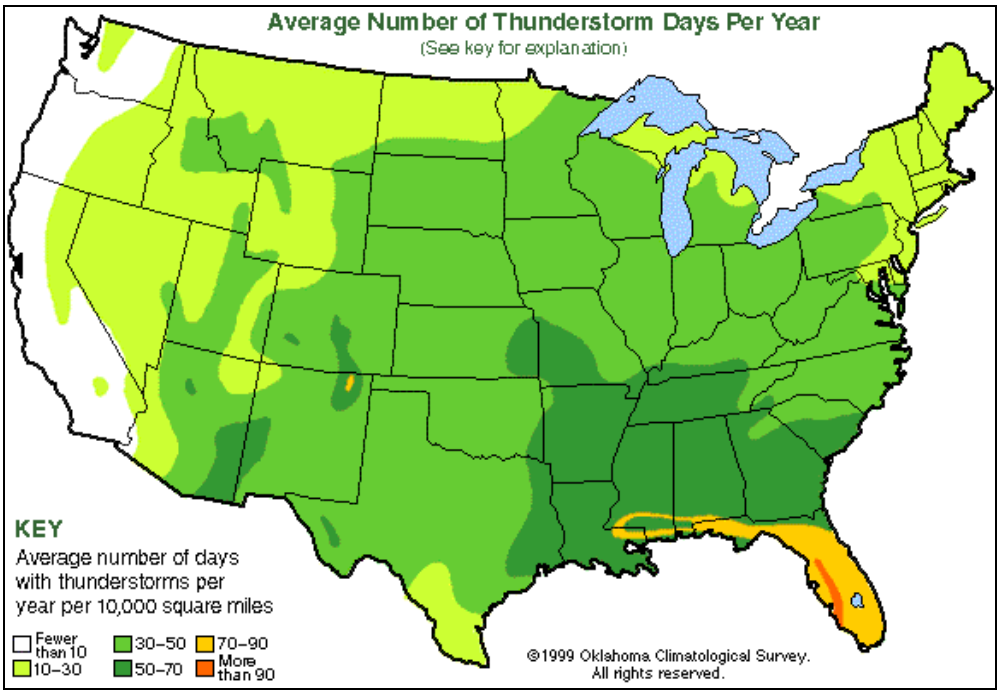

Figure 3.1: Average Number of Thunderstorm Days per Year (from Oklahoma Climatological Survey)

A likely location for thunderstorm development occurs where the warm, moist air from the Gulf of Mexico encounters the cooler, dry air from Canada- in the Great Plains states. Because thunderstorm development is a necessary prerequisite for tornadoes, this region is also geographically more likely than other areas of the country to experience favorable conditions for tornado development (Trapp et al., 2007).

Tornadoes

Once a storm reaches a point where there are updrafts, downdrafts, and rotation aloft, tornado formation is possible. Rotation is created by wind shear, when winds at various levels in the atmosphere are moving at different speeds. Generally, winds at the surface are slowed by friction, while winds at higher altitudes move more quickly because of the energy produced by the storm system. In an attempt to balance the different speeds out, an area of the system called the mesocyclone begins rotating, and

can eventually form a tornado (NSSL, 2006). About half of all mesocyclones spawn a tornado (Pidwirny, 2006).

Once a mesocyclone begins to rotate, a vortex can drop towards the ground, first as a funnel cloud, then turning into a tornado once it touches the ground. Low air pressure in the center of the vortex pulls air inward violently (at speeds up to 400 kph), which then spirals upward into the clouds. As it cools adiabatically, the air usually forms condensation, which allows for the vortex of air to become visible. If no condensation occurs, the vortex remains invisible until it collects enough dust and debris to give the tornado its characteristic appearance (Lutgens and Tarbuck, 2010).

The size and strength of any given tornado can vary, however most (about 74%) have wind speeds between 105 and 178 km/hr and last less than three minutes. These weaker events (classified as EF0 or EF1 on the Enhanced Fujita intensity scale) can at most break windows or slide cars off a road (Pidwirny, 2006). Table 3.1 below gives a complete breakdown of tornado scale and intensity.

Table 3.1: Enhanced Fujita Intensity Scale (from the Storm Prediction Center)

F-Scale	Category	Wind Speed (Kph)	Comments
0	Weak	105-137	Light Damage. Trees have broken branches, windows broken, damage to signs.
1	Weak	138-178	Shingles blown off roofs, mobile homes pushed off foundations, moving cars pushed off roads.
2	Strong	179-218	Considerable damage. Roofs torn off houses, mobile homes destroyed, Large trees uprooted.
3	Strong	219-266	Severe damage. Roofs and walls torn off buildings. Heavy cars lifted and thrown.
4	Violent	267-322	Homes completely leveled, structures with weak foundations blown some distance.
5	Violent	>322	Homes lifted off foundations and carried large distances, disintegration of most structures.

How Urban Areas Might Influence Storms

While the meteorological processes behind thunderstorm and tornado development are relatively well understood and have been researched thoroughly, the potential impact of an urban environment on these processes is not as well known (NOAA, 2004). However, since urban areas have a wide range of effects on the surrounding weather, altering just a few of these basic meteorological processes could possibly create conditions far more conducive to thunderstorm development than would exist otherwise.

To begin, the contrast between temperatures in the rural area and the urban area sometimes creates a weak, stationary cold front outside of the city (NOAA, 2004). This surface-level front is capable of influencing any other mesoscale or synoptic weather system that moves through the area. If one of these systems happens to be a warm front, large amounts of instability will be created as the warm air comes into contact with the colder, rural air at the surface- instability that is a contributing factor in thunderstorm development (NOAA, 2004). The whole process is further exacerbated by the rapidly rising warm air coming from the nearby urban area, which is itself unstable (Bauerlein, 2009). Combined, these conditions are ideal for the development of severe weather in the form of thunderstorms.

There is little published work that discusses the possible influence of cities on thunderstorms and tornadoes. In 1971, Atkinson studied thunderstorm patterns around London, concluding that more storms formed within the city center and to the east (downwind), than to the western rural area (Atkinson, 1971). Stanley Changnon has been at the forefront of U.S. research, with over 40 years of work on the subject. His early

research showed a 30% increase in thunderstorm activity within and to the east of Chicago- with a statistically significant increase in activity extending almost 50 miles into Northwest Indiana (Changnon, 1968; Changnon and Huff, 1977; Changnon, 1980). Data from six of eight U.S. cities with populations over one million showed a correlation between urban extent and enhanced thunderstorm activity, especially downwind from the urban area (Huff and Changnon, 1973). Other studies by Harnack and Landsberg (1975) and Changnon (1978) found the same results for Washington, DC and St. Louis, respectively. They saw an increase in thunderstorms within the city, as well as a measurable effect downwind to the east. More recent case studies found that large urban areas such as Atlanta see increased storm activity during strong heat island events in the summertime (Bornstein and Lin, 2000).

A study of air flows and heat island events in New York City showed that, during a heat island event, air flow increased and sped up the movement of both cold and sea-breeze fronts located outside of the city. During non-heat island times, decelerating airflows led to slower frontal movements. The decelerations were shown to cause horizontal divergence- airflow split to form two halves that passed around the city. With more horizontal divergence, there was less vertical movement of air inside the city. In other words, the absence of a heat island led to less vertical uplift and fewer thunderstorms. Thunderstorm activity was enhanced when a strong heat island was present (NOAA, 2004).

Other research has discussed the enhanced convection and subsequent thunderstorms that occur in an urban landscape. This is mainly a result of the excess heat being emitted from the urban center (NOAA, 2004). A recent study by Changnon in 2001

tracked the number and location of thunderstorms in the Chicago area for a period of 50 years. In the spring and summer, when conditions in the Midwest are most favorable to thunderstorm development, the monitoring station located in downtown Chicago measured a statistically higher number of storms than its rural counterpart- stations that were only a few miles apart. The end result of the study suggested that storm activity was enhanced with increasing urbanization, and that urban influences on local meteorological processes facilitated extreme weather events. While this particular study only focused on Chicago, the author did suggest that increased storm activity could be expected for any large city. Frequency and strength of the storms would be dictated by overriding climate factors such as geographic location, but the general trend could remain the same (Changnon, 2001).

Studies also imply that the size of the urban center plays a role in where exactly storms develop. Large cities, like New York, have enough of an effect on the atmosphere to create storms in the city as well as downwind. On the other hand, smaller cities like Atlanta and Washington, DC have less of an effect in their city centers, but a measurable effect downwind. This is an important distinction because it shows the correlation between the amount of urbanization and how quickly the produced convection can lead to thunderstorm development (Changnon, 2001).

Taking these results into consideration, tornado development in urban areas can be influenced in three ways: 1) higher temperatures in urban areas create more convective lifting, leading to unstable atmospheric conditions and thunderstorm development; 2) the warm and cool temperature contrasts between the urban area and the surrounding rural land creates two different air masses that, when they meet, enhance the convective uplift

and lead to further instability; and 3) the increased friction found in urban areas leads to greater wind shear, which increases the likelihood that rotation will begin once a storm has formed.

CHAPTER IV: Purpose and Significance

Purpose

Considering that the U.S. is prone to far more tornadoes each year than most other countries and that the amount of urbanized land is growing, understanding how these urban areas might affect tornado development could be valuable information. Urban areas cannot be the direct cause of any given tornado because such severe events are part of a larger storm system belonging to an ever larger regional weather pattern. However, urbanization might create weather conditions favorable to tornado genesis, thus increasing the chances of a tornado occurring (Aguirre et al., 1993). Very recently, in March of 2009, NASA announced a joint study between themselves, Purdue University, and the University of Georgia that linked the 2008 Atlanta tornado to the UHIE (Bauerlein, 2009). The purpose of the study was an attempt to determine whether the urban area led to conditions more favorable for thunderstorm and tornado development. The results found that the increased heat and convection coming from Atlanta's urban area contributed to the tornado genesis process.

The goal of this project is to determine if there has been a historical correlation between urban expansion and the occurrence of tornadoes, and will be accomplished by comparing land use changes for the past 30 years to the number of tornadoes striking areas classified as urban. While the NASA study only proved a relationship between the UHIE and one isolated tornado event, this study will determine if that relationship exists on a larger spatial and temporal scale. Specifically, this study will address three general research questions: 1) Has there been a relationship between urban growth and tornado

occurrence in the central United States for the past 30 years? It is hypothesized that as land use in the U.S. has become increasingly marked by anthropogenic changes, tornadoes have become more prevalent in these areas. 2) Is the size of an urban area related to the number of observed tornadoes? One expects to find a relationship between size and number of tornadoes, simply because a larger urban area is a larger geographic target. 3) Do larger urban areas experience tornadoes at a more frequent rate than smaller urban areas? It is expected that the size of an urban area influences the rate at which tornadoes occur.

Significance

If the expected results are confirmed, the information could be beneficial to disaster relief planning around the country. Densely populated urban areas, if found to be more prone to tornadoes, are extremely vulnerable to the destruction such violent storms could cause. Knowing that an urban area is more likely to be struck by such severe weather is important to a wide variety of people and industries, from (among others) those who construct buildings and housing, officials responsible for creating and maintaining advanced warning systems, members of law enforcement and emergency management, and city planners. Factors to consider include:

1) In any given urban area, a large percentage of the population resides in low-income housing that is not designed to withstand severe weather events such as a tornado. The structures are vulnerable to such events, as they are poorly constructed. (NOAA, 2004).

2) Tornadoes appear with little to no warning or preparation time beforehand, and they have the ability to suddenly disrupt major transportation routes and energy availability to a large number of people (NOAA, 2004).
3) As urban expansion increases, the effect on local climates will only get worse as more stresses are placed upon the natural environment (EPA, 2009B).
4) Computer models estimate that if a large tornado were to hit an urban area of the size of Washington, DC, it could potentially leave hundreds of thousands homeless and up to 13,000 people dead. Results could be even worse for larger cities such as Chicago, where deaths could reach 45,000 (Wurman et al., 2007). These high numbers take into consideration the fact that most tornadoes occur between 3 and 6 pm (see Figure 4.1)- during the late afternoon rush hour when many people are traveling and vulnerable to weather events.
5) Because of the difficulty in predicting tornadoes, average warning times are less than 15 minutes. In a large urban area, trying to alert thousands of people in such a short amount of time is extremely difficult.

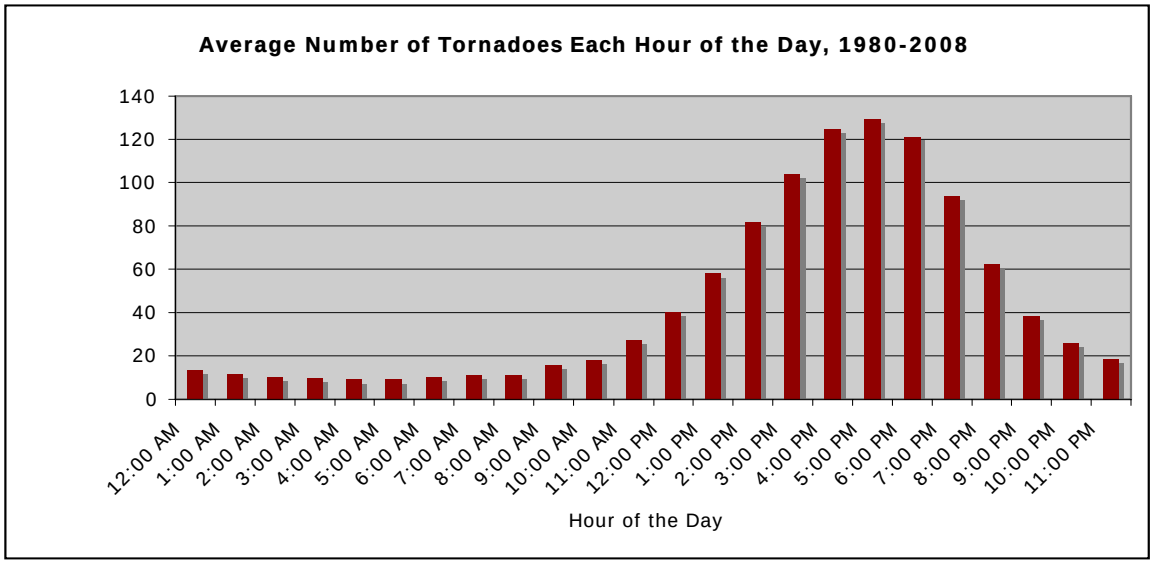

Figure 4.1: Average Number of Tornadoes Each Hour of the Day (data from the Storm Prediction Center)

Research into this topic would provide disaster management officials with valuable information regarding the chances of experiencing such extreme weather. Such information could provide a foundation for policy support that would address concerns that arise from the possibility of such an event occurring (Silva et al., 2009). If urban areas are proven to increase the likelihood of tornado formation, city managements could then explore ways to mitigate the effects through construction codes or advanced warning systems that give people more time to prepare. The results could also prove a link between anthropogenic processes and the hazards of extreme weather. This would allow us to better understand how human activity can influence even the most powerful and rare natural events.

CHAPTER V: Methodology

Study Area

The study area for this project covers the 30 largest Metropolitan Statistical Areas within eight central U.S. states. While tornadoes occur in every state, they are more concentrated in some areas versus others. To select states that most commonly experience tornadoes and determine the study region, first the average number of tornadoes occurring in each state per year was calculated. Tornado information was downloaded from the Storm Prediction Center's website (http://www.spc.noaa.gov/climo/historical.html). The National Weather Service has kept records on tornado occurrences since 1950. The records only include reports of verified tornadoes, not storms with damaging winds or hail. There is a different file for each decade, with the exception of the 2000s, which has been split into two files.

While data is available back to 1950, the time period for this study was limited to 1980 until 2008, due to the unreliability of the tornado records, and the lack of land use data. Tornado reporting between 1950 and 1975 was haphazard and reporting methods were far less reliable than they are today. After the super tornado outbreak in 1974, the National Weather Service began promoting awareness of the storms, which lead to more accurate public reporting methods and higher quality data (Prada and McKay, 2009).

Once downloaded and merged together, the output file contained one row of information for each reported tornado in the United States from 1980 until 2008. A variety of information is included for each record, including: date (month, day, year), time, location (by state), F-scale (or EF-scale after January of 2007, when the Fujita

storm intensity scale was updated), number of injuries, fatalities, estimated property loss (in dollars), starting and ending latitude and longitude, length, and width.

The tornado occurrences file for the 29-year period was converted into a point file using the starting latitude and longitude location for each tornado. Overall, 32,386 tornadoes struck the U.S. between 1980 and 2008.

The average number of tornadoes per year, per 10,000 square kilometers was calculated for each of the 48 contiguous states. The average per 10,000 km^2 was used so that the results did not favor larger states. From this, the study location was narrowed to only those states with an average of at least two tornadoes for every 10,000 square kilometers. These states were selected to ensure there would be sufficient tornado data for analysis. Table 5.1 and Figure 5.1 show the area and tornado information for each of the 48 contiguous states.

Table 5.1: Tornado Densities by State, 1980-2008

State	Area (10K km^2)	Number of Tornadoes	Yearly Average	Density
Alabama*	13.39	1,022	35.24	2.63
Arizona	29.45	114	3.93	0.13
Arkansas**	13.70	918	31.66	2.31
California	40.86	266	9.17	0.22
Colorado	26.96	1,334	46.00	1.71
Connecticut	1.29	37	1.28	0.99
Delaware*	0.53	30	1.03	1.94
Florida*	14.46	1,568	54.07	3.74
Georgia	15.19	737	25.41	1.67
Idaho	21.59	152	5.24	0.24
Illinois**	14.58	1,257	43.34	2.97
Indiana**	9.43	597	20.59	2.18
Iowa**	14.57	1,413	48.72	3.34
Kansas**	21.29	2,175	75.00	3.52
Kentucky	10.44	479	16.52	1.58
Louisiana*	11.87	1,029	35.48	2.99
Maine	8.33	30	1.03	0.12
Maryland*	2.52	196	6.76	2.68
Massachusetts	2.12	41	1.41	0.67

Michigan	15.00	485	16.72	1.12
Minnesota	21.89	981	33.83	1.55
Mississippi*	12.33	1,093	37.69	3.06
Missouri**	18.09	1,066	36.76	2.03
Montana	38.14	251	8.66	0.23
Nebraska**	20.03	1,506	51.93	2.59
Nevada	28.66	56	1.93	0.07
New Hampshire	2.40	24	0.83	0.35
New Jersey	1.94	83	2.86	1.47
New Mexico	31.54	288	9.93	0.31
New York	12.58	253	8.72	0.69
North Carolina	12.70	673	23.21	1.83
North Dakota	18.34	816	28.14	1.53
Ohio	10.67	491	16.93	1.59
Oklahoma**	18.13	1,650	56.90	3.14
Oregon	25.14	68	2.34	0.09
Pennsylvania	11.75	458	15.79	1.34
Rhode Island	0.27	10	0.34	1.27
South Carolina*	7.99	596	20.55	2.57
South Dakota	19.99	941	32.45	1.62
Tennessee	10.90	567	19.55	1.79
Texas*	68.49	4,417	152.31	2.22
Utah	21.98	79	2.72	0.12
Vermont	2.49	14	0.48	0.19
Virginia	10.31	399	13.76	1.33
Washington	17.43	65	2.24	0.13
West Virginia	6.28	63	2.17	0.35
Wisconsin	14.53	675	23.28	1.60
Wyoming	25.33	342	11.79	0.47
* Meets density criteria for number of tornadoes				
** Meets density criteria and is not a coastal state				

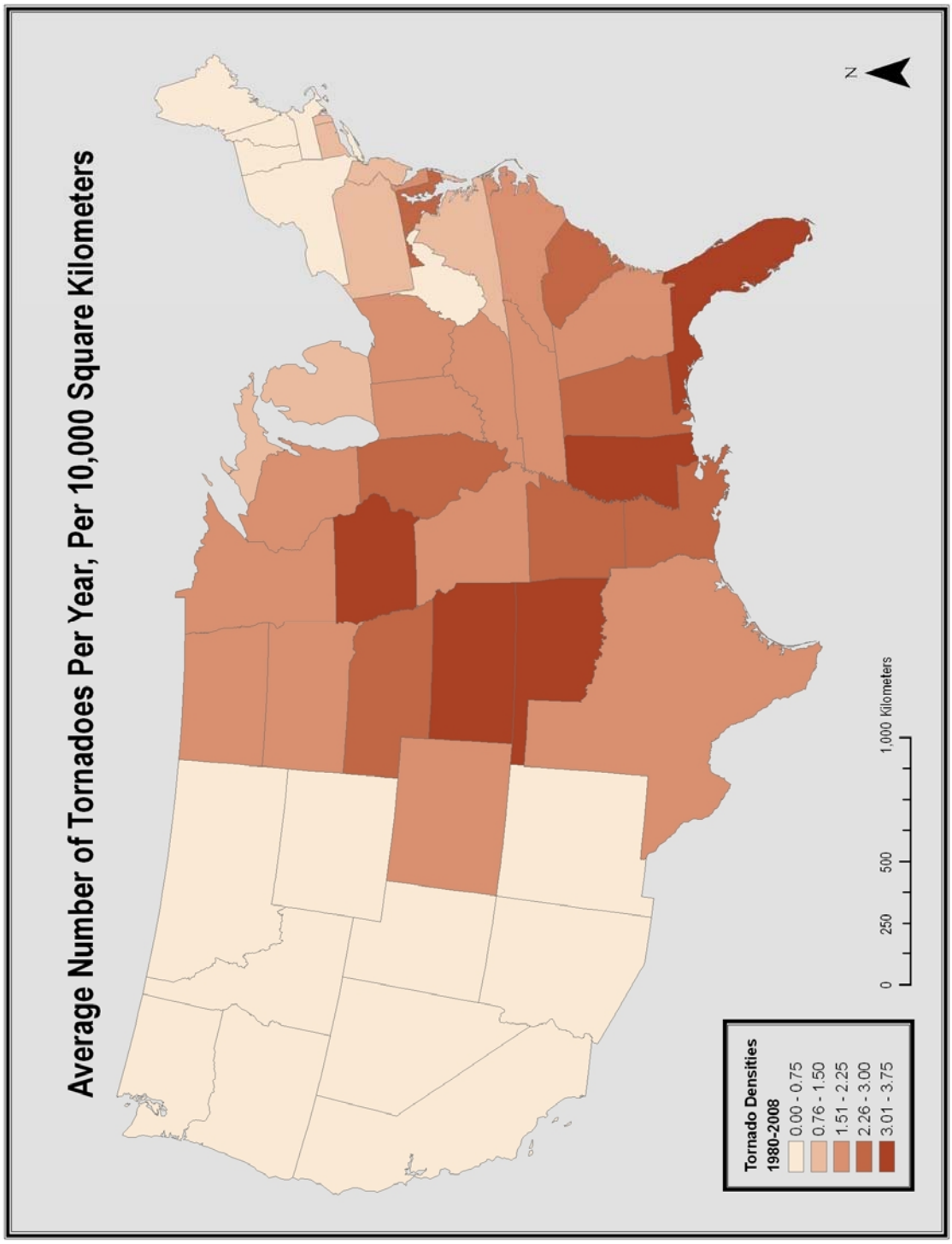

Figure 5.1: Map depicts the density of tornado occurrence from 1980-2008, by state.

Sixteen states met the qualifications based on this criterion. In order to reduce the bias from hurricanes and other tropical storms that spawned tornadoes, all states bordering either the Atlantic Ocean or Gulf of Mexico were eliminated. Eight states remained: Arkansas, Illinois, Indiana, Iowa, Kansas, Missouri, Nebraska, and Oklahoma (see Figure 5.2).

Within these eight states, 30 Metropolitan Statistical Areas (MSAs) were selected based upon their geographic size. The census bureau defines a MSA not necessarily as a city, but as an area that is highly urbanized, such as a suburb or township. Census tiger line files displaying MSA boundaries from the year 2000 were used to calculate the area of all MSAs within the eight study states, and the 30 largest were selected. The largest MSAs were chosen because they were more likely to have recorded measurable urban expansion since 1980

The results included three MSAs from Arkansas (Fayetteville-Springdale, Fort Smith, and Little Rock), five from Illinois (Chicago, Peoria, Rockford, Round Lake Beach- McHenry-Grayslake, and Springfield), eight from Indiana (Anderson, Elkhart, Evansville, Fort Wayne, Indianapolis, Jeffersonville-Clarksville-New Albany, Lafayette, and South Bend), three from Iowa (Cedar Rapids, Davenport, Des Moines), two from Kansas (Topeka and Wichita), four from Missouri (Joplin, Kansas City, Springfield, and St. Louis), two from Nebraska (Lincoln and Omaha), and three from Oklahoma (Lawton, Oklahoma City, and Tulsa). The geographic area of the 30 MSAs varied from Chicago's almost 4,000 km^2 to Anderson's roughly 50 km^2. Figure 5.3 displays the location of the MSAs selected for study.

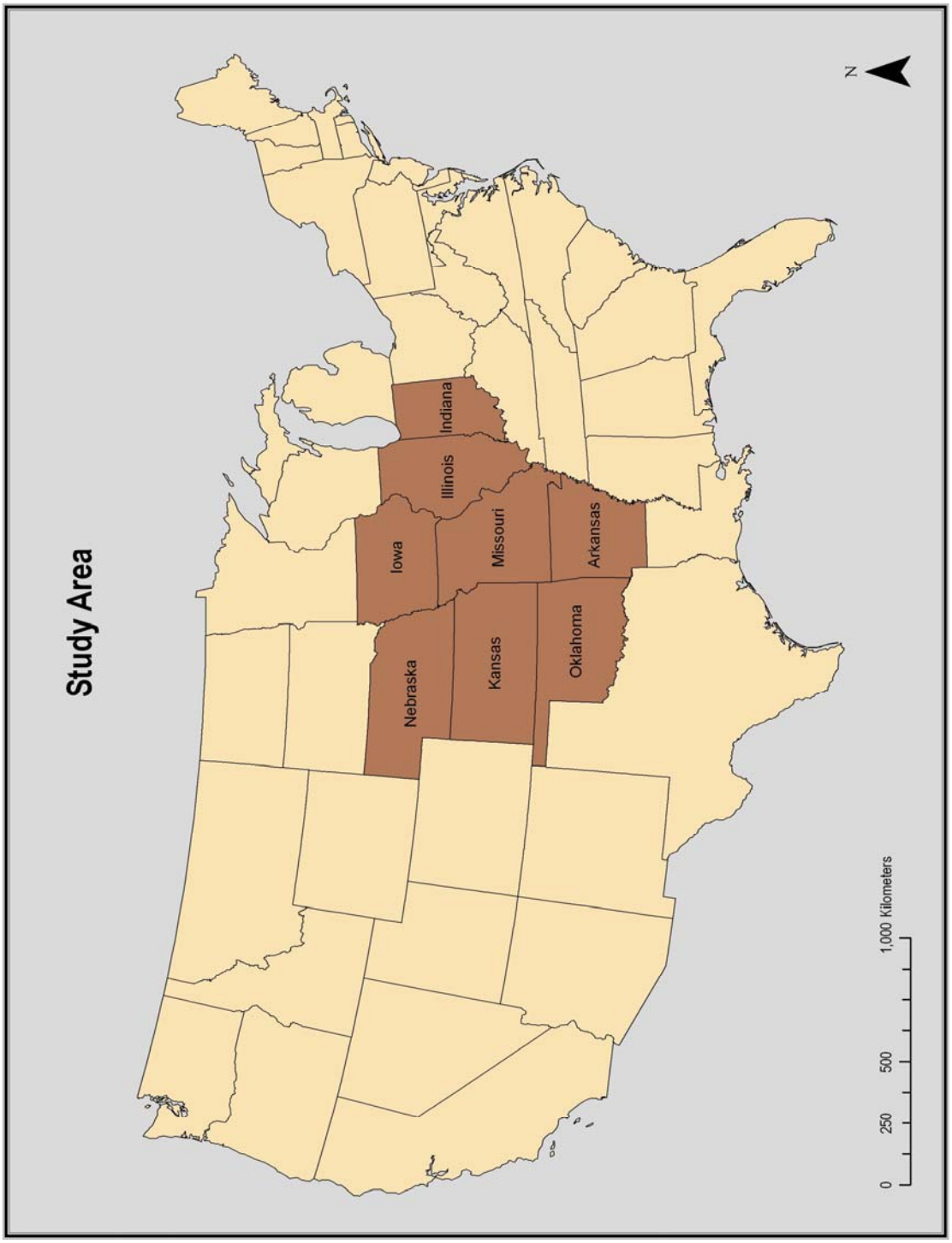

Figure 5.2: Map depicts the eight states with an average of two tornadoes per 10,000 km2 that were the study area of this project.

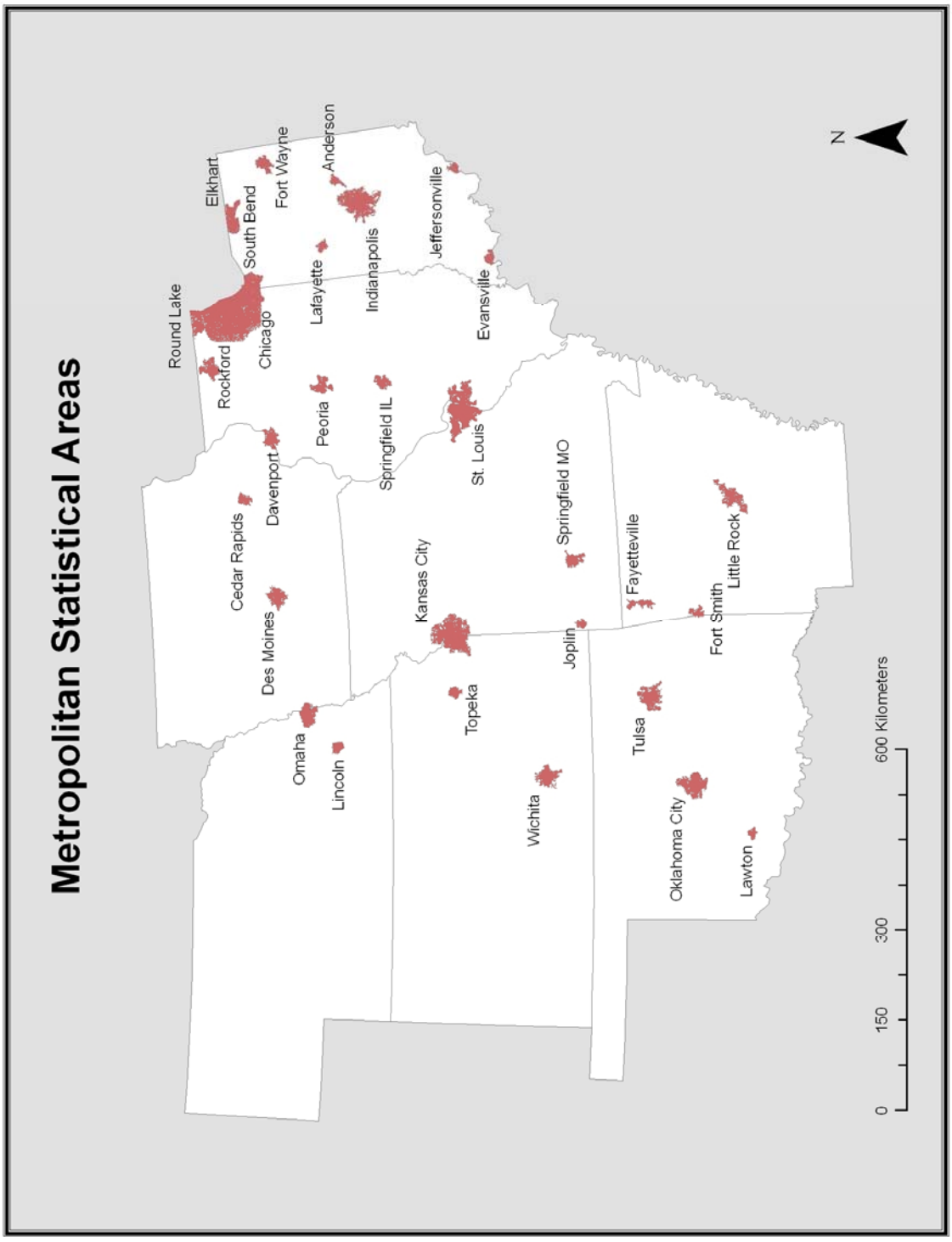

Figure 5.3: Map depicts the 30 largest MSAs in the eight states investigated in this study.

With the study area defined and the list of all tornado occurrences throughout the study time period, the next step was to measure urban expansion in each of the 30 MSAs. To do so, land use data for each of the three decades in the study (1980, 1990, and 2000) were acquired.

For the 1990 and 2000 decades, the United States Geological Survey's (USGS) Land Cover Institute published land use land cover datasets. The datasets were classified into 24 categories using Landsat Thematic Mapper (TM) imagery from 2001, with a spatial resolution of 30 meters. These data were split into 17 zones in order to cover the entire United States, of which zones numbered 6 through 12 covered the entire study area. Because each zone covered an expansive area, an Area of Interest (AOI) around each MSA was selected. To ensure no urbanized part of an MSA was accidentally cut off, the AOIs were drawn well outside the urban extent of each area. The AOI for each MSA was used to subset the larger zone image. Some locations, such as Davenport, Iowa, split two zones- therefore, both zones were used to cover the entire MSA.

To calculate the area of each MSA in the 2000s, the rasters were converted to polygon files that outlined urban extent. First, those pixels classified as urban or developed by USGS (values 22,23,or 24) were selected, and a new urban raster was created. This raster was converted into a polygon, and the attributes dissolved. Locations that had two input rasters (such as Davenport) were merged together, resulting in 30 polygons for the 30 MSAs. Finally, the area of each polygon was calculated.

The process for determining the area of each of the MSAs in the 1990s was similar. The USGS LULC classified data was published using Landsat TM imagery from 1992, with the same 30-meter spatial resolution. A difference was that the initial files

available from USGS were available by state, not zone. The files for each of the eight states used in the study were downloaded, and AOIs were created around the MSAs. An important step was to ensure the AOIs around the MSAs matched the AOIs from the 2000s as closely as possible, so that there was no chance any part of the MSA was eliminated based upon the boundary of the AOI. There was a slight difference in the extraction step, as USGS assigned different numerical values to urban pixels in the 1990 dataset. The results were polygons outlining the urban extents of the MSAs. Again, some MSAs crossed state lines (such as Chicago and St. Louis), so the two polygons for those MSAs had to be merged together. Finally, the area of each of the MSAs in the 1990s was calculated.

For the 1980's, no classified data was available from USGS. However, historical Landsat satellite imagery (used by USGS in their classifications for 1990 and 2000 LULC projects) was available for download via the Global Visualization Viewer (GLOVIS). To cover the study area and analyze urban extent, 24 Landsat TM were downloaded; each image contained less than 10% cloud coverage and had a quality of at least nine.

Once the 24 images were downloaded, urban areas were identified visually. The MSAs appearing on each image were outlined using an AOI. The individual TM scenes were then subset into 30 smaller, more manageable files that only covered the MSAs and their immediate vicinities.

The next step was to classify the pixels of each small image into categories- urban, rural, and water. First, training sites were used to create a signature profile for the image. The sites, usually between 80 and 100, were drawn in various urban, rural, and

water locations. A high number of training sites were necessary to capture the different pixel values between similar features (e.g. streets, dense buildings, and suburban neighborhoods all have different pixel values, yet they are all developed areas). Once completed, the training sites were used to create a signature profile, which was then the basis for a supervised classification. The result was a classified raster, with an attribute table that contained the same number of attributes as training sites that were used. The training site and supervised classification process was repeated for each image, the end result being 30 classified images.

Pixels classified as urban were then extracted. This produced 30 urban rasters, which were then transformed into polygons representing the boundaries of the MSAs in the 1980s. The area of each was then calculated.

With the polygon files created and the area calculated for each of the MSAs in all three decades, the next step was to count the number of tornadoes occurring in those urban areas over time. The tornado dataset was subdivided into three subsets, one for each decade of analysis.

The 30 individual MSA layers for the 2000s were merged into one file and spatially joined with the tornadoes dataset to obtain a count of the number of events per MSA in that decade. The same process was repeated for the 1990s and 1980s. Table 5.2 contains the area and base number of tornado events for each MSA over the 29-year study period. Tornado occurrences by decade are then mapped in Figures 5.4, 5.5 and 5.6.

Table 5.2: Area and Tornado Information (by Decade)

MSAs	Area 2000	Tornadoes 2000	Area 1990	Tornadoes 1990	Area 1980	Tornadoes 1980
Anderson	56.70	0	59.79	1	52.65	0
Cedar Rapids	109.55	2	112.41	2	99.56	3
Chicago	3911.63	16	2976.36	7	2880.77	5
Davenport	208.74	1	206.30	2	175.77	2
Des Moines	244.39	4	241.82	4	238.04	7
Elkhart	137.93	0	80.37	1	64.60	0
Evansville	84.50	0	105.39	1	53.46	3
Fayetteville	113.15	1	73.93	0	69.34	0
Fort Smith	94.84	0	76.67	5	51.32	0
Fort Wayne	184.23	1	167.87	2	141.58	0
Indianapolis	781.72	4	646.36	6	489.89	3
Jeffersonville	65.20	1	75.47	0	56.16	0
Joplin	60.89	0	63.79	6	48.36	1
Kansas City	1037.67	6	849.60	1	841.10	2
Lafayette	71.02	3	54.43	1	43.06	2
Lawton	69.16	0	66.77	0	59.39	1
Lincoln	146.00	0	102.68	1	67.76	0
Little Rock	317.67	4	321.14	3	232.41	1
Oklahoma City	509.25	5	500.93	6	448.29	8
Omaha	415.55	2	304.72	1	247.09	2
Peoria	186.36	1	149.18	2	94.81	0
Rockford	232.37	0	145.82	0	139.42	0
Round Lake	146.74	0	83.73	0	59.09	0
South Bend	174.36	4	116.90	1	108.26	3
Springfield IL	142.41	4	86.96	0	77.48	2
Springfield MO	199.46	4	144.65	0	91.83	0
St. Louis	1309.38	6	1078.38	7	956.16	5
Topeka	110.55	1	93.01	0	39.98	1
Tulsa	409.10	3	473.21	7	304.16	8
Wichita	332.30	1	263.77	7	229.08	4

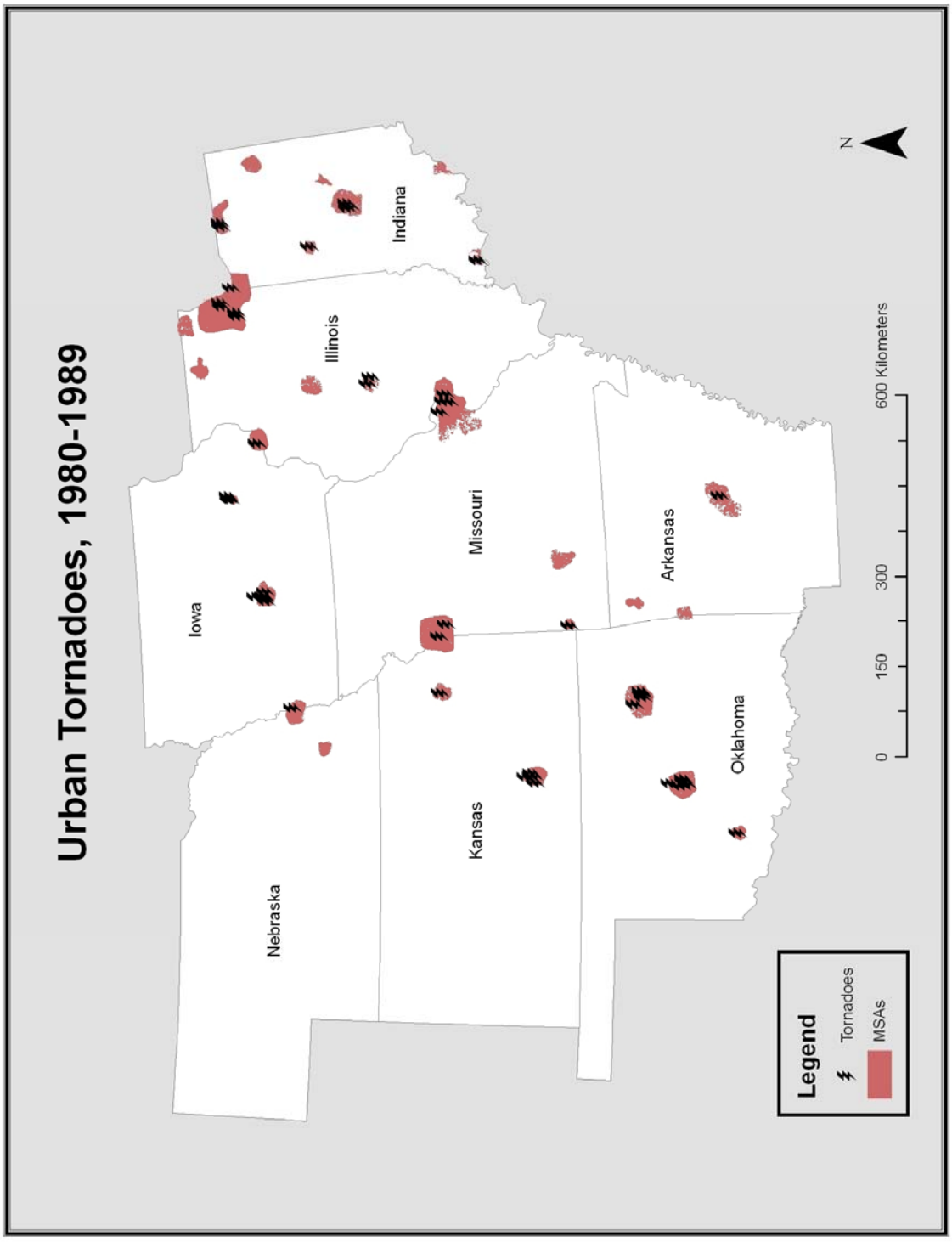

Figure 5.4: Map depicts the location of all urban tornadoes, from 1980-1989.

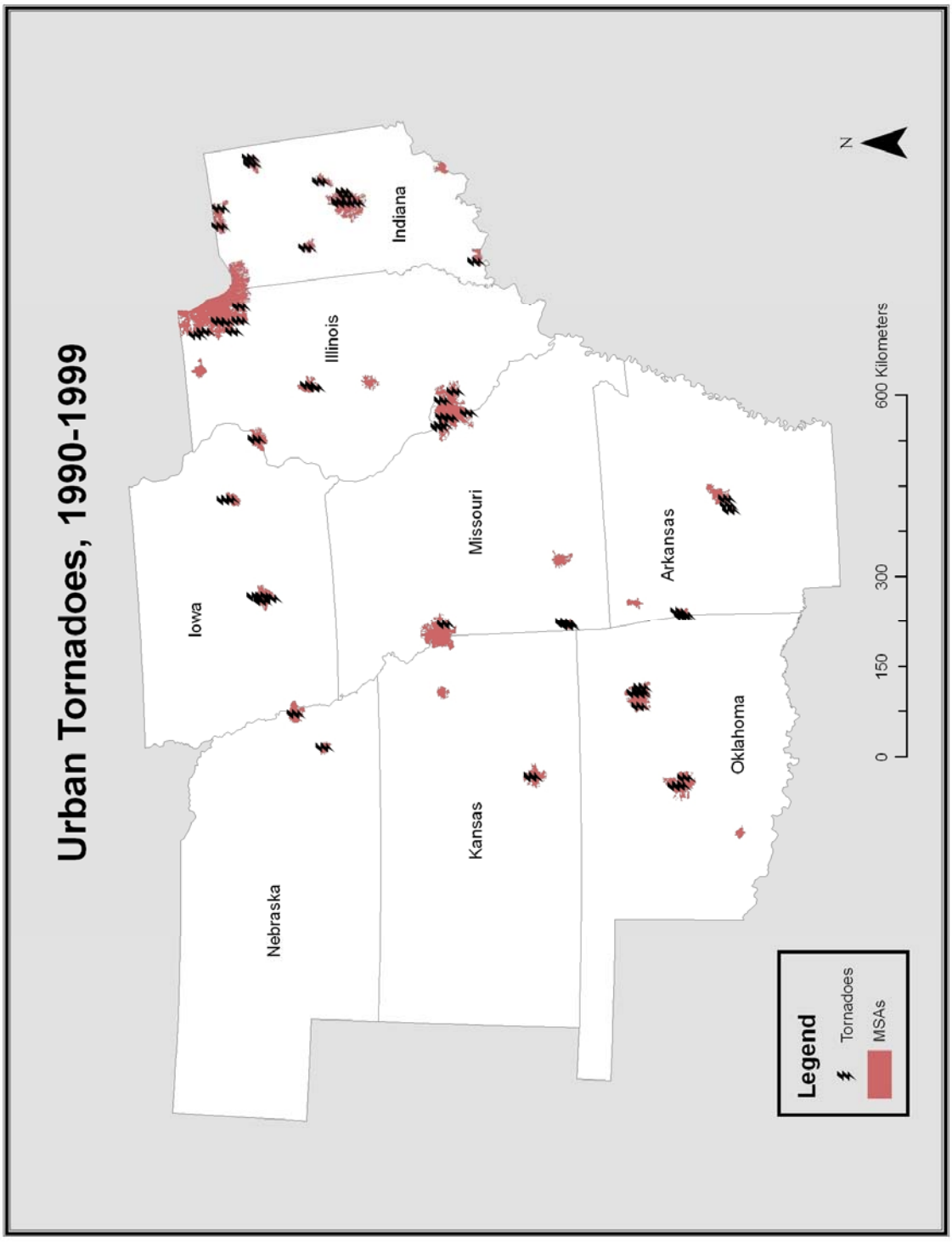

Figure 5.5: Map depicts the location of all urban tornadoes, from 1990-1999.

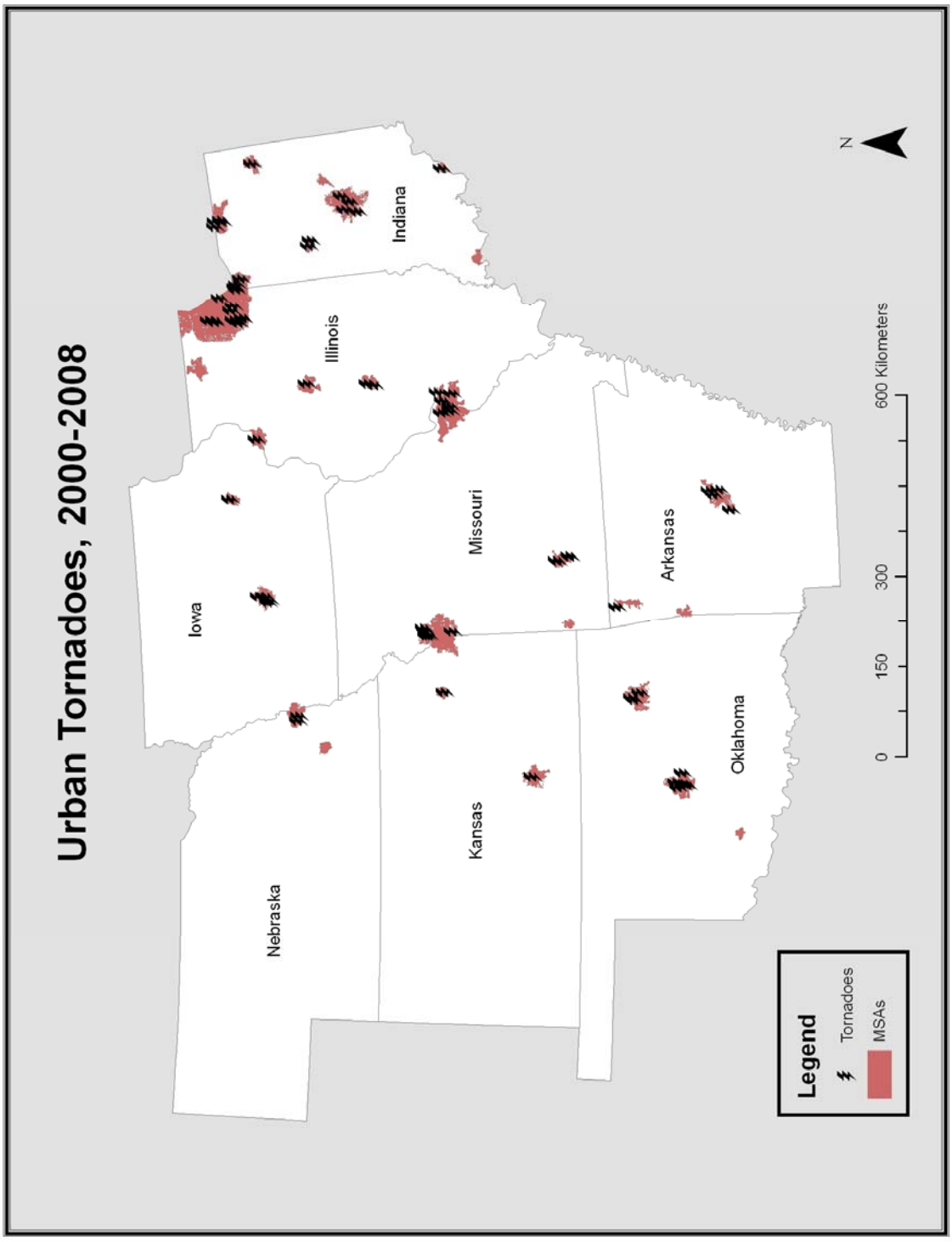

Figure 5.6: Map depicts the location of all urban tornadoes, from 2000-2008.

The next step was to determine if a relationship exists between the amount of urban expansion and tornado occurrence. To do so, the percent change in average yearly tornadoes and percent change in area between each of the three decades was calculated (using average yearly tornadoes instead of base number of tornado events was necessary to account for the one less year of data in the 2000s decade).

A linear regression model was fit to each of the three decades of data. To determine if the change in frequency of tornadoes is a function of urban growth, the model was defined as $PcT = \alpha + PcA(\beta) + \varepsilon$, where PcT equals the percent change in average number of tornadoes, PcA equals the percent change in urban area, α equals the y-intercept, β is the slope of the model, and ε is the error (residual). Using the ordinary least squares (OLS) method, the model placed a straight line through the data points so that the sum of the squared residuals (the distance between the line and each point) was as small as possible. To determine whether urban expansion affected the number of tornadoes, the change in urban area was used as the independent value, while the change in average number of tornadoes was the dependent variable.

First, the statistical significance of the relationship was tested. Significance values are calculated using the known sample size, and range from 0 to 1. A value lower than 0.05 indicates the relationship is statistically significant. For each data set, the strength of the linear relationship was then measured by calculating the Pearson correlation coefficient (r), which can range from -1 to 1. Values between 0.09 and -0.09 are generally considered to have no relationship, those from -0.1 to -0.3 or 0.1 to 0.3 have a weak relationship, those from -0.3 to -0.5 or from 0.3 to 0.5 have an average relationship, and values from -0.5 to -1 or 0.5 to 1 have a strong relationship. The square of the correlation

coefficient (r^2) shows how well the variables fit together in a line of regression, and can range from 0 to 1. The closer the value is to zero, the weaker the correlation is between the variables.

Finally, to determine if a relationship exists between the size of an MSA and the number of tornadoes (and if the size of the MSA affects the rate of tornado occurrence), the average area of each MSA was calculated, as well as the average number of tornadoes occurring each year over the entire study period.

Two additional regression models were calculated using these data. The first model, defined as $T= \alpha + A(\beta) + \varepsilon$, compared the average number of tornadoes per year (T) and the average area (A) of each MSA throughout the three decades of study, to discover if there was a relationship between the size of the MSA and the number of tornado events. The second regression model, defined as $R= \alpha + A(\beta) + \varepsilon$ determined the relationship between the rate of tornado occurrence (R) and the area (A), to see if larger MSAs experienced a higher rate of tornado events and vice versa for smaller MSAs. In each of the statistical calculations the area was used as the independent variable, while the tornado data (either the average number of events or rate of occurrence) was used as the dependent variable. The statistical significance of each model was tested, and the (the Pearson's coefficient and r^2 value were calculated to determine the strength of the relationship.

CHAPTER VI: Results

Is there a relationship between urban expansion and tornado occurrence?

Table 6.1: Percent Change in Area of Each MSA (by Decade)

MSAs	% Change, 1980-1990	% Change, 1990-2000	% Change, 1980-2000
Anderson	13.56	-5.16	7.70
Cedar Rapids	12.91	-2.55	10.03
Chicago	3.32	31.42	35.78
Davenport	17.37	1.19	18.76
Des Moines	1.59	1.06	2.67
Elkhart	24.40	71.64	113.51
Evansville	97.15	-19.82	58.07
Fayetteville	6.61	53.06	63.17
Fort Smith	49.41	23.69	84.80
Fort Wayne	18.57	9.74	30.13
Indianapolis	31.94	20.94	59.57
Joplin	31.90	-4.56	25.89
Kansas City	1.01	22.14	23.37
Lafayette	26.41	30.49	64.95
Lawton	12.43	3.58	16.45
Lincoln	51.54	42.18	115.46
Little Rock	38.18	-1.08	36.69
Louisville	34.36	-13.60	16.09
Oklahoma City	11.74	1.66	13.60
Omaha	23.32	36.37	68.18
Peoria	57.34	24.92	96.55
Rockford	4.59	59.35	66.66
Round Lake	41.71	75.25	148.34
South Bend	7.98	49.16	61.06
Springfield IL	12.25	63.76	83.81
Springfield MO	57.52	37.89	117.21
St. Louis	12.78	21.42	36.94
Topeka	132.67	18.85	176.53
Tulsa	55.58	-13.55	34.51
Wichita	15.14	25.98	45.06

Table 6.2: Summary Statistics, Percent Change in Area

	1980s-1990s	1990s-2000s	1980s-2000s
Maximum	132.67	75.25	176.53
Minimum	1.01	-19.82	2.67
Mean	30.18	22.18	57.72
Standard Deviation	29.20	26.15	43.64

There is a large range in the percent change in area for each decade among the 30 MSAs (Tables 6.1 and 6.2). The range is reflected not only in the large difference between the maximums and minimums, but also in the high standard deviations. The averages, however, indicate a generally positive trend. An interesting anomaly occurs with the percent change between the 1990s and 2000s data, in which some of the values were negative (indicating that a few of the MSAs lost area between these two decades). Of these MSAs, Evansville, Indiana recorded the largest negative change, losing 19.8% of its area.

On average, the area of the 30 MSAs grew by 58%, and each recorded a positive percent change over the whole time period of the study. Between 1980 and 2000, the largest percent change in area occurred in Topeka, Kansas (which grew 177%), while the smallest was in Des Moines, Iowa (which only grew 3%).

Table 6.3: Percent Change in Average Yearly Tornado Events for each MSA (by Decade)

MSAs	% Change 1980s-1990s	% Change 1990s-2000s	% Change 1980s-2000s
Anderson	0.06	-100.00	0.00
Cedar Rapids	-33.33	11.00	-26.00
Chicago	40.00	154.00	255.60
Davenport	0.00	-44.50	-44.50
Des Moines	-42.86	11.00	-36.57
Elkhart	0.00	-100.00	0.00
Evansville	-66.67	-100.00	-100.00
Fayetteville	0.00	0.00	0.00
Fort Smith	0.00	-100.00	0.00
Fort Wayne	0.00	-44.50	0.00
Indianapolis	100.00	-26.00	48.00

Jeffersonville	0.00	0.00	0.00
Joplin	500.00	-100.00	-100.00
Kansas City	-50.00	567.00	233.50
Lafayette	-50.00	233.00	66.50
Lawton	-100.00	0.00	-100.00
Lincoln	0.00	-100.00	0.00
Jeffersonville	0.00	0.00	0.00
Oklahoma City	-25.00	-7.33	-30.50
Omaha	-50.00	122.00	11.00
Peoria	0.00	-445.00	0.00
Rockford	0.00	0.00	0.00
Round Lake	0.00	0.00	0.00
South Bend	-66.67	344.00	48.00
Springfield IL	-100.00	0.00	122.00
Springfield MO	0.00	0.00	0.00
St. Louis	40.00	-4.86	33.20
Topeka	-100.00	0.00	11.00
Tulsa	-12.50	-52.43	-58.38
Wichita	75.00	-84.14	-72.25

Table 6.4: Summary Statistics, Percent Change in Average Yearly Tornadoes

	1980s-1990s	1990s-2000s	1980s-2000s
Max	500.00	567.00	255.60
Min	-100.00	-445.00	-100.00
Mean	1.93	4.44	8.69
Standard Deviation	104.85	166.60	80.17

Many of the MSAs recorded large changes in the percentage of tornado events over time (Tables 6.3 and 6.4). For example, Kansas City, Missouri, saw a 567% increase in average yearly tornadoes between the 1990s and 2000s. On the other hand, over the same time period, Peoria, Illinois recorded a 445% decrease in average yearly events.

Over the course of the whole study period, the 30 MSAs experienced an 8% increase in the average number of tornadoes occurring each year. However, with a standard deviation of 80, the percent change values varied greatly.

The scatter plot of the data and the lines of regression are presented in the following three Figures (6.1, 6.2, and 6.3).

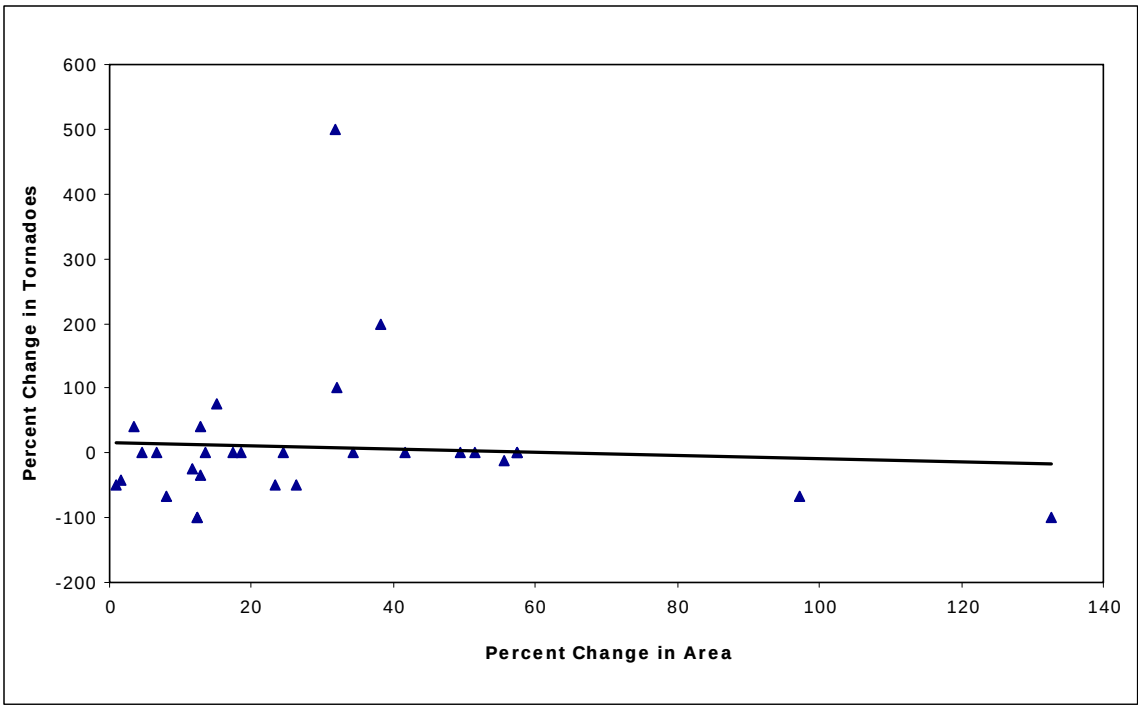

Figure 6.1: Graph depicts percent change in area and tornadoes for each MSA, 1980s-1990s.

Table 6.5: Results of the Regression Model Showing the Relationship between Percent Change in Area and Percent Change in Tornadoes, 1980s-1990s

	1980s-1990s
Pearson Correlation	-0.06
Significance	0.74
r^2	0.01
Adjusted r^2	-0.03
Regression Equation	y = -0.24x + 15.91

The high significance value implies that there is no significant relationship between the two variables at the 0.05 level. With a correlation coefficient very close to zero, this indicates that there is no correlation between urban expansion and tornado events between the 1980s and 1990s. The r^2 value is also very low, indicating the regression equation does not fit the data well.

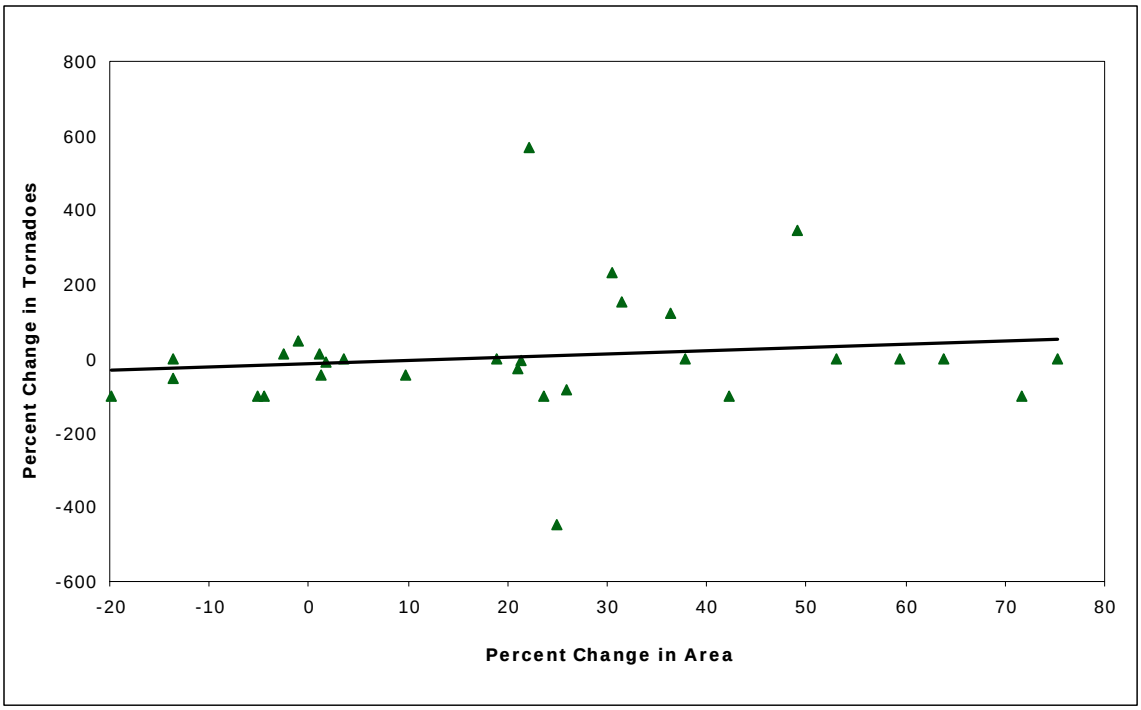

Figure 6.2: Graph depicts percent change in area and tornadoes for each MSA, 1990s-2000s.

Table 6.6: Results of the Regression Model Showing the Relationship between Percent Change in Area and Percent Change in Tornadoes, 1990s-2000s

	1990s-2000s
Pearson Correlation	0.14
Significance	0.47
r^2	0.02
Adjusted r^2	-0.02
Regression Equation	y = .87x – 13.24

The significance value indicates the relationship is not significant at the 0.05 level, and occurs by chance. The correlation coefficient of 0.14 is higher than in the previous decade, and indicates that there is a very weak relationship between the two variables during this time.

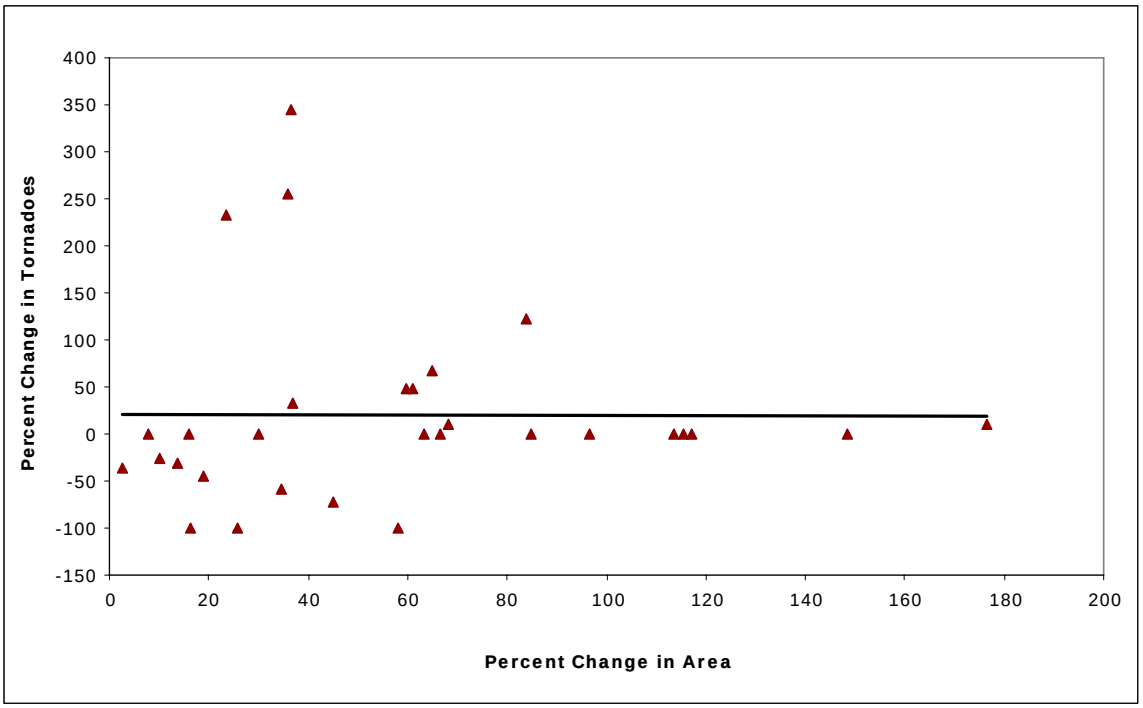

Figure 6.3: Graph depicts the overall percent change in area and tornado events, 1980s-2000s

Table 6.7: Results of the Regression Model Showing the Relationship between Percent Change in Area and Percent Change in Tornadoes, 1980s-2000s

	1980-2000
Pearson Correlation	-0.003
Significance	0.99
r^2	0.00
Adjusted r^2	-0.04
Regression Equation	y= -0.01x + 20.51

Table 6.5 displays the relationship variables for the entire study period, from the 1980s to the 2000s. The significance value shows that the variables are not significantly related at the 0.05 level. The Pearson Correlation of -.003 indicates that there is no measurable relationship between the overall percent change in tornadoes and the percent change in area. The r^2 value is actually zero, meaning the regression equation does not fit the data at all.

Is the size of an MSA directly related to the number of tornado events?

The average number of yearly tornadoes, the average area of each MSA over the 30 year time period, and the rate of tornado occurrence are presented in Table 6.8.

Table 6.8: Average Number of Yearly Tornadoes, Average Area, and the Rate of Occurrence for each MSA over the Entire Study Period.

MSAs	Average Tornadoes	Average Area (in km^2)	Rate of Occurrence (Average Tornadoes/ Average Area)
Anderson	0.03	56.71	0.0006
Cedar Rapids	0.24	108.51	0.0022
Chicago	0.97	3263.92	0.0003
Davenport	0.17	197.94	0.0009
Des Moines	0.52	244.09	0.0021
Elkhart	0.03	94.63	0.0004
Evansville	0.14	81.45	0.0017
Fayetteville	0.03	85.81	0.0004
Fort Smith	0.17	75.94	0.0023
Fort Wayne	0.10	165.56	0.0006
Indianapolis	0.45	642.65	0.0007
Jeffersonville	0.03	65.94	0.0005
Joplin	0.24	59.68	0.0040
Kansas City	0.31	911.79	0.0003
Lafayette	0.21	57.50	0.0036
Lawton	0.03	65.11	0.0005
Lincoln	0.03	105.81	0.0003
Little Rock	0.28	292.74	0.0009
Oklahoma City	0.66	489.82	0.0013
Omaha	0.17	323.46	0.0005
Peoria	0.10	144.45	0.0007
Rockford	0.00	172.54	0.0000
Round Lake	0.00	96.52	0.0000
South Bend	0.28	134.84	0.0020
Springfield IL	0.21	103.62	0.0020
Springfield MO	0.14	146.65	0.0009
St. Louis	0.62	1118.97	0.0006
Topeka	0.07	81.51	0.0008
Tulsa	0.62	398.82	0.0016
Wichita	0.41	277.72	0.0015

The average area and average number of yearly tornado events for each MSA are plotted in Figure 6.4, and the statistics are presented in Table 6.9.

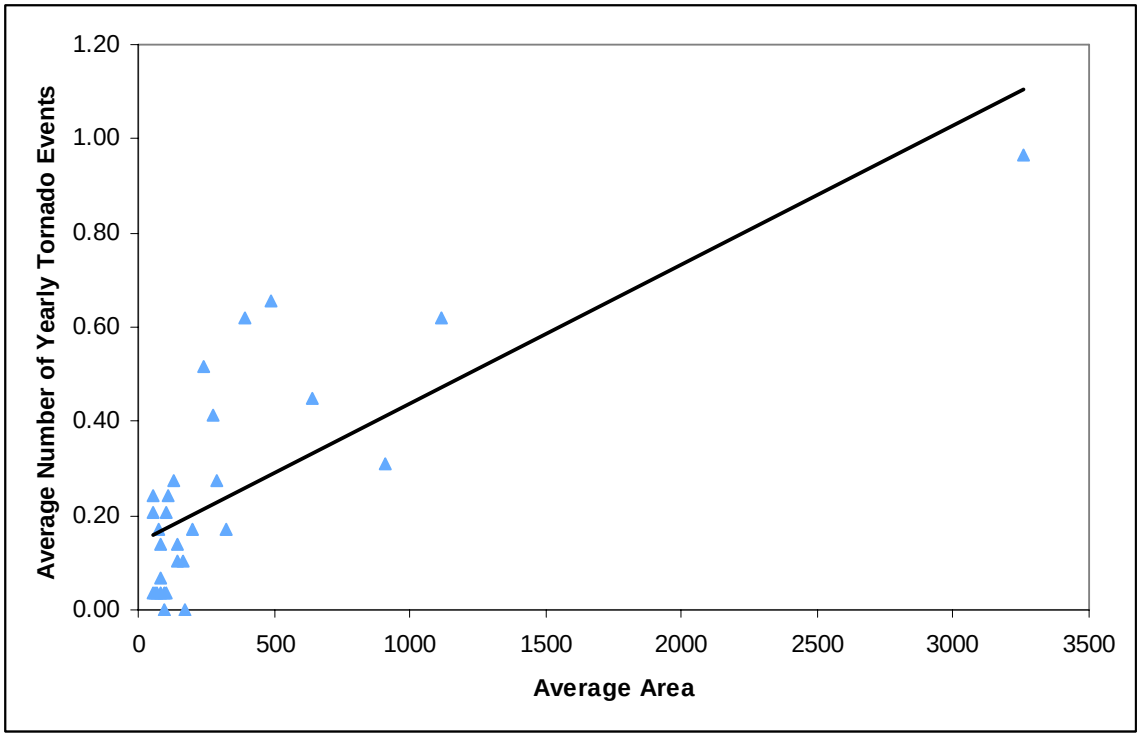

Figure 6.4: Graph depicts the average area and average number of yearly tornado events for each MSA.

Table 6.9: Results of the Regression Model Showing the Relationship between the Average Area and Average Number of Yearly Tornadoes.

	Value
Pearson Correlation	0.76
Significance	0.00
r^2	0.57
Adjusted r^2	0.56
Regression Equation	y=.0003x + .14

The r^2 value indicates that the regression equation fits the data well, and the high Pearson correlation coefficient indicates that there is a strong relationship between the two variables. Also, the significance value of 0 implies that the variables are related at the 0.05 level. These results indicate that larger MSAs are more likely to experience a tornado event than smaller MSAs, most likely because they are larger geographic targets.

Does the size of an MSA affect the rate of tornado occurrence?

Figure 6.5 and table 6.10 display the relationship between the rate of tornado occurrence and the area of each MSA.

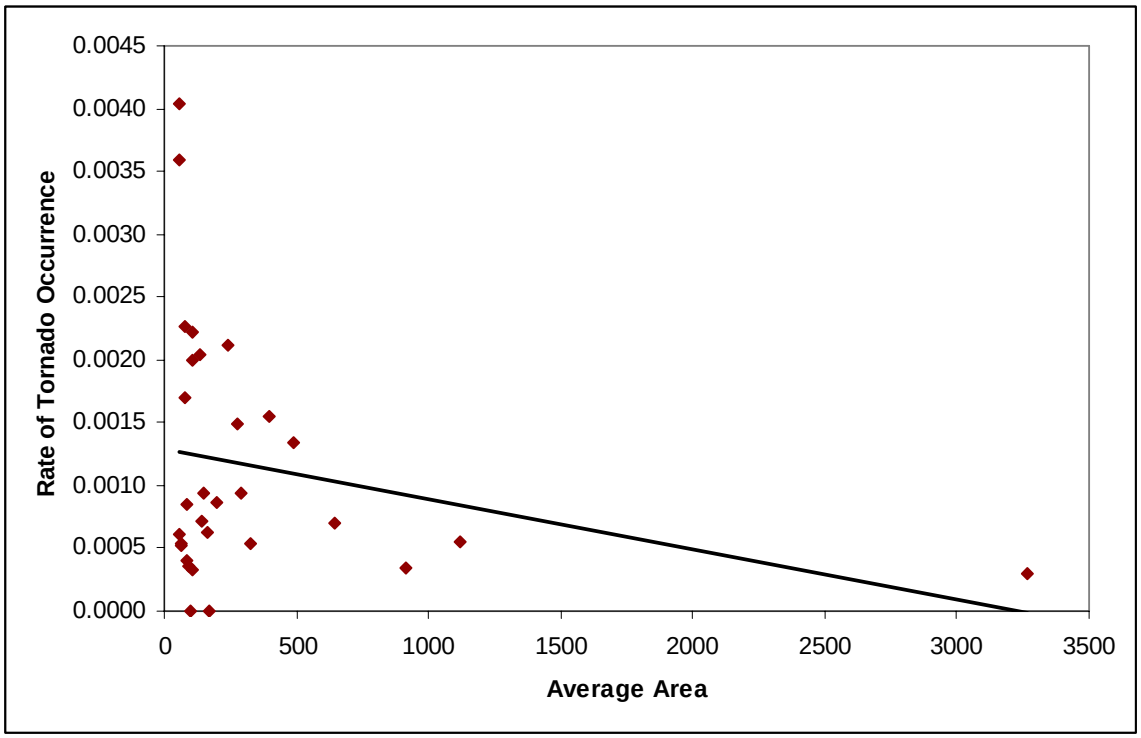

Figure 6.5: Graph depicts the average area and rate of tornado occurrence for each MSA.

Table 6.10: Results of the Regression Model Showing the Relationship between the Average MSA Area and the Rate of Tornado Occurrence.

	Value
Pearson Correlation	0.25
Significance	0.20
r^2	0.06
Adjusted r^2	0.03
Regression Equation	y = -4E-07x + 0.001

The significance value shows that, at the .05 level, the variables are not related. With a low correlation and r^2 value, there is no measurable relationship between the size

of the MSAs and the rate at which they experience tornado events (i.e. when size is taken into account, large MSAs are not experiencing tornadoes at a more frequent rate than smaller MSAs).

CHAPTER VII: Conclusions

Theoretically, urban expansion should result in an increase in observed tornadoes. This idea is based not only on the 'heat island' effect that cities have on their surrounding environment (that creates conditions more conducive to tornado development than would otherwise exist), but also because a larger city becomes a bigger geographic target for a storm. The results from the study, however, indicate otherwise.

While there was a strong correlation between the size of the MSA and the average number of tornadoes that occur each year, there was no measurable relationship between the size and the rate at which tornadoes occur. These results indicate that, while the size of an MSA is reflected in the number of observed tornadoes, this relationship occurs only because a larger MSA is a more expansive target. A larger area does not necessarily influence the frequency at which those storms occur.

With absolutely no correlation between an increase in urban area and an increase in tornadoes hitting those urban areas over the 29 year study period, the hypothesis (that an increase in urban land would increase the number of tornado events) was disproved. To determine why the results were unexpected, it is important to address any potential biases or errors that might have influenced the results. Errors could have occurred with the data or even in the theory used as a basis for the project.

Data/ Human Errors

First, the data itself (both tornadoes and imagery) could contain a number of errors. Regarding the tornado data, the reporting is still not perfect. Reporting methods have become increasingly more accurate, but methods have changed in the past 29 years.

Today, meteorologists, amateur storm chasers, and weather observers using wireless internet and cell phones can instantly (and more accurately) report storm observations. These methods are recent developments in weather observation, creating a more accurate dataset than in the past. But even today, there are inaccuracies. Some short-lived tornadoes are misclassified as straight-line wind storms, and some might not be reported at all (Prada and McKay 2008). The odds of a tornado occurring in a densely populated area being misclassified or unreported are smaller than with a tornado that occurs in a rural area, but it is still possible. Because such errors occur in the dataset and not with the analysis, there is no way to adjust for them, however slight they may be.

There could also be errors with the classified imagery used to calculate the area of each MSA. First, a different classification was used for each decade of data. USGS used a classification algorithm in 2000 that differed from the algorithm used for the 1990 data. The area calculations for seven of the MSAs (Anderson, Cedar Rapids, Evansville, Kansas City, Little Rock, Jeffersonville-Clarksville-New Albany, and Tulsa) suggested that the MSAs became smaller, sometimes dramatically so, between 1990 and 2000, which is unlikely. As a result of using a different algorithm, it is possible that the 2000 classification is more accurate and that some pixels labeled as urban in 1990 were misclassified and should not have been included.

The 1980 data was also classified differently than the other decades. Because data already classified was not available from USGS, the satellite images needed to be classified before urban rasters could be created. Because the classification process used included the manual selection of training sites, human error could have affected the results. Ideally, to create more accurate results, the same classification algorithm or

process should be used for each of the three decades of data. This would ensure that there would be no difference in the pixel values classified as urban in the raster outputs, no matter what decade was being analyzed.

While incorrect tornado and urban area datasets create inaccuracies in the analysis, these errors probably did not have a large impact on the final results. If the errors were adjusted for, it would not greatly alter the percent change data used as the basis for the statistical analysis. An inherent problem with the analysis is that there were not enough large cities included in the study area. Even though the biggest MSAs of this region were considered, only a handful are great enough in size to have an immediate influence on a storm system and enhance tornado development. The 30th largest MSA within the study area was Anderson, Indiana; and at only 52 square kilometers (while it will have some minor influence on the surrounding weather) it is not large enough have a profound effect. To obtain results that better fit the hypothesis, it would be necessary to expand the boundaries of the urban areas to include all areas where their influence might be felt (namely downwind, to the east). Then, instead of only counting those tornadoes that occur within the urban boundary of the MSA, those tornadoes occurring downwind would be counted as well. Making this adjustment would acknowledge that the urban effect might take time to register in the atmosphere, and thus the MSA's influence on the storm system (and possibly tornado development) would occur after the storm had moved beyond the urban extent of the city.

Theory Errors

The urban influence on the surrounding weather is well documented. There is little doubt that an urban area increases the temperature and convection necessary to form

thunderstorms and eventually tornadoes. But a problem with the theory lies in the fact that scientists still do not fully understand the mechanics of tornado development. The various phases of thunderstorm development are well-documented, up through the formation of the mesocyclone. What is unclear, however, is why some mesocyclones drop into funnel clouds and eventually tornadoes, while others do not. The trigger for such an event has never been adequately explained. With this key piece of information missing, it is difficult to measure exactly how an urban area influences the actions of the mesocyclone. It is quite possible that some urban effects, such as the increased surface roughness and increased friction, might decrease the likelihood that a tornado forms over a city. But until the entire tornado process is completely understood, there is no way to be completely sure about the effect an urban area would have.

And finally, while a large urban area could possibly influence the development of a small-scale event like a tornado, there are any number of meteorological conditions that have a stronger influence (such as the presence or absence of El Niño, the location of the jet stream, the dominating wind pattern, and location of air warm and cold air masses). These overriding conditions must be ideal for storm development first, before an individual thunderstorm or tornado can occur. The influence of an urban area will not create these ideal conditions on its own- it can only enhance conditions already present.

Final Thoughts

Considering the influence an urban area has on the surrounding environment, it is very likely that anthropogenic effects have a strong effect on surrounding weather patterns. However, based on this research, it is difficult to tell if an urban area can significantly influence a small-scale, short-lived event such as a tornado. While most of

the results were not expected, future work on the subject could perhaps conclude otherwise. Expanding the definition of the urban areas to include not only the urban extents but also the area upon which they have an influence (i.e. downwind) could result in a much better correlation between the urban expansion and tornado occurrence.

The results of this study, while not proving a relationship between urban expansion and tornado events, should not imply that there is little chance of a tornado hitting a densely-populated urban area. As with all acts of nature, there is some randomness to the process. But natural phenomena can be influenced by human constructs, and the potential effects of urban areas on weather and climate should not be underestimated.

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