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THE MAGNITUDE, FREQUENCY AND SPATIAL DISTRIBUTION OF TORNADOES IN TEXAS: AN ASSESSMENT OF TORNADO RISK

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1. INTRODUCTION

Understanding the risk posed by tornadoes is an important component of emergency planning and management efforts. In any given year tornadoes have the potential to cause millions of dollars in property damage and, in some cases, a significant number of injuries or loss of life. To understand the risk posed by tornadoes, it is important to understand the frequency and spatial distribution of tornadoes of varying magnitudes. Moreover, any assessment of tornado risk must take into account the density and spatial distribution of the population.

The purpose of this paper is to analyze the magnitude, frequency and spatial distribution of tornadoes in the State of Texas and then apply this knowledge to an assessment of tornado risk. In the first part of this paper, maps are generated to show the spatial distribution of tornadoes in the state. These data are then used to create a map showing the density of strong or violent tornadoes by county. The principle aim is to identify those regions of the state that have a higher probability of significant tornadoes.

In the second part of this paper, the county tornado data are combined with county population data to create a spatial model of tornado risk. The purpose of this analysis is to create a composite variable for tornado risk that takes into account: 1) the historical frequency of strong or violent tornado events, and 2) the likelihood that a tornado will cause significant property damage, injuries, or loss of life, given the population density within a county.

2. TORNADO DATA

2.1 BACKGROUND

In 1987, Fujita published an exceptional map showing the spatial distribution of tornadoes in the United States. (1) The map was based on a dataset containing the magnitudes and locations of 23,264 tornados observed between 1930 and 1978. Given such a large dataset, the map was exceptional insofar as each tornado event was mapped by hand and the map took three years to construct.

After Fujita's tornado map was completed, the University of Chicago Tornado Tape became available. (1) This dataset included the magnitudes and locations of 31,054 tornadoes observed between 1916 and 1985. Subsequently, Fujita used this dataset to produce computer generated grid-point tornado maps. Although Fujita used these grid-point maps to analyze both the spatial and temporal distribution of tornadoes in the United States, by today's standards, these maps appear unrefined and are difficult to interpret.

In addition to Fujita's classic work, Grazulis has published what is perhaps the most comprehensive description of tornadoes in the United States. (2) In the first volume of *Significant Tornados*, Grazulis provides a comprehensive analysis describing the spatial distribution of tornadoes mapped by state. In the second volume, Grazulis provides an exceptional chronology of tornadoes. In this volume, the author describes the location, time of day, magnitude, path length and width, and the damage associated with every known significant tornado in the United States from 1880 to 1989.

2.2 THE SPC TORNADO ARCHIVE

Although the books authored by Fujita and Grazulis provide an excellent foundation for understanding the spatial and temporal distribution of tornadoes in the United States, it is difficult to analyze the original tornado data because these data are not readily available in a digital format. (1, 2) To overcome this problem, digital tornado data were obtained from the NOAA Storm Prediction Center (SPC). A project was then undertaken to assemble a tornado database for the United States that can be easily imported into a geographic information system. (5) By compiling tornado data in a GIS format, those interested in tornadoes can readily view, query, and analyze the tornado data to suit their needs. In a GIS format, users can zoom into an area of particular interest, and they can create custom maps that are suitable for printing. More advanced GIS users can also integrate the tornado dataset with other GIS data layers to complete more sophisticated types of overlay analysis or build spatial models.

The SPC tornado archive is a digital database containing the magnitudes and locations of tornadoes observed between 1950 and 1995. The tornado database was compiled from two sources. The data for 1950-59 were compiled from National Weather Service Office reports published as part of the *Climatological Data: National Summary*. (4) The tornado data for 1959-95 were derived from reports published as part of the *Storm Data* publication TD3910. (3)

Within the SPC database, tornadoes are located by either a single latitude and longitude coordinate pair (single point tornadoes) or by multiple coordinate pairs (long track tornadoes). In the case of long track tornadoes, two coordinate pairs can be combined to form a tornado track line segment, and one or more line segments can be combined to locate the path of the tornado.

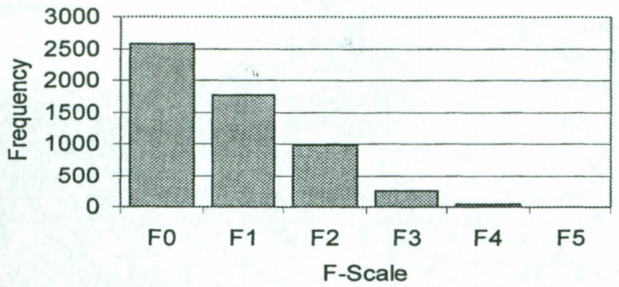
In addition to the coordinate information, the SPC database contains more than thirty attribute fields including the time, date and year of the tornado event, the magnitude of the tornado on the Fujita scale, the length of the tornado path and the width of the tornado path. Given the difficulty of estimating tornado path length, path width and magnitude from post-event damage surveys, there is almost certainly some interpretation in the reporting of tornado attributes. This is especially true in the case of tornadoes that occur in non-urban environments where tornado damage is not as evident. Nevertheless, the SPC tornado archive represents the most complete digital database available.

3. THE NATURE OF TORNADOES IN TEXAS

3.1 MAGNITUDE AND FREQUENCY

To analyze the magnitude, frequency and spatial distribution of tornadoes in Texas, the SPC database was queried to select only those tornado events that occurred within the state borders. Figure 1 shows the frequency of different magnitude tornadoes recorded between 1950 and 1995. For Texas, there are 5633 single point and long track tornadoes within the SPC database. Of these, 4339 (77 percent) are classified as relatively weak tornadoes (F0-F1), 1247 (22 percent) are classified as strong tornadoes (F2-F3) and 47 (less than 1 percent) are classified as violent (F4 and F5).

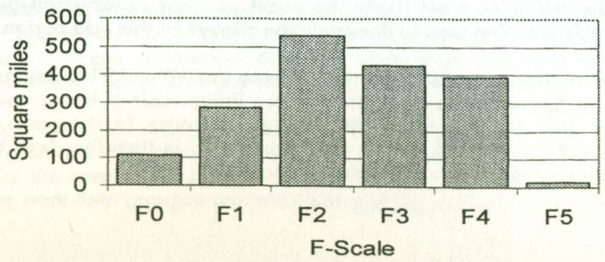
FIGURE 1
MAGNITUDE AND FREQUENCY OF TORNADOES IN TEXAS



Although the data in Figure 1 show a decrease in the frequency of higher magnitude tornadoes, it is important to recognize that both path length and path width tend to increase with F-scale. (1) To analyze the probability of being struck by different magnitude tornadoes, it is therefore important to consider the total area struck by each class of tornado using the path length multiplied by the path width for each tornado. In some cases, the average path length or average path width for a given magnitude tornado was substituted if one of these values was missing.

In Texas, F2, F3 and F4 tornadoes affect larger areas, even though F0 and F1 tornadoes are more common (Figure 2). This result suggests that the probability of being struck by F2, F3 or F4 tornado is greater than the probability of being struck by an F0 or F1. F5 tornadoes tend to have long path lengths and path widths, but the low frequency of these tornadoes results in a much smaller total area being struck. In terms of risk, the historical record in Texas suggests that F2, F3 and F4 tornadoes are the most hazardous. When the large area struck by these tornadoes is combined with their violent and destructive force, the element of risk is very high in terms of property damage, injury and loss of life.

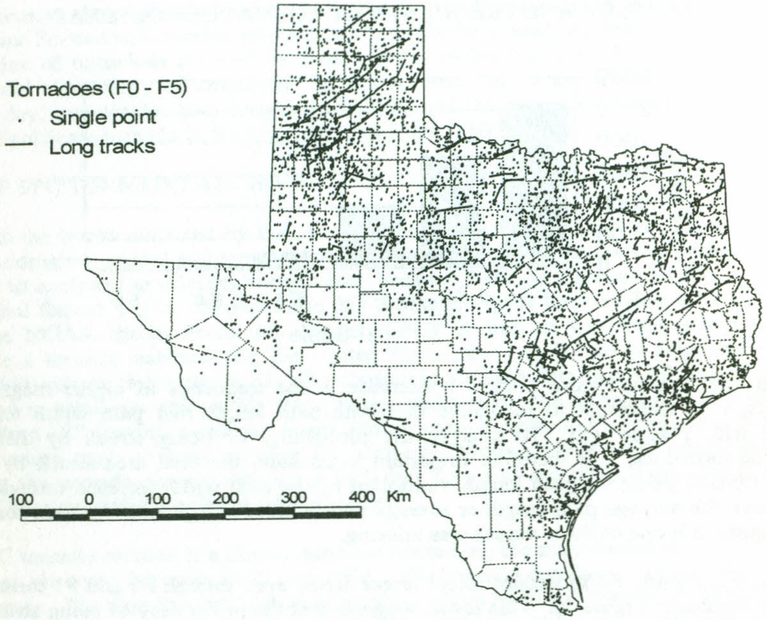
FIGURE 2
AREA STRUCK BY TORNADOES OF DIFFERENT MAGNITUDE



3.2 SPATIAL DISTRIBUTION

Figure 3 shows the distribution of all single point and long track tornadoes (F0-F5) recorded between 1950 and 1995. Based upon this map, it becomes apparent that the state can be roughly divided into two regions with respect to the occurrence of tornadoes. Along the Mexico border in the southwestern part of the state, the frequency of tornadoes appears to be significantly lower when compared to the northern, central and eastern parts of the state. Moreover, a visual interpretation of the data suggests an almost random distribution of tornadoes in the non-border region.

FIGURE 3
SPATIAL DISTRIBUTION OF TORNADOES IN TEXAS

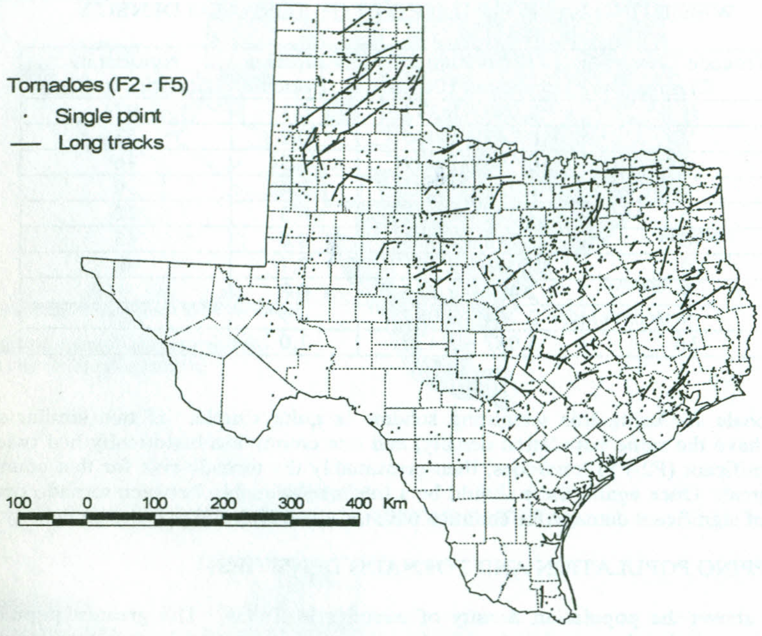


To interpret these results correctly, it is important to keep in mind that data concerning the frequency of tornadoes can be influenced by population density. In the earlier years before Doppler radar (1950 to about 1990), it is likely that many tornadoes in the southwestern part of the state were not observed given the relatively low population density in much of this part of the state. Nevertheless, the difference between the border region and the rest of the state is quite pronounced, and it seems likely that the difference is not solely an artifact of observation bias. The relatively low frequency of tornadoes along the border region is most likely the result of some observation bias and the dry atmospheric conditions that tend to dominate the climate in this arid region.

In terms of tornado risk, it is also important to note that F0 and F1 tornadoes do relatively little damage. In fact, a tornado's ranking on the Fujita scale is based upon a post-event damage survey and, by definition, the damage is minor in the case of F0 and F1 tornadoes. To evaluate the risk to life and property, it is therefore best to examine the spatial distribution of higher magnitude tornadoes. (2)

Figure 4 shows the spatial distribution of strong (F2-F3) and violent (F4-F5) tornadoes in the state. Although the overall density of strong and violent tornadoes is much lower, the spatial pattern is very similar. Once again, along the Mexico border region, the frequency of strong and violent tornadoes is quite low. In the northern, central and eastern parts of the state, the frequency of strong or violent tornadoes is significantly greater.

FIGURE 4
SPATIAL DISTRIBUTION AND STRONG AND VIOLENT TORNADOES



4. HISTORICAL ASSESSMENT OF TORNADO RISK

4.1 METHODOLOGY

For a particular county, the risk of significant damage caused by tornadoes is largely a function of two variables: 1) the county population density and 2) the probability of a strong or violent tornado occurring within the county. Simply stated, the risk of property damage, injury or death should increase directly with either an increase in population density or an increase in the frequency of tornadoes.

To analyze tornado risk, a spatial model was constructed that takes into account both of these variables. The population density for each county in the state was mapped based on 1999 census data. These population densities were then weighted based upon the probability of a strong or violent tornado occurring in the county. To create this weighting factor, the historical record of significant tornadoes was used. For each county, the total number of recorded strong and violent tornadoes was divided by the county area to calculate the tornado density. The tornado density for each county is expressed here as the number of significant tornadoes per 100 square miles. The county tornado densities were then grouped into ten classes using an equal interval classification.

Table 1 shows the weighting factors based upon the county tornado density. Although the use of ten classes is somewhat arbitrary, it provides for a 10 percent increase in the weighting factor to distinguish one class range from the next. To calculate relative tornado risk for those counties in the highest class, the county population densities were multiplied by a weighting factor of 1. To calculate the relative tornado risk for those counties in the second highest class, the population densities were multiplied by a weighting factor of 0.9. For those counties in the third highest class, population densities were multiplied by a weighting factor of 0.8, and so on.

TABLE 1
WEIGHTING FACTORS BASED UPON TORNADO DENSITY

Tornado Density Class	Class Range (tornadoes/100 mi^2)	Weighting Factor	Number of Counties in Class
1	0.000 – 0.343	0.1	97
2	0.343 – 0.686	0.2	53
3	0.686 – 1.029	0.3	36
4	1.029 – 1.372	0.4	30
5	1.372 - 1.715	0.5	12
6	1.715 – 2.058	0.6	13
7	2.058 – 2.401	0.7	6
8	2.401 – 2.744	0.8	4
9	2.744 – 3.087	0.9	1
10	3.087 – 3.430	1.0	2

The rationale for using this weighting scheme is quite simple. If two similar sized counties have the same population density, and one county has historically had twice as many significant (F2-F5) tornadoes, then presumably the tornado risk for that county is twice a great. Once again, there should be a linear relationship between tornado density and risk of significant damage for counties with the same area and population density.

4.2 MAPPING POPULATION AND TORNADO DENSITIES

Figure 5 shows the population density of counties in Texas. The greatest population densities are obviously associated with the major urban centers in the state including Dallas, Fort Worth, Houston, Austin, San Antonio, El Paso, Lubbock and Amarillo. In addition, population densities are relatively high along the I35 corridor connecting the Dallas-Forth Worth area to Austin and San Antonio. Given the higher population densities and the built environment of these urban centers, the potential for significant damage, injury, and loss of life is obviously greater when compared to more rural counties with lower population densities.

Figure 6 shows the frequency of significant tornadoes by county in the state, with the number of significant tornadoes normalized by the county area. These are the same data shown in Figure 4 expressed as the density of strong or violent tornados per 100 square miles. For cartographic reasons, the ten classes described in Table 1 are shown as five categories in the legend of Figure 6.

As might be expected, the counties along the Mexico border region tend to have lower tornado densities and those in the northern, central and eastern parts of the state tend to have higher tornado densities. For counties with a high population density in the southwestern part of the state, the lower tornado densities should reduce the overall tornado risk.

FIGURE 5
POPULATION DENSITY OF COUNTIES IN TEXAS

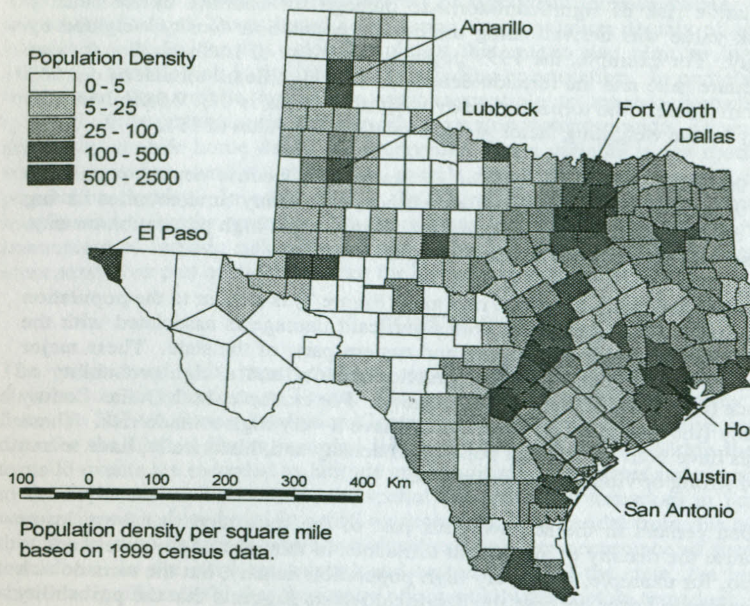
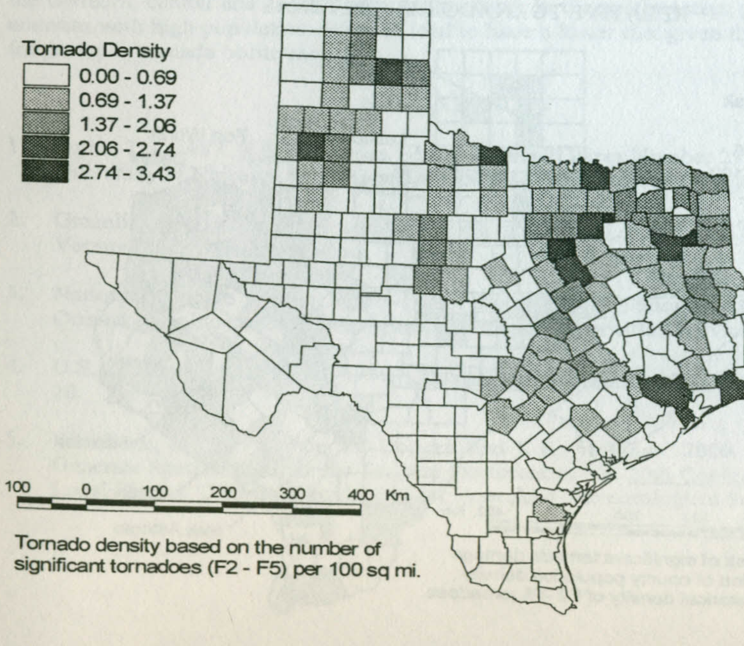


FIGURE 6
TORNADO DENSITY OF COUNTIES IN TEXAS



4.3 RESULTS

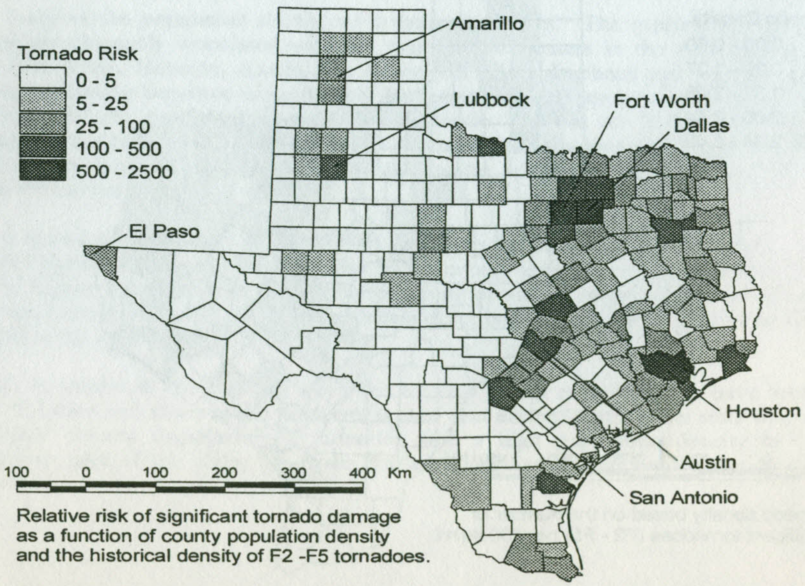
To assess the relative risk of significant tornado damage for counties in the state, a dimensionless risk value was derived using the county population density weighted by the tornado density. For example, the 1999 population density of Lubbock County was 251 people per square mile and the tornado density is 1.98 significant tornadoes per 100 square miles. From Table 1 the tornado density weighting factor is 0.6. Multiplying the population density by the weighting factor yields a relative risk value of 151.

Figure 7 shows the relative tornado risk for all counties. Because county population densities tend to vary over several orders of magnitude, with many rural counties having a low population density and a few urban counties having very a high population density, the risk values also vary over several orders of magnitude.

As might be expected, the relative tornado risk map (Figure 7) is similar to the population density map (Figure 5). The greatest risk of significant damage is associated with the major urban counties in the northern, central and eastern parts of the state. These major urban counties tend to have both a high population density and a high probability of tornado occurrence (expressed as the tornado density). For example, both Dallas County and Tarrant County (the Dallas - Fort Worth area) have a very high tornado risk. These particular counties have both a very high population density and, historically, have seen a high frequency of strong or violent tornado events.

Those major urban centers in the southwestern part of the state tend to have a lower tornado risk because the density of significant tornadoes in this part of the state tends to be lower. El Paso, for example, has a very high population density, but the tornado risk is an order of magnitude lower because the historical record suggests that the probability of significant tornadoes is very low. The lowest risk value (0.017) is associated with Loving County. In this case, the county population density is very low and there are no recorded F2-F5 tornadoes in the database.

FIGURE 7
RELATIVE TORNADO RISK IN TEXAS



Relative risk of significant tornado damage as a function of county population density and the historical density of F2 -F5 tornadoes.

4.4 DISCUSSION

This analysis has shown how relative risk of significant tornado damage varies spatially across the State of Texas based solely upon the population density of counties and the historical tornado density. Another factor that might also play an important role in assessing tornado risk is the integrity of building construction. In particular, it is widely recognized that mobile homes are very susceptible to tornado damage, and provide relatively little protection in the case of a strong or violent tornado. During the course of this study, mobile home density was considered as a variable in the spatial model. The results, however, tend to show that mobile home density is closely correlated with population density. In other words, the counties with the greatest number of mobile homes tend to be the counties with the greatest population densities. Nevertheless, this assessment of tornado risk might be significantly improved if mobile home density was incorporated as part of the risk factor for less populated rural counties.

5. CONCLUSIONS

The purpose of this paper was to analyze the magnitude, frequency and spatial distribution of tornadoes in Texas. The tornado data used in this study were obtained from the NOAA Storm Prediction Center (SPC). This digital archive contains tornado data for the United States recorded between 1950 and 1995. Within the SPC dataset, tornado events are recorded as latitude and longitude coordinates and classified according to the Fujita scale. To examine the spatial distribution of tornadoes in Texas, these data were mapped and analyzed in a GIS environment. The results from this analysis suggest that the Mexico border region has a significantly lower occurrence of strong and violent tornadoes. In the northern, central and eastern parts of the state, the historical record shows a significantly higher frequency of potentially destructive tornadoes.

To assess tornado risk in the state, a spatial model was constructed to incorporate both the population density of counties and the probability of significant tornadoes based upon the historical record. The results from this analysis strongly suggest that the greatest tornado risk in the state is associated with the high population densities of the urban counties in the northern, central and eastern parts of the state. In the southwestern part of the state, counties with high population densities tend to have a lower risk given the relatively low frequency of tornado occurrence.

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