1. Introduction

Population induced biases in the United States and Canadian tornado records have been the subject of numerous studies and formal papers (Snyder 1977; Changnon 1982; Schaefer and Galway 1982; Twisdale 1982; Doswell and Burgess 1988; Grazulis 1993; King 1997; Doswell et al 1999; Ray et al. 2002). There is general consensus that the actual number of tornadoes is significantly higher than the number of tornadoes reported. One can infer from data in Figure 2 much of the bias is the result of lacking F0 tornado reports prior to 1990 The increase in the number of weak tornado reports is attributed to better detection through incorporation of WSR-88D radar as well an increased number of trained storm spotters and storm chasers (Doswell et al. 1999; McCarthy 2003).

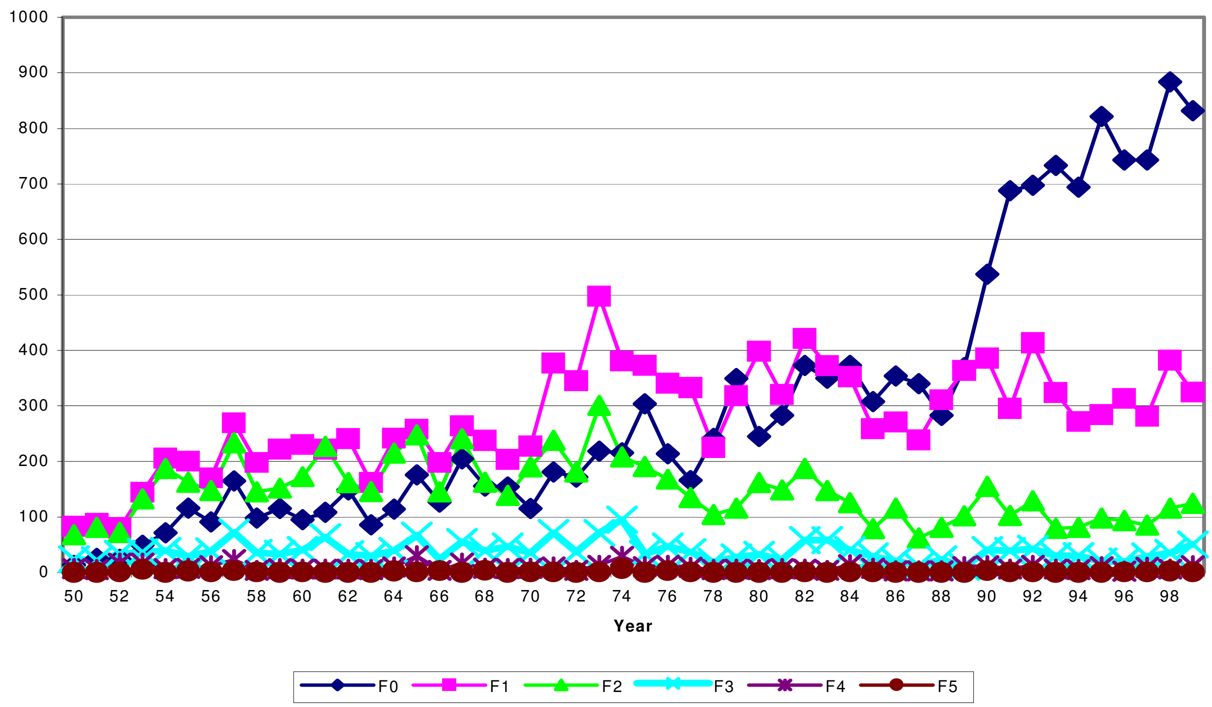

FIG. 1. The number of tornadoes in each Fujita Scale category by year from 1950–2000. Each F-Scale category is differentiated by color and shape (from McCarthy 2001).

There are numerous studies which quantify population induced reporting bias but few if any estimates on the number of tornadoes with wind speeds capable of producing significant damage but fail to strike a well-built structure and therefore cannot exceed F2 on the Fujita Scale. Examples of such tornadoes discussed in the literature include 10 April 1979 Seymour, TX (Doswell and Burgess 1988) and 7 April 2002 Throckmorton, TX (McCarthy 2003). Since an F-rating is determined solely by observed damage there is likely to be a greater frequency of higher F-scale rated tornadoes in more densely populated counties due to the greater density of available structures. Conversely, a lower frequency is expected in less densely populated counties. Tornado intensity risk assessment based on F-scale rating alone may be insufficient as a result of this potential bias. This proposed study will test the hypothesis that there are greater frequencies of higher F-rated tornadoes in more densely populated counties and attempt to quantify any apparent bias.

2. Background

The Fujita Scale (or F-scale) was developed by its namesake Theodore Fujita of the University of Chicago in 1971 (Fujita 1971). The F-scale was designed as a wind speed scale by logarithmically connecting the Beaufort wind scale to the speed of sound (Mach 1) in twelve increments (Fig. 2). Only in rare instances are associated wind speeds within a tornado measured, therefore, wind speed is inferred by observed damage. The F-rating of a particular tornado is determined by the point of maximum damage, usually to structures, along its path. Tornadoes which fail to strike a well-built structure are usually defaulted to the weak F0/F1 category. A rating beyond F5 is considered inconceivable. Should such a storm strike, resulting damage would be inseparable from F5 damage.

The Fujita Scale was designed as a wind scale, however, in application it is a damage scale (Doswell and Burgess 1988; McCarthy 2003). Since an F-rating is based on observed damage (or lack thereof) there are several potential inconsistencies with damage assessment:

- Spatial and temporal structural differences exist from region to region and from community to community.

- There is inherent subjectivity with damage surveys (Edwards 2003; Schaefer and Livingston 2003). For example, one surveyor may suggest F1 damage while another suggests F2 damage.
- Not all tornado damage is surveyed by experts if surveyed at all (Speheger 2002).
- Many tornadoes prior to F-scale incorporation were given a rating through the examination of newspaper articles (Grazulis 1993).
- The damage reported may have been caused by another mechanism (King 1997).

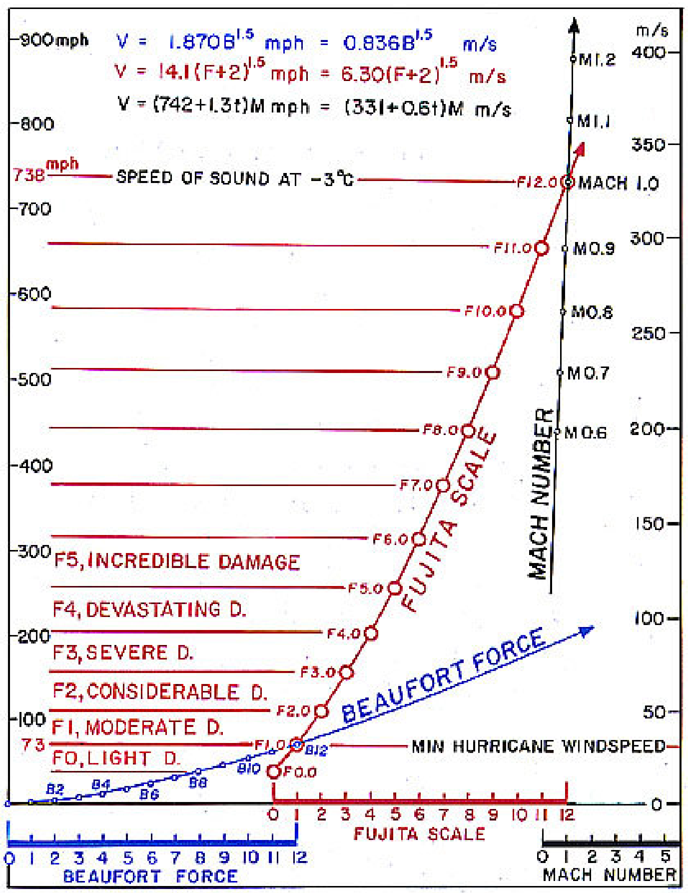

FIG. 2. The Fujita Scale (from Fujita 1971).

3. Methods

The initial area of study includes every county in Minnesota, Iowa, North Dakota, South Dakota, Iowa, Wisconsin, Illinois, Missouri, Nebraska, Kansas, and Oklahoma as well as the Texas Panhandle and the portions Colorado and Wyoming east of the Rocky Mountains. Tornado data from the National Climatic Data Center (NCDC) storm database were used for the full 1950 – 2001 period of study. All years of study are full years. A tornado path recorded in more than one county is tabulated in all counties of occurrence. About 8% of tornadoes prior to 1982 were neglected as they are not accompanied by an F-rating in the NCDC database.

Tornado frequency categories of F0-F5, F1-F5, and F2-F5 were set up for initial investigation and compared with year 2000 United States Census county population density. The observed frequency of tornadoes for each county in the region of study is determined by

$$\text{Tornado Frequency} = \frac{\text{Number of Tornadoes}}{\text{Years of Study}} * \frac{2500}{\text{County Area}} = \text{number } [2500 \text{ km}^2]^{-1} [\text{yr}]^{-1} \quad (1)$$

where the 2500 dimensionless unit in the numerator is a multiplication factor of county area designed to normalize county area in terms of 2500 square kilometers. Analysis of tornadoes per 2500 square kilometers of county area provides a more accurate frequency assessment since some county areas are significantly larger in area than others and will tend to have significantly more tornadoes recorded than smaller neighboring counties.

One advantage of analyzing the number of tornadoes at the county level per 2500 square kilometers per year is the ability to maximize the limited amount of data points available by counting each individual tornado rather than *tornado days per year*, used by Grazulis (1993). The tornado day method gives a county credit if one or more tornadoes strike the county on a given day. If one tornado is observed in a particular county during a given day than it is *one tornado day*. If five tornadoes pass through a particular county that day then it is still *one tornado day*. This method could discriminate against counties that historically receive multiple tornadoes in a given day from cyclical supercell thunderstorms. The effect of isolated single day outbreaks where multiple tornadoes strike a county is negated. The tornado day method does, however, eliminate the problem of distinguishing between long-track tornadoes versus successive tornadoes (where a tornado develops, dissipates, and redevelops) as discussed by Doswell and Burgess (1988). The tornado day method will give a fair approximation as to how many days per decade, century, etc. a given county will be struck by a tornado but it will not indicate how many tornadoes will strike the county during the same time frame.

The tornado day method will be utilized in future data analysis and results will be compared with the tornado number approach. Since a given county could have two or more tornadoes with differing F-ratings on the same day the tornado with highest rating will be used to categorize the tornado day for the county (e.g. an F2 tornado day).

4. Preliminary Results and Discussion

Tornado frequency from 1950 – 2001 for each county was broken down into F0 – F5, F1 – F5, and F2 –F5 categories, plotted using a linear scale, and compared with year 2000 county population density (Fig. 3). There is limited sampling for a separate F3 – F5 category and analysis of these tornadoes is omitted from the test data. Further data analysis will incorporate this category as well as an F4 – F5 category.

From Figure 3, larger urban areas such as Chicago, St. Louis, Oklahoma City, Kansas City, and the Twin Cities have a higher frequency of F1+ and F2+ tornadoes than surrounding areas. A plot of tornado frequency versus population density for Oklahoma counties (Fig. 4) and the northern five tiers of Texas Panhandle counties (Fig. 5) reveal an apparent logarithmic trend toward increasing tornado frequency in all categories of interest supporting the hypothesis that more densely populated counties tend to have a greater frequency of higher F-rated tornadoes.

Logarithmic trendlines can be utilized as both a population reporting bias and damage bias quantification tool since the line equation can be written as

$$y = c^* \ln(x) + d \tag{2}$$

where y is tornado frequency and x is population density. The derivative is

$$dy/dx = c/x \tag{3}$$

where

$$\text{limit as x approaches infinity} = 0. \tag{4}$$

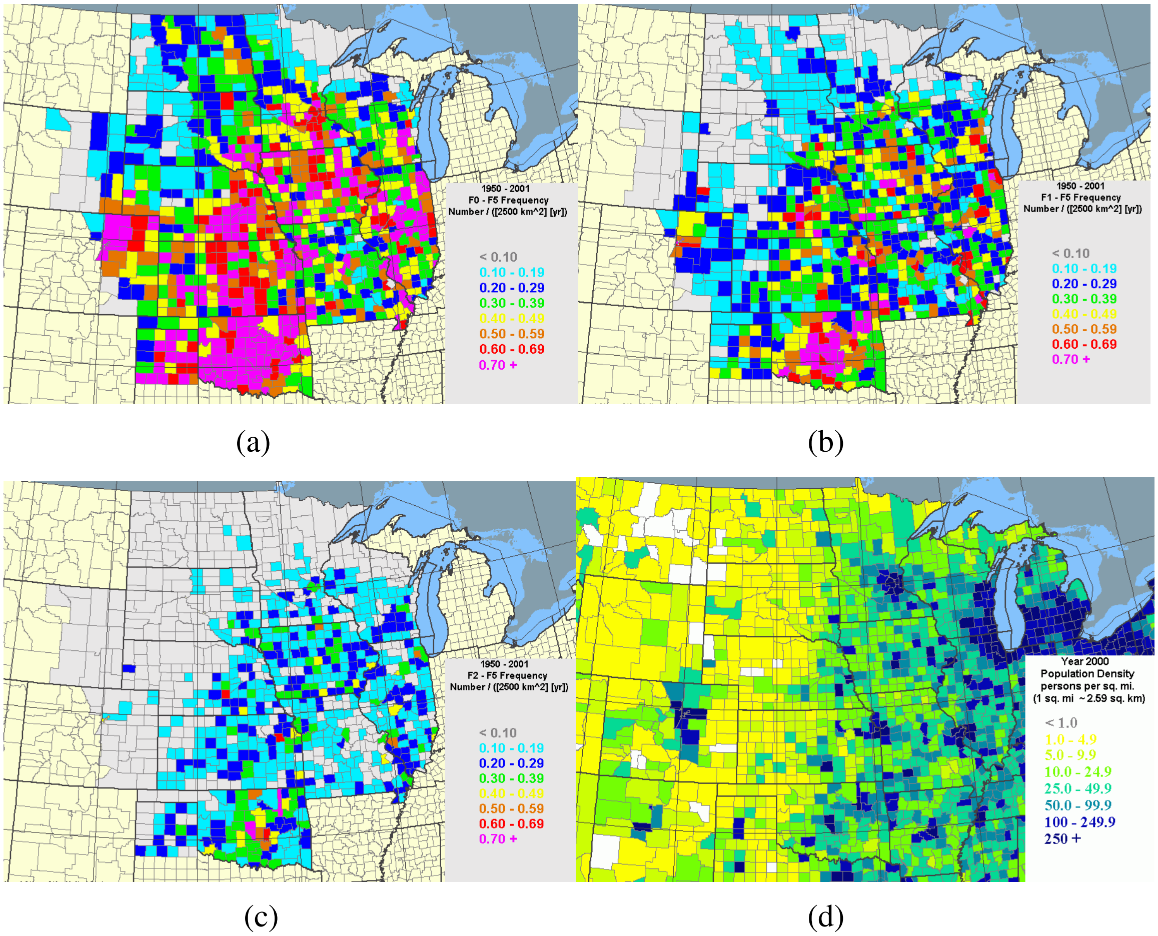

FIG. 3. (a) The annual average frequency of F0-F5 tornadoes by county from 1950-2001, (b) for F1-F5, (c) for F2–F5, (d) year 2000 population density in persons per square mile (The population density figure can be generated online at http://www.nationalatlas.gov).

Since there is some theoretical climatological maximum of tornado frequency for a given area the mathematical expression is logical. As population density approaches infinity (the point where every tornado is observed and strikes a well-built structure) the rate of increase in tornado frequency with respect to population density approaches zero. The tornado frequency at this limit can be assumed to exist over the whole region provided there is not a significant natural climatological difference in tornado frequency within the region.

For Oklahoma (Figure 4), the frequency limit of F0+ tornadoes nears 1.20, the F1+ limit approximates 0.85 and the F2+ limit approximates 0.50. These values were entered into the tornado frequency equation using the Oklahoma state area of

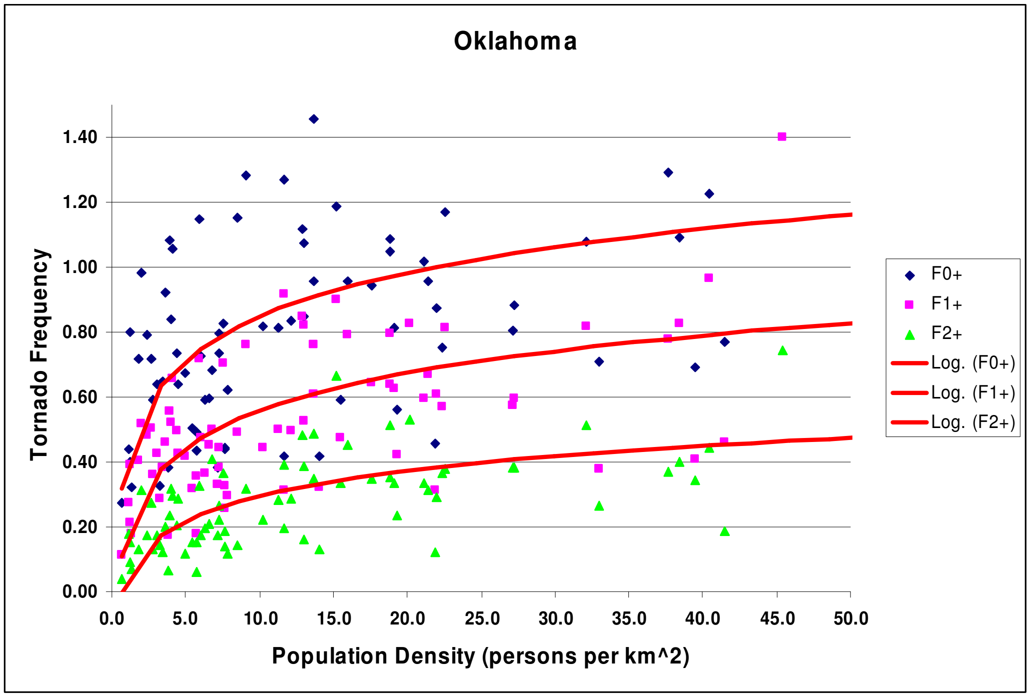

FIG. 4. Tornado frequency versus population density for Oklahoma counties excluding population density greater then 50 for legibility. Logarithmic trendlines for each category are in red.

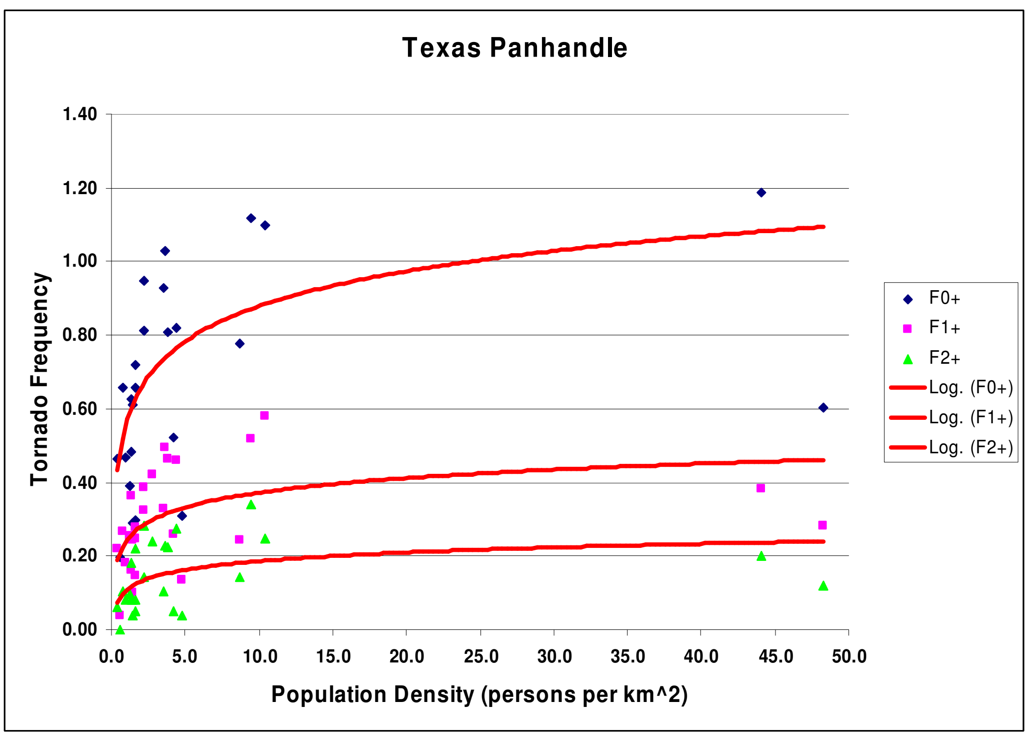

FIG. 5. Tornado frequency versus population density for the northern five tiers of Texas Panhandle counties. Logarithmic trendlines for each category are in red.

180,970 km^2 (69,903 mi^2), yielding theoretical values of 84 F0+ tornadoes, 59 F1+ tornadoes, and 35 F2+ tornadoes. Fifty-two year reported averages for rated Oklahoma tornadoes are 57, 37, and 19 for each category respectively. If one makes the stated assumptions in the preceding paragraph, there is a 47% greater occurrence of all tornadoes in Oklahoma than reported tornadoes in the 52-year data set. This increase is likely attributed to population induced reporting bias, primarily for F0 tornadoes, and is slightly lower than estimates by Snow et al (2000) and Ray et al (2002) who employed differing methods over a larger geographical area. For the F1+ and F2+ categories there is an increase of 59% and 84% respectively. These increases could be attributed to population induced damage bias. Interestingly, much of the signal from is from counties with population density below 20 persons [km^{-2}] (Fig. 4 and 5) rather than large metropolitan counties.

Since significant natural climatological variation may exist within a state, further analysis and quantification will be necessary on a scale smaller than a state area. The choice for such a scale is the National Weather Service County Warning Area (NWS CWA). County Warning Areas are similar in area and contain a statistically large county sample size. Use of CWA's is not completely unproblematic. Climate variation still exists within a CWA however potential error is reduced from a statewide analysis. Potential inconsistencies discussed by Schaefer and Livingston (2003) are also introduced as CWA's tend to incorporate counties from more than one state.

In addition to spatial scale variation, temporal scale modification is warranted for comparison between periods in order to see how reporting and demographic changes affect the frequency curves. A simple breakdown into two 26-year periods of study will differentiate time periods of differing F2 tornado frequency observed in Figure 2. Decadal analysis could be useful in regions of highest tornado frequency (i.e. regions where larger sample size exists).

5. Summary

With discussion of the Fujita Scale it is imperative to distinguish between tornado intensity and tornado damage. Since the Fujita Scale in application is a damage scale rather than a wind speed scale, intense tornadoes that fail to strike a well-built structure cannot exceed an F2 rating despite obtaining wind speeds capable of higher F-rated damage. Examples of such tornadoes are only casually documented in the literature. Currently there are no estimates on the number of these tornadoes capable of producing significantly more damage should a well-built structure happen to be in the path. Because of this bias the observed frequencies of F-scale damage categories are not necessarily an accurate assessment of recurring tornado intensity for a given area. With expanding population an accurate risk assessment becomes more critical as structures are built on previously undeveloped land.

The objective of this research is to more accurately assess the frequency of F-scale tornado intensities. Results from preliminary investigation support the hypothesis of a greater frequency of higher F-rated tornadoes in more densely populated counties. Plots of tornado frequency versus population density suggest a logarithmic correlation which can be used to mathematically quantify damage bias as well as population reporting bias. Further investigation is necessary on a smaller spatial scale such as by NWS CWA to limit potential spatial tornado climatology differences. Temporal scale modification will allow for data comparison between periods. Further investigation is also warranted for F3+ and F4+ tornado frequency categories in order to determine if a limit to population damage bias exists with increasing intensity. In addition, use of the tornado day method will potentially limit further inconsistencies within the data.

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