4.2 THE ROBUSTNESS OF TORNADO HAZARD ESTIMATES

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1. INTRODUCTION

The Storm Prediction Center (SPC) maintains a database containing information about every tornado reported in the United States. Data goes back through 1950. During the 51 years of record, there have been many changes in tornado reporting efficiency. These have resulted in an increase of approximately 23 storms each year (Fig. 1). While the year-to-year changes are small, when they are integrated over a half-century their effect is marked! Further, the changes are not linear; rather, there are marked discontinuities in the time trend. These changes are more likely a product of changes in American society than in the actual tornado climatology (Schaefer and Brooks, 2000). For instance, cellular phones, which are now common place but unknown in the 1950's, make it much more likely that people will report a tornado that they observe while they are traveling.

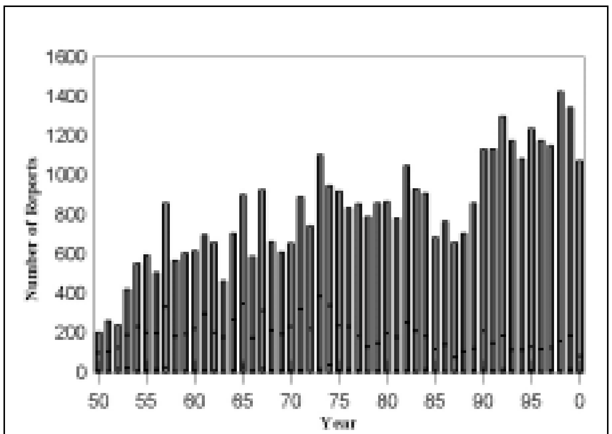

Figure 1: The number of tornadoes reported in the United States each year.

Discontinuities also are found when the storms are sorted by intensity. One striking feature is that while the total number of tornadoes reported each year has increased, the yearly number of strong and violent tornadoes (those rated at F2 and greater) reported has actually decreased over the past half century (Fig. 2).

This drop in strong violent tornado frequency is a result of changes in the way the intensity of tornadoes are rated. Storms that occurred from 1950 through the mid-1970s were rated based upon newspaper accounts. From the mid-1970s on, most tornado ratings were made by personnel from the local NWS office (at times augmented by outside experts) who made surveys of the tracks of the most significant storms. The inflated number of strong and violent tornadoes likely results from the reality that devastation sells newspapers.

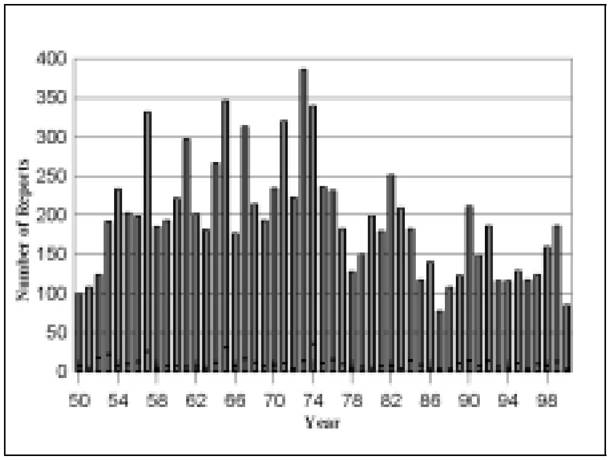

Figure 2: The number of strong and violent tornadoes in the United States each year.

The reporting of tornado track characteristics has also changed markedly over the span of the database. For instance, there is a feeling among many meteorologists that very long tornado tracks are most likely actually the result of a sequence of tornadoes that develop in association with the same parent thunderstorm (Doswell and Burgess, 1988). The impact of this paradigm shift on the record is seen by an examination of the average annual track length by year (Fig. 3). Over the 38 years before 1988, the average tornado track was reported as 4.1 miles, but during the 12 years since 1988 this dropped to only 2.5 miles. While other factors may play a role, the shifts to tornado families rather than the singular long track events contributes weightily.

The requirement for reporting track width changed in 1994. Before then, instructions were to report the "mean" width of the tornado track. However the NWS Operations Manual was rewritten in July 1994 so that the "maximum" width of the tornado any place along its track was to be reported. Interestingly, this change had little effect on the overall statistics. The annual average

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of the reported tornado width changed very little even though a different basic parameter is reported (Fig. 4).

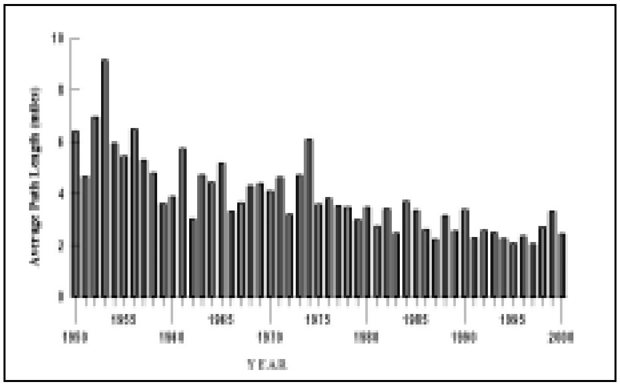

Figure 3: Mean United States tornado track length by year.

Because of these changes in the basic characteristics of the historic tornado record, we felt that it would be valuable to examine how the global characteristics of the data set have changed. Such an assessment is necessary if these data are to be used for such things as base lining numerical models, validating theoretical predictions, or assessment of tornado risk.

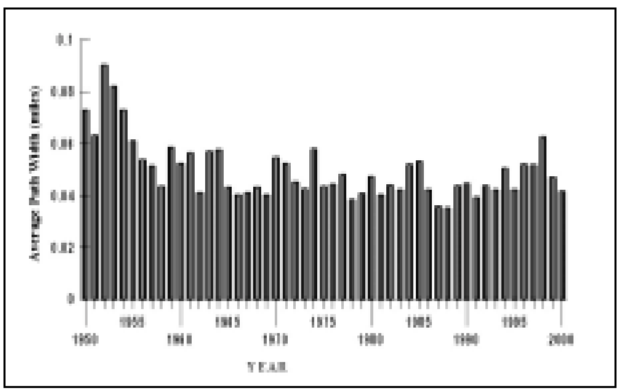

Figure 4: Average reported tornado track width by year.

2. DISTRIBUTION OF TORNADO PARAMETERS

Distributions of various tornado characteristics recorded in the SPC database from 1950 through 1983 were presented in Schaefer, et. al., (1986). Similar distributions were calculated using the 1983 - 2000 data. One significant difference between the distributions is immediately obvious. In the older data, there were a significant number of tornadoes that had either length or width missing. In the newer data (since about 1980), most of the reports contain both length and width. To account for this difference, when the data were grouped into length and width bands, the smallest categories used were length less than 0.2 km and width less than 10 m.

The distribution of reported tornado lengths (plotted on a logarithmic horizontal axis) for the two time periods shows that neither distribution is log-normal (Fig. 5). However, the two distributions do have considerable differences in the two shortest length categories. It is apparent that lengths that were left missing in the older data were not all extremely short tornadoes, but that a good portion of them had lengths ranging from about a quarter to a half a kilometer. In contrast, the distribution of tornadoes with path lengths of about 4 km and longer are essentially the same for both data periods.

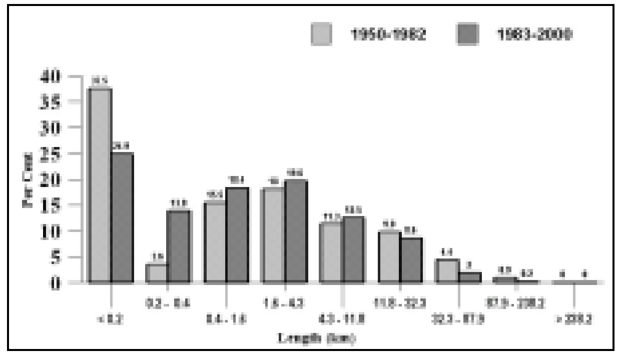

Figure 5: Distribution of tornado track length for the periods 1950 - 1982 (grey) and 1983 - 2000 (black).

In an effort to see if the track length of a tornado is indicative of its intensity, the joint distribution of tornado track length and F-scale rating was computed (Fig 6). This distribution is illustrated via a quartile diagram. For each F-scale, the median length and the lengths that are greater than 25% and 75% of the reports are each plotted. Figure 6 shows that while there is a general tendency for stronger storms (higher F-scale values) to be longer, path length does not provide a distinct discrimination by intensity. The median lengths of both F-3 tornadoes and F-5 tornadoes lie within the middle two quartiles of the F-4 lengths. One cannot use tornado track length as a proxy for an intensity observation.

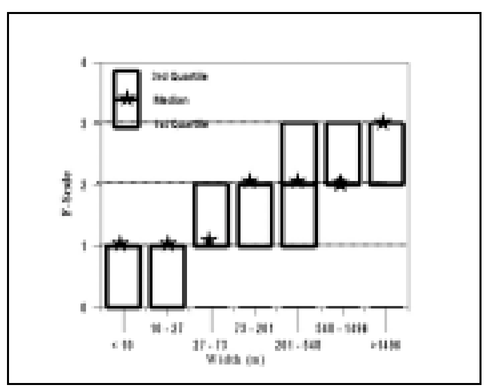

Figure 6: Distribution of track length by F-scale -- 25% of the observations at a given F-scale are less than the 25% quartile and 25% of them are greater than the 75% quartile value.

The distributions of tornado path width for the two data periods (Fig. 7) accentuate the points raised with the length data. As with length, width distributions are not log-normal. The main differences between the data from the early years and from the later years are with smaller (narrower) tornadoes. Apparently the unreported widths in the pre-1980 data were not all the lowest possible report value; rather, they likely were distributed among widths less than about 75 meters. The distribution for wider categories is essentially the same in the early years and the later ones.

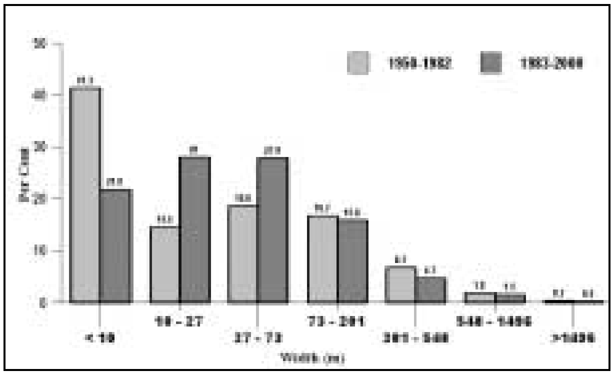

Figure 7: Distribution of tornado track width for the periods 1950 - 1982 (grey) and 1983 - 2000 (black).

The relationship between width and intensity is especially interesting (Fig. 8). A simplified model can be used to show that there is a relationship between the width of a tornado's sensible funnel and its maximum wind speed (e.g., Dergarabedian and Fendell, 1971). The underlying assumptions to this analysis, such as hydrostatic conditions and Combined Rankine Vortex flow (Davies-Jones and Kessler, 1974) are questionable. Although the notion that a tornado's intensity is related to the way it looks (its diameter) is intuitively appealing, the data do not support it. As Fig. 8 vividly illustrates, it is virtually impossible to look at a tornado and say with any certainty what its Fujita-scale rating is!

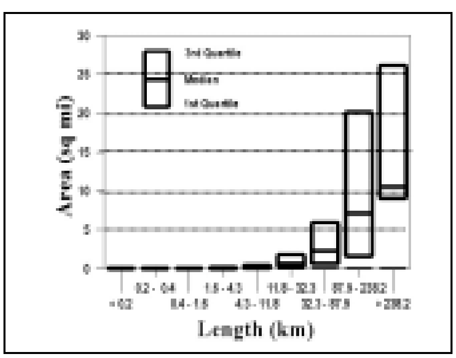

Figure 8: Distribution of tornado path width by F-scale -- legend as in Figure 6.

The mean area of a sample is not simply the product of the sample's mean length and the sample's mean width. The correlation between length and width is also a significant factor. Comparison of the distributions of tornado damage area computed from the early years of the database (1950 - 1982) to the one from the more recent years (1983 - 2000) shows major changes (Fig. 9). The earlier distribution appeared almost like a skewed log-normal curve superposed on a "no report" spike. For the later years, the distribution is almost linear when plotted on a logarithmic axis. The most marked changes between the two distributions occurred for small areas, whereas little change occurred for larger areas. This arises from the lack of a strong correlation between length and width rather than the missing data problem.

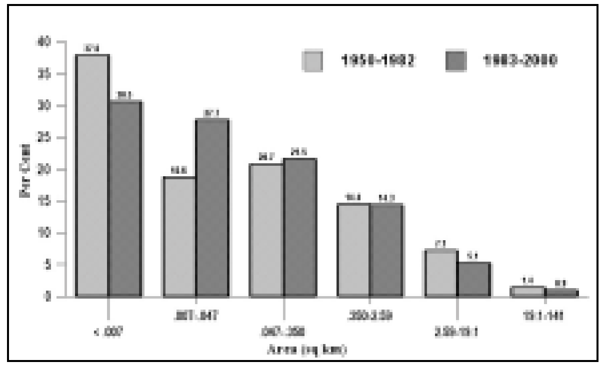

Figure 9: Distribution of tornado damage area for the periods 1950 - 1982 (grey) and 1983 - 2000 (black).

Abby and Fujita (1979) propose the use of track length as a proxy for area. The quartile plot (Fig. 10) of area as a function of width indicates that if any such relationship exists, it is weak at best. In fact the correlation coefficient between width and length (Table 1) is essentially zero (-0.062). The reason for this slightly negative correlation is the high variance of the relationship. Indications of this are seen by closeness of the medians to the first quartile markers in Fig. 10. For instance, there are only 12 tornadoes that had a path length greater than 238.2 km. Of these, 3 had a reported width of 30 feet (the smallest possible report), 6 had a reported width of 300 feet. These very short width, very long track tornadoes drive the correlation coefficient to a slightly smaller negative number.

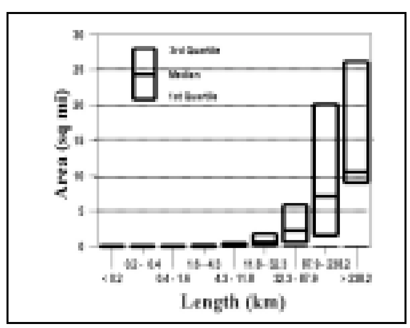

Figure 10: Distribution of tornado area by track length -- legend as in Figure 6.

Tornado Track Characteristics based on 40,522 Tornadoes (1950- 2000)

	Mean	Median
Length	5.8 km	0.8 km
Width	77 m	27 m
Area	1.19 km^2	0.03 km^2

Correlation Coefficients

Length/F-Scale	0.409	Length/Width	0.308
Width/F-Scale	0.408	Length/Area	-0.062
Area/F-Scale	0.305	Width/Area	0.616

Table 1: Tornado track characteristics as recorded in SPC database.

3. IMPACT OF DATA BASE CHANGES ON TORNADO HAZARD ESTIMATES

A key use of historic tornado information is in the estimation of the local tornado hazard. Such estimates are mandated for both nuclear power plant sites and for sites that process nuclear materials (American Nuclear Society, 1983). Since the hazard estimates are used for both design and regulatory purposes, they should be relatively robust with respect to increasing the period of the database. An appropriate question is, how do the changes in the database that have been discussed so far impact tornado hazard calculations?

One simple method of tornado hazard estimation is the "Minimum Assumption Tornado-Hazard Model" (Schaefer, et. al., 1986). This empirically based model uses the observed length and width of each tornado to calculate the percentage of the area surrounding a site that has been affected by tornadoes in the past. When normalized by year, this gives a point probability of tornado damage occurrence. Because of the nature of the assumptions, the model gives a very conservative hazard estimate (high probability). For details on the method and specifics on how it is applied, interested readers are referred to the original paper.

The hazard of any tornado occurring, regardless of intensity, computed from the entire 51 years of data is given in Fig. 11. This can be compared to a similar chart (Fig. 12) computed with 34 years of data that originally appeared in Schaefer, et. al. (1986).[1] The general pattern of the features of the analysis, and the magnitude of the risk in regional areas are largely unchanged. However, some differences are apparent. In Northwestern Pennsylvania, the 1950-2000 data set indicates a small area of greater than 10^{-4} risk that was not present in the 1950-1982 data. This area is a reflection of the 30 tornadoes that occurred in that area during the outbreak on May 31, 1985. This illustrates that the statistics for rare events such as tornadoes are most volatile in areas where major tornado outbreaks are possible but unlikely during a short 50-year sample. Similarly, the extension of the 10^{-4} risk area from Georgia up into the Carolinas could possibly be the result of two tornado outbreaks, one on March 28, 1984 and the other on March 27 1995 (the "Palm Sunday II Outbreak"). The small 10^{-5} risk area in Western North Dakota that disappeared between Fig. 12 and Fig. 11 shows the problem of comparing contours. For the early period, the risk was slightly above the threshold value. However with few tornadoes in the more recent years, the normalization lowered the value to just below the threshold. An artifice of the analysis scheme rather than a feature in the data causes the double minimum in Southern Missouri in Fig. 11. It demonstrates that fallacious features can develop unless the detail in an analysis is comparable with the scale of the input data.

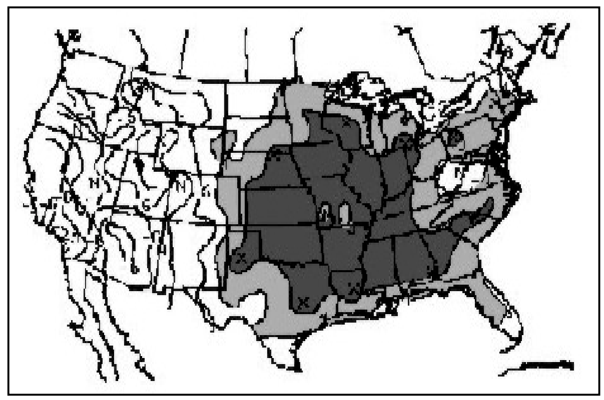

Figure 11: The tornado hazard across the contiguous United States computed using data from 1950-2000. Contours are labeled as the negative-exponent of the risk expressed in scientific notation but with a base between 0 and 1 (e.g. 4 indicates $0.1 \cdot 10^{-4}$, or $1 \cdot 10^{-5}$). Areas with a risk greater than $0.1 \cdot 10^{-4}$ are lightly shaded; areas with a risk greater than $0.1 \cdot 10^{-3}$ are darkly shaded.

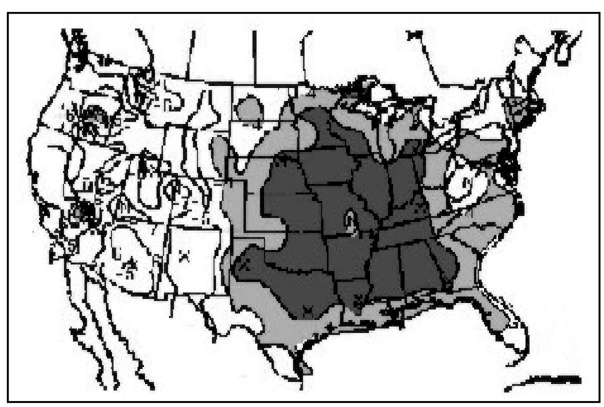

Figure 12: The tornado hazard across the contiguous United States computed using data from 1950-1982. Legend as in Fig. 11.

[1] Since the original 1986 chart was hand analyzed with the associated implicit smoothing, and Fig. 12 in this paper was recalculated and plotted via computer, there are differences between the two presentations.

Similar diagrams can be drawn giving the risk of tornadoes above any given F-scale. Since most of the increase in tornadoes over the span of the SPC database was in weak tornadoes (F-0 and F-1), charts of the risk from F-2 or greater tornadoes (strong and violent tornadoes) were developed from the full 51-year dataset (Fig. 13) and for the 1950-1982 period (Fig.14). The risk from all tornadoes and the risk from only strong and violent tornadoes is nearly the same. This reflects the fact that weak tornadoes typically produce only small damage areas. The scarcity of tornado events in the Western United States contributes to small-scale detail in the pattern of risk from F2 and greater tornadoes west of the Rocky Mountains. With very little data, the value of the analysis is debatable.

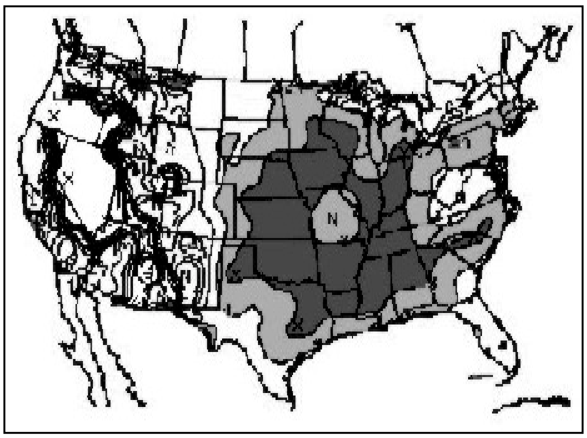

Figure 13: The hazard from F-2 and stronger tornadoes across the contiguous United States computed using data from 1950-2000. Legend as in fig. 11.

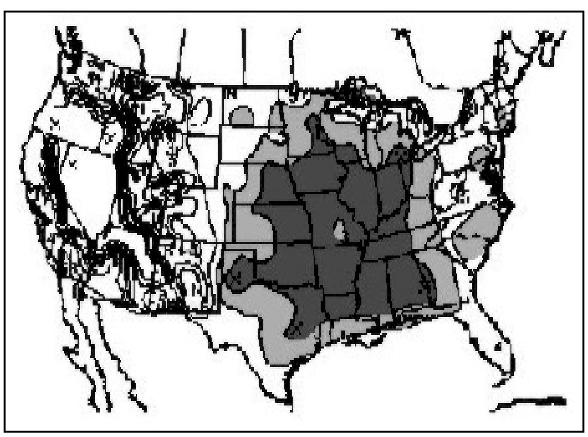

Figure 14: The hazard from F-2 and stronger tornadoes across the contiguous United States computed using data from 1950-1982. Legend as in fig. 11.

A better way to examine how the tornado hazard varies is through the use of exceedance diagrams. Such a diagram shows the risk at specific points from events exceeding various thresholds (Fig. 15). The ordinate on this chart indicates the probability that tornadoes in the F-scale range indicated on the abscissa will be equaled. For example, there is a probability of $6 \cdot 10^{-4}$ that a F-0 or greater tornado will occur in Central Oklahoma in a given year, while for northeast Pennsylvania, this probability about 60% less ($1.5 \cdot 10^{-4}$). As another example, the probability of an F-4 or greater tornado over Central Oklahoma is $1 \cdot 10^{-4}$, while for central South Carolina it is over an order of magnitude lower ($3 \cdot 10^{-5}$). To change these from F-scale exceedance to wind speed, it is necessary to accept a model relating wind speeds to F-scales. Several of these are available in the literature (i.e., Minor, et. al., 1977). These values can be directly inserted onto the abscissa in lieu of the F-scales.

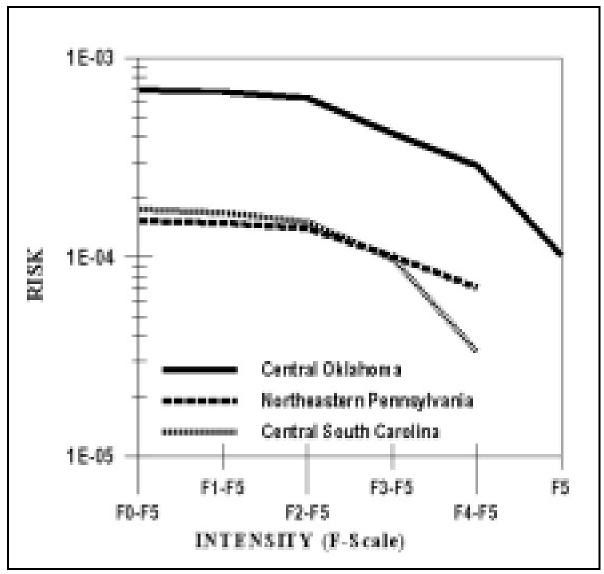

Figure 15: Exceedance diagram of tornado risk for central Oklahoma, northwestern Pennsylvania, and central South Carolina. These were computed using 1950-2000 data.

Since exceedance diagrams, in contrast to contour patterns, do not depend on specific threshold values, they are appropriate to show how robust the risk computations are. Exceedance diagrams for Central Oklahoma calculated from the early years in the data set (1950-1982) and for the entire data set are shown in Fig. 16. This chart shows that there has been very little change in the data. For any tornado occurrence, the risk calculated from the entire data set is $6.9 \cdot 10^{-4}$, while for the entire data set it is $6.1 \cdot 10^{-4}$. The biggest difference between the two curves occurs for F-3 and greater tornadoes where the risk of $2.8 \cdot 10^{-4}$ computed for the 1950-1982 data increases to $4.2 \cdot 10^{-4}$ when the entire 1950-2000 data set is used. This increase is a result of the May 3, 1999, tornado outbreak when six F-3 tornadoes, two F-4 tornadoes and one F-5 tornado occurred. Even in the most tornado-prone region of the country, the lack of a long historical tornado record creates sampling problems for computing exact risks for extreme events. However, despite this problem, the probabilities still remain qualitatively similar and within the error bands that would be generally associated with this type of analysis.

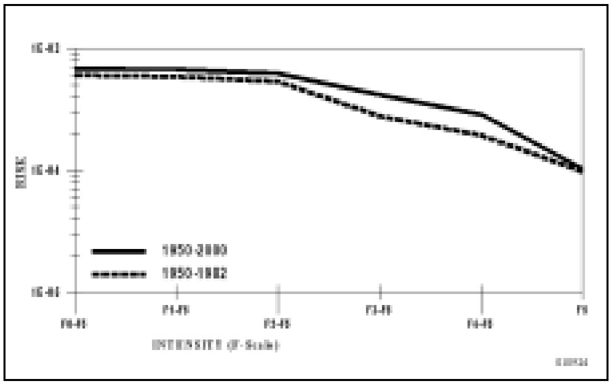

Figure 16: Exceedance diagram showing the tornado hazard for central Oklahoma computed from 1950-200 data and computed from 1900-1982 data.

The exceedance diagrams for northwest Pennsylvania show marked variation between the two time periods for F-3 and greater tornadoes (Fig 17). Here the risk of an F-3 or greater tornado changed from $1.8 \cdot 10^{-6}$ for the pre-1983 data to $1.1 \cdot 10^{-4}$ for the entire 51-year data sample. Also, no F-5 tornado has ever occurred in the area considered. If an F-5 tornado ever occurs there in the future, there will be an infinite percentage increase in the estimated hazard for high-end tornadoes. Even the most robust models become volatile when they do not have enough data to work with.

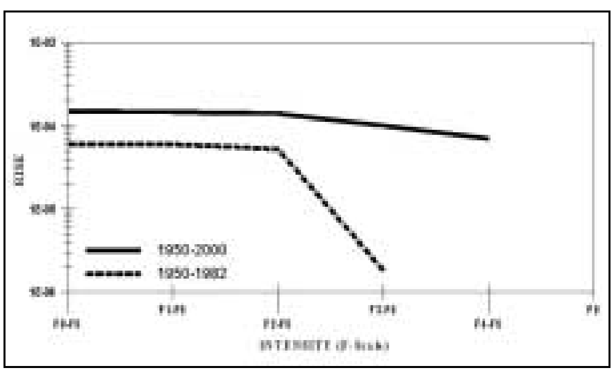

Figure 17: Exceedance diagram showing the tornado hazard for northwest Pennsylvania computed from 1950-200 data and computed from 1900-1982 data.

The central South Carolina exceedance diagram (Fig. 18) shows how the comparison of contour charts like Figs. 11 and 12 can be misleading. The hazard from any tornado at that point computed from the 1950-1982 data there is $1.04 \cdot 10^{-4}$. This value is nearly the same as the contouring threshold ($0.1 \cdot 10^{-3}$). When the central South Carolina value is merged with values from surrounding points in an objective analysis, the resulting "analyzed" value is just below the threshold. The tongue of higher risk over the Carolinas in Fig. 11 was not a result of two large tornado outbreaks, but simply an artifice of the analysis scheme used. The tornado data in South Carolina are remarkably robust even though two outbreaks occurred in recent years.

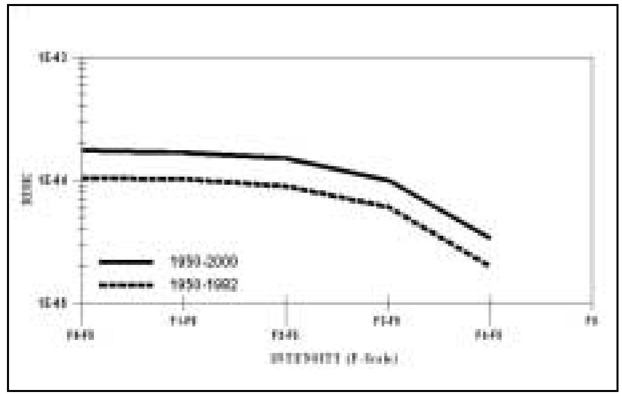

Figure 18: Exceedance diagram showing the tornado hazard for central South Carolina computed from 1950-200 data and computed from 1900-1982 data.

4. CONCLUSIONS

Over the past half-century, there have been many changes, both in number of tornadoes reported and in the characteristics of their tracks. Even with the changes, when these data are used to estimate the local tornado hazard, the results are surprisingly robust. This gives us confidence in using this type of analysis as an aid in assessing relative risk from point-to-point and as an aid in determining reasonable design standards.

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