A Minimum Assumption Tornado-Hazard Probability Model

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(Manuscript received 10 January 1986, in final form 17 June 1986)

ABSTRACT

One of the principle applications of climatological tornado data is in tornado-hazard assessment. To perform such a hazard-potential determination, historical tornado characteristics in either a regional or local area are compiled. A model is then used to determine a site-specific point probability of a tornado greater than a specified intensity occurring. Various models require different climatological input. However, a knowledge of the mean values of tornado track length, tornado track width, tornado affected area and tornado occurrence rate as both a function of tornado intensity and geographic area, along with a violence frequency distribution, enable most of the models to be applied.

The NSSFC-NRC tornado data base is used to supply input for the determination of these parameters over the United States. This climatic data base has undergone extensive updating and quality control since it was last reported. For track parameters, internally redundant data were used to check consistency. Further, reports which deviated significantly from the mean were individually checked. Intensity data have been compared with the University of Chicago DAPPLE tornado base. All tornadoes whose recorded intensities differed by more than one category were reclassified by an independent scientist so that the two data sets are consistent.

1. Introduction

One of the principle applications of climatological tornado data is tornado-hazard assessment. Even though the tornado is a rare localized event, modern society has become so complex that even the associated low risks have become important. During the 1974–78 span, 37 separate catastrophies, each resulting in more than $20 million in insured losses, were associated with tornadoes (Insurance Information Institute, 1979). The potential effect of such a disaster on any individual insurance carrier is devastating.

With the advent of nuclear reactors and associated facilities, the need for hazard assessment has moved from the realm of the insurance industry to that of the engineer, architect, regulator and emergency preparedness planner. Nuclear installation design requires consideration of dynamic (wind) pressure extremes, static pressure drop and the effects of windborne missiles (Nuclear Regulatory Commission, 1978). All of these factors can be directly related to a tornado's maximum velocity or intensity. The direct application of tornado hazard-potential estimates is mandated.

High concentrations of people in areas of high tornado hazard require special planning. Officials at hospitals, schools and factories all should be aware of their relative risk. Disaster plans (Abernathy, 1976) should be prepared. Further, various minor modifications to buildings can be performed to mitigate tornado effects (Mehta et al., 1980; Minor, 1976). However, to make any such structural retrofitting economically feasible, it is necessary to estimate the damage probabilities.

2. NSSFC tornado data base

To perform such a hazard analysis, it is first necessary to obtain a complete, consistent statistical database detailing all available information about each individual occurrence. The National Severe Storms Forecast Center (NSSFC) in conjunction with the Nuclear Regulatory Commission pursued newspaper accounts of all tornadoes reported over the contiguous United States starting in 1950 (Kelly et al., 1978). Data were compiled on each tornado's path length and average path width. Also noted were the latitude/longitude of touchdown and retraction points, numbers categorizing the track length, track width, tornadic intensity (Fujita, 1973) and the monetary amount of damage produced by the storm. The tornado intensity estimate is given by a rating on the "F-scale" (Fujita, 1981). This is a subjective rating system which categorizes intensity estimates according to the amount, type and appearance of tornado damage.

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Since the intensity categorization is entirely subjective, a strong possibility of biases, inconsistencies and/or inaccuracies in the data exists (Forbes and Wakimoto, 1983). In an effort to alleviate this, independent studies were conducted to reconcile any significant differences between the NSSFC database to a similar database compiled by the University of Chicago (Fujita, 1981; Tecson et al., 1979; Tecson et al., 1982; Tecson et al., 1983). Any tornado which had recorded intensities varying by two or more categories between the two datasets (or was rated F4 and above in one dataset and not the other) was recategorized from the original clippings (Grazulis, 1983). Approximately 4% of the NSSFC data were modified by this change.

In 1890 Hazen noted an "exceedingly slight" difference exists between a tornado rating system based upon observed violence and one based upon property loss. Thus, as a check on the reality of the intensity data, the F-scale can be correlated to the damage cost category as compiled in the NOAA publication Storm Data. It must be cautioned that while an intensity ranking is overtly subjective, a cost ranking also has pitfalls. Tornado damage figures are typically based upon near-real-time reports. Many data are missing, and only a single value is often given for multitornado outbreaks. Because of this, these statistics are also only rough estimates of actual damage (Kessler and Lee, 1976).

To perform the correlation, the reported damage category is converted to a monetary value by assigning the value at the logarithmic midpoint of each ging. These costs are then normalized to 1967 values by using the urban consumer price index (Department of Labor, 1983). This comparison was possible for 16 303 storms. The resulting regression line, along with bracketing "standard error of estimate" curves is given in Fig. 1. Since these data are measured in broad groups rather than by a continuous variable, ordinary correlation methods are not applicable (Brooks and Carruthers, 1953). Rather, the Spearman rank correlation coefficient (Snedecor, 1965) is more appropriate. A relatively high rank correlation of 0.56 exists between these two types of categorization. Further, the large sample size virtually guarantees that there is consistency. It is concluded that the F-scale intensity categories are representative of tornado severity.

It must be noted that the determination of all of the primary parameters (intensity, path width and path length) is to some extent subjective. The F-scale for tornado intensity is based on a worst-damage assessment. The recorded value can be an underestimate of the true intensity if there were no damageable or perishable objects along the tornado's track. Path width, defined as the mean-damage width along the entire path, cannot be exactly determined without driving zigzag across the path and/or flying over the entire damage area. Although skipping paths are loosely defined, path length is the most accurate parameter subjective.

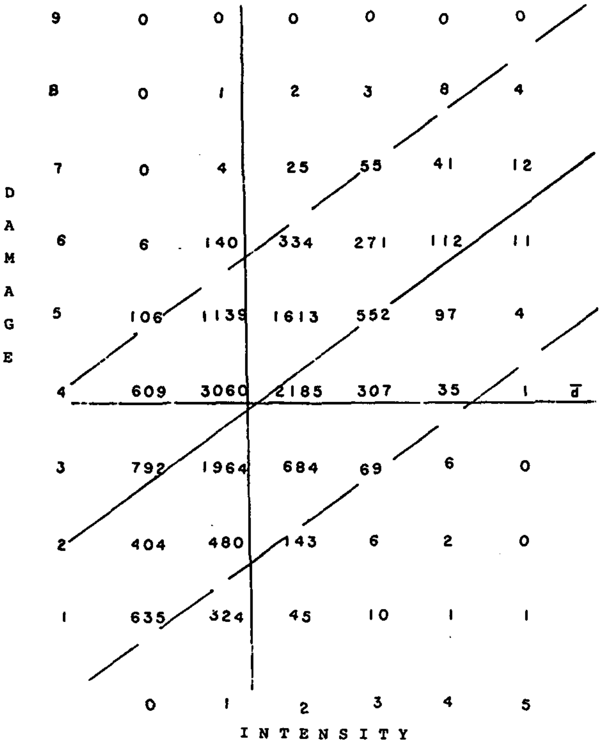


FIG. 1. Distribution of tornadoes by damage and intensity categories. Regression line and standard error of estimate curves.

The geographic coverage of the database was increased by adding ancillary data compiled by the Canadian Climatic Center, (Newark, 1981). These data include information on over 900 tornadoes which occurred across Canada during 1950–79 inclusive. With this additional dataset, statistical computations at or near the northern border of the United States should become more indicative of actual conditions.

3. Statistical properties of United States tornadoes

The NSSFC database contains information on 22 840 tornadoes which occurred between 1 January 1950 and 1 January 1983 over the contiguous United States, Since the latitude/longitude of both ends of a tornado track are recorded, it is relatively simple to restratify the storms by modified Marsden squares affected or any other geographical configuration.

Since the NSSFC database is simply a codification and compilation of data already available in other sources, it was decided not to make any assertions as to value of unrecorded parameters. If a storm's length, mean width and/or intensity could not be ascertained from the original sources, no entries are made for them in the record. This convention allows the individual user to make his own decisions, based upon his requirements, as to what to do with missing data.

In the NSSFC dataset, 8.1% of the tornadoes are missing an intensity estimate. Since length and width observations as well as an intensity categorization are required for risk analysis, 39.4% of the tornado reports are lacking enough information to preclude use. A standard ploy used by risk modelers is to assign a minimum category to any missing data. This assumes that if the tornadoes had been more noteworthy, more would have been reported on it (McDonald and Abbey, 1979).

For the United States, the average tornado has a 7.1-km length (standard deviation of 15.1 km), 117-m width (standard deviation of 193 m) and 1.68-km^2 area (standard deviation of 6.96 km^2). Since these measurements must be positive and since the standard deviations are larger than the mean values, highly skewed distributions exist. Many more small tornadoes than large ones occur. Thus, in many ways, the median tornado is more representative than the average; this "typical" United States tornado is 1.6 km long, 43 m wide and devastates 0.10 km^2.

There is a marked difference between the 0.98 mi median length found here and a previously reported median length of 3.2 km found from 1950–77 data (Schaefer et al., 1980). A possible reason for this can be found by examining the time trend of complete reports contained in the database (Fig. 2). A shape-preserving filter proposed by Tukey (1977) has been applied to show the data trend. It is seen that in recent years the percent of reports which contain length, width and intensity information has increased markedly. Most of this increase has been in the information reported with small tornadoes. This trend is emphasizing small tornadoes. However, whether this is real or simply an illustration of the "if nothing was reported, it must be small" principle cannot be determined.

The weakest intensity category (F0) accounts for 23% of the tornadoes which have a severity estimate. Lengths and widths are known for 52% of the F0 tornadoes. For this weakest class of tornadoes the average length is 1.8 km. The average width is 42 m. The mean area affected by an F0 tornado is 0.16 km^2. The median or typical F0 tornado length is 0.5 km, its width is 16 m, and the median area is 0.03 km^2.

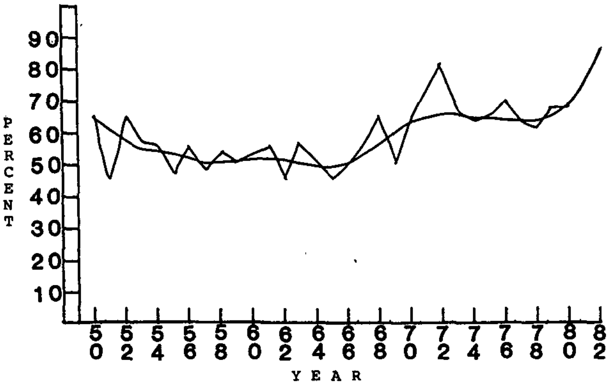


FIG. 2. Percent of reports in the NSSFC database which contain all elements. Solid line is a smoothed fit.

At the other end of the spectrum are the 38 extremely violent F5 tornadoes. These storms, which make up less than 0.2% of the total population, average 55.0 km in length, 563 m in width and devastate 30.76 km^2. Again extreme variability exists. Median values for these extreme events are a length of 37.7 km, a width of 454 m and an area of 24.15 km^2.

The statistical properties of the tornado intensity categories are shown in Table 1. Average category values for length, width and area are shown. Since the categories are discrete rather than continuous, tacit assumptions regarding intracategory distributions are necessary to compute fractional values. The table also contains dimensional value associated with the category average through a logarithmic distribution.

Several elementary principles are illustrated by Table 1 and should be noted: 1) the average area is not equal to the product of the average length times the average width; 2) although an individual measurement can be related to a category, the average category cannot be related directly back to the average value; and 3) highly skewed distributions have average conditions which differ significantly from typical conditions.

4. Interrelationships between geometric track parameters and intensity categories

Surveys of various tornado hazard models (Abbey, 1976; Reinhold and Ellingwood, 1982) show that a correlation between the length and width of the damage area is typically postulated. Many of these models also hypothesize an explicit relationship between damage area and intensity. Since these correlations are the foundation of the models, their statistical relevance should be examined.

The interrelationship between track length and width is of primary importance. This correlation is explicitly used in the modeling work of Thom (1963). It is implicit in other more recent models. The correlation coefficient between length and width is 0.282. Since the product of average length and average width equals average area if there is zero correlation, this low value might be fortuitous.

By considering categorized data, much higher correlations are obtained. The distribution by the length and width category is shown in Fig. 3. The rank correlation of these data is 0.549. By treating these data as continuous, a regression line can be computed and drawn on the figure. The interval within which there is 95% confidence in the predictand width value can be obtained via a Student-t test (Walpole and Myers, 1978). Because of the spread of the confidence interval, very little credence can be given to categorical width values obtained via a regression-from-length category.

A relationship between length and area is needed to

TABLE 1. Characteristics of United States tornadoes

	Intensity (F-Scale)							
	0	1	2	3	4	5	Unknown	Total
Nominal speed (m s^{-1})	<32	33–50	51–70	71–92	93–116	>117	—	—
Number	5212	8466	5559	1388	330	38	1847	22 840
Number with both length and width	2714	5703	3959	1143	288	34	402	14 243
Length								
Mean (km)	1.8	4.2	9.1	19.4	36.1	55.0	4.6	7.1
Standard deviation	4.9	7.8	15.2	25.2	39.3	43.9	8.6	15.1
Median (m)	0.5	1.6	3.5	10.9	22.2	37.7	1.6	1.6
Mean category (P_l)	0.37	1.84	1.40	2.06	2.72	3.12	0.86	1.05
Equivalent length from P_l	0.8	1.3	2.5	5.5	11.6	18.5	1.4	1.7
Standard deviation	0.68	0.90	1.06	1.09	1.00	0.90	0.94	1.08
Mode category	0	0	1	2	3	3, 4 (tie)	0	0
Width								
Mean (m)	42	85	153	265	396	563	92	117
Standard deviation	80	145	209	322	354	290	145	193
Median (m)	16	43	90	164	272	454	43	43
Mean category (P_w)	0.80	1.38	1.94	2.48	2.98	3.35	1.46	1.55
Equivalent width from P_w	13	24	48	88	158	241	27	31
Standard deviation	0.82	0.94	0.98	0.96	0.85	0.64	1.005	1.07
Mode category	1	1	2	3	3	1	1	
Area								
Mean (km^2)	0.16	0.54	1.89	6.42	15.25	30.76	0.67	1.68
Standard deviation	0.78	1.86	5.98	13.51	24.59	26.20	2.77	6.96
Median (m^2)	0.03	0.05	0.34	1.86	6.50	24.15	0.05	0.10
Mean category (P_A)	0.10	0.33	0.73	1.30	1.86	2.38	0.36	0.51
Equivalent area from P_A	0.03	0.05	0.14	0.51	1.87	6.21	0.06	0.09
Standard deviation	0.33	0.56	0.74	0.84	0.72	0.69	0.60	0.730
Mode category	0	0	0	1	2	3	0	0
Category Definition								
Length (km)	<0.5	0.5 < 1.6	1.6 < 5.0	5.0 < 16	16 < 50	>50		
Width (m)	<16	16 < 48	48 < 161	161 < 499	499 < 1609	>1609		
Area (km^2)	<0.03	0.03 < 0.26	0.26 < 2.6	2.6 < 25.9	25.9 ≤ 258.9	>258.9		

apply the DAPPLE hazard analysis methodology (Abbey and Fujita, 1975, 1979; Fujita, 1978). While the 0.689 correlation found here is much higher than the length of width correlation, only 47% of the variance between length and area is explained by a linear relationship. The categorized distribution (Fig. 4) has a rank correlation of 0.814. The 95% confidence interval is about two area-categories (two orders of magnitude in dimensional units) wide.

For completeness, the width-to-area relationship was also examined. The correlation coefficient is 0.717. When categories are considered (Fig. 5), the rank correlation is 0.747 with a confidence interval of slightly greater than two categories.

An area-to-intensity correlation is the principle foundation of hazard models proposed by McDonald (1980) and Reinhold and Ellingwood (1982). Since intensities by definition are categorized, rank correlation is needed. The distribution (Fig. 6) has a Spearman rank correlation of only 0.584. Further, the 95% confidence interval encompasses about three area categories.

An intensity to width correlation is implicit in the application of the DAPPLE technique (Abbey and Fujita, 1979). These parameters have an even more dispersed joint distribution (Fig. 7). The rank correlation coefficient is 0.542. At least a 3.5-width-category band is necessary for 95% confidence in the regression fit.

The rank correlation between length and intensity is even lower (Fig. 8). The coefficient is 0.546 with quite a wide confidence band. It should be noted at this time that if missing data entries were to be arbitrarily categorized into the lowest group, all of these correlations would improve markedly. However, the validity of such a forced relationship is questionable.

5. Hazard assessment

Because of the excessively large confidence intervals for the regression predictands, the statistical hazard as-

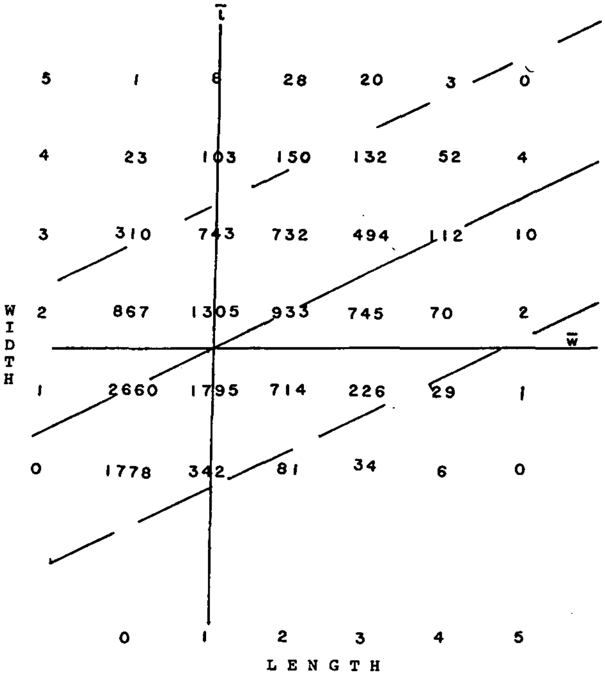


FIG. 3. Distribution of tornadoes by length and width categories; regression line and 95% confidence band indicated.

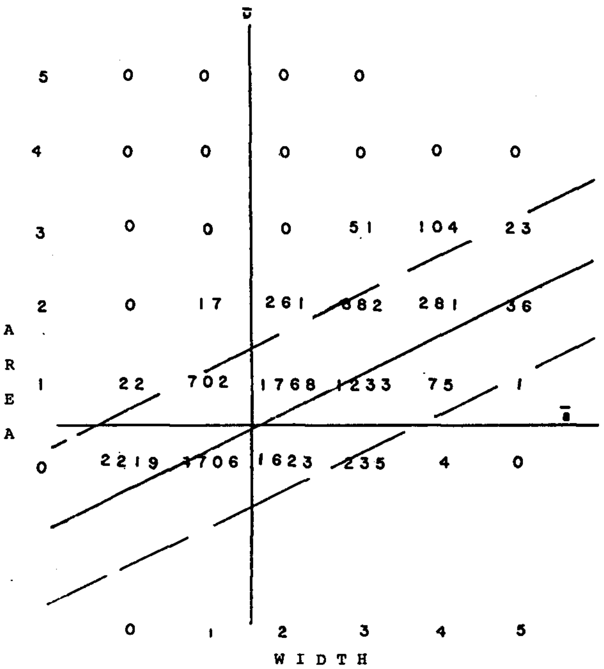


FIG. 5. Distribution of tornadoes by width and area categories; regression line and 95% confidence band indicated.

sessment models are of marginal validity. As an alternate approach, a purely empirical minimum assumption tornado hazard assessment model (MATHAMOD) is developed. In its essence, the probability of a tornado striking a point is the ratio of the annual mean area covered by tornadoes to the area over which tornadoes may occur (Thom, 1963). From this basic definition, various subtle modifications are necessary

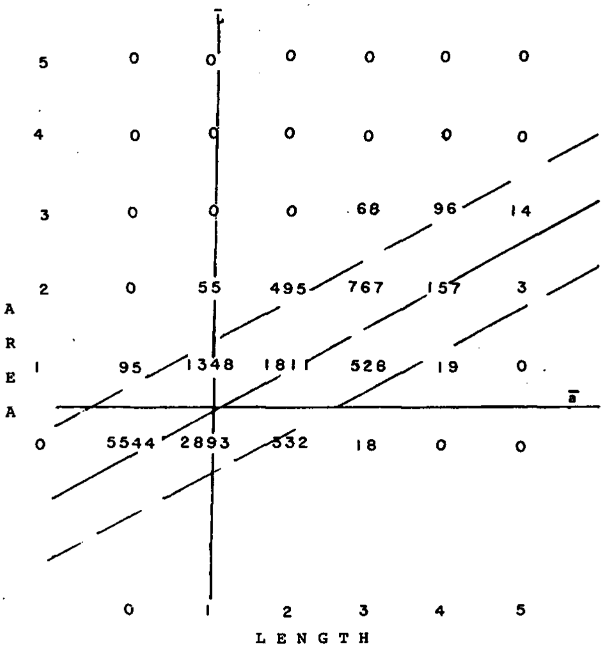


FIG. 4. Distribution of tornadoes by length and area categories; regression line and 95% confidence band indicated.

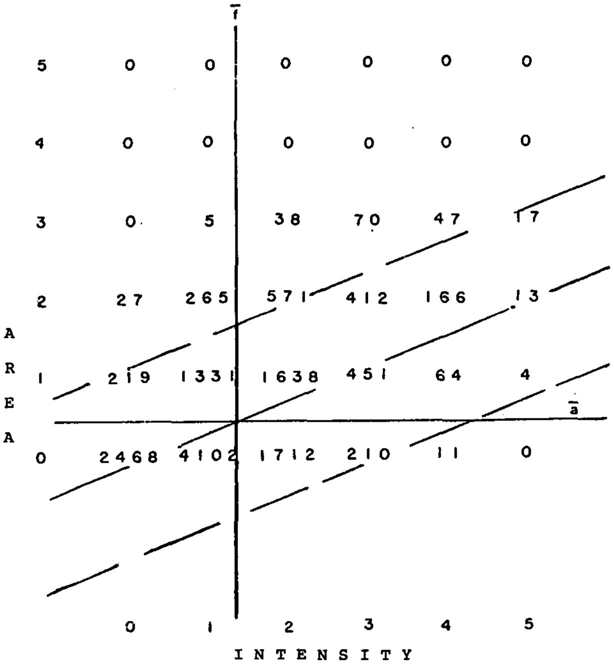
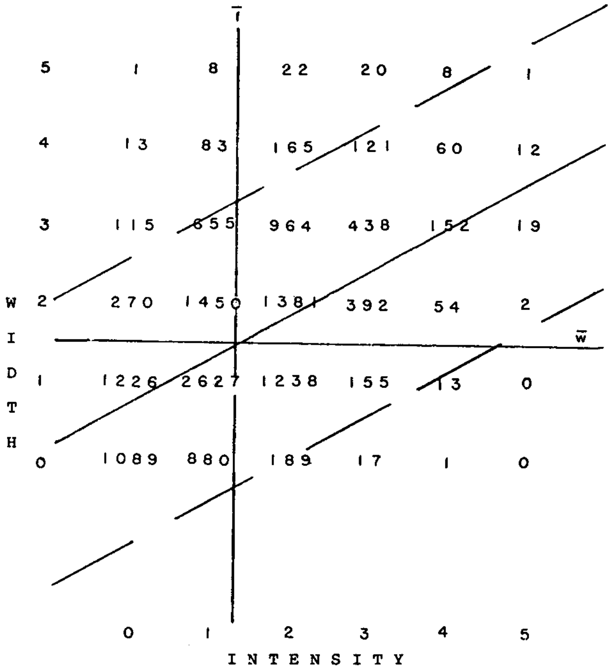


FIG. 6. Distribution of tornadoes by intensity and area categories; regression line and 95% confidence band indicated.



	0	1	2	3	4	5
5	1	8	22	20	8	1
4	13	83	165	121	60	12
3	115	655	964	438	152	19
2	270	1450	1381	392	54	2
1	1226	2627	1238	155	13	0
0	1089	880	189	17	1	0

FIG. 7. Distribution of tornadoes by intensity and width categories; regression line and 95% confidence band indicated.

for the generation of useful products. Since tornado climatology is dependent upon topography, orography, geography and meteorology, the mean area covered by tornadoes must be considered as a regional parameter.

Many engineering applications require data on tornadic wind speed rather than intensity. The intensity categories (F-scale) have been related to typical wind speeds (Fujita, 1977). While this is not an exact scientific procedure (Minor et al., 1977), it represents only an "educated guess" as to the velocities needed to produce the observed damage. It must be noted that since the damage is categorized, wind speeds associated with damage at category break points are the only ones that can be specified. A continuous speed distribution cannot be obtained without further assumptions.

The hazard probability is obtained by simply summing the damage area (length times width) of each tornado of intensity greater than the desired threshold which was reported within a localized quasi-homogeneous region. This tornado-affected area is then divided by the size of the region and the duration of the database. If the probability of a tornado with maximum wind speed (v) exceeding a critical value (v_0) is needed, only tornadoes in damage categories (F) associated with winds greater than v_0 are considered. The annual probability, P, is given as

$$P = (\sum_{i=1}^{n} l_i w_i)/AY$$

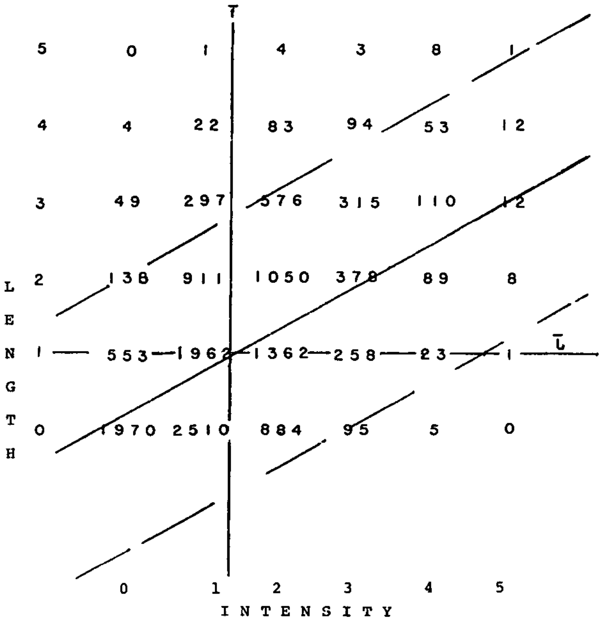
where A is the regional area, Y is the number of years data available, l_i is the length of tornado "i", w_i is its width, and n is the number of tornadoes in area A.

In the NSSFC database, tornadoes are located by the coordinate of significant points along their paths. For computational purposes, the tornado damage area is assigned to the latitude/longitude of the touchdown point. Effectively, this assumes that tornado damage is uniformly distributed across the region of interest (A). Also, the damaged area within A attributable to storms which form outside of A is tacitly postulated to be equal to the damaged area outside of A attributable to storms which form within A. This simplifies the computations since the entire damage area can be assigned to the region of storm touchdown.

A second implicit assumption in applying this technique on the NSSFC database is that tornado reports which do not include explicit length and width measurements have zero area. This is not as drastic as it first sounds. Since 50% of tornadoes have an area of 0.10 km^2 or less, typically about 25 incomplete reports within the region of interest are needed before the summed area is off by 2.59 km^2.

The minimum assumption model has been applied across the coterminous United States to determine areas of high hazard probability. For these calculations, the regional areas are assumed to be 2° "Marsden" squares. The squares are overlapped so that values are available at every 1° latitude/longitude. This technique provides a light smoothing to the data and suppresses small-scale fluctuations (Kelly et al., 1978).

The all-tornado hazard map (Fig. 9) has a rather surprising pattern. The high annual probability zone



	0	1	2	3	4	5
5	0	1	4	3	8	1
4	4	22	83	94	53	12
3	49	297	576	315	110	12
2	138	911	1050	378	89	8
1	553	1962	1362	258	23	1
0	1970	2510	884	95	5	0

FIG. 8. Distribution of tornadoes by intensity and length categories; regression line and 95% confidence band indicated.

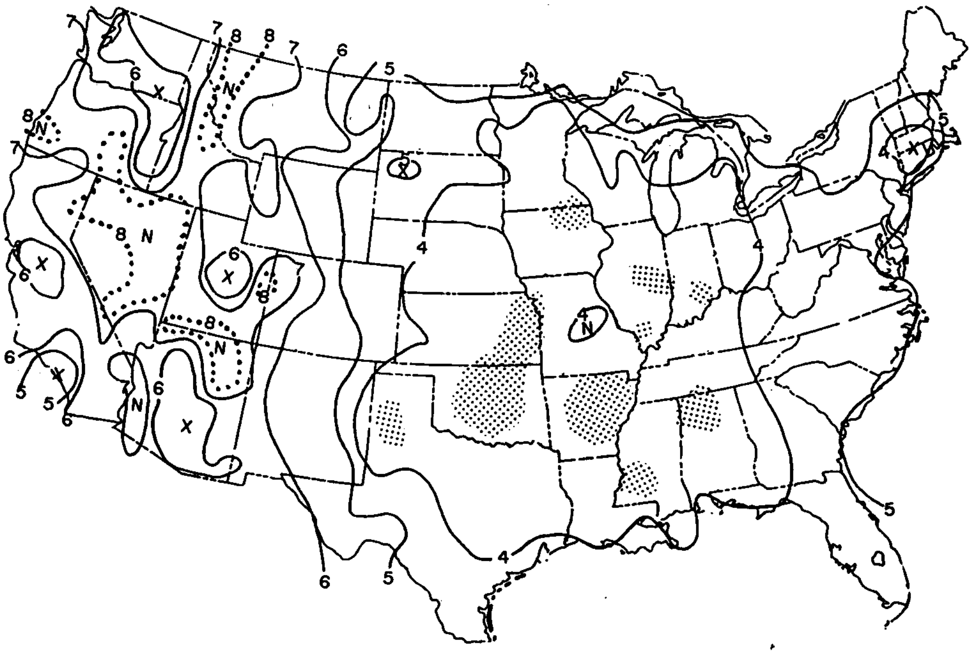


FIG. 9. Probable annual tornado from any tornadoes. Contours are labeled in negative powers of 10 per year (i.e., 4 indicates 10^{-4}). Maxima denoted by "X", minima by "N". Stippled area has hazard greater than $4 \cdot 10^{-3}$ per year. Dotted line indicates 10^{-8} or less.

does not correspond to tornado alley. Rather than a single longitudinal zone, a "V" shaped pattern is evident. The highest probability, 6.1×10^{-4}, occurs in central Oklahoma, but a secondary maximum of 5.8×10^{-4} is found in central Arkansas. The Arkansas high hazard probability zone agrees with a high tornado incidence region that was frequently noted during the early part of the century (e.g., Day, 1930; Kendrew, 1937; Ward and Brooks, 1936). Such early data compilations typically only included large, destructive tornadoes (Galway, 1977). Thus, moderate size tornadoes had a much higher chance of being reported than small ones. These moderate-sized storms have a greater effect on the point hazard potential than the more frequent small ones.

A Missouri minimum in the Ozarks region is also noted. This agrees with many studies (e.g., Jamison, 1978). A small isolated high-hazard probability area is found in southern New England; this area is highlighted in many climatologies (e.g., Court, 1970). A minimum is found in the mountains of West Virginia. In the west a maximum is found in the Los Angeles area, and again this agrees with other studies (e.g., Hales, 1983).

F1 or greater tornado hazard, nominally indicating speeds less than 32 m s^{-1}, is shown in Fig. 10. Changes from the all tornado data are minimal.

When weak tornadoes are excluded, F2 or greater storms remain. These are associated with winds of over 50 m s^{-1}. At this level the hazard pattern starts to become apparent (Fig. 11). The West Virginia minimum has almost disappeared.

When the cutoff velocity is raised to 71 m s^{-1} (F3), the pattern becomes quite disjointed (Fig. 12). The high probability areas in Arkansas and California no longer exist, the definite minima have developed in the High Plains.

The hazard of violent tornadoes is depicted in Fig. 13. Here F4 and F5 storms, those with winds greater than 93 m s^{-1}, are shown. Definite pockets of increased hazard are now present. The Arkansas feature has disappeared.

At the F5 level (Fig. 14) the disjointed pattern is highly amplified. High-hazard probability areas are obvious. Central Oklahoma is still the most dangerous locale, but the northern Mississippi–Alabama border region runs a close second.

Because of the extremely low probabilities, and the limited time period considered, caution should be exercised when trying to give a literal meaning to probabilistic statements (Simiu and Scanlan, 1978) on tornado hazard. For instance, the exclusion of preperiod storms (e.g., Tri-State tornado of 1925; Mattoon tornado of 1917) and postperiod storms (e.g., Carolina outbreak of 1984; U.S.–Canada outbreak of 1985) can impact the statistics when annual probabilities of 10^{-7} are considered. However, the charts do give a fair representation of the relative tornado hazard across the country.

6. Possible user alterations

Statistically based tornado hazard models often contain factors to "correct" the input data. One com-

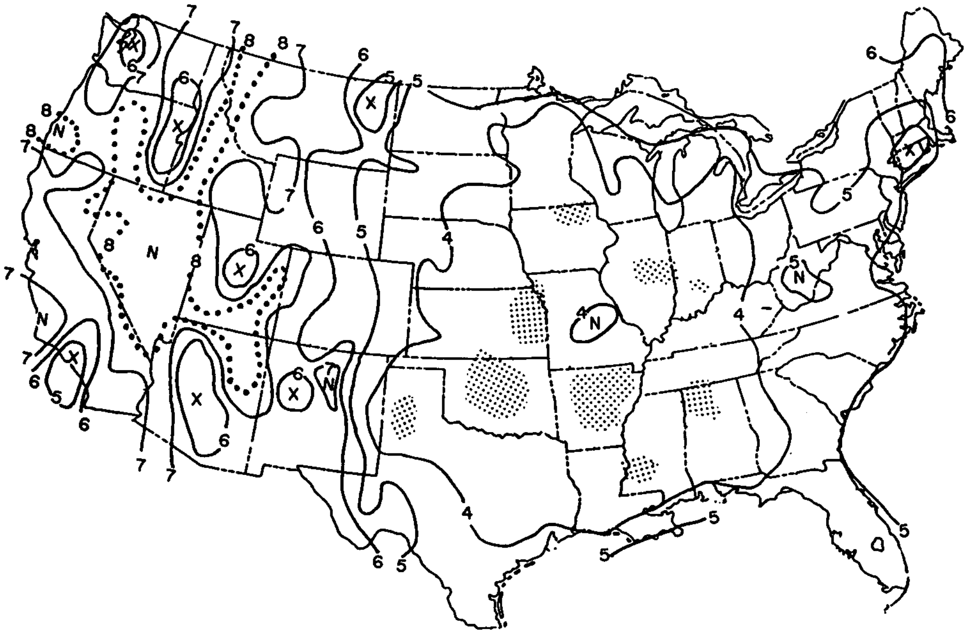


FIG. 10. Probable annual tornado hazard from F1 or greater tornadoes—labels similar to Figure 9.

mon modification of the observations attempts to account for the observed variation of a tornado's intensity within its track. In hazard modeling the areas and lengths used represent the dimensions of the entire damage track, while the intensity is indicative of the strongest part of the storm. Typically, the area associated with the high intensity scale is only a small fraction of the total tornado area. An F4 tornado contains zones of F1, F2 and F3 damage. While this is obvious, specification of the actual percentages is quite difficult. A common approach is to assume the existence of a constant matrix giving the proportion of the total area

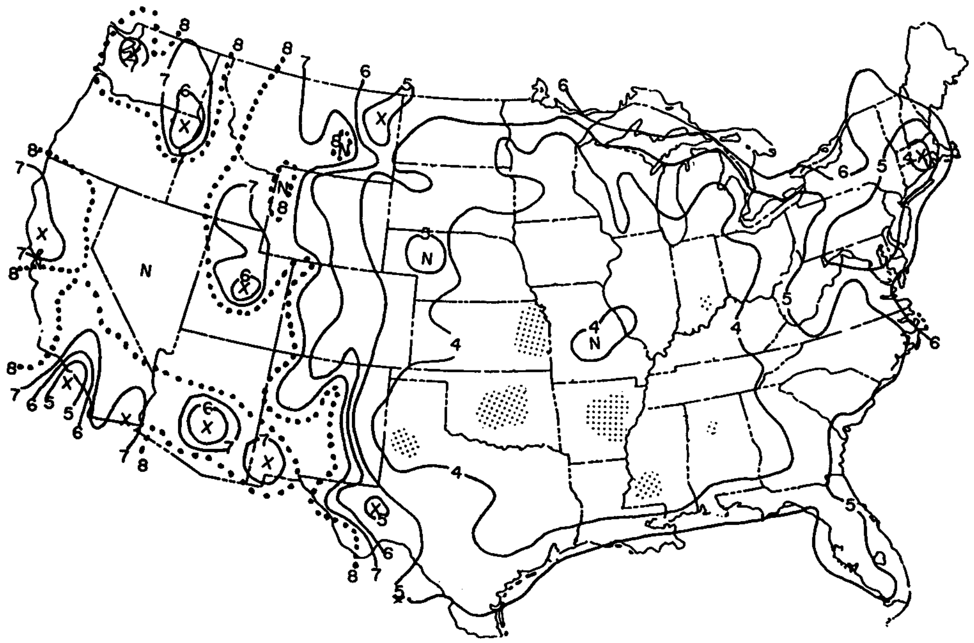


FIG. 11. Probable annual tornado hazard from F2 or greater tornadoes—labels similar to Figure 9.

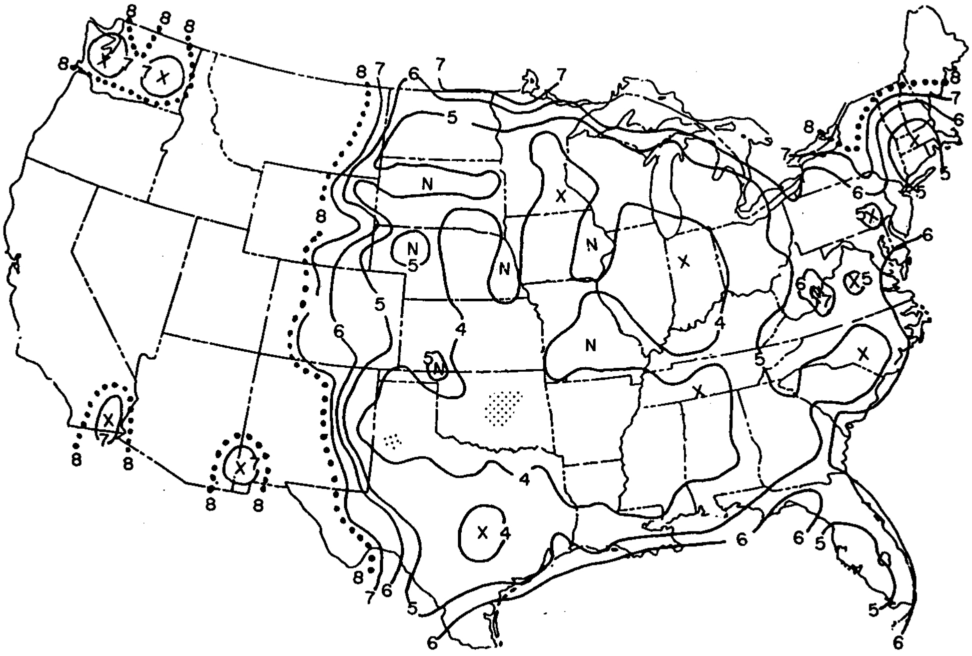


FIG. 12. Probable annual tornado hazard from F3 or greater tornadoes—labels similar to Figure 9 (note 10^{-7} contour has been omitted).

(length or width), which is affected by various intensity winds, as a function of the maximum intensity of the tornado (e.g., Reinhold and Ellingwood, 1982). This matrix is either determined from theoretical models (e.g., Wen, 1975), detailed surveys of selected tornado tracks (Abbey and Fujita, 1975), or a combination of both.

Regardless of how this matrix is obtained, the relationship is assumed to be invariant. All tornadoes are assumed to exhibit common intensity distributions. A

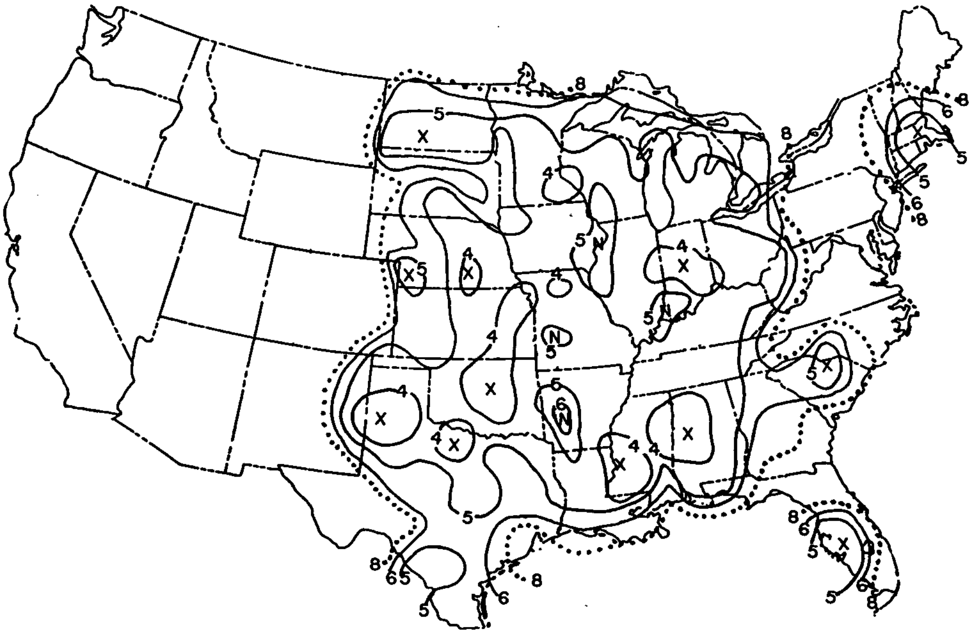


FIG. 13. Probable annual tornado hazard from F4 and F5 tornadoes—labels similar to Figure 9 (note 10^{-7} contour has been omitted).

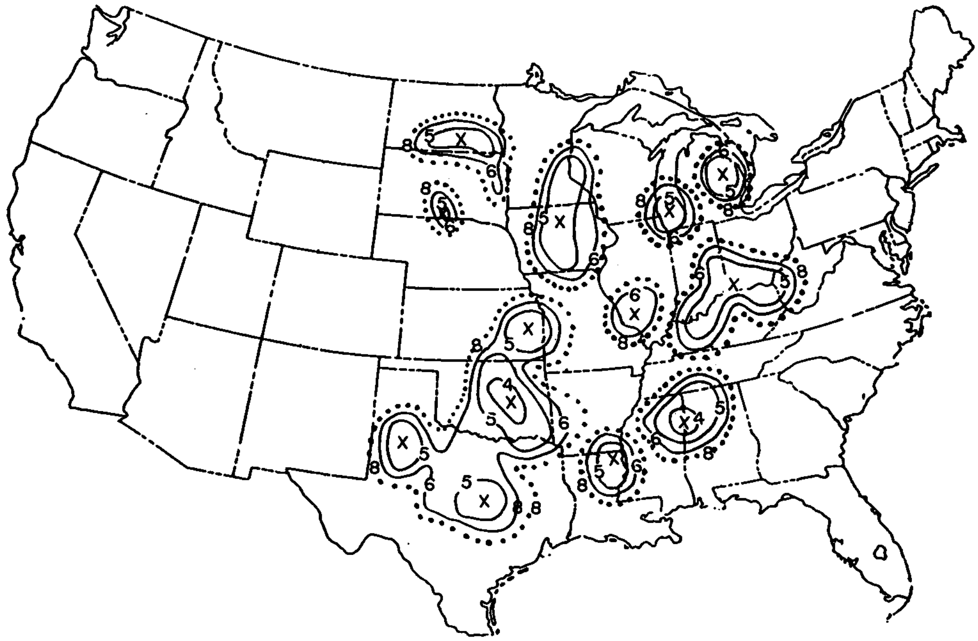


FIG. 14. Probable annual tornado hazard from F5 tornadoes—labels similar to Figure 9 (note 10^{-7} contour has been omitted).

summary of the variation of intensity along the length of tornadoes from five surveyed tornado outbreak cases (150 total tornadoes) compiled by Research Triangle Institute (1981) is given in Table 2. For example, it shows that on April 3–4, 1974, there were six F5 tornadoes having a total path length of 485.9 km. Of this

TABLE 2. Pathlength–intensity variation data.

Rated tornado intensity	Tornado group	No. tornadoes	Path lengths (km) Total	F0	F1	F2	F3	F4	F5
F1	3–4 April 1974	31	474.6	271.9	202.7				
	Red River Valley	1	11.2	6.1	5.1				
	Grand Gulf	2	23.5	14.3	9.2				
	Totals	34	509.3	292.3	217.0				
F2	3–4 April 1974	30	580.0	132.7	197.9	249.4			
	Red River Valley	5	290.9	69.2	70.8	33.8			
	Grand Gulf	2	21.7	10.6	5.3	5.8			
	Bossier City	3	62.9	22.7	21.1	19.1			
	Totals	40	855.5	235.2	295.1	308.1			
F3	3–4 April 1974	35	1142.4	104.6	275.1	362.0	400.6		
	Red River Valley	2	49.9	25.4	10.9	9.0	4.5		
	Grand Gulf	2	51.1	5.5	17.0	25.6	3.1		
	Bossier City	1	15.3	3.9	5.6	4.8	1.0		
	Cabot, Ark.	1	24.1	10.4	4.8	6.8	2.1		
	Totals	41	1282.8	149.8	313.4	408.2	411.3		
F4	3–4 April 1974	24	1380.5	186.6	213.4	368.4	292.8	318.6	
	Red River Valley	2	138.4	22.5	25.7	57.1	20.9	12.1	
	Grand Gulf	2	41.8	10.9	8.2	7.9	13.6	1.1	
	Bossier City	1	10.9	3.2	0	3.2	2.6	1.9	
	Totals	29	1571.6	223.2	247.3	436.2	329.9	333.7	
F5	3–4 April 1974	6	485.9	64.4	49.9	91.7	117.5	90.1	72.4
F1–F5	Totals	150	4705.1	964.9	1122.7	1244.2	858.7	423.8	72.4

mileage, only 15% exhibited F5 damage while 24% experienced F3 intensity.

A chi-square contingency table test (Davis and Goldsmith, 1972; Croxton et al., 1967) can be used on these data to show whether it is reasonable to assume that the tornadoes of a certain intensity in one outbreak statistically resemble the tornadoes of the same intensity in another outbreak. In other words, Do all the tornadoes in an F-category come from the same population as far as a long-track intensity variation is concerned?

After examining all possible combinations, it can be concluded that with the exception of F1 tornadoes, no homogeneity of pathlength intensity variation within an intensity category could be found at the 1% level. There is less than a 1% probability that the cases studied belong to the same population. The concept of an invariant DAPPLE ratio is not supported by the data.

Other alterations are used in attempts to account for the presence of large bodies of water within the regional area, unreported tornadoes, intensity classification errors, etc. (Tecson et al., 1983; Twisdale, 1982). Such corrections are often quite reasonable. For example, examination of Fig. 9 through Fig. 14 shows the desirability of a land area correction along the Great Lakes, Atlantic and Gulf of Mexico coasts. This would be accomplished by multiplying the MATHAMOD value in each square by the ratio of total area of the region to the land area within the region. It is noted that such a correction along the Pacific Coast raises the probability at Los Angeles by 60%, increasing the hazard there to values compatible to those typical of the Dakotas. Perhaps a similar type modification of the data should also be considered along the Mexican border. Further, even though Canadian data have been added, 80% of the reports from there are incomplete, giving low probabilities along the northern United States border. "Corrections" could be applied there.

Essentially, all the alterations, including the within-storm intensity variation, can be formulated as a multiplicative factor that operates on the observed data. From the defining formula of MATHAMOD, it is seen that such a procedure can easily be applied. Such corrections for the unknown have a place, but they should only be used with the full knowledge of a user who is aware of the sensitivity of his problem.

The purpose of our analysis and this paper is to suggest basic principles to guide operational decisions. "We would emphasize the essential and general; leave scope for the individual and accidental; but remove everything arbitrary, unsubstantiated, trivial, far-fetched or supersubtle. If we have accomplished that, we regard our task as fulfilled (Clausewitz, 1976)."

Acknowledgments. This study was performed under Interagency Agreement RES-76-106 between the Office of Nuclear Regulatory Research, Nuclear Regulatory Commission and the National Severe Storms Forecast Center, National Weather Service, NOAA. The National Weather Service Office of Meteorology paid for publication of this manuscript. Lagniappes to Beverly Lambert for her usual expert typing of the manuscript, and Dr. Preston Leftwich for assistance in making this work readable.

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