An Augmented Tornado Climatology

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ABSTRACT

Careful screening of the National Severe Storms Forecast Center's tornado log eliminated almost 20% of the reports as doubtful, leaving 17 659 tornadoes during 27 years, 1950–76 (654 annually). Newspaper accounts and other local information provided intensities (Fujita scale) for all but 2346 tornadoes and path lengths for all but 2011 tornadoes. There were 14 409 tornadoes for which both intensity and path length estimates were made. Of these, 61.7% were weak (<112 mph), 36% strong (113–206 mph), and only 2.3% violent (207–318 mph). However, the 340 violent tornadoes caused 68% of the 3070 fatalities attributed to tornadoes for which force estimates could be made (113.7 annually). Most violent tornadoes came in swarms except in southeastern United States, where no day had more than one. Some 61% of the violent tornadoes had intermediate paths (3.2–31 mi), while 73% of weak and strong tornadoes had short paths. Violent tornadoes occurred at all times of day and night, while weak and strong tornadoes showed diurnal trends. May and June accounted for 40.8% of all tornadoes. Other aspects of tornado climatology are shown in tables, diagrams and maps of average annual incidence normalized to 10 000 mi^2 area per year.

1. Introduction

One major problem facing the tornado climatologist is the presence of significant biases in the historical record (Asp, 1963; Court, 1970; Galway, 1977). In an effort to mitigate the problem, the National Severe Storms Forecast Center (NSSFC) has maintained an operational log of severe local storm occurrences within the contiguous United States since late 1954 (Pautz, 1969). This data base has been extended back in time to 1950 by use of *Climatological Data* (a monthly summary of weather activity published by the Environmental Data Service). The operational log has been meticulously screened against the climatological record to eliminate fallacious reports. This "filtered" log comprises the NSSFC tornado history. For comparative purposes, only about 80% of the tornadoes reported by Pautz have been retained in the current record. In 1976, NSSFC in conjunction with the Nuclear Regulatory Commission (NRC) embarked on a project to cross reference the 17 659 reported tornadoes between 1950 and 1976 inclusive. The goal of this project is to obtain as complete and consistent a tornado set as possible for the contiguous United States; in this paper, the 24 states most susceptible to severe local storms have been examined.

Local research associates were employed in each state. They were supplied with a copy of the NSSFC tornado history and commissioned to pursue all newspaper accounts of the reported storms. From the information thus gleaned, the significant characteristics of each event were recorded. Among the information obtained were estimates of the FPP indices (Fujita and Pearson, 1973) defined in Table 1, time of occurrence, deaths, injuries and path description. Although very few tornadoes were added to or deleted from the data base, the amount of ancillary data has been greatly enhanced. It must be noted that even with this cross referencing of tornadoes, classification of the characteristics for each and every tornado was not possible (Table 2). These data have been melded with the original tornado history. This paper presents some statistical analyses which can be derived from this augmented data set and offers tentative explanations for the results. A copy of the data set is available on request from the National Severe Storms Forecast Center.

2. Tornadoes in normalized solar time

In order to assess the hourly occurrence of tornadoes as a function of diurnal temperature change, the time of tornado touchdown in the NSSFC data set has been converted to local mean solar time (LMT). This time is a function of longitude, such that local noon occurs when the sun crosses the local meridian.

Local mean time, in combination with the times of local sunrise and sunset times, are used to normalize the day. This transformation divides the daylight period (sunrise to sunset) into 12 equal duration increments. Similarly, the night (sunset to sunrise) is divided into 12 periods. For convenience, this transformed time is defined as normalized solar time (NST). Note that an "hour" during the day is not necessarily equal to one at night. Further, the length of an hour depends on the latitude and the day of the year. This transformation is employed so that any relationship between the diurnal cycle and tornado occurrence can be examined. For example, a tornado which occurred exactly at sunrise is indicated as having occurred at 0600 NST, irrespective of its location or date. It is only through such a normalization that the diurnal characteristics of tornadoes can be examined without the complexities of variable sunrise–sunset times contaminating the averaging process.

The annual average NST distribution of reported touchdown time for every tornado during the 27-year period is shown in Fig. 1. In order to compensate partially for time inaccuracies, the data have been categorized into one "hour" increments. In the mean, peak occurrence is during the late afternoon, while minimum occurrence is just prior to sunrise. This closely follows the diurnal temperature curve. Thus, most tornadoes occur at that time of day when thermal instability is usually the greatest.

Bimonthly curves of annual average NST tornado distribution are given in Fig. 2. Owing to the large variation in the number of reports between bimonthly periods, the curves are plotted in a semi-logarithmic form to emphasize details (Bagnold, 1941). While the cold season curves (Fig. 2a plot B and Fig. 2c plot F) are not as markedly unimodal as the others, the afternoon maximum and late night minimum are found for all periods. However, there is a shift in the phase with season. During the winter, the maximum is found around sunset, while during summer it shifts to midafternoon. This may be due to the effect of shorter winter days with less incident solar radiation persisting for a shorter time than during the Northern Hemisphere summer. The July–August peak at 1530 NST approximates a local standard time (LST) of 1630–1700. The winter peak at sunset also corresponds to about 1700 LST. The significance of the peak tornado frequency occurring around 1700, the typical quitting time for the work-a-day world, is examined more carefully in the next section.

TABLE 1. Ranges of wind speed, path length and path width corresponding to F, PL and PW.

Scale	F (mph)	PL (mi)	PW (yards)
0	<72	<1.0	<17
1	73–112	1.0–3.1	18–55
2	113–157	3.2–9.9	56–175
3	158–206	10–31	176–556
4	207–260	32–99	0.34–0.9*
5	261–318	100–315	1.0–3.1*
6	319–380	316–999	3.2–9.9*

* Miles.

TABLE 2. Number of tornadoes in NSSFC data base by availability of intensity and path length estimates.

Availability	P Available	No P	Total
F available	14 409	904	15 313
No F	1 239	1 107	2 346
Total	15 648	2 011	17 659

3. Diurnal tornado intensity

If an observing bias exists, such as the one suggested above, it could be expected that weaker, less destructive tornadoes would be reported more frequently when the number of potential observers is greatest. If no one actually sees the characteristic funnel cloud, F0 and F1 damage is likely to be attributed to straight line winds or downbursts. On the other hand, the damage associated with more devastating storms probably has a greater likelihood of being classified as tornado-related even if there are no visual observations of a funnel. Thus, a 1700 LST reporting bias would be identifiable as a proportionate increase in the number of weak tornadoes reported.

Intensity data (F-scale) were available for 15 313 tornadoes (87% of entire sample). These data have been divided into three categories: weak (F-0 and F-1), strong (F-2 and F-3), and violent (F-4 and F-5). The percentage of tornadoes in each category as a function of NST is given in Fig. 3. Since no bias in the late afternoon is apparent, it may be concluded that increased commuter traffic does not increase the number of tornadoes reported.

However, a definite diurnal trend is present in the distribution of both weak and strong tornadoes. The

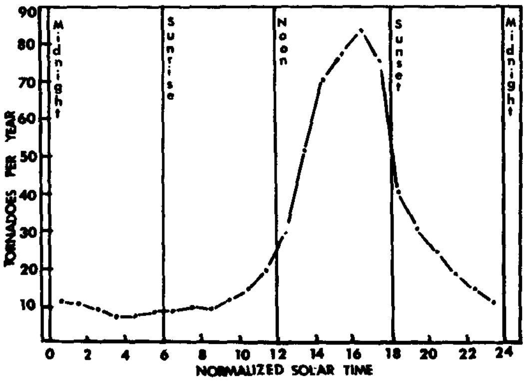
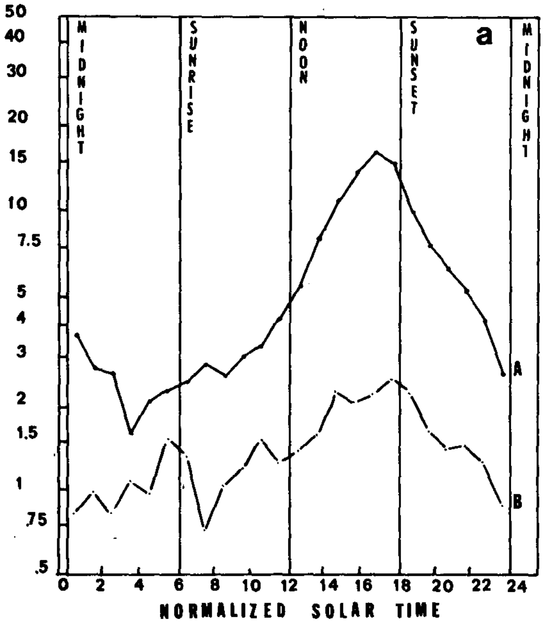
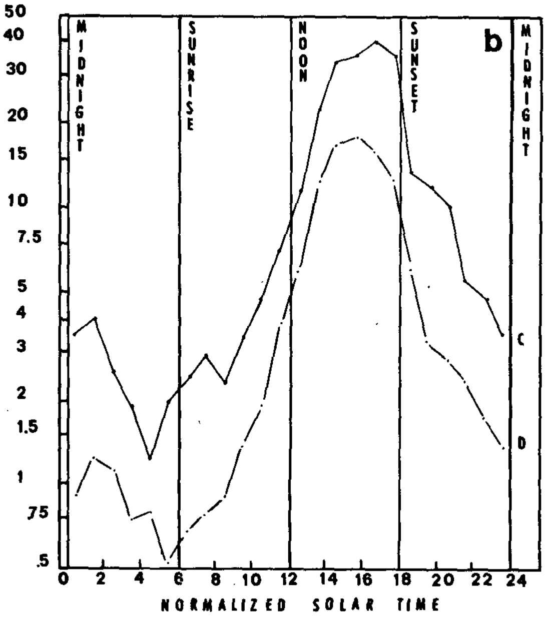


FIG. 1. Average annual diurnal (NST) distribution of tornadoes (1950–76).

proportion of observed tornadoes that are weak maximizes at midday. During the early morning hours before sunrise, the frequency of strong tornadoes is approximately the same as that of weak ones. However, at midday the number of weak tornadoes is greater than that of strong ones. Thus, it may be inferred that the number of weak tornadoes observed is a function of the amount of sunlight present. It is also quite probable that the total number of tornadoes recorded between sunset and sunrise is an underestimate of the actual number of occurrences.





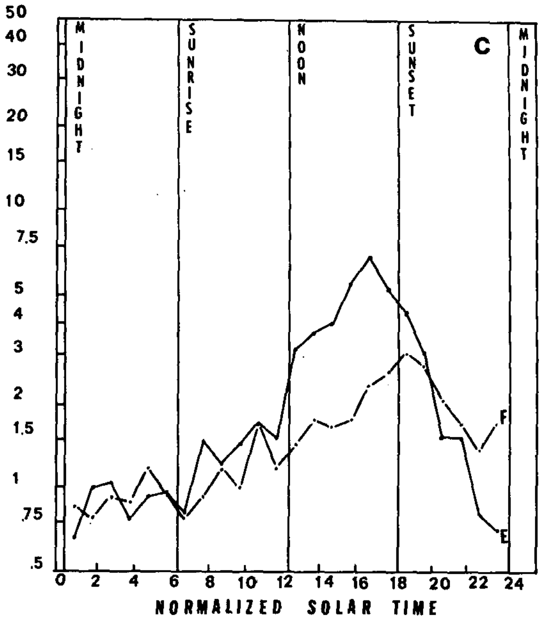


FIG. 2. Average annual diurnal distribution of tornadoes by bimonthly periods January and February, March and April (a), May and June, July and August (b) and September and October, November and December (c).

4. Seasonal and geographical variations of tornado intensity

The bimonthly distribution of tornadoes for which intensities could be assigned is shown in Fig. 4a. In agreement with previous tornado climatologies (e.g., Loomis, 1842), the highest tornado frequency occurs during the four-month period March–June. Almost 65% of the reported tornadoes occurred during this time; over 40% of the tornadoes are found during May and June.

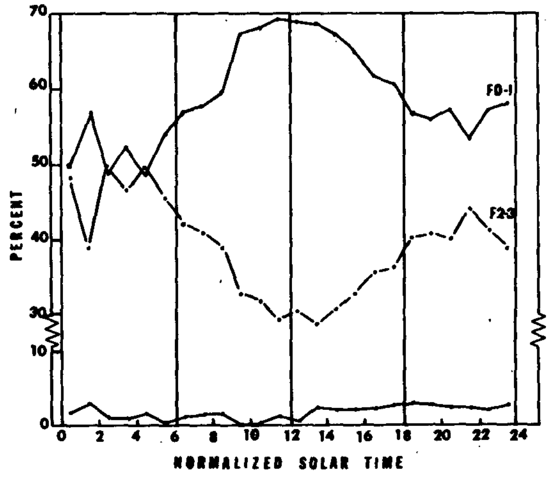


FIG. 3. Percentage of hourly distribution of tornadoes attributable to each F category.

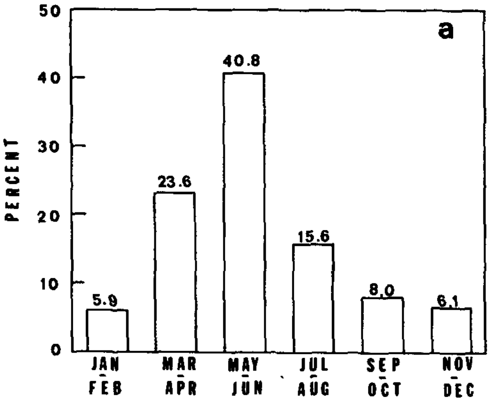


FIG. 4a. Bimonthly tornado distribution.

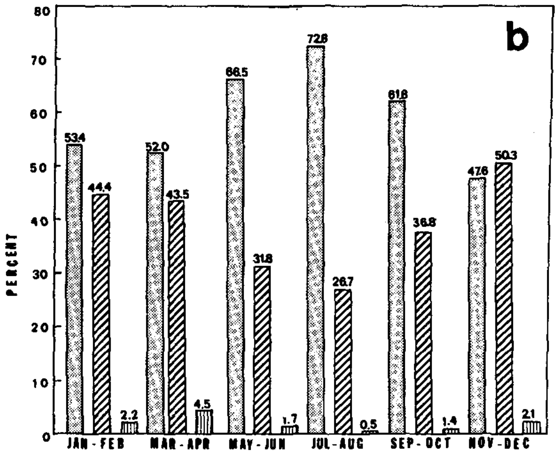


FIG. 4b. F-category breakdown within each bimonthly period (expressed as a percentage of corresponding bimonthly period): weak, stippled; strong, cross hatching; violent, vertical hatching.

The percentage of tornadoes within the three intensity categories for each two-month period is depicted in Fig. 4b. The intensity distribution has a substantial seasonal variation. The percentage of weak tornadoes increases steadily from March to August, while the percentage of strong tornadoes shows a steady decline. The percentages shown in Fig. 4b are for classes of tornadoes occurring during the two-month period. Thus, for example, if 66.5% of the May–June tornadoes are classified as weak, this represents 66.5 ×40.8%=27.1% of all tornadoes for the year.

The absolute number of violent tornadoes varies seasonally in the same way as does the total number of tornadoes. The percentage of violent tornadoes during a given month is relatively constant throughout the year, varying between 0.5 and 4.5% of the monthly total.

Geographical distributions have been constructed by tabulating the number of tornadoes in 2° latitude-longitude "squares." The totals were then normalized by area and by year. Such values are computed at 1° latitude and longitude increments east of 107°W. This process is similar in concept to the smoothing used by Skaggs (1969) with equal area data. The 2°

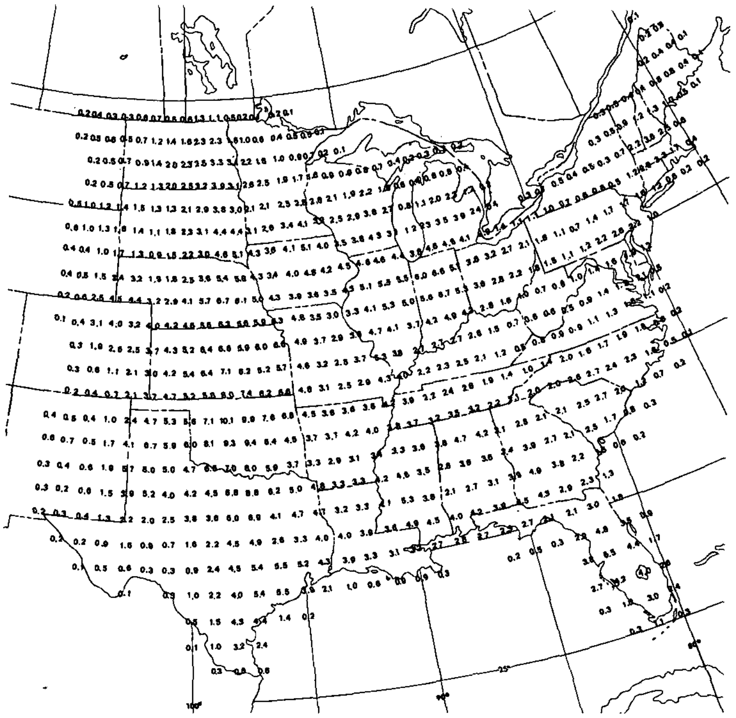
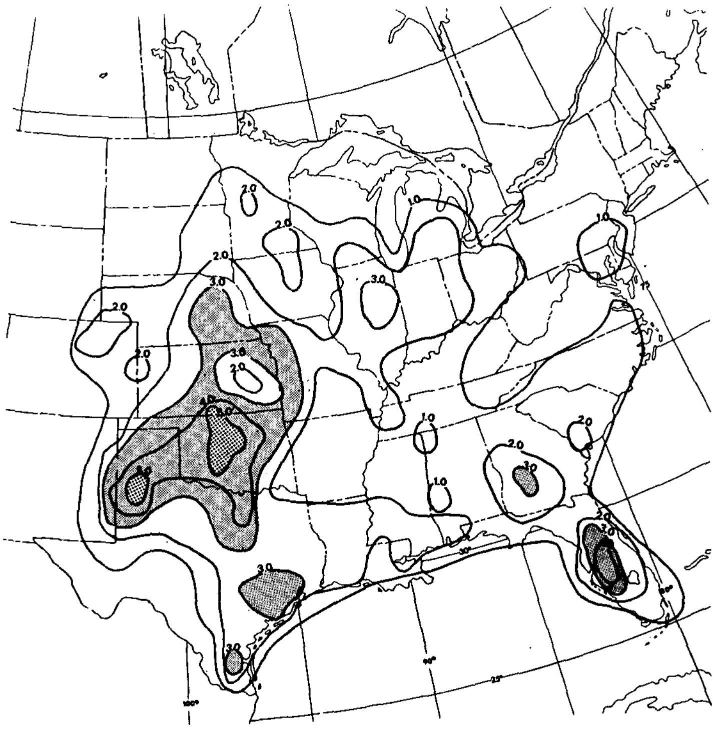
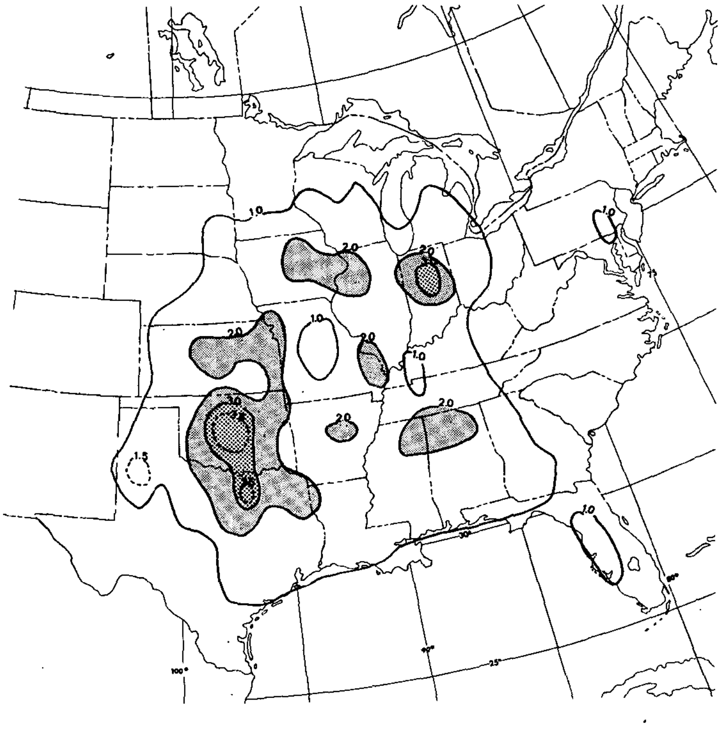


FIG. 5. Frequency of all tornadoes per 2° overlapping square normalized to 10 000 mi² area per year (1950–76).

overlapping squares presentation is equivalent (ignoring modest error caused by varying areas between adjacent 1° squares) to smoothing 1° square data with a running box-car average. Thom's (1963) climatology, on the other hand, was based on a Hann running average applied directly to 1° data. The Hann



(a)



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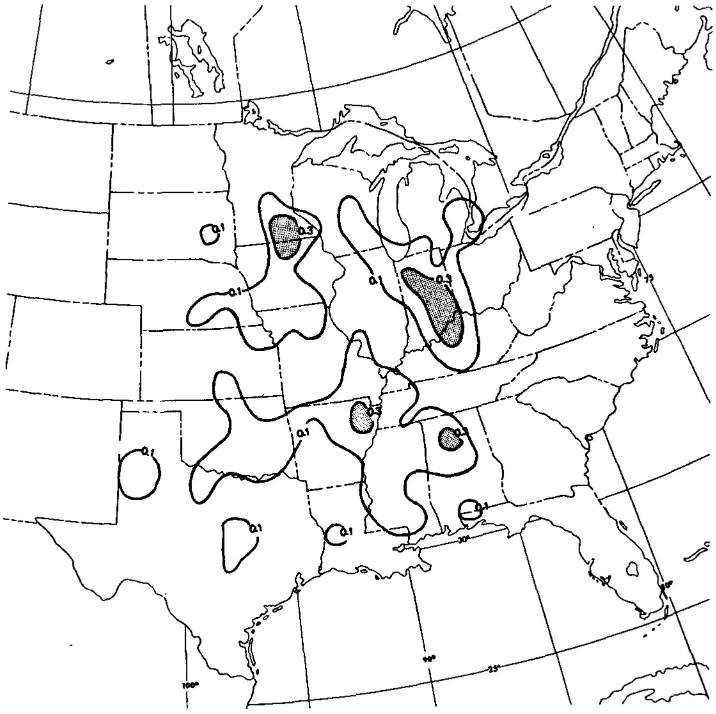


(c)

FIG. 6. Frequency per 2° overlapping square for (a) weak, (b) strong and (c) violent tornadoes normalized to 10 000 mi^2 area per year (1950–76).

average smooths more than the box-car technique; but the box-car average suffers from a slightly increased phase shift for small-scale variations in the data (Blackman and Tukey, 1958).

The map comprising Fig. 5 shows the computed annual tornado frequency. Actual numbers, rather than isotorns (defined by Brown and Roberts, 1937), are presented on the figure. The apparent axis of most frequent tornadic activity, "tornado alley," runs approximately between the 97 and 98°W meridians. This axis shows up well in most previous climatologies (e.g., Thom, 1963). A secondary axis curves from southwest to northeast starting over the Caprock escarpment of west Texas, passing through northwest Missouri, and ending in north central Indiana. Pautz's (1969) analysis indicated a similar axis.

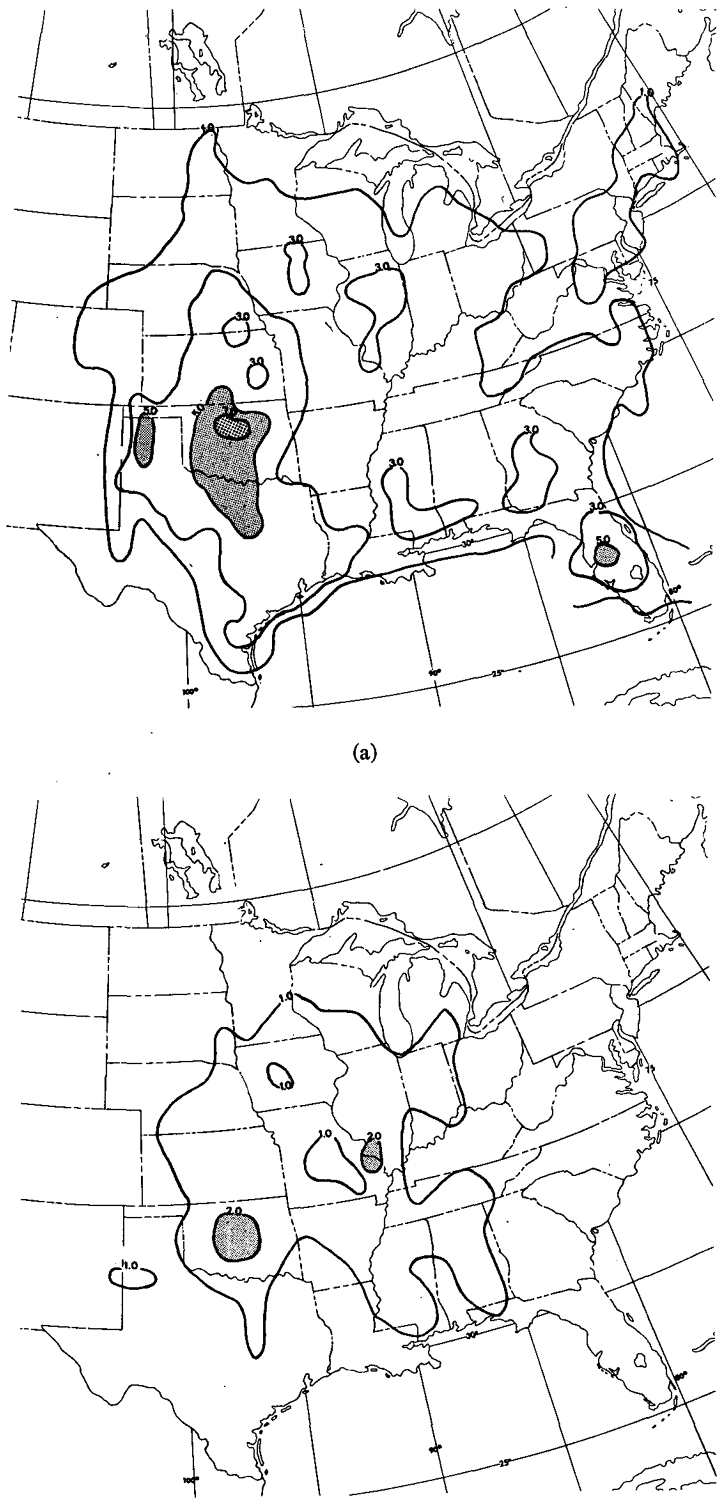
Small pockets of increased tornado activity also occur along the Gulf Coast; a rather pronounced zone of minimum frequency occurs over the Ozark Plateau. Previous climatologies hinted at the existence of these features, but they were much less pronounced.

The frequency map of weak tornadoes (Fig. 6a) generally shows only subtle variations from that for all tornadoes. Again the aforementioned two axes of maximum activity are apparent. However, a pronounced relative minimum is present of the Flint Hills region of eastern Kansas. This minimum may be a result of a terrain effect over moderately sized rolling hills, or may be a reflection of the decreased population density of this area compared with the surrounding areas (U.S. Department of Commerce, 1972). Another area of enhanced weak tornado activity occurs in west central Florida.

Strong tornadoes (Fig. 6b) occur most frequently in the region stretching from 83–103°W and 29–45°N. A small region of increased frequency is also present over the Florida Peninsula. Within this broad area, several local maxima exist. One prominent area lies in a portion of tornado alley from Dallas, TX, to Enid, OK. A second prominent maximum occurs in the Indianapolis, IN, vicinity.

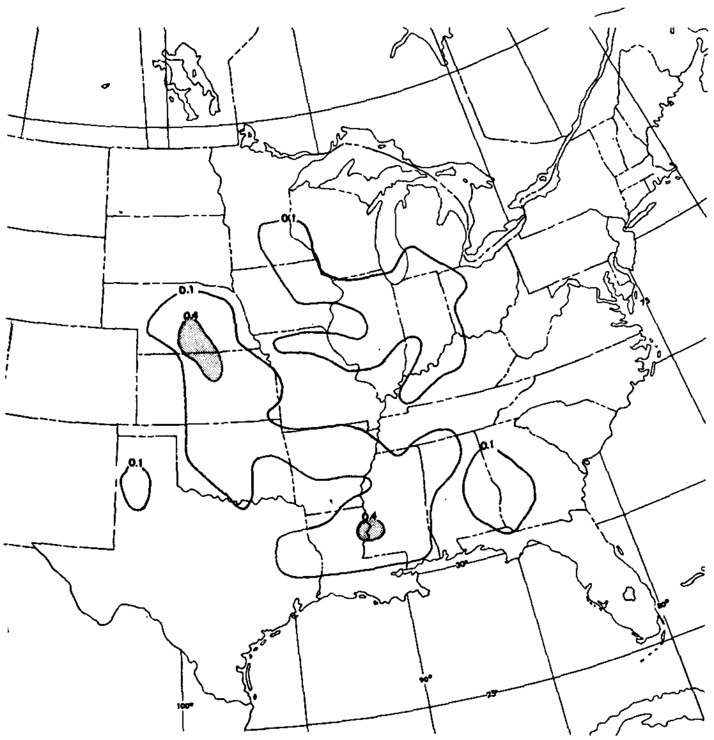
An indication of the problems inherent in dealing with the climatology of rare events is shown by the geographical distribution of violent tornadoes (Fig. 6c). Over the 27-year span of this study, only 340 violent tornadoes were reported. Four distinct regions of maximum frequency are evident. However, two of the four maxima can be directly attributed to the occurrence of one or two tornado outbreaks (Galway, 1977). Of the 14 violent tornadoes which occurred near Rochester, MN, 10 of them occurred in the outbreaks of 6 May 1965 and 30 April 1967. Similarly the maximum in Indiana and Kentucky reflects the Palm Sunday (11 April 1965) and the 3–4 April 1974 outbreaks. In contrast, tornado outbreaks do not dominate the climatology of violent storms in the Arkansas and Alabama maxima. Over the 27-year period, no one day in these regions had more than two violent tornadoes.

While the areal frequency maximum for violent tornadoes is not within the classical tornado alley, the data sample is too small to draw any statistically significant conclusions.



(a)

(b)



(c)

Fig. 7. Frequency per 2° overlapping square of (a) short-path, (b) intermediate-path and (c) long-path tornadoes normalized to 10 000 mi^2 area per year (1950–76).

5. Geographical distribution of path length

The path length of a tornado is directly related to the probability of damage associated with that storm. Abbey and Fujita (1975) used this premise as a basis for assaying damage probability. Wilson and Morgan (1971) suggested that long path length (>100 mi) violent storms are the "most prominent members of a larger class of very strong tornadoes." It is the combination of strength and total area affected that makes long-path tornadoes significant. However, it should be observed that intense short-path tornadoes can be devastating when they strike a populated area. The higher frequency of short-path tornadoes can be a compensating factor for the lower impact areas in any given storm.

Path lengths could be associated with 15 648 tornadoes (89%). These were categorized into short (PL-0 and PL-1), intermediate (PL-2 and PL-3), and long (PL-4 and PL-5) and their frequency plotted in the overlapping square format (Fig. 7). Short-path tornadoes (Fig. 7a) have a geographic distribution which is markedly similar to that of weak tornadoes. Again, there are indications of two axes. The maxima are localized into small pockets over central Oklahoma, the Texas Panhandle and central Florida. Minima occur in eastern Kansas and in central Missouri.

Intermediate track tornadoes (Fig. 7b), like strong intensity tornadoes, occur rather amorphously across the mid-portions of the country. Again, the principal maxima occur in central Oklahoma and immediately southeast of St. Louis. A secondary maximum is present near Plainview, TX, and relative minima occur over central Missouri and central Iowa.

The 325 long-track tornadoes (Fig. 7c) have a very complex incidence pattern. One favored region occurs in Mississippi and Louisiana. Climatologically, this region is more frequently characterized by plentiful low-level moisture than other parts of the tornado-prone area (Dodd, 1965). This plentiful moisture is a prerequisite for severe, tornado-producing thunderstorms (Miller, 1972). When severe storms develop in this region, they can be expected to have a longer lifetime and path length than storms which occur in the drier west Texas-Oklahoma region. The existence of the pronounced maximum in south central Nebraska and north central Kansas is consistent with the geographical distribution of expected path lengths determined by Howe (1974).

6. Fatalities, intensity and path length

Diurnally, the percentage of tornadoes which produce fatalities reaches a maximum in the late

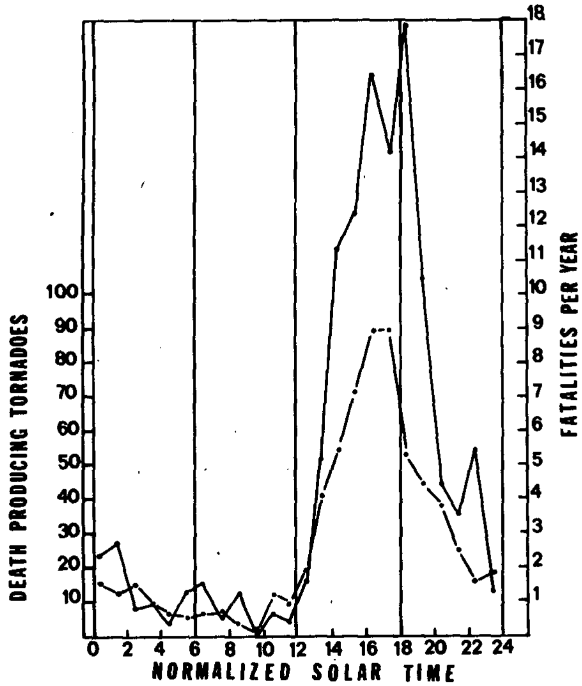


FIG. 8. Diurnal distribution (NST) of tornadoes causing fatalities (dashed) and number of fatalities per year (solid) for 1950–76.

afternoon (Fig. 8). This distribution is well correlated with the diurnal occurrence of tornadoes shown in Fig. 1. The actual time of fatalities was estimated by noting the time a tornado entered a county in which a death occurred. These fatality data were then normalized per year. The hourly fatality rate curve is very disjointed, with many relative maxima and minima present. Most fatalities occur immediately after sunset. However, this figure is heavily biased by the 8 June 1953, Flint, MI, tornado which touched down 28 min after sunset and left 116 fatalities in its wake.

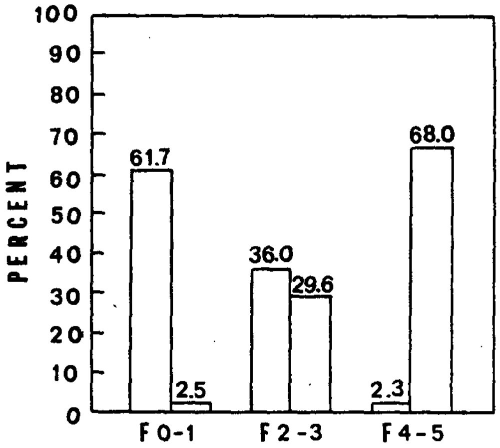


FIG. 9. Percentage of all F-scale tornadoes in each F category and percentage of fatalities associated with each category.

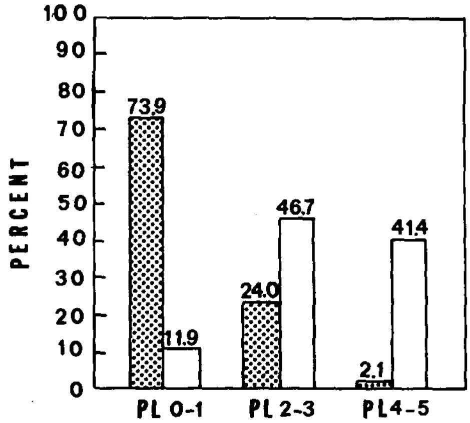


FIG. 10. Percentage all PL-scale tornadoes in each path length category and percentage of fatalities associated with each category.

Tornadoes which had an intensity assigned to them caused 3092 deaths. The percent of tornadoes in each intensity category and the percent of fatalities associated with them are shown in Fig. 9. The majority (61.7%) of the tornadoes are weak, the frequency decreasing monotonically with increasing intensity (36.0% strong, 2.3% violent). The distribution of fatalities shows the opposite effect, with the percentage increasing with more forceful storms. Specifically, only 2.3% of tornadoes are violent but they cause 68% of the deaths. These results are in general agreement with those of Linehan (1957), Pearson (1971) and Kessler and Lee (1976).

When path length category is compared to fatalities, a different picture emerges (Fig. 10). Catagorizable storms accounted for 3070 fatalities. As expected, the frequency of occurrence decreases with increasing path length. But more people die from intermediate track tornadoes (1434) than from long-track ones (1271). Short-track tornadoes are much more effective killers than weak intensity ones. Fatalities occur most frequently with violent tornadoes and with tornadoes of intermediate path length.

The question naturally arises as to whether there is a relationship between path length and intensity. Both these characteristics could be estimated for 14 409 (82%) of the reported tornadoes. As seen in Table 3, the exact relationship between these parameters is not clear. Only about one-quarter (28%) of the long-track tornadoes are violent, while over

TABLE 3. Distribution of 14 409 tornadoes by force (weak, strong, violent) and length (short, intermediate, long).

F scale	PL0–1	PL2–3	PL4–5	Total
4–5	47	205	84	336
2–3	2 921	2 117	175	5 213
0–1	7 615	1 206	39	8 860
Total	10 583	3 528	298	

TABLE 4. Distribution of 3070 tornado fatalities by force (weak, strong, violent) and length (short, intermediate, long).

F-scale	PL0–1	PL2–3	PL4–5	Total
4–5	140	901	1052	2093
2–3	174	512	215	901
0–1	51	21	4	76
Total	365	1434	1271	

one-half (59%) of them are strong. Further, the majority (61%) of the violent storms have an intermediate track.

Deaths attributable to tornadoes which have both F and PL reported are shown in Table 4. These data are consistent with the graphs of fatalities as a function of either force or track length. Violent tornadoes with intermediate or long path length each comprise about 1% of the sample, but each produces approximately 30% of the fatalities.

7. Regional variations in tornado characteristics

Average distributions of tornado characteristics for three quasi-homogeneous geographical areas have been computed to determine if any significant regional variations exist. The areas, shown in Fig. 11, are designated as the Great Plains (GP), Midwest (MW) and Southeast (SE). Each contains an equal number of 2° latitude-longitude squares. Further, to mitigate the effect of local observational biases, portions of at least four states are included in each region. These areas were positioned away from significant mountains and coastal regions to eliminate possible topographic effects.

The GP region contains 394 642 km², and lies almost entirely within classical tornado alley. The MW region (379 212 km²) is dominated by a large area of high point frequencies for violent tornadoes (Fig. 6c). In an early effort to type tornadoes, Brown (1933) made a distinction between "cyclonic" and "convectional" tornadoes. The former type occurred in conjunction with a well-developed cyclonic low-pressure area, while for the latter type such a cyclone was weak or lacking. These data indicated that convectional tornadoes are extremely rare over the 414 496 km² SE area.

The regional distribution of tornadoes for which both intensity and track length could be estimated is given in Table 5. As anticipated, the GP region has over 1½ as many tornadoes reported as either of the other two regions. However, the percentage of reported tornadoes in the weak category and in the short path group is substantially greater here than in the MW or SE. Interestingly enough, the percent of tornadoes which fall into the violent category is the same in both MW and SE. The greater frequency indicated in Fig. 6c for the MW arises from the areal normalization. There is a substantial increase in the number of strong tornadoes in the SE over the MW.

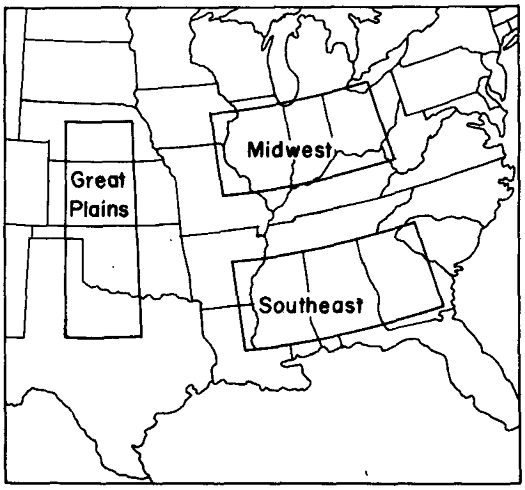


FIG. 11. Three quasi-homogeneous geographical regions: Great Plains (GP), Midwest (MW) and Southeast (SE).

The path length statistics for MW and SE are quite similar. While there are numerically more (and thus a higher areal frequency in Figs. 7b and 7c) intermediate and long-track tornadoes over the GP than the other regions, on a percentage basis short-path tornadoes are more favored there. Brown and Roberts (1935) noted that "the length of the tornadic track is apparently much greater in the case of the cyclonic than the other type." This implies a higher frequency of long-track tornadoes in the SE. These new data do allow substantiation of this hypothesis, but they do indicate that some factors (perhaps a more abundant moisture supply) is present which makes the region between the Appalachians and the Mississippi River more conducive to long-track tornadoes than that between the Mississippi River and the Rockies.

The temporal distribution of tornadoes in NST for three regions is given in Fig. 12. Owing to the rela-

TABLE 5. Percentage distribution of tornadoes by force and length of tornadoes within each region.

Area	Number of tornadoes	F0–1	F2–3	F4–5	PL0–1	PL2–3	PL4–5
Great Plains (GP)	2136	64.7	33.7	1.6	74.1	23.1	2.5
Midwest (MW)	1383	57.7	39.0	3.3	66.5	30.2	3.3
Southeast (SE)	1395	49.7	47.0	3.3	66.4	29.9	3.7

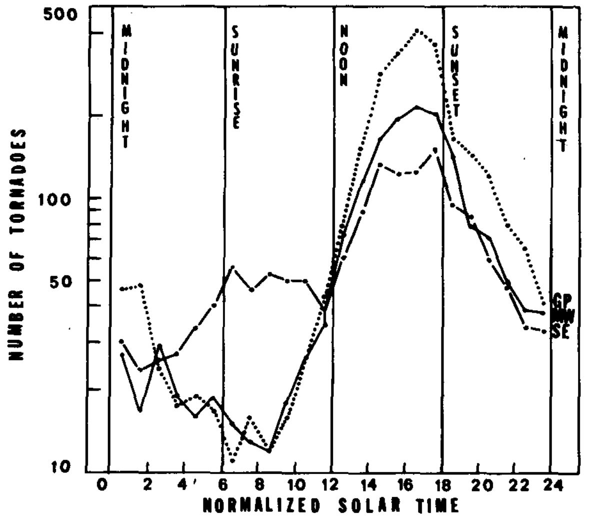


FIG. 12. Diurnal distribution of tornadoes in the three regions: Great Plains (dotted line), Midwest (solid line) and Southeast (dashed line).

tively small number of reports, tornado occurrences have not been normalized by year. Note that while the GP and MW regions have similar diurnal trends, a dramatic change occurs in the SE. The curve for that section of the country is bimodal with a secondary peak around sunrise; Skaggs (1969) has noted this effect. This secondary maximum cannot be attributed to insolation and must reflect other influences. Wallace (1975) found a diurnal maximum of precipitation near sunrise over the SE during the months of November through March, but did not find a corresponding maximum in thunderstorm activity. Thus, a maximum in tornado activity does not imply a maximum in thunderstorms.

8. Conclusions

A brief overview of the potential information content of the data collected in the joint NSSFC-NRC project has been presented. While it is still possible to upgrade further the quality of the tornado record, the bias in the historical data set has been considerably reduced. The analysis presented shows a general agreement with previous climatological work as summarized by Abbey (1976).

In closing, we would like to echo the conclusion of a classic paper in tornado climatology (Brown and Roberts, 1937): "It might be said at this point that it is not the purpose of the paper to criticize other than constructively and to indicate a possible better method of handling difficult material or data.

"These statistical studies are to be used as signposts indicating possible lines of research from which the origin and causal conditions of these phenomena may be derived."

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