SATELLITE & MESOMETEOROLOGY RESEARCH PROJECT
Department of the Geophysical Sciences
The University of Chicago

ESTIMATE OF AREAL PROBABILITY OF TORNADOES FROM INFLATIONARY REPORTING OF THEIR FREQUENCIES

by

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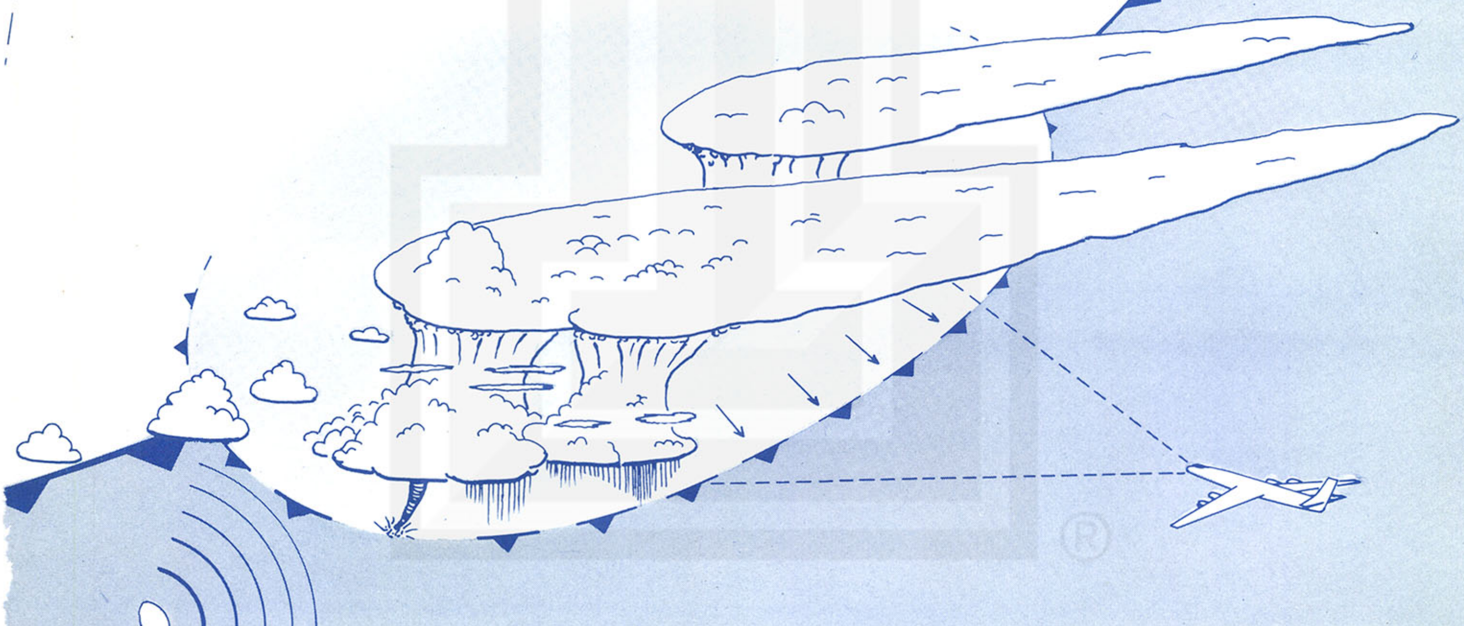

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(Continued on back cover)

CORRECTION

In order to cover the largest possible range of individual tornado areas, the area categories presented in page 10 have been expanded to seven, of which "decagiant tornado", the largest-area storm may occur only once or twice a year. As shown in the following table, the term "regular tornado" was changed to "macro tornado", thus completing a sequence, micro, meso, and macro.

REVISED TABLE OF SEVEN CATEGORIES OF INDIVIDUAL TORNADO AREAS

Area Category	Individual Area, a (sq. mi.)	Log a
Trace Tornadoes	$0 < a < 0.001$	$\log a < -3$
Decimicro Tornadoes	$0.001 \leq a < 0.01$	$-3 \leq \log a < -2$
Micro Tornadoes	$0.01 \leq a < 0.1$	$-2 \leq \log a < -1$
Meso Tornadoes	$0.1 \leq a < 1$	$-1 \leq \log a < 0$
Macro Tornadoes	$1 \leq a < 10$	$0 \leq \log a < 1$
Giant Tornadoes	$10 \leq a < 100$	$1 \leq \log a < 2$
Decagiant Tornadoes	$100 \leq a$	$2 \leq \log a$

Thus, the trace tornado is characterized by an area smaller than about 150-ft square which may be regarded as the smallest individual area caused, for instance, by a funnel touching the ground momentarily. The Tri-state tornado of 18 May 1925, identified as the worst single storm on record, affected 164 sq. miles. This area belongs to the low end of the "decagiant" category, suggesting that an individual tornado area in excess of 1000 sq. miles, which may be identified as "hectogiant tornado", may never be created by Mother Nature.

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ABSTRACT

During the past half century, the reported annual tornado frequency increased by one order of magnitude, from less than 100 to almost 1,000, giving the impression that tornado probability in the United States had increased continuously. Computation of frequency deviation from 5-year running averages showed a random deviation of up to 50% from the 5-year average frequencies, thus reaching the conclusion that the inflationary frequencies are a result of ever improving tornado reporting systems. Based upon individual tornado areas as derived from Storm Data, tornadoes were classified into four categories: Giant, Regular, Meso and Micro tornadoes. It was found that over 50% of the total tornado areas were caused by Giant tornadoes which represent only about 3% of the total frequency and that Micro tornadoes, about 40% of the total frequency, accounted for only 1% of the total tornado areas. Finally, the areal probability of tornadoes was computed to determine the probability that a spot will be affected by a tornado.

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1. Introduction

If we turn our clock back into the 1800's, historical tabulation of frequency by Finley (1884) indicates that only up to 5 or 6 tornadoes were reported annually until 1874 when 17 were reported. Hazen (1890) tabulated tornado frequencies between the years 1873 and 1888 in an attempt to relate them to sunspot activities. As presented in Table I, both Finley and Hazen gave increasing numbers of tornadoes early in the 1870's. A maximum number of 589 was reached in 1883 followed by a gradual decrease toward the end of the 19th century.

Table I. Tornado frequency in the 1800's. Numbers with* are from Hazen (1890), all others from Finley (1884).

1800	0	1810	0	1820	0	1830	3	1840	3	1850	0	1860	5	1870	2		1880	112	269*
1801	0	1811	0	1821	3	1831	2	1841	0	1851	1	1861	0	1871	1		1881	84	169*
1802	0	1812	0	1822	0	1832	1	1842	2	1852	1	1862	0	1872	2		1882		286*
1803	0	1813	0	1823	2	1833	2	1843	0	1853	0	1863	2	1873	2	8*	1883		589*
1804	1	1814	1	1824	1	1834	1	1844	1	1854	6	1864	0	1874	17	15*	1884		462*
1805	0	1815	0	1825	0	1835	4	1845	1	1855	2	1865	0	1875	55	69*	1885		374*
1806	0	1816	0	1826	1	1836	1	1846	0	1856	0	1866	1	1876	44	68*	1886		243*
1807	0	1817	0	1827	0	1837	2	1847	0	1857	3	1867	0	1877	66	111*	1887		183*
1808	0	1818	1	1828	0	1838	3	1848	0	1858	1	1868	0	1878	57	108*	1888		259*
1809	0	1819	0	1829	0	1839	2	1849	0	1859	3	1869	1	1879	71	92*			

More reliable statistics became available from the year 1916 due to an improvement in reporting efficiency. Wolford's (1960) statistical paper tabulated various aspects of tornado occurrences including the annual and geographical tornado occurrences. He constructed a chart of tornado frequency by one degree latitude-longitude "squares" for the period of 1953 to 1958 involving 3,540 tornadoes. Thus, the average pattern of tornado frequency over the entire United States became quite evident. A ten-year tabulation of statistics covering the period 1953-62 was made by Thom (1963) who also divided the United States into one degree "squares" of longitude and latitude. A longer period of statistics on tornado occurrences based upon SELS LOG edited by Pautz (1969) has become available. A total of 11,608 tornadoes during the 1955-67 period was located in respective one-degree "squares" in order to show detailed geographic pattern of tornado occurrences during the recent 13-year period.

For further investigation of individual tornadoes, there are several data sources which are readily available. Since 1916 when a total of 150 tornadoes were reported, the U. S. Weather

Bureau has been collecting and publishing tornado data. The annual and monthly publications giving these data are:

1916 through 1934:	Report of the Chief of the Weather Bureau
1935 through 1949:	U. S. Meteorological Year Book and Monthly Weather Review
1950 through 1960:	Climatological Data, National Summary
1961 to present:	Storm Data

By examining tornado frequencies reported in these publications, it was found that the annual frequency of about 200, reported until about 1952, increased significantly in 1953 when 437 were tabulated. Since then the frequency averaged over 600, thus giving the impression that tornado activities tripled over the United States.

It should be noted that the reported annual frequency depends on a number of factors. As stated by Reichelderfer (1957), these factors are greater population density to report tornadoes in areas which formerly were relatively unpopulated, greater public awareness and observation of tornadoes through tornado forecasts disseminated over radio and TV stations, improved storm reporting networks and techniques, more trained cooperative observers, and the establishment of community warning networks. Thus, he clearly indicated that no tornado will be reported unless there are people who know what tornadoes are and how to report them for national tabulation.

The purpose of this report is first to find out the relationship between population density and the density of reported tornadoes. Then the dimensions of tornadoes related to their size distribution are examined in an attempt to assess the probability of experiencing a tornado at given points in the United States. Such a probability, which may be called the areal probability, can be obtained after knowing the areas affected by individual tornadoes. The variation in damage area by individual tornadoes is so large that the number of tornadoes per area is of little value unless the size of tornadoes is somehow taken into consideration.

2. Density of Tornado Frequency

The fact that the annual tornado frequency is still increasing implies that the density of tornado frequency could be related closely to the population density growth. This may not be varied in the eastern part of the United States where the population density seems to be high enough to report even small tornadoes. In the western plain states, however, it is unlikely that all tornadoes are observed in some form and reported for tabulation.

In order to compute the number of tornadoes per area per year, a unit was chosen to be the number of occurrences per 100-mile square per year. This unit which may be called the "frequency density unit" is abbreviated as f.d.u. Namely,

$$1 \quad \text{f.d.u.} \quad = \quad 10^{-4} \text{ per sq. mile per year.}$$

To compute the frequency density in the United States it would be convenient to make use of the tornado frequencies given in each longitude-latitude "square" (abbreviated as one-degree square in this paper) such as computed by Wolford (1960), Thom (1963), and Pautz (1969).

Frequency density, f, in f.d.u. is defined by

$$f \quad = \quad \frac{1}{\Delta Y} \frac{\Delta F}{\mu \Delta S} \times 10^4 \quad \text{f.d.u.} \tag{1}$$

where ΔY is the number of statistical years, ΔF the total frequency inside a one-degree square with its area, ΔS, and μ the fractional land area within the one-degree square. Namely,

$$\mu \quad = \quad \frac{\Delta L}{\Delta S} \tag{2}$$

where ΔL is the land area. The area of a one-degree square can be written as a function of latitude, thus

$$\begin{aligned} \Delta S &= (\text{1-deg longitude}) \times (\text{1-deg latitude}) \\ &= (69.4 \text{ mi})^2 \cos\phi \\ &= 4816 \cos\phi \text{ sq. mi.} \end{aligned} \tag{3}$$

where ϕ denotes the mean latitude of the one-degree square. By putting this quantity into Eq. (1), we have

$$\begin{aligned} f &= \frac{\Delta F}{4816\,\mu\,\Delta Y \cos\phi} \times 10^4 \text{ f.d.u.} \\ &= 2.08\,\frac{\Delta F}{\mu\,\Delta Y \cos\phi} \quad \text{f.d.u.} \end{aligned} \tag{4}$$

In computing the frequency density, Pautz's (1969) data were used because of the longest statistical period of 13 years, or $\Delta Y = 13$. Thus, the areal frequency of each one-degree square was computed and was contoured with isolines corresponding to 1, 2.5, 7.5, 10, 12.5 15, 17.5, and 20 f.d.u.'s. (see Fig. 1). Included also in the figure are the cities with a population over 100,000 in the 1960 census. These cities are shown in three-size circles designating population over 100,000, 500,000, and 1,000,000. It is seen that more tornadoes are reported over plains than over mountainous regions. This fact may partially be due to the fact that tornadoes may not be efficiently reported in the mountains because of obstructions and lack of buildings. It should be noted also that friction of rough terrain will act against the formation and the development of tornadoes. Of interest also is that there is little relationship between the location of large cities in the east and local maxima of a tornado's areal frequency. This independence would indicate that the reporting efficiency of tornadoes is already high there.

On the other hand, there are local maxima near Chicago, St. Louis, Kansas City, Oklahoma City, Dallas, Lubbock-Amarillo, and Denver, suggesting that the high population density around these cities is increasing the reporting efficiency to a certain extent. A local maximum of about 21 f.d.u. is seen near Oklahoma City. A minimum frequency over the Ozarks and a significant maximum over Southern Illinois are quite similar to those near Boston where a significant maximum is found. It would be of value to carry out more complete statistical studies of tornado frequency taking into consideration the topography and population density as well.

3. Annual Frequency of Tornadoes

Realizing that not all tornadoes are reported each year, we shall attempt to establish reasonable statistics based upon the data available to us. For this purpose, the following terms are defined.

F. . . . . ANNUAL FREQUENCY, total reported number of tornadoes of year n

$\bar{F}_{5m}$ . . . . 5-YEAR MEAN FREQUENCY, five-year running mean of tornado frequency between years n-2 and n+2

$\bar{F}_{hm}$ . . . . HISTORICAL MEAN FREQUENCY, mean frequency of tornadoes between 1916 and the last year of statistics

I. . . . . FREQUENCY INDEX, $F/\bar{F}_{5m}$, the ratio of tornado frequency and 5-year mean frequency

e. . . . . REPORTING EFFICIENCY, $\bar{F}_{5m}/\bar{F}_{hm}$, the ratio of 5-year mean and historical mean frequencies.

1971 1972

802 718

875 770

73 50

END OCT

Total # Tornadoes 1643 - 1949

1643 - 1 tornadoes ~~report~~
1648 - 1 "
1661 - 1 "
1666 - 1 "
1671 - 2 "
1680 - 1 "
1682 - 1 "
1722 - 1 "
1724 - 1 "
1728 (or 29?) - 1 "
1730? - 1 "
1731 - 1 "
1742 - 2 "
1745 - 1 "
1748 - 1 "
1749 - 1 "
1752 - 1 "
1754 - 1 "
1755 - 1 "
1756 - 2 "
1758 - 1 "
1759 - 1 "
1760 - 1 "
1761 - 1 "
1762 - 1 "

1765 - 2 tornadoes
1767 - 2 "
1768 - 1 "
1769 - 1 "
1770 - 1 "
1772 - 1 "
1773 - 4 "
1774 - 1 "
1775 - 2 "
1776 - 3 "
1777 - 1 "
1778 - 1 "
1779 - 1 "
1782 - 2 "
1783 - 1 "
1784 - 6 "
1785 - 2 "
1786 - 1 "
1787 - 4 "
1788 - 3 "
1789 - 3 "
1790 - 3 "
1791 - 1 "
1792 - 2 "
1793 - 2 "

1794 - 5 tornadoes
1795 - 2 "
1796 - 1 tornadoes
1797 - 2 "
1798 - 4 "
1799 - 1 "
1800 - 1 "
1801 - 1 "
1802 - 3 "
1803 - 2 "
1804 - 4 "
1805 - 1 "
1806 - 4 "
1807 - 3 "
1808 - 9 "
1809 - 1 "
1810 - 5 "
1811 - 4 "
1812 - 2 "
1813 - 5 "
1814 - 14 "
1815 - 4 "
1816 - 2 "
1817 - 9 "
1818 - 6 "

1819 - 11 tornadoes
1820 - 10 "
1821 - 7 "
1822 - 2 "
1823 - 6 "
1824 - 2 "
1825 - 8 "
1826 - 5 "
1827 - 2 "
1829 - 3 "
1830 - 12 "
1831 - 6 "
1832 - 1 "
1833 - 6 "
1834 - 15 "
1835 - 10 "
1836 - 2 "
1837 - 5 "
1838 - 7 "
1839 - 5 "
1840 - 12 "
1841 - 5 "
1842 - 7 "
1843 - 8 "
1844 - 7 "

1845 - 11 tornadoes
1846 - 4 "
1847 - 4 "
1848 - 4 "
1849 - 2 "
1850 - 7 "
1851 - 11 "
1852 - 4 "
1853 - 3 "
1854 - 16 "
1855 - 8 "
1856 - 15 "
1857 - 16 "
1858 - 12 "
1859 - 15 "
1860 - 28 "
1861 - 6 "
1862 - 4 "
1863 - 12 "
1864 - 10 "
1865 - 15 "
1866 - 13 "
1867 - 11 "
1868 - 19 "
1869 - 13 "

1870 - 12 tornadoes
1871 - 9 "
1872 - 1 "
1873 - 5 "
1874 - 4 "
1875 - 4 "
1876 - 4 "
1877 - 7 "
1878 - 4 "
1879 - 2 "
1880 - 28 "
1881 - 1 "
1882 - 3 "
1883 - 5 "
1884 - 6 "
1885 - 8 "
1886 - 4 "
1887 - 3 "
1888 - 4 "
1889 - 1 "
1890 - 8 "
1891 - 3 "
1892 - 4 "
1893 - 6 "
1895 - 2 "

1896- ~~[illegible]~~ 5 tornadoes

1897- 2 "

1898- 7 "

1899- 3 "

1901- 2 "

1902- 3 "

1903- 1 "

1904- 3 "

1905- 2 "

1906?- 1 "

1907 - 1 "

1908 - 1 "

1909- 2 "

1911- 2 "

1913- 2 "

1914- 2 "

1915- 1 "

Total # Tornadoes

1916 — 87 tornadoes reported
1917 - 144 " "
1918 - 85 " "
1919 - 68 " "
1920 - 93 " "
1921 - unable to number because several pages missing from "Report of the Chief of the Weather Bureau"
1922 - 119 tornadoes reported
1923 - 106 " "
1924 - 140 " "
1925 - 127 " "
1926 - 119 " "
1927 - 176 " "
1928 - 209 " "
1929 - 201 " "
1930 - 205 " "
1931 - 106 " "
1932 - 155 " "
1933 - 278 " "
1934 - 153 " "
1935 - 199 " "
1936 - 170 " "
1937 - 163 " "
1938 - 223 " "

1939 -	162	tornadoes	reported
1940 -	130	"	"
1941 -	122	"	"
1942 -	175	"	"
1943 -	158	"	"
1944 -	174	"	"
1945 -	140	"	"
1946 -	109	"	"
1947 -	177	"	"
1948 -	198	"	"
1949 -	258	"	"

Table II. Tabulation of tornado parameters related to annual frequencies. Based on 16,533 tornadoes from Storm Data during a 54-year period, 1916 - 1969.

Year (Y)	Annual Frequency (F)	Annual freq. found	Mean Frequency ($\bar{F}_{5m}$)	Frequency Index ($I = F/\bar{F}_{5m}$)	Reporting Efficiency ($e\% = 100\ \bar{F}_{5m}/306.1$)
1916	90	87 ←			
17	121	144			
18	81	87	88.6	0.914	29
19	64	68	91.6	0.699	30
1920	87	93	89.0	0.978	29
21	105	—	93.2	1.127	30
22	108	119	106.4	1.015	35
23	102	106	112.8	0.904	37
24	130	141	114.0	1.140	37
1925	119	128	125.0	0.952	41
26	111	120	145.2	0.764	48
27	163	175	158.6	1.028	52
28	203	209	173.2	1.172	57
29	197	201	169.8	1.160	55
1930	192	204	167.4	1.147	55
31	94	106	178.4	0.527	58
32	151	155	168.4	0.897	55
33	258	278	166.0	1.554	54
34	147	153	177.4	0.829	58
1935	180	200	176.6	1.019	58
36	151	170	167.6	0.901	55
37	147	163	168.6	0.872	55
38	213	223	157.4	1.353	51
39	152	162	150.8	1.008	49
1940	124	130	154.8	0.801	51
41	118	122	142.6	0.827	47
42	167	175	146.0	1.144	48
43	152	158	145.2	1.047	47
44	169	174	143.0	1.182	47
1945	121	140	142.6	0.848	47
46	106	109	148.8	0.712	49
47	165	177	164.8	1.001	54
48	183	198	180.4	1.014	59
49	249	253	213.6	1.166	70
1950	199		227.8	0.874	75
51	272		278.6	0.976	91
52	236		338.6	0.696	111
53	437		417.4	1.047	136
54	549		469.4	1.172	153
1955	593		595.0	0.995	194
56	532		620.6	0.857	203
57	864		628.6	1.374	205
58	565		633.6	0.892	207
59	589		663.6	0.888	217
1960	618		622.4	0.994	203
61	682		601.6	1.133	197
62	658		626.4	1.051	205
63	461		682.6	0.675	223
64	713		660.2	1.080	217
1965	899		711.0	1.264	232
66	570		750.8	0.759	246
67	912		729.0	1.250	238
68	660	3395	678.0		
69	604	3913	742.6		
1970	649	3571	714.2		
71	888				
72	770				

After defining the above parameters, annual frequencies from Storm Data were used to compute tornado parameters presented in Table II. Three parameters in the table were then plotted in Fig. 2 in order to show both short- and long-range variation of tornado parameters. It is seen that the minimum and maximum frequencies of 64 and 912 occurred in the years 1919 and 1967, respectively. A middle graph of a 5-year mean frequency had been increasing during this statistical period. It is of interest to find that these 5-year means smooth the annual variations considerably, suggesting strongly that tornado activities averaged over 5-year periods change rather gradually. Long period, natural variations of frequency, if any, are overwhelmed by artifical variations of reporting conditions during the past 50 years.

Under assumptions that the natural variation period of tornado frequencies is less than 5 years and that the artifical variation in tornado reporting conditions varies gradually without short-period fluctuation, already defined frequency index, I, represents the annual fractuation of tornado frequencies. As presented in the lower graph in Fig. 2, the frequency indeces fluctuate wildly between 0.53 and 1.56 which are extreme values which occurred in the years 1931 and 1933, respectively. A frequency distribution of active and inactive years as defined by the frequency index is shown in Fig. 3. Out of 50 years, 14 years were characterized by the frequency indeces within 5% of the median index of 1.00. The rather rapid decrease on both sides indicates statistically that tornado frequency may vary a factor of three from one year to the next.

The reporting efficiency, e, was computed from

$$e = \bar{F}_{5m} / \bar{F}_{hm\,(1916-1969)}$$
$$= \bar{F}_{5m}/306.2 \qquad (5)$$

which gives a comparison of a specific year's efficiency with that of the historical efficiency averaged over a 54-year period, 1916 - 1969. The last column of Table II gives the reporting efficiency computed from Eq. (5). The table clearly shows that the efficiency in earlier years was less than 30% of the historical average which was surpassed in 1952. Thereafter the reporting efficiency increased with slight oscillation but steadily until 1966 when a 246% efficiency was accomplished. We may thus conclude that the reporting efficiency is far from the saturation value which can be reached only when 100% of tornadoes of given definitions are detected and reported for national tabulation.

What are tornadoes? This is a simple question but it has not been answered completely. The Glossary of Meteorology (1959) states that a tornado is a violently rotating column of air, pendant from a cumulonimbus cloud, and nearly always observable as a funnel cloud or tuba. A waterspout is defined in the Glossary as a tornado occurring over water. These definitions of tornadoes and waterspouts are debatable; nevertheless, we have to obtain observational evidences of

A, funnel cloud and typical tornado damage

B, typical tornado damage but no funnel cloud

C, funnel cloud and typical tornado noise but no damage

D, funnel cloud but no damage

E, long but narrow damage swath but no funnel sighting

F, funnel cloud over water

G, --etc.

in order to accomplish proper classification of reported storms.

During the past 20 years, waterspouts in Storm Data increased from practically zero to 291 in the year 1969, mostly in Florida. Meanwhile, the annual frequency of funnel clouds increased much faster than that of tornadoes (see Fig. 4). This simply means that more people are now interested in reporting small storms such as waterspouts and funnel clouds which had been more or less neglected prior to 1950. If such a trend continues into the 1970's, the inflationary frequency is likely to misrepresent the extent of tornado activities in the United States.

4. Proposed Classification of Tornadoes According to their Damage Areas

Because of the fact that the reported tornado frequencies kept increasing during the past 50 years, one would naturally think that the probability of tornado damage at a given location has also been increasing in proportion to the annual tornado frequency. It should be noted that the inflationary frequencies are likely to be contributed by the inclusion of small tornadoes which had not been reported when reporting systems were inadequate. We may safely assume that the size of the mean tornado of each year tends to decrease as the annual frequency increases.

Battan's (1959) study of tornado duration revealed important facts about the tornadoes. He concluded that the duration of the average tornado is approximately 4 min.; a reported duration of more than about 16 min. should raise suspicion that more than one funnel may have been involved, and durations exceeding 40 min. should be taken as indications that more than one tornado funnel was probably involved. These results imply that the increasing frequency of small tornadoes will definitely reduce the duration of average tornadoes. Fujita's (1963) study of extremely large tornadoes revealed conversely that an individual funnel lasted for about 45 minutes. One of the family of Palm Sunday tornadoes of 1956 traveled 274 miles in 4 hours and 23 minutes. According to the survey by Fujita, et. al. (1970), this tornado family consisted of six tornadoes, each of which lasted for about 40 minutes.

Foregoing studies of tornado duration lead to an important conclusion that the average values of each tornado parameter such as duration, damage area, maximum windspeed, etc., will become meaningful only if the distribution of each individual parameter can somehow become known to us. For example, the interpretation of mean income for individuals or families can be made properly only if the income distribution of all individuals involved in the statistics is known. Especially when the scatter is large, the average value by itself does not mean much unless the distribution of the scattered values can be specified.

Although the tornado frequencies are tabulated in Storm Data or in equivalent literatures, quantitative description of each tabulated storm is not available for all storms. The parametarization of tornadoes can somehow be made on their lengths, widths, time, location, deaths, injuries, and property damage. Of these the product of the length and mean width can be used at least in parameterizing the tornado-affected areas.

We shall now define the "Individual Tornado Area, a" by

$$a = \ell \times \bar{w} \tag{6}$$

where ℓ is the length of tornado and $\bar{w}$, the mean width. As shown schematically in Fig. 5, the tornado length is likely to represent the length along the path between the initial and the final damage points. Methods of determining the damage widths may vary according to both the nature of storms and the subjectivity of individual reporters. Nevertheless, the individual tornado area as computed from Eq. (6) will represent the area of the rectangle in Fig. 5, which may not be the integrated damage area but is a good measure of the tornado-affected area. One advantage of using individual tornado areas is that both ℓ and $\bar{w}$ for large numbers of tornadoes are given in the Storm Data. During three years, 1965, 1967, and 1969 for instance, 1,168 tornadoes out of grand total of 2,339 were characterized by both lengths and widths including short length and narrow width. These values will permit us to learn about the distribution of individual tornado areas.

Of 214 tornadoes in 1969 with known length and width, 35 or 16% were less than 0.01 square mile in individual tornado area. Some of these small tornadoes may not be reported as tornadoes if their touch-down points were away from property of some value. Two of the smallest tornadoes in 1969 were characterized by damage areas of less than 0.0002 square mile. Some large tornadoes, on the contrary, resulted in 10 to 50 square mile areas. That is to say, a large tornado involves an area over 100,000 times larger than an extremely small one which is, nevertheless, reported as a tornado. It should be emphasized that the variation in damage area by individual tornadoes is so large that the probability of tornado frequency in f.d.u. is of little value unless the sizes of tornadoes are somehow taken into consideration.

The extent of tornado damage within an individual tornado area varies considerably. Ideally, the isolines of maximum windspeeds of 75 mph, 150 mph, etc., should be drawn to determine the tornado-affected area as a function of the maximum windspeed. A recent study of the Lubbock tornadoes of 11-12 May 1970, by Fujita (1970) revealed that a majority of severe damage assumed to be caused by the wind in excess of 150 mph is seen inside the suction swaths shown schematically in Fig. 6. The total area of suction swaths is at least one order of magnitude smaller than the individual tornado area surrounding the swaths. Further studies of suction swaths are being carried out by the author for use in improving tornado statistics taking both wind and pressure effects into consideration.

Despite the fact that an individual tornado area as defined above does not always represent the extent and the severity of each tornado, it is the only quantity available in Storm Data to characterize a large number of past storms. The author has attempted to classify tornadoes into the following four categories.

(1) Giant Tornadoes: tornadoes with their individual damage area in excess of 10 square miles. These tornadoes are characterized by multiple suction spots rotating along the circle of maximum wind. They may be abbreviated as "Ginadoes".

(2) Regular Tornadoes: tornadoes with their individual damage area ranging between 1 and 10 square miles. Most of them are accompanied by several suction spots. These tornadoes may be abbreviated as "Regunadoes".

(3) Meso Tornadoes: tornadoes with their individual damage area ranging between 0.1 and 1.0 square mile. Due to their small, horizontal dimensions, they are sometimes accompanied by suction spots. These tornadoes may be abbreviated as "Mesonadoes".

(4) Micro Tornadoes: tornadoes with their individual damage area less than 0.1 square mile. Due to their very small, horizontal dimensions, their circulation around the core is more or less axially symmetric, without being accompanied by suction spots. These tornadoes may be abbreviated as "Micronadoes".

Both funnels aloft and waterspouts are likely to be tabulated as micronadoes should they touch down to produce damage.

To show the distribution of tornadoes belonging to each of these four categories, a scatter diagram in Fig. 7 was prepared by plotting individual tornadoes as a function of their length and mean width. Since the coordinates represent logarithms of length and width, isolines of individual tornado areas tilt 45^{o} toward the lower right. Plotted in the figure are 285 tornadoes with reported length and width in 1965 Storm Data. It should be noted that the number of tornadoes belonging to each category decreases as the individual tornado area increases from that of micronadoes to ginadoes.

Similar statistics were made for 1967 and 1969 tornadoes with reported lengths and widths. The result given in Table III reveals that the number of ginadoes is only 1 to 4 per cent of the total number of tornadoes with reported length and width.

Table III. Frequencies of tornadoes with reported length and width in 1965, 1967, and 1969 Storm Data. Numbers in parenthesis denote percentage of each frequency.

Year	1965	1967	1969	Total
Ginadoes	13(4%)	3(1%)	7(3%)	23(3%)
Regunadoes	69(23%)	61(22%)	39(18%)	169(21%)
Mesonadoes	88(30%)	103(37%)	81(38%)	272(34%)
Micronadoes	129(43%)	113(40%)	87(41%)	329(42%)
Total	299(100%)	280(100%)	214(100%)	793(100%)

During these three years a total of 389 tornadoes were reported as "short length and narrow width", suggesting that all of them are likely to be micronadoes with 0.1 sq. mile or less individual tornado area.

5. Cumulative Tornado Areas

Although giant tornadoes are very small in number in each year their effects upon structure and human life are much more than those of meso- and micronadoes combined which constitute over 75% of tornadoes with reported length and width. It is of interest to learn that 157 people were killed by 23 ginadoes, 234 by 169 regunadoes, 19 by 272 mesonadoes, and only 10 by 329 micronadoes in 1965, 67, and 69. No one was killed by 389 tornadoes which are listed as short path and narrow width. A total of 1,157 undimensioned tornadoes in these years killed 45 people, suggesting that the average size of undimensioned tornadoes is much smaller than that of reported lengths and widths. Thus, the statistics made from dimensioned tornadoes will overestimate tornado characteristics rather than underestimating them.

In order to find the total tornado areas caused by each of the four categories of tornadoes in 1965, 1967, and 1969, Table IV was prepared. It is evident in the table that the tornado area decreases significantly as individual tornado area decreases from ginadoes to micronadoes.

Table IV. The total tornado areas produced by different-category tornadoes with reported lengths and widths in 1965, 1967, and 1969 Storm Data. The areas are in sq. miles and the number in parenthesis denotes the percentage of each area.

Year	1965	1967	1969	Total
Ginadoes	353(58%)	73(26%)	286(66%)	712(54%)
Regunadoes	221(36%)	170(60%)	116(27%)	507(38%)
Mesonadoes	35(5%)	36(13%)	27(6%)	98(7%)
Micronadoes	4(1%)	3(1%)	2(1%)	9(1%)
Total	613(100%)	282(100%)	431(100%)	1327(100%)

The results appearing in this table are striking because the total tornado area of micronadoes is just about 1% each year while their numbers are in excess of 40% of tornadoes with reported dimensions.

In order to develop further tornado statistics based upon storm areas, we shall define the "cumulative tornado area, A" by

$$A = \int_{a_0}^{a} a\, n\, da \tag{7}$$

where a_0 is the area of the smallest reported tornado and n , a new parameter called the "tornado number". The tornado number is the number of tornadoes within a small increment of individual tornado area, a . In a differential form it can be written as

$$n = \frac{1}{a} \frac{\partial A}{\partial a} \quad . \tag{8}$$

The cumulative tornado number, N , is defined as the total number of reported tornadoes with individual area up to a . In an integral form, N is given by

$$N = \int_{a_0}^{a} n \, da \tag{9}$$

which naturally increases with a , the upper limit of integration.

We shall now determine the empirical value of $A = f(a)$ based upon our statistical analysis of 1965, 1967 and 1969 Storm Data. Presented in Fig. 8 is the cumulative area, A, as a function of a for each year. In obtaining analytic functions of these distributions, it is necessary to satisfy the conditions,

$$\left(\frac{\partial A}{\partial a}\right)_{a \to \infty} = 1 \quad \text{and} \quad \left(\frac{\partial A}{\partial a}\right)_{a \to 0} = \text{const.} \tag{10}$$

because the addition of an unusually large tornado will increase the cumulative area as much as a , the individual tornado area. The second condition is empirical, so that the curve departs from the origin with a positive gradient. One of the analytical solutions satisfying Eq. (10) and reported values of A as well can be expressed by

$$A = a + A_0\left(1 - \frac{1}{2} e^{-ka} - \frac{1}{2} e^{-0.1ka}\right). \tag{11}$$

This formula consists of two parts, one is a linear part and the other includes a fast and a slow exponential decay. The quantity inside the parenthesis can be tabulated as a function of k and a which is given in Table V.

Table V. Values of $1 - \frac{1}{2} e^{-ka} - \frac{1}{2} e^{-0.1ka}$ to be used for empirical formulae of A.

A in sq. mi.	0	1	2	4	6	10	20	40	60
k = 0.1	0.000	0.053	0.101	0.185	0.255	0.364	0.524	0.656	0.724
k = 0.2	0.000	0.101	0.185	0.314	0.406	0.524	0.656	0.775	0.850
k = 0.3	0.000	0.144	0.255	0.406	0.500	0.604	0.724	0.850	0.917

With the aid of this table the value of A_0 and k for each year can be obtained. Three curves computed for the years 1965, 1967, and 1969 are shown in Fig. 8.

The tornado numbers as defined by Eq. (8) can be obtained simply by differentiating Eq. (13) or (16), thus

$$n = \frac{1}{a}\frac{\partial A}{\partial a} = \frac{1}{a} + \frac{kA_0}{2a}\left(e^{-ka} + 0.1\,e^{-0.1ka}\right). \tag{12}$$

This equation indicates that the tornado numbers approach infinity as the individual area decreases to zero. If we try to include tiny tornadoes or the lower end of the micronado category in our statistics, the tornado number will increase almost to infinity. It should be noted that the cumulative area contributed by these small tornadoes is extremely small despite their high frequency.

6. Areal Probability of Tornado Damage

The foregoing discussion shows the necessity of establishing tornado probabilities based upon individual tornado area rather than just the number of tornadoes without regard to their dimensions. People often ask the question, " What is the average area of tornadoes ?" Such a question can be answered only if we specify the size of the smallest tornadoes to be included in the statistics. We may, thus, express the mean tornado area, $\bar{a}$, by

$$\bar{a} = \frac{\int_{a_s}^{\hat{a}} a\,n\,da}{\int_{a_s}^{\hat{a}} n\,da} = f\,(a_s) \tag{13}$$

where a_s is the smallest tornado area included in the mean-area computation and $\hat{a}$, the largest individual area.

It is feasible to compute $\bar{a}$ from Eq. (11) and (12). However, the combination of Tables III and IV will also give us the mean area of tornadoes for the years, 1965, 1967, and 1969. The mean tornado areas, thus computed from these tables are:

Tornadoes with a_s larger than 0.1 sq. mi. (larger than mesonadoes)

1965: $\bar{a} = \dfrac{609 \text{ sq. miles}}{160 \text{ tornadoes}}$ = 3.8 sq. mi. per storm

1967: $\bar{a} = \dfrac{279 \text{ sq. miles}}{167 \text{ tornadoes}}$ = 1.7 sq. mi. per storm

1969: $\bar{a} = \dfrac{429 \text{ sq. miles}}{127 \text{ tornadoes}}$ = 3.4 sq. mi. per storm

All tornadoes with reported lengths and widths

$$1965: \quad \bar{a} = \frac{613 \text{ sq. miles}}{299 \text{ tornadoes}} = 2.0 \text{ sq. mi. per storm}$$

$$1967: \quad \bar{a} = \frac{282 \text{ sq. miles}}{280 \text{ tornadoes}} = 1.0 \text{ sq. mi. per storm}$$

$$1969: \quad \bar{a} = \frac{431 \text{ sq. miles}}{214 \text{ tornadoes}} = 2.0 \text{ sq. mi. per storm}$$

As shown in Tables III and IV, some 100 micronadoes in each year contributed only as much as several sq. miles of cumulative tornado areas. By adding the number of short and narrow micronadoes reported in each of these three years, the total number of dimensioned tornadoes would increase to 451 in 1965, 427 in 1967 and 304 in 1969. These numbers will thus reduce the mean tornado area to

$$1965: \quad \bar{a} = 1.4 \text{ sq. mi. per storm}$$

$$1967: \quad \bar{a} = 0.7 \text{ sq. mi. per storm}$$

$$1969: \quad \bar{a} = 1.4 \text{ sq. mi. per storm}$$

The above computation reveals that the mean tornado area of all dimensioned storms in these three years may be assumed to be 1.1 sq. mi. for these years. According to Table II, the reporting efficiency of the years 1965 and 1967 were 232% and 238%, respectively. In early years when the reporting efficiencies were less than 50%, it is likely that large tornadoes were reported more efficiently than small ones. The mean tornado areas during early years would have been considerably larger than 1.1 sq. mi.

The frequency density map of Fig. 1 gives the density of tornado frequency in f.d.u. = 10^{-4} occurrence per sq. mile per year. The map was constructed from the Severe Local Storm Occurrences edited by Pautz (1969) which include 11,608 tornadoes between 1955 and 1967 based on SELS Log. The average number of tornadoes was about 730 which corresponds to 237% reporting efficiency, suggesting that the distribution of tornado dimensions is comparable to those of 1965 and 1967. We may safely assume that the mean tornado area of the storms used in producing Fig. 1. is close to 1.0 sq. mi. per storm.

Therefore, we are able to replace one storm by one sq. mi. area in order to equate

$$\text{one storm per sq. mi. per year} = \text{one sq. mi. per sq. mi. per year}$$

$$\text{or} \qquad \text{one f.d.u.} = 10^{-4} \text{ per year}$$

which represents the probability that a specific location is included inside a tornado area. That is to say, one f.d.u. gives a probability of a tornado at a given point once in 10^4 = 10,000 years.

For instance, a given spot or point in Chicago with f = 13 f.d.u. will be hit by a tornado once every 770 years, Kansas City, 750 years, Lubbock, 670 years, etc. The highest frequency density seen near Oklahoma City is about 21 f.d.u. which corresponds to a chance in 470 years. This would mean that a structure in the highest tornado risk area will have a chance to be included in a tornado area once in about 5 centuries.

7. Conclusions and Recommendations

The results presented in this paper show that the area affected by an individual tornado varies widely between 0.001 and 100 sq. miles. Thus, the tornado statistics based only upon the storm frequency cannot be used in establishing the probability of tornadoes affecting local communities.

Improved statistics approached by classifying storms into 4 classes, Ginadoes, Regunadoes, Mesonadoes and Micronadoes according to their individual area, revealed the important fact that over 50% of the total tornado areas was caused by ginadoes which constitute only about 3% of total tornado frequencies. Micronadoes which are 40% of the reported tornadoes produced just about 1% of total tornado areas.

It is important to carry out further research on tornado statistics based upon the individual tornado area as a function of categorized tornado damage. These damage categories may be separated by 100 mph increments of maximum wind, corresponding pressure, and time changes. They may be expressed by

Class 0,	0-100 mph maximum windspeed
Class I,	100-200 mph maximum windspeed
Class II,	200-300 mph maximum windspeed

The areas of tornadoes in each of these classes must be estimated in order to establish a tornado probability related to the severity of storms and their damage. Such an attempt will expedite the calculation of tornado risk, while the inflationary report of tornado frequencies in recent years can be evaluated properly for the improvement of future tornado reporting systems by NOAA and other agencies.

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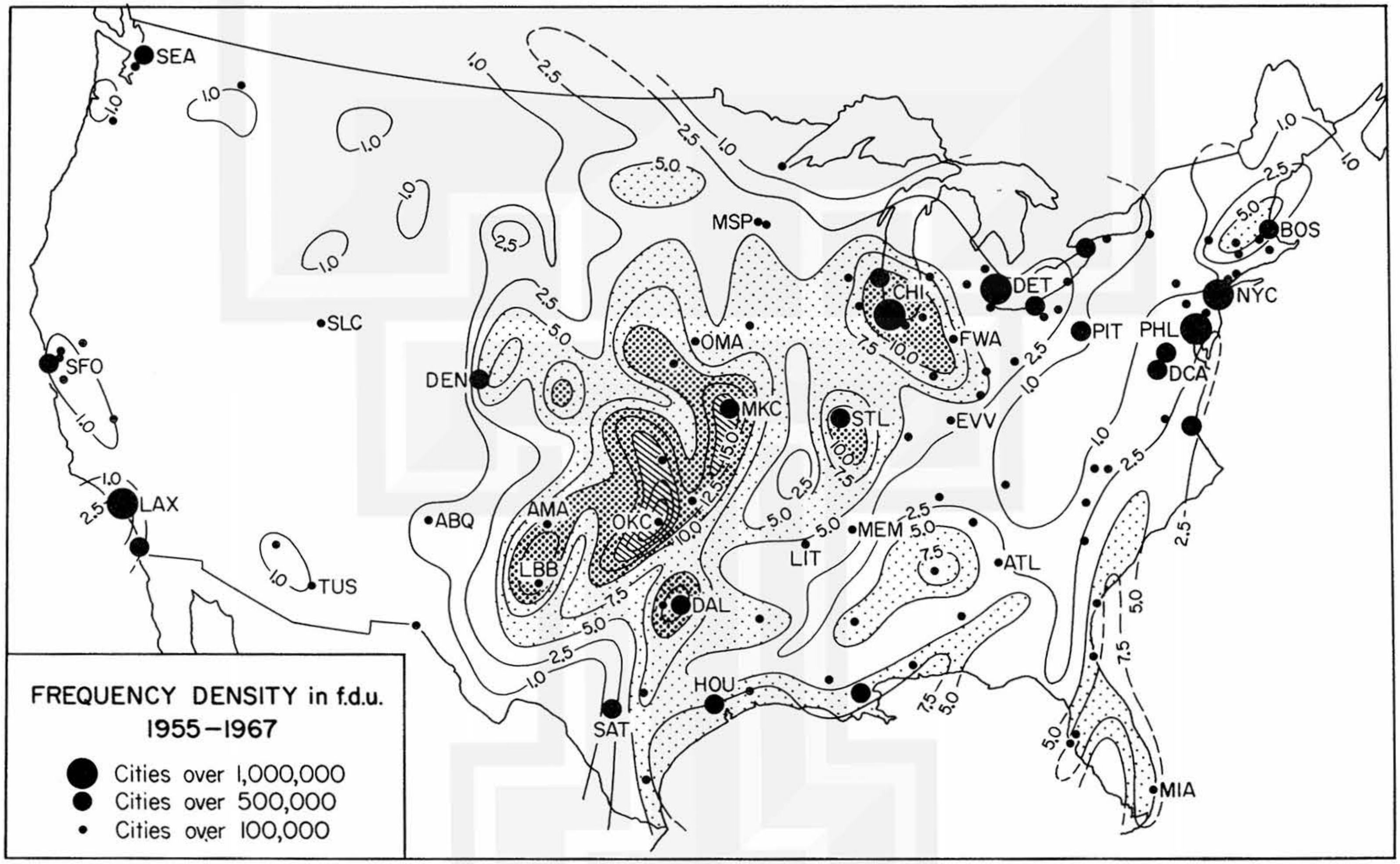

Fig. 1. Frequency density of 1955-1967 tornadoes in frequency density unit (f.d.u.) = 10^{-4} per square mile per year. Tornado numbers by one-degree squares from ESSA Tech. Memo WBTM FCST 12 were adjusted by the effects of both longitude convergence and water areas inside each square. The largest density of 21 f.d.u. is located near Oklahoma City.

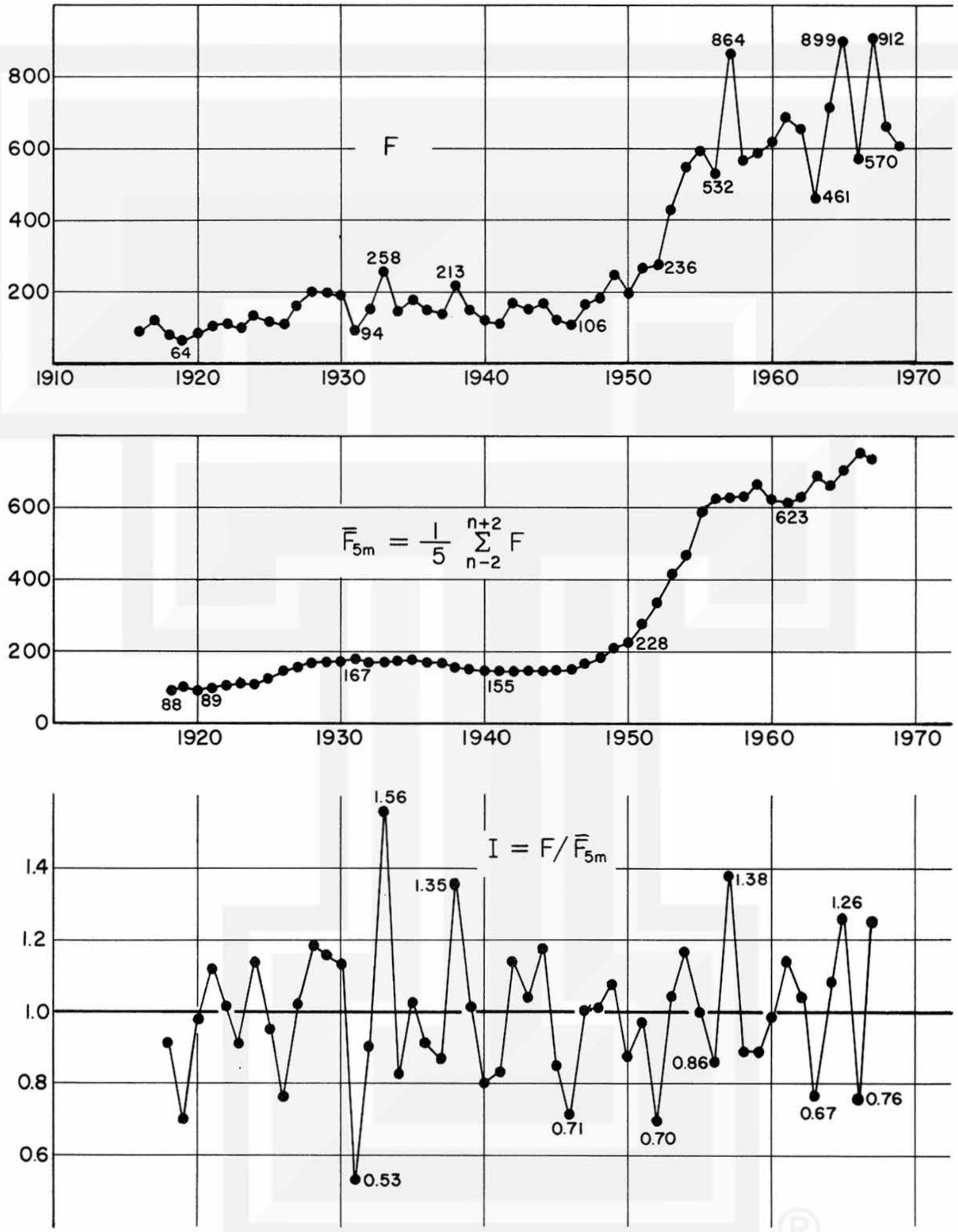

Fig. 2. Historical variation of tornado frequency over the United States. Upper: Annual frequency, F; Middle: Mean frequency, $\overline{F}_{5m}$; and Lower: Frequency index, I.

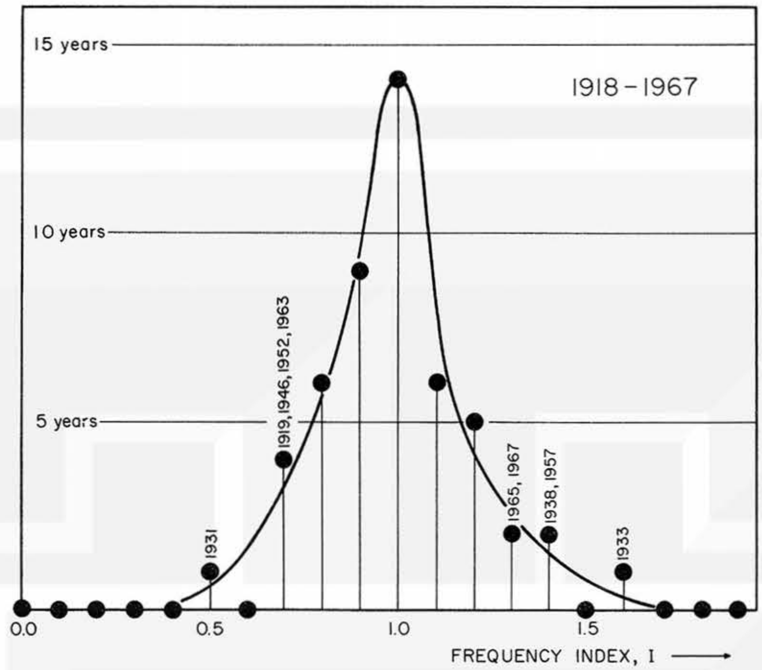

Fig. 3. Distribution of frequency indeces occurring during the 50-year period, 1918-1967. Note that the distribution drops off very rapidly from the center value.

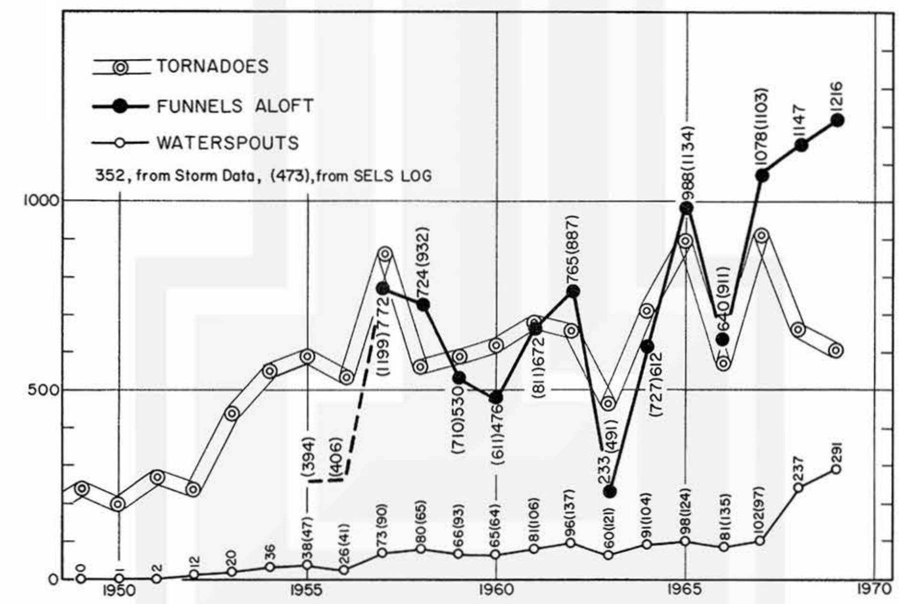

Fig. 4. Annual frequencies of tornadoes, funnels aloft, and waterspouts reported in the United States excluding Hawaii, Puerto Rico, and Alaska. Three graphs were plotted from Storm Data. Frequencies in parenthesis which are, in most years, larger than those from Storm Data were obtained from Pautz (1969).

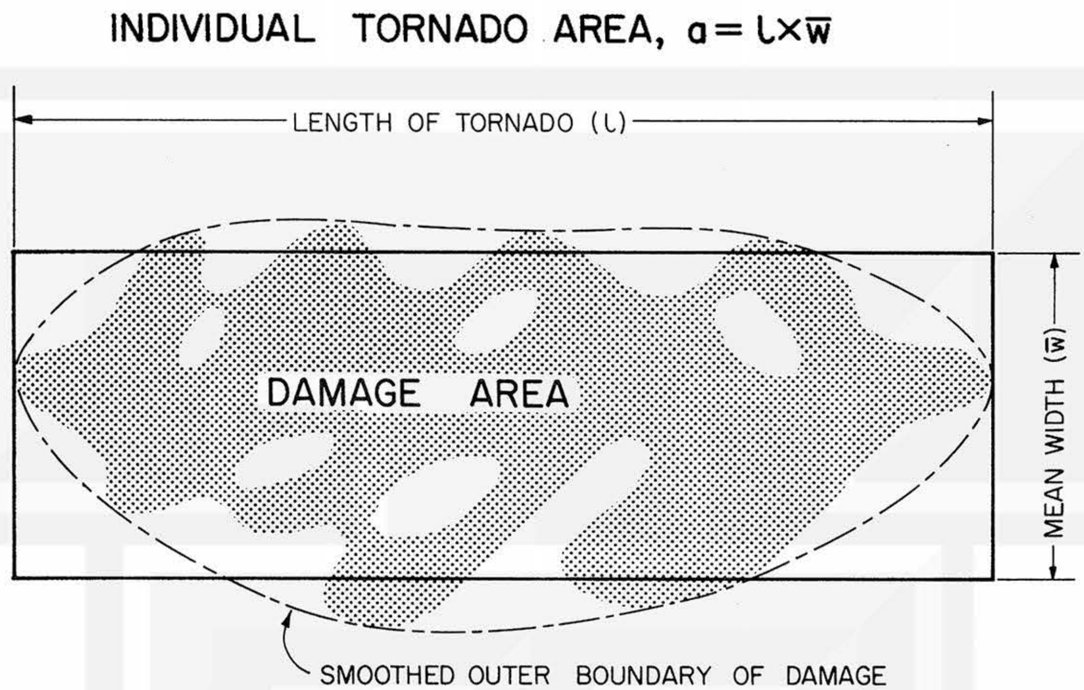

Fig. 5. Schematic figure showing the relationship between tornado damage areas and the individual tornado area defined as the product of the length and the mean width. Estimation of damage areas by individual storms is not only subjective but also rather rarely made or reported. Nonetheless, the individual tornado area, thus defined, is a good measure of the extent of most tornadoes with areal variation between 0.001 and 100 sq. miles.

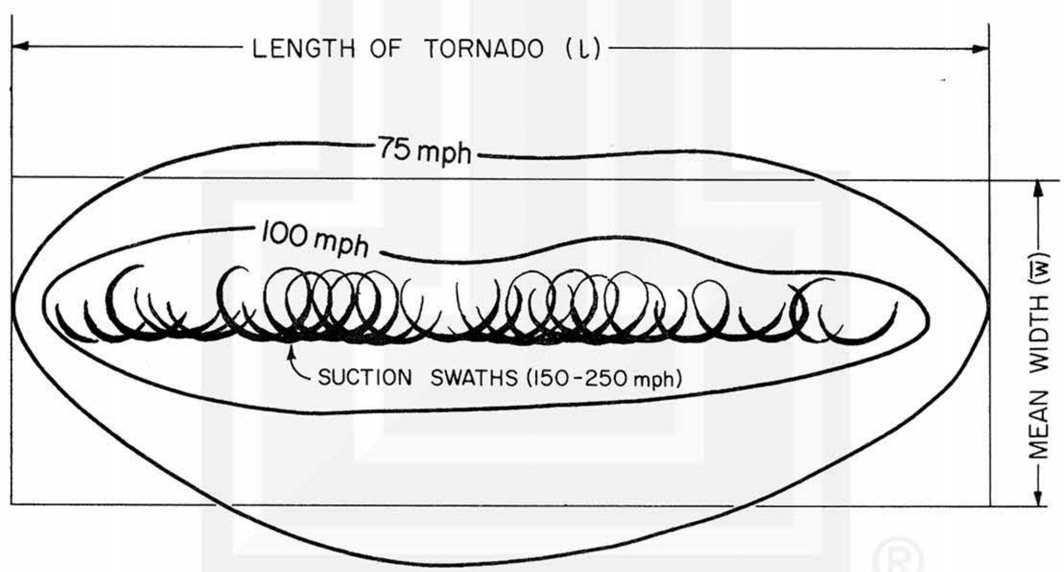

Fig. 6. Schematic figure of suction swaths surrounded by isotachs of maximum tornado wind, 75 and 100 mph. For further description refer to Fujita (1970).

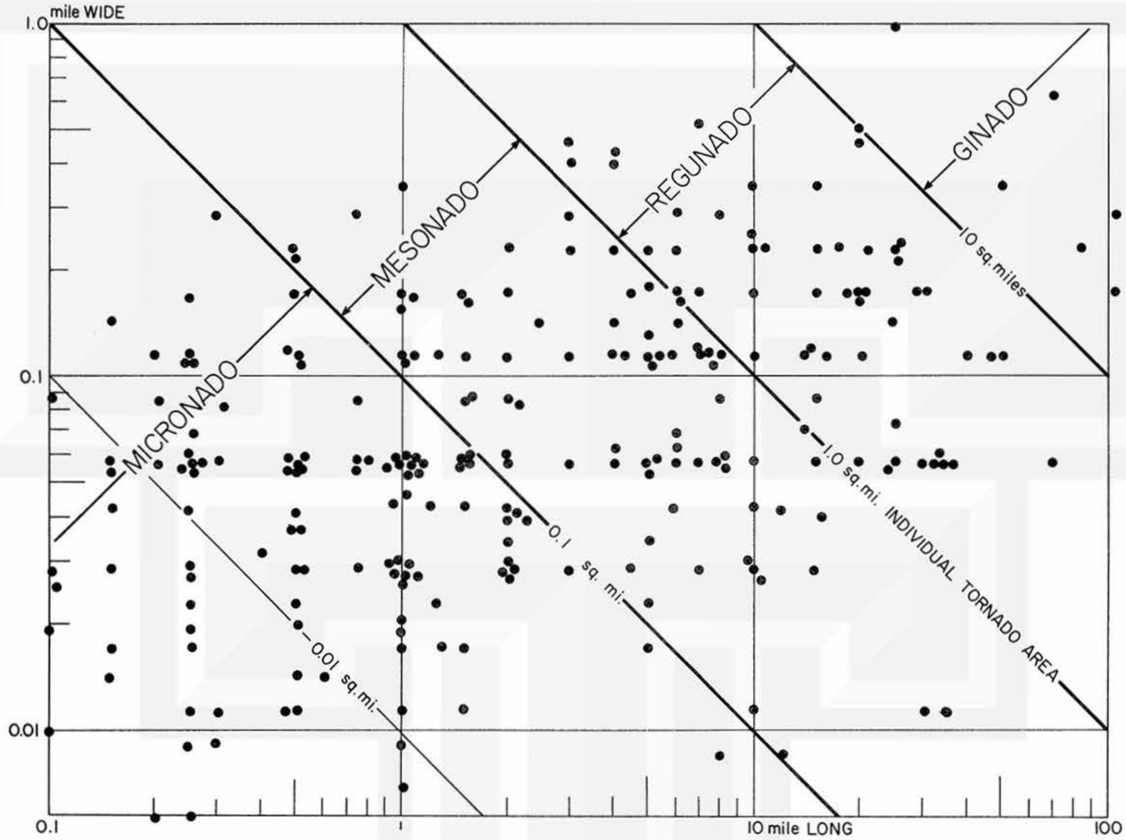

Fig. 7. Tornadoes in 1965 with lengths and widths reported in Storm Data are plotted at their respective positions of the lengths and the mean width. A total of 285 storms are entered in the chart. These tornadoes are classified, according to their individual areas, as Giant, Regular, Meso, and Micro tornadoes.

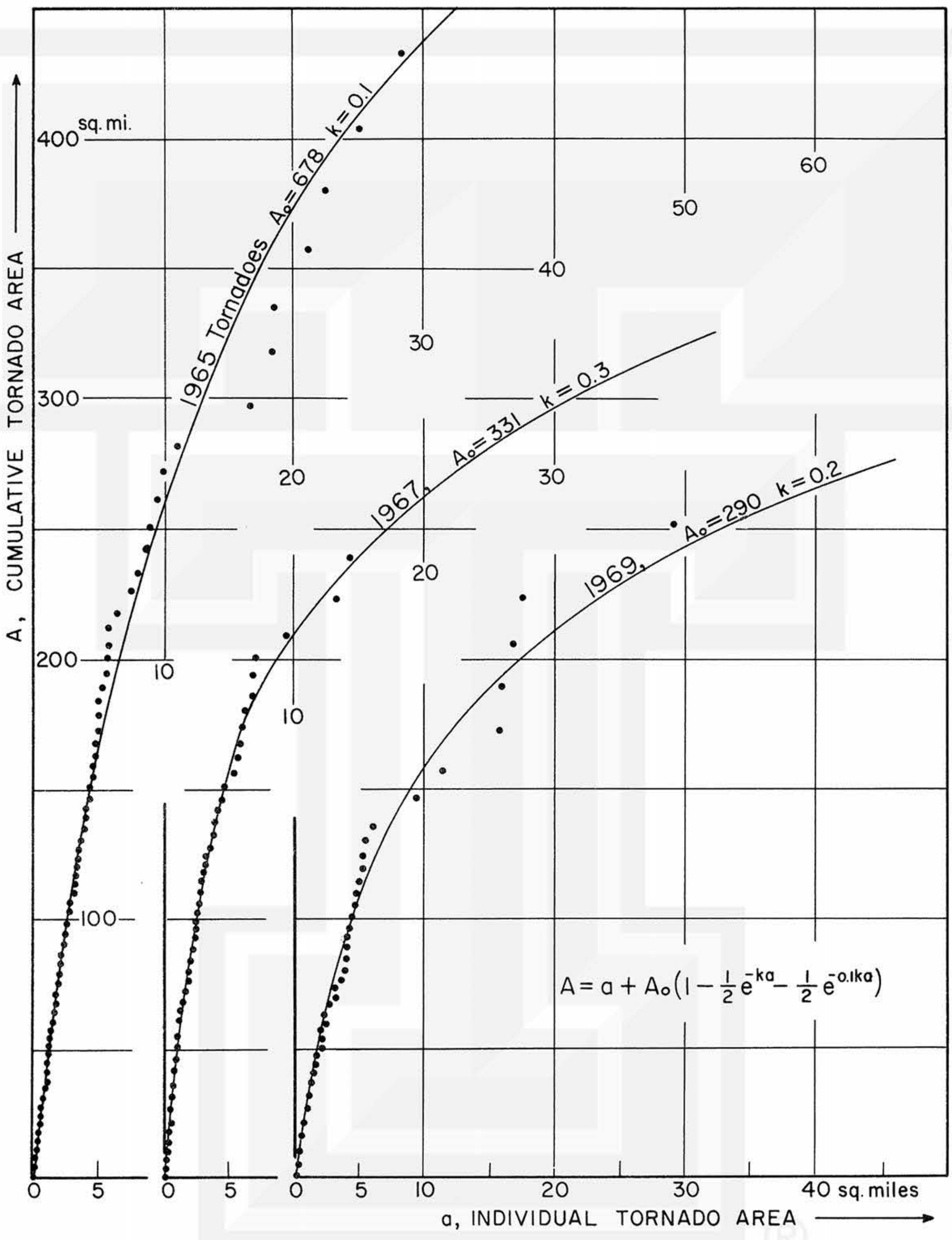

Fig. 8. Cumulative tornado areas plotted against individual tornado areas with lengths and widths tabulated in Storm Data. Each curve was computed from Eq. (11) by using two constants obtained empirically.

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