U.S. DEPARTMENT OF COMMERCE
Environmental Science Services Administration
Research Laboratories

ESSA Technical Memorandum ERLTM-NSSL 49

TORNADO INCIDENCE MAPS
Revised

Arnold Court

National Severe Storms Laboratory
Norman, Oklahoma
First Printing August 1970
Revised May 1973

FOREWORD

Discussions on tornado climatology, cosponsored by the National Severe Storms Forecast Center (NSSFC) and the National Severe Storms Laboratory, were held at NSSFC, Kansas City, Missouri, on 1 August 1968. These discussions illuminated a need for improved scientific reporting of tornado occurrences and led to the study described in these pages.

In his comprehensive review, Dr. Court considers practically all published reports of tornado distribution in the United States and clearly illustrates both the difficulties inherent in systematic classification of tornado occurrences and some ways by which current practice can be improved. His recommendations are provided in section 6.

Dr. Court began this study during the spring semester 1969, while on a Faculty Research Leave from San Fernando Valley State College, and completed it the following year. Although this work has not been commissioned by the NSSL, our staff is pleased to have assisted in its preparation; of particular importance has been the photographic work by Mr. Charles Clark.

Edwin Kessler
Director, National Severe
Storms Laboratory

TABLE OF CONTENTS

	Page
FOREWORD	
ABSTRACT	1
1. INTRODUCTION	1
1.1 Purpose	1
1.2 Representation	2
1.3 Early Studies	4
2. 1881-1915	6
2.1 Finley	6
2.2 Objections	8
2.3 Second Tabulation	10
2.4 Abbe's Analysis	12
3. 1916-1950	14
3.1 Renewed Interest	14
3.2 Location by Counties	16
3.3 Tornado Days	19
4. 1951-1965	20
4.1 Coordinate Tabulations	20
4.2 Official Publications	22
4.3 Location of Maximum	25
4.4 Smoothed Maps	28
5. RECENT	29
5.1 Regions	29
5.2 Official Compilations	32
5.3 Encyclopedias and Textbooks	33
5.4 Competition	34
6. CONCLUSIONS	36
6.1 Perception	36
6.2 Methodology	38
7. REFERENCES	41
8. FIGURES	49

TORNADO INCIDENCE MAPS

Arnold Court[1]

Tornado occurrences in the United States have been tabulated and shown on maps since 1884, but very few of the 109 such maps, reproduced and discussed here, show actual tornado incidence per year per unit area; most are totals for periods of 6 to 62 years, by states, or by latitude-longitude quadrangles of varying areas. In the past century, the apparent center of maximum tornado incidence has moved southwestward, from western Illinois to Iowa and Missouri, to Kansas, and now to central Oklahoma, where the annual incidence per 10,000 square miles is 3 to 21 tornadoes, depending on the period for which reports are used. Proliferation of official tabulations, by states and quadrangles and for varying periods, has obfuscated the pattern of tornado occurrence, and failure to tabulate and map the actual damage areas has precluded a clear depiction of actual tornado hazard. To eliminate confusion, tabulations and damage area maps by 5-year and 10-year periods beginning in 1956 are recommended.

1. INTRODUCTION

1.1 Purpose

Tornado incidence in the United States has been mapped more than 40 times in the past 90 years, but in so many different ways so that few pairs of maps are directly comparable. As the various maps have been reproduced in textbooks, reference works, and articles, often without details as to basis or manner of construction, readers have been needlessly confused about the true picture of tornado incidence.

---

[1] Professor of Climatology, California State University, Northridge (Los Angeles), California 91324.

No effort is made in this report to present a "true" pattern of tornado incidence, but some suggestions toward such a depiction are offered in the conclusion. Instead, the 90-year history of tornado maps and other representations is discussed in detail, and reproductions are offered of all available published maps of tornado incidence. Many are not true maps at all, but merely locational enumerations or "pseudo-maps", as discussed in the next section.

Some of the 109 maps and other representations included here are facsimiles with errors of varying degree, while others are almost exact copies which have received much wider dissemination than the publications in which the originals appeared. The presentation is generally in chronological order of the data depicted (not of publication date), but the discussion may be in slightly different order, to maintain topical continuity.

The sequence of tornado maps and pseudo-maps depicts the changes in the professional and popular perception pattern of tornado occurrences - the way in which meteorologists and educated laymen thought and think that tornadoes occur in the United States. Human responses to the threat of tornadoes, whether by constructing storm cellars, purchasing insurance, or planning warning networks, are based on perception, not reality. Perception is not the same for all people, partly because of conflicting sources of information, or misinformation. Tornado perception has varied markedly during the past century, whatever the actual tornado incidence has been or is.

Many different aspects of tornadoes have been tabulated and mapped over the years, including the number of individual funnels, the number of days on which tornadoes occurred, the number of deaths due to tornadoes, and the total property damage caused by them. Concerning the tornadoes themselves, the time of occurrence speed and direction of travel, and dimensions of the destructive path have all been listed and enumerated, but none of these has been shown on maps.

Discussion of the spatial distribution of a highly localized phenomenon, such as tornadoes, is simplified by adoption of a distinction, not ordinarily made, between two words: occurrence will be used in its normal connotation, while incidence will apply to "specific occurrence", the number of occurrences in a unit area. A recurrent theme in this report is the effort, by a few perceptive students, to achieve tornado incidence statistics instead of crude occurrence figures. Speculations on the reasons for the general lack of such information are offered in the conclusion.

1.2 Representations

Occurrences of a phenomenon, such as tornadoes, can be represented in several ways, as outlined in table 1. The

Table 1. Methods of Tabulating or Depicting Phenomena, such as Tornado Occurrences, Days, Deaths, or Damage

Listings Usually chronological, often with descriptive details; of

(1) All reported occurrences, or

(2) Major or significant occurrences only.

Enumerations Total numbers during some specified period:

(1) Columnar, often with numbers of different phenomena in separate columns

(a) by counties or states, usually alphabetically, or

(b) by regions, usually in geographic arrangement.

(2) Locational, by numbers entered in each county or state on a "pseudo-map".

Graphs Usually chronological, to show;

(a) time trend, from consecutive annual values,

(b) annual variation, by totals or averages for each month, week, pentad, or day, and

(c) diurnal variation, by totals or averages for each hour.

(1) Simple, often arranged alphabetically.

(2) Locational, by graphs inserted in or near each state on a graph-map.

Maps

(1) Pictorial, by circles or symbols indicating magnitude in each county or state.

(2) Choropleth, by shading each state or county according to value.

(3) Isopleth, by lines showing equal intensity per unit area.

tentative classification is shown by increasing degree of complexity; generally the utility and clarity of the presentation increases with the complexity.

Listing is the simplest method, and is useful primarily as a basis for more elaborate presentations. Yet many reports on tornadoes devote more space to simple listings of notable tornadoes than to summarizing them in tables, graphs, or maps.

Enumerations give the total number of occurrences during one or more years, sometimes offering totals for different aspects in adjacent columns, such as total tornadoes, total deaths, and total damage. The enumeration is by various districts, such as counties within a state or states of the United States, generally in alphabetical order. In rare cases, the totals are divided by the area of the county or state to give true incidence. A common variation is to present the enumeration as numbers on a base map rather than in a table, but such a presentation is not a true map and is called here a "number-map" or "pseudo-map."

Graphs are often used to show the variation with time of a phenomenon, either as bars or as a fictitious continuous function of time. Such variations may be year by year, or may be for the annual (month-by-month) or diurnal (hour-by-hour) variation. Several such graphs may be placed one below the other, sometimes in alphabetical order, or they may be inserted in their appropriate locations on a map - which is still not a true map, and is called here a "graph-map".

Maps represent data by area by symbols of various kinds. On cartograms, the numbers of a locational enumeration are shown by symbols, such as circles, whose size is proportional to the numbers; no tornado cartograms have been found. Greater generalization is attained by a choropleth map, in which the various states (or counties) are shaded in different ways, each indicating an interval on the enumeration scale.

Isopleth maps offer the greatest degree of generalization and interpretation. Isopleths are contour lines of the presumed actual distribution of the phenomenon, which in practice is measured or sampled over arbitrary regions (counties, states, or latitude-longitude quadrangles) whose boundaries have little relation to the variations of the phenomenon. Isopleths differ significantly from other forms of representation, in that they must refer to unit areas, and hence must show incidence, as defined above. All the other methods of representation may show either occurrences or incidence.

1.3 Early Studies

Regrettably, no accurate recent tornado incidence maps are available. Most representations of the past two decades have

been of tornado occurrences in entire states, or by 1° or 2° "squares" of latitude and longitude. Areas of such quadrangles vary by more than one-third from the southern to the northern limits of the conterminous United States.

Numbers of both individual tornadoes and of tornado days have been tabulated; some pseudo-maps list both. Deaths also have been mapped, but rarely as incidence, and not at all as specific mortality, with reference to population "at risk" rather than to area. Almost all representations are based on points of origin, or "first contact with ground," of tornadoes, not on total area affected.

To make comparisons of different maps and pseudo-maps even more difficult, many show the total number of reports during some period, varying from 5 to 63 years, rather than the average per year. Compilers have lost sight of the primary function of their intended product, which should be to provide estimates of the frequency of tornado occurrence at any given location or, better yet, the probability of tornado damage.

Early students of tornadoes were much more perceptive, although their information was too meagre for valid conclusions. In his monumental Climatology of the United States, Lorin Blodget (1857, p. 403) wrote:

> **The frequency and distribution of these tornadoes is a subject of practical interest, as in the case of the hurricanes. They occur over every part of the United States where the rain fall is abundant, and at the seasons of its greatest abundance. There are none on the great plains so far as known, at a distance from the Mississippi sufficient to reach the dry regions; they are most numerous in the Mississippi valley, and from this eastward they are quite equally distributed from Canada to Georgia. In the old forests, particularly of New York and Pennsylvania, the tracks of those which prostrated the older growth a century since may still be traced by the belt of trees of uniform size and peculiar aspect which grew up subsequently. The earth hillocks are thickly crowded over the soil of these belts, on all tracks where the soil readily turns up with the roots of trees. From the clue to frequency which such tracks give, these storms must be placed at very remote intervals for any one locality —the permanence of such a forest trace could be relied upon for at least five hundred years, and they now exist in only a few conspicuous lines, averaging fifty miles distant perhaps, and lying in threads of thirty to two hundred rods in width, and ten to fifty miles in length. The tracks are so narrow that great frequency would be required to mark the entire surface, yet it must be concluded that they are not more frequent than the hurricanes, while the space they cover is the smallest thread in comparison to those gigantic displays of atmospheric disturbance.**

Windfalls of trees in Wisconsin, as reported by government land surveyors between 1834 and 1865, were analyzed in detail by Increase A. Lapham, civil engineer, geologist, and meteorologist. His letters and articles were a major factor in the creation in 1870 of the first government weather service

(Miller, 1931). He became "Assistant to the Chief Signal Officer" in charge of the Chicago office, from which he issued the first official forecast, a storm warning, on 8 November 1870. A few months later, however, he relinquished this post to return to his business interests in Milwaukee, where he had lived since 1836, but continued to help the new weather service by calculating barometer reduction tables and preparing instructions and background studies.

One of these studies, reported in May 1872 in an unpublished letter to the Chief Signal Officer, as quoted by Burley and Waite (1965), summarized his study of the 360 windfalls. He found "about one chance in probability in 10,000 that any particular farm of 160 acres (in any one year) will be visited" by a tornado. This is 4 tornadoes per 10,000 square miles per year, somewhat more than the average reported incidence of 2.8 in Wisconsin in recent years. But it was a much more rational statement than the conclusions of most tornado tabulations of the ensuing century.

These tabulations are discussed, with emphasis on the geographical pattern of tornado occurrence or incidence, in the following four sections, followed by conclusions.

2. 1881 - 1915

2.1 Finley

The first comprehensive tornado tabulation was the "Report on the Character of Six Hundred Tornadoes" by John Park Finley (1884), then a sergeant in the Signal Corps. He wrote prolifically on tornadoes for the next decade and 50 years later, long after retirement as a colonel, was still active. Born in Ann Arbor, Michigan in 1854, Finley (1925) "received education at the High School and State Normal College, Ypsilanti, and... specialized in meteorology and climatology in the four-year course at the Michigan Agricultural and Mechanical College..." He later studied at the University of Michigan and at Johns Hopkins University.

Entering the Signal Corps in 1877, Finley "finished regular courses of instruction and became Assistant to the Chief Signal Officer... in charge of the field investigations of violent local storms with headquarters at Kansas City." There he "first advised the building of tornado caves in 1879 as a means of saving life" (Finley, 1888b, p. 64). Commissioned in 1883, he served in Boston as forecast official and officer in charge of the New England division, in San Francisco in similar capacities for the Pacific Coast division, and later as forecast official in Washington.

Between 1880 and 1896, Finley (1925) wrote 23 Signal Corps publications, 61 "books, monographs, pamphlets and articles published by the National Bureau of Statistics," 5 "public documents published by authority of the Congress," 6 scientific journal articles, 39 newspaper and magazine articles, 7 commercial publications, and 9 "miscellaneous" items, and gave 41 public lectures, most of them illustrated. Almost all this activity was about tornadoes, although some concerned cyclonic storms, hurricanes, frosts, and other topics.

When the civilian Weather Bureau was created in 1891, Finley retained military status but was "appointed by the President as Weather Bureau expert pursuant to special Acts of Congress." He served as a Forecast Official, and "Special Forecast Official for the prognostication of violent local storms." Although later Finley (1925) listed among his assignments "editor of the Monthly Weather Review," this must have been for only one or two numbers, since his name does not appear as editor of any of the annual volumes; during the 1880s each monthly issue often bore the name of a different junior officer as editor.

Finley (1932) "continued climatological work during ... nearly 12 years of public service in the Philippine Islands between 1899 and 1914, part of the time being served in Europe and Asia." After retirement, he was "consulting meteorologist and statistician" for "The National Storm Insurance Bureau ... organized in 1920 for the practical operation of the Finley System of Weather and Crop Insurance" (Finley, 1929); aviation was added to the bureau's title later. Finley died in 1943, according to Library of Congress index cards, but no obituary or biography has been located.

Finley's first major publication "was written in 1881-1882, but it was not published for distribution until 1884. The first edition had to be suppressed on account of many typographical errors, and they were not all eliminated from the second edition..." (Finley, 1888a). It presented a detailed table of the time, place, and characteristics of 600 tornadoes and a map summarizing the total number of tornado reports, by states, and of the years for which information was available in each. From this Finley compiled a map (reproduced here as fig. 1A) of the "Geographical distribution of tornadoes during a period of 87 years from 1794 to 1881, inclusive," by isolines and shading. "The lines of equal distribution are drawn for a common difference of five, and the figures at the ends of the lines indicate the relative frequency with which tornadoes occurred within the various areas bounded by these lines." Thus the lines are not true isopleths, which would show frequency per unit area.

This first tornado occurrence map was redrawn for a double page, two color insert (fig. 1B) in American Weather by General

A. W. Greely (1888), who had just become Chief Signal Officer and hence Finley's superior. Of it he wrote:

> Data of this kind is always incomplete, especially in the thinly settled portions of the country, and so the lines of equal frequency are somewhat uncertain; but there can be no doubt, however, that the relative frequency is greatest in the valleys of the lower Missouri and of the upper Mississippi. It has been demonstrated by Ferrel that this region is theoretically liable to tornadoes owing to the counter-currents of cold air from the northward, and warm, very moist southerly winds from the Gulf of Mexico, which latter currents tend to cause an unstable state of the atmosphere.
>
> Finley has pointed out that tornadoes rarely if ever occur west of the 100th meridian, in which regions the lack of aqueous vapor and the want of intensity in other phenomena of cyclonic storms furnish sufficient reasons for their non-existence.
>
> The tornado follows a definite path, which, as a general rule (about eighty per centum), is from the southwest toward the northeast. About ten per centum move from northwest to southeast. The path of greatest violence varies, as a general rule, between one hundred and six hundred yards in width, and from one to fifty miles in length. The progressive movement of the tornado is very rapid, being rarely under twenty miles an hour or over fifty miles, and the time taken in the passage of the immediate centre is between five and ten minutes.

Later, Finley (1887) indicated the locations of each individua tornado by large dots on a map (fig. 2A) "showing the geographical distribution of tornadoes as observed during a period of 125 years, 1760-1885." Another booklet (Finley, 1888b) contained a different map (fig. 2B) of "The geographical distribution of tornadoes to show the areas of maximum tornado frequency by states" and the years for which data were available. Individual state maps showing tracks of all tornadoes were included, along with tables; these were reprinted (Finley, 1889) in successive issues of the American Meteorological Journal.

2.2 Objections

Some colleagues complained that Finley had included many non-tornadoes, and had accepted exaggerated statements about path length, width, and damage. Dr. Gustavus Hinrichs (1888-1889), founder and director of the Iowa Weather Service, maintained that many of Finley's tornadoes were really "derechoes". This

"straight blow of the prairies," he said, "is a powerfully depressing and violently progressing mass of cold air, moving destructively onward ... generally towards the southeast;" formerly he had called them squalls. Hinrichs also complained:

> The climate of Iowa has been most outrageously maligned both by thoughtless or sensational newspaper correspondents and by official and semi-official publications of the Signal Service in ascribing to Iowa an excessive tornado frequency. Both of these ever-grinding tornado mills for Iowa have furnished abundant material for frightening people from settling in Iowa, and for coaxing residents of Iowa into the thriving tornado insurance institutions of both the East and the West.... John P. Finley's tornado maps for the several states ... are worse than even the sensational advertisements of the tornado insurance companies.

After examining the circumstances of the 107 Iowa tornadoes, 1875-1888, listed by Finley, Hinrichs found "only 7 multiple and 9 single notable tornadoes" and 14 minor and doubtful ones -- "the real tornado frequency of Iowa has averaged one a year," and the total occurrences were only one fourth of Finley's figures. Hinrichs also recommended strongly that "the only truly scientific method of tornado record will be by date," rather than counting as a separate occurrence each time that a tornado touched the ground, or each of two or three parallel storms.

Finley's (1890) essay won the $200 first prize in the "tornado competition," the first such contest of the American Meteorological Journal, announced in its issue of September, 1888 (p. 221); entries were due on 1 July 1889, with a $5 fee. The $50 second prize went to Alexander McAdie, then a student at Clark University, and another $50 was divided between John M. Bennett and Professor H. A. Hazen. Finley (1888a) had bitterly refuted a claim by Hazen to priority in discovering that tornadoes usually formed southeast of a low-pressure center, and Hazen (1890), advocating an electrical theory of tornadoes in opposition to Ferrel's dynamic explanation, which Finley accepted, digressed to deprecate Finley's tabulations.

More pertinent objections to Finley's tabulations were voiced by Professor Cleveland Abbe, astronomer turned meteorologist who also had aided in creating the national weather service and become its principal forecaster, chief scientist, and editor (Abbe, 1955). In discussing "Recent Progress in Dynamic Meteorology" for the "Record of Science for 1887 and 1888" in the General Appendix to the Annual Report of the Smithsonian Institution, Abbe (1888) wrote:

> The number of tornadoes likely to occur in any State in any one year is shown approximately by the figures ... copied from Finley ...; but the relative geographical distribution is only fairly shown by adopting some such unit of area as 100 miles square or 10,000 square miles ... (This) annual average frequency ... should replace the misleading statement of the number of tornadoes on record in any State, without considering the area of the State or the number of years and observers ...
>
> When we consider the narrowness and shortness of the destructive portion of the depths of most 'tornadoes', we see that even in Kansas and Iowa the probability that any given spot will be visited by one is at the rate of less than 1 per cent per century, or less than the chance of death by lightning or railroad accident, or other casualty.

Abbe recomputed Finley's state totals to give the "annual average per 10,000 square miles", but because he didn't map these figures, Finley's first map (fig. 1) was widely used for half a century. Perhaps in response to Abbe's criticism, one of the 22 tables in Finley's small book (1887, p. 118) showed the "average number per year" per state and also the "average number per year for 10,000 square miles." The numbers differed because Finley divided state totals by the entire span of years for which he had any data, while Abbe divided by only the number of years in which tornadoes were reported to obtain annual incidence per 10,000 square miles:

	Kans.	Ill.	Mass.	Mo.	Iowa	Nebr.
Abbe	8.85	1.13	1.12	0.77	0.58	0.24
Finley	0.67	0.44	----	0.52	0.49	0.43

Earlier in the book, Finley said that "Kansas and Missouri rank the highest in regard to frequency," without further elaboration.

2.3 Second Tabulation

Five years after the weather service was transferred from the Army Signal Service to the new Weather Bureau, its young (39) new chief (Moore, 1896a) reported that the St. Louis tornado of 27 May 1896, in which 306 persons were killed, had been "the means of awakening general interest in tornadic phenomena, and also of stimulating the business of tornado insurance". He directed the compilation and publication of tornado records of the preceding 8 years, because "the purchasers of tornado insurance should also be supplied with whatever information might be furnished to the companies."

In compliance, Professor A. J. Henry (1896) listed the characteristics of all known tornadoes from 1 January 1889 to 30 June 1896, with as much care and detail as Finley had used. He found that "rigid adherence to the rule adopted for classifying tornadoes would include a number of storms which, by the accident of chance, passed through a thinly settled region or diminished in intensity before reaching any considerable settlement. The property loss caused by a single severe hailstorm is often greater in the aggregate than that of a dozen such storms, yet their insertion in the lists is proper and necessary."

Henry's figures were used by his chief (Moore, 1896b) in a comprehensive discussion presented to the Missouri State Board of Agriculture, apparently during an inspection visit in September, 4 months after the devastating tornado. Moore, who had risen from printer to senior forecaster during 15 years in the Signal Service (Whitnah, 1961), discounted Finley's work:

> Statistics of the occurrences of tornadoes have been collected by the signal service and weather bureau from 1874 to the present time. Unfortunately the tornado reporters were, in a majority of cases, persons unskilled in the observation of complex physical phenomena, and it also seems that there was a tendency on the part of some to report as many storms as possible. The signal service authorities compiled and published a list of 600 tornadoes, said to have occurred in a period of eight years, 1874 to 1881, both inclusive. This would give an average of 75 per annum.
>
> Continuing the compilation down to the middle of 1887, a record was made of nearly 2,000 additional tornadoes, said to have occurred in the United States previous to that date. The increase in the later years is so great and the reports now on file with the weather bureau, from which the record was made, are, in many cases, so vague that a careful investigator is led to believe that many storms, unattended by material destruction, which should have been classed as thunderstorms, have been erroneously set down as tornadoes. Many of the records of storms, moreover, are so imperfect that we are warranted in rejecting them.
>
> In order to determine the frequency of tornadoes, we may sum up the number of storms each year and divide by the number of years, or we may simply count the number of days on which tornadoes formed and determine the average number of days with tornadoes. The objection to the first method is that a single tornado, if observed at half a dozen different points,

> will count as six tornadoes, as may have been done by the signal service. We believe the second method preferable, and have, therefore, used the published and manuscript lists of tornadoes as a means of determining the number of days on the average with tornadoes...
>
> From these data (1875-1889) it would appear that there are on an average 55 days each year on which a tornado is liable to occur somewhere in the territory liable to tornado visitation... Evidently so broad and general a statement has little practical value when it is desired to know, so far as the records of past years throw light upon the subject, the possibility of a locality being visited by a tornado...

Comparing the Iowa tornado tabulations of the Signal Service and Hinrichs, Moore showed "the difficulty of attempting to reach definite conclusions respecting tornado frequency from the data collected by the signal service." Although Moore had retabulated Finley's data to show an 1875-1889 average of 55 tornado days, he made no effort to map or continue such a tabulation and merely summarized Henry's information on "number of tornadoes and money value of property destroyed," by years and by states.

2.4 Abbe's Analysis

Again Abbe objected to state totals. In an editor's note (which, like his previous article, has escaped recent students of tornado statistics), Abbe (1897) said:

> The chance of injury from a tornado evidently depends upon both the frequency of tornadoes per unit area and on the area covered by the path of the tornado, viz., the product of its length by its breadth. The area of destruction in any individual case will rarely amount to more than 25 square miles.

To Henry's data he added the 8-year (1874-1881) table prepared by Finley (1884); Finley's later tabulation (1887) could not be used because it did not give data by years. From this combination Abbe obtained "the number of tornadoes annually per state and per unit area" of 10,000 square miles, by dividing the total for each state by its area and by 16. He should have used 15.5 because Henry's tabulation ended in June, 1896; this error was later corrected by Hunter (1925). Abbe's maximum values were 0.90 for Illinois, 0.86 for New Jersey, 0.79 for Kansas, and 0.61 for Iowa. He did not map his results, but offered this interpretation:

> If these large areas be divided up into 100 smaller ones of 100 square miles each, or 10 miles square, then the possibility that some one of these will be visited by a tornado within a year is less than 1 per cent, but the probability that any specific one of these smaller areas will be so visited is only the hundredth part of 1 per cent per annum, or 1 per cent per century. Within such a smaller area of 10 miles square the destructive path of the tornado, when it finally comes, will probably cover less than 25 square miles, so that the probability that some one of the 100 areas of 1 square mile will be struck is less than one-fourth of 1 per cent per century; but for any specific area or farm of 1 square mile the probability is much less than one-sixteenth of 1 per cent per century. In fact, the probability that a given house will be destroyed by a tornado is less than the probability that it will be destroyed by lightning or fire.

This final comment was reiterated in Abbe's (1899) short popular article, along with the estimate that a given square mile would experience a tornado only once in 1,000 years. This is not consistent with his previous estimate of 1/16 per cent per square mile century, or 6.25×10^{-6} per square mile per year. However, if the average tornado damage area is 10 square miles and the annual incidence is 1 per 10,000 square miles, the point probability of tornado damage is 0.001 or 1 per 1,000 years.

Earlier, William Morris Davis (1894, p. 282) had said in his Elementary Meteorology, the standard textbook in the field for more than two decades, that "... the danger from tornadoes at any one place is much less than has been supposed. The annual loss to the country by fire and flood greatly exceeds that caused by tornadoes." Although he devoted 12 pages to describing and explaining tornadoes, with diagrams, Davis gave no tables, graphs, or maps of their occurrence.

Despite Moore's (1896a) professed interest, after 1 year as Weather Bureau Chief, in comprehensive tornado reporting, the collection of such information was suspended the next year. Thus, Henry (1906), for his massive "Climatology of the United States," had only his own tabulation, that by Finley, and Abbe's interpretations, which he quoted at length. But he offered no map of tornado incidence, and Finley's representations remained for 45 years the sole depiction of tornado hazard, which seemed centered in Kansas and Missouri.

Finley's first tornado incidence map (fig. 1A) was the basis for three representations in the first quarter of the 20th century. Greely's (1888) version (fig. 1B) was copied, with

poor results, in Milham's Meteorology (1912, p. 339). Another version (fig. 2C) was used by Ward (1917) for an article on tornadoes, but was not included in an excerpt of the article nor in Ward's book (1925, p. 351), in which the full article formed the tornado chapter, because "A map showing the distribution of tornadoes is apt to be more or less misleading ... and must not be taken too literally." Still another version of Finley's first map appeared (fig. 2D) in the first two editions of Kendrew's (1922) The Climates of the Continents.

For almost 40 years, Snowden D. Flora, Weather Bureau meteorologist and later climatologist for Kansas, tried valiantly to remove the tornado stigma from his state. While accepting Henry's (1896) evidence that "the total number of tornadoes in Kansas is somewhat greater than the number in any other state," Flora (1915) cited Abbe's arguments and insisted that "When the relative areas are considered, however, the number of tornadoes in Kansas per unit area is practically the same as the corresponding number of Iowa and is but slightly greater than the number of Illinois."

3. 1916 - 1950

3.1 Renewed Interest

Collection of tornado statistics was resumed by the Weather Bureau in 1916; in some states, such as Kansas, it began 1 or 2 years earlier. "The details were printed regularly, year by year, in the Report of the Chief of the Weather Bureau, with a chart for each year to illustrate the occurrence," according to Hunter (1925), who was responsible for the tabulations for many years.

Within 2 decades, these statistics would be used for two careful and cogent compilations, more realistic than any published thereafter. But the first few years brought forth no new tabulations or discussions. One of the few popular articles (Pickwell, 1924) of the day offered dramatic photographs of three tornadoes, no maps or tables, and confusing misinformation:

> The prevailing idea that tornadoes occur during midsummer has crept into textbooks, but ... statistics ... show that nearly 80 per cent take form in the first three months of spring ... Texas, Oklahoma, Kansas, and Missouri run neck and neck for funnel-cloud honors .... New England is never visited.... The outer walls of the funnel may travel at from 300 to 500 miles per hour .... As a whole the tornado ... never travels less than 40 miles per hour and often more than 60.

More prosaic was Hunter's (1925) own summary of the first 8 years of data. He corrected the 1916-1923 tabulations and combined them into a single table. He also added 6 months to Henry's (1896) data, used by Abbe (1897), and included Finley's earlier counts. The combined results appear in two choropleth maps of "Average occurrence of tornadoes, per year per State, for 25 years," (fig. 3A) and "Average loss of life from tornadoes per year per State, for 17 years" (fig. 3B). Not only did Hunter map annual averages, not totals, but he offered in his table 3 "The average per year per unit area in each State" to correspond with Abbe's (1897) table; he did not specify the unit area as 10,000 square miles. Leading states were Iowa 0.91, Kansas 0.88, and Arkansas 0.83.

No further reproduction or copying of Hunter's maps has been found, but the table provided new ammunition for Flora (1928). He told the annual convention of the American Meteorological Society, in Kansas City at Christmas:

> Undoubtedly, Kansas is in what is known as the tornado belt of the country but ... at the western edge of this belt. Of the 176 storms tabulated (1914-1928) 45 per cent occurred in the eastern third of the State, 34 per cent in the middle third, and but 21 per cent in the western third. There is no reason to think that Kansas is more infested with tornadoes than several other States.... The tabulation by Hunter ... showed during 25 years more tornadoes per unit area in Iowa than in Kansas and practically as many in Arkansas, Illinois, and Missouri.

The following year Flora (1929) continued his defense: "In the 13 years ending with 1928 more tornadoes occurred in Kansas than in any other State," but both Iowa and Arkansas had more, considering their relative areas.

Much more rational than Hunter's presentation was that by his superior, Preston C. Day, longtime Chief of Climatological Services in the Weather Bureau. Under his direction, Keith B. Allan prepared a pseudo-map (fig. 5A) according to Abbe's recommendations of 30 years earlier, although Day (1930) did not mention Abbe. Tracks were plotted for all 1,481 tornadoes reported up to 1928 since 1916, when the Weather Bureau first began "to collect tornado statistics on a uniform basis for all parts of the country." The map was then divided by east-west and north-south lines 100 miles apart to form squares of 10,000 square miles. Each track "was counted in each square over which it passed," and the totals were divided by 13 to give true annual tornado incidence per unit area - the only such representation ever published.

An isopleth version (fig. 5C) of this most correct of all tornado incidence compilations was prepared by Allan for the U.S.

part of Handbuch der Klimatologie (Ward and Brooks, 1936); this version, in turn, was redrawn schematically (fig. 5B) for Kendrew's (1937-1943) third and later editions.

Unfortunately for Flora, Allan's data showed "an area of maximum occurrence of tornadoes over extreme northeastern Kansas at slightly more than 3 per cent" per 10,000 square miles, three times Hunter's value; incidence was nearly as great "in nearby portions of Nebraska, in central Arkansas, and generally over the greater part of Iowa," - which would have annoyed Hinrichs.

A map (fig. 3C) bearing "lines representing ... the number of tornadoes which occurred within a radius of 40 miles of any point ... during the 10-year interval" 1916-1925 was issued by the National Board of Fire Underwriters (1929). The lines were labeled by "points of charge or deficiency for use with the National Board Grading Schedule for Cities and Towns," related to relative frequency by:

Relative Frequency:	2	4	6	8	10	12	14	16	18
Points Charge:	0	5	10	15	20	25	30	40	50

No record has been found of the method for determining the decadal number of tornadoes within 40 miles of a point. A 40-mile circle contains 5,027 square miles, so multiplication of the 10-year frequencies by 0.2 gives annual incidence per 10,000 square miles. Maximum tornado expectation was shown on the Red River north of Dallas, in central Arkansas, and in southeastern Kansas, all at 50 points, or 18 x 0.2 = 3.6 per 10,000 square miles per year. This maximum is close to Day's (1930) value, but in different locations.

A similar actuarial use was intended for two maps of relative tornado frequency prepared by Finley (1932), based on all his old data (Finley 1884, 1887) as well as the more recent reports. One map (fig. 4A), copyrighted in 1929 but for an unspecified period, had 21 lines between the regions of minimum occurrence in eastern Nevada and of maximum occurrence in northern Missouri, southern Iowa, and eastern Kansas; a secondary maximum was shown in southern Texas, with a notable deficiency over Oklahoma, apparently the continuation of the lack of reports apparent in his early maps (figs. 1 and 2). On the second map (fig. 4B), copyrighted in 1931, 41 lines separated the minimum region, now extending well into Idaho, from the maximum region in northern Missouri; the Texas maximum and Oklahoma deficiency both were much less pronounced.

3.2 Location by Counties

Tracks, used by Allan for Day's (1930) map (fig. 5A), were also studied during the early 1930s by Dr. Charles Wilson Brown, longtime professor of geology at Brown University, and discussed

at three meetings of the American Geophysical Union. The first paper (Brown 1933) gave a graph of the yearly distribution of reported tornadoes from 1880 to 1931 and two maps of tracks of 2,017 tornadoes from 1917 to 1931: cyclonic (1,390) "associated with a well-developed cyclonic low-pressure area" (fig. 6A) and convective (627), "if cyclonic control seemed to be feeble or wanting and temperature developments indicated the existence of an unstable atmospheric condition" (fig. 6B).

The two track maps were drawn by a student assistant, Wyndham O. J. Roberts, who had tabulated and classified the tornadoes and became coauthor of two later papers (Brown and Roberts, 1935, 1937). In the second paper, the analysis was extended to all 3,911 tornadoes reported in 52 years, 1880-1931, and a combined track map was offered (fig. 6C). It is reproduced here from the original kindly supplied by Mr. Roberts, for the past 25 years meteorologist for the Illinois State Water Survey.

Annual variation was graphed by groups of states, discussed in section 5.1. "The graphs showing the number of tornadoes occurring in the different states would be of great value if the states were of equal area," so the totals for each state were divided by the state's area, "eliminating areas not subject to tornadoes," such as half of Michigan, a third of Nebraska, a half of Texas, and a tenth of Tennessee. Kansas and Iowa were still first and second in total frequency, but ranks changed for other states. However, this method was "still quite unsatisfactory," because it considered only "the number of tornadoes occurring, disregarding their average length and width."

Efforts to use the actual path length and an assumed average width of 0.1 mile, however, became very confused in the second and third papers. During 15 years, Kansas (81,744 square miles) had 2,855 miles of tornado track, so that "one linear mile of tornado path occurred for each 28.66 square miles of Kansas" in that period. Such "occurrence ratios," computed for each county, revealed that "one northeast county on the Missouri River is twice as subject to tornadoes as any other county in the state."

In their final paper, Brown and Roberts (1937) mapped, (fig. 5D)"Areal Frequencies of Tornadoes in the United States by Counties" according to the "occurrence ratio," defined on the map as "1 mile of tornado track 1-10th mile wide to square miles of county area in 51 years," rather than 52 years. But the numbers in the legend range from 5 to 100, 100+, and None, with the smallest numbers in tornado alley; 10 is considered a "high frequency".

Apparently these numbers actually are the "liability ratio," which can be inferred from the text as the ratio of total area to 10 times the devastated area, not reduced to annual basis.

The reciprocals of 520 times the mapped values thus would give the estimated annual per cent of area devastated, or at least struck, by tornadoes:

Occurrence Ratio:	5	10	20	30	40	60	80	100
Annual % Struck	.0384	.0192	.0096	.0064	.0048	.0032	.0024	.0019

If tornado paths average 0.1 mile wide and 10 miles long, for a net area of 1 square mile, 3 tornadoes per 10,000 square miles per year (the maximum on Day's map, fig. 5A) would represent 0.03 per cent annual devastation, in general agreement with the data of Brown and Roberts. They converted Day's (1930) annual unit area incidence map to isopleths, which were superposed over their county-by-county choropleth map (fig. 5D).

Perhaps because the significance of this map was unclear, it was not used in any later meteorological publications, and no further analysis has appeared of the area actually affected by tornadoes for the whole country. Nor have other writers accepted the term isotorn, proposed by Brown and Roberts (1937, p. 144) for "lines enclosing irregular areas of equal tornado frequency"; it does not appear in the Glossary of Meteorology (Huschke, 1959).

The "Geographic distribution of deaths in tornadoes in the United States, 1922 to 1935" was represented (Metropolitan, 1936) by shading the states according to the total number of deaths, by 50-death intervals; Illinois led with a 14-year total of 672. At least Hunter (1925) had given mortality by states on an annual basis (fig. 3B).

The 121 tornadoes reported in Nebraska during 22 years, 1916-1937, had paths averaging 288 yards wide and 7.5 miles long, "or an average land coverage of 1.2 square miles each," Lemons (1938) found. Thus, he said, more than 10,000 years would be required for all parts of the state to be struck by tornadoes, without repetitions.

Tornadoes were not discussed, tabulated, or mapped in the 1912 and 1923 editions of Bulletin W, nor in its 1930 successor, nor in the famous 1941 Climate and Man. An extensive report on "Losses from tornadoes, other windstorms, and hail" was prepared in the late 1930s by Robert J. Martin, but not published, perhaps because of wartime restrictions; a mimeographed summary, "Tornadoes in the United States, 1916-1937, inclusive" was issued by the Weather Bureau in 1940. Its maps of the total and average numbers of tornado occurrences and deaths, by states, received only limited distribution, and did not affect professional or public perception of tornado incidence, and therefore are not reproduced here.

But Martin's data, especially his analysis that "1,000 tornadoes, selected at random" 1927-1936 traveled an average of 45 miles per hour along paths averaging 396 yards wide and 13.4 miles long, was used extensively by Flora (1953) and hence continues to be cited.

"A rather complete tabulation of the total and average yearly number of tornadoes and deaths of damage caused by them in each State or section for the period 1916-1942" was given by Baldwin (1943) for comparison with similar data in the customary annual report for 1943; the data were not mapped. Greatest average annual numbers were Kansas 15.7, Iowa 14.9, Texas 13.3, and Arkansas 10.1.

3.3 Tornado Days

Days on which tornadoes had occurred, rather than number of individual tornadoes, had been advocated by Hinrichs (1888-1889) and Moore (1896b) as the proper statistic for climatic tabulation, but no maps of tornado days appeared for half a century. In a "Preliminary Report on Tornadoes," prepared in response to wartime requirements for protection of military installations, Showalter and Fulks (1943) gave pseudo-maps of the total number of tornado days, by states 1880-1942, for the year (fig. 7A) and for each month (figs. 7B-7M), the first monthly tornado maps. The 63-year totals were neither divided by 63 nor adjusted to unit area.

From these monthly and annual totals of tornado days, Petterssen derived for the second edition of his textbook (1956, p. 190) another pseudo-map (fig. 9B), mislabeled as the "Geographical distribution of tornadoes in the United States, 1880-1942" by "states or groups of states". Besides equating tornado days with tornado occurrences, this pseudo-map shows the months of maximum frequency by single letters: March-April is designated as MA in Georgia and Tennessee, April-March as AM in Arkansas, Louisiana, and Texas, while AM means April-May in Oklahoma and Missouri; Florida's maximum month is April, but is labeled JUL. In addition, seven "main regions according to the annual variation" are indicated; these are compared with other regionalizations in section 5.1.

In the second edition of Petterssen's (1958) smaller elementary textbook, the same pseudo-map of total tornado days in 63 years was used, but the legend became further distorted to "Average number of tornadoes by states," specified as "average annual number" and "average number during the months indicated." No Kansan, apparently, objected to being credited with an annual average of 413 tornadoes, about 6 times the current estimate, so the same error continued in the third edition (Petterssen, 1969), where the figure was redrawn (fig. 9C) for clarity, eliminating the months but retaining the 63-year totals of tornado days as annual averages.

The 1880-1942 tornado day data given by Showalter and Fulks (1943) were used in the famous "Thunderstorm Rainfall" (Hydromet, 1945). One graph map (fig. 9A) shows the monthly totals by histograms, and a similar chart (fig. 8A) gives the corresponding figures adjusted to unit area, but not to an annual basis, as "Tornado days per 10,000 square-mile-area per state." Twelve other maps (fig. 8) give unit area totals by states for each month with superposed isopleths (in red in the original) of the average number of days with thunderstorms.

The annual unit-area graph map (fig. 8A) was reproduced by Taylor (1954, p. 238) and also by Flora (1949), who continued his efforts to save the good name of his home state:

> There is a general belief that Kansas, often miscalled the 'cyclone state,' is the place of the most frequent occurrence of tornadoes. When relative areas are considered, records show that Iowa and Arkansas lead in this respect, and several states and the District of Columbia have had nearly as many or more tornadoes per unit area.

The Hydromet unit-area map presumably also was the basis for a tiny choropleth map of the "Number of tornado days per year over equal areas, by states" in a "Golden Nature Guide" (Lehr et al., 1957, p. 101). "Equal areas" are not defined, nor is a source or period of record indicated. The states east of the Rockies are shaded at intervals of 10 days/year, with apparently Iowa, Kansas, Arkansas, Alabama, and South Carolina credited with more than 40.

Also offered by Hydromet (1945) was a map (fig. 9D) of the months having the greatest number of tornado days, 1880-1942. This was redrawn, much more clearly (fig. 9E) for Visher's atlas (1954, p. 171), which included among its 1031 representations of U.S. climate only one other tornado map, an isopleth depiction (fig. 10A) of the "Normal annual number of tornadoes (based on state averages)." No source or period of record was given for this map, listed as "original". Its area of greatest annual number, more than 10 tornadoes (per state?) includes most of Arkansas, Oklahoma, Missouri, Kansas and Iowa.

4. 1951 - 1965

4.1 Coordinate Tabulations

Around 1950, a new procedure was introduced into the routine tabulation of tornado occurrences in the Climatological Services Division of the Weather Bureau. For more than three decades, at the end of each year, the tracks of all individual tornadoes, as reported by state climatologists, had been entered on a large map of the country, on which counties were shown. Totals for each

state were then obtained, with tracks crossing state boundaries credited to each state affected.

The additional step was to tally the "points of first contact", i.e., the beginnings of each track, by quadrangles of latitude and longitude, 1° on a side. Areas of such quadrangles decrease from 4,109 square miles at 30-31°N to 3,354 square miles at 45-46°N, but only three users of such summaries have attempted to compensate for this bias; most ignore it. Summaries by coordinate quadrangles offer much greater detail than summaries by states, or even than by the 100-mile squares used by Allan for Day (1930), but not as fine as the county-by-county mapping of Roberts for Brown (1933).

For the first tornado incidence map based on such coordinate quadrangles, by Fawbush et al.,(1951), each quadrangle total was divided by the actual area of the quadrangle and then multiplied by 2,500 to approximate the "Total number of tornadoes per 50-mile square reported in the period 1920-1949" by months and annually (fig. 11A). These adjusted 30-year totals were expressed by isopleths (isotorns?) with irregular progression. The region of maximum incidence, from northeastern Oklahoma to northern Iowa, had more than 2 tornadoes per 10,000 square miles per year.

The various reprintings of the annual map (fig. 11B-F) do not give the details of its construction, and thus imply that the data were tabulated originally by true 50-mile squares rather than by regions 20 to 60 per cent larger (Flora, 1953, p. 34; Kimble, 1955, p. 101; George, 1960, p. 449; Miller, 1966, p. 90). In their own reprinting of the map, Fawbush and Miller (1953) identified it as giving frequency, but without specifying the areal unit.

This annual map was also reprinted in "An Information Digest for Air Commanders" (USAWS, 1955), with the caution that the numbers indicate the chance "not that a specific point within the area will be hit, but that a hit will occur within the 2500 square mile area." In addition, another pseudo-map (fig. 10E) was offered of the 30-year totals, 1920-1949, of tornadoes occurring within 60 miles of each of 68 Air Force bases; "during the past 15 years, a total of seven have actually struck Air Force bases."

Tornado occurrences ending in 1949, the last year used by Fawbush, et al., (1951) but beginning four years earlier, in 1916, and by states only, were used in Flora's (1953) Tornadoes of the United States for three maps of 34-year state totals: of tornado occurrences (fig. 10B), of deaths (fig. 10C) and of damage (fig. 10D). These cursory pseudo-maps, bearing only state names and numbers, contrast strongly with the reproduction, on an adjacent page, of the shaded incidence map (fig. 11C), prepared by Fawbush et al. (1951).

In Flora's second edition, published a year later, 3 1/2 more years' data, to the end of June 1953, were added to these three pseudo-maps, and to tables listing tornadoes, tornado deaths, and tornado damage by years. But his Table II, "States having the greatest number of tornadoes per unit area", was unchanged. It gave, for 13 states, the area, the average annual number of tornadoes, 1916-1949, and "Average annual number per unit area of 10,000 square miles," listed here in table 2.

Assuming that "the average tornado path covers approximately three square miles," apparently derived from Martin's unpublished 1940 study, Flora offered also the chances "that a given square mile ... will be struck in any one year." These figures, given in table 2, do not correspond exactly with the 1916-1949 unit area frequencies; perhaps they were based on a different period. Such "chances" are conceptually identical to the "liability ratio" of Brown and Roberts (1937), discussed earlier (page 18).

Flora (1953, pp. 29-32) continued to defend Kansas:

> Their greatest frequency in occurrence has been in Iowa, northwestern Missouri, and eastern Kansas. Iowa has had more of them in proportion to its size than any other state.... Fatalities have been greater in Illinois than in any other state.... More deaths caused by tornadoes have been reported in Indiana, Kentucky, and Tennessee than in Kansas and Iowa.... Property damage from tornadoes ... has been greater in Oklahoma than any other state.

A decade later, Spohn and Waite (1962) rallied to Iowa's defense, in the spirit of Hinrichs, and declared that, based on 1916-1961 data, "the reporting intensity center has since shifted southwestward." Iowa, they said, is "immediately northeast of the heart of the most destructive tornado zone," and was now fourth among states in total number of tornadoes since 1916.

Flora's (1953) book was apparently the sole basis for an extensive article by the photographic editor of Nature (Evans, 1954), which included several photographs but no tables or maps. Flora's figures were offered as "Weather Bureau estimates" of the chances of "any single square mile being visited by a tornado within any given year," as given here in table 2. Although Flora's tornado risk for Arkansas was 1 in 1,933, Asp (1956) found that on the average (1923-1955) less than 1 square mile in the 53,850-square-mile state was hit by tornadoes per year.

4.2 Official Publications

All data used by Flora, by Fawbush et al., and by all other students of tornado distribution came from the tabulations of

the Weather Bureau, which itself did not issue any extensive report on tornadoes during its first 60 years of existence. The first government publication on tornado distribution since Finley's (1884), USWB Technical Paper No. 20 (Wolford, 1952), gave no consideration to unit areas, and offered annual average by states in only one table. Instead, it returned to the technique used by Brown and Roberts (1935), showing the tracks of each reported tornado, 1916-1950, on 12 monthly maps and an annual map (fig. 25) of all 5,204 tornadoes. But this map was not gridded to count the tracks by true squares, as Allan had done (Day, 1930) to estimate annual tornado incidence. The annual track map was reproduced in Manos' (1958) study of tornado action in spreading histoplasmosis.

Annual tabulated averages were: Kansas 17.66, Iowa 14.23, Texas 13.74, Oklahoma 11.40, Arkansas 9.25; these figures have been converted to annual incidence values in table 2. Deaths were also tabulated but neither mapped nor graphed. National averages were 149 tornadoes, 66 days, and 227 deaths annually.

Suspecting that the great expansion in tornado reporting after 1950 might provide a pattern different from that presented in Technical Paper No. 20, Lee (1958) tabulated tornado reports by states, adjusted to 10,000-square mile areas, for the 7 years 1950-1956. As Abbe had done 70 years earlier, Lee divided the 7-year totals for each state by the state's area (fig. 13B). Had he also divided by 7 he could have shown, for comparison with other studies, annual incidences per 10,000 square miles, as given here in table 2.

"Average monthly variation in tornado frequency, based on a total of 6,970 tornadoes" 1916-1954 was shown (USWB, 1955) by bar graphs for each state on a poster (fig. 13A) and possibly used on the back of the "Daily Weather Map". Annual averages were given for the whole country, but not for individual states.

Tornado occurrences by quadrangles 2° on a side, rather than the 1° grid used by Fawbush et al., (1951) were used in the USWB "Forecasting Guide No. 1" (Winston, 1956) for a shaded isopleth map (fig. 12A) of the "Total number of reported tornadoes per 2° latitude-longitude square over the United States, 1916-1955." This map was later redrawn (fig. 12E) for an article by House (1963) based on his chapter in the Guide, and this version was used in Science (Walsh, 1965), erroneously credited to "Technical Paper No. 20, 1960."

Actually, a very similar map (fig. 12B) did appear as one of two new maps, on different bases and for different periods, in the revision (Wolford, 1960) of Technical Paper No. 20, in which data for 8 more years were added to the tables and graphs in the original paper. The same map (fig. 12B) was also issued by the Weather Bureau as a single-sheet leaflet (USWB,

Table 2. Annual Tornado Incidence per 10,000 Square Miles, Computed from Data of Various Publications, and Flora's Annual Chance of Given Square Mile Being Struck in Any One Year

Author Year Published: Years of Data:	Flora 1953 ? ? Chance	Flora 1953 1916- 1949 Incid.	Wolford 1952 1916- 1950 Incid.	Lee 1958 1950- 1956 Incid.	Wolford 1960 1916- 1958 Incid.
Iowa	1:1,203	2.8	2.54	1.70	2.48
Kansas	1:1,613	2.1	2.15	8.86	2.95
Arkansas	1:1,933	1.6	1.73	3.17	1.95
Oklahoma	1:2,262	1.5	1.65	8.33	3.46
Mississippi	---	1.3	1.24	2.16	1.51
Alabama	---	1.1	1.50	1.24	1.46
Missouri	---	1.0	1.13	2.57	1.50
Indiana	1:3,559	0.9	1.00	3.94	1.73
Illinois	1:3,987	0.9	0.84	2.20	1.25
Florida	---	---	0.80	3.27	1.11

1960a), citing 7,206 tornadoes in the 40-year period; House's (1963) figure was 7,867. The map was reproduced, unchanged, in an architect's Reference Guide (Mageneau and Gilbertson, 1960) along with several graphs and tables from Technical Paper No. 20, revised (Wolford, 1960), which also had been issued with L. S. numbers.

This version, and six other Weather Bureau tornado graphs and tabulations, mostly for 1916-1955 but one for 1916-1958, and four Air Force Fact Sheets were also reproduced in "Tornado alley" (USAWS-USWB, 1960). It included a pseudo-map (fig. 13C) of "Average annual tornado frequency" by states for 42 years (1916-1957), 2 years more than the isopleth map. In turn, this 42-year pseudo-map was reprinted in The Airman (USAF, 1961), and was redrawn (fig. 13D) for a new college climatology textbook (Critchfield, 1960).

The same basic 40-year isopleth map, with a line for one tornado per quadrangle added from the Guide version and the shading changed, illustrated (fig. 12D) a discussion of storm

hazards by Reichelderfer (1957). Redrawn again to eliminate numbers on the isopleths, this map (fig. 12C) appeared in the Scientific American (Tepper, 1958) to show "Frequency of tornadoes in the U. S. from 1916 to 1965," without quantitative specification. This article has been reprinted as part of a science education series, and may have been seen by more secondary and college students than any other representation of tornado occurrence.

McKay and Lowe (1960) extended Winston's (1956) map to Western Canada (fig. 12F) by adding 1916-1955 Canadian data for 2° quadrangles, obtained largely from newspaper accounts. Some of the isopleths near the border were adjusted to agree with the added data, but this correction has not appeared on any other versions of the original map.

Although the basic map (fig. 12) in Winston's (1956) Forecasting Guide and Technical Paper No. 20, revised (Wolford, 1960) used 40 years of data, 1916-1955, the monthly track maps, and all tables and graphs in both were for 3 more years, 1916-1958. In addition, the latter paper offered a pseudo-map (fig. 14A) of totals by 1° quadrangles for only 6 years, 1953-1958. Thus this official government publication presented tornado occurrences in three different ways (track, and 1° and 2° quadrangle totals) for three different periods (43, 40, and 6 years) -- but none per unit area per year.

In each version, however, one of the tables did offer annual averages per state, but not per unit area. The 1916-1958 averages showed some shifts from the 1916-1950 values in the original Technical Paper No. 20. Kansas was still first with 24.21 per year, followed by Texas with 23.23, Oklahoma with 19.91 and Iowa with 13.93. Incidence figures based on these averages are given in table 2.

4.3 Location of Maximum

On the widely-reproduced maps (fig. 12) in Forecasting Guide No. 1 (Winston, 1956) and Technical Paper No. 20, revised (Wolford, 1966), the isolines of total occurrences in 40 years, by 2° quadrangles not adjusted for area, showed a maximum of more than 250 around Wichita, Kansas. This is 3.12 tornadoes annually per 10,000 square miles, close to the maximum value on Day's (1930) map (fig. 5) 30 years earlier, but farther to the southwest. But the other representation in Technical Paper No. 20, revised (fig. 14A), the pseudo-map of 6-year totals by 1° quadrangles, showed a maximum five times greater and 200 miles still farther southwest; 37 tornadoes in 6 years in the quadrangle in extreme southwestern Oklahoma, or 15.4 tornadoes annually per 10,000 square miles. This map was reissued (fig. 14B) (USWB, 1960b) to include 1959 data, with maximum incidence still in southwestern Oklahoma; data from a portion of this pseudo-map was used by Orton (1964), as discussed later.

The apparent shift in the location of maximum tornado incidence per unit area from Kansas, based on 1916-1955 data, to Oklahoma, in the 1953-1958 tabulation, would have delighted Hinrichs and Flora. After Flora's death in 1957, his campaign to clear the name of Kansas was continued by the late F. C. Bates (1962), then a professor at the University of Kansas:

> The title, 'Cyclone State,' has been worn like a hair shirt by Kansas since 1923. Innocently projected by 'The Wizard of Oz' and statistically merited until 1961, this title has conveyed for Kansas an image of dusty plain incessantly lashed by these awesome storms.

Until 1949 Kansas reported about 17 tornadoes per year, Oklahoma 14, and Texas 9, he said, but since 1953, with more intensive reporting, the figures had been Kansas 57, Oklahoma 62, and Texas 87. Thus, " ... the title, 'Cyclone State,' has now passed to Texas for the greatest number of tornadoes reported over the 46-year period, or to Oklahoma for the greatest frequency per unit area ..." But Bates did not specify the unit area, and instead offered a map (fig. 16E) bearing two sets of isopleths, one showing a maximum in south central Kansas of more than 250 tornadoes, 1916-1955, the other a maximum in central Oklahoma of over 300 tornadoes, 1916-1961. The corresponding incidence rates are 7.5 and 8.4 per 10,000 square miles per year.

Texas scornfully rejected Bates' nomination. In "The Climate of Texas and the Adjacent Gulf Waters," the Weather Bureau state climatologist (Orton, 1964) wrote:

> From 1916 to 1961, 1,281 tornadoes are known to have touched ground in Texas. This is an average of only 1 tornado for each 231 square miles. Area for area, tornadoes occur more frequently in Oklahoma and Kansas.

Orton transferred to a map of Texas and parts of adjacent states the 1953-1959 totals for 1° quadrangles (fig. 14B) from a recent leaflet (USWB, 1960a). He found that "the area along the Red River from about Childress, Texas, to Ardmore, Oklahoma, has the highest tornado frequency of any area of similar size in the United States." Actually, this pseudo-map for 1953-1959 showed seven more tornadoes in extreme southwestern Oklahoma and adjacent Texas than did Wolford's (fig. 14A) for 1953-1958. Thus the incidence rose from 15.4 to 15.8 annually per 10,000 square miles, and was only slightly less in the next quadrangle to the east. Orton also commented on "a greater frequency of large tornadoes with wide paths and long trajectories in North Texas and Oklahoma than in South Texas."

Apparently Bates' figures had come from data by 2° quadrangles in two different representations, for 40 and 46 years, respectively. The first (fig. 12), of 1916-1955 totals, used by Winston (1956) and Wolford (1960), showed a maximum in south central Kansas. The other (fig. 16A), for 1916-1961 totals, prepared by Max Feinsilber for Sadowski (1965) and reproduced in Tornado Preparedness Planning (USWB, 1968), showed a maximum of 305 tornadoes in the quadrangle in extreme southwestern Oklahoma and neighboring Texas.

Through oversight, both Sadowski and the preparedness pamphlet labelled the 1916-1961 pseudo-map as giving totals for 45 years, instead of 46. Redrawn to make the numbers slightly smaller (and in the process omitting many state boundaries), this pseudo-map illustrates (fig. 16B) a new elementary textbook (Miller and Thompson, 1970, p. 189), retaining the erroneous "45-year period" in the legend. Another representation of 1916-1961 tornado data, a graph-map (fig. 15B) of "Average number of tornadoes by months," by states (USWB, 1962) was correctly labeled as for 46 years. Also correctly labeled was a pseudo-map (fig. 16C) of "Average annual tornado frequency" by states, "based on a total of 11,053 tornadoes over a period of 46 years, 1916-1961" (Knight, 1964).

Still another 1916-1961 tabulation, by 1° quadrangles, (fig. 15A), issued by USWB (1962a), was reproduced by Spohn and Waite (1962) and by Burley and Waite (1965) in studies of Iowa and Wisconsin tornadoes, by Roth (1963), and perhaps others. The data were expressed by Longley (1970) as 10-year averages per 1° quadrangle on a chropleth map (fig. 16F) for an elementary textbook.

The 305-tornado maximum in southwestern Oklahoma appears clearly on a map of "Tornado frequency" (fig. 16D) by Sadowski (1965), a much more graphic presentation, although its legend does not specify the numbers as being for 2° quadrangles, not adjusted for area. This total of 305 is actually not the greatest such concentration. For the pseudo-map (fig. 16A) used by Sadowski, and in Tornado Preparedness, the 1° totals (fig. 15A) had been grouped into 2° quadrangles bounded by parallels and meridians for even degrees of latitude and longitude. In this coarser mesh, the greatest tornado total is in southwestern Oklahoma, 98-100°W, 34-36°N, at 305 tornadoes in 46 years, or about 8.5 per 10,000 square miles annually. But the 2° quadrangle offset 1° to the east, at 97-99°W, 34-36°N, has a total of 334, or 10 percent more. The greatest total for a 1° quadrangle (fig. 15A) in each of two "squares," in northeastern and central Oklahoma, is 88 in 46 years, or 6 percent still more.

4.4 Smoothed Maps

A central Oklahoma maximum in "Mean annual frequency of tornadoes, 1953-62" of 5.0 for a 1° quadrangle appears on a pseudo-map (fig. 17A) in Thom's (1963) refreshing effort at applying mathematical statistics to estimating "the probability of a tornado striking a point", not merely a unit area. Detailed data on the widths and lengths of tornado paths in Iowa and Kansas were found to be consistent only since 1953, so 1953-1962 was considered "a kind of standard period" for computation.

Widths (in yards) and lengths (in miles) were fitted separately by log-normal distributions, and then combined, with the appropriate covariance, into a log-normal distribution of tornado damage area, with a mean of 4964.8 yard-miles, or 2.8209 square miles. This is not much less than the 3 square miles found by Martin and used by Flora (1953), but is double the 1.2 square miles estimated for Nebraska by Lemons (1938), and a tenth of Abbe's (1897) estimate of the damage area as "less than 25 square miles." The annual numbers of tornadoes in central Iowa were fitted by a negative binomial, which gave a mean annual frequency of 1.37.

As Lapham, Abbe, and Brown and Roberts had considered much earlier, Thom (1963) wrote:

> The probability of a tornado striking a point is the ratio of the mean area covered by tornadoes per year to the area over which the tornadoes may occur.

Assuming that the number of tornadoes per year varies geographically but the mean path area of tornadoes does not, he proposed that the probability of tornado damage anywhere in the United States could be estimated as 2.8209 T/A, where T is the mean annual frequency of tornadoes in an area of A square miles. Hence he offered a smoothed "map of the total number of tornadoes occurring in 1° squares," and a table of the areas of such quadrangles. The "total number" in each quadrangle was the average of the observed total for that quadrangle and 1/4 the sum of the totals in the four adjacent quadrangles. These 10-year totals were divided by 10 for a second pseudo-map (fig. 17A) of annual values, "needed for estimating probability of a tornado striking a point."

The computation would have been further simplified if the smoothed values had been divided by the areas to give true estimated areal incidence per year. (The central Oklahoma maximum is 12.9 annually per 10,000 square miles.) Thom offered no justification for his particular "Hann" smoothing, but said: "Data from other areas should also be analyzed to determine whether the tornado characteristics presented here are invariant

over larger areas or possibly physically invariant." Although no such studies have appeared, Thom has said in conversation that his assumption of invariance is confirmed. His pseudo-map was further smoothed by isopleths (fig. 17B) to illustrate Kessler's (1966) popular paper.

"Tornado frequency 1916-1963, based on reports of 1° squares" was shown by isopleth shading (fig. 18A) in the 1965 version (FAA-USWB, 1965) of "Aviation Weather". Shadings were for 10-30, 30-50, and over 50. Thus a large crop of civilian pilots have been told to expect more than 50 tornadoes in an area from Fort Worth to Dodge City, to Omaha, without being informed how often: 2.8 or more annually per 10,000 square miles.

"The mean number of tornadoes per hour for the period 1916-1964" was mapped (fig. 18D) for the United States east of 104° W by Skaggs (1969). For his 1967 doctoral dissertation at the University of Kansas, he forsook latitude-longitude quadrangle tabulations and used data by counties, as Brown and Roberts (1935, 1937) had done. All tornadoes originating in a county were credited to the square, 100 miles on a side, in which most of the county fell. Totals for the 100-mile squares were then accumulated, four at a time, into 157 overlapping 200-mile squares, using each original total in each of the four larger squares containing it.

Because his primary interest was in the harmonic analysis of the diurnal variation in tornado incidence, and the spatial variation in such representations, Skaggs divided the smoothed 49-year totals for each 200-mile square by 24 to obtain an "average hourly total". To reduce these values to annual incidence per 10,000 square miles, for comparison with other representations of tornado incidence, they must be multiplied by 24 X 10,000 / 40,000 X 49 = 0.12245. Thus the 49-year maximum "mean number per hour" of 30 tornadoes per 200-mile square in northern Oklahoma and southern Kansas corresponds to 3.7 per 10,000 square miles per year. This is only slightly more than the 40-year maximum of 3.1 shown (fig. 12) in the same place by Winston (1956) and Wolford (1960) and their copiers, but much less than the 12.9 in central Oklahoma on Thom's 1953-1962 pseudo-map (fig. 17A).

5. RECENT

5.1 Regions

Times of occurrences to the nearest hour, local standard time, of the first report of each tornado, 1916-1964, were also combined by Skaggs (1969) into frequencies for each 200-mile square, and represented by 12 harmonics. The diurnal variation of tornado occurrence in each square was characterized by 12 phase angles and 12 values of the relative reduction in variance attained by the 12 harmonics. These 24 attributes were then

subjected to cluster analysis to group the 157 squares into three broad regions of similar diurnal variation; these regions were further divided into a total of 8 subregions (fig. 22D).

Various groupings of states (table 3) had previously been used (Wolford, 1952, 1960; Lee, 1958) for graphs, but not maps, of the diurnal variation in tornado occurrence. The same groupings were used for graphs of the annual variation in tornado incidence, a practice begun by Brown and Roberts (1935). Unfortunately, the groupings changed with each investigator; although Lee intended "to study the distribution State by State, monthly and hourly, for comparison with the results of the earlier study" by Wolford (1952), he found that different arrangements were more suitable, thus preventing direct comparison (table 3). Lee also provided diurnal variation graphs for other state groupings: New England, North Atlantic, Rocky Mountain, Pacific Coast. His annual variation graphs were for individual states, except for some combinations of northeastern states.

Table 3. State Groupings Used for Tornado Frequency Graphs

Annual Variation

Brown and Roberts (1935):

Georgia, Alabama, Mississippi, Louisiana, Tennessee, Arkansas;
Texas, Oklahoma;
Kansas, Iowa;
Missouri, Illinois, Indiana, Ohio;
Nebraska, Wisconsin, Michigan.

Annual and Diurnal Variation

Wolford (1952, 1960):

Florida, Georgia, Alabama, Mississippi, Louisiana;
Texas, Arkansas, Oklahoma, Missouri, Kansas;
Iowa, Nebraska, Minnesota, South Dakota, North Dakota.

Diurnal Variation

Lee (1958):

Georgia, Alabama, Mississippi, Louisiana;
Tennessee, Arkansas, Kentucky, Missouri;
Illinois, Indiana, Wisconsin, Michigan;
Iowa, Nebraska, Minnesota, South Dakota, North Dakota;
Individually: Florida; Texas; Oklahoma; Kansas.

House (1963):

Same as Wolford (1960), above, with Georgia omitted in the legend of his fig. 4.

Regionalization of tornado occurrences primarily on the basis of the month of greatest frequency (fig. 9D) had been presented by Hydromet (1945) and copied (figs. 9B, 9C, 9E) by Visher (1954) and Petterssen (1956).

Regions of an entirely different sort from those mapped by Skaggs (1969) and Hydromet (1945) were described (fig. 22C) by Linehan (1957) for his Clark University dissertation, revised and published as USWB Technical Paper 30. Of 8,741 deaths caused by tornadoes as reported by the Weather Bureau during 38 years, 1916-1953, Linehan rejected 69 as erroneous or inadequately documented, but found 70 additional reports. All except 8 of these 8,742 could be assigned to specific calendar days; each reported death was plotted as a dot on a large U.S. map.

Thus, " ... to organize these widespread but areally contrasted death clusters into groups whose characteristics possess some measure of homogeneity, ... the country has been divided into a number of tornado death regions" based on "the number of deaths and the manner of their distribution." Four such regions were shown on his map (fig. 22C) and used in related discussion.

Linehan's efforts were to no avail. A decade later, a new pseudo-map (Metropolitan, 1967) of tornado mortality (fig. 22B) offered only state totals for 5 years, 1962-1966, the same method followed 30 years earlier (Metropolitan, 1936). No consideration was given to either unit areas or population.

Sadowski (1965) had been much more realistic in estimating (fig. 22A) "potential casualties per square mile for 45 years" (actually 46 years); this pseudo-map was reprinted, with the same title, in "Tornado Preparedness Planning" (USWB, 1968), and without the "45 years" in "Operations of the Weather Bureau" (USWB, 1967, p. 29). To obtain "potential casualties", the 46-year tornado total in each 2° quadrangle was multiplied by two ratios. One was the area of the quadrangle divided into the average tornado damage area, assumed to be 2 square miles, although Thom (1963) had computed the average as 2.8209 square miles, and Flora (1953) had accepted Martin's estimate of 3 square miles. The other was the 1960 population density, in persons per square mile, of the quadrangle, or actually of the counties falling mostly within it. The county area was also used for the tornado incidence computation, apparently on the unstated assumption that all reported tornadoes formed over land.

Sadowski's (1965) maximum potential casualties are 11.5 tornado-persons per square mile per year in the 2° quadrangle including Connecticut, Westchester county, Long Island, New York City, and Sandy Hook; he pointed out that "no tornadoes have occurred in New York City," although they have occurred in Westchester county and in nearby New Jersey.

5.2 Official Compilations

Tabulations, graphs, and pseudo-maps -- but very few real maps -- of tornado occurrence have been issued by various elements of the national weather service in the past decade in profusion. Some blatant contradictions regarding the distribution of tornadoes over the United States appear.

Oldest disseminator of tornado information is the Environmental Data Service (EDS), ESSA, formerly the Office of Climatology, USWB. Its state climatologists gather the basic observations on individual tornadoes, and the Climatology Division of its Office of Data Information combines them in various ways. Besides monthly reports (in the Monthly Weather Review until 1949, in the Climatological Data, National Summary, 1950-1958, and since then in Storm Data), this division prepares various summaries for publication and for supply to other ESSA elements, other government agencies, and the public.

Many are as "Letter Supplements", used for at least two decades to answer public inquiries. These tables, graphs, or maps are either prepared to meet specific requests or taken from other publications, such as reports and articles. They are designated "L.S. 0000"; the same four-digit number followed by "Rev" is used for successive versions of the same basic presentation, distinguished by date. Some confusion is possible in this procedure as discussed later (fig. 20A, B). No record is available of all versions of "Letter Supplements".

Other tornado publications have been prepared by both the Emergency Warning Branch and the Technical Procedures Branch of the Weather Analysis and Prediction Division, Office of Meteorological Operations, Weather Bureau. This division, and its predecessors, supplied some of the tornado material issued by the ESSA Public Information Office. Four versions of one 16-page pamphlet were:

"Tornadoes," (USWB, 1965a) with pseudo-map (fig. 17C) of "Average annual tornado frequency," apparently 1953-1962.

"Tornadoes," (USWB, 1966) with different text and pseudo-map (fig. 20C) of "Annual average tornado frequency by states, 1953-1964".

"Tornado," (ESSA, 1967) with rearrangement of the same text and untitled choropleth map "based on 1953-1965 figures," apparently of annual averages by states.

"Tornado," (ESSA, 1969a) a reprinting in brighter colors, so that choropleth map shades were almost indistinguishable in the first printing but somewhat clearer in the 1970 printing.

The data in the second "Tornadoes," labeled as 1953-1964, agree with neither of two pseudo-maps (figs. 20A, 20B), each titled "Average annual tornado frequency by states, 1953-1964," issued by USWB (1965b and c). The first has numbers one-tenth those given as "Tornado Frequency by States, 1953-1962" on a map-back poster (fig. 19A) (USWB, 1964). The second bears numbers one-twelfth those on a pseudo-map (fig. 19B) of "Tornado frequency by states, 1953-1964" (Kutschenreuter, 1965). But these numbers are slightly smaller than those on the "Tornadoes" (USWB, 1966) pseudo-map (fig. 20C) ostensibly for the same period.

On the first edition of "Tornado Statistics," (ESSA, 1966) the pseudo-map (fig. 21B) of "Annual average tornado frequency by states, 1953-1965," showed numbers much larger than the 1916-1964 state averages in an adjacent table. Another table gave numbers of tornadoes and tornado days, deaths, and damages, by years 1916-1965. The first table indicated the 49-year nationwide annual average was 240.35 tornadoes, the total of the state averages, rather than 12,878/49 = 263; the second showed a 12-year average of 628. No such discrepancies appeared in the second edition (ESSA, 1968), which offered no tables, only graphs and a pseudo-map (fig. 21D) of "Tornado indicence by states, 1953-1967" showing 15-year totals, not averages. The third edition (ESSA, 1969b) added one more year to the pseudo-map totals (fig. 21E).

The 1916-1964 annual average was cited correctly as 263 in "A Proposed Nationwide Natural Disaster Warning System (NADWARN)" (Kutschenreuter, 1965). It contained reasonably current data: a pseudo-map (fig. 19B) for 1953-1964, and graphs of "Tornado frequency by months ... 1916-1964". But its implementation, "Tornado Preparedness Planning" (USWB, 1968), less up-to-date, included Sadowski's (1965) pseudo-map (fig. 16A) by 2° quadrangles for 1916-1961, and a choropleth map (fig. 21C) of "Average annual number of tornadoes by state" for an unspecified period, which appears identical to the small untitled 1953-1965 map in the third and fourth printings of "Tornado" (ESSA 1967, 1969a). Public officials and citizens can compare 1953-1965 state data on a choropleth map with 1916-1961 data on a pseudo-map, by 2° quadrangles, in the same publication to assess their need for tornado preparedness.

5.3 Encyclopedias and Textbooks

The variety of tornado occurrence pseudo-maps and a few true maps appearing in research publications in recent years has not been reflected in reference works and textbooks. No tornado incidence maps, but some photographs, appear in current major encyclopedias: Americana, Britannica, Chambers, Colliers, McGraw-Hill. The most extensive discussion in any current encyclopedia is in W. A. Baum's meteorology-climatology article in Colliers, citing annual tornado occurrences as about 250 nationally, with a maximum of 25 in Kansas; neither unit area

nor point probability is mentioned. The Brittanica article, by Robert G. Stone, has been revised to place the region of maximum incidence "from Iowa to northeastern Texas."

Textbooks in meteorology and climatology offer a wide variety of pseudo-maps, with little discussion; those of Taylor (1954), Petterssen (1956, 1959), George (1960), Miller (1966), Longley (1970), and Miller and Thompson (1970) have already been mentioned.

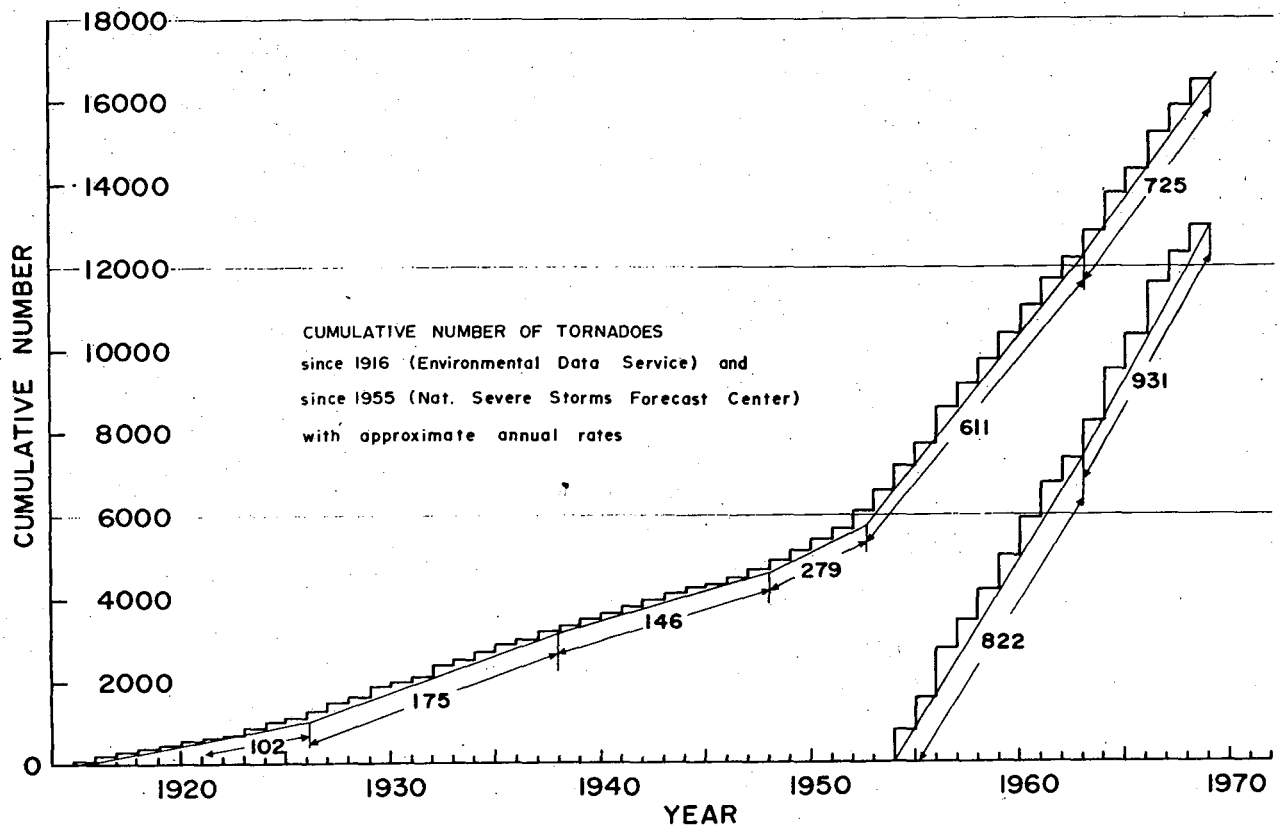
"Iowa, Arkansas, Kansas, Mississippi, Alabama, and Missouri lead in frequency of tornadoes per year per unit area, ranging from 2.7 to 1.0 in that order," Day (1966, pp. 178-179) said, without specifying the unit area as 10,000 square miles, or the period; this order differs from those of Table 2 (page 24). Day's elementary textbook was illustrated with a pseudo-map (fig. 21A) of state totals for the five year period 1960-1964. The same statement and the same pseudo-map were retained in the second edition (Day and Sternes, 1970), with addition of another pseudo-map, of "annual average tornado frequency by states, 1953-1964," from the second "Tornadoes" (USWB, 1966) (fig. 20C).

Two recent college climatology texts present identical data, differently mapped (figs. 18B-C), of total tornado occurrences and tornado days in 45 years, 1916-1960, by states (Critchfield, 1966, p. 128; Rumney, 1968, p. 78), and the same bar-graphs of total occurrences and total days, by months; Critchfield's first edition (1960) had a similar pseudo-map, (fig. 13D) for three years less.

No map, but a table of "Total number of tornadoes per state and total number of tornadoes per 1,000 square miles per state for the period 1953-1964" appears in a recent climatology workbook by Neuberger and Cahir (1969) for prospective high school earth science teachers. Reduced to annual incidence per 10,000 square miles, the 12-year totals become 9.6 in Oklahoma, 7.3 in Kansas, 6.0 in Massachusetts, 5.2 in Iowa, and less than 5.0 elsewhere. " ... The very high frequency in Massachusetts," they say, "may be distorted, but the data do suggest ... a secondary maximum ... in New England. ... In any event, to assert that tornadoes pose the greatest threat in Texas merely because more have been reported from that large state is unjustified."

5.4 Competition

The latest presentation of tornado statistics in tables, pseudo-maps, and maps, and the first presentation in a century based on sources other than official compilations, is a Technical Memorandum (Pautz, 1969) prepared by the staff of the Severe Local Storms (SELS) unit of the National Severe Storms Forecast Center in Kansas City and published by its parent organization, the



Office of Meteorological Operations of the Weather Bureau. Hailstorms and windstorms are also included, but the greatest attention is given to tornadoes.

Data came primarily from the "operational log of severe local storm occurrences within the conterminous United States," compiled continuously since late 1954 from teletype reports, newspaper clippings, and special reports. These reports were checked against and supplemented by the regular reports of the Environmental Data Service (EDS), published monthly in Storm Data. "Some tornado reports in the SELS log which did not appear in Storm Data were retained" if validated by the source and contents of the report.

As a result, a total of 11,608 tornadoes were recognized during the 13 years, one-third more than the 8,655 tornadoes given by EDS in Climatological Data, Annual Summary, year by year. Cumulative totals of tornadoes reported since 1916 by EDS and its predecessors, and the corresponding totals since 1955 of the SELS log are shown in the accompanying figure. As indicated by the numbers beneath the straight lines fitted to these totals, only 102 tornadoes per year were reported until 1927, then about 175, 146, and 279 per year until 1953. Since then, the EDS reports averaged 611 a year until 1964, 725 a year since, while the SELS log shows 822 a year and later 931. After 1963, each reporting rate increased by more than 100 per year, for unknown reasons.

Six of the seven tornado distribution maps and pseudo-maps in the memorandum are reproduced here; the seventh is a pseudo-map of "Year of greatest number of tornadoes, 1955-1967," by states. Of greatest interest are the first and last illustrations, a pseudo-map (fig. 23A) of "Total tornadoes 1955-1967 by 1° squares" and a shaded isopleth map (fig. 24C) of "Total tornadoes 1955-1967 by 2° squares." Both indicate a maximum concentration in north-central Oklahoma, midway between the two concentration centers on the two representations in Technical Paper 20, rev. (Wolford, 1960) (figs. 12A and 14A). The largest 1° total, 104, corresponds to 20.6 tornadoes annually per 10,000 square miles.

Even more revealing is the southwestward extension of tornado alley across the base of the Texas Panhandle, a region without significant tornado reports in previous compilations. In the last two decades, the High Plains have been transformed from rangeland to intensive irrigation agriculture, with a dramatic increase in rural population. Notable also is "a tendency for occurrences to be clustered around population centers," although the memorandum maintains that this bias is diminishing.

Tracks and damage areas of tornadoes were not considered in the compilation, and whether a tornado was counted in each quadrangle or state crossed by its path is not specified. Quadrangle totals were not divided by 13 for annual averages or adjusted for the varying areas, but the various state totals were divided for a pseudo-map (fig. 23B) of "Average annual number of tornadoes and tornado days per year, 1955-1967." Hinrichs, Flora, and Bates, would have been gratified that the state roster was led by Texas, with 143.6 tornadoes on 55.5 days. Oklahoma had 79.9 tornadoes on 28.6 days, while Kansas was a close third on tornadoes, 78.8, and second on days, 30.1.

The other three pseudo-maps, by states, of the months with the most tornadoes (fig. 23C) and most tornado days (fig. 24A), and of each state's percentage of the national total (fig. 24B), offer some differences from similar presentations in "Thunderstorm Rainfall" (Hydromet, 1945).

6. CONCLUSIONS

6.1 Perception

Tornado incidence in the United States has been described with increasing accuracy over the past century, but in recent years the precision and utility of the portrayals has not progressed as rapidly as the reporting. During the second half of the 19th century, interest in identifying and describing tornadoes was intensified by the rapid growth of dynamic meteorology, and the massive westward expansion of permanent settlement into what is now tornado alley.

Meteorological requirements have dominated climatic considerations in descriptions and representations of the time and place of tornado occurrences. When and where they happened has been tabulated more to seek clues about forces and forecasts than to provide estimates of point probabilities of occurrence. Most of the entries in Kramer's (1950) comprehensive bibliography concern dynamics, not locations. This subordination of informational to operational approaches has denied the public the best possible advice on its chances of encountering a tornado.

Dependence of complete tornado reporting upon a dispersed population, averaging at least several persons per square mile, has long been recognized. Finley's maps (figs. 1 and 2) showed an obvious deficiency over Indian Territory, not settled until 1889; this bias persisted on his maps (fig. 4), half a century later. In a comprehensive "History of Tornado Observations and Data Sources," Asp (1963) agreed with Flora (1929) that "more tornadoes are likely to be reported ... from those areas near Weather Bureau offices." He recognized "a tendency for data on tornadoes to be weighted toward the centers of population;" he (Asp, 1956) had found a correlation of +0.45 between population and tornado reports per 100 square miles in Arkansas, 1923-1955.

Popular perception of the nature and extent of the tornado hazard has developed and changed as westward population movement and faster communications caused more occurrences to be reported and summarized. Blodget (1857) considered tornadoes to be coincident, temporally and spatially, with rainfall, "most numerous in the Mississippi valley, and ... equally distributed from Canada to Georgia." Forty years later, after Finley's (1884, 1887) publications, the popular picture hadn't changed much:

> Tornadoes are more frequent in the Mississippi valley and in certain of the southern states than in other parts of this country. (Davis, 1894, p. 273).

> The regions of greatest frequency of tornadoes are the lower Missouri, the central Mississippi, and the Ohio river valleys.... Few tornadoes occur in the United States west of the 100th meridian. (Waldo, 1896, p. 246).

Lack of additional systematic reporting caused this picture to prevail for another 30 years (Milham, 1912; Ward, 1925), with the presumed center of maximum incidence in Missouri, Iowa, and western Illinois -- despite Hinrichs' (1888-1889) protestations.

For the last half-century the apparent center has moved generally southwestward to eastern Kansas (Hunter, 1925; Day, 1930; Brown and Roberts, 1937) to central Kansas (Fawbush et al.,

1951; Winston, 1956; Wolford, 1960) to central Oklahoma (Thom, 1963; Skaggs, 1969; Pautz, 1969). But the various analyses were based on reports for differing periods, some from 1916 or 1920 onward, others beginning in 1953. The true distribution of tornadoes may have changed with time, but such change cannot be established from the available data.

Many of the maps and pseudo-maps showing tornado occurrence maxima in different places do not give true incidence per unit area, but rather by latitude-longitude quadrangles of different areas. Only Day (1930), Brown and Roberts (1937), Fawbush et al, (1951), and Skaggs (1969) offered representations by true unit areas. No official government publication on tornadoes offers a direct answer to the pressing practical problem: the probability that a given spot will be struck, or affected, by a tornado.

Casualty insurance interests, to whom this is the central question, have induced a few tornado studies (Moore, 1896a; Thom, 1963) and have produced at least one map (National Board, 1929) attempting to show incidence. The U. S. Air Weather Service (1955) tabulated the frequency of tornadoes within 60 miles of its bases. Life insurance companies, however, appear not to have bothered to compute the infinitesimal risk, dependent on location, of death from tornado, although Sadowski (1965) estimated total potential casualties. Lightning deaths, less than twice as numerous as tornado deaths, 1959-1965, were mapped (Zegel, 1967) by dots and also per 100,000 persons by counties and per million persons by states.

Tornado warning services and networks, developed rapidly in the past two decades, show a creditable record in reducing tornado deaths and injuries. But their establishment has proceeded without good estimates of tornado probabilities. Municipal authorities receive much more help in predicting the probable use of snow removal equipment than in justifying organization of a tornado warning service.

The Natural Disaster Warning Group (Kutschrenreuter, 1965) could offer no specific information about the point probabilities of tornadoes, but only (fig. 19B) 12-year totals of tornadoes and tornado days, by states. "Tornado Preparedness Planning" (USWB, 1968), "directed primarily to local leaders in the area of the United States most vulnerable to tornadoes ..." (two-thirds of the country), gave no guidance on how often a given city or county might experience one.

6.2 Methodology

Tornado incidence in the United States cannot be determined or mapped with complete accuracy, but it can be represented more realistically and with less confusion than has been done in recent years. Despite the many difficulties in identifying,

classifying, measuring, recording, and reporting tornadoes (Asp, 1963), the government weather service assiduously assembles and publishes such information. Unfortunately, much less attention is given to data analysis and presentation than to initial collection.

Many presentations are by state totals for some awkward number of years, although such presentation seems as illogical as would be the publication of only state totals of temperature or rainfall. Tornado tabulation by latitude-longitude quadrangles, while a definite improvement over state totals, leaves something to be desired, because of the varying areas of such quadrangles. Apparently this procedure arose through the presence of geographical coordinates on the large base maps used for entering tornado reports. A similar base map could be prepared with grid-lines marking off true equal areas -- as used by Day (1930) and Skaggs (1969). From data accumulated by such equal-area rectangles, true incidence maps could readily be drawn.

Whether incidence maps should be for individual tornadoes or for tornado days requires careful consideration. Days rather than individual tornadoes were recommended by Hinrichs (1888) and Moore (1896b), more interested in the meteorological conditions in which tornadoes form than in the damage done. Days were studied exclusively in "Thunderstorm Rainfall" (Hydromet, 1945) for comparison with the chief subject, thunderstorms, which cannot be identified individually and have always been counted by days. But the non-meteorologist is interested in the one tornado that may affect him, and hence the public is better served by tabulations and maps of tornado incidence rather than of number of days on which they occur.

Tornado days, however, are of interest in meteorology and climatology and should be tabulated and mapped somewhat more realistically. Tornado outbreaks usually cover far more than a single state, but two separate outbreaks may occur on the same day in different parts of the country, such as the Gulf coast and the Missouri valley. Some procedure should be devised for defining such clusters, perhaps by specifying a maximum distance between component tornadoes. Then "cluster days" could be tabulated according to the location of the cluster center.

Thoughtful students from Abbe (1888) to Thom (1963) have stressed the importance of the area covered by a tornado rather than its point of origin or first ground contact. Yet few efforts have been made since the monumental studies by Brown and Roberts (1935, 1937) to determine such figures.

More investigations are needed of the characteristic widths and lengths of tornado paths in different seasons and different parts of the country. The estimates for Iowa so elegantly developed by Thom (1963) may not apply to Florida or Massachusetts.

Not until the seasonal and areal variation in tornado damage areas has been established with fair accuracy can the true tornado incidence be computed from statistics of first contact.

Alternatively, the point of last report, the end of the tornado track, could be recorded along with the starting point. Although some pathological tornadoes move in other directions, and some even traverse loops, most travel northeastward, and a straight-line motion between the two points could be assumed; a standard width could be inflated somewhat to compensate for the slightly longer curving or sinuous actual track. Such figures could be used readily in a computer program to produce figures of presumed damage area.

Over what period should tornado damage areas be tabulated and averaged? The official weather service has computed standard 30-year "normals" only for temperature, pressure, and precipitation. None is offered for tornadoes, winds, fog, thunderstorms, or other elements. In one respect, this dereliction is welcome: recent research (not yet formally published) has shown that 30-year averages are no more useful for practical climatology than averages over much shorter periods, of 10 or 15 or 20 years.

Tornadoes have been reported, with reasonable consistency, for 55 years, but the numbers have increased markedly, as shown graphically on page 35. By 5 and 10-year periods, they are:

First year:	1916	1921	1926	1931	1936	1941	1946	1951	1956	1961
5-year sum:	443	564	864	830	787	727	902	2187	3168	3413
10-year sum:	1007		1696		1514		2989		6581	

Ten-year periods, beginning in 1916, may be suitable for presenting tornado occurrences; for some purposes, combinations may be desirable.

For meaningful presentation, the information available on tornado occurrences, and also on damage area, should be tabulated by true unit areas, on base maps gridded at 100-mile intervals, as Allan did for Day (1930) and as Skaggs (1969) did. From these, isopleths can be drawn to represent tornado incidence during the decade, as accurately as the data permit. The first four of these could be combined into one 40-year map, 1916-1955, representing conditions as observed before the present era of radar, special observers, and warning networks.

Another 10-year incidence map could be drawn for the "modern" period, 1956-1965, and perhaps a tentative 5-year map for 1966-1970. But revising maps to add 1 more year's data is more confusing than helpful; for no other climatic element are new maps of totals or averages drawn each year. Offical maps published every 5 years should suffice for all purposes; if carefully and properly drawn, they would go far toward informing the public of the

tornado danger, per unit area, during a recent period and thus, by implication, in the future. Because slight shifts with time in the tornado incidence pattern are quite possible, the most recent decade is a better estimator of the next one than the past half-century. Obviously, tornado compilations by states should be discouraged.

Tornado occurrences, and tornado damage areas, averaged for 5-year and 10-year periods by true unit areas and represented by careful ispopleth maps, will aid materially in alleviating the present confusion about the true distribution over the United States of tornado incidence.

7. REFERENCES

Abbe, Cleveland (1888), Recent progress in dynamic meteorology. Record of Science for 1887 and 1888, Gen. App. to Annual Rept. of the Board of Regents of the Smithsonian Institution to the end of June 1888, 355-424.

Abbe, Cleveland (1897), Tornado frequency per unit area, Monthly Weather Rev. 25, 250-251.

Abbe, Cleveland (1889), Tornado, Century Mag., 35, 596-598.

Abbe, Truman (1955), Professor Abbe and the Isobars, (Vantage, New York), 259 pp.

Asp, M. O. (1956), Geographical distribution of tornadoes in Arkansas, Monthly Weather Rev. 84, 143-145.

Asp, M. O. (1963), History of tornado observations and data sources, Key to Meteorological Records Documentation No. 3.131, Weather Bureau, U. S. Department of Commerce, 25 pp.

Baldwin, J. L. (1943), Preliminary report on tornadoes in the United States during 1943 and totals and averages, 1916-1942, by states, Monthly Weather Rev., 71, 195-197.

Bates, F. C. (1962), Tornadoes in the central United States, Trans. Kansas Acad. Sci. 65, 215-246.

Blodget, Lorin (1857), Climatology of the United States, (Lippincott, Philadelphia, Pa), 536 pp.

Brown, Charles Wilson (1933), A study of the time-, areal- and type-distribution of tornadoes in the United States, Trans. Am. Geophys. Union 14, 100-106.

Brown, Charles W., and W. O. J. Roberts (1935), The distribution and frequency of tornadoes in the United States from 1880 to 1931, Trans. Am. Geophys. Union 16, 151-158.

Brown, Charles W., and W. O. J. Roberts (1937), The areal frequency of tornadoes in the United States by counties, 1880-1931, Trans. Am. Geophys. Union 18, 144-146.

Burley, M. W., and P. J. Waite (1965), Wisconsin tornadoes, Trans. Proc. Wisconsin Acad. Sci., Arts and Letters 54, 1-35.

Critchfield, Howard J. (1960), General Climatology (Prentice-Hall, Englewood Cliffs, N.J.), 465 pp; (1966), 2nd ed.

Davis, William M. (1894), Elementary Meteorology (Ginn and Co., Boston, Mass.), xii + 355 pp.

Day, John A. (1966), The Science of Weather (Addison-Wesley, Reading, Mass.), x + 214 pp.

Day, John A., and Gilbert L. Sternes (1970), Climate and Weather (Addison-Wesley, Reading, Mass.), 407 pp.

Day, P. C. (1930), Weather Bureau gets data on behavior and effects of tornadoes, Yearbook of Agriculture, U. S. Department of Agriculture, 530-534.

ESSA (1966), Tornado statistics, ESSA/PI 660029, Environmental Science Services Administration, leaflet.

ESSA (1967), Tornado, ESSA/PI 660028, Environmental Science Services Administration, 16 pp

ESSA (1968), Tornado statistics, 1953-1967, ESSA/PI 660029, Environmental Science Services Administration, leaflet.

ESSA (1969a), Tornado, ESSA/PI 660028, Environmental Science Services Administration, 16 pp.

ESSA (1969b), Weather Bureau severe local storm warning service and tornado statistics, 1953-1968, ESSA/PI 690036, Environmental Science Services Administration, folder.

Evans, Edna Hoffman (1954), Are tornadoes growing worse? Nature, 47, 293-296.

FAA-USWB (1965), Aviation Weather, (U. S. Government Printing Office, Washington, D. C.), 300 pp.

Fawbush, Ernest J., Robert C. Miller, and Lloyd G. Starrett (1951), Methods of forecasting tornado development, Bull. Am. Meteorol. Soc., 32, 1-9.

Fawbush, Ernest J. and Robert C. Miller (1953), Forecasting tornadoes, Air Univ. Quart. Rev., 6, 108-117.

Finley, J. P. (1884), Report on the character of 600 tornadoes, Papers of the Signal Service, No. 7, 29 pp. (First publication, 1882, withdrawn for correction.)

Finley, J. P. (1887), Tornadoes: What They Are and How To Observe Them, With Practical Suggestions for the Protection of Life and Property, (Insurance Monitor Press, New York, N.Y.), 196 pp.

Finley, John P. (1888a), The relation of tornado regions to areas of low pressure, Am. Meteorol. J., 5, 83-87.

Finley, John P. (1888b), Tornadoes: What They Are and How To Escape Them, (J. H. Soule, Washington, D. C.) 90 pp. (Also published as Signal Corps Circ. No. 22)

Finley, John P. (1889), State tornado charts, Am. Meteorol. J. 5, 446-476, 501-507, 545-551.

Finley, John P. (1890), Tornadoes, (First Prize Essay), Am. Meteorol. J. 7, 165-179.

Finley, John P. (1925) Weather, crop and social insurance in the United States through climatological investigations by the Finley system, 1880-1925, National Storm Insurance Bureau, New York, N.Y., iii + 39 pp.

Finley, John P. (1932), Climatological business charts for the protection and benefit of commerce, aviation and agriculture and the promotion of insurance against weather hazards, National Storm and Aviation Insurance Bureau, New York, N.Y., (typescript), 6 pp.

Flora, S. D. (1915) Tornadoes in Kansas, Monthly Weather Rev., 43 615-617.

Flora, S. D. (1928) Kansas tornadoes, 1914-1928, Monthly Weather Rev., 56, 412-415.

Flora, S. D. (1929), Tornadoes in Kansas, Monthly Weather Rev., 57, 97-98.

Flora, S. D. (1949), The nature of tornadoes, Weatherwise 2, 27-30.

Flora, S. D. (1953), Tornadoes of the United States, (Univ. of Oklahoma Press, Norman, Oklahoma) 194 pp; (1954) 2nd ed.

George, Joseph J. (1960), Weather Forecasting for Aeronautics, (Academic Press, New York, N.Y.), ix + 693 pp.

Greeley, A. W. (1888), American Weather, a Popular Exposition of the Phenomena of the Weather Including Chapters on Hot and Cold Waves, Blizzards, Hailstorms, and Tornadoes, (Dodd, Mead & Co., New York, N.Y.), xii + 286 pp.

Hazen, H. A. (1890), Tornadoes, (A Prize Essay), Am. Meteorol. J. 7, 205-229.

Henry, A. J. (1896), Tornadoes 1889-1896, Annual Report of the Chief of the Weather Bureau for 1895-1896, xxiii-xl.

Henry, A. J. (1906), Climatology of the United States, USWB Bull. Q. (WB No. 361), Weather Bureau, U. S. Department of Agriculture, 1012 pp.

Hinrichs, Gustavus (1888-1889), Tornadoes and derechoes, Am. Meteorol. J. 5, 306-317, 341-349, 385-393.

House, Donald C. (1963), Forecasting tornadoes and severe local storms, Meteorol. Monographs, 5, No. 27, 141-155.

Hunter, Herbert C. (1925), Tornadoes of the United States, 1916-1925, Monthly Weather Rev., 53, 198-204.

Huschke, Ralph E., ed. (1959), Glossary of Meteorology (Am. Meteorol. Soc., Boston, Mass.), vii + 638 pp.

Hydrometeorological Section (1945), Thunderstorm Rainfall, Pt. 2, USWB-USCE Hydrometeorological Rept. 5, (Waterways Experiment Station, Vicksburg, Miss.), ix + 155 figures, (pub. 1947).

Kendrew, W. G. (1922), The Climates of the Continents, 1st ed.; (1927), 2nd ed., reprinted in 1930; (1937), 3rd ed., reprinted in 1941, 1944 & 1948; (1953), 4th ed.; (1961), 5th ed., reprinted in 1963, (Oxford Univ. Press), xii + 473 pp

Kessler, Edwin (1966), A storm's incalculable energy, Natural History 75, No. 4, 12-17.

Kimble, George H. T. (1955), Our American Weather, (McGraw-Hill Book Co., New York, N.Y.), 323 pp.

Knight, David C. (1964), The Science Book of Meteorology, (Franklin Watts, Inc., New York, N.Y.), 215 pp.

Kramer, Harris P. (1950), Selective annotated bibliography on tornadoes, Meteorol. Abstracts and Bibliography, 2, No. 5, 307-332.

Kutschenreuter, Paul A. (1965), A proposed nationwide natural disaster warning system, Environmental Science Service Administration, (U. S. Government Printing Office, Washington, D. C.), viii + 113 pp.

Lee, J. T. (1958), Tornadoes in the United States, 1950-1956, Monthly Weather Rev. 86, 219-228.

Lehr, Paul E., R. Will Burnett, and Herbert J. Zim (1957), Weather, (Golden Press, Long Island City, N.Y.,), 160 pp.

Lemons, Hoyt (1938), Some meteorological aspects of Nebraska tornadoes, Monthly Weather Rev. 66, 205-208.

Linehan, Urban J. (1957), Tornado deaths in the United States, U. S. Weather Bureau Tech. Paper 30, iv + 48 pp.

Longley, Richmond W. (1970), Elements of Meteorology (John Wiley & Sons, Inc., New York, N.Y.), vi + 317 pp.

Mageneau, Eugene F., and Victor C. Gilbertson (1960), Tornadoes, J. Am. Inst. Architects 33, No. 5, 73-82. (Reprinted as AIA Tech. Reference Guide TRG 13-2).

Manos, Nicholas E. (1958), The tornado as an epidemological tool, Bull. Am. Meteorol. Soc., 39, 460-468.

McKay, G. A., and A. B. Lowe (1960), The tornado in western Canada, Bull. Am. Meteorol. Soc., 41, 1-8.

Metropolitan Life Insurance Company (1936), Life and property losses in Tornadoes in the United States, Statistical Bull. 17, 1-2.

Metropolitan Life Insurance Company (1967), Deaths from tornadoes in the United States, 1962-1966, Statistical Bull. 48, 2.

Milham, Willis Isbrister (1912), Meteorology, (reprinted, 1925), (Macmillan, New York, N. Y.), 598 pp.

Miller, Albert (1966), Meteorology, (Charles E. Merrill Publ., Co., Columbus, Ohio), vii + 128 pp.

Miller, Albert and Jack C. Thompson (1970), Elements of Meteorology, (Charles E. Merrill Publ., Co., Columbus, Ohio), xvi + 402 pp.

Miller, Eric R. (1931), New light on the beginnings of the Weather Bureau from the papers of Increase A. Lapham, Monthly Weather Rev., 59, 65-70.

Moore, Willis L. (1896a), Annual report of the Chief of the Weather Bureau for 1895-1896, xiii - xvi.

Moore, Willis L. (1896b), The winds -- tornadoes, 29th annual report of the Missouri State Board of Agriculture for the Year 1896, 166-182.

National Board of Fire Underwriters (1929), Maps: tornadoes, hurricanes (in Atmospheric Sciences Library, ESSA, M82.3/73 N277m).

Neuberger, Hans, and John Cahir (1969), Principles of Climatology, (Holt, Rinehart, and Winston, Inc., New York, N.Y.), xiii + 138 pp.

Orton, Robert B. (1964), The climate of Texas and adjacent Gulf waters, U. S. Weather Bureau, xviii + 105 pp.

Pautz, Maurice E., ed. (1969), Severe local storm occurrences, 1955-1967, ESSA Tech Memo WBTM FCST 12, U. S. Weather Bureau, iv + 77 pp.

Petterssen, Sverre (1956), Weather Analysis and Forecasting, 2nd ed., II, Convective Clouds and Weather (McGraw-Hill Book Co., New York, N.Y.), xii + 266 pp.

Petterssen, Sverre (1958), Introduction to Meteorology, 2nd ed., (McGraw-Hill Book Co., New York, N.Y.), ix + 333 pp; (1969), 3rd ed., xi + 333 pp.

Pickwell, Gayle (1924), Tornadoes, the funnel clouds, Nature 3, 147-149.

Reichelderfer, F. W. (1957), Hurricanes, tornadoes and other storms, Ann. Am. Acad. of Political and Soc. Sci., 309, 23-25.

Roth, Richard J. (1963), Severe local weather and the property insurance industry, Third Conf. on Severe Local Storms, (Am. Meteorol. Soc., Urbana, Ill.).

Rumney, George R. (1968), Climatology and the World's Climates, (Macmillian, New York, N.Y.), 656 pp.

Sadowski. Alexander (1965), Potential casualties from tornadoes, paper presented at the 244th National Meeting, Am. Meteorol. Soc., Reno, Nevada.

Showalter, A. K. and J. R. Fulks (1943), Preliminary report on tornadoes, U. S. Weather Bureau, 163 pp.

Skaggs, Richard H. (1969), Analysis and regionalization of the diurnal distribution of tornadoes in the United States, Monthly Weather Rev., 97, 103-115.

Spohn, H. R. and P. J. Waite (1962), Iowa tornadoes, Monthly Weather Rev., 90, 398-406.

Taylor, George F. (1954), Elementary Meteorology, (Prentice-Hall, Englewood Cliffs, N.J.), vii + 364 pp.

Tepper, Morris (1958), Tornadoes, Scientific American 198, 31-37.

Thom, H. C. S. (1963), Tornado probabilities, Monthly Weather Rev., 91, 730-736.

USAF (1961), Roar of the beast, The Airman, 5, No. 4, 24-25.

USAWS (1955), Tornadoes and related severe weather: An informational digest for air commanders, rev. June 1955, Air Weather Service, U. S. Air Force, Washington, D. C., 10 pp.

USAWS-USWB (1960), Tornado alley, U. S. Air Force, Scott Air Base, Illinois, 30 pp.

USWB (1955), Average monthly variation in tornado frequency, based on a total of 6970 tornadoes, period 1916-1954, U. S. Weather Bureau, folded map.

USWB (1960a), Tornado distribution in the United States, L. S. 5703, U. S. Weather Bureau, 1 p.

USWB (1960b), Tornadoes, 1953-1959 (by 1 degree squares), L. S. 5913 revised 1960, U. S. Weather Bureau, 1 p.

USWB (1962a), Tornadoes, 1916-1961 (by 1 degree squares) L. S. 5913 revised April 1962, U. S. Weather Bureau, 1 p.

USWB (1962b), Average number of tornadoes by months, L. S. 6208 revised 1962, U. S. Weather Bureau, 1 p.

USWB (1964), Tornadoes, Poster (map-back), revised April 1964, U. S. Weather Bureau, 1 sheet.

USWB (1965a), Tornadoes, U. S. Weather Bureau, 16 pp.

USWB (1965b), Annual average tornado frequency by states, 1953-1964, L. S. 6507, May 1965, U. S. Weather Bureau, 1 p.

USWB (1965c), Annual average tornado frequency by states, 1963-1964, L. S. 6507, revised October 1965, U. S. Weather Bureau, 1 p.

USWB (1966), Tornadoes, ESSA/PI 60006, U. S. Weather Bureau, 16 pp.

USWB (1967), Operations of the Weather Bureau, U. S. Weather Bureau.

USWB (1968), Tornado preparedness planning, U. S. Weather Bureau, 28 pp.

Visher, Stephen S. (1954), Climatic Atlas of the United States, (Harvard Univ. Press, Cambridge, Mass.), xii + 403 pp.

Waldo, Frank (1896), Elementary Meteorology, (American Book Co., New York, N.Y.), 373 pp.

Walsh, John (1965), Tornadoes: Weather Bureau office in Kansas City is nerve center for severe storm warning network, Science 148, 1306-1308.

Ward, R. DeCourcy (1917), The tornadoes of the United States as a climatic phenomena, Quart. J. Roy. Meteorol. Soc. 43, 317-329; (Abridged version without map in Nature, 101, 395-399, 1918; reprinted in Annual Rept. Smithsonian Institution, 1918, 139-145).

Ward, R. DeCourcy (1925), The Climates of the United States, (Ginn & Co., Boston, Mass.), xvi + 5.8 pp.

Ward, R. DeCourcy and Charles F. Brooks (1936), The Climates of North America; Mexico, United States, Alaska, Handbuch der Klimatologie, eds. W. Koppen and R. Geiger, 2, sec. J., Pt. 1 (Borntager, Berlin)., xii + 327 pp.

Whitnah, Donald R. (1961), A History of the United States Weather Bureau, (Univ. of Illinois Press, Urbana, Ill.), ix + 267 pp.

Winston, Jay S., ed. (1956), Forecasting tornadoes and severe thunderstorms, Forecasting Guide No. 1, U. S. Weather Bureau, 34 pp.

Wolford, Laura V. (1952), Tornado occurrences in the United States, Tech Paper 20, U. S. Weather Bureau, 43 pp; (1960) revised edition, 43 pp.

Zegel, Ferdinand H. (1967), Lightning deaths in the United States; a seven-year survey from 1959 to 1965, Weatherwise, 20, 169-173, 179.

8. Figures

The following 26 pages contain reproductions of 109 published maps, pseudo-maps, and map-diagrams representing in some way the frequency of occurrence over the United States of tornadoes, tornado days, or tornado deaths. They are arranged generally in chronological order of the last year of the data represented, not necessarily of year of publication. Thus, various depictions of the same basic set of data appear together, even though some may have been published, or republished, much later.

Each representation is identified by citation to an entry in the preceding list of References. Each is mentioned, or discussed, in the text, which is also largely chronological.

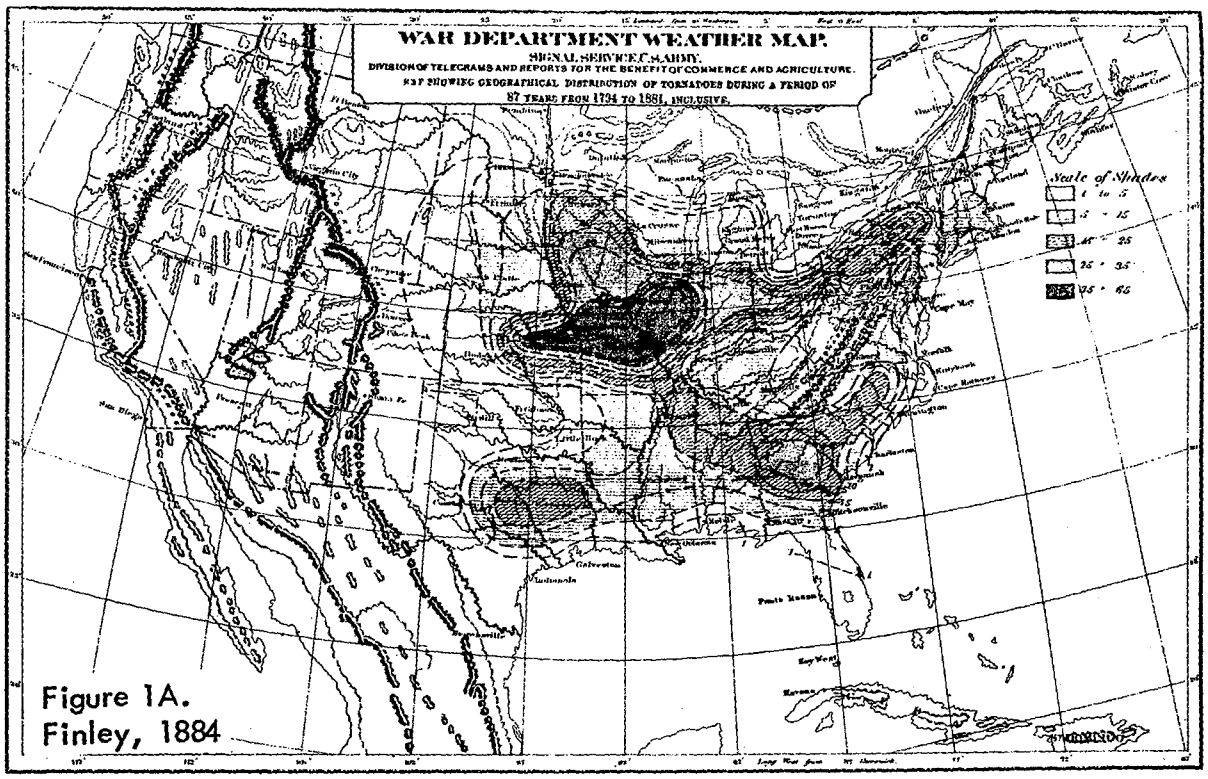


Figure 1A.
Finley, 1884

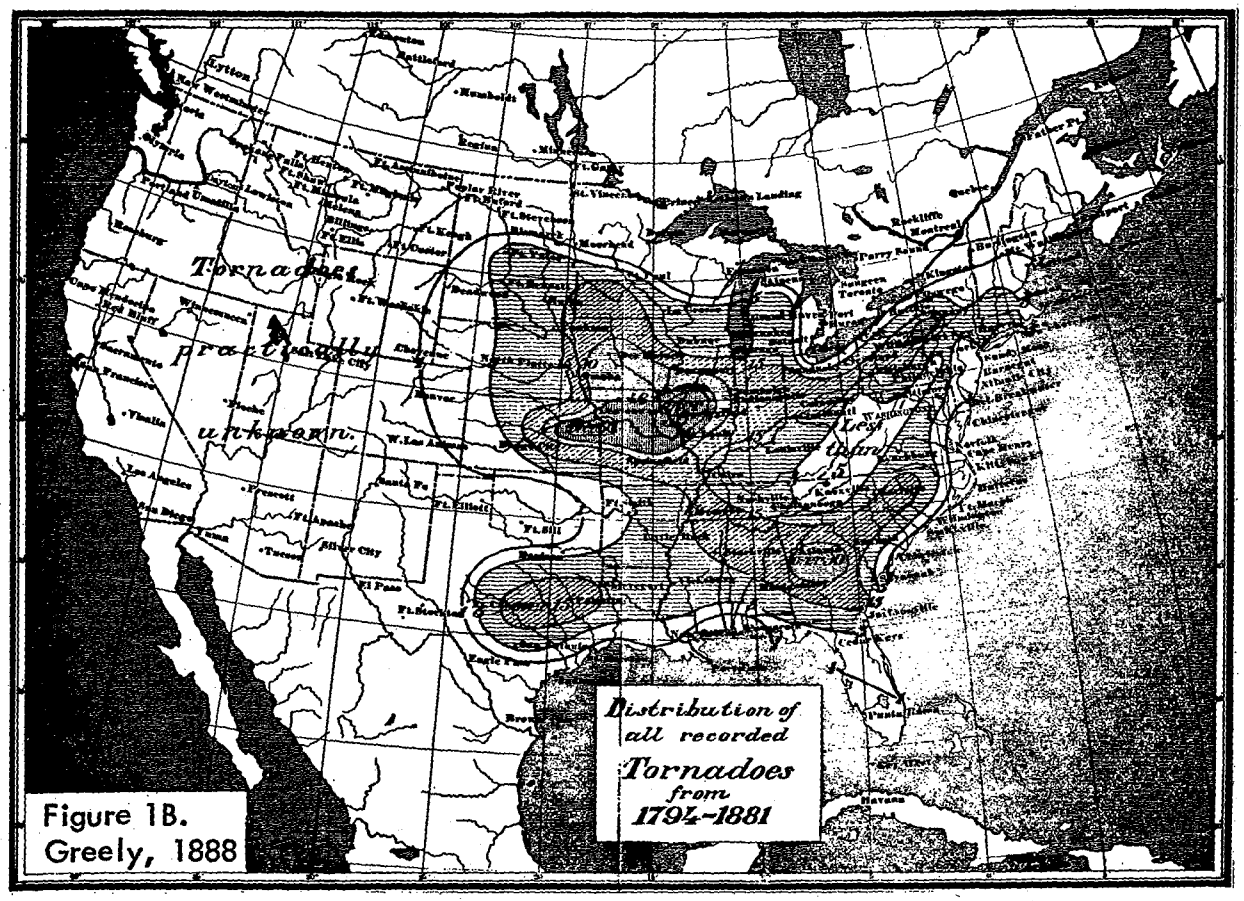


Figure 1B.
Greely, 1888

Figure 2A.
Finley, 1887

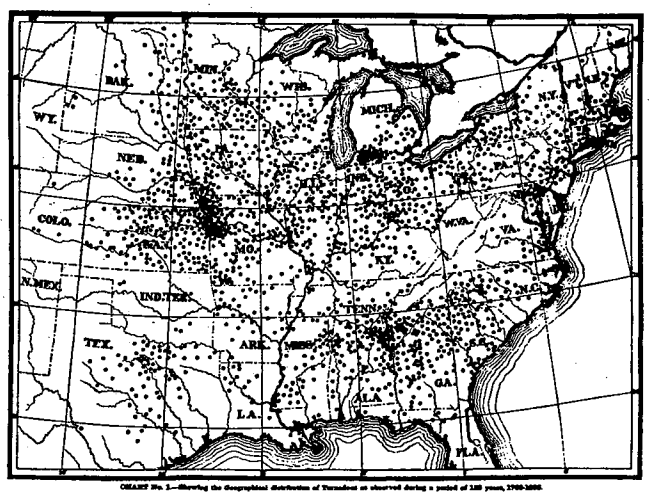
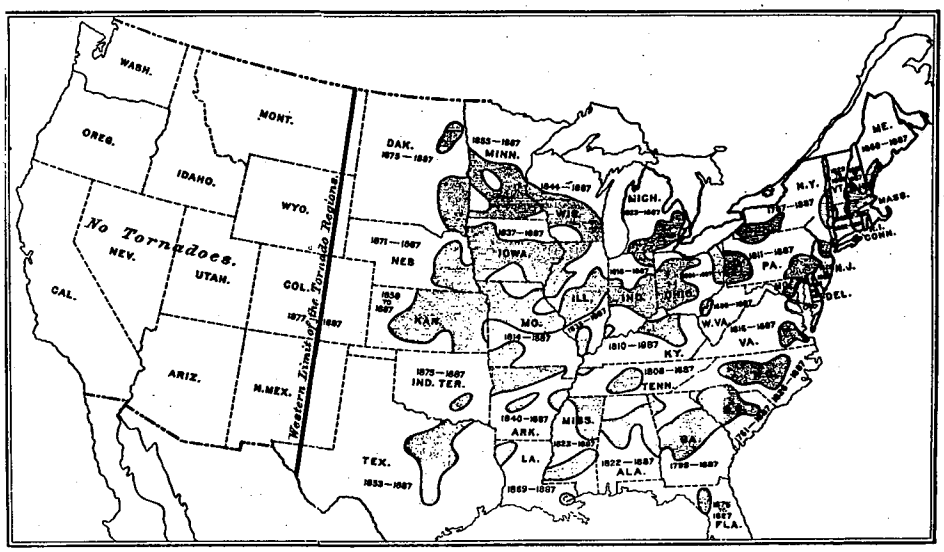


Figure 2B.
Finley, 1888b



The Geographical distribution of Tornadoes to show the areas of maximum tornado frequency by States; also the total period of observation in each State.

Figure 2C.
Ward, 1917

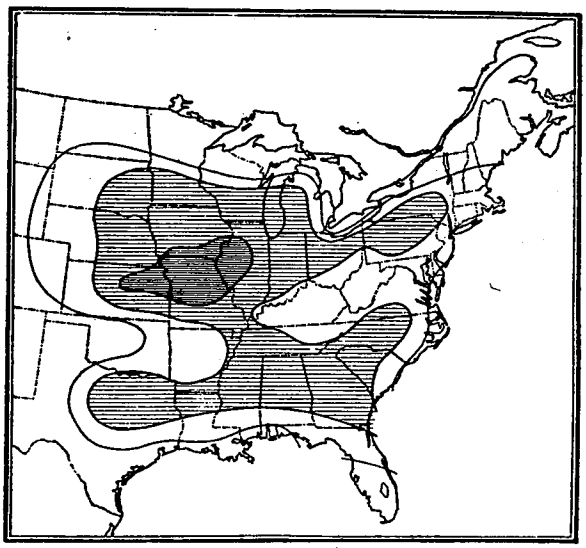


FIG. 4.—Distribution of Tornadoes in the United States. (After Finley.)

Figure 2D.
Kendrew, 1922

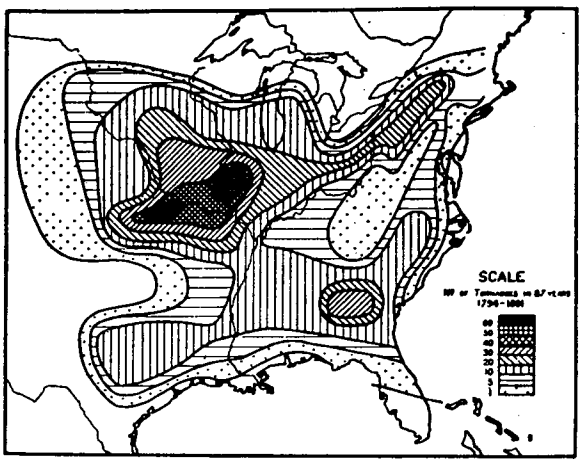


FIG. 109. Frequency of tornadoes. (Finley.)

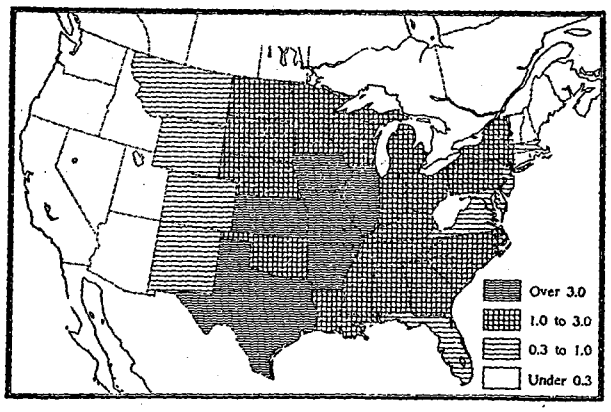


FIG. 1.—Average occurrence of tornadoes, per year per State, for 25 years

Figure 3A. Hunter, 1925

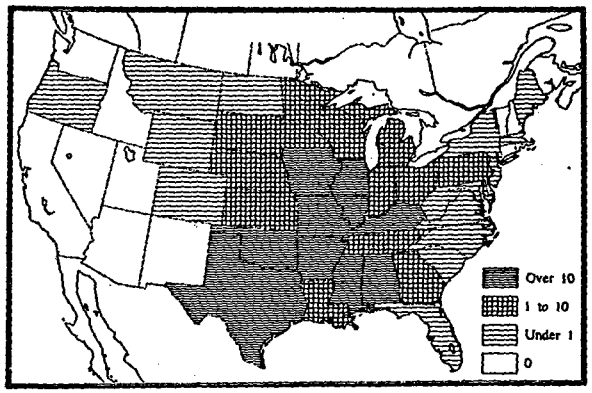


FIG. 2.—Average loss of life from tornadoes, per year per State, for 17 years

Figure 3B. Hunter, 1925

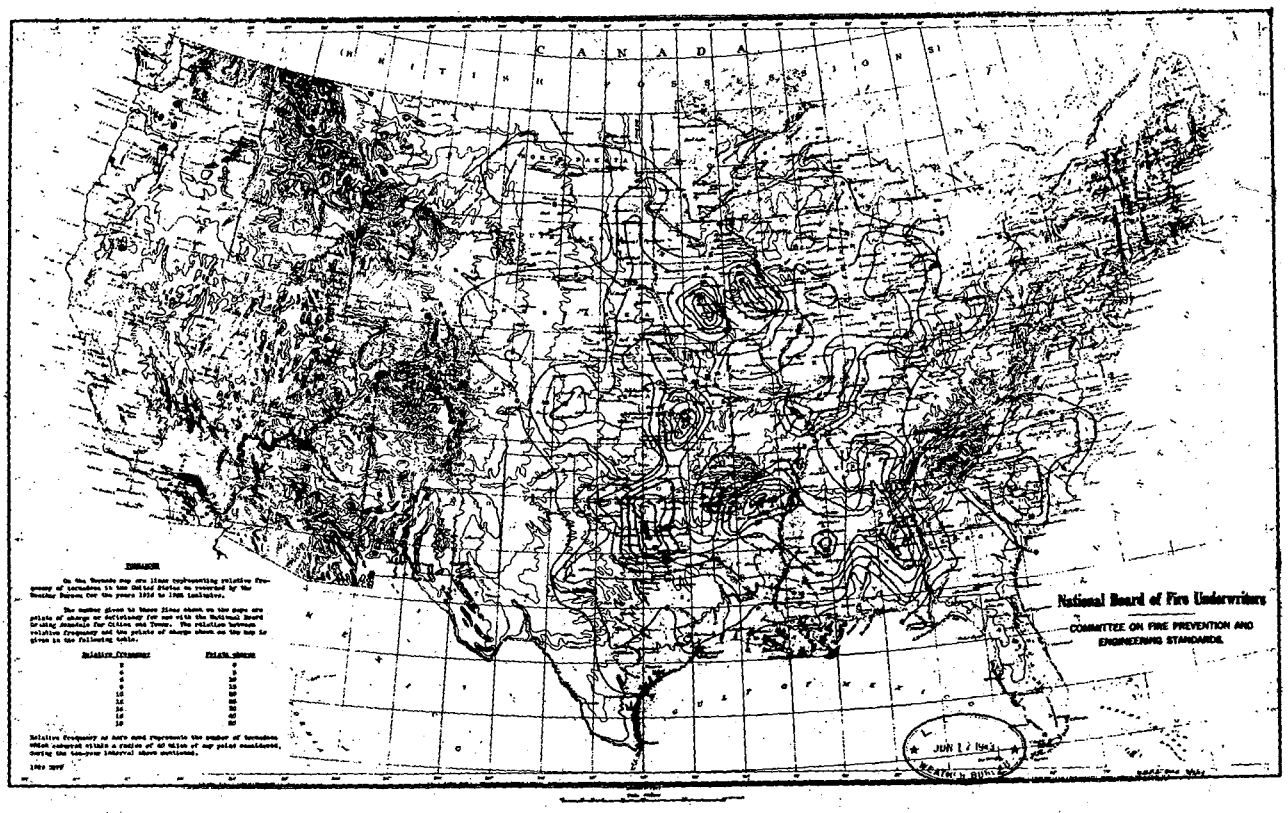


Figure 3C. National Board, 1929

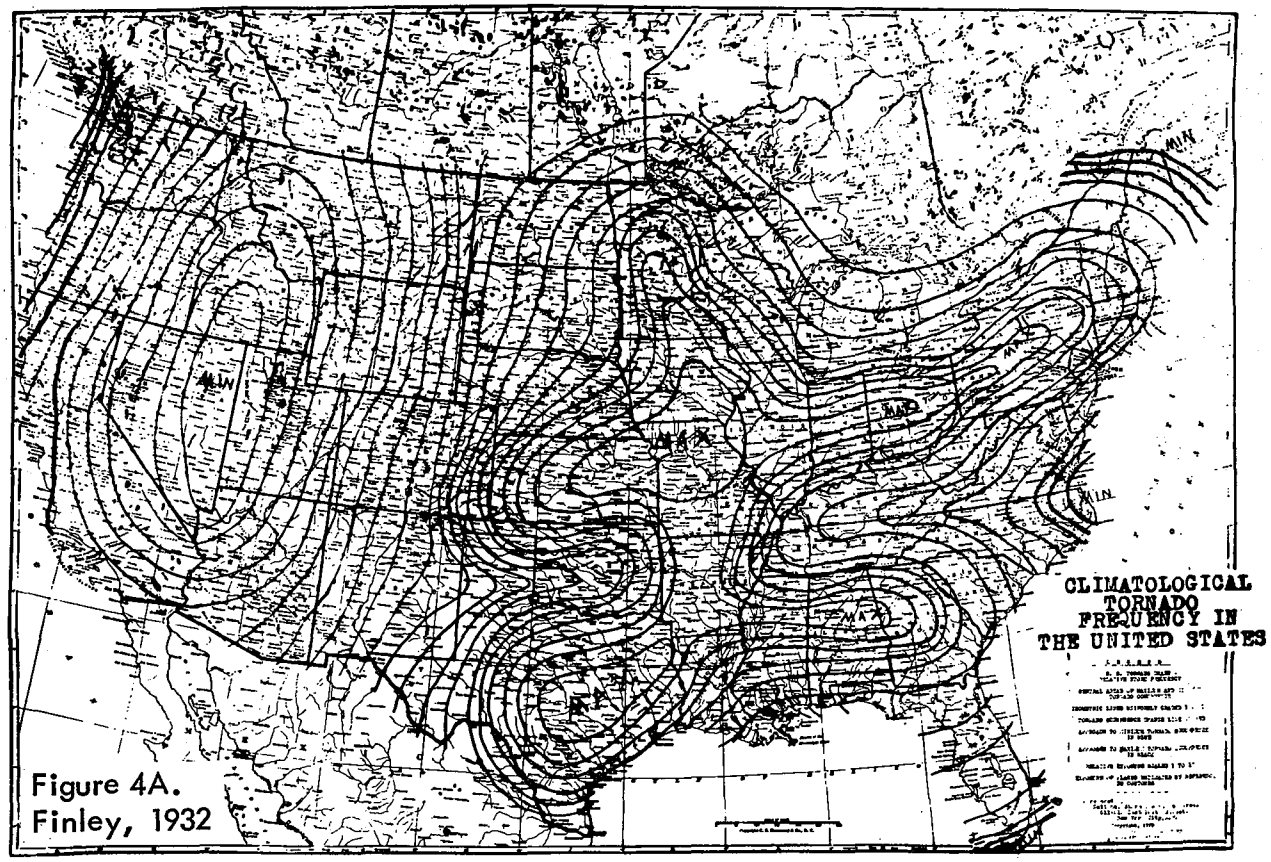


Figure 4A.
Finley, 1932

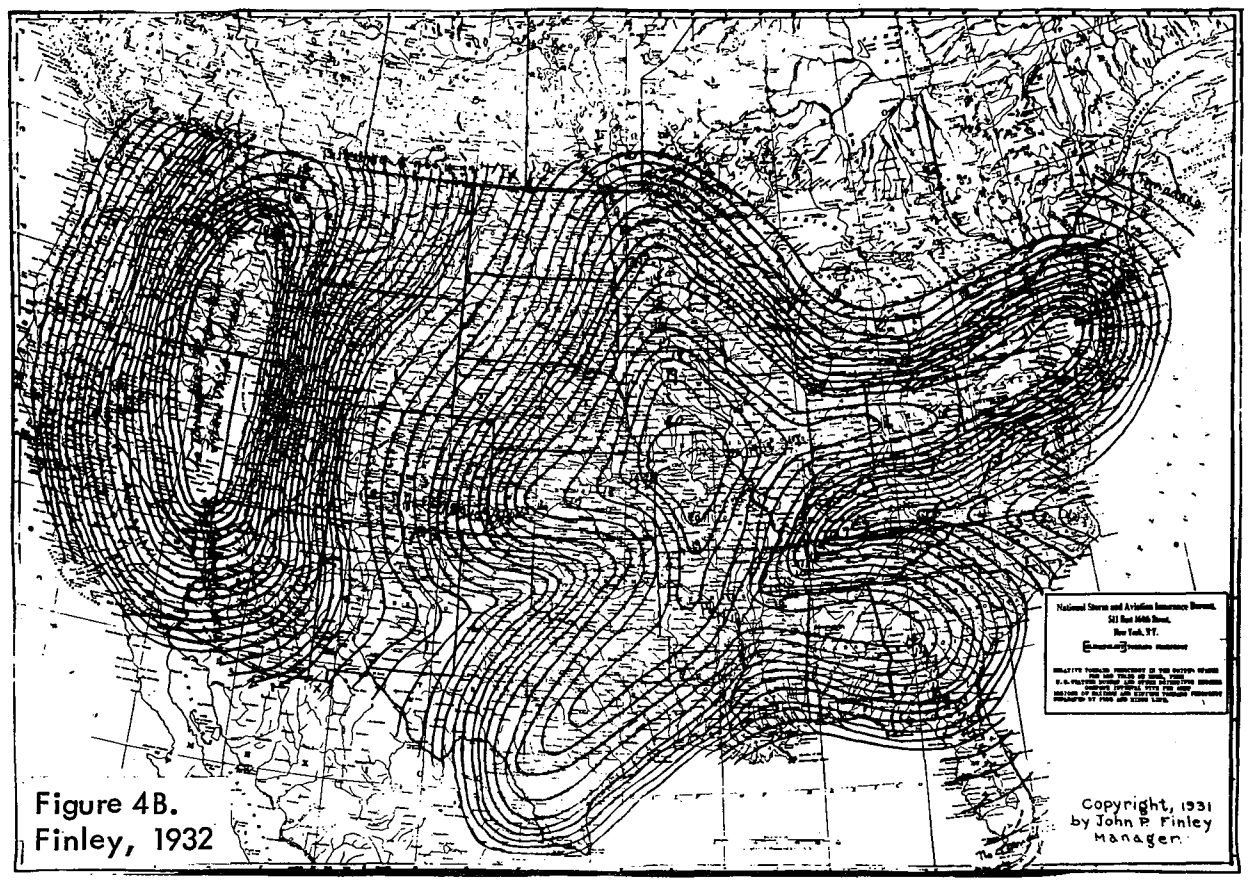


Figure 4B.
Finley, 1932

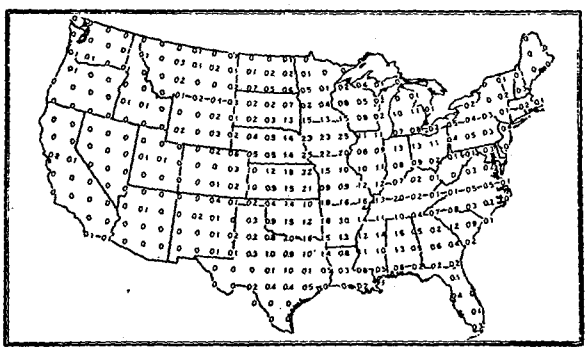


FIGURE 196.—Tornado occurrences in the United States, 1916 to 1928, inclusive. In this chart the country is divided into equal areas of 10,000 square miles each, regardless of State boundaries

Figure 5A. Day, 1930

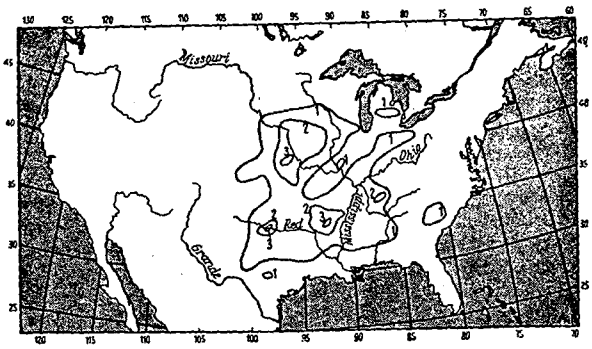


FIG. 124. Mean annual number of tornadoes (in squares with 100-mile sides), based on K. B. Allan.

Figure 5B. Kendrew, 1937

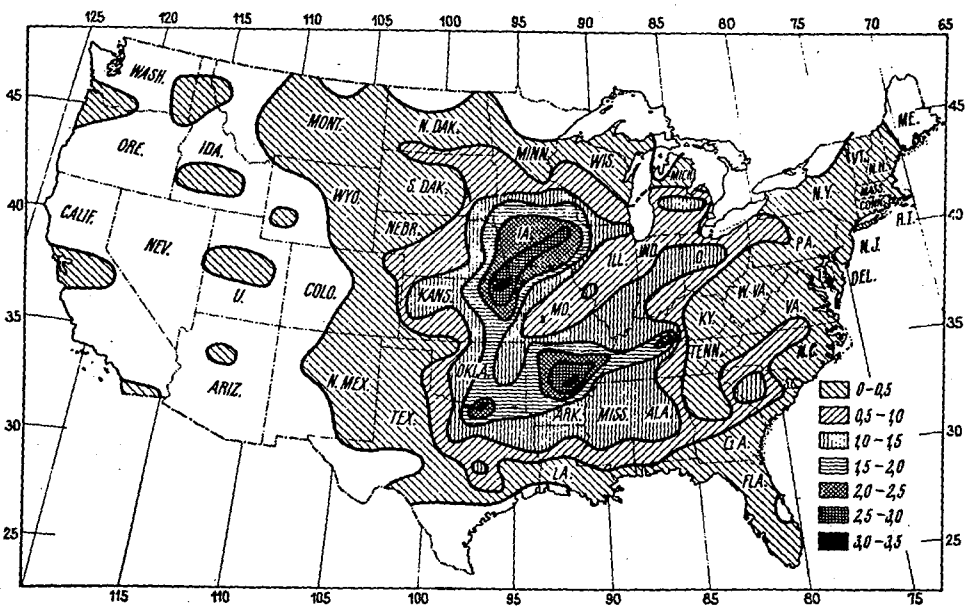


Figure 5C. Ward and Brooks, 1936

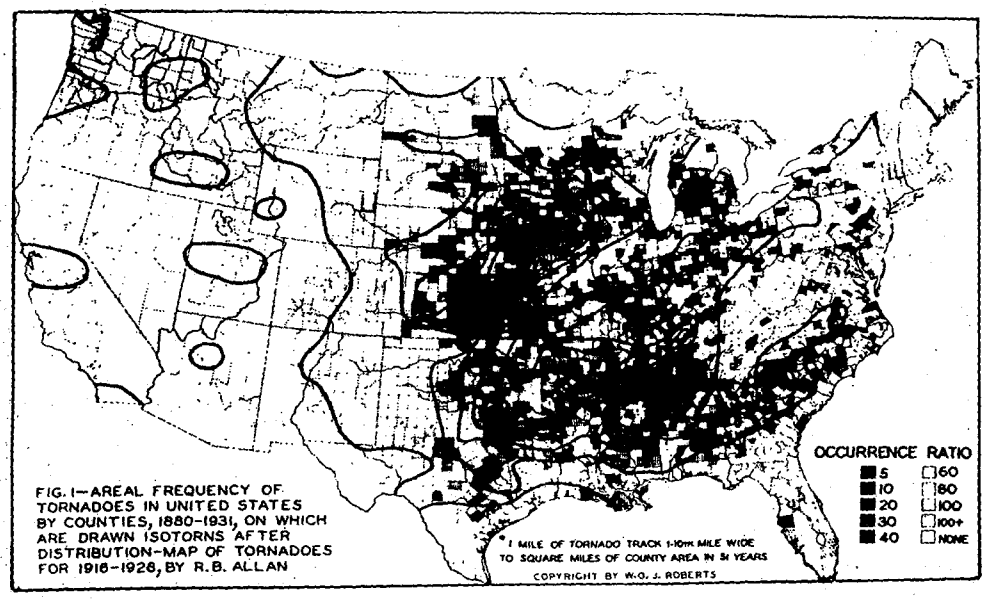


Figure 5D. Brown and Roberts, 1937

Figure 6A.
Brown, 1933

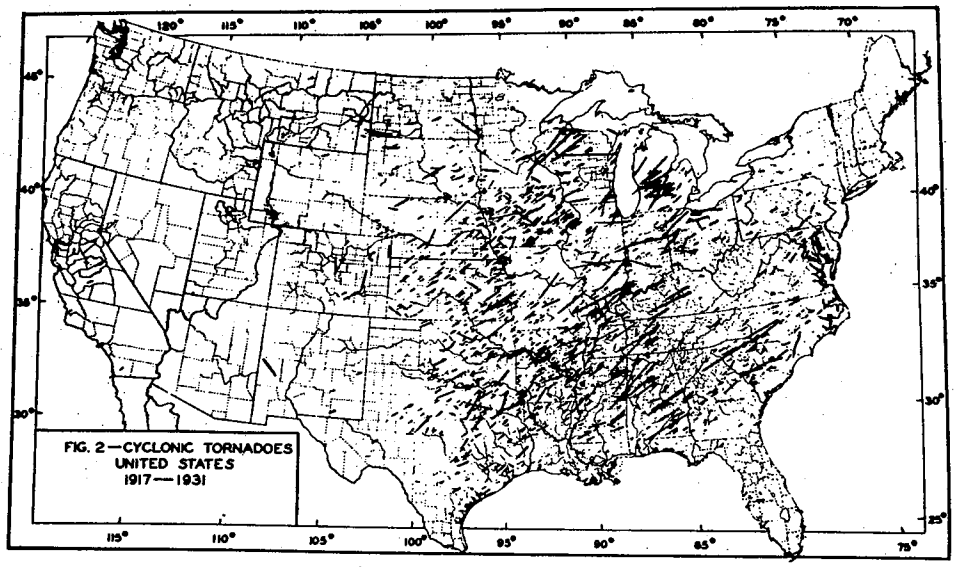


Figure 6B.
Brown, 1933

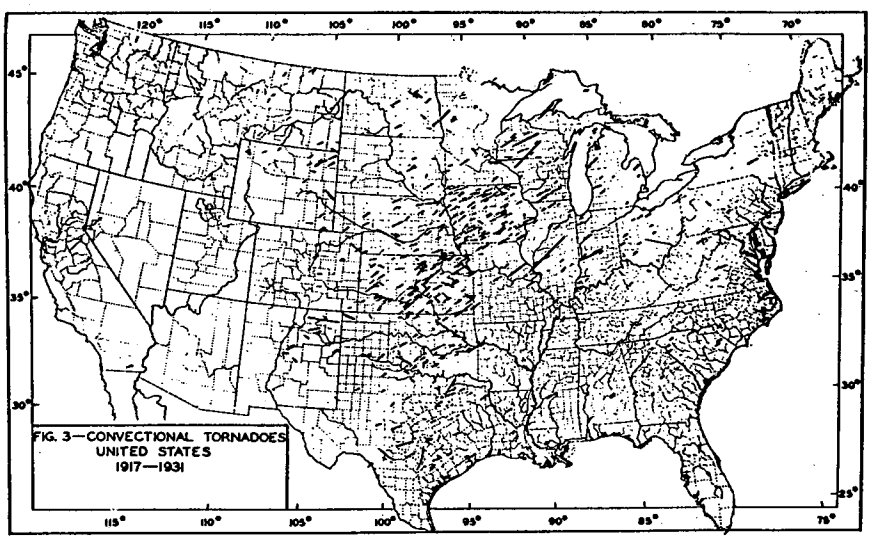
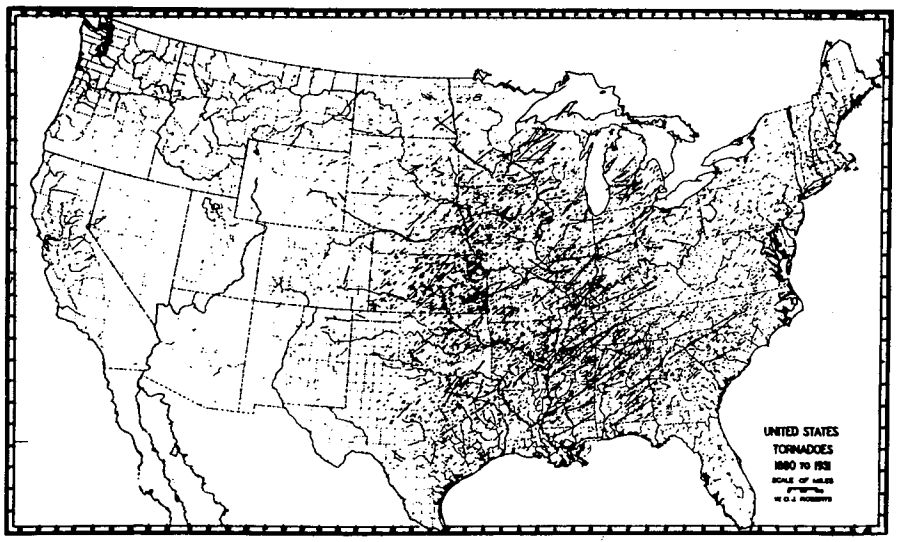


Figure 6C. Brown and Roberts, 1935



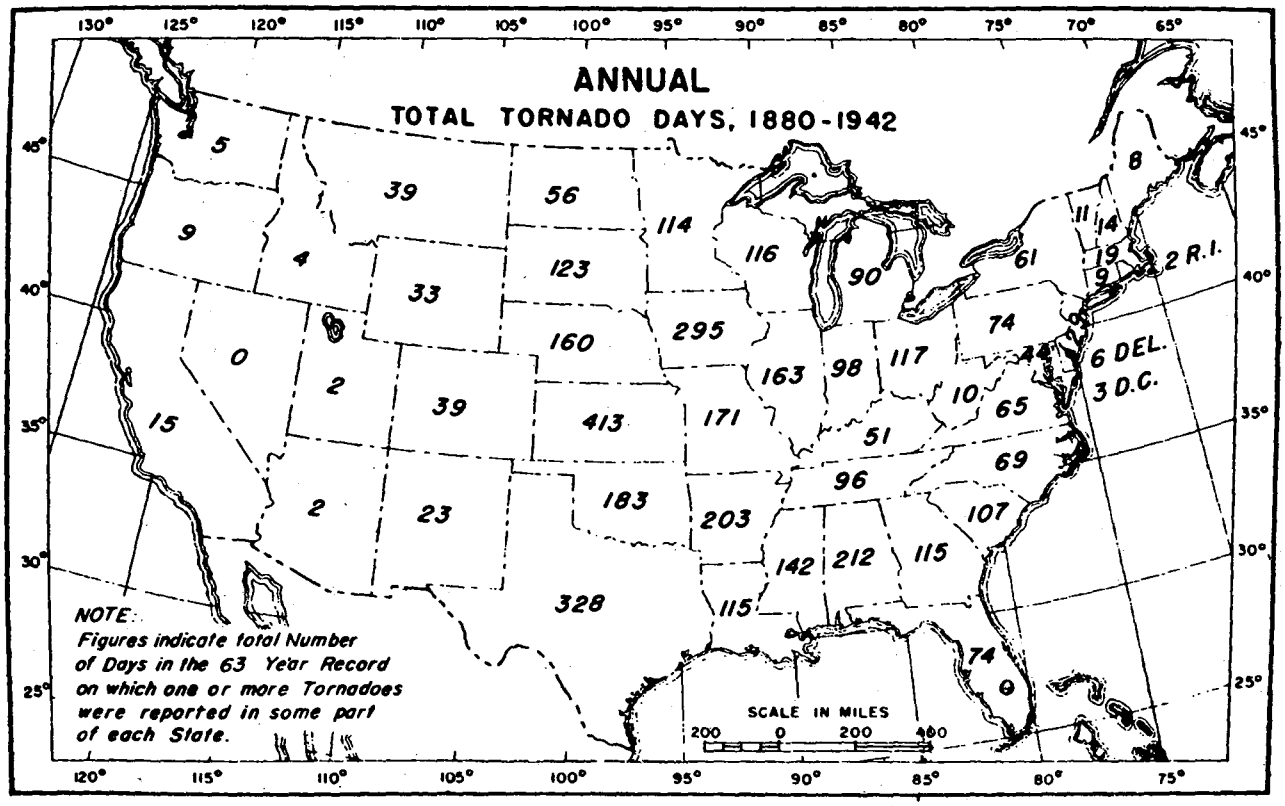
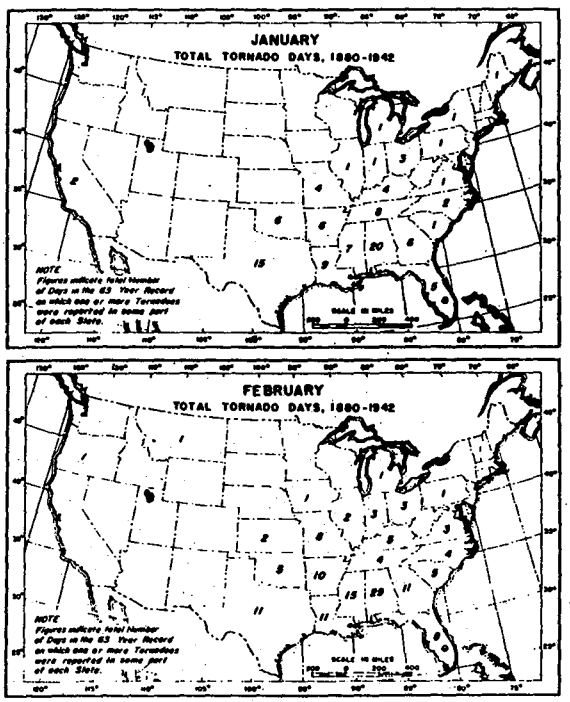
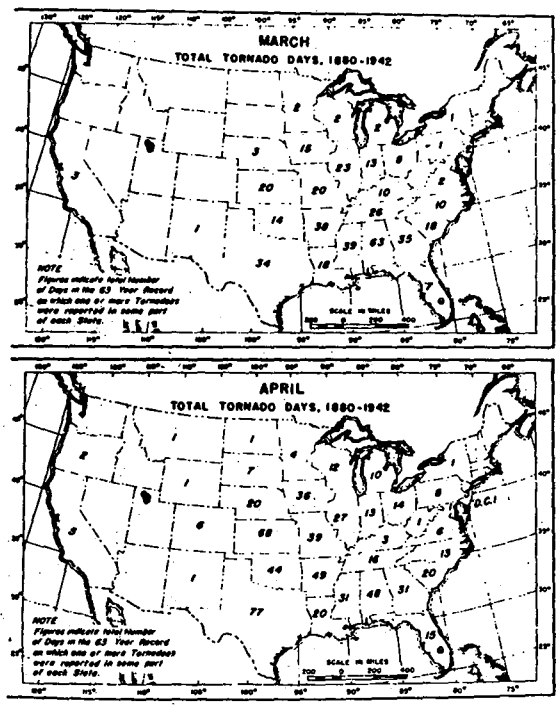


Figure 7A. Showalter and Fulks, 1943

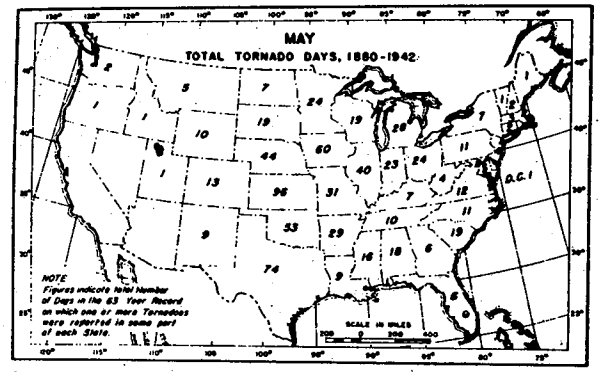


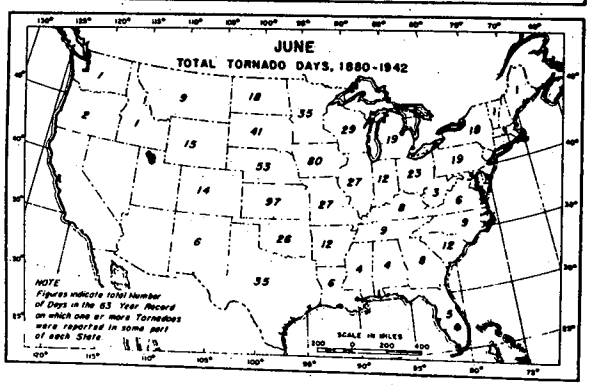
Figures 7B and 7C



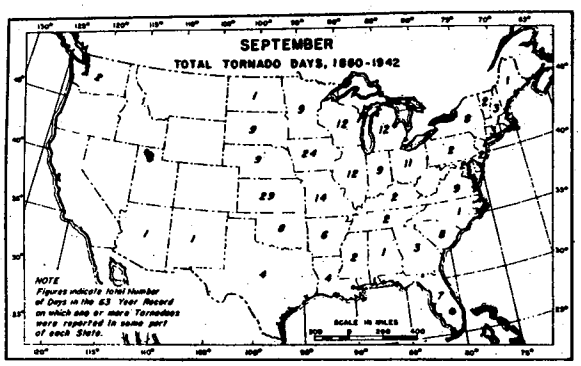
Figures 7D and 7E

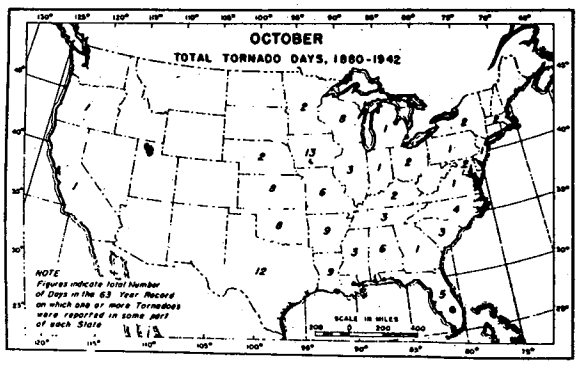
Showalter and Fulks, 1943





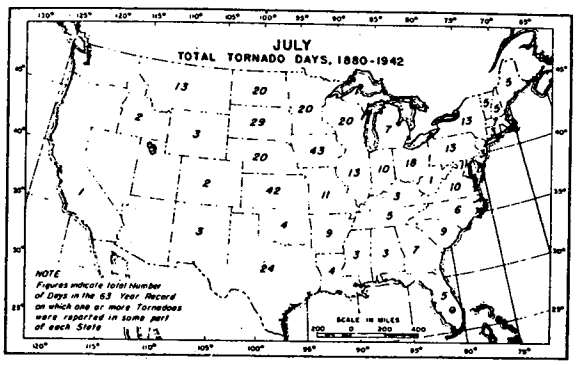
Figures 7F and 7G

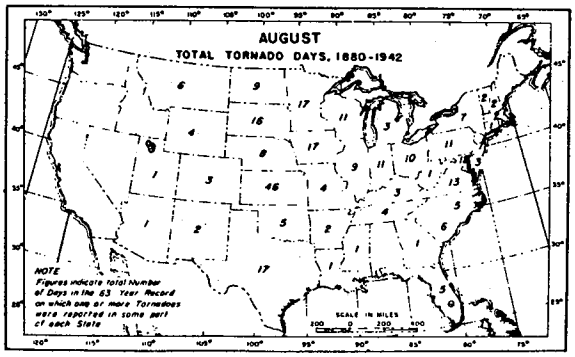




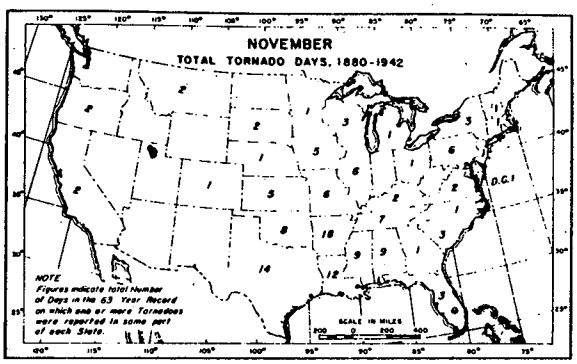
Figures 7J and 7K

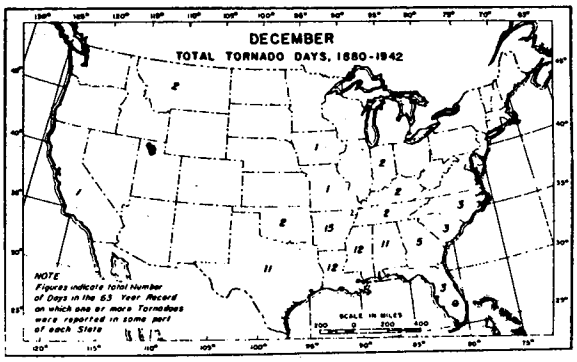
Showalter and Fulks, 1943





Figures 7H and 7I





Figures 7L and 7M

Showalter and Fulks, 1943

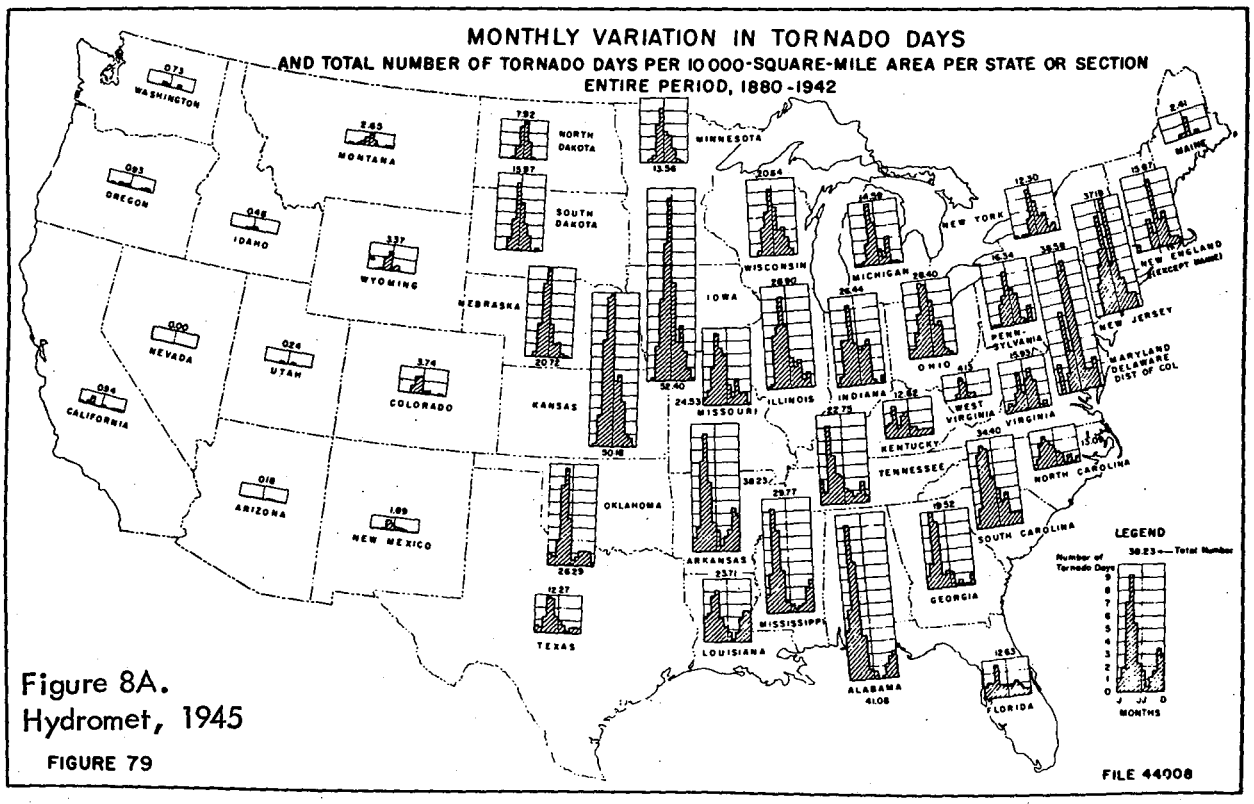


Figure 8A.
Hydromet, 1945

FIGURE 79

TORNADO DAYS PER 10 000-SQUARE-MILE AREA PER STATE OR SECTION

Figures 8B - 8E

Hydromet, 1945

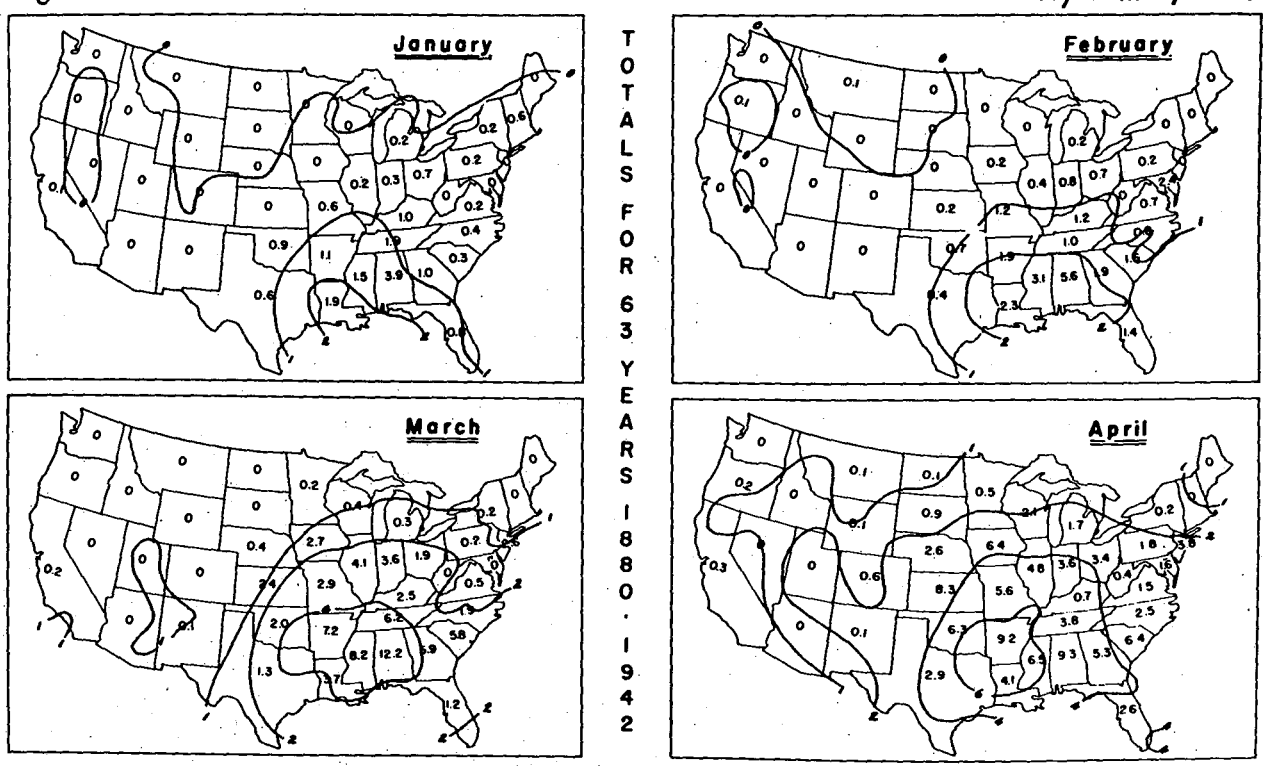


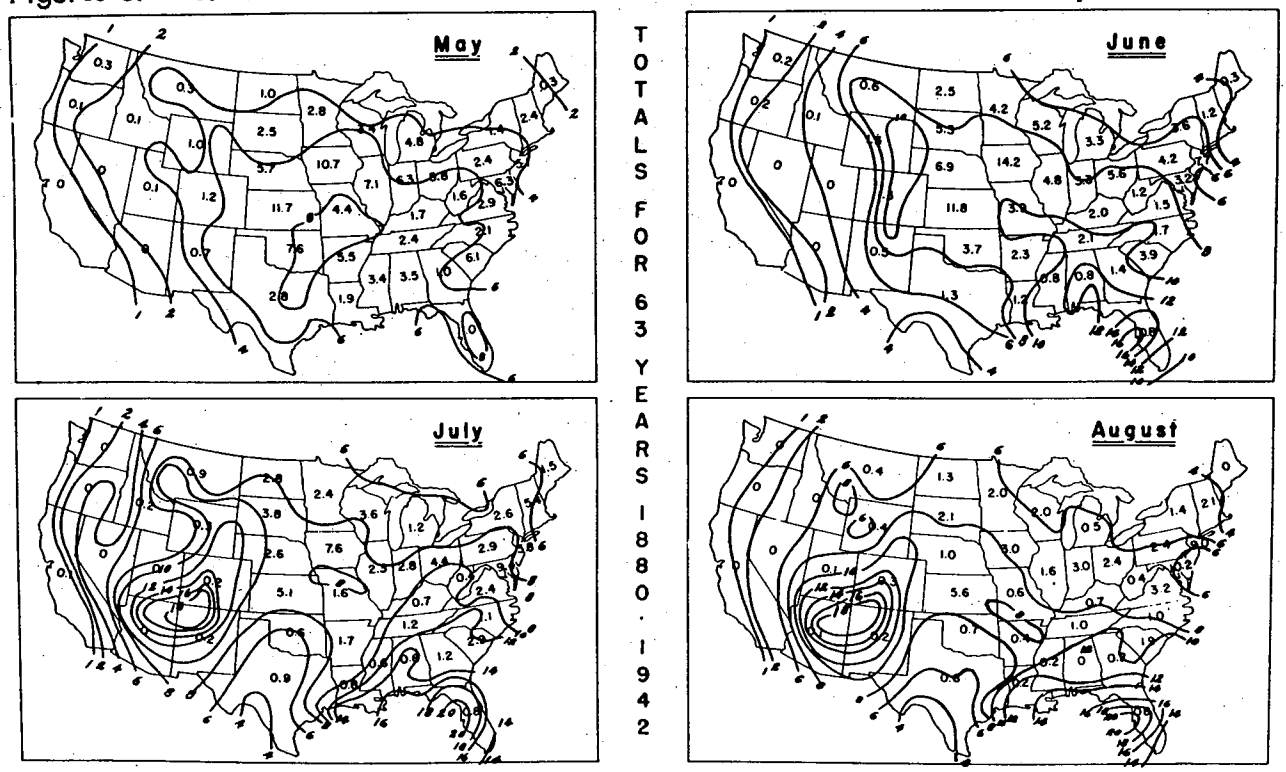
Figure 80

File 45019-1

TORNADO DAYS PER 10 000-SQUARE-MILE AREA PER STATE OR SECTION

Figures 8F - 8I

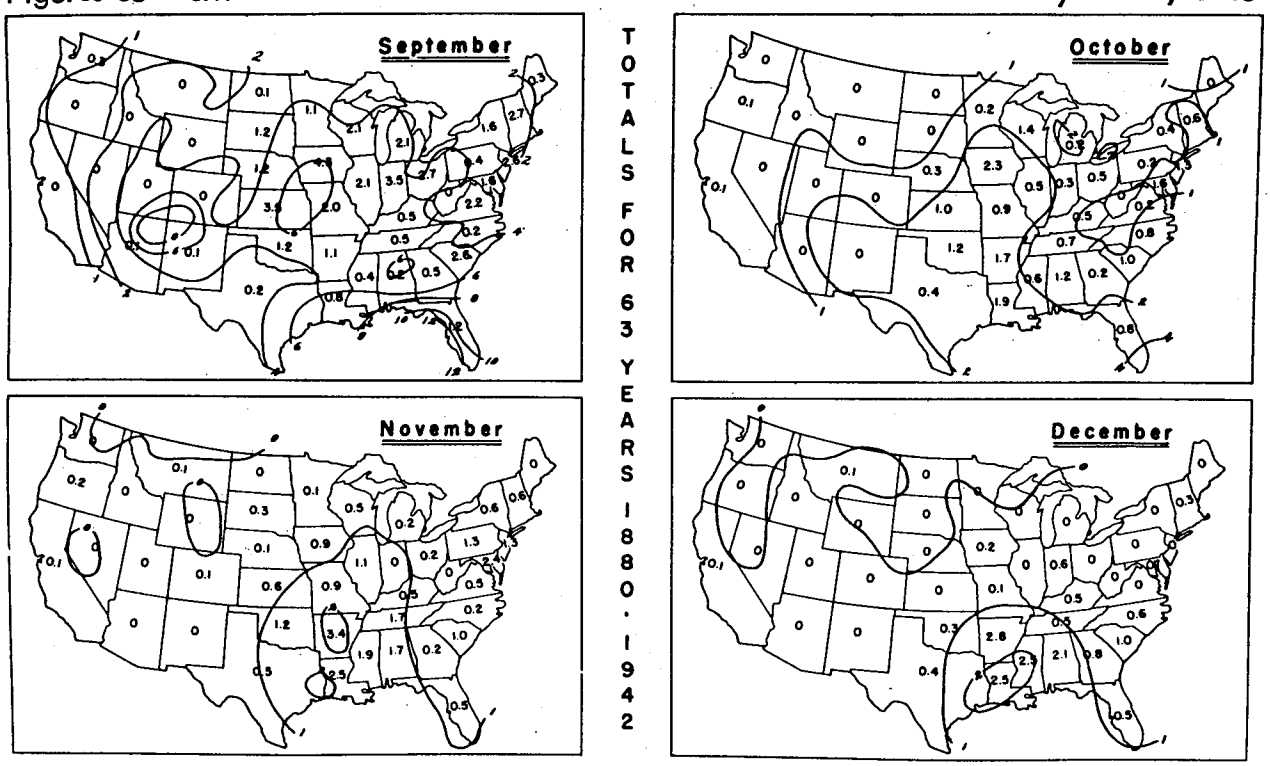
Hydromet, 1945



TORNADO DAYS PER 10 000-SQUARE-MILE AREA PER STATE OR SECTION

Figures 8J - 8M

Hydromet, 1945



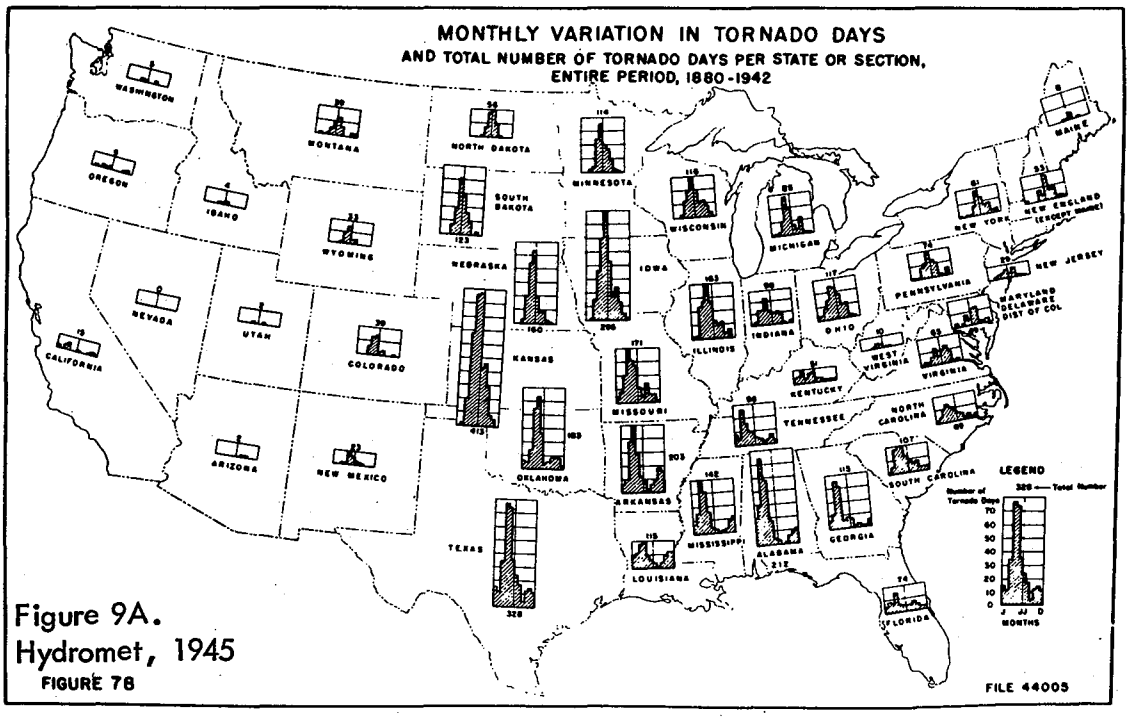


Figure 9A.
Hydromet, 1945
FIGURE 78

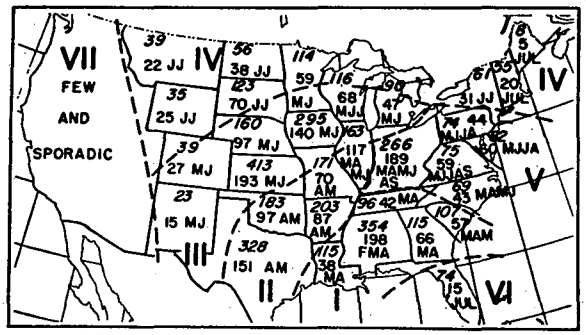


FIG. 25.15.2. Geographical distribution of tornadoes in the United States, 1880–1942. The areas represent states or groups of states. Upper figure shows total number, and lower figure the number of tornadoes during the months indicated. The roman numbers indicate main regions according to annual variation. (*Compiled from data by Showalter and Fulks* [27].) More recent counts show that the number of tornadoes is larger than indicated in the chart. The ratio of the number during season of maximum to the annual total is, however, representative.

Figure 9B. Petterssen, 1956, 1958

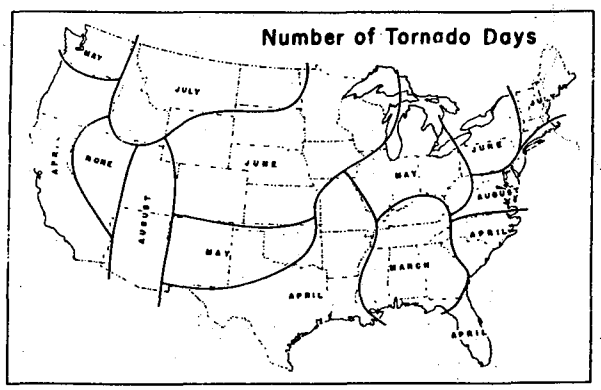


Figure 9D. Hydromet, 1945

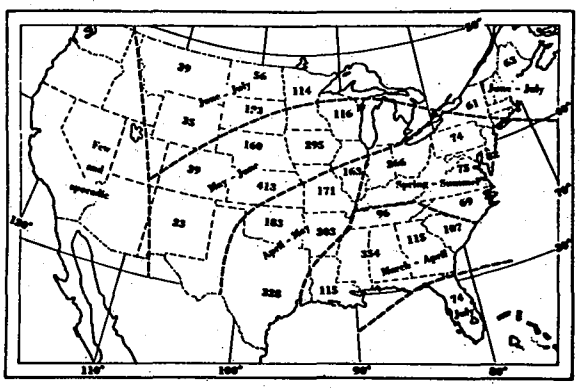


Fig. 7.18 Normal annual number of tornadoes by states and the "tornado season."

Figure 9C. Petterssen, 1969

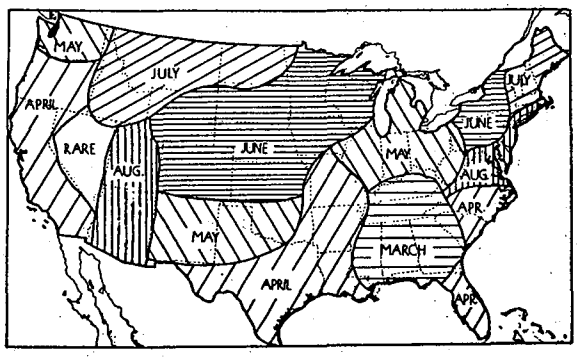


Figure 9E. Visher, 1954

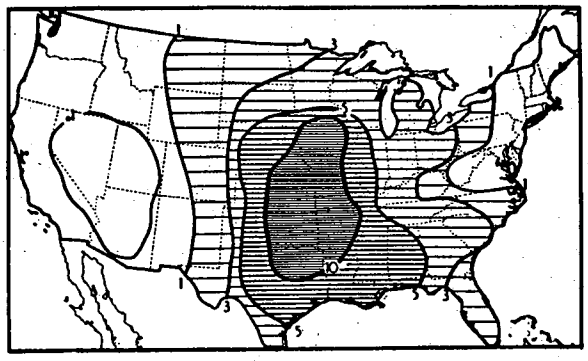


Figure 10A. "Normal annual number of tornadoes". Visher, 1954

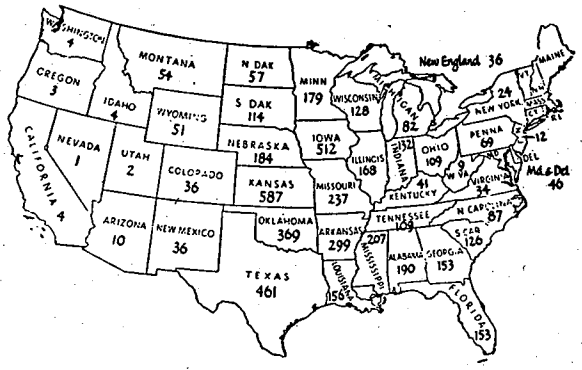


FIG. 3.—Number of tornadoes, by states, reported in 34-year period ending with 1949. (From official records of the U. S. Weather Bureau.)

Figure 10B. Flora, 1953

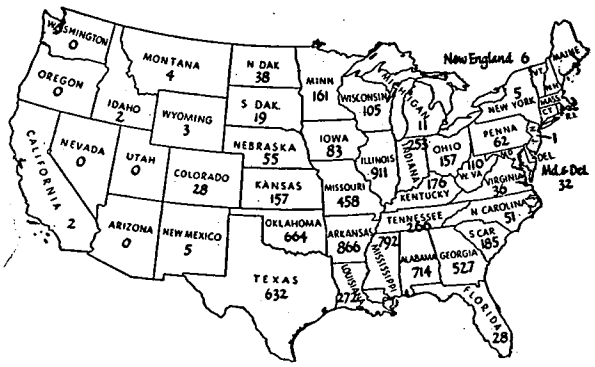


FIG. 5.—Number of persons killed in each state by tornadoes in 34-year period ending with 1949. (From official records of the U. S. Weather Bureau.)

Figure 10C. Flora, 1953

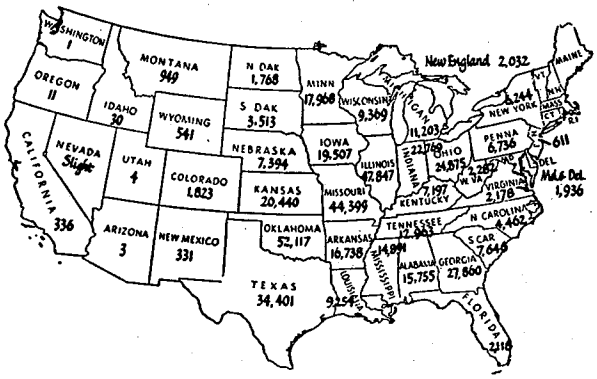


FIG. 6.—Tornado damage to property, by states, over the 34-year period ending with 1949. Losses given in thousands of dollars; add ,000 to each amount to obtain actual loss. (From official records of the U. S. Weather Bureau.)

Figure 10D. Flora, 1953

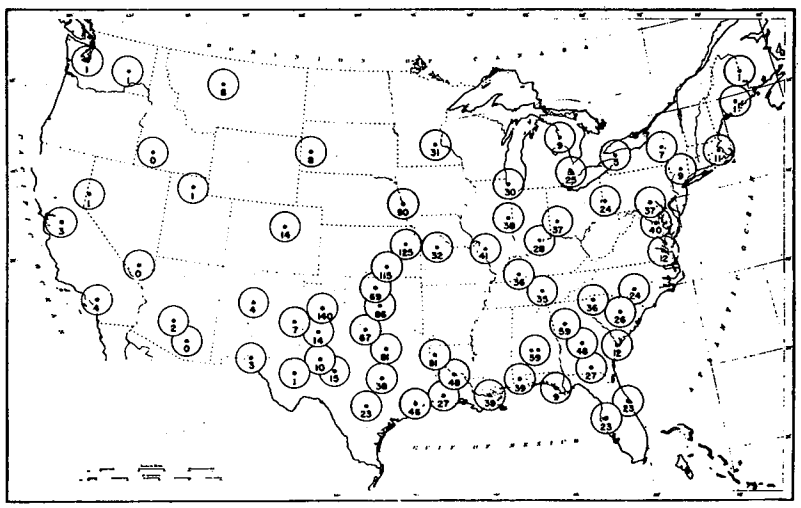


Figure 10E. Tornado occurrences within 60 miles of Air Force bases (1920-1949)". USAWS, 1955

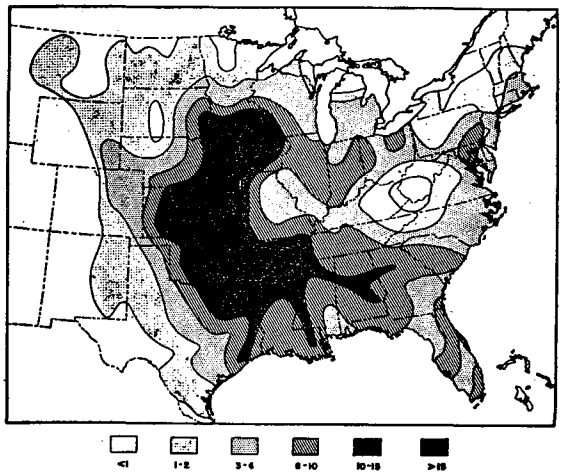


FIG. 2. Total number of tornadoes per 50-mile square reported in the period 1920–1949.

Figure 11A. Fawbush, et al, 1951

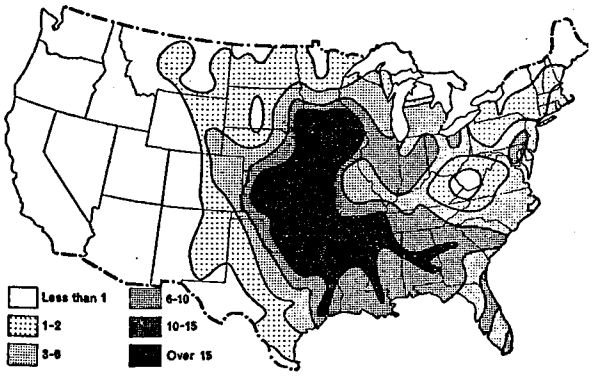


Figure 11B. Kimble, 1955

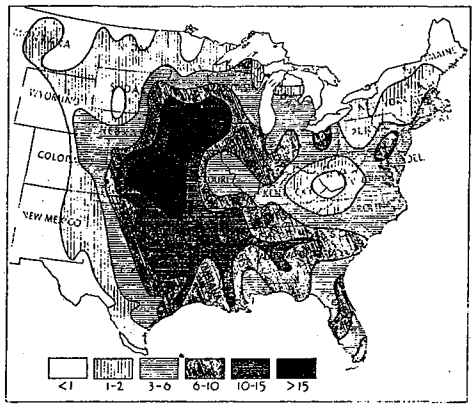


Figure 11C. Flora, 1953

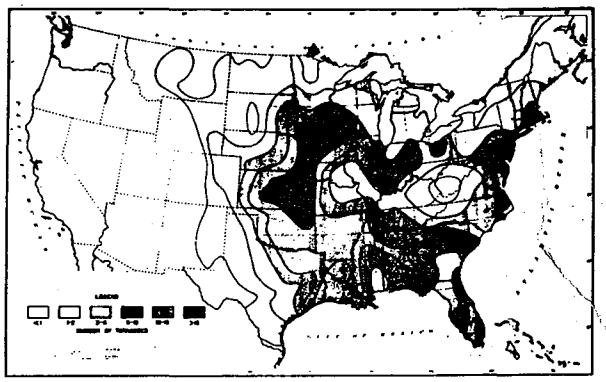


CHART I. TOTAL NUMBER OF TORNADOES PER 50-MILE SQUARE REPORTED IN THE PERIOD 1920-1949

Figure 11D. USAWS, 1955

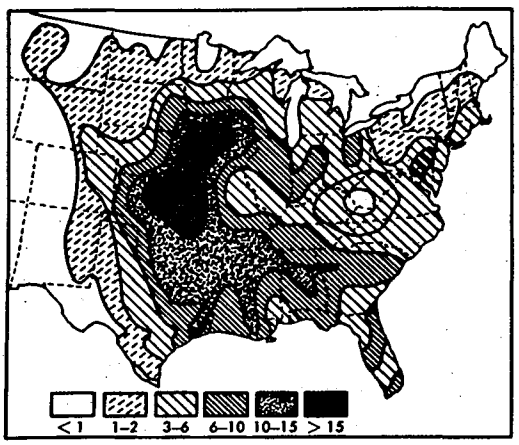


Fig 3-32. **Total number of tornadoes per 50-mile square reported in the period of 1920–1949. (After Fawbush, Miller and Starrett, *Bull. Amer. Met. Soc.*, Jan. 1951.)**

Figure 11E. Miller, 1966

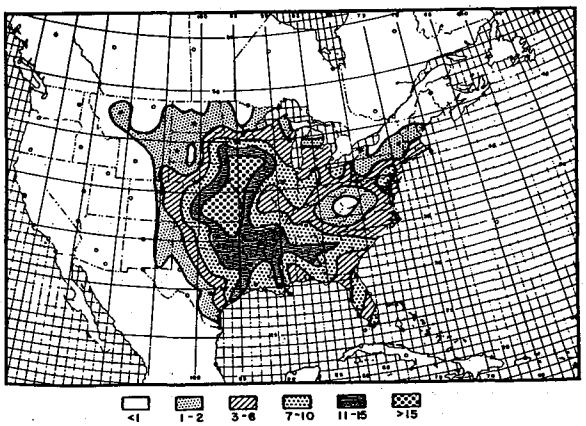


FIG. 14.36. Total number of tornadoes per 50-mile square reported in the period 1920–1949 (after Fawbush, Miller, and Starrett).

Figure 11F. George, 1960

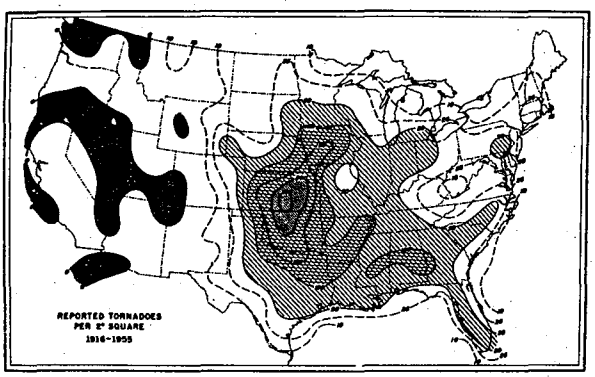


Figure 1. Total number of reported tornadoes per 2° latitude-longitude square over the United States, 1916-1955.

Figure 12A. Winston, 1956

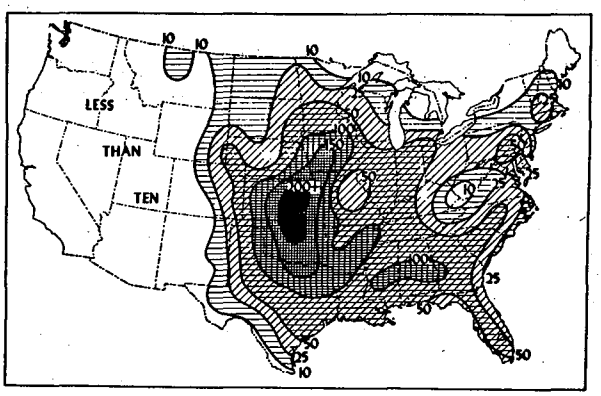
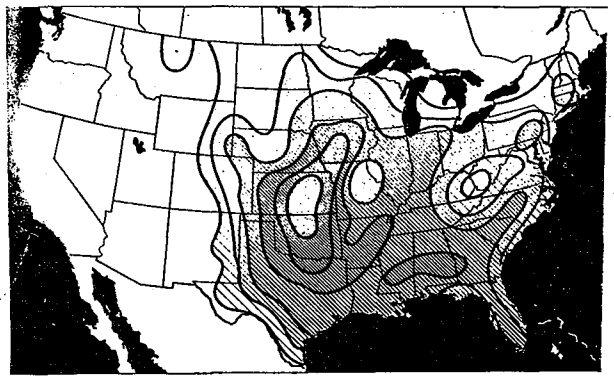


Figure 12B. Wolford, 1960



FREQUENCY OF TORNADOES in the U. S. from 1916 to 1955 is shown on this map. Darkest shading shows the greatest number; in the white areas they are very rare. Tornadoes occur throughout the year, hitting a peak in late spring and early summer

Figure 12C. Tepper, 1958

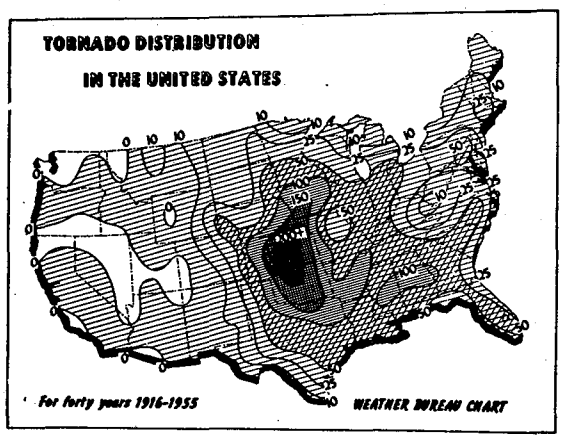


Figure 12D. Reichelderfer, 1957

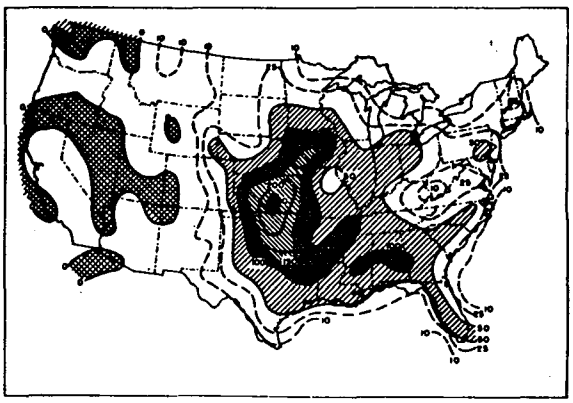


FIG. 1. Total number of reported tornadoes per 2-deg latitude-longitude square over the United States, 1916–1955.

Figure 12E. House, 1963

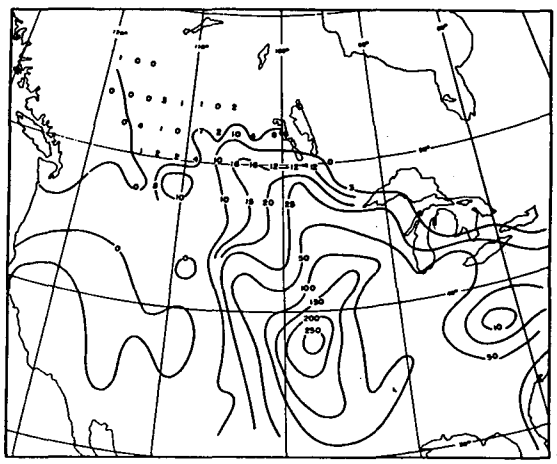


FIG. 2. Total number of tornado situations per 2-deg latitude-longitude square, 1916–1955 over the Canadian prairies; isopleths in the United States are for tornado reports and taken from "Forecasting Tornadoes and Severe Thunderstorms" [3].

Figure 12F. McKay and Lowe, 1960

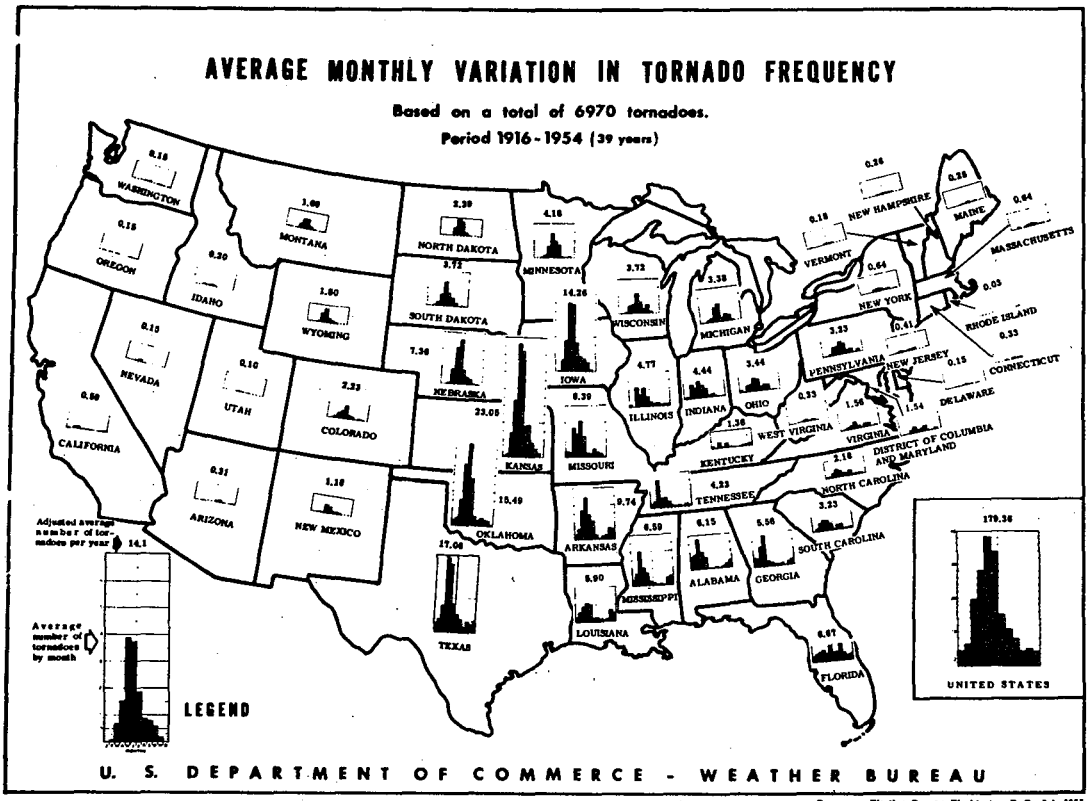


Figure 13A. USWB, 1955

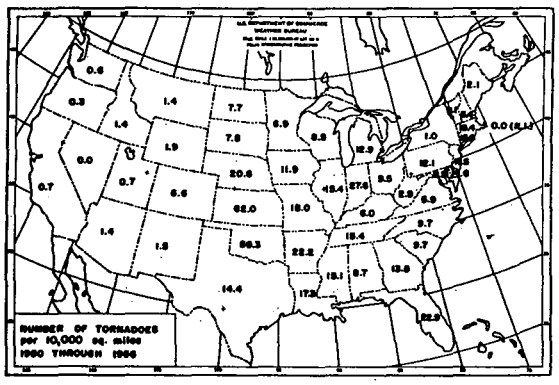


Figure 13B. Lee, 1958

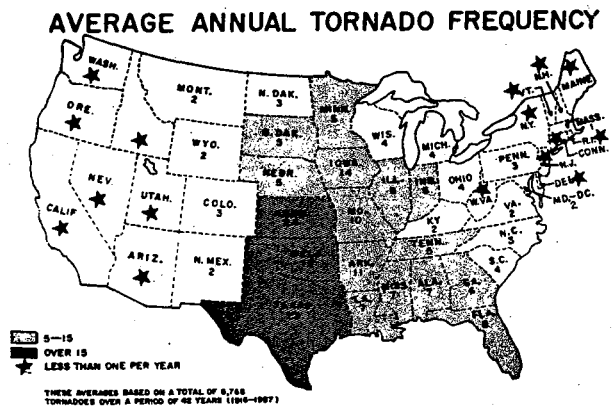


Figure 13C. USAWS-USWB, 1960

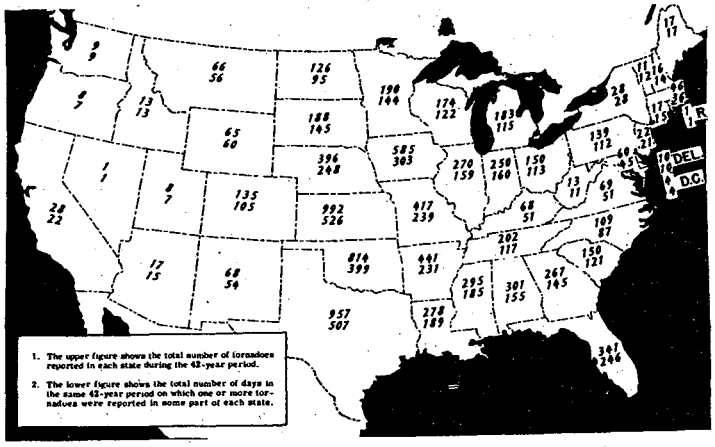


Figure 13D. Critchfield, 1960

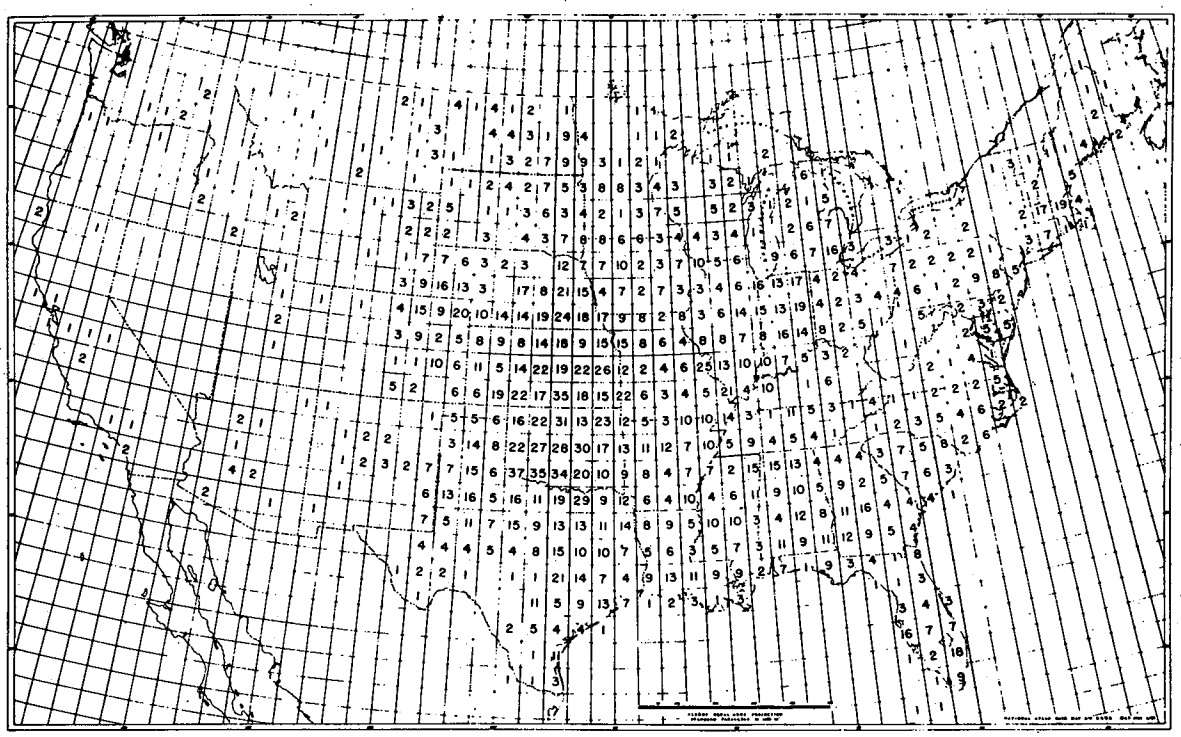


Figure 16.--TORNADOES BY 1 DEGREE SQUARES, 1953-58
(Based on first point of contact with ground of 3,540 tornadoes.)

Figure 14A. Wolford, 1960

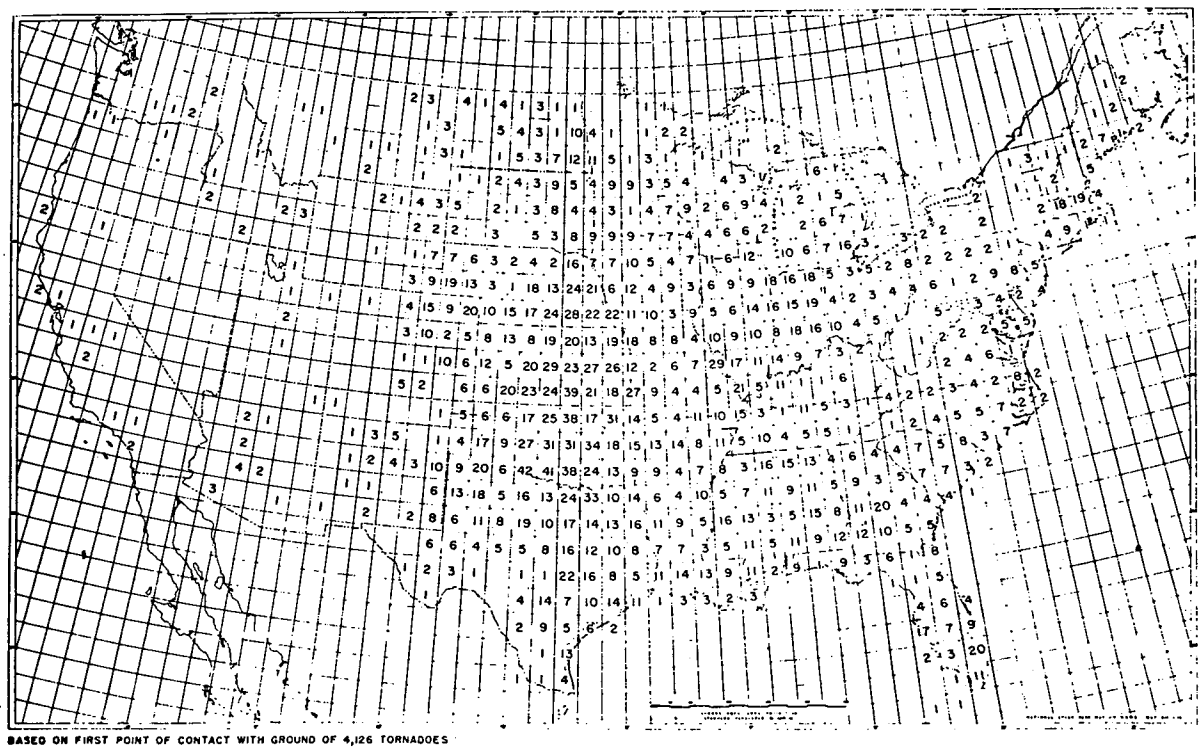
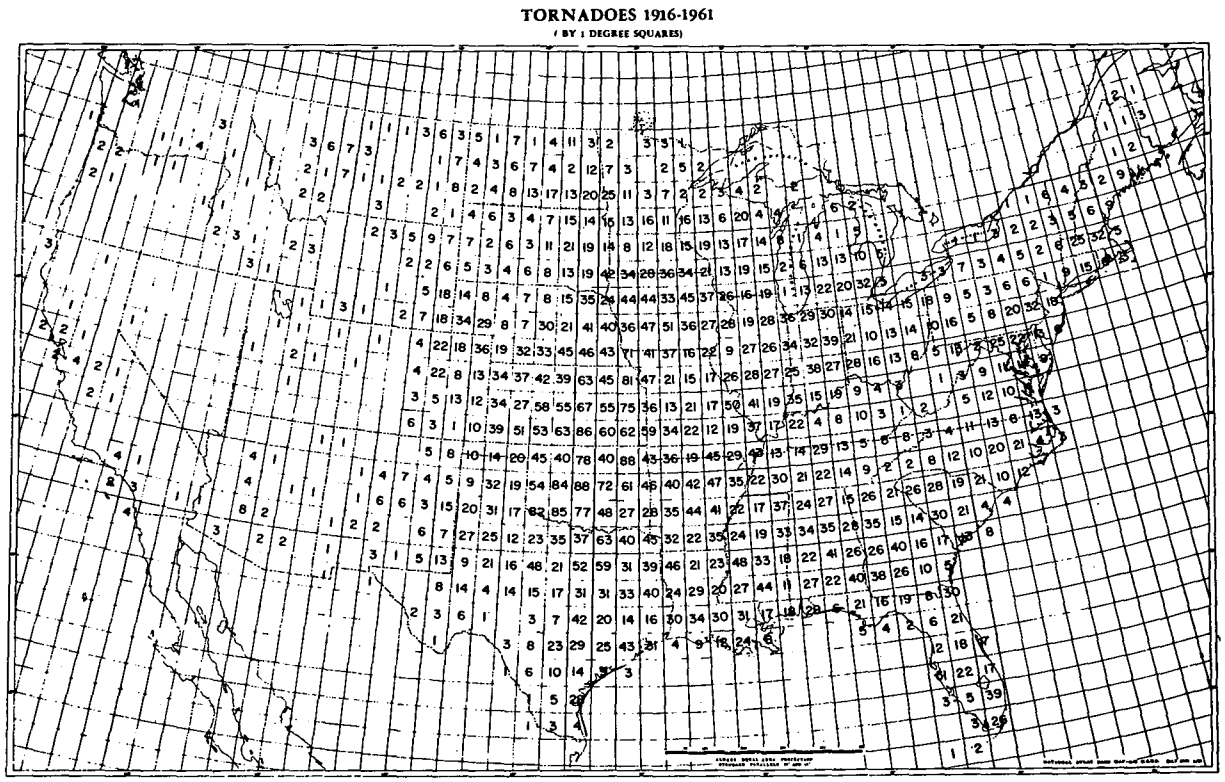


Figure 14B. "Tornadoes, 1953-1959 (by 1 degree squares)" L. S. 5913 revised 1960. USWB 1960b



Based on first point of contact with ground of 11,055 tornadoes.

Figure 15A. L. S. 5913 revised April 1962. USWB, 1962a

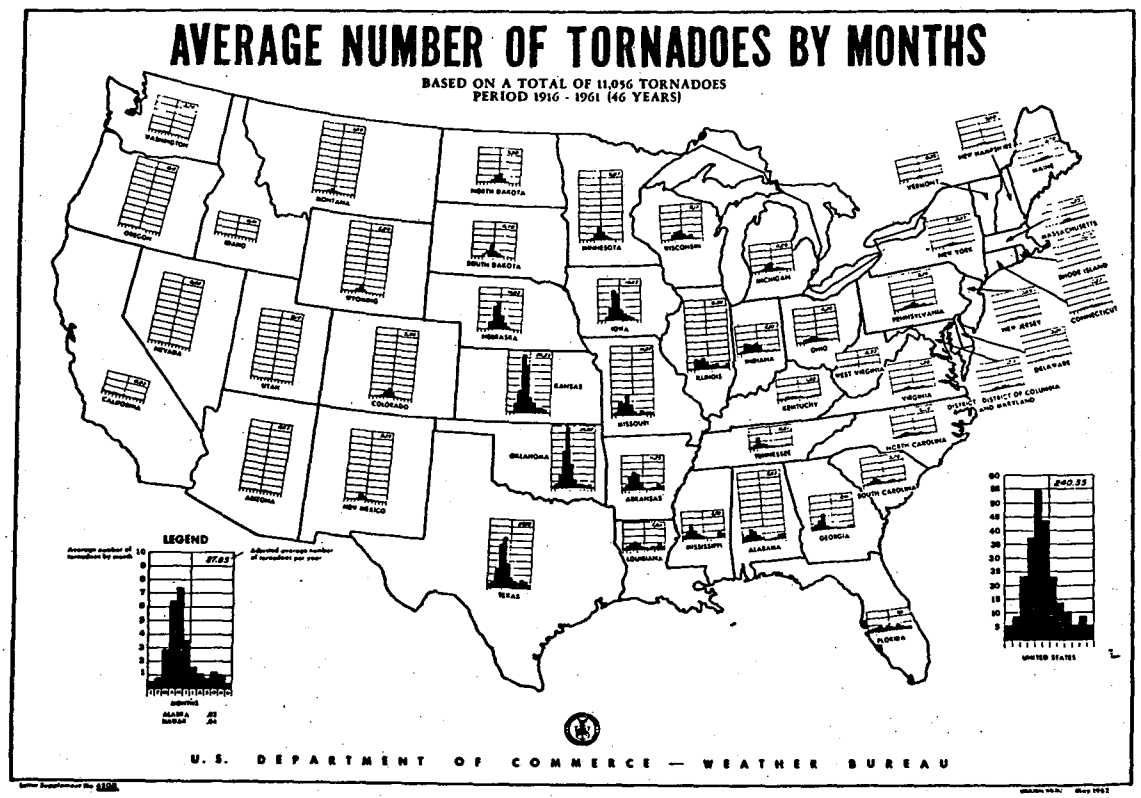


Figure 15B. USWB, 1962b

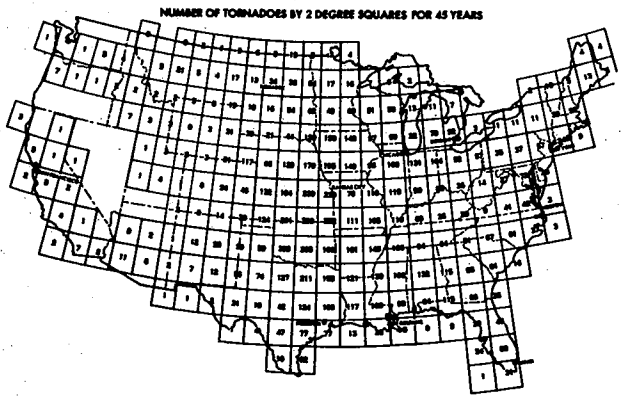


Figure 16A. Sadowski, 1965

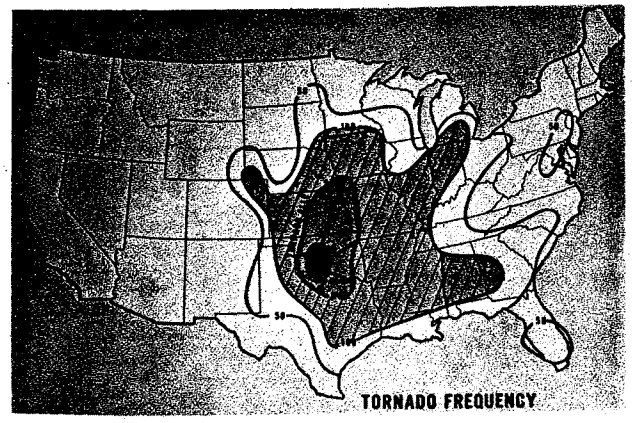
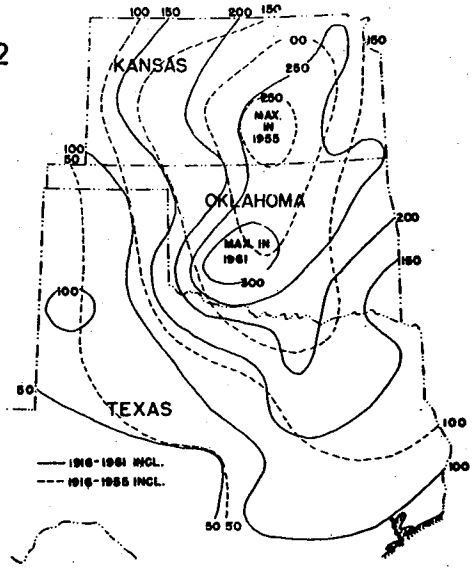


Figure 16D. Sadowski, 1965

Figure 16E. Bates, 1962



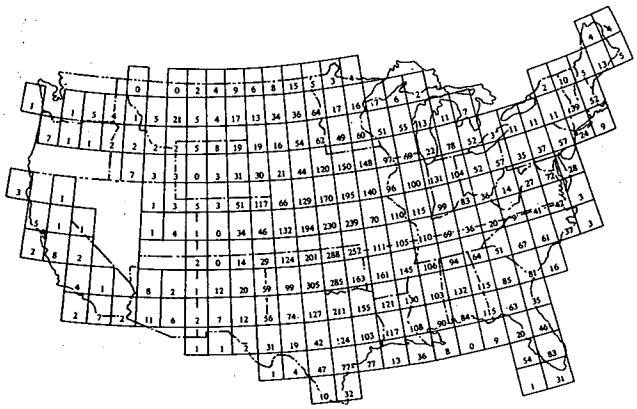
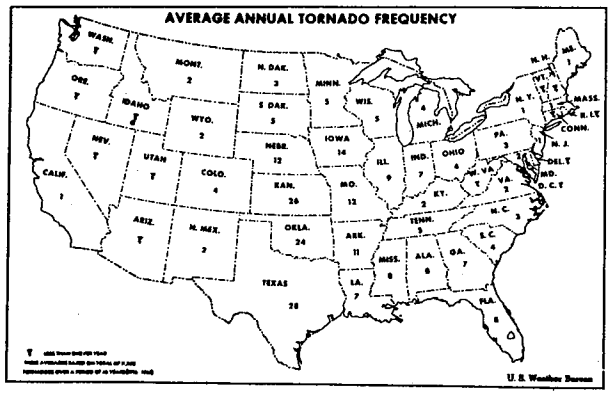


FIG. 6-16. Total number of tornadoes by two-degree squares during a 45-year period (1916-1961). (Courtesy of ESSA.)

Figure 16B. Miller and Thompson, 1970

Figure 16C. Knight, 1964



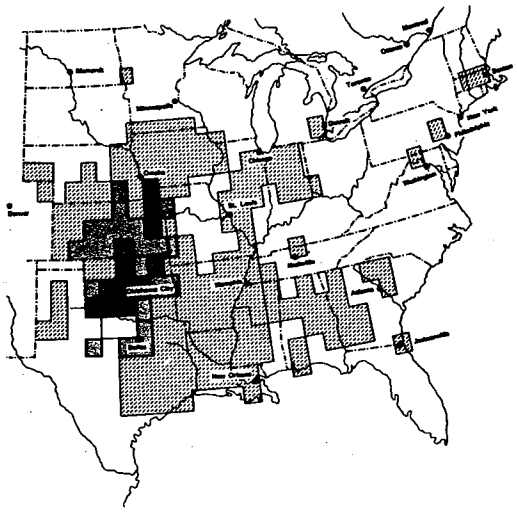


Figure 16F. Longley, 1970

FIGURE 11.9 Distribution of tornadoes in the United States in mean number per decade per degree square, 1916 to 1961 (after Roth) (light shading 5–10; moderate, 10–15; heavy, 15–30.) (From Roth, Richard J., 1963: Severe local weather and the property insurance industry. *Amer. Meteor. Soc., Proc. Third Conf. on Severe Local Storms.*)

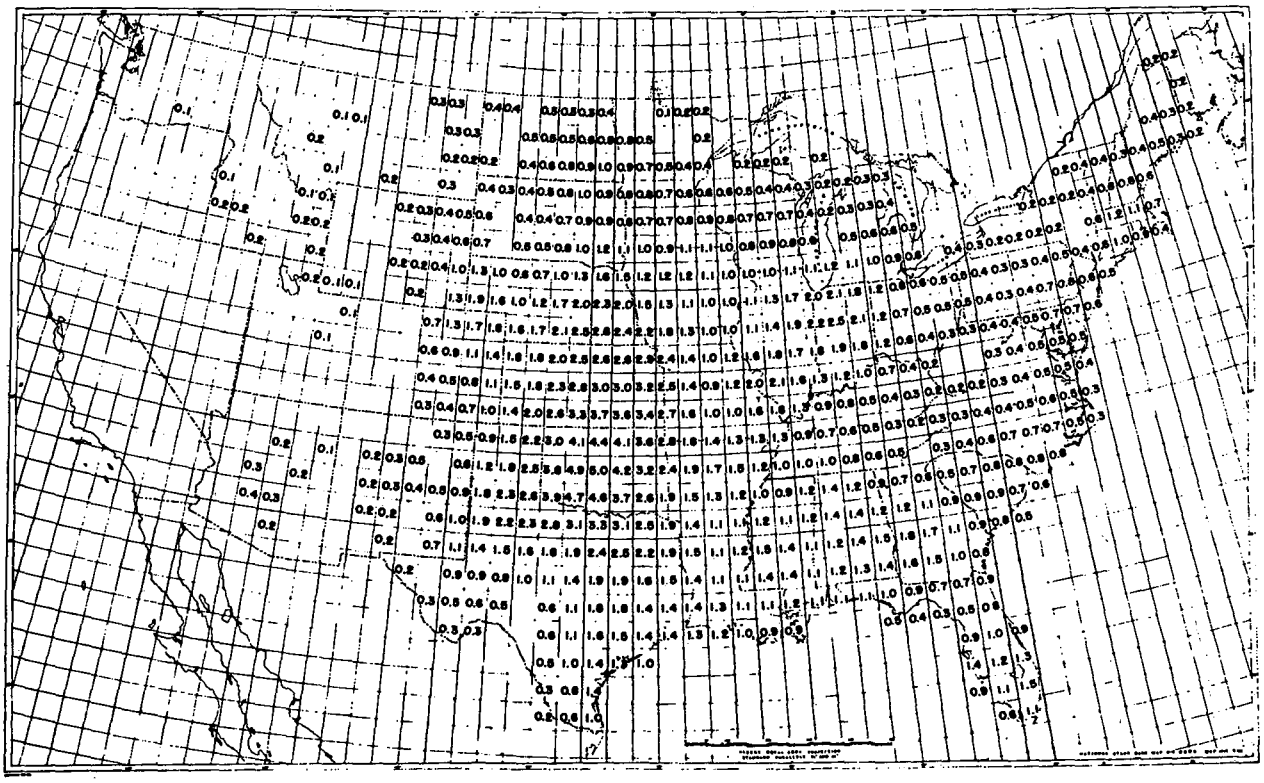


FIGURE 4.—Mean annual frequency of tornadoes, 1953–62.

Figure 17A. Thom, 1963

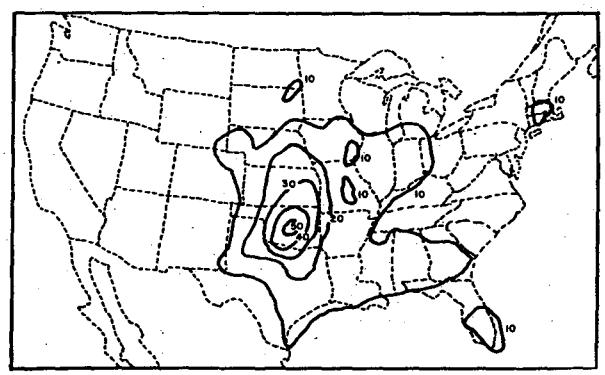


Figure 17B. Kessler, 1966

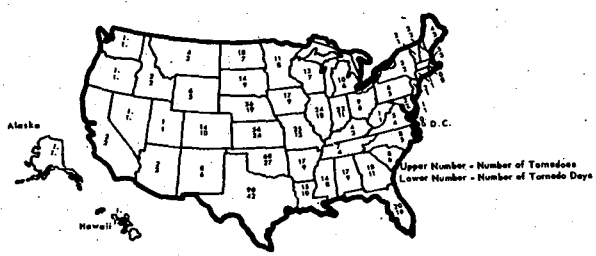


Figure 17C. USWB, 1965a

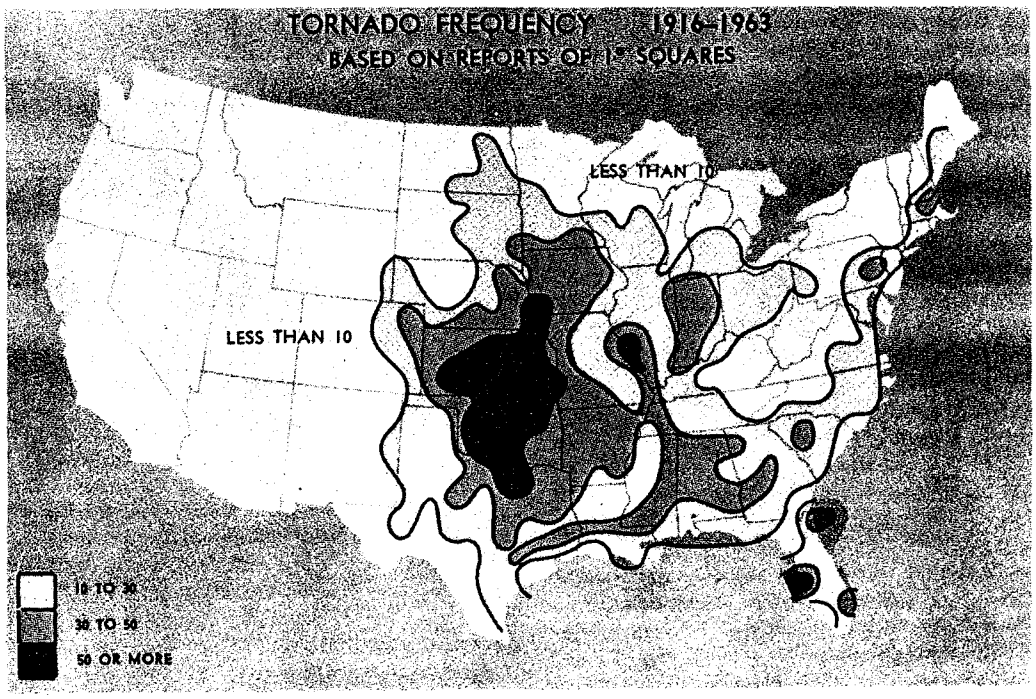


FIGURE 97. Tornado frequency, 1916–63.

Figure 18A. FAA-USWB, 1965

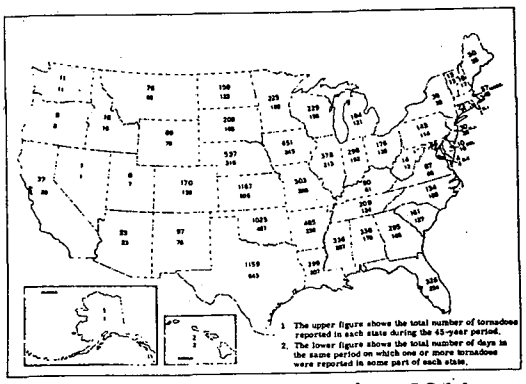


Figure 18B. Critchfield, 1966

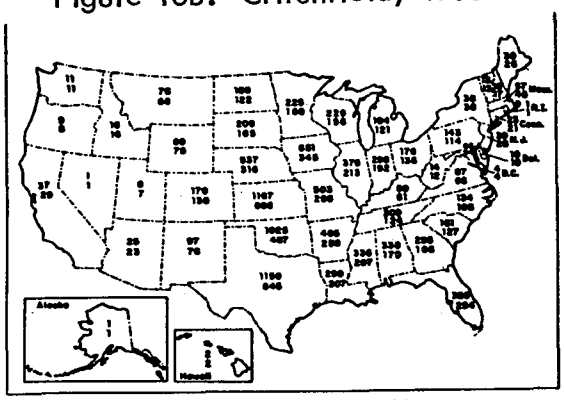


Figure 5.14. Tornado frequency in the United States from 1916 to 1969, by states. Upper figure indicates the total number of tornadoes reported during the period. Lower figure indicates the number of days during the period when tornadoes were reported. [U.S. Weather Bureau]

Figure 18C. Rumney, 1968

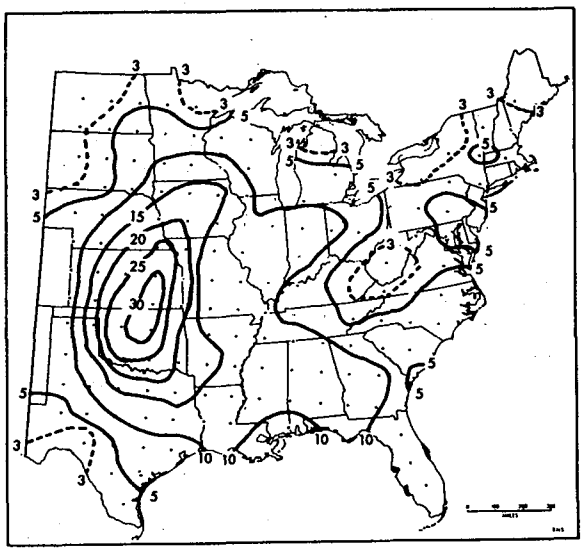


FIGURE 2.—Map showing the mean number of tornadoes per hour for the period 1916–1964.

Figure 18D. Skaggs, 1969

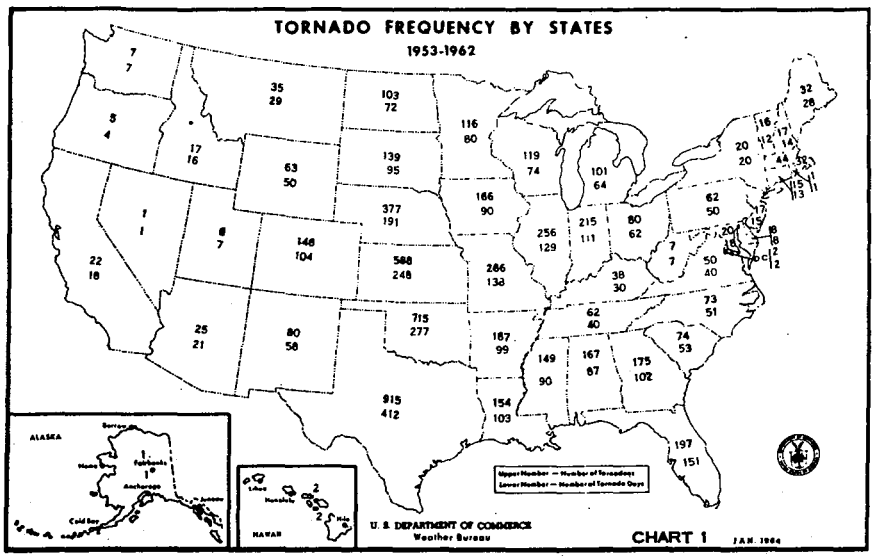


Figure 19A.
USWB, 1964

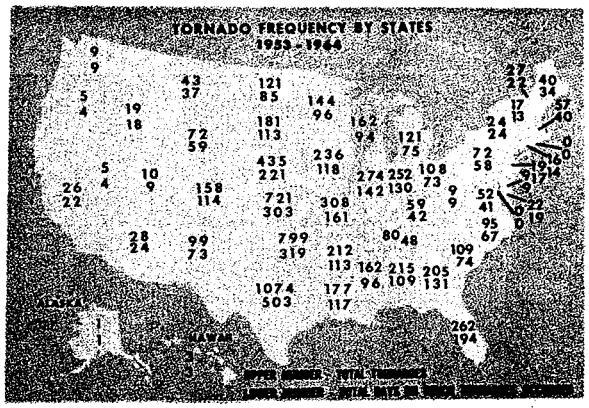


Figure 19B.
Kutschenreuter, 1965

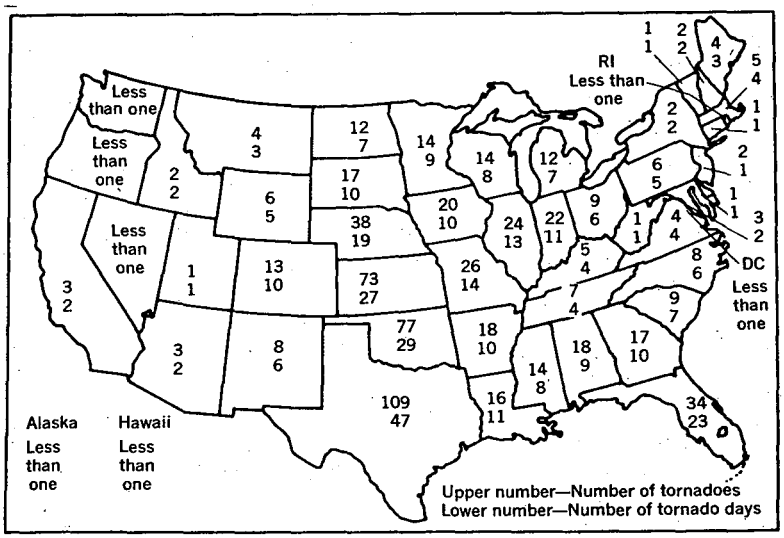


Figure 19C. Day and Sternes, 1970

Fig. 12–5 Annual average tornado frequency by states, 1953–1964. Tornadoes occur in many parts of the world and in all 50 states. But no area is more favorable for their formation than the continental plains of North America, and no season is free of them. Normally, the number of tornadoes is at its lowest in the United States during December and January, and at its peak in May. The months of greatest total frequency are April, May, and June. From *Tornadoes*, ESSA, 1966, p. 8.

Figure 20A.
USWB, 1965b

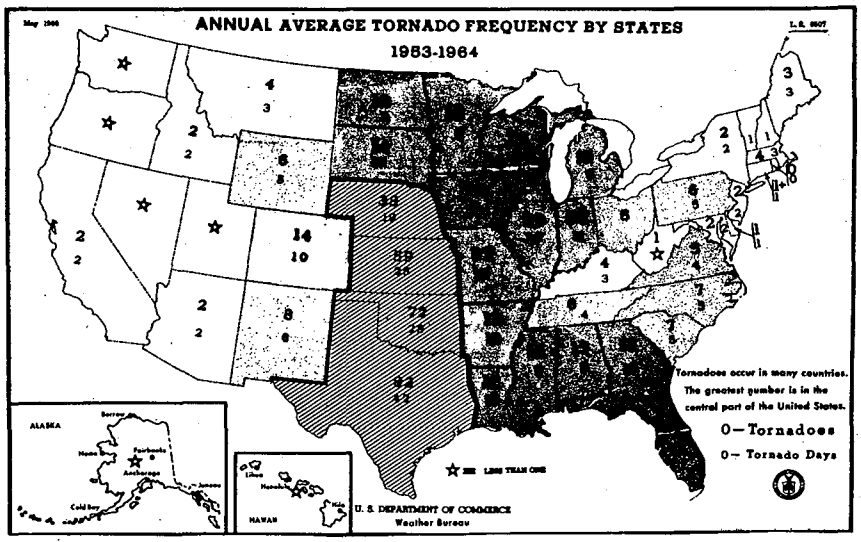


Figure 20B.
USWB, 1965c

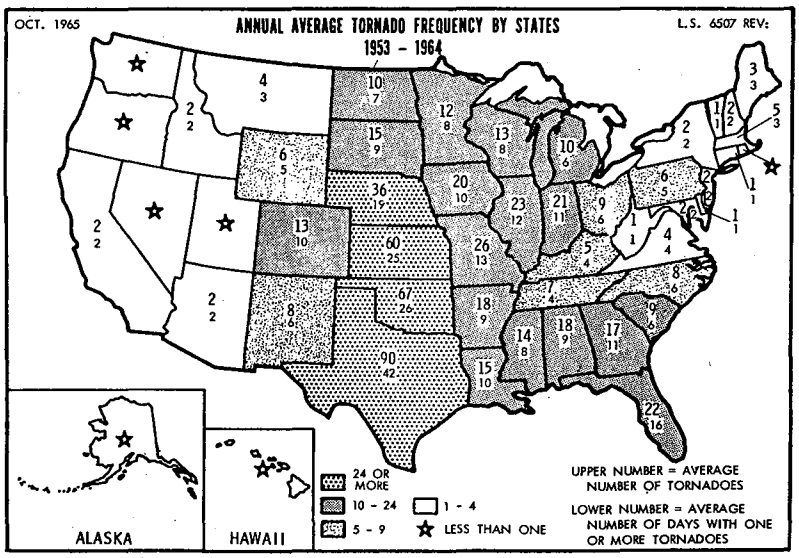
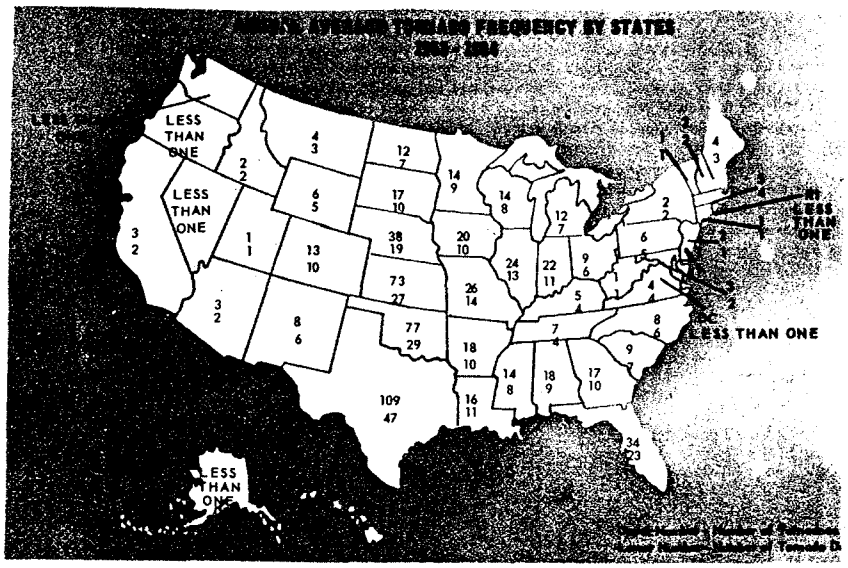


Figure 20C.
USWB, 1966



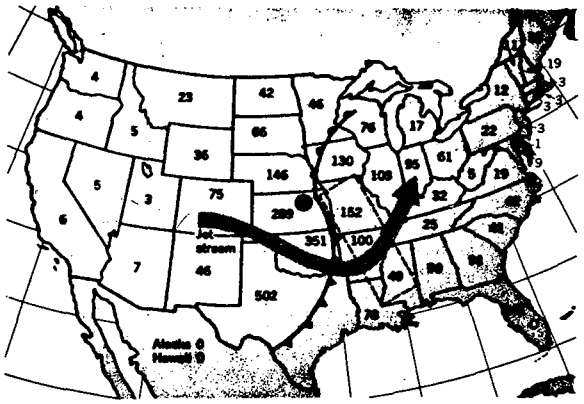


Figure 21A. Day, 1966

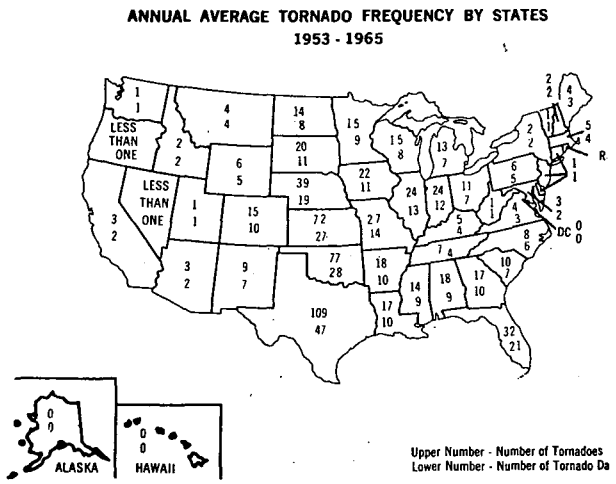


Figure 21B. ESSA, 1966

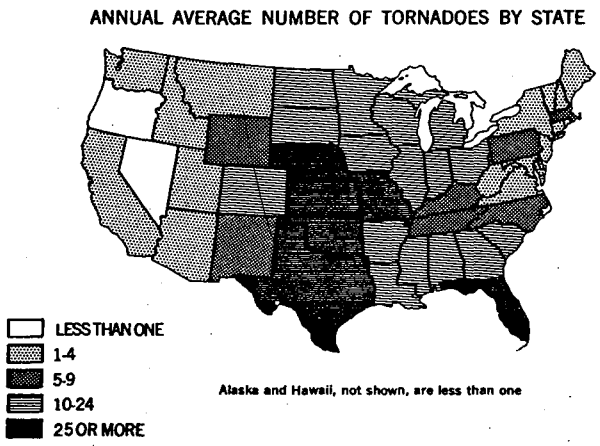


Figure 21C. USWB, 1968

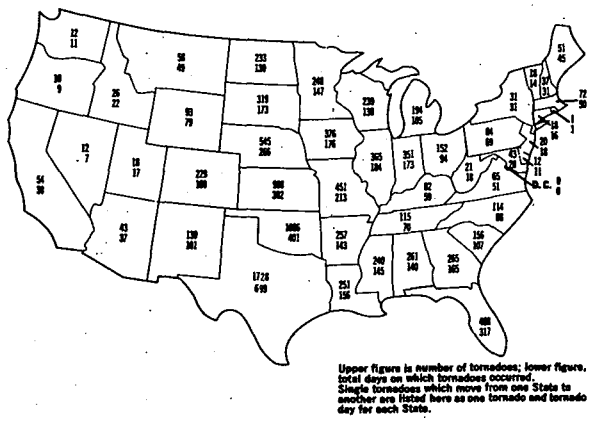


Figure 21D. ESSA, 1968

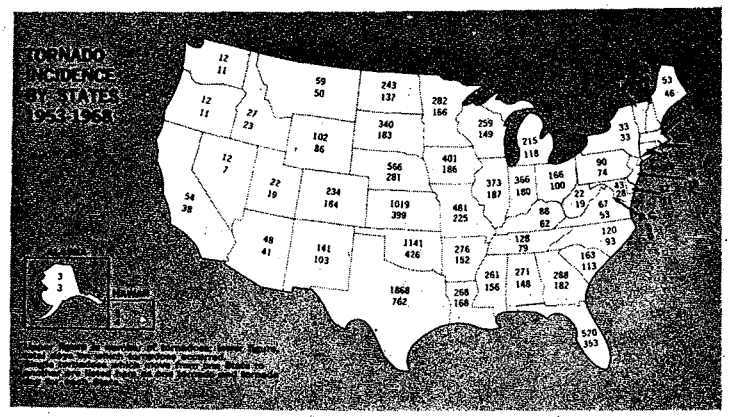


Figure 21E. ESSA, 1969b

Figure 22A.
Sadowski, 1965

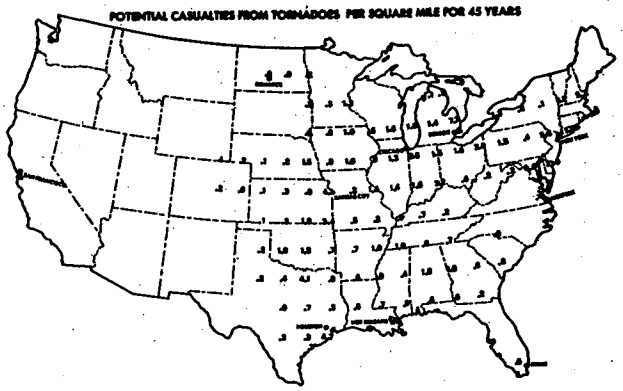
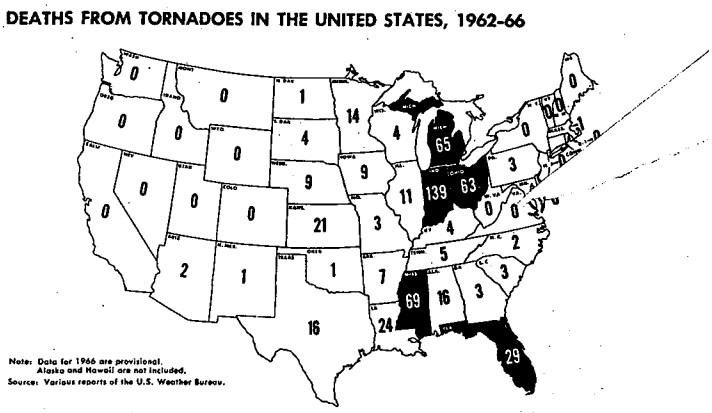


Figure 22B. Metropolitan
Life Insurance Company, 1967



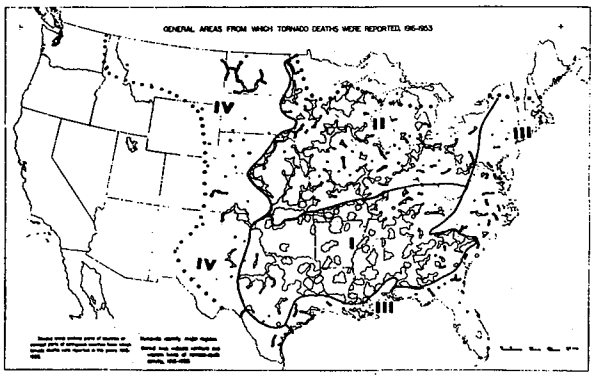


Figure 22C. Linehan, 1957

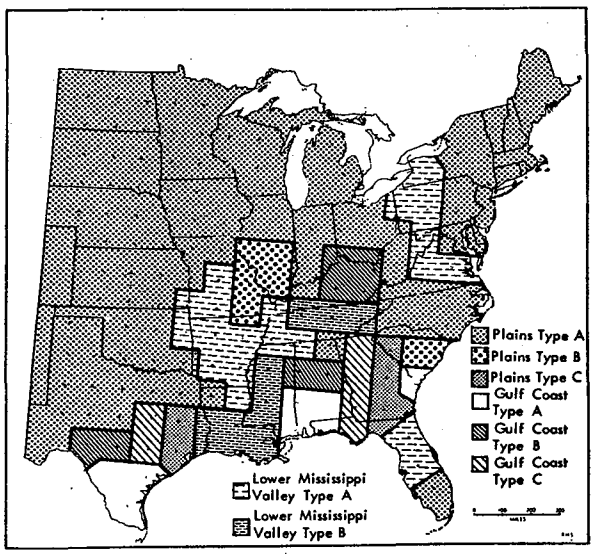


Figure 22D. Skaggs, 1969

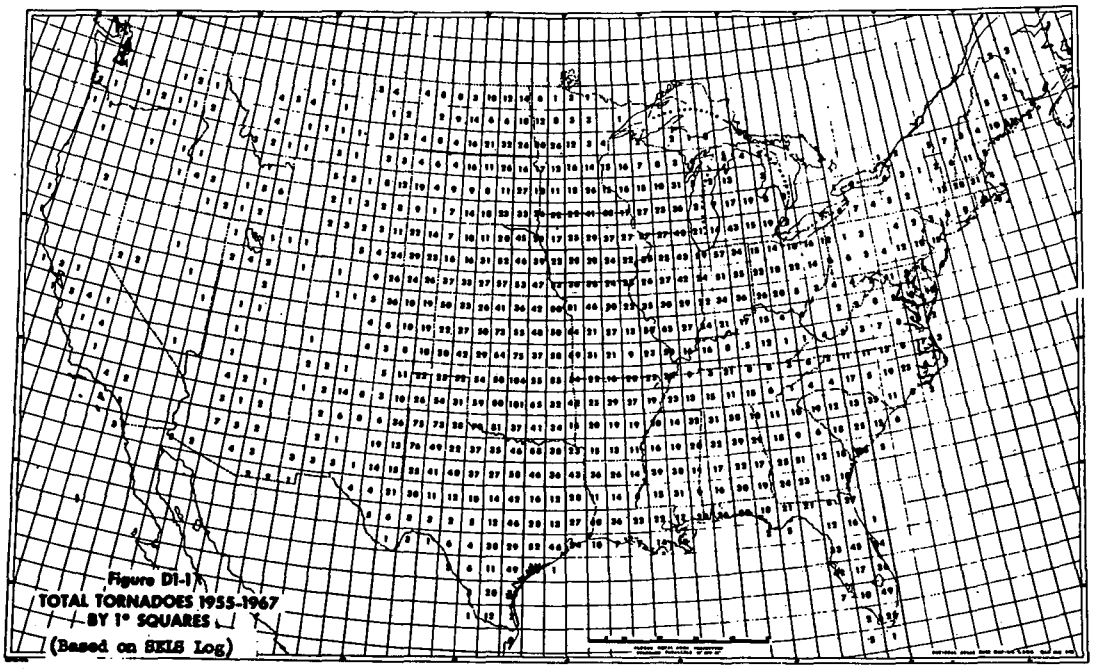


Figure 23A. Pautz, 1969

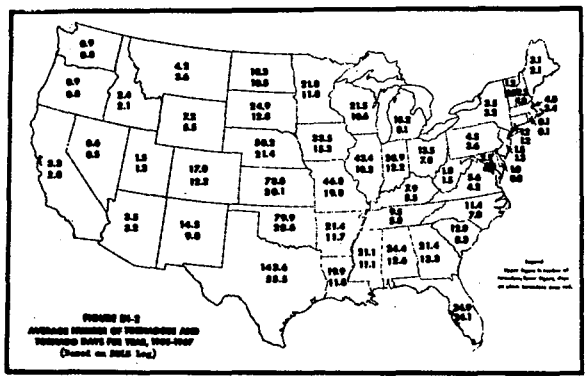


Figure 23B. Pautz, 1969

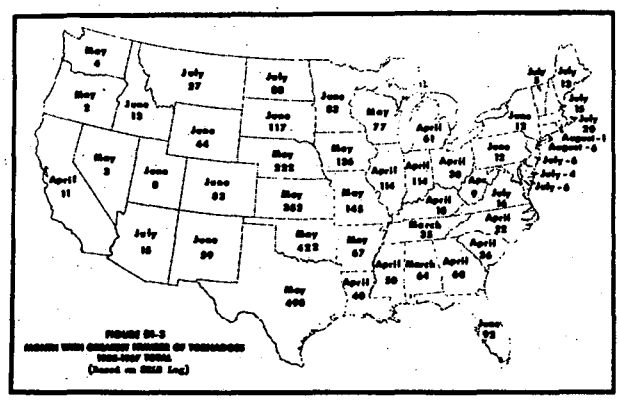


Figure 23C. Pautz, 1969

Figure 24A. Pautz, 1969

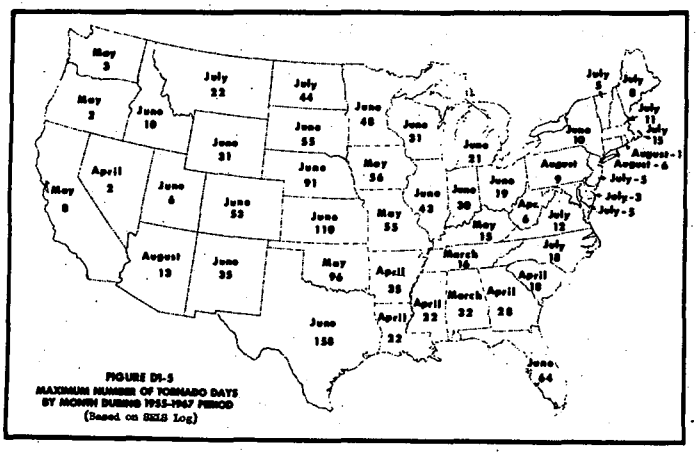


Figure 24B. Pautz, 1969

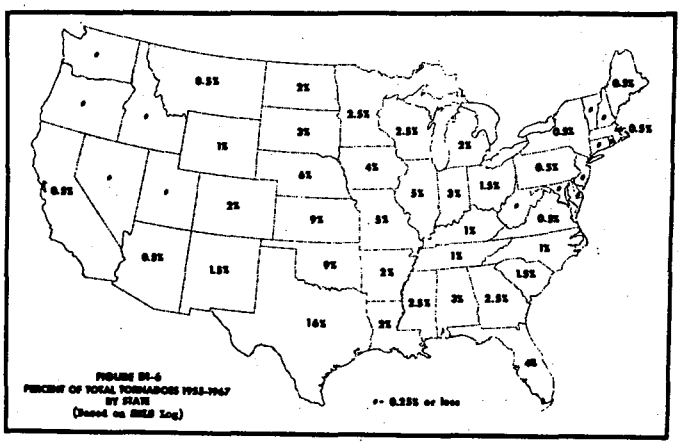
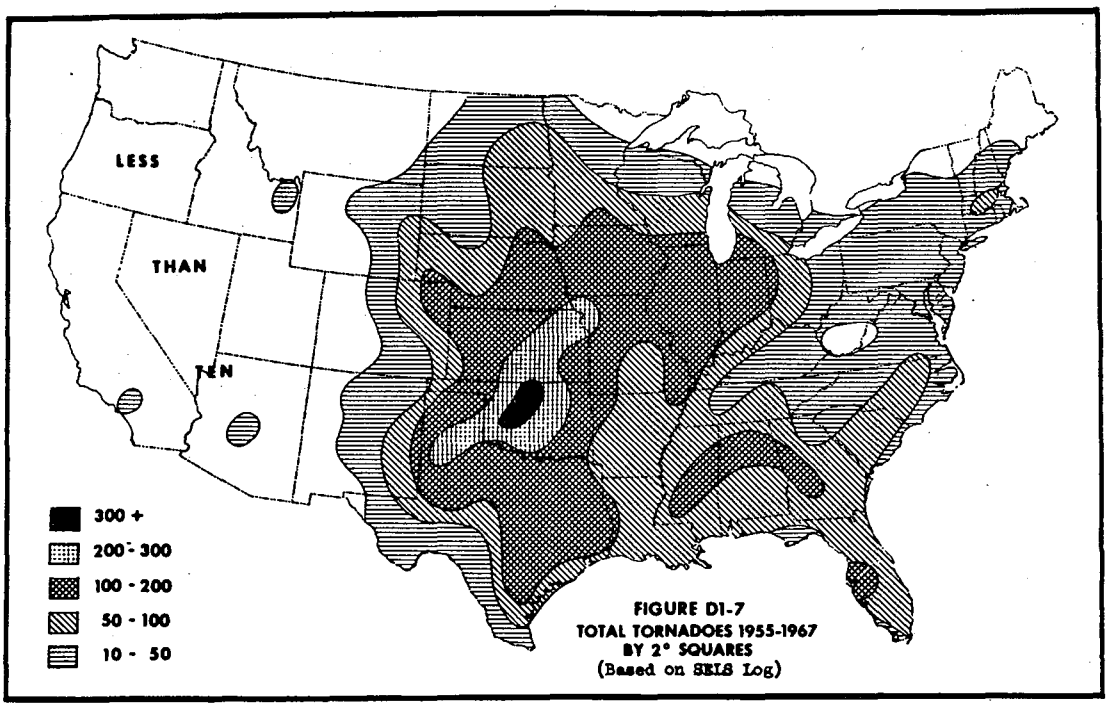


Figure 24C. Pautz, 1969



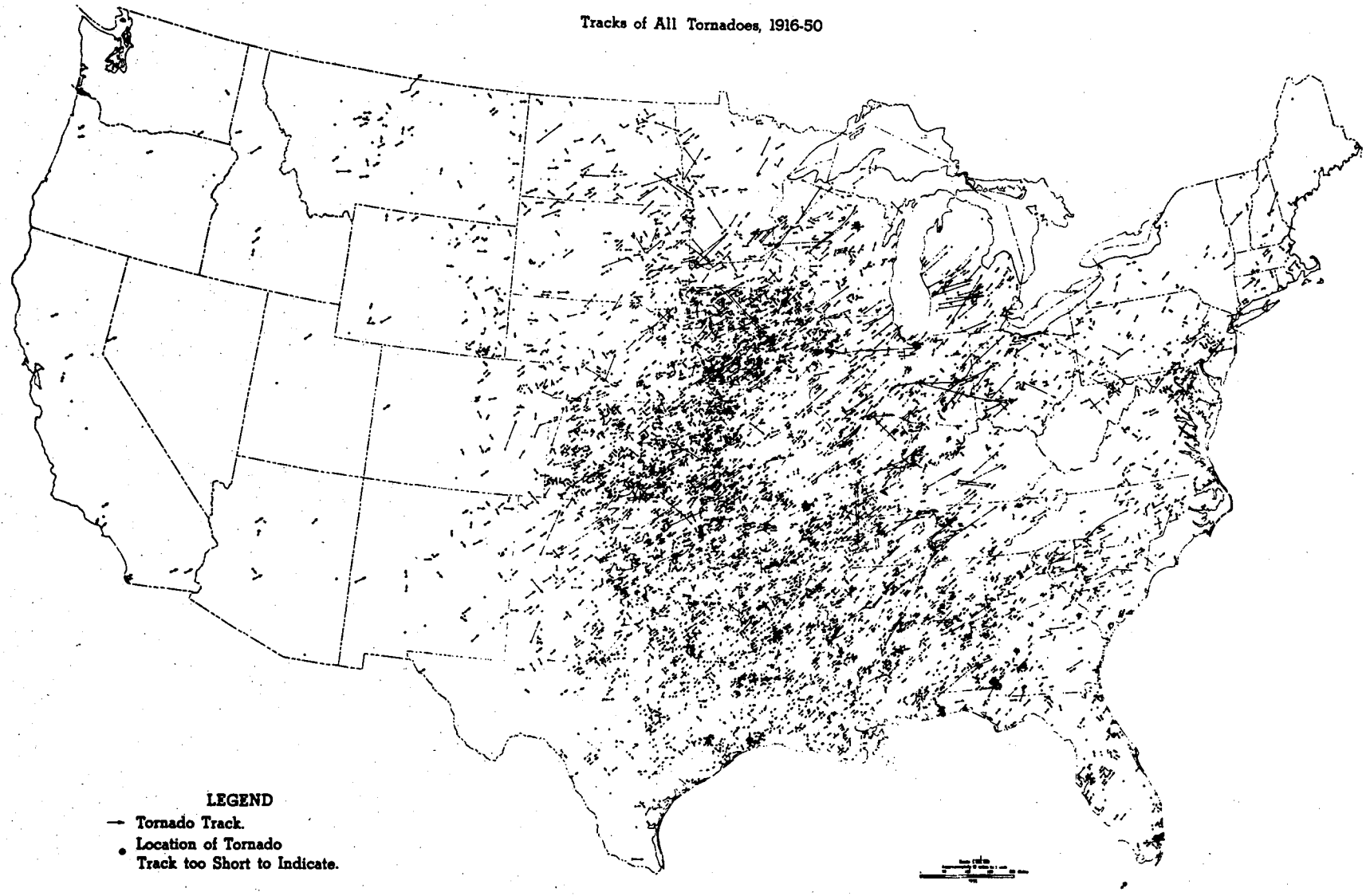


Figure 25. Wolford, 1952, 1960; Linehan, 1957

NATIONAL SEVERE STORMS LABORATORY

The NSSL Technical Memoranda, beginning with No. 28, continue the sequence established by the U. S. Weather Bureau National Severe Storms Project, Kansas City, Missouri. Numbers 1-22 were designated NSSP Reports. Numbers 23-27 were NSSL Reports, and 24-27 appeared as subseries of Weather Bureau Technical Notes. These reports are available from the Clearinghouse for Federal Scientific and Technical Information, 5285 Port Royal Road, Springfield, Virginia 22151, for $3.00, and a microfiche version for $0.65. CFTSI numbers are given below in parentheses.

No. 1 National Severe Storms Project Objectives and Basic Design. Staff, NSSP. March 1961. (PB-168207)

No. 2 The Development of Aircraft Investigations of Squall Lines from 1956-1960. B. B. Goddard. (PB-168208)

No. 3 Instability Lines and Their Environments as Shown by Aircraft Soundings and Quasi-Horizontal Traverses. D. T. Williams. February 1962. (PB-168209)

No. 4 On the Mechanics of the Tornado. J. R. Fulks. February 1962. (PB-168210)

No. 5 A Summary of Field Operations and Data Collection by the National Severe Storms Project in Spring 1961. J. T. Lee. March 1962. (PB-165095)

No. 6 Index to the NSSP Surface Network. T. Fujita. April 1962. (PB-168212)

No. 7 The Vertical Structure of Three Dry Lines as Revealed by Aircraft Traverses. E. L. McGuire. April 1962. (PB-168213)

No. 8 Radar Observations of a Tornado Thunderstorm in Vertical Section. Ralph J. Donaldson, Jr. April 19((PB-174859)

No. 9 Dynamics of Severe Convective Storms. Chester W. Newton. July 1962. (PB-163319)

No. 10 Some Measured Characteristics of Severe Storms Turbulence. Roy Steiner and Richard H. Rhyne. July 1962. (N62-16401)

No. 11 A Study of the Kinematic Properties of Certain Small-Scale Systems. D. T. Williams. October 1962. (PB-168216)

No. 12 Analysis of the Severe Weather Factor in Automatic Control of Air Route Traffic. W. Boynton Beckwith. December 1962. (PB-168217)

No. 13 500-Kc./Sec. Sferics Studies in Severe Storms. Douglas A. Kohl and John E. Miller. April 1963. (PB-168218)

No. 14 Field Operations of the National Severe Storms Project in Spring 1962. L. D. Sanders. May 1963. (PB-168219)

No. 15 Penetrations of Thunderstorms by an Aircraft Flying at Supersonic Speeds. G. P. Roys. Radar Photographs and Gust Loads in Three Storms of 1961 Rough Rider. Paul W. J. Schumacher. May 1963. (PB-168220)

No. 16 Analysis of Selected Aircraft Data from NSSP Operations, 1962. T. Fujita. May 1963. (PB-168221)

No. 17 Analysis of Methods for Small-Scale Surface Network Data. D. T. Williams. August 1963. (PB-168222)

No. 18 The Thunderstorm Wake of May 4, 1961. D. T. Williams. August 1963. (PB-168223)

No. 19 Measurements by Aircraft of Condensed Water in Great Plains Thunderstorms. George P. Roys and Edwin Kessler. July 1966. (PB-173048)

No. 20 Field Operations of the National Severe Storms Project in Spring 1963. J. T. Lee, L. D. Sanders and D. T. Williams. January 1964. (PB-168224)

No. 21 On the Motion and Predictability of Convective Systems as Related to the Upper Winds in a Case of Small Turning of Wind with Height. James C. Fankhauser. January 1964. (PB-168225)

No. 22 Movement and Development Patterns of Convective Storms and Forecasting the Probability of Storm Passage at a Given Location. Chester W. Newton and James C. Fankhauser. January 1964. (PB-168226)

No. 23 Purposes and Programs of the National Severe Storms Laboratory, Norman, Oklahoma. Edwin Kessler. December 1964. (PB-166675)

No. 24 Papers on Weather Radar, Atmospheric Turbulence, Sferics, and Data Processing. August 1965. (AD-621586)

No. 25 A Comparison of Kinematically Computed Precipitation with Observed Convective Rainfall. James C. Fankhauser. September 1965. (PB-168445).

No. 26 Probing Air Motion by Doppler Analysis of Radar Clear Air Returns. Roger M. Lhermitte. May 1966. (PB-170636)

No. 27 Statistical Properties of Radar Echo Patterns and the Radar Echo Process. Larry Armijo. May 1966. The Role of the Kutta-Joukowski Force in Cloud Systems with Circulation. J. L. Goldman. May 1966. (PB-170756)

No. 28 Movement and Predictablity of Radar Echoes. James Warren Wilson. November 1966. (PB-173972)

No. 29 Notes on Thunderstorm Motions, Heights, and Circulations. T. W. Harrold, W. T. Roach, and Kenneth E. Wilk. November 1966. (AD-644899)

No. 30 Turbulence in Clear Air Near Thunderstorms. Anne Burns, Terence W. Harrold, Jack Burnham, and Clifford S. Spavins. December 1966. (PB-173992)

No. 31 Study of a Left-Moving Thunderstorm of 23 April 1964. George R. Hammond. April 1967. (PB-174681)

No. 32 Thunderstorm Circulations and Turbulence from Aircraft and Radar Data. James C. Fankhauser and J. T. Lee. April 1967. (PB-174860)

No. 33 On the Continuity of Water Substance. Edwin Kessler. April 1967. (PB-175840)

No. 34 Note on the Probing Balloon Motion by Doppler Radar. Roger M. Lhermitte. July 1967. (PB-175930)

No. 35 A Theory for the Determination of Wind and Precipitation Velocities with Doppler Radars. Larry Armijo. August 1967. (PB-176376)

No. 36 A Preliminary Evaluation of the F-100 Rough Rider Turbulence Measurement System. U. O. Lappe. October 1967. (PB-177037)

No. 37 Preliminary Quantitative Analysis of Airborne Weather Radar. Lester P. Merritt. December 1967. (PB-177188)

No. 38 On the Source of Thunderstorm Rotation. Stanley L. Barnes. March 1968. (PB-178990)

No. 39 Thunderstorm - Environment Interactions Revealed by Chaff Trajectories in the Mid-Troposphere. James C. Fankhauser. June 1968. (PB-179659)

No. 40 Objective Detection and Correction of Errors in Radiosonde Data. Rex L. Inman. June 1968. (PB-180284)

No. 41 Structure and Movement of the Severe Thunderstorms of 3 April 1964 as Revealed from Radar and Surface Mesonetwork Data Analysis. Jess Charba and Yoshikazu Sasaki. October 1968. (PB-183310)

No. 42 A Rainfall Rate Sensor. Brian E. Morgan. November 1968. (PB-183979)

No. 43 Detection and Presentation of Severe Thunderstorms by Airborne and Ground-Based Radars: A Comparative Study. Kenneth E. Wilk, John K. Carter, and J. T. Dooley. February 1969. (PB-183572)

No. 44 A Study of a Severe Local Storm of 16 April 1967. George Thomas Haglund. May 1969. (PB-184-970)

No. 45 On the Relationship Between Horizontal Moisture Convergence and Convective Cloud Formation. Horace R. Hudson. March 1970. (PB-191720)

No. 46 Severe Thunderstorm Radar Echo Motion and Related Weather Events Hazardous to Aviation Operations. Peter A. Barclay and Kenneth E. Wilk. June 1970. (PB-192498)

No. 47 Evaluation of Roughness Lengths at the NSSL-WKY Meteorological Tower. Leslie D. Sanders and Allen H. Weber. August 1970.

No. 48 Behavior of Winds in the Lowest 1500 ft in Central Oklahoma: June 1966 - May 1967. Kenneth C. Crawford and Horace R. Hudson. August 1970.

☆ U.S. GOVERNMENT PRINTING OFFICE: 1977—777-067/1216 REGION NO. 8