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A Tornado Climatology for the Northeastern United States

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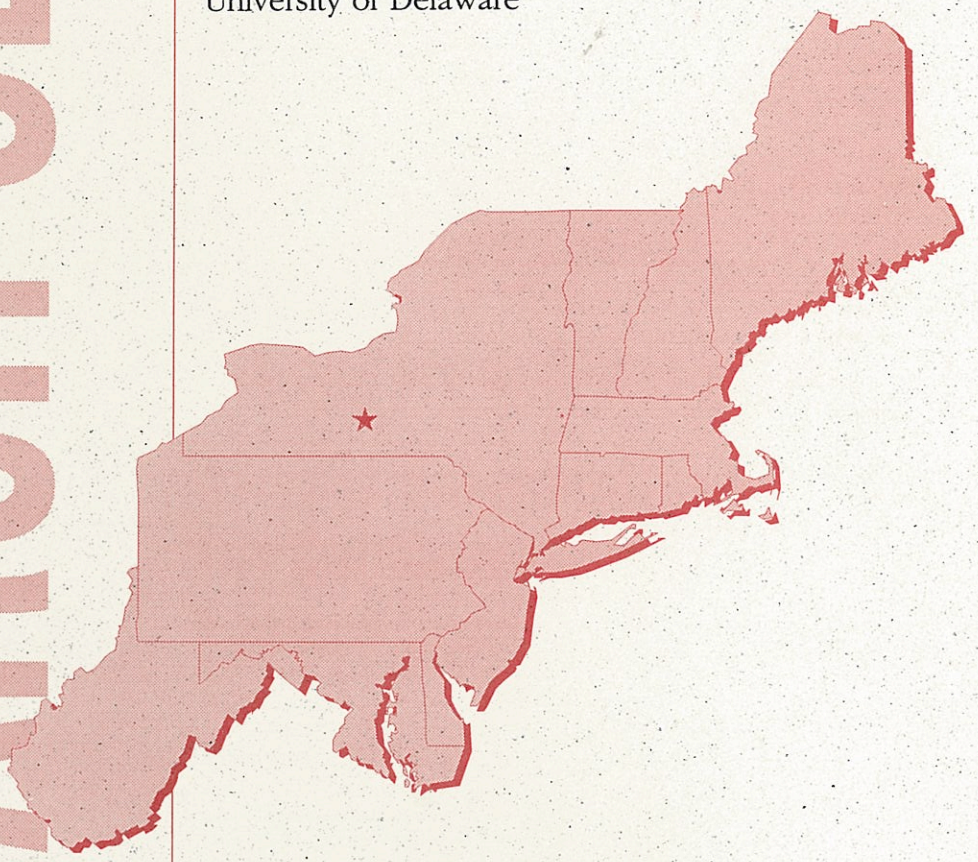

Cornell University
Ithaca, New York
Publication No. RR 94-2
February 1994

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The Northeast Regional Climate Center is supported by a Grant from the National Oceanic and Atmospheric Administration.

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CONTENTS

INTRODUCTION

Tornadoes are the world's most intense atmospheric disturbances. As such, they are often responsible for devastating property damage, injuries and loss of life. The United States has a far greater rate of occurrence of tornadoes than any other country in the world (Eagleman 1985). In particular, the eastern two-thirds of the United States averages approximately 700 tornadic events annually, while the other countries with significant totals including Canada, the former Soviet Union and Australia average less than 100 events each year (Eagleman 1985; Grazulis 1991). This high incidence of tornadic storms is directly related to the geography of the North American Continent. The proximity of the Gulf of Mexico to the high latitude landmass of central Canada leads to the establishment of strong air mass contrasts across the eastern two-thirds of the United States. The Gulf of Mexico acts as a source region for warm, moist maritime tropical air masses which move north across the eastern Great Plains and Mississippi Valley, while cold, dry continental polar air moves from central Canada, south through the northern Great Plains. As these air masses meet across the eastern United States, often in conjunction with strong mid-latitude cyclones, severe thunderstorms frequently result. If the thermal and dynamic characteristics of the atmosphere are suitable, tornadic storms may also form in association with these severe thunderstorms.

The greatest number of tornadoes occur in a band extending from Texas, north through Oklahoma, Kansas, and eastern Nebraska and then east through Iowa, Illinois and into the Ohio Valley. This area of the country is often referred to as "tornado alley" because of the number and severe intensity of tornadoes that occur in this region. Significant but smaller numbers of tornadic storms occur in the southeast United States and the northern Great Plains. West of the Rocky Mountains, tornadoes are quite rare, although tornadoes have occurred in each of the coterminous United States. Compared to the Great Plains, the number and intensity of tornadoes in the northeast United States is unimpressive. However, the number that occur in this 12-state area each year is nearly as large as the number that occur annually in any other country. Moreover, the high population density in many areas of the northeastern United States makes the potential for disaster during a tornadic event very great.

The purpose of this research report is to document the spatial and temporal characteristics of tornadoes across the northeastern United States during the 41-year period from 1950 through 1990. Although other studies have examined the spatial and temporal characteristics of tornadoes across the entire United States (i.e. Flora 1953; Wolford 1960; Skaggs 1969; Galway 1977; Kelly et al. 1978; Grazulis 1984; 1991), only the study of Leathers (1993) has concentrated on the tornado climatology of the northeast region. This report presents maps detailing the distribution of tornado occurrences as well as injuries and fatalities associated with tornadic events. In addition, data are presented on the diurnal and annual cycles of tornadic occurrence and on the interannual variability of tornadoes. The northeastern United States includes the 12-state region designated as such by the Regional Climate Centers Program of the National Oceanic and Atmospheric Administration. The states include Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, Vermont and West Virginia. In

addition, tornado data from the states of Michigan, Ohio and Virginia are used to present a complete picture of the spatial distribution of tornadoes across the entire northeastern portion of the United States. Unfortunately, tornado data for the surrounding Canadian provinces of New Brunswick, Ontario, and Quebec are not readily available.

TYPICAL CONDITIONS ASSOCIATED WITH NORTHEAST TORNADOES

The atmospheric patterns associated with tornadic storms across the northeastern United States have been studied by David (1977) and Leathers (1993). In general, the most typical pattern that leads to a tornadic event somewhere across the region includes an area of low surface air pressure in the lower Great Lakes region with a strong cold front trailing to the south and west. Ahead of this area of low pressure, southerly winds cause temperatures and humidities to rise to relatively high levels throughout the lower portion of the atmosphere, causing unstable conditions. At middle levels of the troposphere (500 mb), a shortwave system is typically located over eastern North America, with a strong trough over the western Great Lakes and ridging over New England and the western Atlantic. This creates an area of intense upper tropospheric divergence over the Northeast which enhances upward motion and adds to the potential for the development of severe thunderstorms. When these elements come together at the time of maximum diurnal heating (middle afternoon to early evening), severe thunderstorms often result, especially in association with the cold front passage. If the mesoscale environment surrounding a severe thunderstorm is suitable, a tornadic event may ensue.

TORNADIC EVENTS PRIOR TO 1950

Ludlum (1970) suggests that the first reference to a tornadic event in the northeast United States may be found in the journal of Governor John Winthrop. This event occurred in July, 1643 in northeastern Massachusetts and coastal New Hampshire. A portion of Winthrop's journal entry reads as follows:

> *There arose a sudden gust at N.W. so violent for half an hour, as it blew down multitudes of trees. It lifted up their meeting house at Newbury, the people being in it. It darkened the air with dust, yet through God's great mercy it did no hurt... (Ludlum 1970)*

Whether this was indeed a tornadic event is of course uncertain. However, other clear references to tornadoes can be found in early accounts from the 17th century onward. In fact, many of these events resulted in substantial loss of life, injuries and property damage. Ludlum (1970) has documented the tornadic events from the early 17th century through the late 19th century recorded in letters, articles and press accounts from the period. The reader is directed to this work for details of these early events.

During the first half of this century, tornadoes continued to be an important natural hazard across the Northeast. During the period from 1916 through 1949 Flora (1953) documented 196 tornadic events in the 12-state region resulting in over 200 deaths and damage in excess of 25 million dollars (Wolford 1960). A particularly damaging event occurred on June 23, 1944. From approximately 6:30 to 9:30 p.m., four tornadoes moved across rather mountainous portions of West Virginia, Pennsylvania and Maryland killing 153 persons; 103 in West Virginia, 45 in southwestern

Pennsylvania and 5 in western Maryland. In addition, 846 persons were injured and over 5 million dollars in property damage was done (Flora 1953). The death toll from this outbreak is the largest recorded for any single tornadic outbreak that has occurred in the northeast United States.

DATA SOURCES

The tornado data used in the remainder of this study are from the National Climatic Data Center TD-9714 archive. This data set documents tornadic events across the entire United States for the period 1950 through 1990. The tornado reports within this data set are primarily derived from published accounts in Storm Data and from reports compiled by the National Severe Storms Forecast Center. This data set contains information on the location of the tornado touchdown, the time of touchdown, the tornado path length, the path width and the damage, injuries, deaths and other characteristics associated with each event. In addition, an intensity/damage rating is given to each tornado using the F-scale rating system (Fujita and Pearson 1973). Doswell and Burgess (1988) describe the data in more detail, including its potential shortcomings. For the present study, the time and location of the occurrence of a confirmed tornado are the major data elements utilized. The intensity/damage scale rating is also used as a gross indicator of the strength of a particular event. Data concerning the location and timing of tornadic events are unlikely to be contaminated by any data reliability problems, except for potential under-reporting early in the period of record (Kelly et al. 1978; Doswell and Burgess 1988; Leathers 1993). Although problems definitely exist with the intensity/damage scale ratings, their use as a gross indicator of tornado strength is justified (Doswell and Burgess 1988; Leathers 1993).

CHARACTERISTICS

Basic Information

During the 41-year period from 1950 through 1990, 1300 tornadoes were documented across the 12-state northeastern region, giving an annual average of approximately 32 tornadoes. Tornadoes occurred in every state and in each month of the year over this period (Table 1 and Table 2). These 1300 storms occurred on 666 separate days (giving an average of 1.95 tornadoes per tornado day) and they resulted in 3599 injuries and 200 deaths. Of the 3599 injuries that occurred over this time period, more than half were the result of three events; the Worcester, MA tornado of June 9, 1953, the Windsor Locks, CT tornado of October 3, 1979 (Riley and Bosart 1987) and the western Pennsylvania and New York outbreak of May 31, 1985 (Witten 1985). The Massachusetts and Pennsylvania incidents account for the majority of deaths that have occurred over the 41-year period.

Distribution of Tornado Occurrence

In order to present a detailed analysis of the spatial distribution of tornadic events, the total number of tornadoes occurring in 1° latitude by 1° longitude grid squares are tabulated for the entire period of record. These data are subsequently presented as grid-box totals (Figure 1). Although the area of the grid boxes change with latitude, no area normalization correction is used because of the limited latitudinal extent of the region. It is clear that the majority of tornadoes occur to the east of the Appalachian

Table 1. Total reported tornadoes, injuries and fatalities stratified by state for the period 1950 through 1990.

State	Tornadoes	Injuries	Deaths
Connecticut	57	699	4
Delaware	37	69	2
Maine	76	16	1
Maryland	105	112	2
Massachusetts	134	1330	98
New Hampshire	71	25	0
New Jersey	102	67	0
New York	192	156	18
Pennsylvania	406	1002	73
Rhode Island	7	23	0
Vermont	31	10	0
West Virginia	82	90	2
Totals	1300	3599	200

highlands, in the piedmont region from Maryland, north through New Hampshire (Figure 1). Two subregions of high tornado incidence occur in southeastern Pennsylvania and north central Massachusetts. A third region of high tornado totals is found in extreme western Pennsylvania and westward into Ohio. The number of tornadoes per year in 1° latitude by 1° longitude boxes is shown in Figure 1b. These values are calculated by dividing the total number of tornado occurrences in a given grid box by the number of years in the period (41 years). Grid boxes evidencing more than 1 tornado per year over the time period are found in southeastern and western Pennsylvania, central New Jersey, northern Delaware, and Massachusetts. The highest value in the 12-state northeast region is found in central Massachusetts, where an average of 1.7 tornadoes per year have occurred since 1950. Only the grid boxes in extreme northwestern Maine had no reported tornadoes during the study period. Although these values do not represent tornado probabilities (Thom 1963), they do give some indication of the likelihood of a tornadic occurrence in a given region.

In order to give a more detailed presentation of the changing spatial distribution of tornadic events throughout the annual cycle, maps of the monthly distribution of tornadoes are presented in Figure 2. Maps are presented for the nine-month period from March through November. The spatial distribution of tornadoes during the mid-winter months is not shown because of the small number of events during this portion of the annual cycle.

March tornadoes are confined almost entirely to the southern portion of the region (Figure 2a). In fact, the vast majority occur to the south and west of Pennsylvania and New Jersey. During April, the distribution of events is similar to March, but shifts somewhat to the north, with storms reaching northern Pennsylvania, northern New Jersey and New York (Figure 2b). A cluster of events is indicated in southeastern West Virginia and a relatively high occurrence rate continues across the southern portion of the region during this month. In May, the number of tornadoes across New York and New England increases dramatically (Figure 2c). Western Pennsylvania and eastern Ohio have a very high tornado occurrence density, much of which is associated with the outbreak of May 31, 1985. The increase in number continues into June, with tornadic events distributed across the entire region (Figure 2d). During this month, the areas of maximum occurrence are east of the Appalachian Mountains, along the piedmont, and in western Pennsylvania and eastern Ohio. July's distribution

Table 2. Total reported tornadoes, tornado days, injuries and fatalities stratified by month for the period 1950 through 1990.

Month	Tornadoes	Tornado Days	Injuries	Deaths
January	5	4	7	0
February	7	5	2	0
March	44	22	16	1
April	66	45	67	1
May	174	71	697	71
June	242	119	1555	93
July	336	169	330	5
August	213	129	212	13
September	94	54	67	1
October	59	25	607	6
November	56	19	38	9
December	4	4	1	0
Totals	1300	666	3599	200

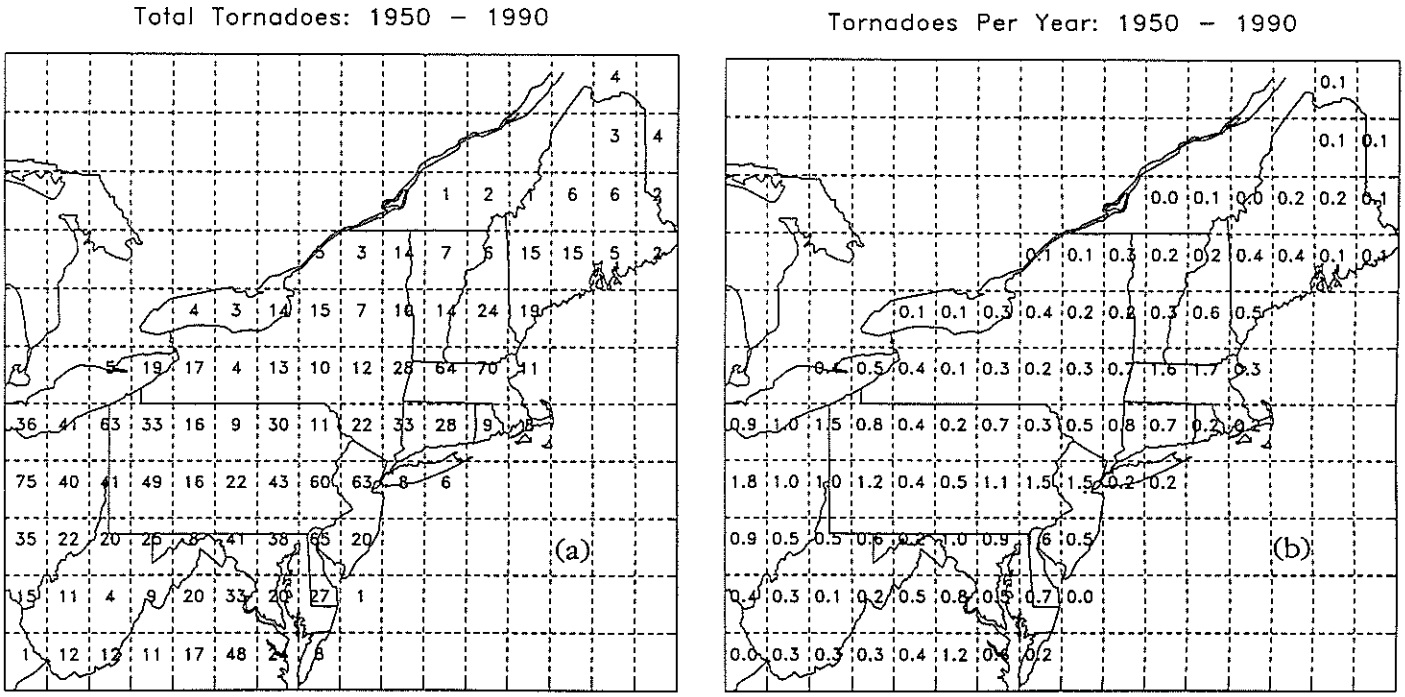


Figure 1. Maps showing a) grid box values of total tornadoes, b) grid box values of tornadoes per year for the period 1950 through 1990. Grid boxes over the Northeast that are empty indicate zero reported tornadoes.

is even more heavily weighted toward the piedmont region, east of the mountains (Figure 2e). High densities of occurrence are found from Delaware, north into southeastern Maine. The total number of tornadoes begins to decrease during August. However, the highest rate of occurrence continues to be found along the piedmont (Figure 2f). During September, the number of tornadoes continues to decrease, with the majority of events occurring in the southern two-thirds of the region (Figure 2g). In October, a tendency for tornadic development along the piedmont is once again evident (Figure 2h), while a large portion of the November tornadoes are found in eastern Pennsylvania and New Jersey (Figure 2i).

Distribution of Injuries and Fatalities Associated with Tornadoes

In the northeast United States, the majority of tornado related injuries have occurred during either high intensity tornadic events or during tornado outbreaks (more than five tornadoes during a single synoptic event; Galway 1977). More than half the 3599 injuries have occurred in three separate incidents; the Worcester, Massachusetts tornado of June 9, 1953 (high intensity F4 tornado), the Windsor Locks, Connecticut tornado of October 3, 1979 (high intensity F4 tornado) and the western Pennsylvania tornado outbreak of May 31, 1985 (several F3 and F4 tornadoes). The result of these events can be clearly seen by inspection of the injury grid box totals of Figure 3a. The boxes encompassing central Massachusetts and central Connecticut account for nearly 2000 tornado injuries, while over 600 injuries are found in the three grid boxes in extreme western Pennsylvania and eastern Ohio. Outside of these areas, the number of tornado related injuries is roughly associated with the number of tornadoes occurring in a given grid box.

Fatalities resulting from tornadoes are distributed in much the same manner as the injuries, with most occurring during two of the three severe events discussed above: those in Worcester, Massachusetts (90 fatalities) and western Pennsylvania (65 fatalities). The third highest number of fatalities from a single event was associated

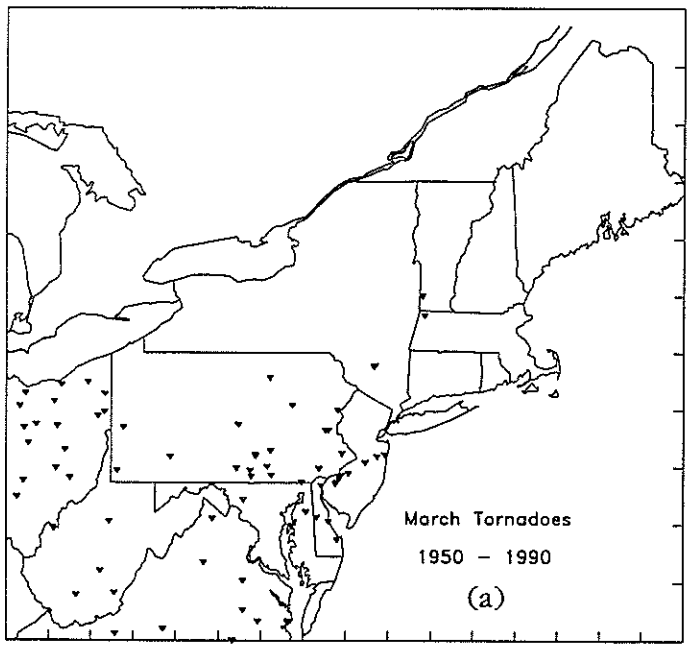
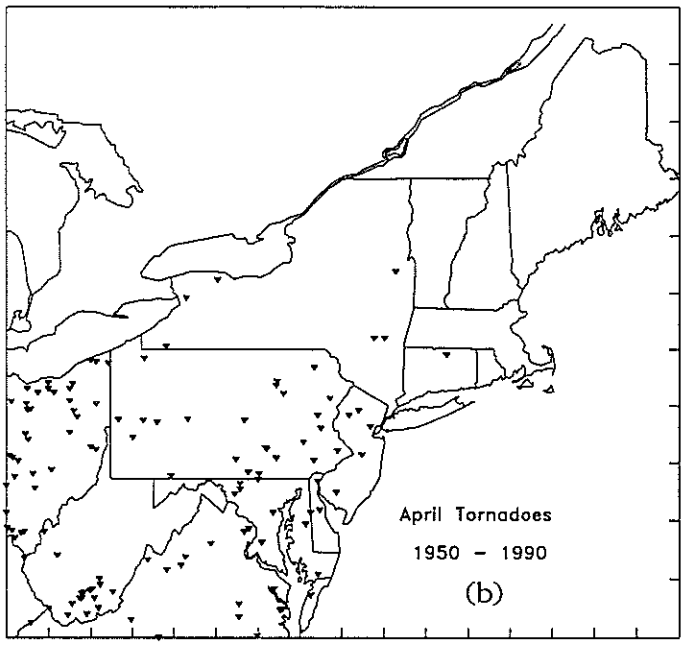
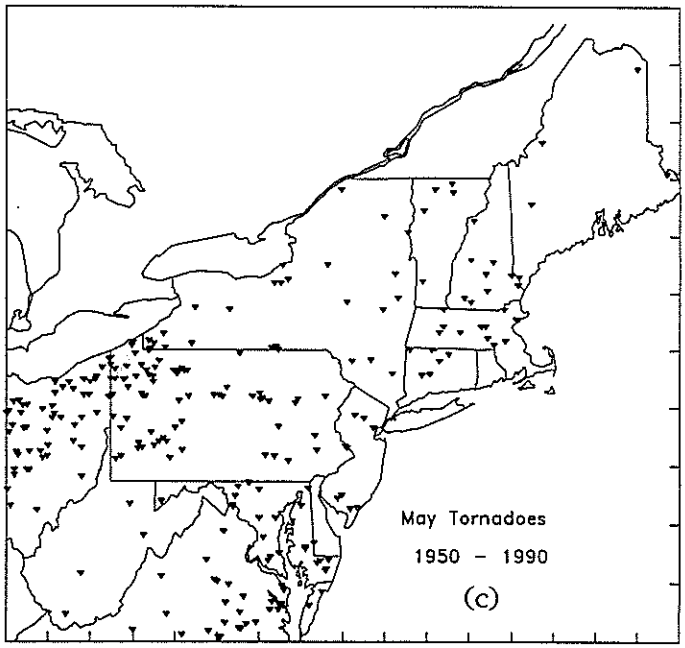
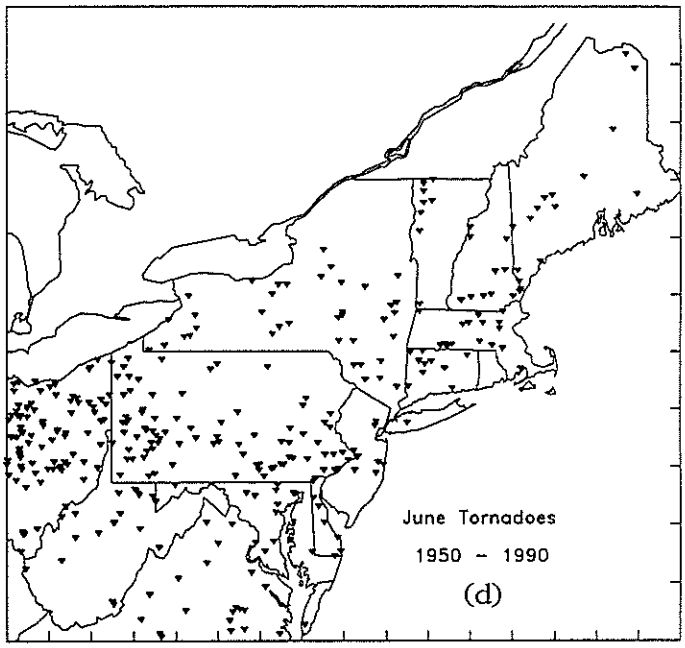


Figure 2. The geographic distribution of reported tornadic events during the month of March for the period 1950-1990.







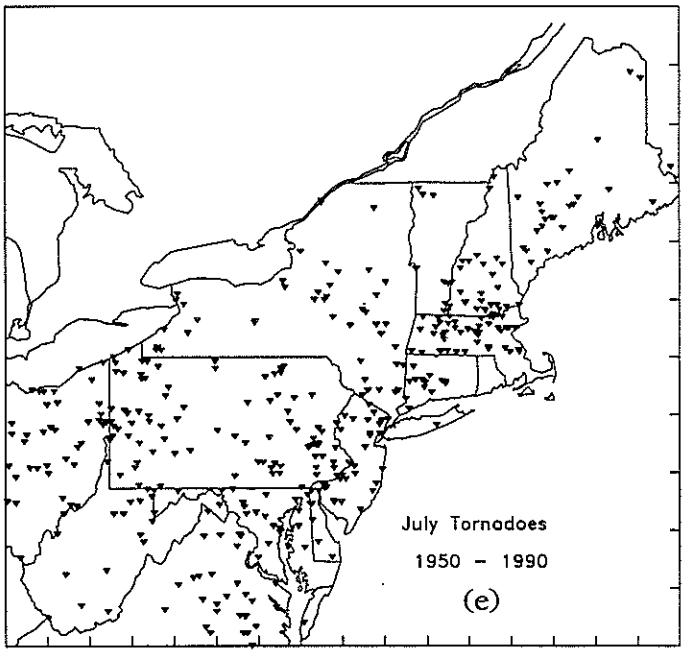
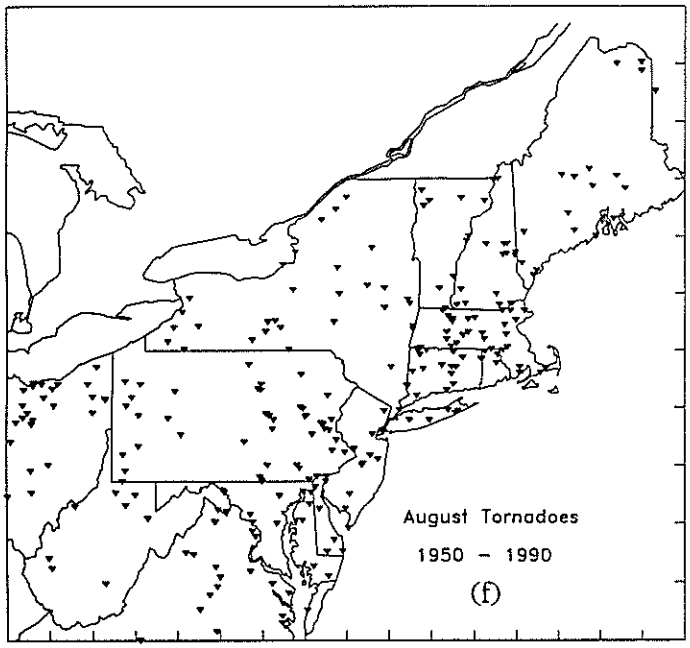
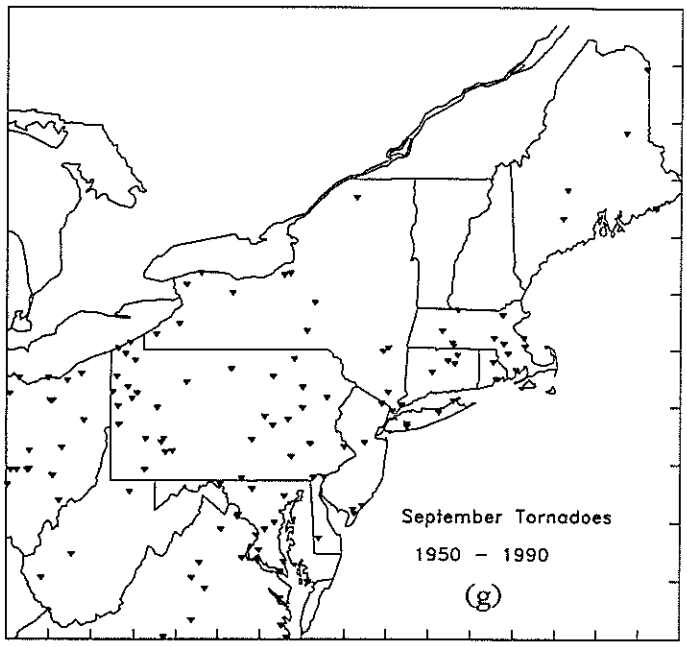
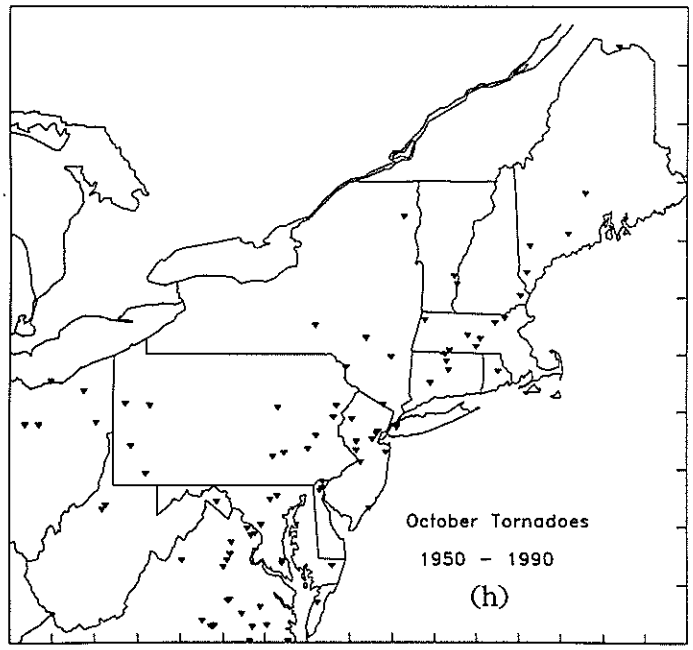


Figure 2 (continued). The geographic distribution of reported tornadic events during the months of April through July for the period 1950-1990.







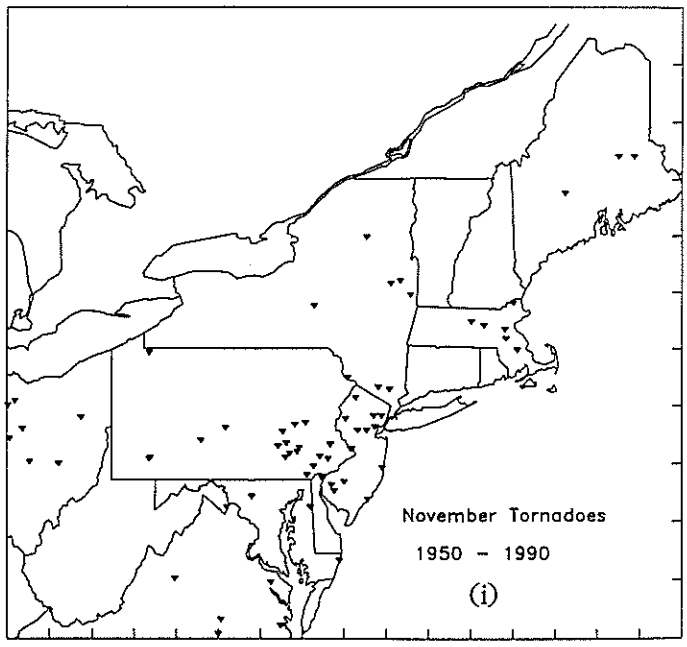


Figure 2 (continued). The geographic distribution of reported tornadic events during the months of August through November for the period 1950-1990.

with a rather weak (F1) tornado that struck in southeastern New York on November 16, 1989 killing nine. The Windsor Locks, Connecticut tornado that injured approximately 500 persons resulted in only 3 fatalities (Riley and Bosart 1987). More than 90% of the deaths associated with tornadoes in the 12-state region have occurred in a latitude band spanning 41° N (central Pennsylvania) to 43° N (central New York) (Figure 3b).

Distribution of Tornado Intensity/Damage

As discussed by Doswell and Burgess (1988), tornado intensity ratings (Table 3) are based primarily on the survey of damage after the occurrence of a tornado. Therefore, the F-scale ratings included in this data set are better thought of as a tornado intensity derived from the resulting damage. Hence, they will be referred to as tornado intensity/damage ratings. The spatial distributions of tornado intensity categories are given in Figure 4, while Table 3 gives damage characteristics associated with storms of each intensity.

Over the 41-year period, 288 F0 tornadoes were reported across the 12-state region and these were homogeneously distributed from southern West Virginia to northern Maine. Low intensity tornadoes such as these are often not reported because the damage associated with them is not easily differentiated from straight line winds associated with a severe thunderstorm. Damage associated with F1 tornadoes is more easily recognized as being associated with a tornadic event. Thus, nearly twice as many F1 tornadoes (582 F1 tornadoes) were reported across the region than F0 storms. In this case, the number of events is large along the piedmont area from Delaware to New Hampshire and in western Pennsylvania and Ohio (Figure 4b). The number of F2 tornadoes is appreciably less than the number of F1 events (323 F2 tornadoes), but their spatial distribution is similar to that of F1 events (Figure 4c). More intense F3 tornadoes are infrequent across the region with only 74 reported over the 41-year period. The spatial distribution of these stronger storms is different from that of the weaker events, with most occurring south of a line from the northern Massachusetts border across central New York (Figure 4d). F4 tornadoes are rare in the Northeast. However, 31 events of this intensity were recorded during the period of record (Figure 4e). Nearly all events of this magnitude cause considerable damage, injuries and loss of life. The majority of F4 tornadoes in western Pennsylvania were associated with the outbreak of May 31, 1985. In addition, the intense tornadoes associated with the Worcester, Massachusetts disaster and the Windsor Locks, Connecticut event are seen in this figure. Four other F4 tornadoes occurred in a single outbreak west of Albany, New York on July 10, 1989. Although several injuries were reported, no fatalities occurred in association with these storms. Interestingly, nearly all events of this intensity have occurred in a latitude band that corresponds to the area where the majority of deaths and injuries have occurred (Figure 4e and 3). Only two F5 tornadoes have occurred in the 12-state region during the period of record (Figure 4f), and both of these occurred along the Pennsylvania, Ohio border during the outbreak of May 31, 1985.

TEMPORAL CHARACTERISTICS

Several authors have investigated the diurnal characteristics of tornadoes across the entire United States (Skaggs 1969; Kelly et al. 1978; Grazulis 1984; 1991). The results from these studies indicate that for the majority of the country, the peak tornado occurrence time is in the late afternoon from 1600 to 1800 (4:00 to 6:00 p.m.) local standard time (LST). Leathers (1993) found a similar peak in northeast tornadoes with

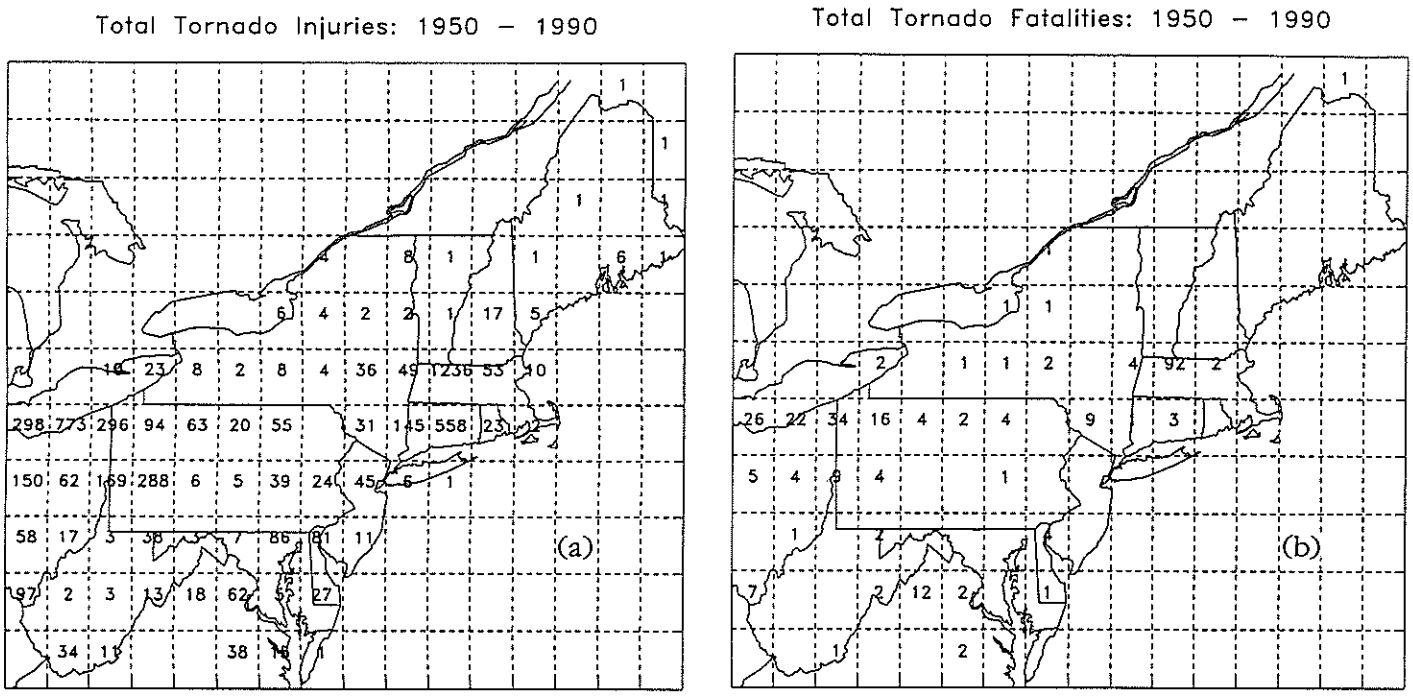


Figure 3. Grid box totals of a) tornado injuries and b) tornado fatalities for the period 1950 through 1990.

Table 3. Characteristics of tornadoes with diverse F-scale ratings.

F-Scale Rating	Description	Winds	Damage
0	Gale Tornado	(40 - 72 mph)	Light damage, branches broken, signs damaged...
1	Moderate Tornado	(73 - 112 mph)	Moderate damage, roofs peeled off, autos pushed off road...
2	Significant Tornado	(113 - 157 mph)	Considerable damage, mobile homes destroyed, frame homes severely damaged...
3	Severe Tornado	(158 - 206 mph)	Severe damage, roofs and walls destroyed, large trees uprooted...
4	Devastating Tornado	(207 - 260 mph)	Devastating damage, nearly all homes destroyed, cars thrown considerable distances...
5	Incredible Tornado	(261 - 318 mph)	Incredible damage, trees lose bark, most structures disintegrate...

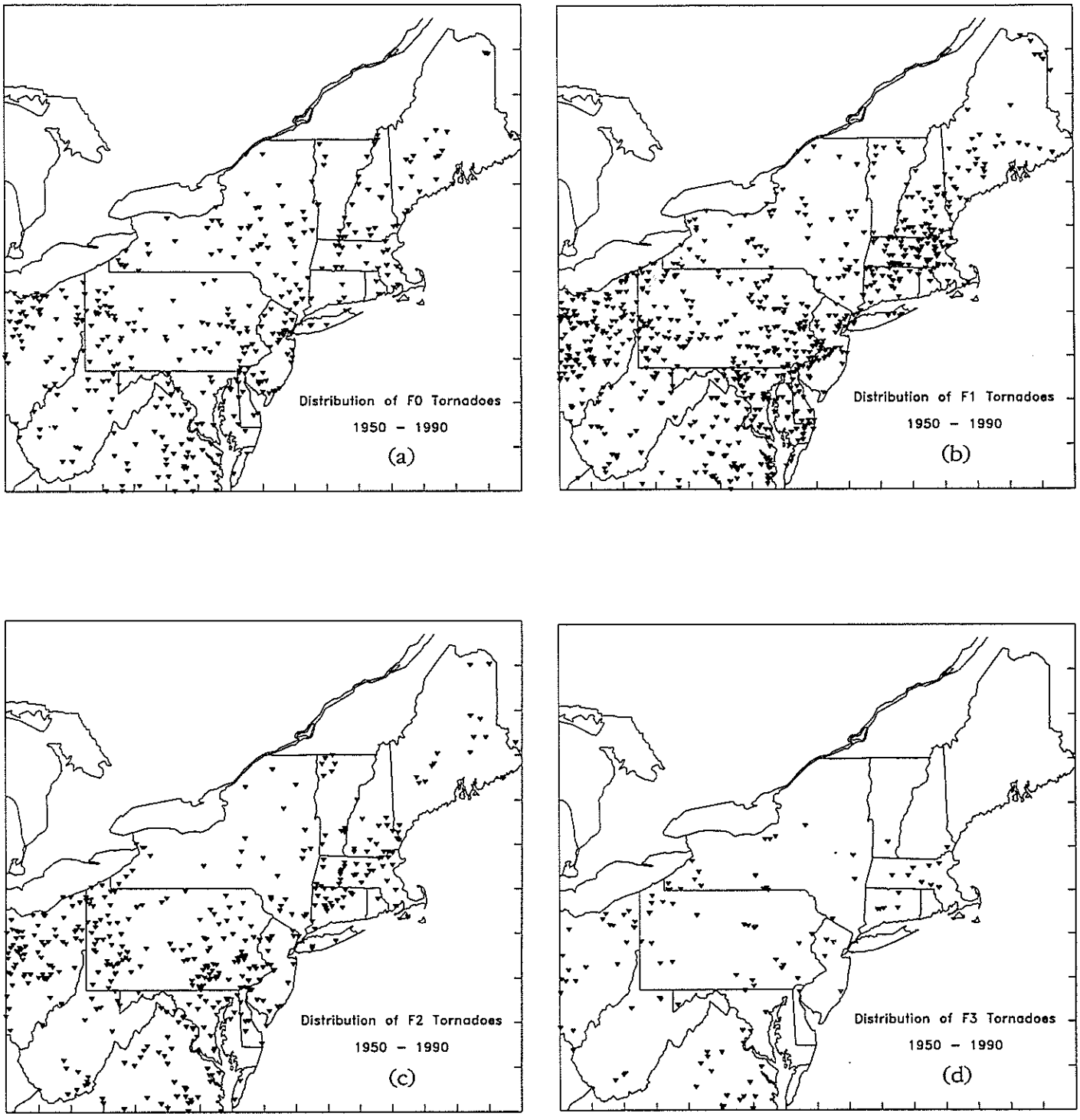
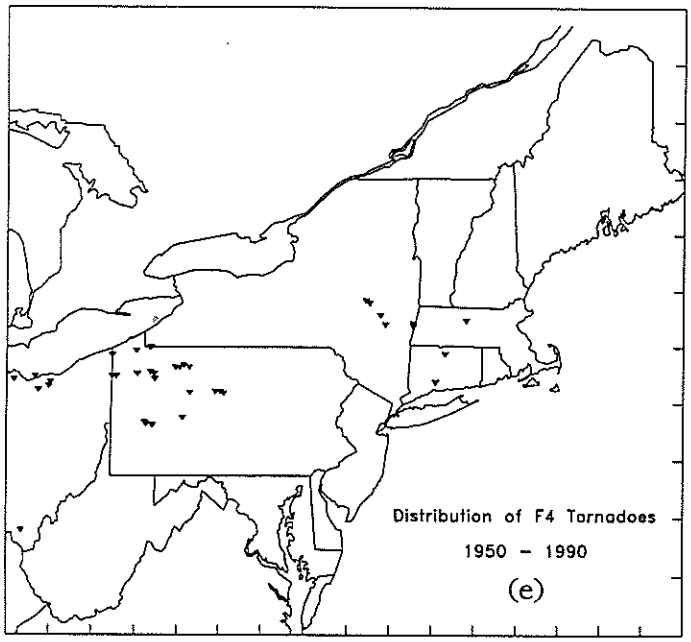


Figure 4. The spatial distribution of reported a) F0, b) F1, c) F2, and d) F3 tornado intensity events for the period 1950 through 1990.



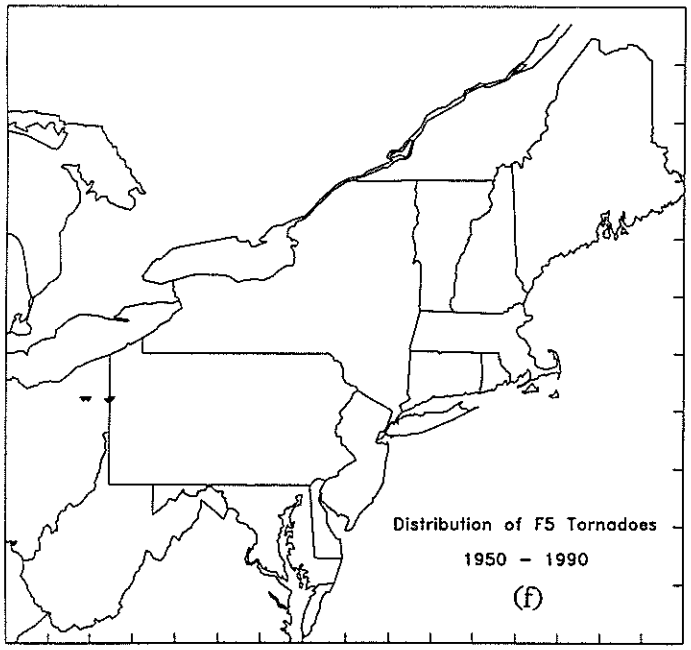


Figure 4 (continued). The spatial distribution of reported e) F4 and f) F5 tornado intensity events for the period 1950 through 1990.

67% occurring between the hours of 1300 to 1900 LST. The distribution of tornado occurrences by two-hour intervals throughout the day is illustrated in Figure 5a. A distinct peak in tornado occurrence times is found from approximately 1300 to 1900 LST. This occurrence peak is associated with the time of maximum diurnal surface heating, an ingredient often important in the establishment of atmospheric instability needed for the growth of severe thunderstorms. Earlier in the day and after sundown, this important element is not present and severe thunderstorms (and tornadoes) are less likely to develop.

The annual cycle of tornadoes across the Northeast is different than that observed for most other areas of the United States. Kelly et al. (1978) found that nearly 65% of the tornadoes reported across the United States strike during the four-month period from March through June. In the Northeast, the annual peak in occurrence takes place later, from June through August (Figure 5b, Table 2). Approximately 61% of the total tornadoes have occurred during this three-month period with July evidencing the greatest number, followed by June and August. The annual distribution of tornado days is very similar, however, July totals are greater than those of August in this category (Figure 5b, Table 2). The largest number of tornadoes per tornado day occurs in the spring and autumn. November has the largest number of tornadoes per tornado day (2.94 tornadoes per tornado day), followed by October (2.36 tornadoes per tornado day) and May (2.35 tornadoes per tornado day). These results are consistent with those reported by David (1977) and Leathers (1993).

The interannual variability of Northeast tornadoes is presented in Figure 6a. During the period from 1950 through 1990 an average of approximately 32 tornadoes occurred each year. The year 1989 had the most tornadic events (70), while in 1950 only 10 storms were reported. Thus, it is clear that the variability of tornadoes from year to year can be quite large. An apparent positive trend in the number of storms per year is indicated by Figure 6a (trend = 0.70 tornadoes/year). It must be noted that improved storm reporting systems, population changes, especially urban to rural migration, and an increase in public awareness concerning severe weather has likely led to much of this positive trend (Leathers 1993). However, the positive trend found in the data since 1950 seems to be associated with a general increase in tornadic storms that has been apparent since 1917. Figure 6b shows the annual tornado totals reported during the period from 1917 through 1990. Clearly, the change in the data sets in 1950 is evident in the time series (Flora 1953). However, even during the early portion of the record (1917 through 1949) a small positive trend in tornadic events is evident (trend = 0.21 tornadoes/year). Moreover, the nearly 5 fold increase in the number of storms between the periods 1917 through 1949 and 1950 through 1990 is not likely to be completely a result of reporting improvements.

CONCLUSIONS

Although the number and intensity of tornadoes across the Northeast may be unimpressive compared to other areas of the United States, it is clear that tornadic events in this region are no less damaging and dangerous. Past events, some dating back to the early 17th century, have led to extensive property damage, numerous injuries and loss of life. Unfortunately, given the population density of the Northeast and the potential for strong tornadic events, similar incidents are likely in the future. The material presented in this report is designed to inform the reader of the spatial and temporal characteristics of tornadoes across the region. It is hoped that this information will lead to increased public awareness of the potential for tornadic events and their attendant dangers.

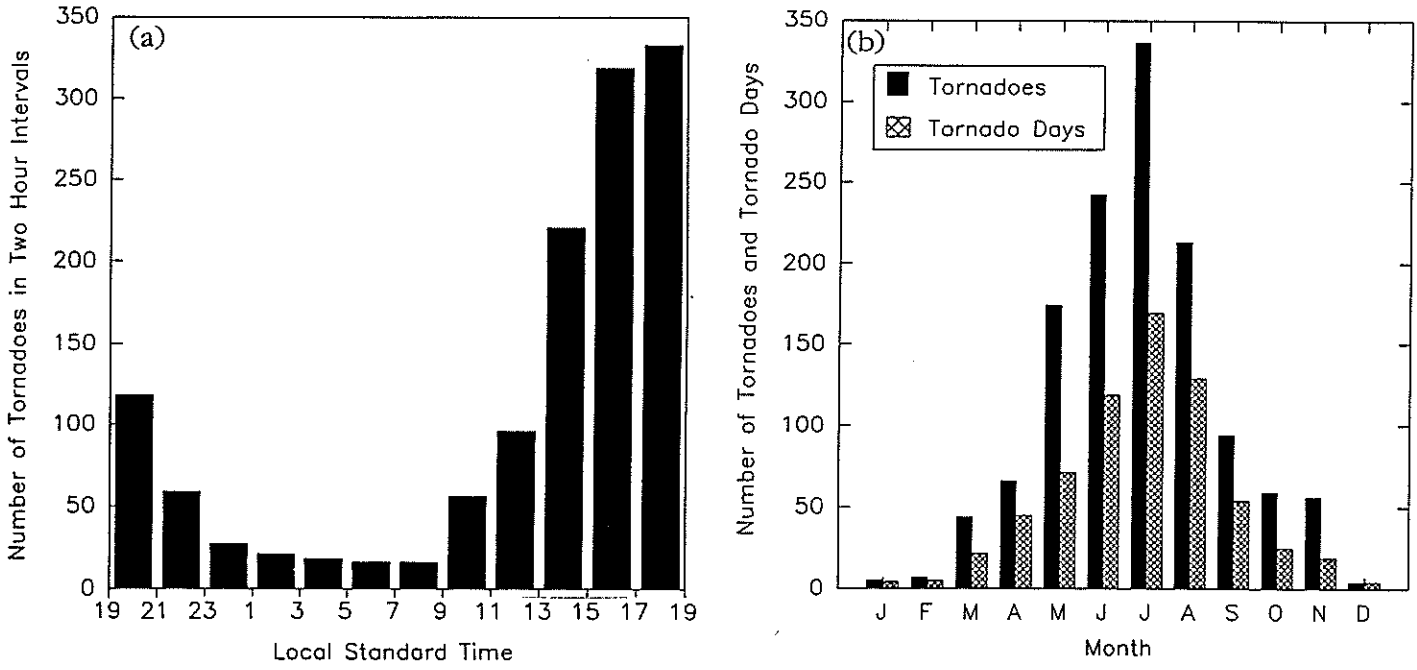


Figure 5. The temporal distribution of reported northeast tornadoes, a) the diurnal cycle and b) the annual cycle. Data from 1950 through 1990.

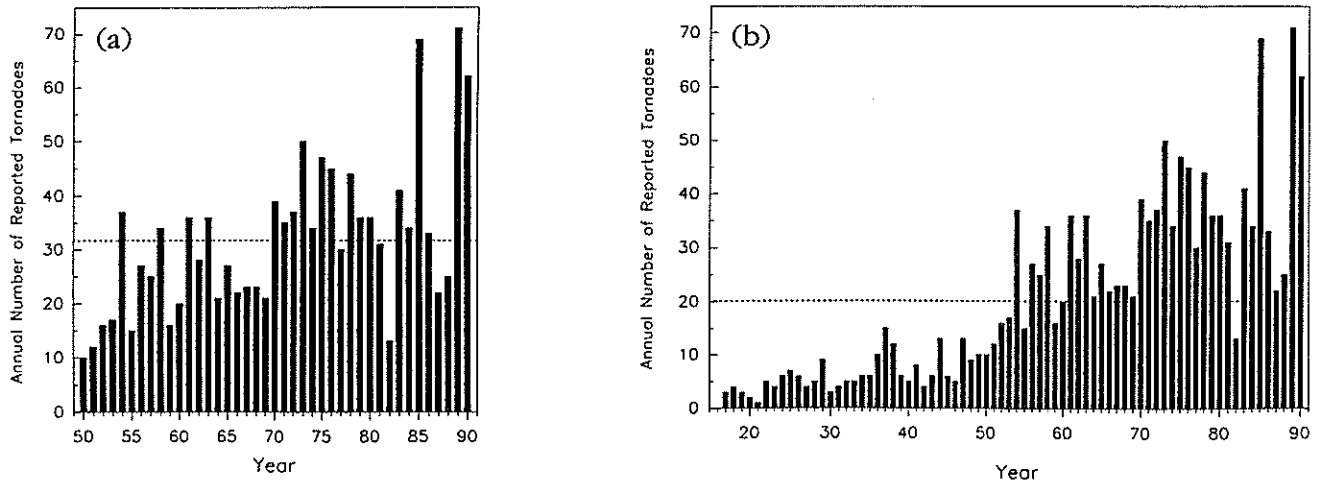


Figure 6. The interannual variability of reported northeast tornadoes, a) for the period 1950 through 1990 and b) for the period 1917 through 1990. Dotted lines indicate average number of tornadoes per year.

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Produced by
Northeast Regional Climate Center
5/95 1C 125-8436