A Synoptic Climatology of Northwest Flow Severe Weather Outbreaks. Part I: Nature and Significance

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ABSTRACT

A climatology of severe weather outbreaks occurring in areas of the contiguous United States where the mid-troposphere flow has a north of west component has been developed for the period 1962–77. During the 16 years, 163 outbreaks of severe weather have been identified that fit a specific set of criteria for "northwest flow". Analyses of this data set reveal the diurnal, seasonal and geographical frequencies and characteristics of this phenomenon. The nature of "northwest flow" outbreaks is examined in relation to the effect on life and property.

1. Introduction

It is generally recognized that severe thunderstorm and tornado outbreaks in the contiguous United States usually occur in areas of southwesterly flow at 500 mb with a long wave trough immediately to the west of the outbreak area (Beebe, 1956). However, in the late spring and summer months, it is not uncommon for outbreaks of severe thunderstorms to occur in areas of northwesterly flow (NWF) at 500 mb. In fact, Miller (1972) has noted that some of the most destructive severe weather outbreaks in the summer are associated with west-northwest or northwest flow in the mid-troposphere.

Both Galway (1958) and Miller (1972) recognized the NWF phenomenon in the early years of severe thunderstorm forecasting and generalized from their operational experiences. Galway went a step further and prepared mean charts based on a number of NWF cases. He showed a mean 500 mb chart with a long-wave ridge present west (upstream) of the outbreak area, and a long-wave trough to the east (downstream). Galway also noted that many times an outbreak was triggered by a short-wave trough that initially appeared minor but deepened as it approached the long-wave trough position.

Aside from Galway's mean charts and a few local studies (Notis and Stanford, 1973, 1976), very little has been done to look at the NWF phenomenon objectively. Therefore, to understand this phenomenon better and ultimately to improve forecast techniques, a comprehensive climatology of NWF outbreaks has been developed from data collected during the 16-year period 1962–77.

2. Criteria for NWF cases

Two basic criteria are used to select cases for this climatological study: (a) the 500 mb flow pattern and (b) the outbreak of severe weather. The 500 mb flow criteria are as follows:

a) The 500 mb chart prepared from observations taken at least 2 h before the beginning of the outbreak (referred to hereafter as 5A), must show:

1) Long-wave trough east (downstream) and long-wave ridge west (upstream) of the geographical midpoint of the outbreak.

2) Averaged 500 mb flow direction over the geographical midpoint of 280° or greater.

b) The 500 mb chart for 12 h after 5A (referred to hereafter as 5B) must show either:

1) Averaged 500 mb flow over the geographical midpoint of 280° or greater, or

2) Averaged 500 mb flow over the geographical midpoint from 250 to 280°, provided that the long-wave trough position remains east (downstream) of the midpoint.

The time of the 5A chart relative to the beginning of the outbreak was based on operational considerations. The forecaster needs at least 2 h after the scheduled radiosonde observation time to receive and analyze the information. Therefore, in order to have a climatology based on data that leads to a NWF outbreak, 5A chart observation times are anywhere from 2 to 14 h before the outbreak commences. The criteria pertaining to the 5B chart allow for a temporary backing of the upper flow while the outbreak is in progress. However, the basic NWF pattern must remain unchanged.

The definition of what constitutes a severe weather outbreak is made difficult by the significant biases in the historical record of severe storms (Galway, 1977; Kelly, *et al.*, 1978). The completeness of the severe weather record is highly related to the population density (Doswell, 1980; Schaefer and Galway, 1982). Also, the chief source for severe storm reports, *Storm Data* (a NOAA EDIS publication), contains wide variations in quality from state to state. Perhaps the most complete source of reports of severe weather events is contained on the SELS severe weather history tapes. These tapes contain reports on the time and location of the following severe weather events: tornadoes, hail ¾″ in diameter or greater, convective wind damage, and convective wind gusts ⩾ 50 kt[1]. The reports have been assembled by screening *Storm Data* and the SELS operational log.[2] In reference to the SELS severe weather history tapes, then, a severe weather outbreak has been defined as either:

- Twenty or more reports of severe weather events in a geographical cluster or in an organized pattern,[3] with the time interval between events not to exceed 3 h; or
- Eight or more reports of severe weather events in a geographical cluster or in an organized pattern which result in multiple injuries, deaths, or damage in excess of $4 million (*Storm Data*), and with the time interval between events not to exceed 3 h.

The second criterion is necessary in order to include several significant outbreaks in which *Storm Data* was not specific enough for 20 individual reports to be included on the SELS tape.[4]

Identification of NWF cases was achieved by systematically cross-checking three sources: SELS severe weather history tapes, *Storm Data*, and 500 mb charts from the Constant Pressure Chart microfilm series. The averaged 500 mb flow direction was determined in the following manner:

- On a photostat from the microfilm, a line was drawn between two points 550 km (300 n mi) upstream and downstream along the isohypse passing through the outbreak center.
- The angle between this straight line and the meridian passing through the outbreak midpoint was used as the averaged 500 mb flow direction. An example of the measurement of the averaged flow angle of a typical NWF outbreak 500 mb pattern is shown on Fig. 1.

3. Climatological results

a. Annual and monthly frequency

During the study period, a total of 163 NWF outbreaks were identified, giving an average annual total of 10.2. However, the totals varied considerably from year to year as illustrated in Fig. 2. This variance probably reflects the prevalent 500 mb long-wave pattern over the United States during a particular NWF season. For example, during 1966 an extended period of NWF at 500 mb existed over the eastern half of the United States from mid-June to mid-August. During that two-month period, 20 NWF outbreaks occurred.

About one-third (51) of the NWF outbreaks qualified as *major* NWF outbreaks (Fig. 2) by causing one or more of the following: (i) more than $20 million damage, (ii) at least three deaths, or (iii) at least ten injuries.[5] The months of June, July and August average about one major outbreak each per year.

Results displayed in Fig. 3 confirm the notion that NWF outbreaks are a summer phenomenon. The months of June, July and August account for 85% of the average annual total. The peak of the NWF outbreak season is in July, which is later in the year than the peak period for tornadoes (Kelly *et al.*, 1978). This seasonal lag in the occurrence of NWF activity appears to be related to the availability of low-level moisture. Low-level moisture in areas of northwest flow aloft is usually insufficient for the production of severe weather outbreaks until early June. The decrease in frequency after July is likely the result of a general decrease in the thermodynamic instability of the atmosphere.

b. Areal frequency

In order to determine a NWF outbreak geographical frequency distribution, a grid was prepared by

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[1] Considerable effort is made to have a consistent and representative data base on the SELS data tape. Each tornado is considered as a separate event logged at the time and location of the initial touchdown. For continuous hail swaths (widespread wind damage) separate reports of hail (wind damage) are restricted to intervals of at least 10 mi.

[2] The SELS operational log consists of a real-time listing of severe weather events compiled from information contained in surface observations, severe weather warnings and statements, storm reports, radar observations, and Air Force Global Weather Center sources.

[3] The reports for each case and the time of their occurrence were plotted on a U.S. map. Visual inspection was then made to determine whether a concentration of reports existed. Generally, a report was not considered as part of a cluster if there was more than a 120 mi gap between the report and the remainder of the cluster. On some occasions the reports line up in a long narrow swath in which the time of the reports is progressive.

[4] A hypothetical example of a significant non-specific *Storm Data* entry might read: "A severe squall line moved eastward through the southern half of the state during the evening hours. Considerable wind damage occurred in many areas. Thousands of trees were uprooted, many homes and farm buildings damaged, and numerous boats were capsized on area lakes. Forty-four persons were injured in overturned mobile homes. Two persons were killed and five injured by falling trees. Two persons were drowned on Lake Marion when their boat capsized."

[5] Casualties attributable to tornadoes, wind or hail.

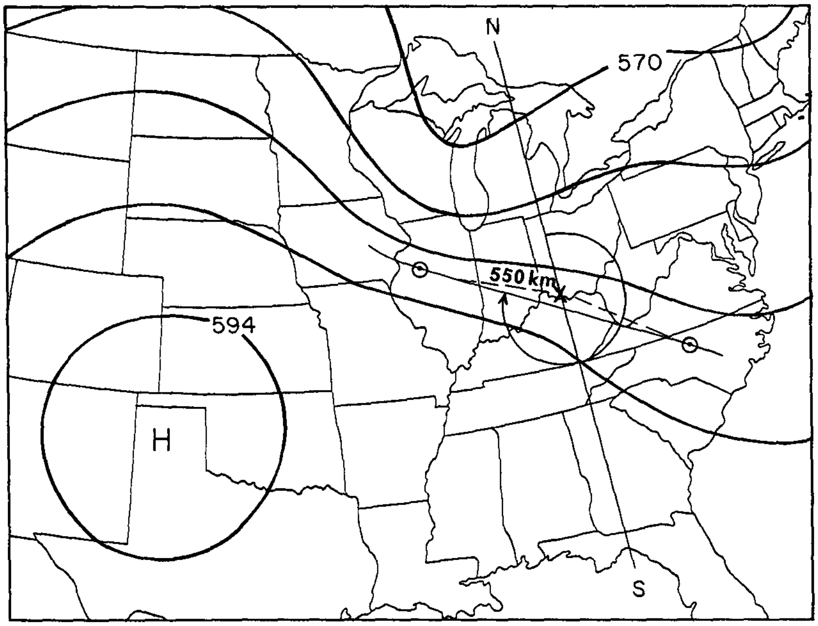

FIG. 1. Determination of averaged 500 mb flow angle. The midpoint of the NWF outbreak is marked by an ×.

dividing the United States into 2° Marsden squares (2° latitude × 2° longitude). The maximum areal difference in such squares from north to south is less than 10%. By consulting the plot of each outbreak, a tally was kept of the number of outbreaks that affected each grid square. The results are displayed in Figs. 4–8.

An outstanding feature of the geographical frequency distribution of NWF outbreaks (Fig. 4) is the well-defined primary high-frequency axis (A1) extending from eastern North Dakota east southeastward to southwestern Pennsylvania. A secondary high-frequency axis (A2) extends roughly from northwestern Iowa south-southwestward to northwestern Texas. Other interesting features include the minimum frequency axis over Missouri and western Arkansas and the frequency maximum over portions of the lower Mississippi and lower Tennessee valleys.

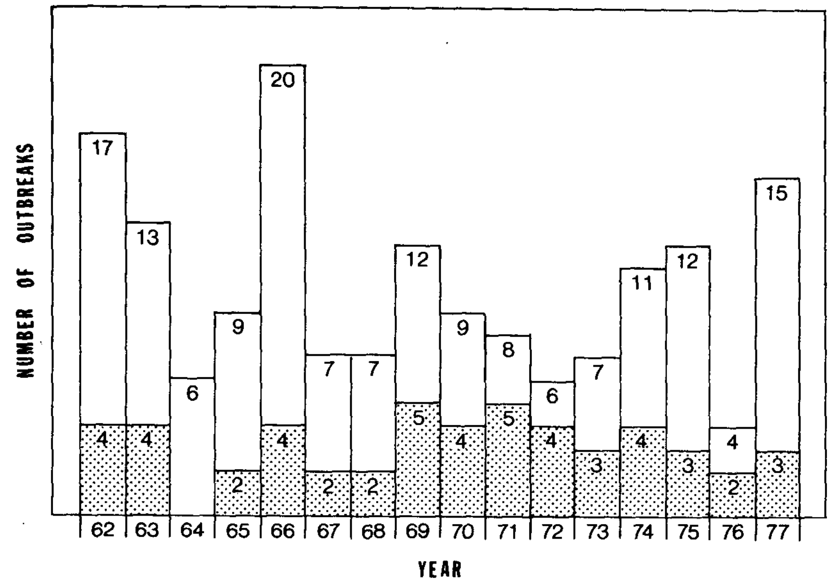

FIG. 2. Northwest flow outbreaks for the period 1962–77. Shown are total cases and major cases, with major cases indicated by shading.

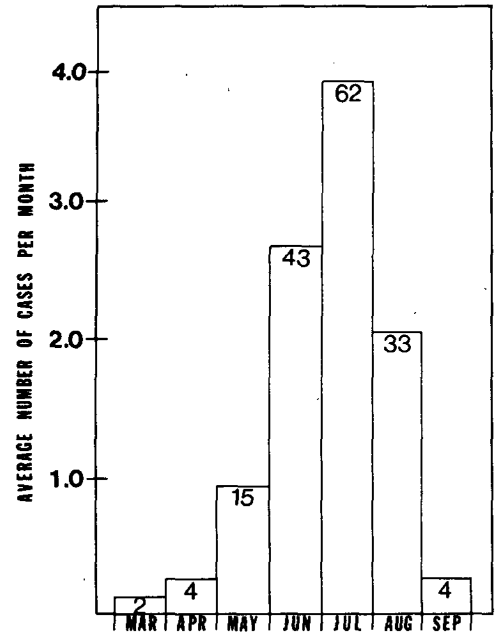

FIG. 3. Frequency of northwest flow outbreaks by month, with total number of NWF outbreak cases per month indicated, 1962–77.

Northwest flow outbreaks appear to be a rare phenomenon in the New York-New England area and south of 32° latitude. The data suggest that NWF outbreaks do not occur west of the continental divide (none occurred in that area during the period of this study).

Figs. 5–8 illustrate that the A1 axis becomes established in June and remains nearly stationary through August. The A2 axis also becomes established in June but the highest frequencies shift northward along the axis as the season progresses. This northward shift of NWF activity is supported by the work of Notis and Stanford (1973, 1976), who found that tornadoes associated with northwesterly flow at 500 mb are most frequent in Oklahoma in May and June, while the peak in Iowa is in July. The marked decrease in NWF outbreak frequency over Oklahoma and northwest Texas in July and August appears to be the result of the northward migration of the mid-troposphere westerlies into the northern plains.

An interesting comparison can be made between the geographical frequency distribution of NWF outbreaks (Fig. 4) and the NWS map of the tracks of all U.S. tornado occurrences between 1930 and 1974 (Fujita and Pearson, 1976). Fig. 9 is a reproduction of that NWS tornado map, showing only those tracks with a discernible northwest–southeast orientation (280–360°). Although a few of these tracks may represent tornadoes that traveled from southeast to northwest (i.e., those in south Texas which may have been associated with a hurricane), the vast majority likely traveled southeastward.[6] Notis and Stanford (1973) have shown that the direction of tornado movement has a high correlation with the 500 mb

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[6] Schaefer *et al.*, (1980) have shown that tornadoes having any component of motion toward the west are extremely rare.

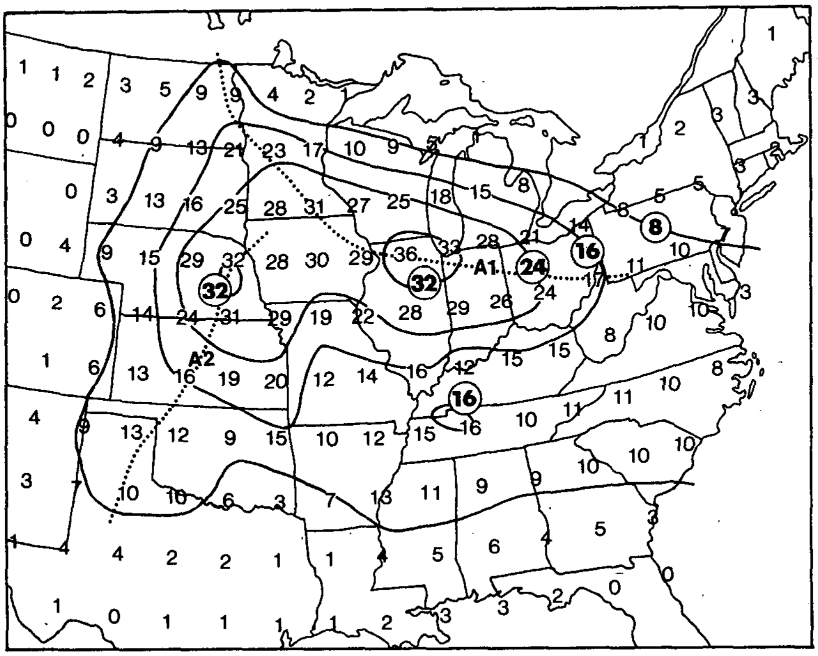

FIG. 4. Total number of NWF outbreaks occurring in 2° Marsden squares for the period 1962–77. Dotted lines indicate major high-frequency axes.

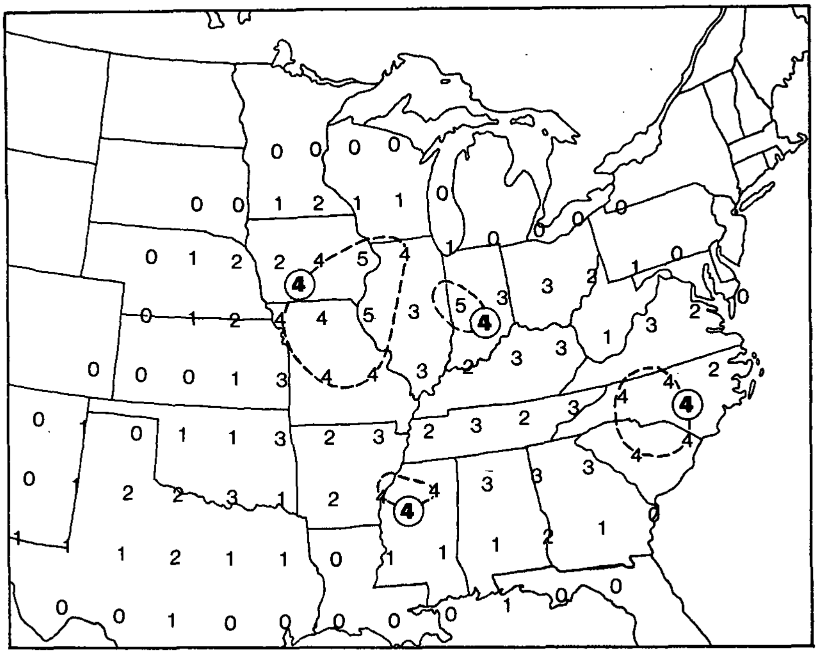

FIG. 5. Number of NWF outbreaks occurring in 2° Marsden squares during May, 1962–77.

flow direction. Thus, while some of the tornado tracks in Fig. 9 probably represent right-moving storms where the 500 mb flow direction is 270° or less, we can assume that for the most part the pattern depicts those longer-track tornadoes associated with northwesterly flow at 500 mb. Note the remarkable similarities in the patterns of Figs. 4 and 9. Specifically, the A1 and A2 NWF high-frequency axes are evident in the pattern of tornado tracks.

A distribution of the tornadoes that have occurred with the 163 NWF outbreaks (Fig. 10) reveals two high-frequency axes corresponding to A1 and A2 of Fig. 4. However, the tornado totals along portions of the A1 axis are much higher than those along the A2

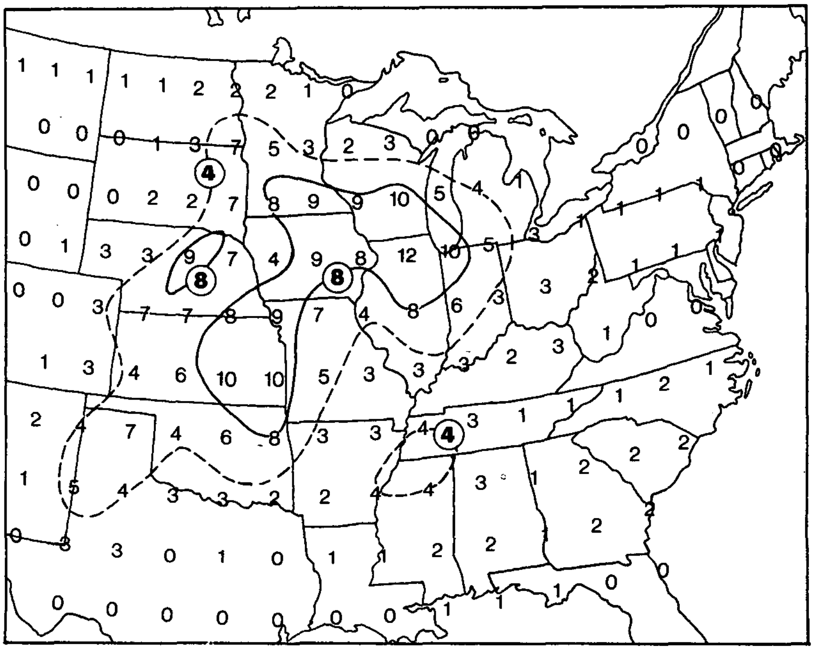

FIG. 6. As in Fig. 5, except for June.

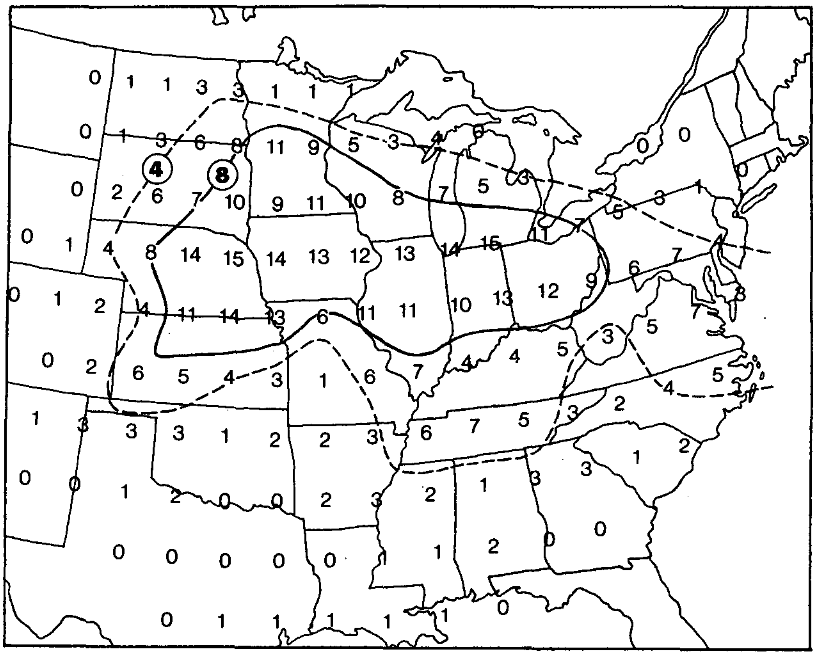

FIG. 7. As in Fig. 5, except for July.

axis. Examination of the data set shows that 34 tornadoes were reported in the northern half of Illinois during one outbreak! This unusual event appears to account for the prominent "bullseye" in Fig. 10 over northern Illinois. When this unique outbreak is disregarded, the contrast in tornado frequency between the A1 and A2 axes is not as dramatic. Nevertheless, the results still indicate that the A1 axis is the primary one for NWF tornado activity.

Notis and Stanford (1973) found that 30% of all tornadoes in Iowa move from a northwesterly direction. Thus, it can be assumed that close to 30% of *all* tornadoes that occur in Iowa are associated with northwesterly flow at 500 mb. This suggests that

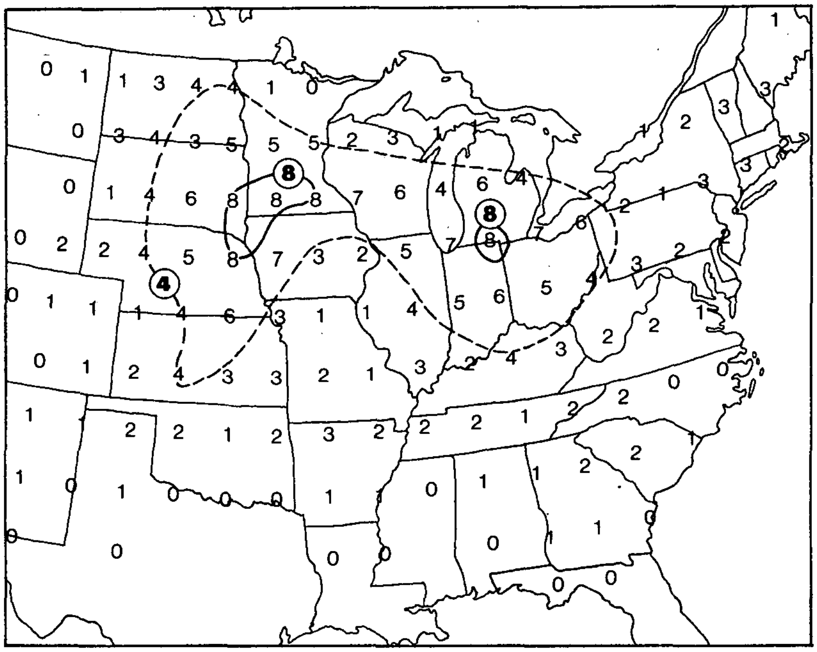

FIG. 8. As in Fig. 5, except for August.

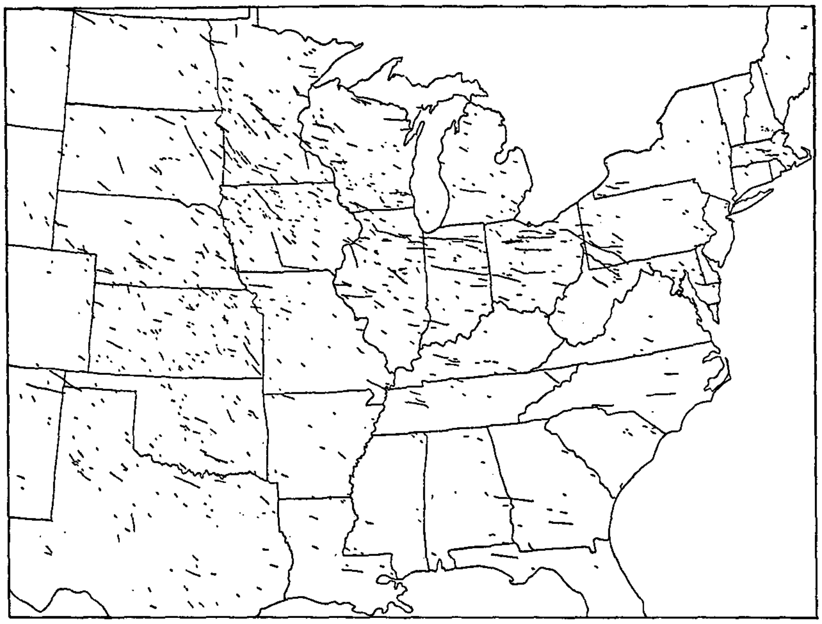

FIG. 9. Tracks of U.S. tornadoes with NW-SE orientation during the period 1930–74. (After Fujita and Pearson, 1976.)

NWF tornadoes associated with the A1 axis (which includes portions of Iowa) probably make a significant contribution to the geographical frequency distribution of *all* tornadoes. Indeed, the tornado frequency map for the U.S. presented by Schaefer *et al.* (1980) reveals an axis of higher frequency from northeast Iowa, east-southeastward to western Ohio.

Using procedures similar to those used in the preparation of Fig. 10, geographic frequency distributions have been developed for large hail and convective wind activity associated with NWF outbreaks. The frequency distribution pattern for NWF convective wind activity is similar to that for NWF outbreaks in general showing the two major axes, A1 and A2;

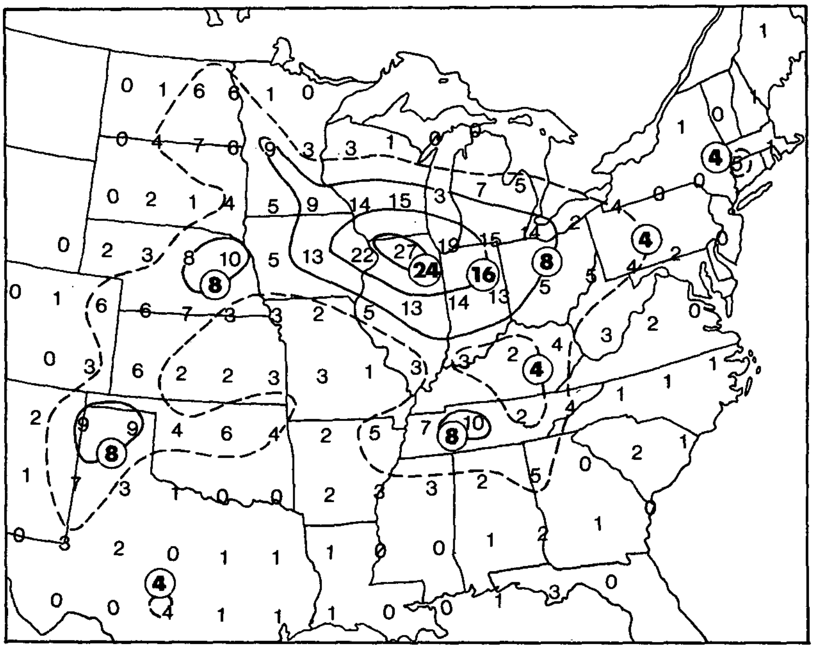

FIG. 10. Total number of NWF outbreak tornadoes reported, per 2° Marsden square, for the period 1962–77.

TABLE 1. Composition of NWF outbreaks.

	Mar	Apr	May	Jun	Jul	Aug	Sep	Annual
NWF Outbreaks	2	4	15	43	62	33	4	163
Percentage of cases with at least one tornado event	100	100	80	86	68	79	75	77
Percentage of cases with at least one hail event	100	100	93	95	90	85	100	91
Percentage of cases with at least one wind event	100	100	100	100	100	100	100	100

however, the frequency distribution for NWF hail activity reveals a pattern with only one major axis in the Plains region (similar to A2). Thus, the NWF hail frequency distribution is not unique when compared with all hail occurrences (e.g., Changnon, 1977).

c. Composition of NWF outbreaks

The average number of tornadoes per NWF outbreak is greatest early in the season, averaging 3.5 or more per month from March through June. During the remainder of the season from July through September, the average number of tornadoes per outbreak drops to 2.6 or less per month. *Seventy-seven percent of all the NWF outbreaks include at least one tornado occurrence.* The month of July has the lowest percentage of occurrence (Table 1); even so, over two-thirds of the July cases include one or more tornadoes.

NWF outbreaks with six or more tornadoes have been considered as NWF *tornado* outbreaks. Only 20% of the NWF cases fit this criterion, and about one-third of these occurred in July. Those NWF outbreaks that occur early in the season are more likely to be tornado outbreaks. Forty-three percent of NWF outbreaks during the period March through May included six or more tornadoes, while only 16% of NWF cases during the period June through September qualified as tornado outbreaks. These findings are consistent with the monthly distribution of tornado outbreaks in general (Galway, 1977).

Major NWF outbreaks are most likely to occur during the months of July and August. However, during these months only about 30% of the major outbreaks are also NWF tornado outbreaks. This suggests that during the summer months those NWF cases which result in casualties and destruction of property generally consist of convective windstorms and include only isolated tornadoes. Supporting this view, Miller (1972) has noted that as the severe weather season progresses into summer, tornado occurrences decrease, while the frequency of straight-line damaging windstorms increases proportionally.

Table 1 illustrates that convective wind events are the characteristic severe weather event associated with all NWF outbreaks. Hail events are not quite as common during NWF outbreaks, but still occur in more than 90% of the cases. NWF hail events are somewhat less common in July and August outbreaks than earlier in the season.

d. Diurnal distribution and duration

One of the main NWF forecast problems is determining when an outbreak of severe weather will begin and when it will end.[7] Figs. 11 and 12 reveal the main diurnal trends in NWF outbreak activity. It is clear that such outbreaks typically begin in the afternoon, near the time when solar heating has produced its greatest effect, and end within a few hours after sunset. However, a sizeable number of outbreaks (26%) continue on into the early morning hours (past midnight CST).

As the NWF season progresses, the average beginning time comes later in the afternoon, from around 1300 CST in May to near 1600 CST in August. A possible explanation for this change is the warming in the middle layers of the atmosphere during the summer season. As summer progresses, lift from dynamic sources decreases, and more heating is required in order to lift a parcel to its level of free convection. This warm cap in the middle levels of the troposphere often retards the start of convection until late afternoon or early evening.

Fig. 13 illustrates the variation in NWF outbreak durations. Early season outbreaks tend to last longer than those later in the season, with the average duration decreasing from almost 10 h in May to less than 8½ h in August. Analysis of the monthly frequency distributions for outbreak duration shows that the decrease from May to August is almost linear. The linear correlation coefficient for a least-squares regression line is -0.997! It seems likely that this decrease in duration is related to the combined effects of seasonal changes in dynamic lift and atmospheric instability.

When the United States is divided into six geographical regions as shown in Fig. 14, NWF outbreaks of the Upper Mississippi Valley[8] show the largest vari-

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[7] The duration of an outbreak is considered as the time interval between the first and last reports of severe weather.

[8] The geographical midpoint of each outbreak was used to determine the region of occurrence.

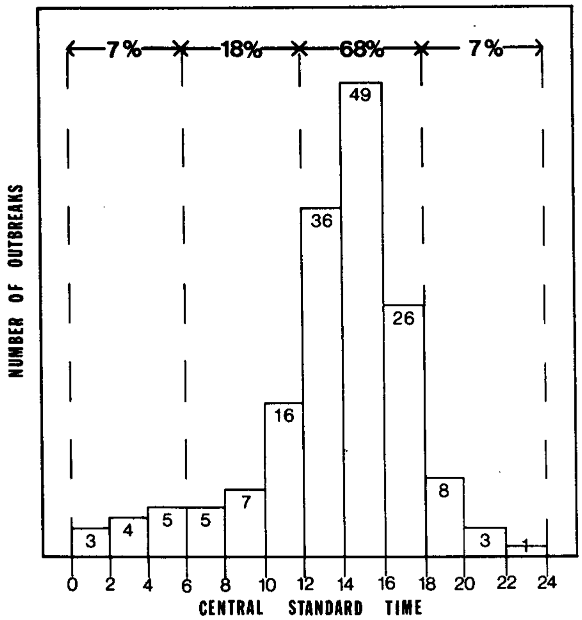

FIG. 11. Bihourly distribution of NWF outbreak beginning times.

ation in beginning times. Outbreaks in this region have begun at all hours of the day except between 2000 and 2200 CST. However, in the Southern Plains the beginning times are more diurnally polarized, with all of outbreaks beginning between the hours of 1000 and 2000 CST. This difference suggests that diurnal heating is almost always a necessary contributor to the initiation of NWF outbreaks in the Southern Plains, while other factors may initiate outbreaks in the Upper Mississippi Valley. Further, NWF outbreaks in the Upper Mississippi Valley have an average duration of almost 10 h—the greatest of any region. This compares with an average duration of only 8 h in the Southern Plains. This difference and the differences in beginning times between the two regions indicate that dynamic influences play a larger part in NWF outbreaks that occur along the A1 high-frequency axis than they do along portions of the A2 high-frequency axis.

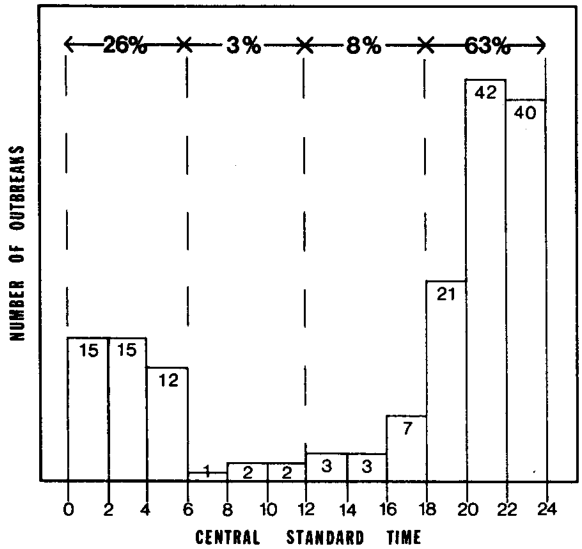

FIG. 12. Bihourly distribution of NWF outbreak ending times.

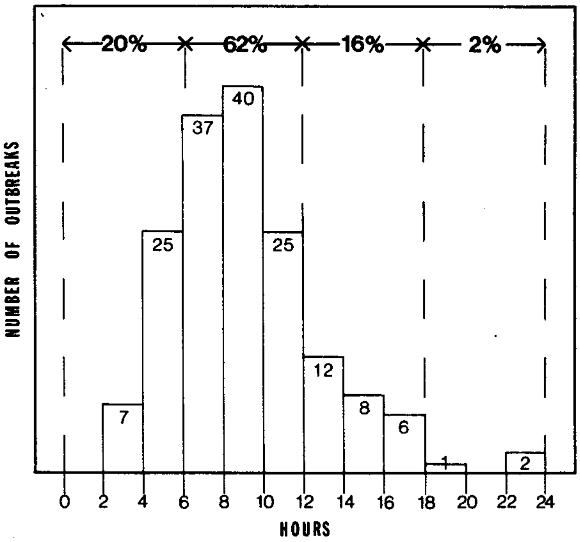

FIG. 13. Distribution of NWF outbreak durations.

Another anomaly occurs in the regional variation of outbreak ending times. The majority (58%) of NWF outbreaks in the Northeast, Southeast and Lower Mississippi Valley regions end between 1800 and 2200 CST, with the most common ending time close to 2000 CST. In the Northern Plains and Upper Mississippi Valley, however, the most common ending time is between 2230 and 2300 CST, and nearly half (46%) of the outbreaks of the Northern Plains region end between 0000 and 0600 CST. These differences are too large to be explained solely as diurnal effects. It may be that these later ending times are associated with the synoptic conditions that result in a high incidence of summer nocturnal thunderstorm activity over the north central United States (Pitchford and London, 1962; Sangster, 1958). This possibility will be examined further in Part II of this study.

e. Outbreaks in series

Miller (1972) has observed that NWF outbreaks are likely to repeat on several successive days. In order to verify this observation, an outbreak series has been defined as any combination of two or more separate outbreaks that occur with no more than two calendar days between any of the outbreaks of the series. With this definition, fully 71% of all the NWF outbreaks that occurred in the 1962–77 period were a part of

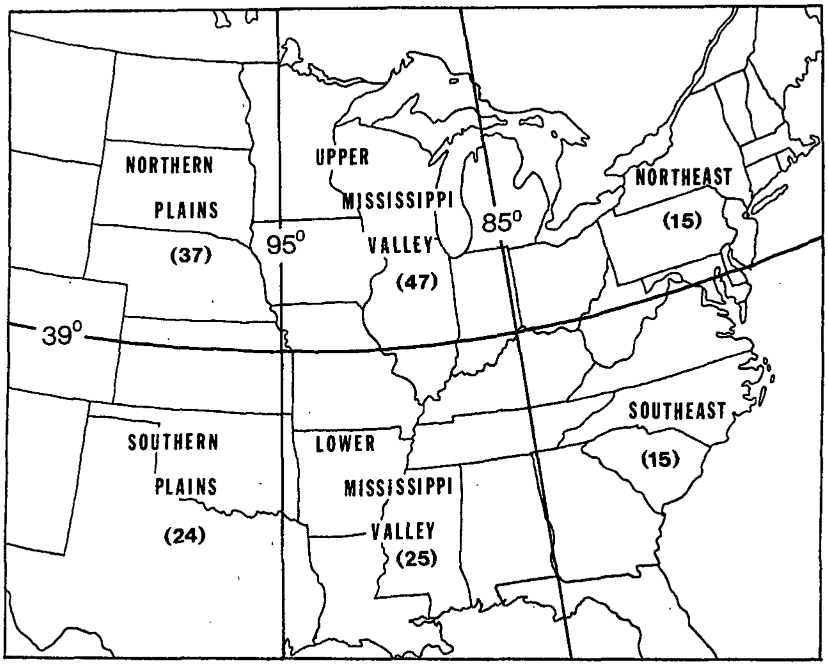

FIG. 14. The six geographical regions used in NWF outbreak statistics. Number of cases per region are shown in parentheses.

a series. Most series involved only two or three outbreaks; however, two series—one in June 1974 and one in July 1966—*involved eight or more separate outbreaks*!

Outbreaks are most likely to be a part of a series during the months of June and July, with only 16% of the June outbreaks being singular and 21% for July. Early season outbreaks are more likely to be singular, with only one-third of the May outbreaks being a part of a series.

On 13 occasions, two separate NWF outbreaks occurred on the same calendar day. These same-day outbreaks were usually located in two different geographical locations and occasionally occurred at different times within the day. Same-day multiple outbreaks seem to be limited to the peak of the NWF season, occurring only in the months of June, July and August. July has had eight such occurrences during the period of this study. Outbreaks occurring on each of two or three *consecutive* calendar days were observed on 25 occasions and involved more than one-third (60) of all the NWF cases. This is perhaps related to the fact that the intensity of atmospheric disturbances in summer is usually weak and the surface synoptic patterns are slow to change. Such behavior is similar to that of High Plains severe weather episodes, as described by Doswell (1980).

Examination of individual outbreaks in a series indicates that only occasionally does there seem to be a southeastward progression chronologically from one outbreak to the next. This suggests that during the typical outbreak series, the 500 mb pattern remains quasi-stable with a series of short waves causing the individual outbreaks. Part II of this study will consider this in greater detail.

In summary, during the period 1962–77 the three months of June, July and August had a combined total of 33 "loner" NWF outbreaks and 33 NWF outbreak series. Fourteen of the outbreak series involved three or more outbreaks. These statistics suggest that *once a NWF outbreak occurs during the main season, there is a 50% chance that this outbreak is the first of a series of two or more*, and about a one in five chance that this outbreak is the first of a series of three or more.

f. Deaths and injuries

During the 1962–77 period, 133 persons were killed and 2045 were injured in NWF outbreaks, giving an average of 8 deaths and 128 injuries per year. Most casualties occur in states along the A1 high-frequency axis from Minnesota and Iowa, east-southeastward to Ohio and Pennsylvania. Ohio experiences more casualties than any other state (25 deaths and 410 injuries). Casualty figures through the Dakotas, Nebraska and Kansas are very low compared with the states along the A1 axis. Some part of this difference can probably be attributed to the much lower population density in the Plains states.

Many metropolitan centers along the A1 axis have experienced major NWF outbreaks during the 16-

year period. Minneapolis, Des Moines, Milwaukee, Chicago, Indianapolis, Cleveland, Cincinnati and Pittsburgh have all been struck by casualty-inflicting NWF windstorms or tornadoes. Cincinnati has experienced three major outbreaks, with the worst being the outbreak of 9 August, 1969, in which a tornado killed 4 and injured 247. Most of these big city NWF disasters have been the result of a tornado occurrence.

Since NWF outbreaks are mostly a summer phenomenon, many casualties can be directly related to outdoor activities of a recreational nature. Campers, boating enthusiasts and fishermen figure heavily in the casualty figures, with casualties usually resulting from convective windstorms which topple trees onto victims or capsize boats. In fact, *40% of all the NWF fatalities are drowning victims.* Water bodies most prone to NWF drownings are the lakes of Wisconsin, Lake Michigan, Lake Erie, Chesapeake Bay, Delaware Bay, the mid-Atlantic coastal waters, and the southwest Missouri lakes.

4. Summary and conclusions

NWF severe weather is generally a summer phenomenon and usually occurs along one of the two high-frequency axes: A1, the major axis extending from the upper Mississippi Valley to the mid-Atlantic states, or A2, a secondary axis oriented NNE–SSW through the Plains region. Wind damage is the characteristic severe weather event associated with NWF outbreaks, but tornadoes do occur, most frequently along the A1 axis. NWF episodes appear to be a special threat to life and property because they are most frequent in areas of high population density (A1 axis), and occur during the peak of outdoor recreational activities.

NWF outbreak duration is usually 8–10 h, with a tendency for early season occurrences to last longer than those late in the season. The diurnal variation in time of occurrence is generally tied to the solar heating cycle, with beginning times coming later in the afternoon as the season progresses. Outbreaks show a marked tendency to occur in series over a period of a few days. This indicates that NWF episodes often occur in situations when the mid-troposphere pattern is not changing rapidly.

Part II of this study will examine the relationship of meteorological parameters to the NWF phenomenon. Plausible explanations will be offered concerning the distinctive characteristics of NWF outbreaks.

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