Climatology of Nontornadic Severe Thunderstorm Events in the United States

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ABSTRACT

While the climatology of excessive rain and tornadoes is well-documented, little is known of storms that produce high winds or large hail. The characteristics of the approximately 75 000 severe thunderstorms which occurred in the United States from 1955 through 1983 are analyzed in an attempt to rectify this situation.

The distribution of over 29 000 storms causing hail larger than 19 mm shows marked diurnal, seasonal, and geographic preferences. These storms occur most frequently during the midafternoon hours of May and June in a zone running from central Texas to Nebraska. Spring storms tend to occur south of the Kansas–Nebraska border and summer storms north of it.

Thunderstorm winds which produce either "structural" damage or are reported as faster than 25.8 m s^{-1} generated about 46 000 reports. These storms typically occur during midafternoon in June and July. While the geographic distribution of violent windstorms is similar to that of hailstorms, a zone of weaker severe thunderstorm gusts lies from northern Iowa to central Ohio. During May, windstorms are predominant across the plains area, but by August these storms are indigenous only to the northern Midwest.

1. Introduction

The National Weather Service has arbitrarily defined severe thunderstorms as storms which produce winds of 25.8 m s^{-1} or more or hail 19 mm diameter or larger. Structural wind damage may infer [sic] the occurrence of a severe thunderstorm (NOAA WSOM C-40, 1982). Frequent lightning, large amounts of small (less than 19 mm) hail and/or excessive local convective precipitation are not sufficient to classify a thunderstorm as severe.

Before proceeding, we must give several caveats concerning the observation of severe thunderstorms. Procedures for determining "structural wind damage" have varied throughout the period. The original requirement of $5000 or more estimated damage before a storm could be counted as severe (Pautz, 1969) inflated to $50 000 through the years (Doswell *et al.*, 1983). The present requirement is for "damage which appears to be caused by winds of this speed (25.8 m s^{-1}) or higher" (NOAA WSOM F-42, 1982).

Compared to our knowledge of tornado climatology (e.g., Kelly *et al.*, 1978), relatively little is known about the spatial and temporal distribution of severe thunderstorm events. The most extensive effort on this subject was Pautz' (1969) examination of severe weather events for the 13 years, 1955–67, using reports collected in real time at the National Severe Storms Forecast Center, augmented by those listed in *Climatological Data* and *Storm Data*. Counts of reports by state, and latitude–longitude quadrangles were given, along with an annual diurnal distribution by state.

This paper is an extension of that pioneering effort. The database is similar to Pautz', but it has been extended to include reports from 1955 through 1983. The reports have been subjected to further quality control since Pautz' report. In an attempt to identify single severe storm events, only reports within an individual county separated by more than 15 min or 18.6 km (10 n mi) from a similar type report (e.g., wind or hail) are counted as separate events. This is not a perfect technique, as it allows a single, long-duration progressive event, such as a hail swath, to be counted several times. However, this is the only current practical method for obtaining a national dataset. Methods involving, say, the tracking of individual storm cells by radar or satellite not only would be cost prohibitive, but for many events (especially in the early years) the needed data simply do not exist.

A myriad of nonmeteorological factors also makes the interpretation of severe thunderstorm occurrence data a dangerous process. Some of the pitfalls are discussed by Galway (1977, 1983), Kelly *et al.* (1978), Doswell (1980, 1984), and Schaefer and Galway (1982). In essence, the problems boil down to this:

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in order to take its proper place in the climatological record, a severe event must be observed, properly perceived as a severe event, and must stimulate the observer (or observing system) to report it for the record.

Obviously, variations in population density have an effect on whether or not an event is observed. While it is tempting to use population data to weight the climatological records, other demographic factors, such as degree of urbanization, highway distribution, distance to an official reporting station, education level of the populace, etc., must also be considered. The net result of these demographic factors on the data is quite complex and most likely nonlinear.

Beyond these factors, severe thunderstorm events may be difficult to observe because of the time of day, the lack of appropriate measuring devices, or because of intervening clouds and/or topographic features. The presence or absence of spotter networks, as well as their training (both in recognition and in reporting procedures), can have a serious impact on whether events are observed.

Proper perception of an event is critical. For many reasons, a truly severe event may not be viewed as significant or, conversely, a nonsevere event may be improperly classified as a severe one. Virga may be reported as a tornado, a tornado may be improperly classified as a downburst, or hail size may be estimated incorrectly. Much of these data originate in observations by essentially untrained people, leaving a considerable potential for errors of perception.

Even a properly observed severe event observation may simply never be documented. A farmer seeing a tornado in his open field may not feel any duty to report it to anyone. Beyond this problem, human tendency is to concentrate upon the most spectacular event and virtually ignore lesser ones. Hail that accompanies tornadic thunderstorms often goes nearly unnoticed, at least in comparison to the attention given to tornadoes (Morgan and Summers, 1982). Wind and hail are reported from the same storm 143 times a year (i.e., 9% of windstorms correspond to hailstorms). When these data are compared to the NSSFC tornado database, it is seen that about 4% of all tornadoes are accompanied by a hail report (939 common reports) and another 4% of the tornadoes are accompanied by a windstorm (912 common reports). Over the 29-year period, only 123 storms have generated reports of hail, winds and tornadoes. Since considerable evidence from research studies of supercell storms (e.g., Browning, 1964) suggests that these events often occur together, clearly a problem exists with the record.

Many steps are involved, reporting events, and the process may work consistently better in some places (and at some times) than others. What is disturbing is the lack of consistency with regard to these factors. If everyone had the same training and followed the same procedures, some simple correction factors could be applied to the data with a reasonable expectation that the results would be representative of the true distribution of severe weather events. However, this is simply not the case.

Even with such problems, these data merit analysis. They are the only existing long-term record of large hail and excessive thunderstorm winds. This litany of problems has been given in the hope that readers aware of the limitations will resist the temptation to use the data for purposes beyond these limits. However, at the very minimum, these data show the general pattern of nontornadic severe thunderstorms across the conterminous United States.

2. Characteristics of the data

Over the 29-year period of record, an average of 2608 severe thunderstorms is reported each year (75 626 total). Of these, 61% (46 453) are wind-related events (Table 1). The monthly distributions of hail and windstorms (Fig. 1) show some interesting details. In contrast to the tornado distribution found by McNulty *et al.* (1979), thunderstorm wind gusts are summertime phenomena. June and July are the months of most activity. Large hail, on the other hand, is a spring event. During April and May, more hailstorms than windstorms are observed. During winter (December, January, and February), 2% of the hailstorms and about 5% of the windstorms occur. For comparison, McNulty *et al.* (1979) noted that 8% of tornadoes occur during the winter.

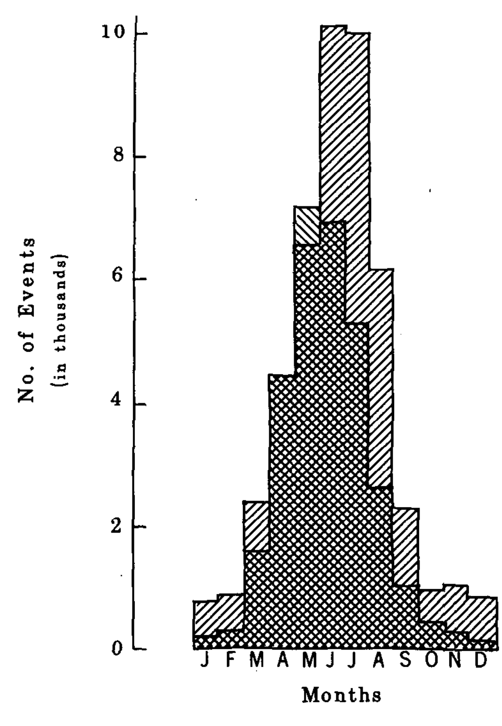

FIG. 1. Monthly distribution of severe thunderstorm wind events (upper right to lower left hatching) and large hail occurrences (upper left to lower right hatching).

TABLE 1. Severe thunderstorm events, 1955–83.

		Annual number	Percent	
Wind				
Damaging	Unknown	1114	70	
Strong	25.8–33.5 m s^{-1}	375	23	
Violent	>33.5 m s^{-1}	113	7	
Total		1602		
Hail				
Giant*	19–51 mm (dia)	828	82	
Enormous**	>51 mm (dia)	178	18	
Total		1006	100	39
	Total Reports	2608		100

* Giant includes walnut and golf ball size.
** Enormous includes hen egg and tennis ball size.

In an effort to stratify the relative strength of these nontornadic but wind-producing severe thunderstorms, wind reports have been sorted into three mutually-exclusive categories. Violent thunderstorm gusts, defined as those greater than 33.5 m s^{-1} (65 kt), occur approximately 113 times a year (3269 total reports) at some site within the contiguous United States. This number of reported violent thunderstorm wind gusts is small, especially when compared to frequency estimates of violent downbursts and microbursts (Fujita, 1981). It must be emphasized that for the sake of content integrity, only gusts where the velocity was measured (or estimated by a trained observer) have been included in this category. The second category, strong thunderstorm gusts, includes reported wind speeds between 25.8 and 33.5 m s^{-1}. Annually, 375 (10 878 total) such strong outflow winds are reported. It should be noted that obstacles (trees, buildings, etc.) can dramatically affect thunderstorm gusts. In the wake of such barriers, wind speed deficiencies as great as 58% extend a distance 50 to 80 times the height of the obstacle (Fujita and Wakimoto, 1982).

For 70% of the severe thunderstorm wind reports (32 306), no associated velocity is given. These reports are placed into the rather amorphous damaging winds category. While this grouping contains reports of storms that merely caused tree damage, it also includes storms like the one that killed 23 people along a 226 km long and 1 km wide path of damage in Mississippi on 1 February 1955. Even though an article entitled "Thunderstorms and Tornadoes of 1 February 1955" (Lee, 1955) appeared in the *Monthly Weather Review*, the official record, *Climatological Data*, states definitely that this was not a tornado. Thus, it can be categorized as only a damaging windstorm.

The monthly distributions for the three categories of severe thunderstorm winds are generally quite similar (Fig. 2). The summer months of June–August (Trenberth, 1983), account for between 55% (damaging winds) and 61% (gusts greater than 33.5 m s^{-1}) of the events. If May, the warmest nonsummer month, is also considered, 69% of damaging windstorms, 74% of strong wind gusts and 76% of violent windstorms occur during the four warm months. In contrast, winter accounts for only 6% (damaging winds) to 3% (violent gusts) of the events. However, there is a secondary maximum, albeit small, during autumn in the wind damage distribution. A similar November peak occurs in the distribution of tornadoes (McNulty *et al.*, 1979). The lack of such a semiannual cycle in the measured wind categories is rather surprising. Another minor but interesting detail is the relative number of storms in July as compared to June. For more occurrences in July than June, the wind damage category is again different.

Reports of large hail (greater than 19 mm) also were categorized. We define *enormous* hail as having a diameter greater than 51 mm (2 in.). This contains stones described as hen egg and tennis ball size (Court and Griffiths, 1982). Hail stones between 19 and 51 mm

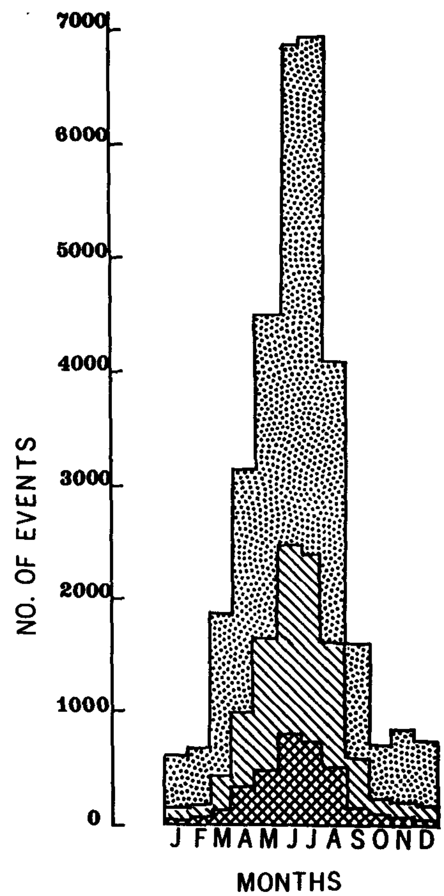

FIG. 2. Monthly distribution of occurrences of thunderstorm related wind damaged (stippled) gusts between 25.8 and 33.5 m s^{-1} (upper left to lower right hatching) and gusts greater than 33.5 m s^{-1} (cross hatching).

in diameter are denoted as *giant*. This grouping includes walnut and golf ball size stones. Enormous hail is quite rare; only 18% (5156 total) of all severe hail reports fall into this category. Giant hail is reported in an average of 828 storms a year (24 017 total storms). Because giant and enormous hail are observed with only the more intense thunderstorms, the hail climatology reported here does not resemble that by Flora (1956) or by Changnon *et al.* (1977) which do not discriminate by hail size.

The monthly distributions of the two hail categories (Fig. 3) show a definite peak in late spring to early summer. Approximately half (51% for enormous, 48% for giant) of the storms occur during May and June. This seasonal preference is so strong that over three-fourths (81% for enormous, 77% for giant) of the large hail events occur in the four-month span, April through July. Further, only a minimal (1% for enormous, 2% for giant) number of hailstorms occur during the winter season. These data emphasize that excessively large hail forms only under a very restricted range of environmental thermal conditions. Not only is thermodynamic stability (the vertical temperature gradient) a factor, but the temperature values themselves must also be considered (Fawbush and Miller, 1953).

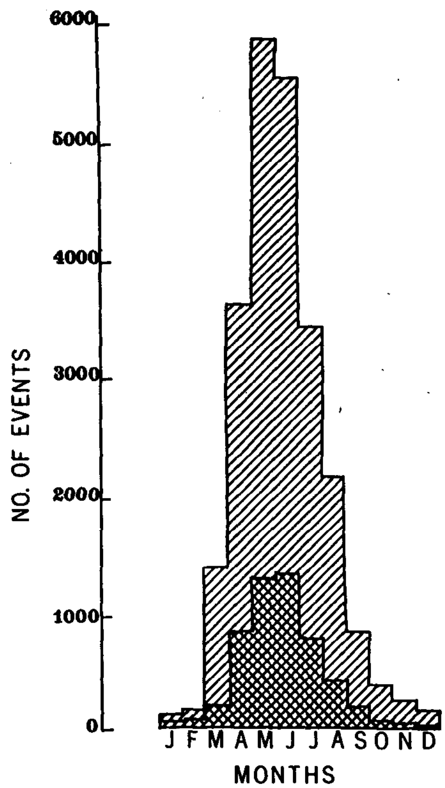

FIG. 3. Monthly distribution of occurrences of hail between 19 and 51 mm diameter (upper right to lower left hatching) and of hail greater than 51 mm diameter (cross hatching).

3. Diurnal variations

In order to relate a weather event to the solar heating cycle, it is necessary to relate occurrence time to actual sun time. An event at 1530 CST on the date of the winter solstice is much later in the solar day than one at 1530 CST in midsummer. One method of doing this is to transform all times to *normalized solar time* (NST) (Kelly *et al.*, 1978).

The NST method of accounting for the diurnal variation converts times to a day with 12 equal-length "hours" between sunrise (0600 NST) and sunset (1800 NST). At night, there are another 12 equal-length "hours," with a nighttime "hour" lasting (in general) a different amount of real time than a daytime "hour."

An example used in Doswell (1984) is instructive. At Kansas City, Missouri, the day of the summer solstice has 14 h, 56 min of daylight. Each daytime "NST hour" is 74.667 ordinary minutes long. On the other hand, each nighttime "NST hour" is only 45.333 ordinary minutes long. A Kansas City severe weather event which occurs at 1630 CDT (or 1530 CST) on the date of the summer solstice is at 1435 NST. On the other hand, an event at 1530 CST on the date of the winter solstice occurs at about 1615 NST.

The "S" in NST stands for *solar*, not *standard*, time. The NST conversion depends upon the latitude and longitude of a particular site as well as the day of the year. Because of this, the NST conversion presentation is not contaminated by discontinuities at time zone boundaries. Rasmusson's (1971) study of the hour of maximum frequency of thunderstorms indicated that storms in the Nebraska Panhandle occur several hours earlier in the day than storms in the rest of the state. While some of this is real, one hour of the difference comes from a change from the Mountain to the Central time zone. Thus, NST allows the comparison not only of data from different seasons, but also from different locations.

The NST distributions of all large hail and severe wind report events have been computed (Fig. 4). In an attempt to compensate for inaccuracies in time, the distribution is computed for one-hour increments simply by truncating the NST time to the hour. A storm exactly at sunrise is a daytime event, while one at sunset is nocturnal. Both frequency distributions are similar. The favored occurrence time is in the midafternoon, with 66% of the hailstorms and 55% of the wind reports occurring between noon and sunset. When the first three NST hours of evening are included, these percentages rise to 81 and 71, respectively. Activity is at a minimum during the hours around sunrise. These curves are very similar to the NST distribution of tornadoes (Schaefer *et al.*, 1980).

When severe hail reports are categorized according to size (Fig. 5), both distributions closely follow the typical diurnal temperature curve by displaying a marked peak in the late afternoon. What is most strik-

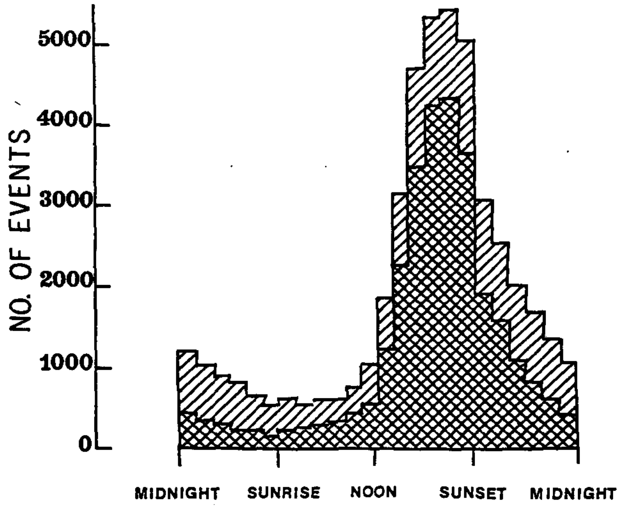

FIG. 4. Hourly distribution in NST of severe thunderstorm wind events (upper right to lower left hatching) and large hail occurrences (upper left to lower right hatching).

ing about these distributions is the extreme rarity of events between midnight and noon. Only 11% of the enormous hail and 13% of the giant hail fall during these hours. The percentage of hail events that are greater than 51 mm in diameter also exhibits a simple diurnal curve. At 1700 NST, 21% of all severe hail reports are for enormous hail, while at 0900 NST only 12% of the hail is of this extreme nature. This implies that hail size increases as instability (and potential updraft speed) increases, perhaps not a surprising conclusion.

The category distributions (Fig. 6) for the three severe thunderstorm wind categories also show a late afternoon peak. However, in contrast to hailstorms, a relatively large percentage of windstorms occur between midnight and noon. These hours account for 21% of wind damage reports—18% of the strong gusts and 21% of the violent gusts. It is of interest that the percentage of measured severe thunderstorm gusts exceeding 33.5 m s^{-1} actually has a maximum before dawn (29% at both 0200 and 0500 NST) and a minimum when the instability is greater (19% at both 1100 and 2100 NST). This explains the inability of forecast algorithms based upon the atmosphere's potential negative buoyancy (e.g., Foster, 1958) to forecast thunderstorm wind gusts (Doswell *et al.,* 1982). Apparently, dynamic effects play a very significant role in the generation of severe thunderstorm wind gusts.

4. Spatial distribution

The numbers of severe thunderstorm events within 2-degree latitude–longitude quadrangles ("squares") were tabulated. The total count in each was then normalized by the area of the square and by the number

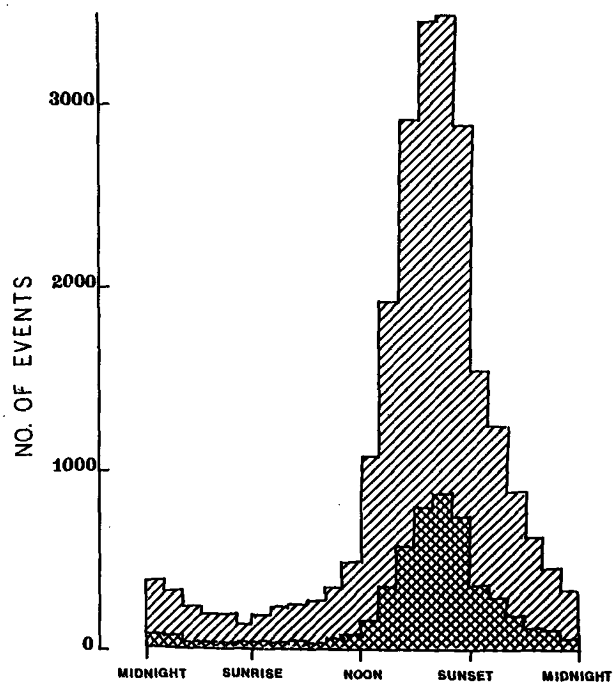

FIG. 5. Hourly distribution in NST of occurrences of hail between 19 and 51 mm diameter (upper right to lower left hatching) and of hail greater than 51 mm diameter (cross hatching).

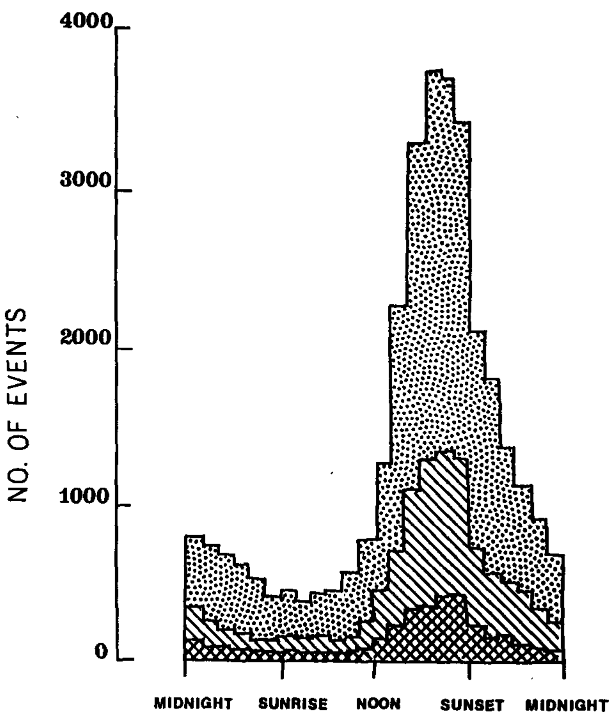

FIG. 6. Hourly distribution in NST of occurrences of thunderstorm related wind damage (stippled) gusts between 25.8 and 33.5 m s^{-1} (upper left to lower right hatching) and gusts greater than 33.5 m s^{-1} (cross hatching).

of years considered. These values were computed at 1-degree latitude and longitude increments over the conterminous United States in an overlapping procedure similar to that used by Skaggs (1969). As noted by Kelly *et al.* (1978), it gives the data a light smoothing, equivalent to that obtained by applying a running "boxcar" average to data collected over 1-degree squares.

Contour charts which depict the geographic pattern can be constructed from these data. The chart for large hail [both giant and enormous (Fig. 7)] has a large zone with more than eight storms per year per 26 000 km^2 extending from central Texas northward through Oklahoma, Kansas, Nebraska, and ending in southeast South Dakota. Inside this zone are several local maxima. The extreme value of slightly more than 20 reports per year lies in northwest Missouri. Caution is advised in interpreting such details. Since cities (Kansas City, Missouri; Oklahoma City, Oklahoma; and Grand Island, Nebraska) are colocated with each maximum, a very good case for a population bias can be made. Another sizable zone of increased large hail frequency is found in the high plains of central Colorado.

This large hail map is very similar to the one constructed from Pautz' (1969) data (Court, 1974). The stability of the pattern as the length of the data record more than doubled (Pautz considered 13 years of data) adds a large measure of credence to its broad scale features. A general agreement between this hail frequency pattern and the tornado frequency pattern (Schaefer *et al.,* 1980) can be seen. Both distributions feature a principal north–south "alley" between 95 and 100°W and a secondary zone of enhanced activity running roughly eastward from Nebraska to Ohio.

When only enormous hail (diameters greater than 51 mm) is considered, very little of the country receives more than two storms per year per 26 000 km^2 (Fig. 8). The maximum value of 4.65 storms annually is in west-central Oklahoma, with a secondary maximum exceeding three storms per year over central Nebraska. The large hail extreme in western Missouri has all but disappeared. A comparison of this distribution with that of violent tornadoes (Kelly *et al.,* 1978) shows significant differences: the region most often visited by the strongest tornadoes lies along and to the east of the Mississippi River, the zone of most prevalent enormous hail is some 700 km westward, over the high plains, from Texas through South Dakota.

The geographic distribution of severe thunderstorm wind gusts (Fig. 9) is much more complex than that of large hail. Two major frequency axes are present. One curves southeastward from southern Minnesota across Iowa, Illinois, Indiana, and Ohio. The other runs southward along the Missouri River from northwestern Iowa to the Kansas City region and then bows slightly westward crossing Kansas, Oklahoma and ending in central Texas. There are also areas of enhanced activity near St. Louis, Missouri where the two major axes approach each other, and in central Alabama. With a

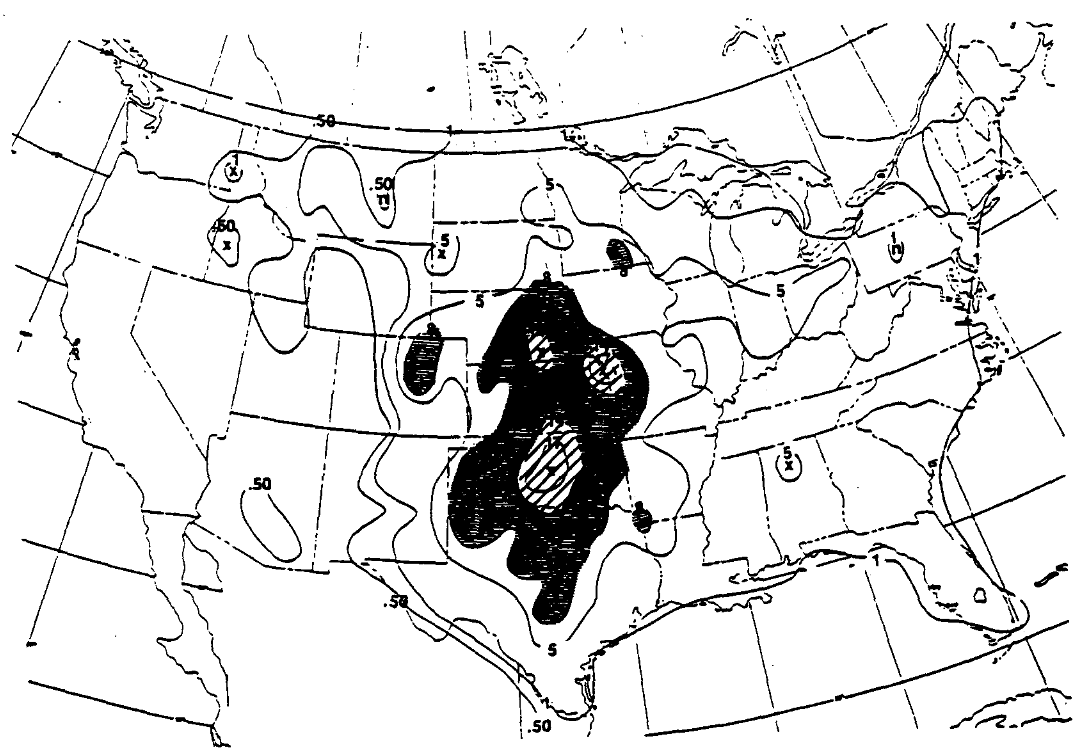

FIG. 7. Frequency of hail greater than 19 mm diameter per 26 000 km^2 per yr.

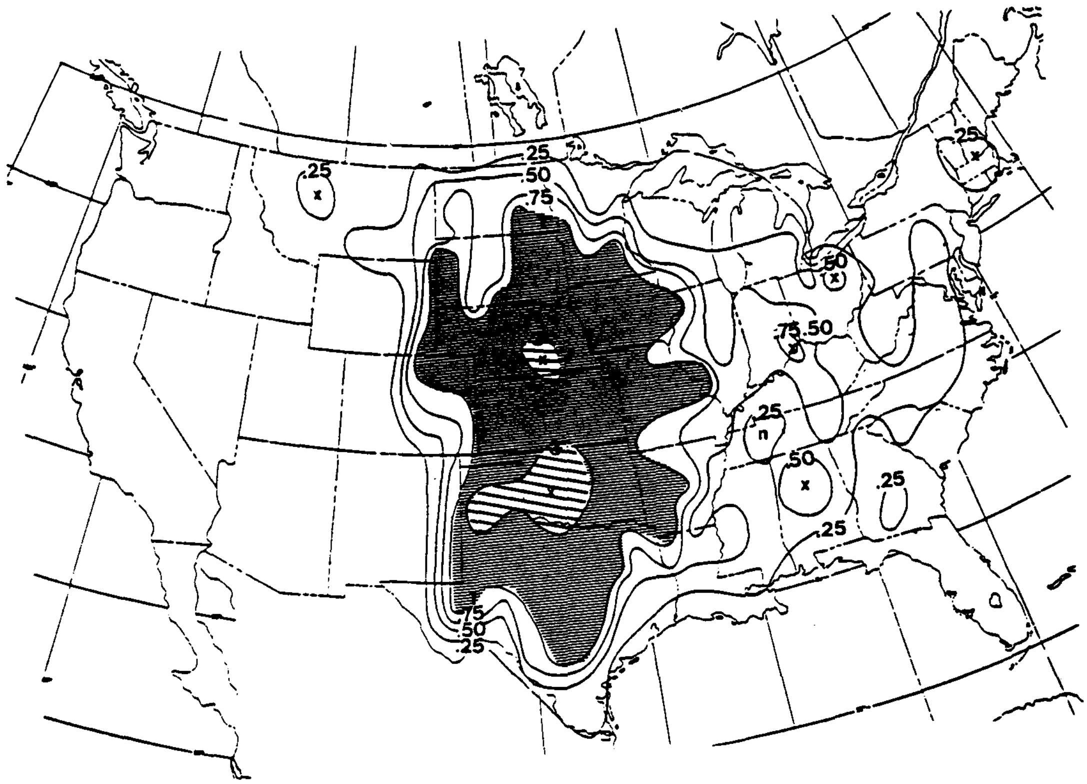

FIG. 8. As in Fig. 7 but for 51 mm diameter per 26 000 km² per yr.

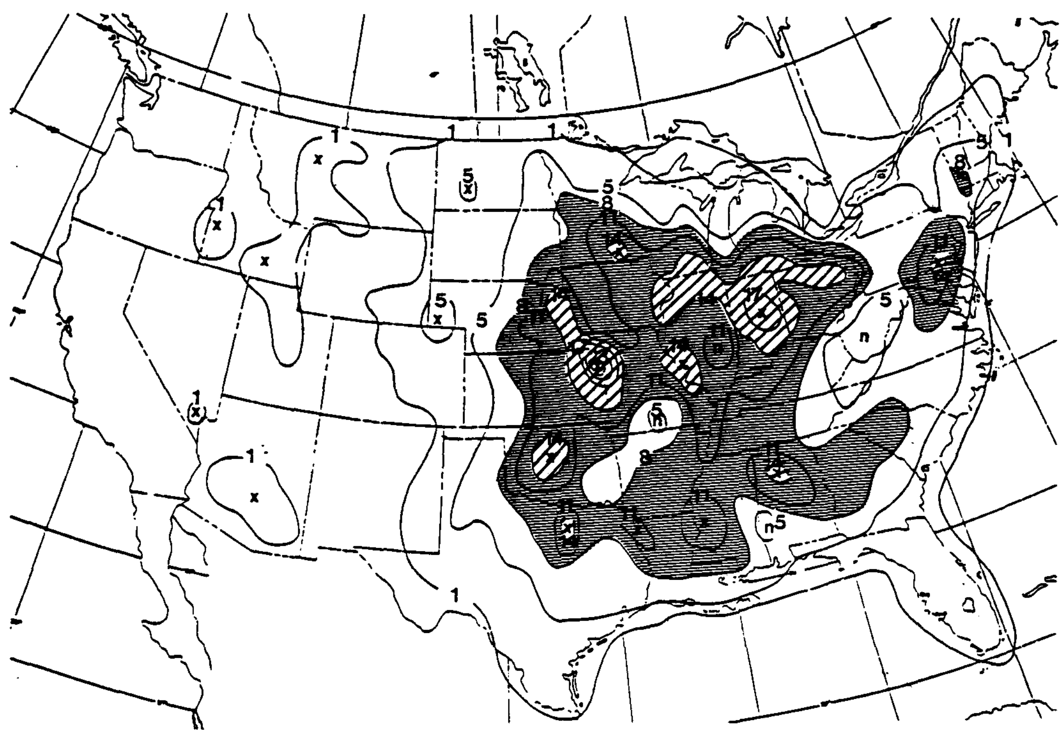

FIG. 9. Frequency of any severe thunderstorm wind occurrence per 26 000 km² per yr.

little imagination, a third axis running eastward from north-central Texas to central Georgia and then northeastward along the lee of the Appalachians to New England can be envisioned. This third zone corresponds to a region of enhanced risk of violent tornadoes (Kelly *et al.,* 1984). Thus, it is not unreasonable to expect severe thunderstorms in these parts of the south and east.

To explain the three axes of enhanced severe thunderstorm gusts, it can be postulated that severe weather occurs rather uniformly across the eastern half of the United States, except in regions of rugged topography. An axis of minimum frequency runs from the Flint Hills of Kansas through the Ouchita range of Arkansas to the Ozark region of Missouri, while a second zone follows the Appalachians northeastward. However, the long tongue of decreased frequency through western Iowa counters such an orographic-based theory.

A relative frequency maximum in severe thunderstorm winds is also present over the Nebraska Panhandle. A large percentage of these reports is associated with wind gusts produced by high-based thunderstorms that are an almost daily summertime occurrence over the high plains (Caracena *et al.,* 1983). These microburst-producing storms are typically the result of relatively weak convection (Brown *et al.,* 1982) and are meteorologically distinct from the hail-producing storms associated with strong convection (Browning and Foote, 1976) that frequent the High Plains region. The Great Plains large hail maximum (Fig. 7) is some 400 km southwest of this wind gust zone which is in the Nebraska Panhandle.

When only measured wind gusts greater than 33.5 m s^{-1} are considered, the pattern becomes much better defined (Fig. 10). The two primary zones of increased frequency seen in the distribution of all wind reports are much more apparent. These two axes are the same as those found by Johns (1982) in his study of severe weather which occurs under northwesterly upper level flow. The axis in the Great Lakes region clearly reflects northwest flow events, which as noted by Johns (1982) have a marked preference for strong gusty winds. However, the Great Plains axis dominates the distribution. The greatest overall severe thunderstorm frequency with respect to tornadoes (except for violent ones), hail, and wind gusts occurs in eastern Kansas, Oklahoma and central Texas. There is also an isolated relative maximum in southeastern Florida. This is noteworthy since most tornado climatologies (e.g., Schaefer *et al.,* 1980) show an enhanced occurrence region in west central Florida. Whether this change from windstorms in the Miami area to tornadoes in the Tampa area is real or a figment of the reporting system remains problematical.

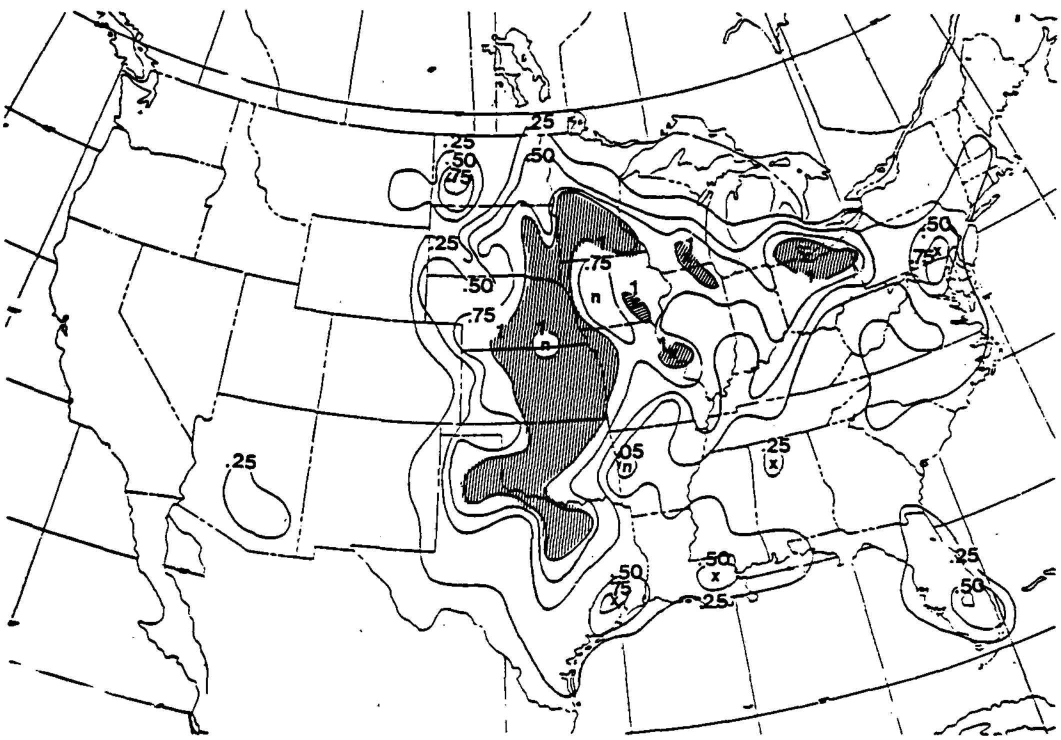

FIG. 10. Frequency of thunderstorm wind gusts greater than 33.5 m s^{-1} per 26 000 km^2 per yr.

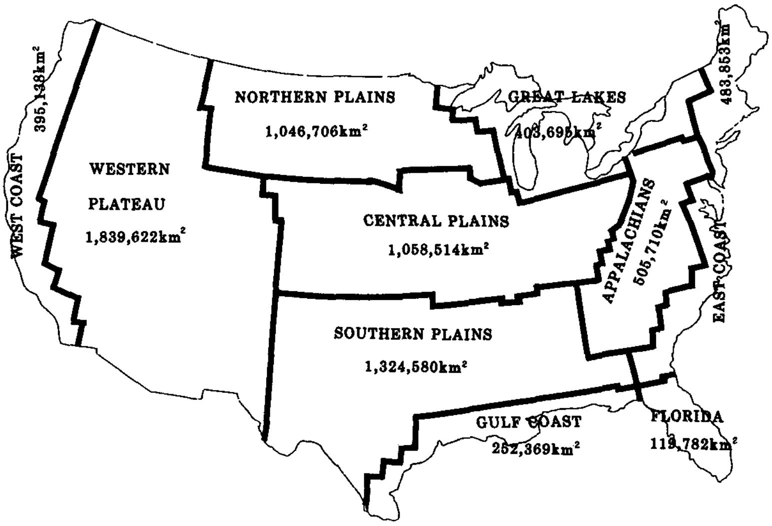

FIG. 11. Climatologically homogeneous regions of the United States.

5. Sectional variations

To seek any significant regional variations in severe thunderstorm climatology, the United States can be subdivided (Fig. 11) into ten climatologically homogeneous regions (Namias, 1978). The type and time (NST) of each severe thunderstorm report were determined within these regions (Table 2). The most active region is the central plains, followed by the southern plains and the northern plains, respectively. The fewest storms are reported along the West Coast, with the penultimate number of events (normalized by areas) occurring over the western plateau. [In a preliminary regionalization reported by Doswell *et al.* (1983), the "north plains" and "south plains" statistics were inadvertently transposed.]

Hailstorms, which on a nationwide basis, are more rare than windstorms, account for a large percentage of the springtime severe weather over the Great Plains. Over 61% of spring events in the southern plains are hailstorms. In the central plains this ratio is 50%, and in the northern plains it is still a relatively high 43%. During summer, the relative distribution of hail and windstorms changes dramatically. The proportion drops to 38% in the southern plains, while in the central and northern plains it is 40% and 41%, respectively.

Spring (March–May) is the favored severe thunderstorm season for only the southern plains and the Gulf Coast regions. Over the remainder of the country, with the exception of the West Coast and Florida, summer is the time of most frequent severe thunderstorm activity. For most regions, both hail and windstorms have the same seasonal peak.

A dichotomy occurs in Florida. Spring is the favored season for large hail occurrence while summer is the principal time for strong thunderstorm-related wind

TABLE 2. Geographic distribution of severe thunderstorm events by season in the United States.

	East Coast	Florida	Great Lakes	Appalachians	Gulf Coast	Northern Plains	Central Plains	Southern Plains	Western Plateau	West Coast
					All hail					
Winter	45 (18)	29 (16)	12 (12)	21 (07)	78 (19)	6 (12)	93 (17)	286 (16)	3 (17)	11 (14)
Spring	576 (15)	270 (15)	514 (14)	345 (16)	602 (16)	577 (15)	4095 (16)	6100 (16)	84 (14)	17 (13)
Summer	906 (15)	177 (14)	1012 (15)	444 (14)	124 (15)	2771 (15)	5431 (16)	2156 (16)	609 (14)	15 (13)
Autumn	64 (16)	23 (13)	121 (18)	47 (16)	38 (13)	143 (17)	680 (17)	566 (17)	76 (15)	6 (14)
					All wind					
Winter	313 (19)	225 (13)	92 (21)	133 (15)	380 (18)	65 (15)	598 (21)	638 (18)	25 (16)	28 (01)
Spring	1319 (16)	449 (15)	965 (16)	725 (15)	960 (14)	775 (16)	4135 (17)	3877 (17)	149 (14)	32 (15)
Summer	3275 (15)	576 (14)	3219 (16)	1688 (15)	626 (14)	3953 (17)	8265 (16)	3542 (16)	1106 (16)	32 (13)
Autumn	443 (18)	115 (15)	347 (18)	240 (15)	244 (12)	330 (17)	1355 (17)	1050 (15)	153 (17)	11 (15)

Note: Figures in parentheses are number of occurrences during 29-year period with NST hour of most frequent occurrence.

gusts. Over Florida, thunderstorms are most frequent during summer (Court and Griffiths, 1982). However, during that season, the atmospheric stratification is too warm to support large hail formation. Thus, in Florida, wind gust occurrences peak with the peak in thunderstorm activity, but large hail (greater than 19 mm) is generally more restricted to the springtime when temperatures aloft are lower. While summer thunderstorms are also the rule over the Gulf Coast region, strongly dynamic synoptic-scale systems traverse the region during the spring, giving rise to the severe thunderstorms. These systems rarely affect Florida. Along the Pacific coast, the sample is too small to draw any conclusions, but spring and summer have virtually the same number of reports.

In each season, peak occurrence is in the afternoon. The only exceptions are in winter. These relatively rare events show little consistency in occurrence time from region to region. However, since thermodynamic instability is a minimum during winter and the storms that do occur seem to derive most of their energy from dynamic effects, the lack of a diurnal dependency for winter severe thunderstorms is not surprising.

The lack of a nocturnal maximum in severe weather activity over the northern or central plains is mildly surprising. Over those regions, summer thunderstorms typically occur at night (Wallace, 1975). Further, thunderstorms there often develop into mesoscale systems which produce long swaths of convective activity before dawn (Maddox, 1980). These data imply that the large majority of severe weather events associated with such mesoscale convective systems (MCS) are produced early in the MCS life cycle, during the daytime.

When the regional hail data are categorized (Table 3), only minor differences between the enormous and giant categories are uncovered. That is, within each region, both giant and enormous hail occur during the same season and at approximately the same time. Enormous hail is rare any place, and is virtually unknown along the West Coast: only four reports of it have been received over this 395 138 km^2 region during the 29 years examined.

Within each region, statistics for the three wind categories (Table 4) are generally quite similar. There are two exceptions. In the southern plains, wind damage peaks in the spring, but strong and violent thunderstorm gusts are most frequent during the summer. Whether or not the springtime damage reports are inflated by misclassified tornadoes is a matter for speculation. Once again, Florida presents a paradox. Wind damage and strong gusts are most prevalent there during summer, but violent gusts (those greater than 33.5 m s^{-1}) are more of a spring phenomenon.

The most striking regional feature in the severe thunderstorm wind climatology is the very early hour favored by springtime storms along the Gulf Coast. The most frequent occurrence for each of the severe wind categories is within one hour of sunrise. Of interest also is that the hour favored by each of the three wind categories individually is earlier than the favored hour when all wind reports are considered together. This is possible because the distributions are multimodal in nature; i.e., they have several relative maxima of the individual groupings superposed and, thus, their sum becomes larger than the sum for any of the hours of the primary maxima. Categorization can distort statistics!

6. Space–time distributions

The regions affected by severe thunderstorms have a very definite annual pattern. Large hail first becomes a significant factor in the "conterminous" United States during April. Each year during this month much of the central and southern plains regions experience over

TABLE 3. Geographic distribution of large U.S. hail events by season.

	East Coast	Florida	Great Lakes	Appalachians	Gulf Coast	Northern Plains	Central Plains	Southern Plains	Western Plateau	West Coast
					Giant hail					
Winter	42 (18)	23 (16)	10 (12)	20 (07)	68 (19)	6 (12)	81 (17)	247 (16)	3 (17)	10 (14)
Spring	519 (15)	246 (14)	454 (14)	296 (16)	534 (16)	493 (15)	3451 (16)	4807 (16)	81 (14)	15 (13)
Summer	815 (15)	166 (14)	908 (15)	380 (15)	112 (15)	2193 (15)	4339 (16)	1710 (16)	513 (14)	15 (13)
Autumn	58 (16)	23 (13)	108 (18)	39 (16)	36 (13)	112 (17)	534 (17)	472 (18)	73 (15)	5 (14)
					Enormous hail					
Winter	3 (15)	6 (00)	2 (16)	1 (01)	10 (16)	0 (**)	12 (18)	39 (20)	0 (**)	1 (15)
Spring	57 (17)	24 (15)	60 (15)	49 (15)	68 (17)	84 (13)	644 (16)	1293 (16)	3 (10)	2 (11)
Summer	91 (15)	11 (14)	104 (15)	64 (14)	12 (13)	578 (16)	1092 (16)	446 (15)	96 (15)	0 (**)
Autumn	6 (15)	0 (**)	13 (16)	8 (15)	2 (13)	31 (15)	146 (18)	94 (16)	3 (06)	1 (14)

Note: Figures in parentheses are number of occurrences during 29-year period with NST hour of most frequent occurrence.

TABLE 4. Geographic distribution of U.S. severe thunderstorm wind events by season.

	East Coast	Florida	Great Lakes	Appalachians	Gulf Coast	Northern Plains	Central Plains	Southern Plains	Western Plateau	West Coast
					Damaging wind					
Winter	259 (19)	167 (13)	71 (21)	93 (13)	297 (18)	40 (15)	492 (00)	526 (18)	15 (16)	14 (01)
Spring	1075 (16)	322 (15)	707 (16)	566 (15)	682 (10)	493 (16)	2804 (16)	2747 (17)	56 (14)	23 (15)
Summer	2659 (15)	379 (14)	2428 (16)	1359 (15)	412 (14)	2427 (17)	5233 (16)	2326 (16)	529 (15)	23 (19)
Autumn	355 (18)	78 (15)	243 (18)	192 (14)	174 (12)	206 (18)	949 (18)	778 (15)	66 (17)	5 (15)
					Strong wind					
Winter	42 (16)	42 (12)	20 (21)	30 (20)	62 (15)	15 (21)	82 (21)	96 (18)	7 (14)	13 (01)
Spring	190 (15)	87 (15)	212 (16)	123 (17)	201 (12)	221 (15)	1050 (17)	852 (17)	82 (14)	7 (09)
Summer	502 (14)	163 (15)	616 (15)	217 (16)	163 (15)	1128 (17)	2322 (16)	886 (16)	461 (16)	4 (12)
Autumn	70 (17)	29 (14)	79 (20)	35 (13)	56 (13)	96 (17)	330 (17)	206 (18)	75 (17)	6 (15)
					Violent wind					
Winter	12 (15)	16 (17)	1 (18)	10 (13)	21 (21)	10 (14)	24 (22)	16 (17)	3 (16)	1 (01)
Spring	54 (15)	40 (14)	46 (17)	36 (14)	77 (13)	61 (15)	281 (15)	278 (17)	11 (13)	2 (00)
Summer	114 (14)	34 (14)	175 (17)	76 (16)	51 (14)	398 (17)	710 (16)	330 (16)	116 (15)	5 (13)
Autumn	18 (16)	8 (16)	25 (15)	13 (13)	14 (01)	28 (20)	76 (17)	66 (18)	12 (15)	0 (**)

Note: Figures in parentheses are number of occurrences during 29-year period with NST hour of most frequent occurrence.

one hailstorm per 26 000 km^2 (Fig. 12a). Further, a rather long narrow area from central Texas northward through Oklahoma to Kansas City experiences over three hailstorms in April. A break in this zone across northeastern Oklahoma and southeastern Kansas exists. While it is tempting to try to account for this break by population density arguments, there are more people living in this region of relatively sparse reports than in the north-central Texas part of the maximum zone. The Ozark minimum, often noted in tornado climatologies, is also very apparent.

During May the pattern remains basically the same (Fig. 12b). However, the hail prone area has expanded both northward into Minnesota and westward into Colorado. Two areas experience an average of over seven severe hailstorms each May. While one of these areas (Kansas City) corresponds to a population center, the other is in the generally rural sections of southwestern Oklahoma. The northward progression of the favored location for large hail continues into the early summer months. In June (Fig. 12c), severe hail ceases to be a factor in south-central Texas, but becomes significant in the Dakotas. The three-storm isopleth for June encompasses the Texas Panhandle, western Oklahoma, Kansas, northeastern Colorado and southern Nebraska. No region has over five storms per 26 000 km^2 during June. While a larger geographic area experiences severe hailstorms during June than during May, the overall frequency of storms is less.

In July (Fig. 12d) Texas (except for a small portion of the Panhandle near Amarillo) and Oklahoma both are relatively hail free. Furthermore, the area experiencing over three storms per year has decreased to two small areas, one in Colorado and the other in Nebraska. The alley of northwest flow activity from North Dakota to Ohio is very well developed. While there was a hint of this feature during June, the decrease in hailstorms across the eastern central plains makes it much more evident in July. As summer ends, so does the large hail threat. During August (Fig. 12e), no three-storm isopleth exists. Further, the one-storm contour has become quite disjointed. The principal threat zone runs essentially north–south from central Kansas to North Dakota.

For the study of monthly variations in the pattern of severe thunderstorm-related winds, attention is restricted to reports with associated wind velocities. This was done in order to get a more homogeneous database than the one containing the rather nebulous "damaging wind" reports. In April windstorms are only a small climatic factor (Fig. 13a). Even at the one storm per 52 000 km^2 level, only a narrow band of occurrence averaging less than 750 km wide and curving from central Texas through central Missouri to Cleveland, Ohio is present. During May (Fig. 13b) severe thunderstorm winds become more frequent, and the zone of activity generally expands. However, over Illinois and Indiana, fewer of these storms occur during May than during April.

Convective wind gust activity continues to increase in the early summer. June (Fig. 13c) has two small areas of over three storms per 26 000 km^2, a much more restricted area than severe hailstorms. Because of this, the effects of northwest flow, severe weather

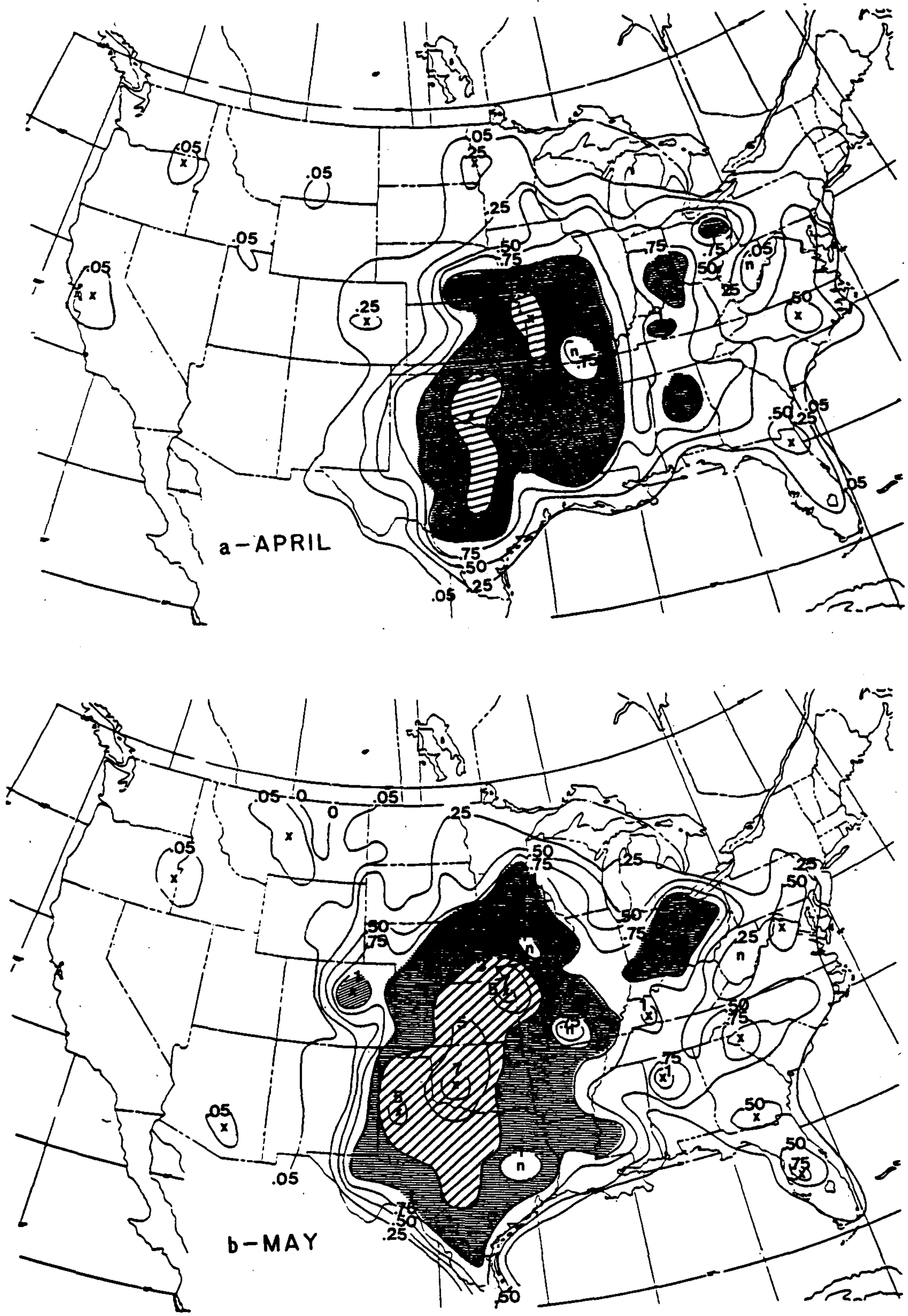

FIG. 12. Monthly frequency of large hail occurrence per 26 000 km² per yr.

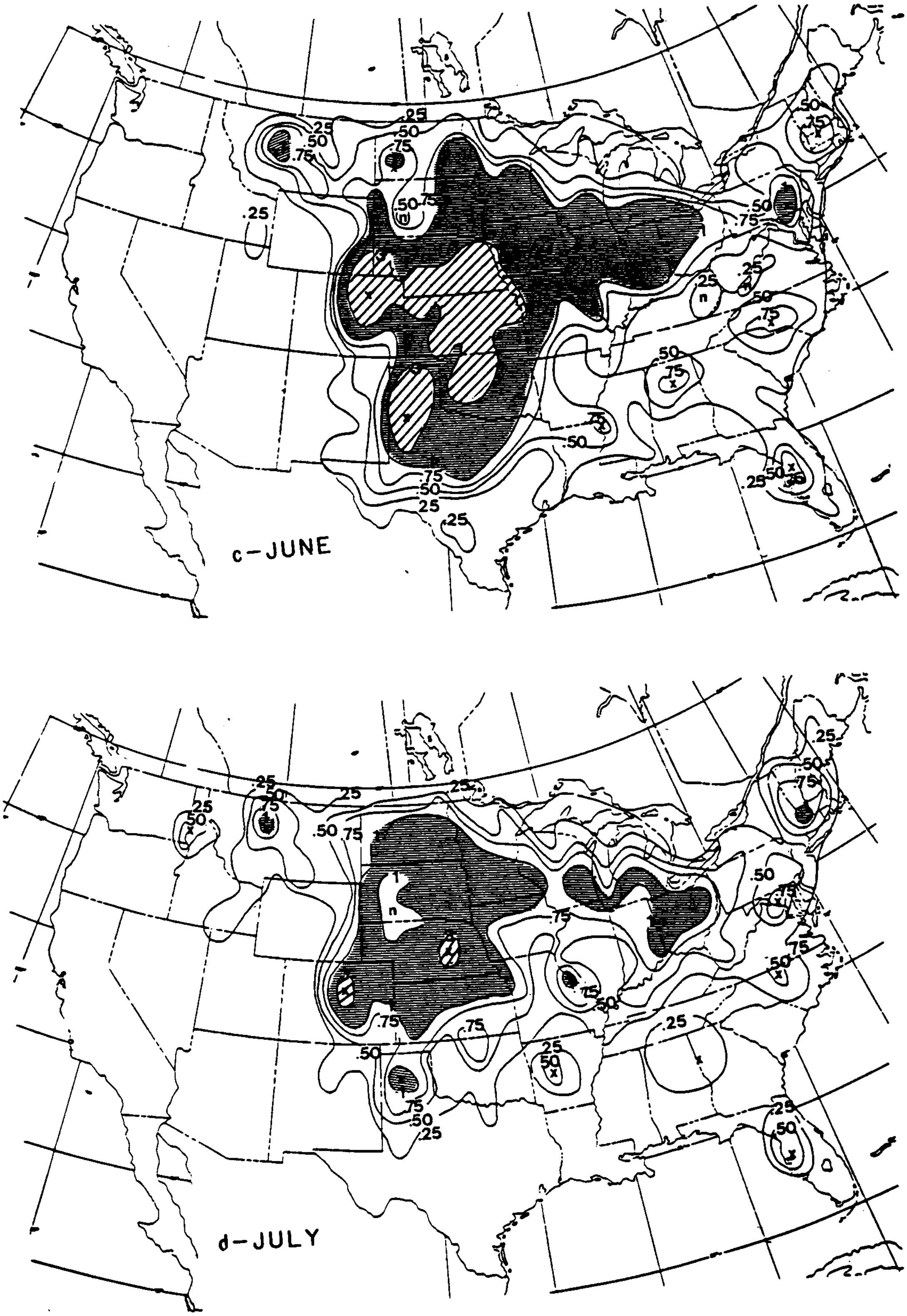

FIG. 12. (*Continued*)

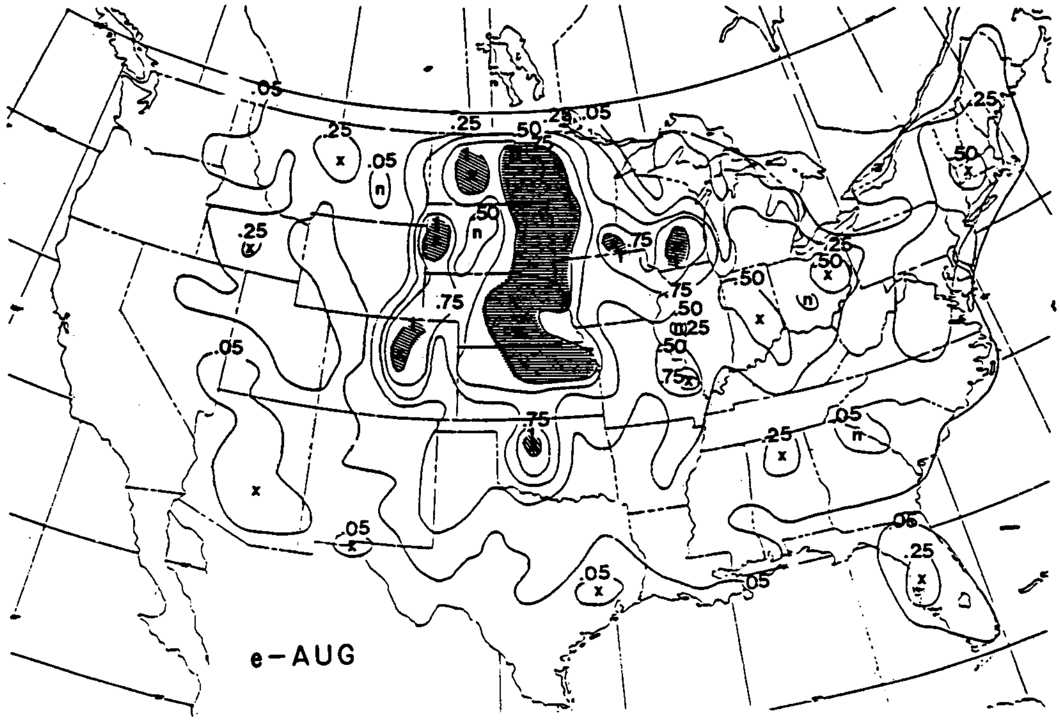

FIG. 12. (*Continued*)

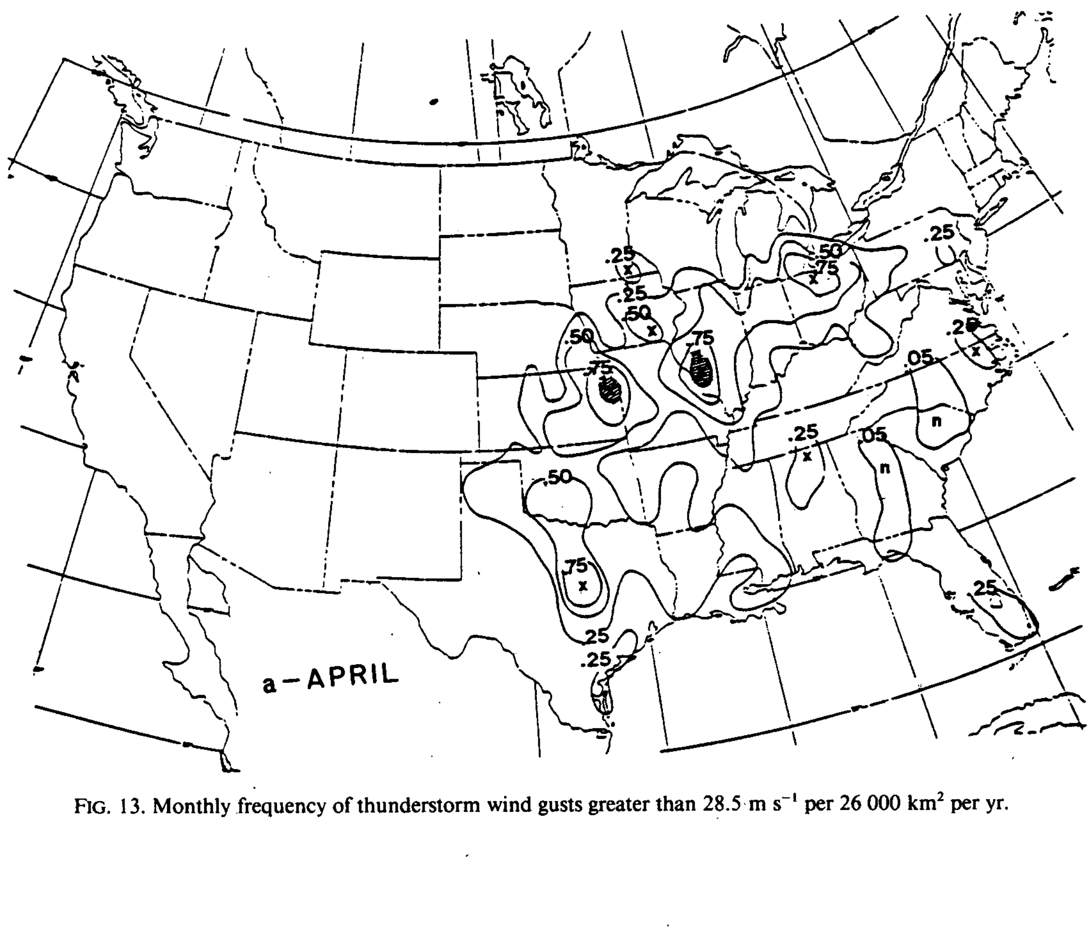

FIG. 13. Monthly frequency of thunderstorm wind gusts greater than 28.5 m s^{-1} per 26 000 km^2 per yr.

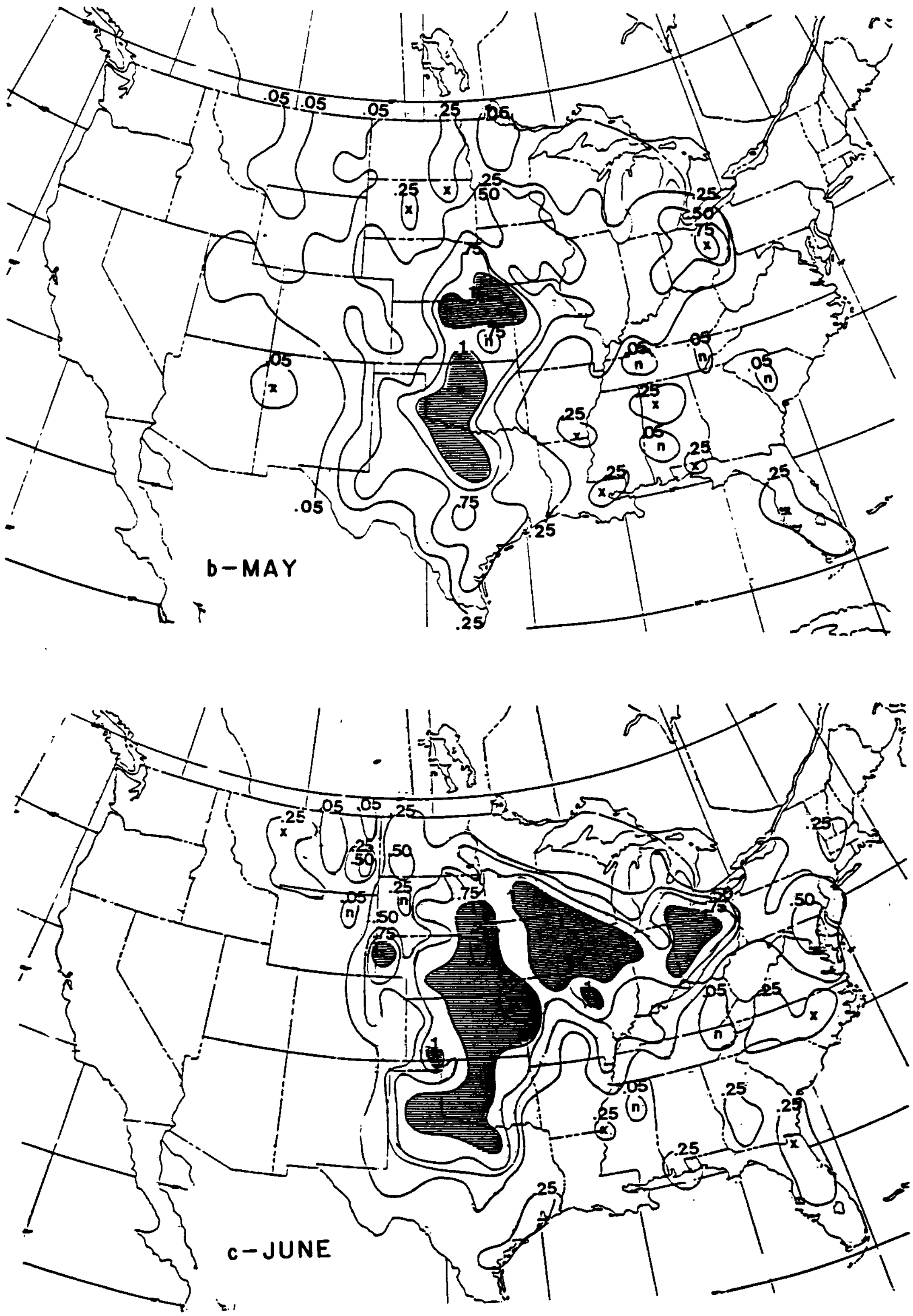

FIG. 13 (*Continued*)

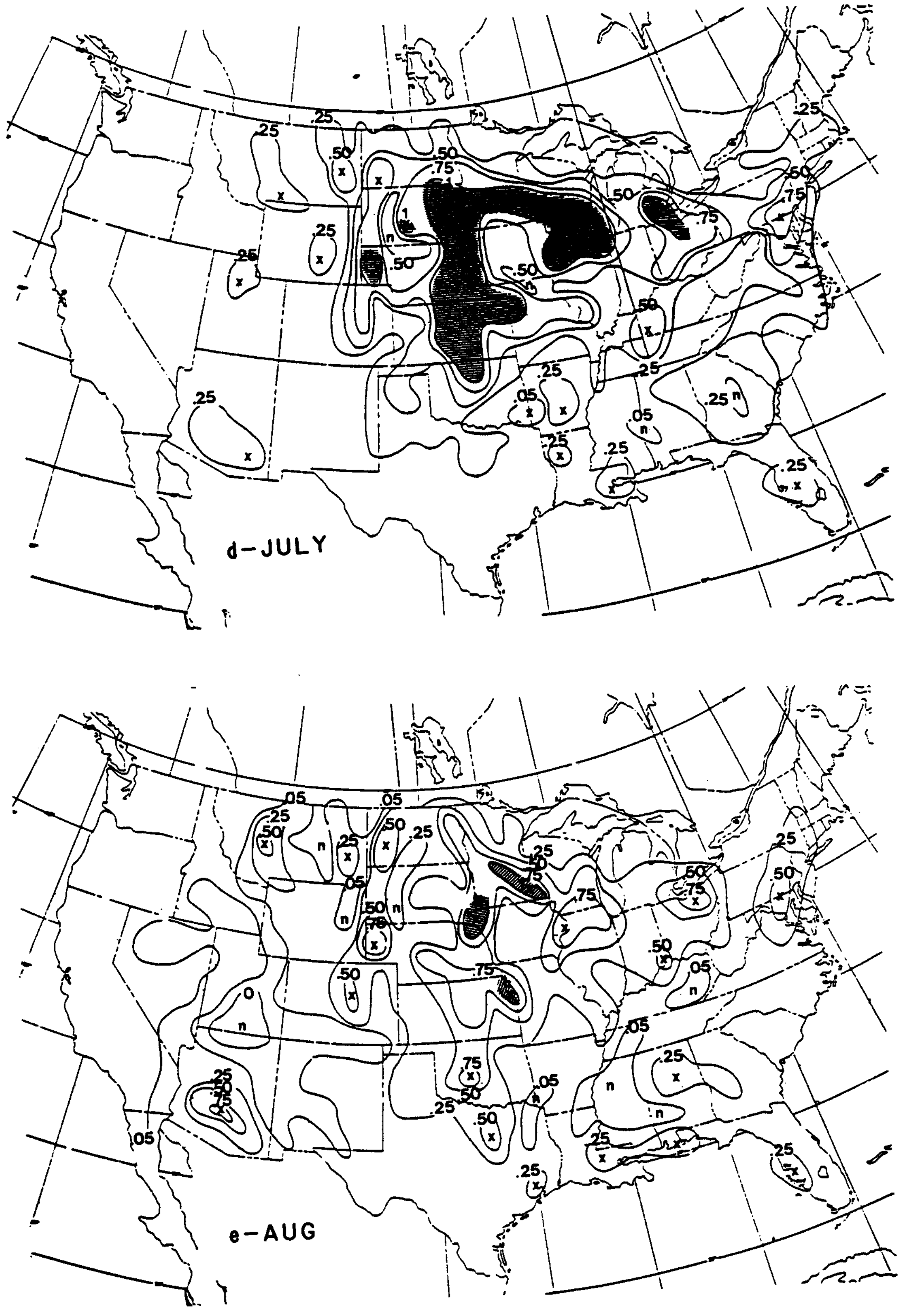

FIG. 13. (*Continued*)

outbreaks are more apparent in the June wind gust climatology than in the hailstorm one. Also, it should be noted that the maximum zone of relative frequency for wind gusts in the Nebraska Panhandle lies significantly north and east of the Colorado hail maximum.

A definite northward shift in the occurrence pattern takes place during summer. Oklahoma storms become quite rare during July (Fig. 13d). Furthermore, the zone of lessened activity, which was in Missouri during June, has expanded to include most of Iowa. By August (Fig. 13e) only three very small areas are affected by severe thunderstorm gusts. The principal zone of activity is in southern Minnesota. The effect of the moisture carried northeastward into Arizona from the Gulf of California by the summer monsoon (Hales, 1972) is seen by the development of a relative maximum of significant amplitude along the Phoenix–Tucson corridor.

These two sets of charts summarize very nicely the nuances of the nontornadic severe thunderstorm climatology of the conterminous United States. The climatology, imperfect as it might be, serves two purposes. On a practical level, it gives some guidance to operational meteorologists and meteorological technicians who must forecast and warn for such storms. On a theoretical level, it poses some interesting, relevant questions for storm dynamicists.

The purpose of our analysis and this paper is to suggest basic principles to guide operational decisions. In line with Clausewitz (1832), ". . . We would emphasize the essential and general; leave scope for the individual and accidental; but remove everything arbitrary, unsubstantiated, trivial, far-fetched, or supersubtle. If we have accomplished that we regard our task as fulfilled."

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