Climatography of Thunder Events in the Conterminous United States. Part I: Temporal Aspects

STANLEY A. CHANGNON, JR.

University of Rochester, Rochester, New York*

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ABSTRACT

Average durations of thunder events are greatest (>120 min) in the Oklahoma–Kansas area and least (<60 min) along the west coast and northeast. The average point duration of thunder activity ranges from 10 000 to 12 000 min along the Gulf Coast, 8000 to 10 000 min in the Midwest, exceeds 6000 min in Arizona, but is only 1000 to 2000 min in the northeast, and 500 to 1000 min along the west coast. Nocturnal thunder events typically last 10 to 30 min longer than those in the daytime in all areas except for the western mountains and extreme southeast where daytime events exceed those at night by 5 to 15 min, on the average.

The trends in thunder event activity during the 1948–77 period indicate four distinctly different characteristics. The stations in the southwestern and northwestern United States exhibit flat, unchanging trends in events during the 30 years, but events in the northern Great Plains–Midwest gradually decreased with time; those in the Great Lakes increased since 1950; and those in the southeastern United States decreased to minimums in the 1960s and then increased to 1977. The temporal distribution of extratropical cyclonic activity in July explains 25% to 50% of the temporal variations in July thunder events over most of the central and eastern United States. However, increases in thunder events since the late 1960s in the Upper Midwest and along the East Coast were not associated with increased cyclonic activity.

1. Introduction

Prior studies of the climatology of thunder days (a 24-h period with one or more peals of thunder) revealed considerable temporal variations in different parts of North America during the 1901–80 period (Changnon 1985). However, a thunder day provides only a minimal description of the thunderstorm activity that occurred in any given 24-h period. A thunder day can range from one peal of thunder lasting less than one minute, up to many hours of thunder and several discrete periods of thunderstorm activity. Regardless, studies of thunder days were pursued because they represent the only historical records of thunderstorm activity before 1940, and thus allow analyses of relatively long-term temporal fluctuations since 1901.

As part of further investigations of the temporal climatology of thunderstorms in the conterminous United States, it was decided to examine several aspects of the thunder event climatology. Changery (1981) utilized the 1948–77 station data on thunder events (labeled as "thunderstorms") to define their annual and monthly average frequencies. Easterling and Robinson (1985) used the same data to examine certain aspects of the diurnal variations in thunderstorm activity. Information on the incidence of thunder events has also been used to assess the risk of thunderstorm and lightning damage to structures (Changery 1981).

This climatography of the thunder events examines two major aspects. Those relating to the temporal aspects are addressed in this paper, and those relating to the spatial aspects are in the companion (Changnon 1988, henceforth referred to as Part II) paper. The first section herein examines the duration of thunder events, and the second section addresses the temporal trends over the 30-yr study period in the frequency of events. Finally, the temporal frequencies of events in July are compared with frequencies of cyclonic activity across the nation.

2. Thunder events: data and definition

At each of the first-order stations (FOS) operated by the National Weather Service (NWS), the times thunder begins and ends have been recorded since the 1940s. The NWS rules of observation state that the time of beginning is based on the first peal of thunder heard by the weather observer at the FOS. As long as thunder was heard thereafter and occurred within periods no longer than 15 min, the thunder period was defined as continuing. The time a thunder period ended was 15 min after the last peal of thunder. For example, if the weather observer at Little Rock first heard thunder at

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* Also affiliated with the Illinois State Water Survey.

Corresponding author address: Dr. Stanley A. Changnon, 801 Buckthorn Circle, Mahomet, IL 61853.

1602 LST, that time was entered in the records as the beginning of a thunder period. In this example, let us assume that thunder occurred every few minutes thereafter until 1708, the time of the last peal of thunder. Fifteen minutes thereafter, or at 1723, the records would show the "end" of the thunder period. In this fictional instance, the thunder period (event) would be entered as 1602 to 1723. It was also conceivable that a new thunder period could begin at 1724, and on many days, FOS records reveal that two, three, four, or even five thunder periods were recorded. In this study, these periods are also called events.

The National Climate Data Center had searched the written records of the U.S. first-order stations and extracted all the thunder period data for 1948–77 (Changery 1981). These data were procured and used in this study. A total of 152 first-order stations distributed across the conterminous United States were chosen for this analysis (Fig. 1). Each station had complete data for 1948–77. At each station, the 30-yr values of thunder days and thunder events were compared on a monthly and annual basis to determine ratios. The thunder event frequencies were used to calculate monthly and annual averages. The listed durations of all events were combined to yield 30-yr totals for night hours, day hours, and all hours. These in turn were used to calculate monthly and annual averages, and the totals were divided by 30-yr event totals to obtain averages per event. All patterns (maps) were drawn based on linear interpolation between the point values of the 152 FOS.

3. Duration of thunder events

The durations of thunder events were investigated and Fig. 2 is based on the average number of minutes with thunderstorms. The pattern reveals maxima ($>10\,000$ min yr^{-1}) in the Great Plains and in the southeast where both the number of events is high (see Fig. 1 in Part II) and the average event durations tend to be extensive (Fig. 3). The range in extreme values across the United States is considerable, ranging from more than 12 000 min yr^{-1} along the west coast of Florida, to less than 1000 min of thunderstorms along the west coast, and to less than 2000 min in the northeast.

Figure 3 displays the average annual point duration of thunder periods showing peaks of more than 120 min (2 h) in the central Great Plains and in northern Arizona with lesser values radiating out in all directions. The lows in the annual averages are found in the extreme northeast (<60 min), and along the west coast where thunder events have typical durations less than 40 min, or one-third those in the Great Plains. A lesser point duration can relate to several factors including the possibility that in areas with shorter events, storms move faster, storms have smaller areal dimensions, and/or storm producing systems have fewer storms. The area of high event frequency found in the southeastern United States (Gulf Coast and Florida, as shown in Fig. 1 of Part II) is not an equally strong maximum in the duration values, likely reflecting the fact that storm events are often a result of local heating and/or

FIG. 1. First-order stations used in study.

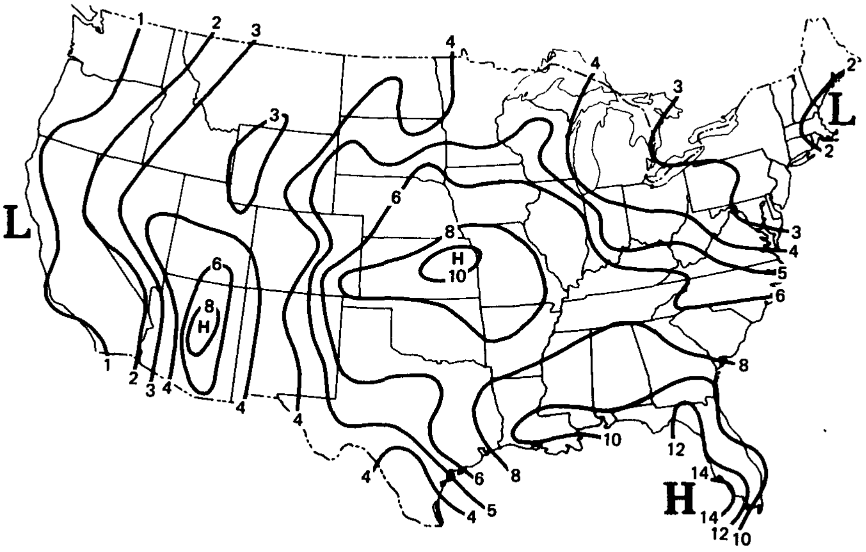


FIG. 2. Average annual number of minutes (in thousands) with thunder.

sea breeze induced convergence which are effects greatly reduced once the initial thunderstorm/s are induced, which in turn cuts off heating and alters the mesoscale flow fields.

Monthly average durations for selected months typical of the four seasons are shown in Fig. 4. The February pattern shows the longest durations in the southern Mississippi Valley which relates well to the area of greatest event incidence (see Fig. 2b, Part II). In May (Fig. 4) the event duration pattern has a maximum > 120 min in the central Great Plains and a maximum in Arizona (>100 min). However, average durations in May are less than 60 min in the northeast and the far west.

In July (Fig. 4) the peak of durations remains in the central Great Plains. Although a high incidence of events exists in southern Florida in July (Fig. 2f, Part II), this is not an area of extensive event durations, as shown in Fig. 4. The October (Fig. 4) values show maximums remaining in the southern Great Plains and in Nevada–Arizona. Elsewhere, average values have greatly decreased from those in July.

A further understanding of thunder events, as defined by point measurements, comes from a comparison of the average monthly event frequency (see Fig. 2, Part II) and their duration frequencies (Fig. 4). Event incidences and durations are both high in the Great Plains, although not exactly in the same locales. Both

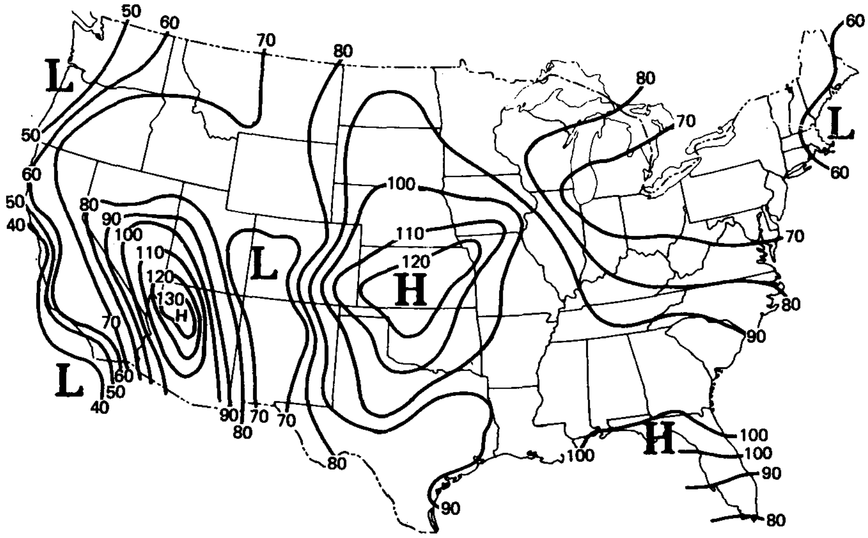


FIG. 3. Annual average duration (minutes) of thunder events.

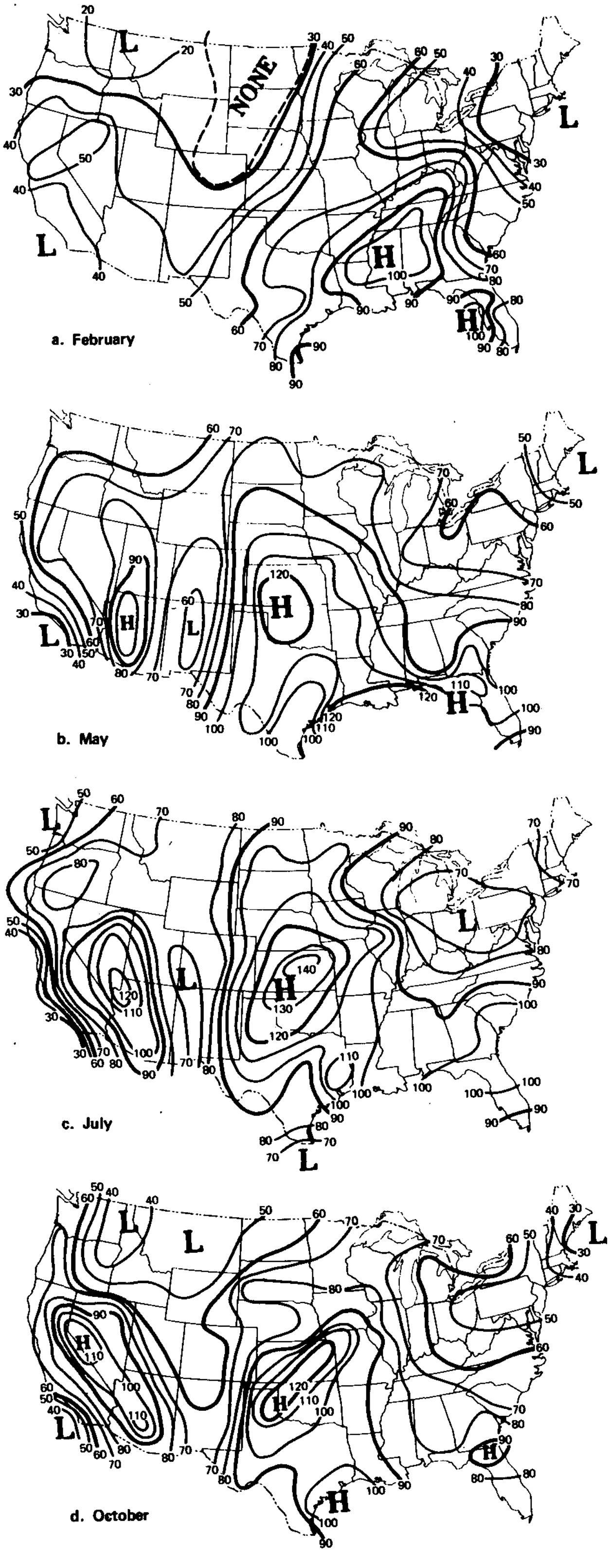


FIG. 4. Average duration (minutes) of thunder events for selected months.

events and their durations show a minimum along the extreme west coast and in the northeastern United States. Although events peak in Florida, the durations do not. Durations are long in Arizona and Nevada in summer and fall, but events there do not attain a comparable maximum.

The durations of thunder events were assessed for the daylight hours (0600–1800) and for the nocturnal hours (1800–0600). This 12-h basis of separation includes a few nocturnal and daylight hours in each sample depending upon season, but these differences were ignored in this investigation. Easterling and Robinson (1985) examined the diurnal distributions of initiations of thunder events, and defined nine regions in the United States, each with different distributions.

Annual and monthly duration averages of the daytime and nocturnal periods were compared. The longest annual average duration occurs at night at most U.S. locations (Fig. 5). These findings agree with those on the start times of events (Easterling and Robinson 1985; and Wallace 1975). Most thunder events occur in summer months (see Fig. 2, Part II), and the well-noted nocturnal maximum of summer convection in the central United States related to the low-level jet (Pitchford and London 1962) produces the nocturnal peak in thunder durations across the central United States (Fig. 5). The areas with daytime maxima are in the intermontane region and adjacent Rocky Mountains, and in the extreme southeastern United States. However, the differences in the averages in the southeast are slight, daytime being 6 min longer at Columbia (SC), 5 min longer at Augusta (GA), and 14 min longer at Miami (FL). Similarly, in the intermontane area, the average daytime values exceed nocturnal averages by 5 to 10 min at most locales. In the areas where nocturnal averages are greater, the differences are typically 10 to 30 min (longer at night).

The patterns based on the average annual durations of thunder events for daytime (Fig. 6), and nighttime (Fig. 7), reveal similar features. Thunder events in both periods are longest in the Great Plains. This is also an area of maximum thunderstorm frequency (U.S. Weather Bureau 1947). The day and night patterns show a sharp decrease in duration of events eastward, achieving a major low in the northeastern United States where average durations are less than 70 min. The patterns differ in the southeastern United States, an area of daytime maximum and a nocturnal minimum, reflecting the effects of daytime convective heating. In both periods, there is a major low in thunder event durations along the west coast.

The average night and day durations per month were also compared. Basically, night values exceeded daytime values in most months. The only stations where daytime averages exceeded nighttime averages in more than 6 months (out of 12) were those in Florida, Augusta (GA), and San Diego (CA).

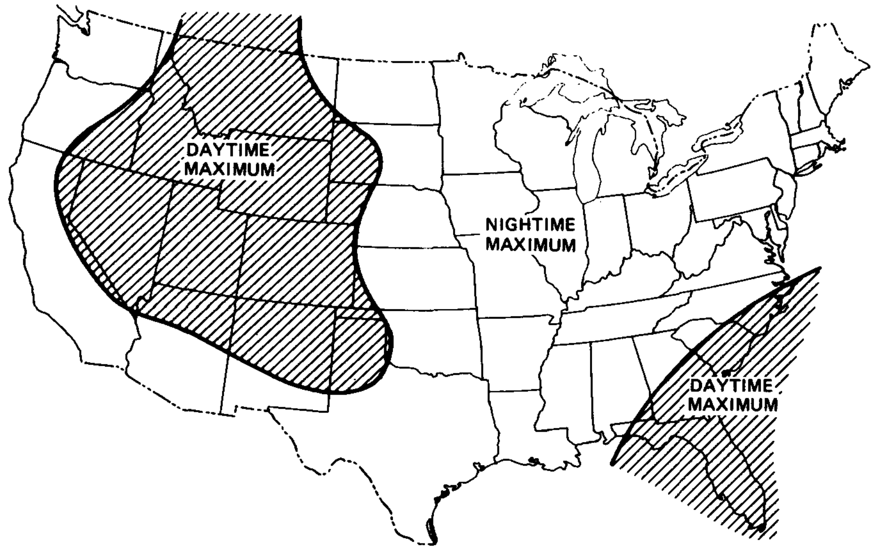


FIG. 5. Areas where daytime (06–18) and nighttime (18–06) thunder events are longest, on the average.

4. Temporal fluctuations of thunder events

A 30-yr period of thunder events was not considered sufficiently extensive to make an in-depth statistical analysis of trends in thunder event activity. Interest in the temporal fluctuations, however, dictated an analysis of the general trends displayed by the 30-yr values. Graphs based on the annual frequencies of thunder events at each FOS were prepared and tests were made of the trend that best fit the data. Each was examined and found to be in one of five possible general classes: 1) a flat linear trend (defined as 5% or less change in events from 1948 to 1977); 2) a general downward linear trend (>5% downward shift) in events over the 30 years; 3) a general upward linear trend (>5% up shift) in events over 30 years; 4) a hump-shaped curvilinear trend with a peak in the middle 10 years (1958–68); or 5) a U-shaped curvilinear trend with a minimum in the middle 10 years.

Examples of the four trends found are displayed in Fig. 8. These are based on the annual values and shown are the annual values and the linear or curvilinear trend

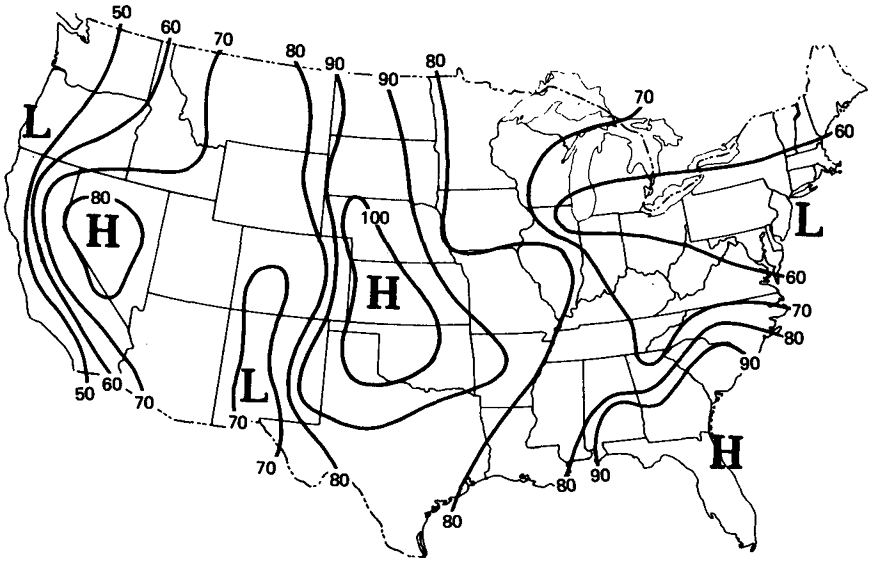


FIG. 6. Annual average duration (minutes) of thunder events in daytime (06–18) hours.

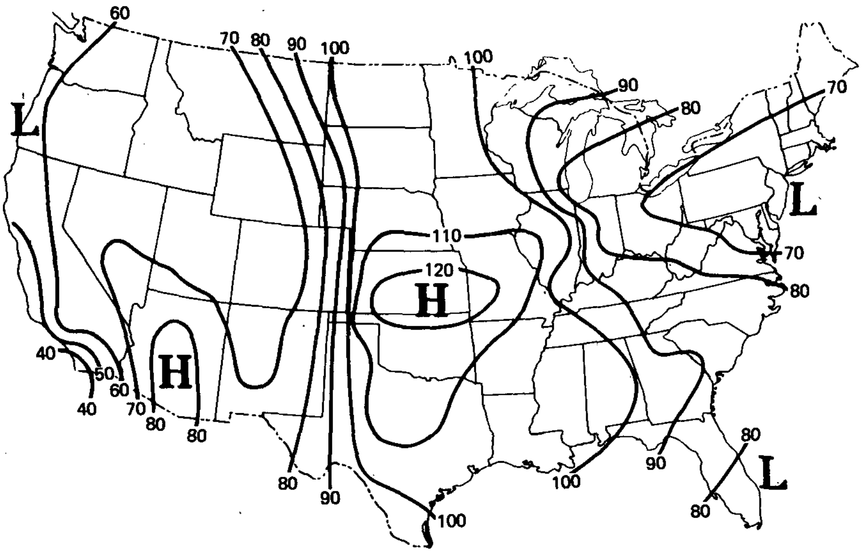


FIG. 7. Annual average duration (minutes) of thunder events in nighttime (18–06) hours.

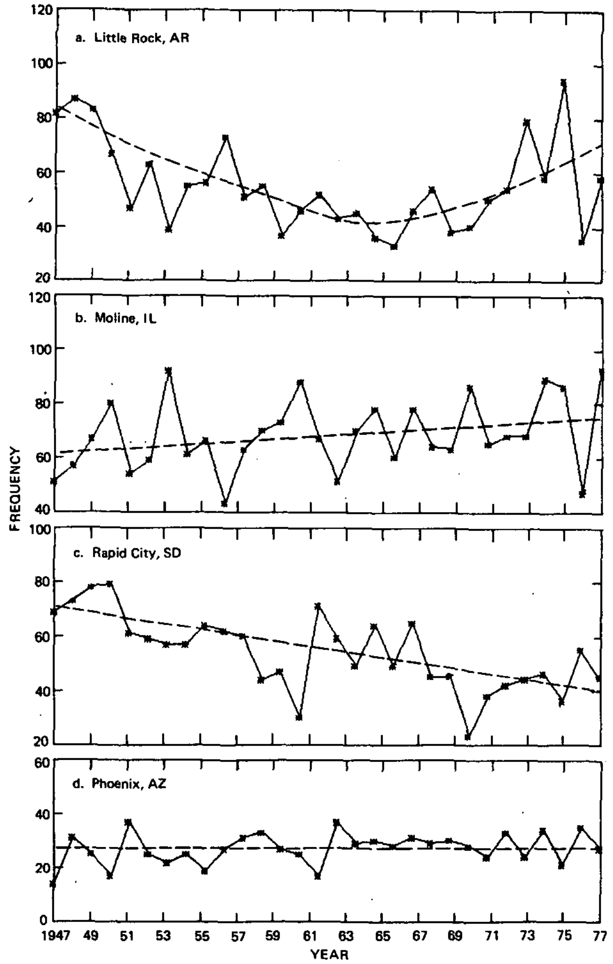


FIG. 8. Annual frequencies of thunder events at selected stations and the linear or curvilinear trends with the best fit to the date (dashed line).

determined as providing the best fit. Little Rock shows a downward trend in thunder events for 1948–60, a low in the 1960s, and then an upward trend to 1977 to illustrate the U-shaped trend. Moline values show a general upward trend over the 30 years. Rapid City (in the northern Great Plains) shows a continuous downward trend, whereas Phoenix shows a flat temporal distribution. The hump-shaped trend was not found at any station.

These classifications of trends found at 152 FOS were plotted. This indicated five regions existed in the United States (Fig. 9). The western and southwestern United States had a "flat trend" of events during this 30-yr period. The stations in the central and northern Great Plains exhibited downward trends, whereas stations in the Upper Midwest showed upward trends. In the southeastern United States, the stations showed a down-then-up curvilinear trend. Lowest values typically occurred in the 1960s with an increase since 1970. These trend results relate well to findings from an analysis of trends in thunder days for 1901–80 (Changnon 1985). Reitan (1979) showed that cyclone frequencies had decreased across the conterminous United States during the 1949–76 period and this agreed with the downward trend in thunder days.

5. Thunder events and cyclones in July

The temporal distributions of thunder events were investigated as to possible causation. The types of fluctuations found to have 10- to 30-yr durations (Fig. 8) may occur for two reasons. First, the fluctuations may be a consequence of searching the historical record a posteriori for an unusual sequence of events. In this instance, any clustering of anomalous years to form multiyear fluctuations may be a chance event unrelated

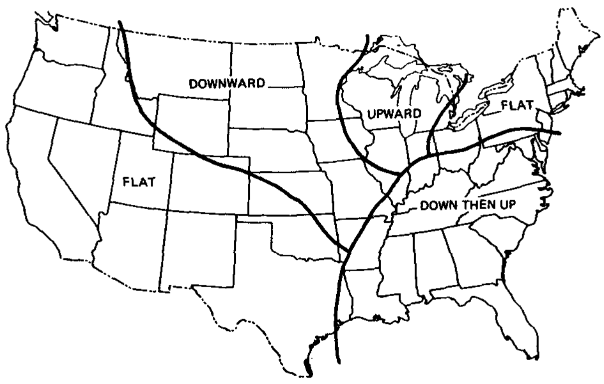


FIG. 9. Areas of similar trends in annual frequencies of thunder events during the 1948–77 periods.

to any climatic forcing. Or, there may exist physical mechanisms in the climatic system causing short-term fluctuations. Zishka and Smith (1980) identified and analyzed all extratropical cyclones in North America for the 1950–77 period. The number of "cyclone centers" in each year were counted for each square formed by 2 deg latitude and 2 deg longitude, based on study of 6-h pressure patterns. These grid square frequencies formed the basis for a comparative study with July thunder event frequencies from FOS for this same 28-year period which encompassed most of the 30 years of thunder event data. It should be recognized that other atmospheric conditions such as local heating, topography, tropical depressions, MCCs, and sea-breeze induced convergence are responsible for considerable thunderstorm activity in various parts of the United States during July. However, the extratropical cyclone data were the only available atmospheric data with sufficient length to examine for temporal relations.

At each FOS the July thunder event value for each year was listed along with the number of cyclones occurring in the 2° by 2° square where the FOS was located. The pattern of average cyclone frequencies based on the grid values determined for each FOS appears in Fig. 10a. No cyclones occurred in the southwestern third of the United States; hence temporal fluctuations of thunder events in this area could not be explained by extratropical cyclonic fluctuations. Taylor (1986) illustrated a bias in gridded cyclone frequencies revealing that counts in more southerly latitudes may be off by up to 14%. This bias is not considered sufficient to affect the July pattern (Fig. 10a) in any major way since July incidences are very low in the southern grid sequences.

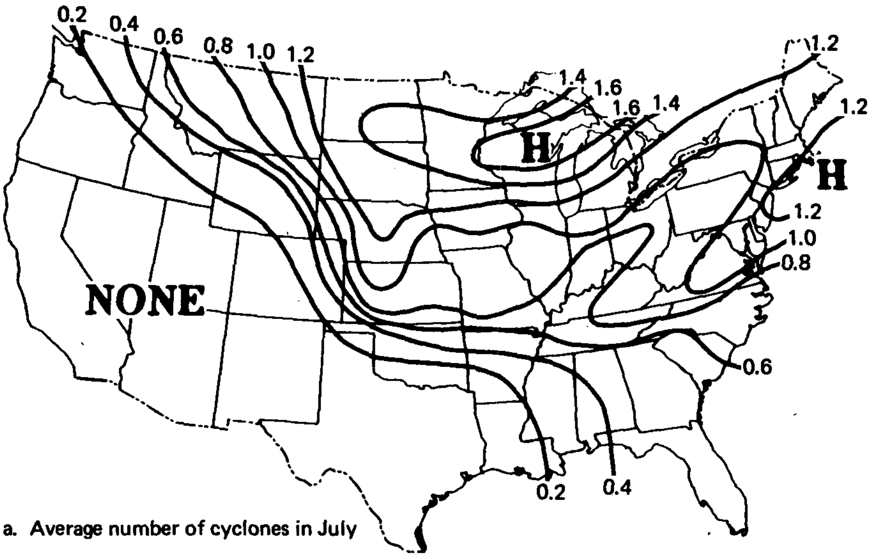
The July average cyclone pattern (Fig. 10a) has a steep south-to-north gradient extending along an axis from Montana to Alabama. A zone of maximization begins in the Dakotas and extends eastward across the Great Lakes indicating some cyclogenesis and a preferred July storm track which agrees with Reitan's (1974) findings on primary cyclone tracks. Evidence of cyclogenesis is also apparent along the East Coast, beginning in the Virginias, in a sector of major cyclogenesis noted by Whittaker and Horn (1981). The interannual variability of July cyclones in a given grid square is high; most FOS had standard deviations for cyclones that exceeded their average values. Those stations where the annual average was greater than their standard deviation were generally those in the north where the July cyclone average was one or more (see Fig. 10a).

The average frequency pattern of thunder events in July (see Fig. 2g, Part II) displays two major highs for the area where cyclonic activity occurs in July. One event maximum is along the lee of the Rockies, and there is a broad high in the southeast. Low thunder event values, on the average, are found in the Great Lakes and New England where the July cyclonic activity is highest. In fact, the July thunder frequency and cyclone patterns (Fig. 2g in Part II and Fig. 10a) do not resemble each other suggesting that the spatial distribution of extratropical cyclones is not a major factor in producing the key features (highs and lows) in the July average thunder event pattern.

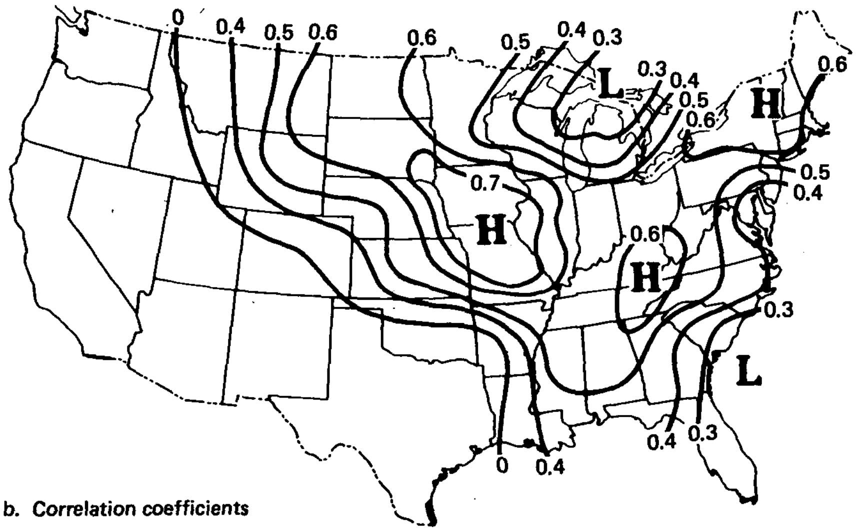
To examine the temporal relationship between thunder events and cyclone frequencies, the 28 pairs of annual values (1950–77) of each FOS were regressed. The resulting pattern based on the simple correlation coefficients of the FOS, appears in Fig. 10b. The pattern shows an area of highest coefficients (> +0.6) in the northern Great Plains and western Midwest, the same area where multiple events per day occur most often (see Fig. 4, Part II). Some stations like Omaha, Moline, and St. Louis had coefficients of +0.7 or higher indicating that the interannual variations in cyclones explained up to 50% of the variations in the thunder events.

The central United States area of strongest cyclone–thunder relationship is in close agreement with the area that experienced downward trends from 1948 to 1977 in annual thunder events (Fig. 9). This suggests that the decrease in thunder events there was largely a result of a temporal decrease in cyclonic activity in that general area. (Since July is the first or second ranked month of thunder events in this area, trends in July events can be expected to be reflected in the annual trends of Fig. 9.) Examination of the cyclone frequencies for the FOS in this central area verified this relationship. The cyclone data from the seven FOS with the highest correlations in this area were averaged for three separate 9-yr periods. Their grid square averages for these were: 13.4 cyclones for 1950–58; decreasing to 9.1 cyclones for 1959–67; and a further decrease to 6.2 cyclones for 1968–76. Whittaker and Horn (1981) revealed comparable decreases in cyclogenesis during 1958–77 in Alberta and the Great Plains where many July cyclones are generated.

The area of lower correlations (coefficients of +0.3 to +0.5) in the Great Lakes (Fig. 10b) is where upward



a. Average number of cyclones in July



b. Correlation coefficients

FIG. 10. Patterns of extratropical cyclones in July and the correlation coefficients based on July cyclones and thunder events, 1950–77.

trends in annual thunder events was noted (Fig. 9). It is also an area of frequent cyclonic activity. However, the poorer correlation in this area occurred because the cyclonic activity decreased with time (like in the Great Plains) but the thunder events increased, particularly in the last 10 years (1968–77). The 9-yr grid square cyclonic averages in this area were 14.5 for the 1950–58; 11.4 for 1959–67; and 9.1 for 1968–76. (Comparable July event averages were 84, 77, and 80). The relative decrease in cyclones was less than in the Great Plains but it was marked. Hence, the recent increase in thunder events in this area had to be the result of other influences on thunderstorm activity, possibly an increase in the MCC frequencies or greater instability on the average. A principal component analysis of 500-mb surfaces over North America for the 1950–80 period revealed that the 500-mb height, in the first component, was lower over southern Canada and Upper Great Lakes Basin, indicating atmospheric instability in that area was increased, whereas it was more stable across most of the United States (Michaels and Gerzoff 1984).

The area with flat (unchanging with time) temporal trends in total thunder events in the northeastern United States (Fig. 9) occurred where correlation coefficients were relatively high, +0.52 to +0.68, as shown on Fig. 10b. Hence, July cyclonic activity explained from 25% up to 46% of the thunder event variations in this area. Cyclone and July thunder frequencies in this area, like thunder events, changed little with time. For example, the Boston grid area had nine cyclones and 65 events in 1950–58; nine cyclones and 54 events in 1959–67; and seven cyclones and 48 events in 1969–76.

The remaining unaddressed area comprising the entire southeastern United States had trends in thunder events that decreased from 1948 into the 1960s, then increased to 1977, as shown in Fig. 9. The cyclone–thunder event correlation pattern for this area is not uniform (Fig. 10b) with relatively low (+0.3 to +0.4 coefficients) along the coast from Georgia to New Jersey, and higher coefficients, +0.4 to +0.6, elsewhere. Thus, cyclonic activity from 1950 to 1977 explained between 10% and 36% of the time variations in July thunder events in this area. In the area of > +0.4 coefficients, the cyclonic frequencies, like July thunder events, decreased from 1950 to low values in the 1960s, then increased to higher values in the 1970s. The 9-yr average grid square frequency (based on those at six FOS in this area) was 7.0 cyclones in 1950–58; 4.6 cyclones in 1959–67; and increasing to 5.8 cyclones in 1968–76. However, in the area of lower correlation coefficients along the Atlantic Coast, the frequency of cyclones showed a decrease into the 1960s then no further change with time. The "point" averages of cyclones and thunder events, based on FOS values of grid squares for cyclones, for 1950–58 were 11 cyclones and 31 thunder events; both decreasing to 6.2 cyclones and 28 events in 1959–67; but changing in 1968–76 with cyclones remaining at 6.2 with thunder events increasing to 33 in this 9-yr period. In essence, the thunder events along the coast increased with time from the late 1960s to 1977, but the cyclones did not. Again, average instability likely was greater in this area, and this is supported by the 500-mb height anomalies along the coast (Michaels and Gerzoff 1984).

6. Summary

The average point durations of thunder events vary considerably across the nation. Annually, the lowest values are less than 30 min in the extreme west and the highest more than 120 min in the central Great Plains. Again, the pattern of event durations, like that for event frequencies, shows a major high in the central United States, a high in the Gulf Coast–Florida, and major lows in the extreme northeast and west coast. Thus, conditions conducive to thunderstorm activity are not only infrequent in the west and the northeast, but when they occur, they do not produce extensive or excessive convection with long-lived storms.

The average durations of thunder events also displays a cyclic movement of the peak of activity across the United States comparable to the frequency of events. In the winter months the peak of storm durations is in the Gulf Coast and southern Mississippi Valley, but by May it has moved north and west to the Great Plains. In midsummer the peak in duration is in the Arizona–Nevada region, a result of the southwest monsoon (Bryson and Lowery 1955). In the fall months, the peaks of thunderstorm durations are in the southeastern and southwestern United States.

In most months and most areas of the United States, thunderstorms at night (1800–0600) last longer (10 to 30 min) at a point than those in the daylight hours. However, at points in the intermontane region and in Florida, daytime thunderstorm events, on the average, are longer than nighttime events by 5 to 20 min. Most areas with a daytime maximum are where daytime heating greatly enhances thunderstorm development. In the central United States and East Coast most thunderstorm activity is related to synoptic-scale weather events, and the effect of enhancement of convection at night leads to nocturnal maximum in durations.

A comparison of patterns of extratropical cyclone frequencies in July and thunder events for the 1950–77 period revealed that the major high and low features of their average patterns are not similar. However, examination of their temporal relationships revealed that except for two small areas, the interannual variations in extratropical cyclones in July (a typical summer month) played a major role in determining the temporal fluctuations found in July thunder events. Of course, this pertains only to that area of the continental United States where these cyclones occur in July. During the 1950–77 period, July cyclonic activity systematically decreased over much of the central United States, and as a consequence, thunder event frequency in July (and annually) diminished more than 5% over this area during this 28-yr period. In much of the southeastern United States, July (and annual) thunder events fluctuated like cyclones, both decreasing from 1950 to low values in the 1960s, then increasing into the 1970s. In the northeastern United States July cyclone frequencies were essentially unchanging over the 1950–77 period and thunder events were also stable.

These areas all exhibited correlation coefficients of +0.5 to +0.7 between events and cyclones, indicating cyclonic activity explained between 25% and 50% of the temporal variations in thunder events. However, two areas of lesser correlation existed, one in the upper Great Lakes and the other along the East Coast (Georgia to New Jersey). In both areas thunder events increased in the later part of the 28-yr period, typically from the mid-1960s to 1977, whereas cyclone frequencies remained stable. Other atmospheric conditions affecting thunderstorm development obviously increased in this time period.

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REFERENCES

Bryson, R. A., and W. Lowry, 1955: Synoptic climatology of the Arizona summer precipitation singularity. *Bull. Amer. Meteor. Soc.*, **36,** 329–339.

Changnon, S. A., 1985: Secular variations in thunder-day frequencies in the twentieth century. *J. Geophys. Res.*, **90,** 6181–6194.

——, 1988: Climatography of thunder events in the conterminous United States. Part II: Spatial aspects. *J. Climate,* **1,** 399–405.

Changery, M. J., 1981: National Thunderstorm Frequencies for the Contiguous United States. NV REG/CR-2252, U.S. Nuclear Regulatory Commission, Washington, D.C., 22 pp.

Easterling, D. R., and P. J. Robinson, 1985: The diurnal variation of thunderstorm activity in the United States. *J. Climate Appl. Meteor.*, **12,** 1201–1210.

Michaels, P. J., and R. B. Gerzoff, 1984: Statistical relations between summer thunderstorm patterns and continental midtropospheric heights. *Mon. Wea. Rev.*, **112,** 778–789.

Pitchford, K. L., and J. London, 1962: The low-level jet as related to nocturnal thunderstorms of the U.S. *J. Appl. Meteor.*, **1,** 43–47.

Reitan, C. H., 1974: Frequencies of cyclones and cyclogenesis for North America, 1951–1970. *Mon. Wea. Rev.*, **102,** 861–868.

——, 1979: Trends in the frequencies of cyclone activity across North America. *Mon. Wea. Rev.*, **107,** 1684–1688.

Taylor, K. E., 1986: An analysis of the biases in traditional cyclone frequency maps. *Mon. Wea. Rev.*, **114,** 1481–1490.

U.S. Weather Bureau, 1947: Thunderstorm climatology and thunderstorm rainfall. Hydrometeor. Rep. No. 5, Vicksburg, MS, 147 pp.

Wallace, J. M., 1975: Diurnal variations in precipitation and thunderstorm frequency over the conterminous U.S. *Mon. Wea. Rev.*, **103,** 406–419.

Whittaker, L. M., and L. Horn, 1981: Geographical and seasonal distribution of North American cyclogenesis, 1958–1977. *Mon. Wea. Rev.*, **108,** 2312–2322.

Zishka, K. M., and P. J. Smith, 1980: The Climatology of cyclones and anticyclones over North America and surrounding ocean environs for January and July, 1950–77. *Mon. Wea. Rev.*, **108,** 387–401.