Warm Season Nocturnal Precipitation in the Great Plains of the United States

ROBERT C. BALLING, JR.

Department of Geography and Laboratory of Climatology, Arizona State University, Tempe, Arizona 85287

(Manuscript received 9 March 1985, in final form 24 July 1985)

ABSTRACT

This paper identifies temporal and spatial patterns in the diurnal cycle of hourly warm season precipitation events over the Great Plains of the United States. Results from 30 years of hourly precipitation records from 515 stations indicate that over 60% of all warm season rainfall (≥0.25 mm) occurs at night from southern Nebraska to panhandle Oklahoma and portions of northern Texas. The larger precipitation events (≥2.54 mm) display a much larger region where 60% of the warm season precipitation occurs at night. Harmonic analysis reveals a remarkably uniform longitudinal gradient in the timing of maximum rainfall frequencies across much of the Great Plains. The more precise identification of these spatial and temporal patterns should be particularly useful in 1) assessing the many theories of nocturnal precipitation in the central United States, 2) verifying numerical precipitation models for the region, and 3) generating rainfall forecasts for various times of the day.

1. Introduction

The predominance of warm season nighttime precipitation in the central United States remains one of the most fascinating climatic features of North America. The combination of intense surface heating, relatively high atmospheric moisture levels, and a location well insulated from oceanic influences normally produces a strong daytime maximum in the diurnal rainfall cycle. With maximum warm season precipitation frequencies occurring after midnight in portions of the central United States, the diurnal rainfall cycle and presumably the convective cycle appear to be completely out of phase with the expected pattern. The physical and dynamical complexities of the nocturnal rainfall phenomenon, along with the practical necessity to understand the precipitation processes of the region, continue to attract many investigators to the problem.

The purpose of this paper is to identify the spatial and temporal patterns found in long-term hourly precipitation records for a large number of collection stations in the Great Plains. The identification of these patterns provides the empirical foundation for assessing the many theories proposed to explain the nocturnal regime and the accuracy of numerical models that simulate precipitation in this region. From a far more practical standpoint, forecasters require more explicit rainfall climatologies in the Great Plains to help in preparing precipitation probabilities for various periods during the day.

2. Previous empirical studies

Studies on the diurnal variability of precipitation regimes in North America, and in particular the Great Plains of the United States, appear throughout the twentieth century literature. Hann (1901) concluded that regions of high continentality are characterized by afternoon convective storms throughout the warm season. Kincer (1916) identified an area in the central United States that failed to agree with Hann's generalizations. Kincer found that 60% of summertime precipitation falls between 2000 and 0800 hours in most of Kansas, Nebraska, and Iowa, with 65% occurring during this nighttime period in southern Nebraska and northern Kansas. Limited evidence of the nocturnal rainfall regime in this region was also found in the U.S. Weather Bureau (1941, 1947) tables of rainfall and thunderstorm diurnal variations.

A more detailed study by Means (1944) produced thunderstorm frequencies in hourly intervals over a five year period for Omaha, Nebraska. Thunderstorms were found to be frequent from 1900 to 0600 hours, and surprisingly infrequent throughout the afternoon period. Rasmusson (1971) applied harmonic analysis to thunderstorm data from 294 stations across the United States and found a region in the central United States where a strong nocturnal maximum dominates the thunderstorm pattern from June through August. First harmonic phase angle isolines showed many locations in the Great Plains with maximum thunderstorm frequency occurring after midnight in the summer months.

The most comprehensive and consistent documentation of diurnal variations in frequencies of thunderstorms and precipitation events in the United States was published by Wallace (1975). Harmonic amplitudes and phase angles in the diurnal cycle of frequencies of thunderstorms and precipitation events of various magnitudes were calculated for approximately 100 stations in the coterminous United States. Results in the Great Plains for the June through August period suggested that severe convective storms tend to occur in the early evening, maximum thunderstorm frequency near midnight, while the maximum frequency of all precipitation events generally is several hours past midnight. Wallace argued that this type of empirical research is extremely valuable in assessing the thermodynamical and dynamical controls of summertime convective storms throughout the United States.

Most recent work for the Great Plains documents a strong nocturnal maximum in lightning (Orville, 1981) and heavy rains associated with flash floods (Maddox *et al.*, 1979, 1982; Crysler *et al.*, 1982). Skaggs (1969, 1980) showed that tornadoes and large hail events in the region display maximum frequencies near 1700–1800, thus occurring approximately six hours before the period of maximum thunderstorm frequencies. These empirical research efforts, generally based on a limited number of Great Plains stations, combine to document a strong summertime diurnal cycle of maximum tornado and large hail frequencies in early evening, thunderstorms and heavy rain events near midnight, and maximum frequency of all rain events several hours after midnight. In this study, the substantially increased station density is used to more explicitly define the spatial structure of diurnal patterns in summertime precipitation frequencies in the central United States.

3. Data and methodology

Hourly precipitation data for the period 1948–77 were purchased from the Illinois State Water Survey for over 600 stations in a nine state region of the central United States. The one magnetic tape per state contained the hourly precipitation rounded to the nearest 0.01 inch (0.25 mm). The original sources of these data included the published hourly precipitation records from the first order stations and the weighing rain gauge charts from the second order and cooperative stations. Problems associated with a limited collection period at some sites left 515 stations in the study area for further analysis.

For the six months of warm season (April–September), a total of 2,270,089 actual hourly rainfall measurements were recorded for the 515 stations. Each observation was corrected to True Solar Time (TST) primarily to avoid problems associated with the mountain/central time zone boundary passing through the study area. Artificial longitudinal gradients in the timing of precipitation events of one hour per 15° of longitude are also eliminated by converting all observations to True Solar Time.

A 515 × 24 matrix of precipitation frequencies was constructed from the large array of TST hourly rainfall data. This matrix contained the total number of warm season precipitation events that occurred in each hourly interval at each station. No row in this matrix had fewer than 1000 total occurrences, and every cell in the 515 × 24 matrix contained a nonzero integer. Because this study deals exclusively with the diurnal variance structure of rainfall frequencies, a few missing days or even months do not seriously jeopardize the overall data quality.

A similar 515 × 24 matrix was constructed using the procedures described above for hourly precipitation measurements ≥ 2.54 mm (0.10 inch). This matrix for the larger rainfall amounts contained 705,063 (31.06% of all occurrences) recorded events for the 515 stations over the 30 year period.

Each row (station) in these matrices was harmonically analyzed to obtain a number of important statistics regarding the diurnal variance patterns. The basic equation of harmonic analysis may be expressed as:

$$\hat{P} = \bar{P} + \sum_{r=1}^{N/2} A_r \cos(r\theta - \Phi_r), \qquad (1)$$

where $\hat{P}$ is the estimated precipitation frequency; $\bar{P}$ the average hourly frequency over the N observations (24 hourly intervals) in the data population; r the frequency, or the number of times the harmonic curve is repeated within the basic interval of 24 hours; θ equals $2\pi X/N$ where X is the hour of the day; and Φ_r is the phase angle of the curve. Because a number of other investigators (e.g., Rasmusson, 1971; Wallace, 1975) have documented the dominating strength of the first harmonic in explaining variance in diurnal rainfall patterns in this region, the statistics reported in this study include

1) The time of maximum precipitation frequency in the diurnal cycle determined explicitly from the phase angle associated with the first harmonic. These values are affected by the use of the midpoint in each hourly interval as the time of precipitation occurrences (e.g., 0130 TST represents the interval 0100–0200 TST).

2) The portion of variance, V_r, explained by the first harmonic; V_r equals $A_r^2/2\sigma^2$ where σ represents the standard deviation of the data population.

3) A standardized amplitude A'_r of the first harmonic equal to $A_r/2\bar{P}$. This value is bounded by zero and unity and provides an index of the concentration of precipitation events in the peak period of the diurnal cycle. If the precipitation events are distributed evenly through the 24 hour period, A'_r equals zero. If all events occur in only one of the hourly intervals, A'_r equals one. The computational procedure used in this investigation produces standardized amplitudes that are by definition one-half as large as the values reported by Wallace (1975).

4. Results

The percentage of all warm season precipitation events occurring at night (2000–0800 TST) exceeds 60% in the southern Nebraska, central Kansas, western

Oklahoma,and apparently some portion of northern Texas (Fig. 1). Hebron, Nebraska displays the highest value, 63.2%, in the study area. Surrounding the area of 60% nighttime rainfall is a large region defined by the 55% isoline. The steepest gradient away from the core area of 60% nocturnal rainfall extends westward towards the front range of the Rockies where daytime showers become more common.

The phase angles (interpretated as the time of maximum precipitation frequency of the first harmonic curves) clarify the pattern of precipitation timing in the Great Plains (Fig. 2). Midnight is the hour of maximum rainfall frequency in the central portion of the study area. Nebraska, Kansas, and Oklahoma each display an east–west gradient of approximately 1 h 100 km^{-1} in the timing of maximum frequency. The eastern Dakotas and the southeastern portions of Iowa and Missouri are characterized by stronger latitudinal gradients in the phase angles. Little spatial coherency is found in the timing patterns of Wyoming, the western two-thirds of Colorado, and southern Missouri.

The relative importance of the diurnal cycle, and the associated first harmonic curves, is critical in evaluating the spatial patterns in the timing of precipitation events. The standardized amplitudes of the first harmonic curves are greater than 0.10 throughout most of the region of nocturnal rainfall (Fig. 3). Outside of the area enclosed by the 0.10 isoline, the warm season rainfall frequencies are fairly evenly distributed throughout the 24 hourly intervals. The highest standardized amplitudes, suggesting the strongest modulation in the diurnal cycle, are located west of the area dominated by the nocturnal precipitation regime. The 306 stations within the 0.10 standardized amplitude isoline (Fig. 3) have an average of 80.32% of their variance explained by the first harmonic curve.

The patterns for the larger precipitation measurements of at least 2.54 mm h^{-1} are similar to the patterns for all rainfall events. A higher percentage of large events occurs at night throughout most of the core area (Fig. 4). A small area in southeastern Nebraska appears to have the strongest tendency for the nocturnal maximum. Crete, Nebraska's value of 69.6% was the highest found anywhere in the central plains.

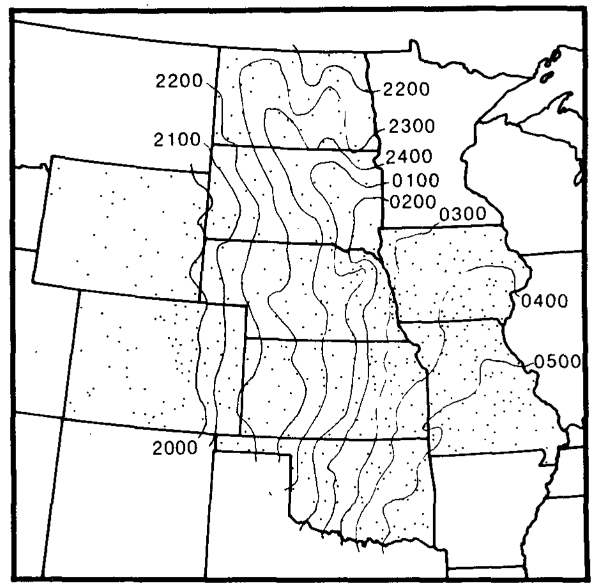

FIG. 2. First harmonic time of maximum rainfall frequency for all events.

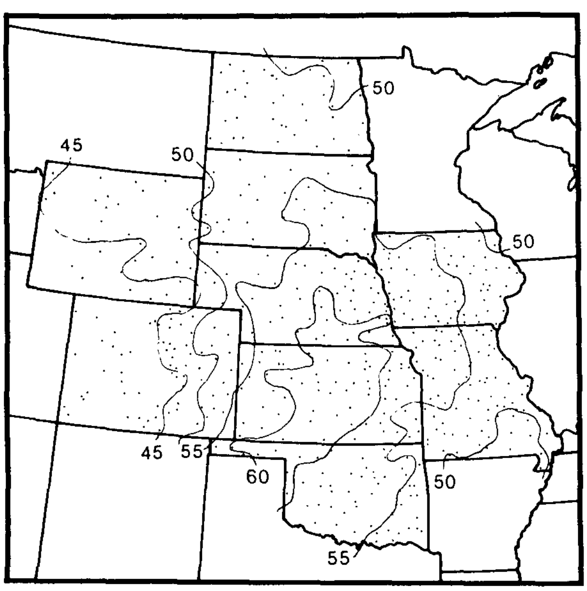

FIG. 1. Percentage of nocturnal (2000–0800 TST) warm season precipitation frequencies for all events ≥ 0.25 mm h^{-1} over the 515 station network.

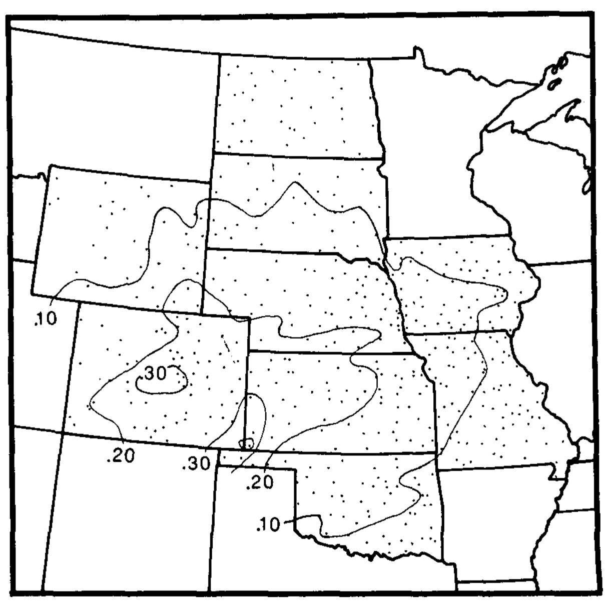

FIG. 3. First harmonic standardized amplitudes for all events.

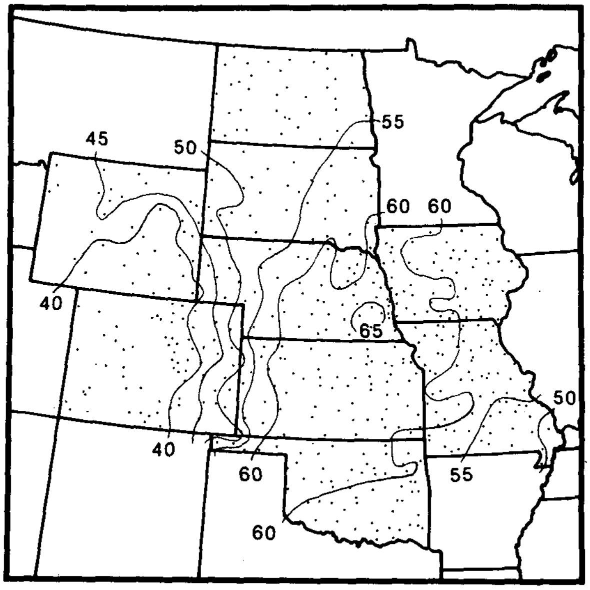

FIG. 4. Percentage of nocturnal rainfall frequencies for events ≥ 2.54 mm h^{-1}.

The first harmonic phase angles suggest a strong east–west gradient of about 1 h 100^{-1} km in South Dakota, Nebraska, Kansas, and Oklahoma (Fig. 5). The east–west gradient does not appear to be the rule in North Dakota, Missouri, and southeastern Iowa. Wyoming and most of Colorado again display a highly variable spatial pattern in the time of the maximum frequencies. These larger precipitation events show a maximum frequency one to two hours earlier than the maximum frequency computed for all precipitation events.

The higher standardized amplitudes for the ≥2.54 mm h^{-1} events suggest a much stronger modulation in the diurnal cycle (Fig. 6). However, the standardized amplitudes for the more intense events are not as large as the first harmonic standardized amplitudes reported for thunderstorms in the region (Wallace, 1975). The strongest modulation in the diurnal cycle of larger precipitation events occurs in southern Colorado, well west of the core area of nocturnal rainfall. The first harmonic curves explain an average of 75.07% of the diurnal variance at 415 of the stations within the 0.10 isoline (Fig. 6), and generally, higher harmonics did not appear to be important in the study area.

5. Discussion

A variety of physical and dynamical processes may contribute to the nocturnal character of the warm season rainfall of the central United States. Many investigators (Means, 1944, 1954; Sangster, 1957; Curtis and Panofsky, 1958; Hering and Borden, 1962; Pitchford and London, 1962; Hoecker, 1965; Bonner, 1966, 1968; Paegle and McLawhorn, 1973; Hoxit, 1975) linked the low-level jet of the Great Plains to the existence of the nighttime rainfall phenomenon. Bleeker and Andre (1951) and Holton (1967) developed a model of nighttime west to east surface air drainage into the plains to account for the nocturnal convection. Hales (1977) proposed that the advection of evaporation-cooled layers from afternoon showers near the Rockies (Karr and Wooten, 1976) could destabilize the nighttime atmosphere of the central plains. Maddox (1980) suggested that the life cycle of mesoscale convective complexes largely accounts for the nocturnal

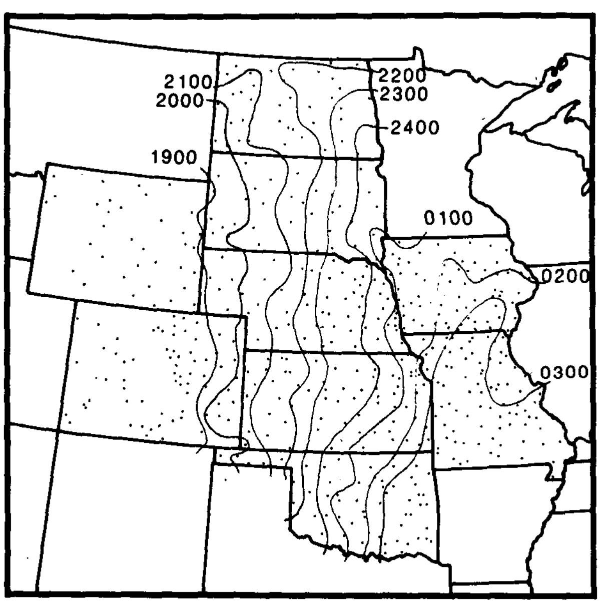

FIG. 5. First harmonic time of maximum frequency for events ≥ 2.54 mm h^{-1}.

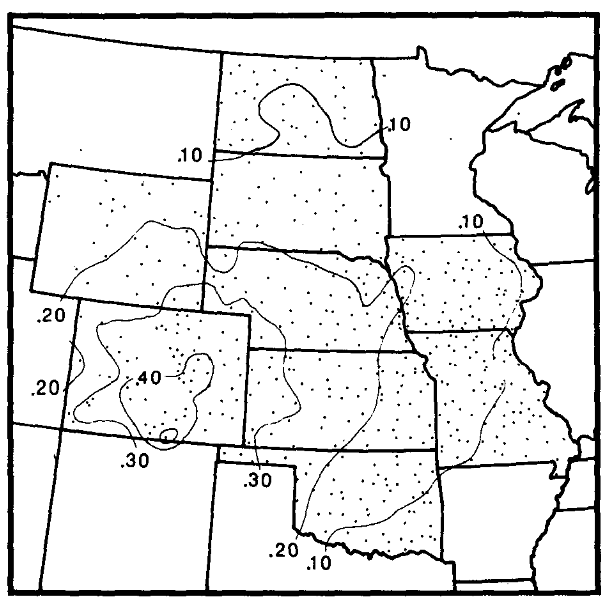

FIG. 6. First harmonic standardized amplitudes for events ≥ 2.54 mm h^{-1}.

character of the warm season rainfall. Others have suggested that frontal passages (Andre, 1949) or atmospheric tidal motions (Wallace and Hartranft, 1969; Hamilton, 1981; Kato *et al.*, 1982) could be associated with the nighttime precipitation patterns. While this group of explanatory "theories" is by no means an exhaustive one, it does provide some background on the debate that surrounds the possible cause of the observed nocturnal rainfall regime.

The increased spatial and temporal resolution in the 1) percentage of nocturnal precipitation frequencies over the central United States, 2) time of maximum rainfall frequencies, and 3) relative importance of the diurnal cycle presented in this study may serve a variety of useful functions. If long-term temporal and spatial patterns in rainfall regimes can be deductively derived from any of the proposed explanatory theories, the hypothesized patterns may be compared to the actual patterns as a valuable test of the theory's validity. Ultimately, numerical models will more clearly identify the relative importance of the various physical and dynamical mechanisms in creating and supporting the nocturnal rainfall patterns, and the results of this study should be useful in the verification process. And at the operational level, the results from this investigation may be immediately useful to meteorologists in preparing precipitation probabilities for different times during the day.

Acknowledgments. This work was supported by NOAA Grant NA84RAA07418 (WR-4-0074). Funding for the hourly precipitation data came from a University of Nebraska-Lincoln Research Council Grant-in-Aid.

REFERENCES

Andre, M. J., 1949: Distribution of the instability weather types with respect to summer cold fronts in the United States. *Bull. Amer. Meteor. Soc.*, **30**, 228–230.

Bleeker, W., and M. J. Andre, 1951: On the diurnal variation of precipitation, particularly over central U.S.A., and its relation to large-scale orographic circulation systems. *Quart. J. Roy. Meteor. Soc.*, **77**, 260–271.

Bonner, W. D., 1966: Case study of thunderstorm activity in relation to the low-level jet. *Mon. Wea. Rev.*, **94**, 167–178.

——, 1968: Climatology of the low-level jet. *Mon. Wea. Rev.*, **96**, 833–850.

Crysler, K. A., R. A. Maddox, L. R. Hoxit and B. M. Muller, 1982: Diurnal distribution of very heavy precipitation over the central and eastern United States. *Nat. Wea. Dig.*, **7**, 33–37.

Curtis, R. C., and H. A. Panofsky, 1958: The relation between large-scale vertical motion and weather in summer. *Bull. Amer. Meteor. Soc.*, **30**, 521–531.

Hales, J. E., Jr., 1977: On the relationship of convective cooling to nocturnal thunderstorms at Phoenix. *Mon. Wea. Rev.*, **105**, 1609–1613.

Hamilton, K., 1981: A note on the observed diurnal and semi-diurnal rainfall variations. *J. Geophy. Res.*, **86**, 12122–12126.

Hann, J., 1901: *Lehrbuch der Meteorologie, 1st ed.*, Chr. Herm. Tauchnitz, 338–346.

Hering, W. S., and T. R. Borden, Jr., 1962: Diurnal variations in the summer wind field over the central United States. *J. Atmos. Sci.*, **19**, 81–86.

Hoecker, W. J., Jr., 1965: Comparative physical behavior of southerly boundary-layer wind jets. *Mon. Wea. Rev.* **93**, 133–144.

Holton, J. R., 1967: The diurnal boundary layer wind oscillation above sloping terrain. *Tellus*, **19**, 199–205.

Hoxit, L. R., 1975: Diurnal variations in planetary boundary layer winds over land. *Bound. Layer Meteor.*, **8**, 21–38.

Karr, T. W., and R. L. Wooten, 1976: Summer radar echo distribution around Limon, Colorado. *Mon. Wea. Rev.*, **104**, 728–734.

Kato, S., T. Tsuda and F. Watanabe, 1982: Thermal excitation of non-migrating tides. *J. Atmos. Terr. Phys.*, **44**, 131–146.

Kincer, J. B., 1916: Daytime and nighttime precipitation and their economic significance. *Mon. Wea. Rev.*, **44**, 628–633.

Maddox, R. A., 1980: Mesoscale convective complexes. *Bull. Amer. Meteor. Soc.*, **61**, 1374–1387.

——, C. F. Chappell and L. R. Hoxit, 1979: Synoptic and meso-α scale aspects of flash flood events. *Bull. Amer. Meteor. Soc.*, **60**, 115–123.

——, P. D. Rodgers and K. W. Howard, 1982: Mesoscale convective complexes over the United States during 1981—Annual summary. *Mon. Wea. Rev.*, **110**, 1501–1514.

Means, L. L., 1944: The nocturnal maximum occurrence of thunderstorms in the midwestern states. M.A. thesis, University of Chicago, 38 pp.

——, 1954: A study of the mean southerly wind maximum in low levels associated with a period of summer precipitation in the Middle West., *Bull. Amer. Meteor. Soc.*, **35**, 166–170.

Orville, R. E., 1981: Global distribution of midnight lightning—September to November, 1977. *Mon. Wea. Rev.*, **109**, 391–395.

Paegle, J., and D. W. McLawhorn, 1973: Correlation of nocturnal thunderstorms and boundary layer convergence. *Mon. Wea. Rev.*, **101**, 877–883.

Pitchford, K. L., and J. London, 1962: The low-level jet as related to nocturnal thunderstorms over midwest United States. *J. Appl. Meteor.*, **1**, 43–47.

Rasmusson, E. M., 1971: Diurnal variation of summertime thunderstorm activity over the United States. Tech Note 71-4, U.S. Air Force Environmental Technical Applications Center.

Sangster, W. E., 1957: An investigation of nighttime thunderstorms in central United States. M.A. thesis, University of Chicago, 34 pp.

Skaggs, R. H., 1969: Analysis and regionalization of the diurnal distribution of tornadoes in the United States. *Mon. Wea. Rev.*, **97**, 103–115.

——, 1980: The diurnal distribution of large hail over the United States. *Prof. Geogr.*, **32**, 293–299.

U.S. Weather Bureau. 1941: *Airways Meteorological Atlas for the United States*, W. B. No. 1314, Government Printing Office, Washington, D.C. 163 pp.

——, 1947: *Thunderstorm Rainfall.* Hydrometeorological Rep. No. 5, Government Printing Office, Washington, D.C. 671 pp.

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

——, and F. R. Hartranft, 1969: Diurnal wind variations, surface to 30 kilometers. *Mon. Wea. Rev.*, **97**, 446–455.