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DIURNAL VARIATIONS IN WARM SEASON PRECIPITATION FREQUENCIES IN THE CENTRAL UNITED STATES

Robert C. Balling, Jr.

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

National Severe Storms Laboratory
Norman, Oklahoma
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Malcolm Baldrige, Secretary

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Anthony J. Calio, Administrator

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ABSTRACT

This project was conducted to identify more clearly temporal and spatial patterns in the diurnal cycle of hourly warm season precipitation frequencies over the central United States. Harmonic analysis of 30 years of data from 1109 stations reveals a number of important time/space dimensions in the hourly rainfall statistics. Topics receiving attention in this report include (a) the remarkably uniform longitudinal gradient in the timing of maximum rainfall frequencies across most of the Great Plains, (b) the sharp break between continental and maritime rainfall regimes, (c) intermonthly patterns in the diurnal variance structures, (d) selected anomalies in the general patterns, and (e) the implications of the empirical findings to the many theories of the widespread nocturnal rainfall phenomenon of the Plains.

1. INTRODUCTION

The warm season nocturnal rainfall regime of the central United States continues to represent one of the most interesting features found in the North American climate system. Despite strong daytime surface heating in the summer period, relatively high atmospheric moisture levels near the surface, and a continental location well insulated from oceanic influences, the central Great Plains region displays most of its convective activity at night. Precipitation events (Kincer, 1916; Wallace, 1975; Balling, 1985), thunderstorms (Means, 1944; Sangster, 1957; Pitchford and London, 1962; Rasmusson, 1971; Wallace, 1975;

Easterling and Robinson, 1985), lightning (Orville, 1981), and heavy rain associated with flash floods (Maddox _et al._, 1979) all exhibit a strong nocturnal tendency in the central United States.

A variety of physical and dynamical processes may contribute to the nocturnal character of the summertime rainfall in the region. Radiative and/or evaporative cloud top cooling (Hales, 1977), downslope air drainage (Bleeker and Andre, 1951; Holton, 1967), atmospheric tidal motions (Wallace and Hartranft, 1969; Hamilton, 1981; Kato _et al._, 1982), lower tropospheric warm advection (Maddox and Doswell, 1982), and the low-level jet (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; Astling _et al._, 1985) have all been proposed as causal mechanisms for the observed diurnal patterns. The recent work by Maddox (1980,1983) on the development, maintenance, and decay of mesoscale convective complexes also provides insights into the mechanisms that are responsible for the diurnal variations in warm season rainfall in the midwestern states.

Over the past ten years, several studies have appeared in the literature that clarify significantly the time and space dimensions in precipitation and thunderstorm data in the central United States (Wallace, 1975; Easterling and Robinson, 1985, Balling, 1985). Balling (1985) used an especially dense network of stations (515 stations in Wyoming, Colorado, North Dakota, South Dakota, Nebraska, Kansas, Oklahoma, Iowa, Missouri) to identify gradients in (a) the time of maximum precipitation frequency, (b) the portion of all rainfall frequencies occurring at night, and (c) the relative importance of the diurnal cycle.

The primary purpose of the project reported here was to extend the spatial extent of Balling's network to include Montana, New Mexico, Texas, Louisiana, Arkansas, Illinois, Indiana, Wisconsin, and Minnesota. Analyses of the warm season precipitation frequencies over the larger areal unit should clarify climatological patterns in the diurnal variations of precipitation over much of the central United States. The more precise identification of these precipitation patterns provides the empirical foundation for (1) assessing the many theories of the nocturnal rainfall regime, (2) evaluating the accuracy of numerical models constructed to simulate rainfall patterns in the region, and (3) aiding forecasters in preparing precipitation probabilities for various periods during the day.

2. HOURLY PRECIPITATION DATA

Hourly precipitation data for the study area (Fig. 1) were obtained from the Illinios State Water Survey. The period of record began in 1948 for all the states and ended variously between 1975 and 1983 (Table 1). All hourly rainfall observations were 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 raingauge chart reports from the second-order and cooperative stations. A limited collection period eliminated many stations leaving a total of 1109 stations in the study area available for further analysis (Fig. 1).

Table 1. Description of hourly precipitation data

State	Number of stations	Years of record
Arkansas	59	1948-1975
Colorado	70	1948-1977
Illinois	66	1948-1983
Indiana	63	1948-1983
Iowa	67	1948-1977
Kansas	66	1948-1977
Louisiana	21	1948-1978
Minnesota	51	1948-1983
Missouri	82	1948-1977
Montana	65	1948-1978
Nebraska	58	1948-1978
New Mexico	54	1948-1978
North Dakota	40	1948-1977
Oklahoma	60	1948-1977
South Dakota	35	1948-1977
Texas	155	1948-1978
Wisconsin	60	1948-1978
Wyoming	37	1948-1977

Figure 1. Distribution of the 11Ø9-station network.

A total of 4,747,104 actual hourly rainfall measurements ≥0.01 inch (0.25 mm) were recorded at the 1109 sites during the warm season months (April to September). Each of these observations was corrected to True Solar Time (TST) to avoid problems associated with time zone boundaries within the study area. The transformation to TST began by assuming that the rainfall during an hour interval occurred at 30 minutes past the hour. The longitude of the station was compared to the local meridian for the associated time zone (e.g., 75° W for the Eastern time zone, 90° W for the Central time zone, and 105° W for the Mountain time zone) to determine a lag between TST and local time. The time correction was then adjusted for the sun-fast or sun-slow problem associated with the Earth's orbital configuration. If the total correction exceeded 1/2 hour, the time of the precipitation frequencies was adjusted ahead or behind to the adjacent time interval. Artifical longitudinal gradients in the time of precipitation events of 1 h per 15° of long. were also eliminated by converting all observations to TST.

An 1109 (station) x 24 (hour) 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 1109 x 24 matrix contained a non-zero integer. Because this study deals exclusively with the diurnal variance patterns in rainfall frequencies, a limited number of missing days at any station does not jeopardize seriously the quality of the data base. Variations in the period of record from one station to the next may create some differences in the climatological patterns in this report.

Four other 1109 x 24 matrices were also constucted from the array of hourly precipitation data. One of these matrices contained the hourly frequencies of warm season events that were ≥ 0.10 inch (2.54 mm) per hour. This matrix of the larger rainfall rates contained 1,467,621 events representing 30.92% of all recorded events. The remaining three 1109 x 24 matrices contained frequencies for all events for (a) April and May, (b) June and July, and (c) August and September.

3. METHODOLOGY

Harmonic analysis (Rasmusson, 1971; Wallace, 1975; Schwartz and Bosart, 1979; Landin and Bosart, 1985; Easterling and Robinson, 1985; Balling, 1985) was applied to each row (station) in these matrices to generate a number of useful statistics regarding the diurnal variance patterns. The basic equation of harmonic analysis may be expressed as:

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

where $\hat{P}$ is the estimated precipitation frequency, $\bar{P}$ is the average hourly frequency over the N observations (24-hourly intervals) in the data population, A is the amplitude of the wave equal to $(a_r{}^2 + b_r{}^2)^{0.5}$, r is the frequency, θ equals $2\pi X/N$ where X is the hour of the day, and Φ is the phase angle of the curve calculated as $\tan^{-1}(a_r/b_r)$. The parameters a_r and b_r are determined as:

$$a_r = (2/N) \sum_{i=1}^{N} P_i \sin(r\theta)$$

and

$$b_r = (2/N) \sum_{i=1}^{N} P_i \cos(r\theta)$$

where P_i is the actual frequency for each hour. Useful statistics from these harmonic analyses that are reported in this study include the following:

(1) The time of maximum precipitation frequency in the diurnal cycle determined explicitly from the phase angles of the harmonic curves. These values are affected by the use of the

midpoint in each hourly interval as the precise time of precipitation events (e.g., 0130 TST represents the interval 0100-0200 TST).

(2) A standardized amplitude A_r' of the harmonics equal to $A_r/2\bar{P}$. This value is bounded by 0 and unity and provides an index of the concentration of precipitation in the peak period of the diurnal cycle. If the precipitation events are evenly distributed through the 24-h period, A_r' equals zero. If all events occur in only one of the hourly intervals, A_r' of the first harmonic equals 1. A useful parameter related to hourly rainfall probabilities may be generated when the standardized amplitude is multiplied by 2 and added to 1. For example, a standardized amplitude of 0.10 implies that the probability of rainfall in the peak period (considering only the first harmonic) is 1.20 times the 24-h mean value. The computational procedure used in this investigation produces standardized amplitudes that are by definition one-half as large as the values reported by others (Rasmusson, 1971; Wallace, 1975; Schwartz and Bosart, 1979; Landin and Bosart, 1985; Easterling and Robinson, 1985).

4. RESULTS: COMBINED WARM SEASON MONTHS

The percentage of all warm season precipitation events occurring at night (2000-0800 TST) exceeds 60% in southern Nebraska, central Kansas, western Oklahoma, and the northeastern portion of the Texas Panhandle (Fig. 2). Surrounding the core region is a widespread area where at least 55% of the rain events occur during the night hours. A south-central portion of New Mexico also displays a 55% isoline that extends into Texas and presumably across the Mexican border. Boothville, Louisiana shows a strong nighttime maximum apparently associated with its location and strong control by oceanic influences.

Areas with strong daytime rainfall preferences are also clearly displayed in Fig. 2. The western region of the study area shows at least 55% of its rainfall frequencies occurring from 0800 to 2000 TST. The strongest daytime maximum occurs in central Louisiana where more than 70% of all warm season events occur in the daytime period at several stations.

The standardized amplitudes associated with the first harmonic indicate where the diurnal cycle is most pronounced across the study area (Fig. 3). Most of the central Plains display an amplitude greater than 0.10; the largest values tend to occur in the western portion of the Plains. Other areas where the standardized amplitudes exceed 0.10 include southeastern Texas, southern Arkansas, and most of Louisiana. Below 0.10, the diurnal patterns are not well defined, and the spatial patterns of the phase angles appear to lose spatial coherency.

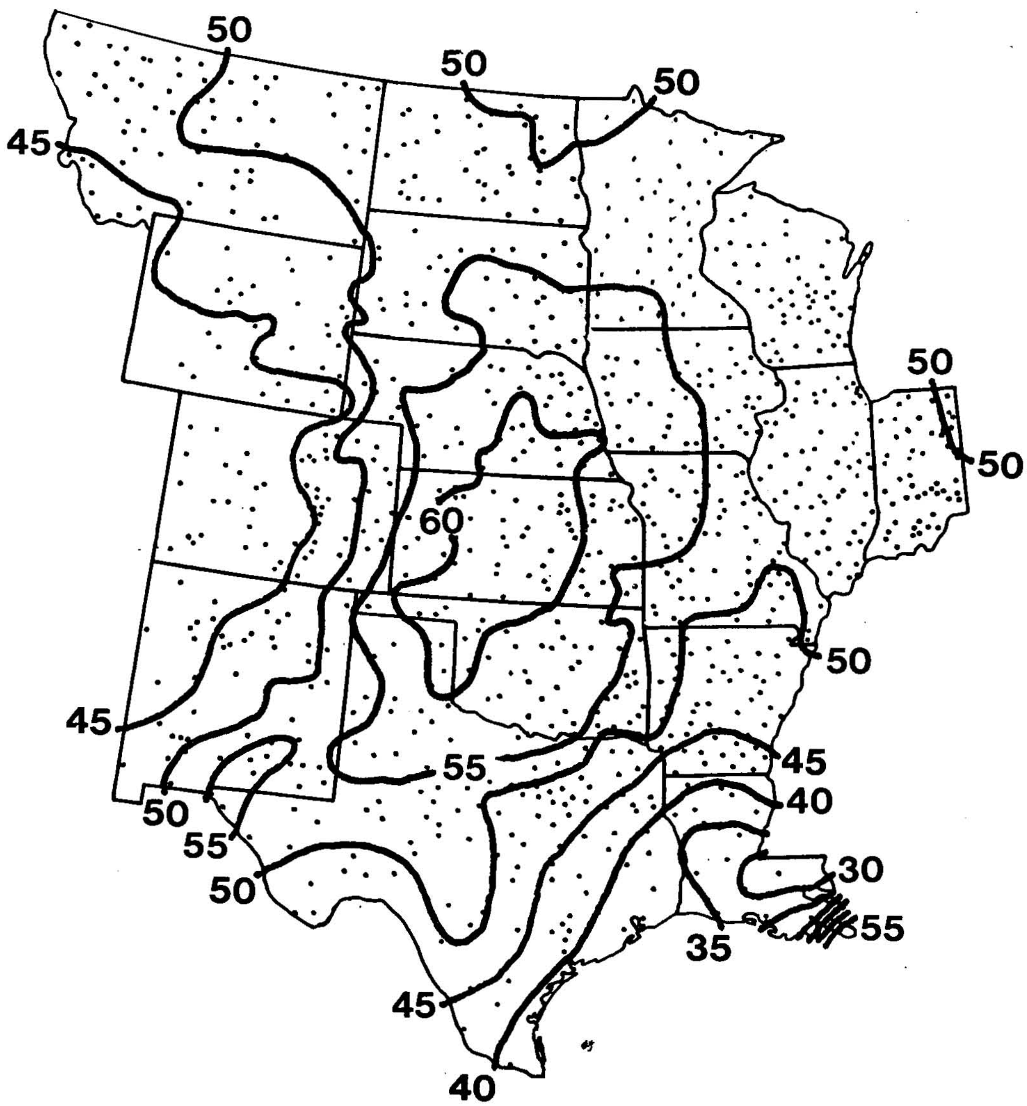

Figure 2. Frequencies (percent) of nocturnal warm season precipitation for all events.

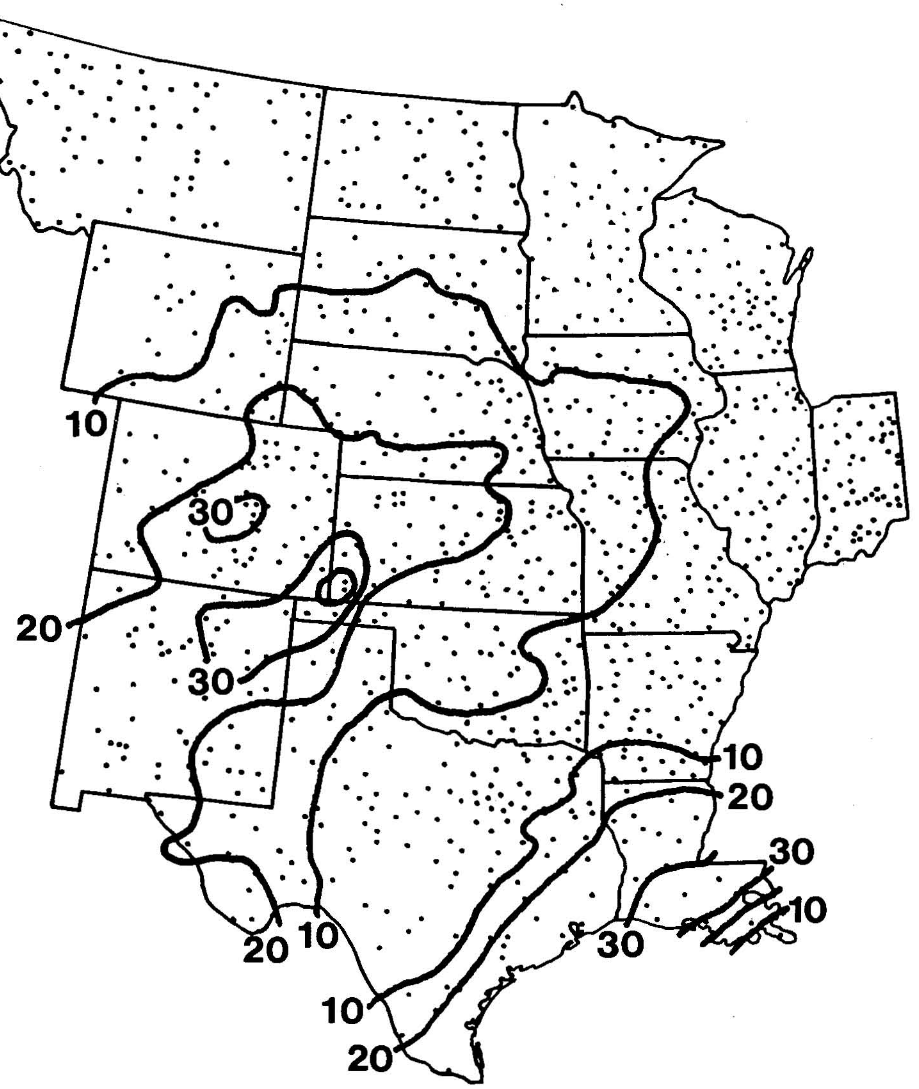

Figure 3. First-harmonic standardized amplitudes (x10^{2}) for all events.

The phase angles associated with the first-harmonic curves help to clarify the precipitation patterns in the central United States (Fig. 4). Isolines of equal time of maximum show a tendency for storms to occur in the early evening near the Front Range of the Rocky Mountains, near midnight in the central Plains, and near 0500 TST in central Missouri. A strong longitudinal gradient of approximately 1 h per 100 km exists across most of the central portion of the study area. This general pattern breaks sharply in southwestern Texas where the time of maximum shifts abruptly from near midnight to midafternoon.

The Gulf Coast shows a very different pattern with a far more latitudinal gradient extending away from the shore. In southeastern Texas, the time of maximum occurs near 1000 TST; in northern Louisiana, the maximum is near 1600 TST. Areas with standardized amplitudes less than 0.10 show a fairly noisy pattern for which meaningful isolines could not be constructed. However, in most of these areas the time of maximum occurrence can be safely interpolated from nearly isoline values.

The second harmonics were rarely important features of the diurnal variations in precipitation frequencies in the central United States. In areas of especially high first-harmonic standardized amplitudes, the second harmonic appears simply to reinforce the primary maximum. The only exception of note occurs in northeastern New Mexico where important second-harmonic curves suggest a secondary maximum of early afternoon showers. Higher

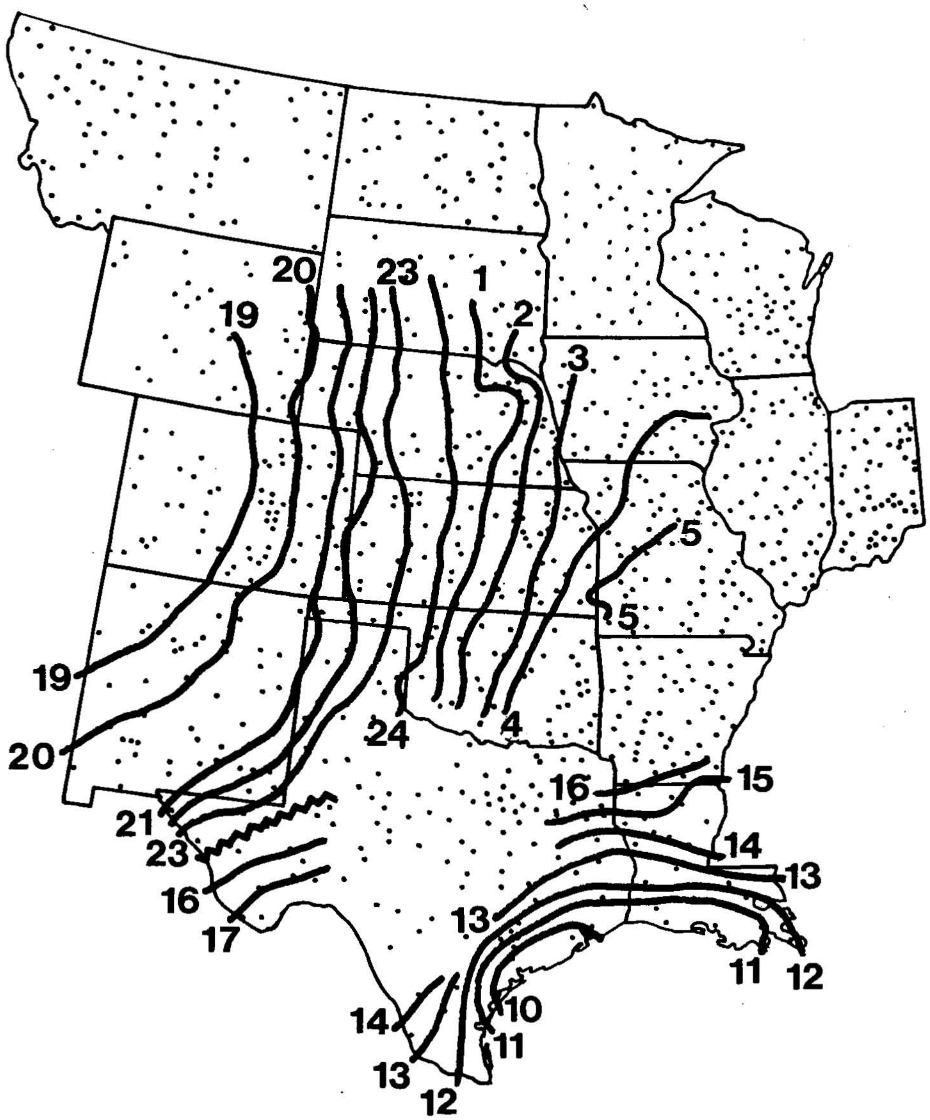

Figure 4. First-harmonic time (TST) of maximum rainfall frequency for all events (Isolines are drawn for only those areas with standardized amplitudes ≥ 0.10).

harmonics (r=3,4,5,6) did not appear to be important anywhere in the study area.

The pattern for the larger precipitation measurements of at least 2.54 mm per hour are generally similar to the patterns discussed for all events. The substantial differences that exist include the following the following:

(1) The bigger events generally have a stronger diurnal modulation in the rainfall frequencies. In a large portion of the central Plains, more than 60% of the precipitation events occur at night (Fig. 5) and a few stations in southeastern Nebraska approach the 70% level. The area of nocturnal domination appears to broaden with increasing latitude in the study area. A steep longitudinal gradient extends westward to the Front Range where less than 40% of the rainfall occurs at night. Central Louisiana shows a tendency for the larger events to occur during the daytime hours. The strong diurnal modulation in these events is also evident in the higher values in the standardized amplitudes (Fig. 6).

(2) Although the same longitudinal gradient of 1 h per 100 km in the timing of maximum events appears across most of the central Plains (Fig. 7), the larger events tend to occur 1 - 2 h earlier. The sharp discontinuity in southwestern Texas is absent for the larger precipitation events. The Gulf Coast again shows a strong tendency for storms to occur near 1400 TST inland, but the late morning values along the coast are absent for the larger events. Some evidence also suggests that the nighttime storms tend to move faster in the northern parts of the Great Plains and slower in the southern Plains.

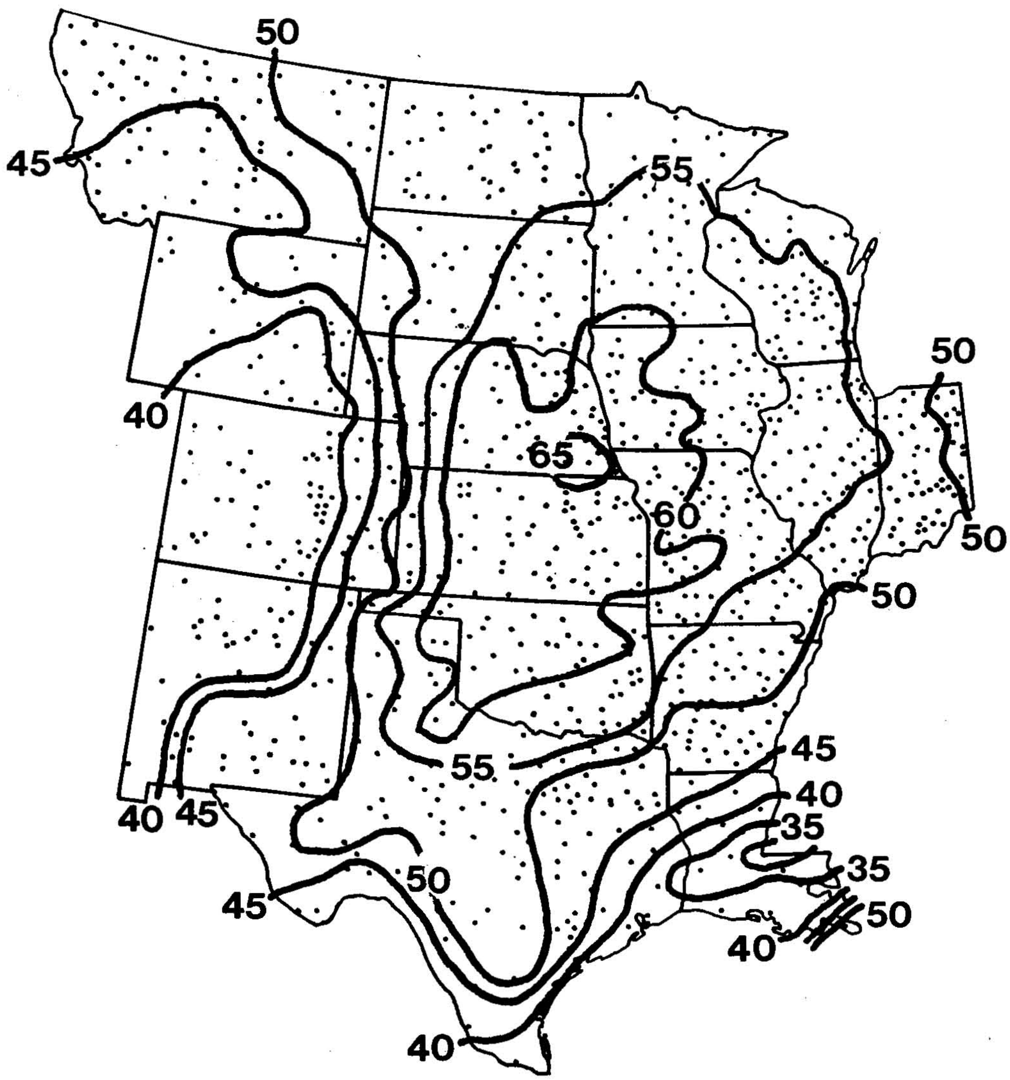

Figure 5. Nocturnal warm season precipitation frequencies (percent) for the larger events.

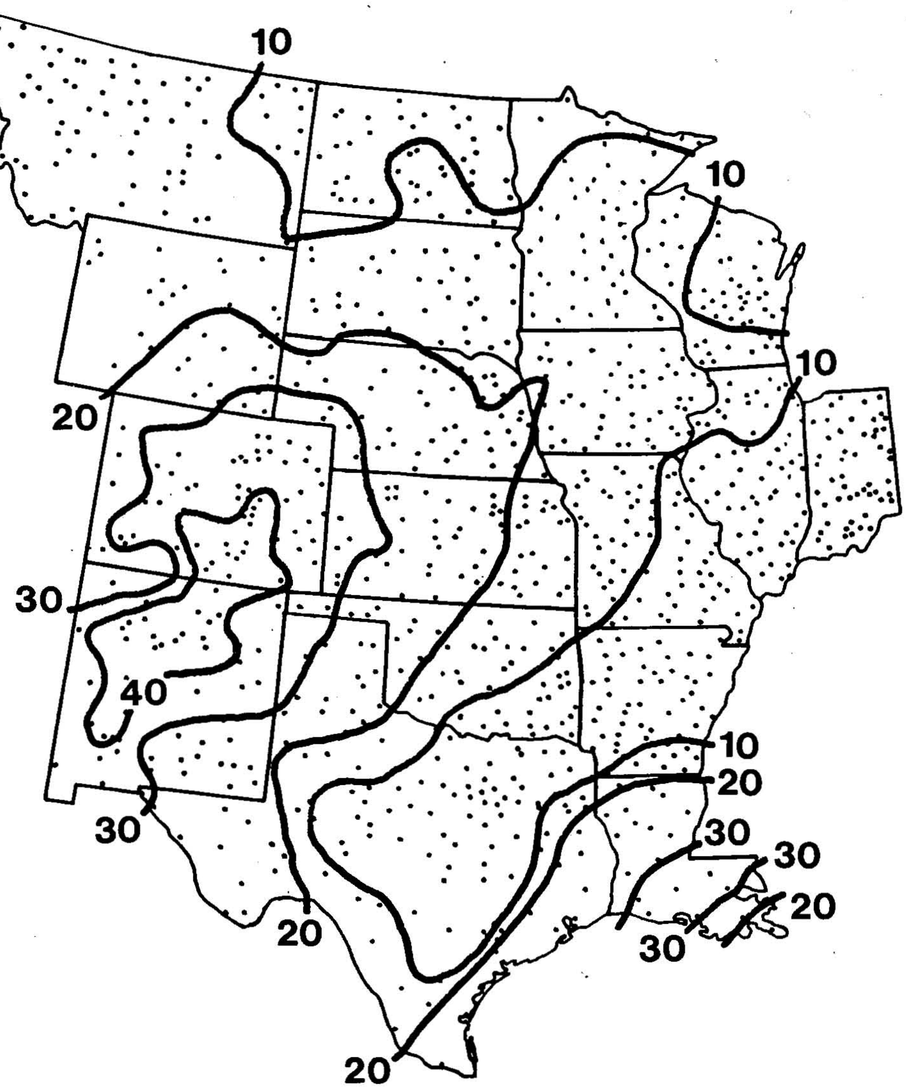

Figure 6. First-harmonic standardized amplitudes (x10^2) for the larger events.

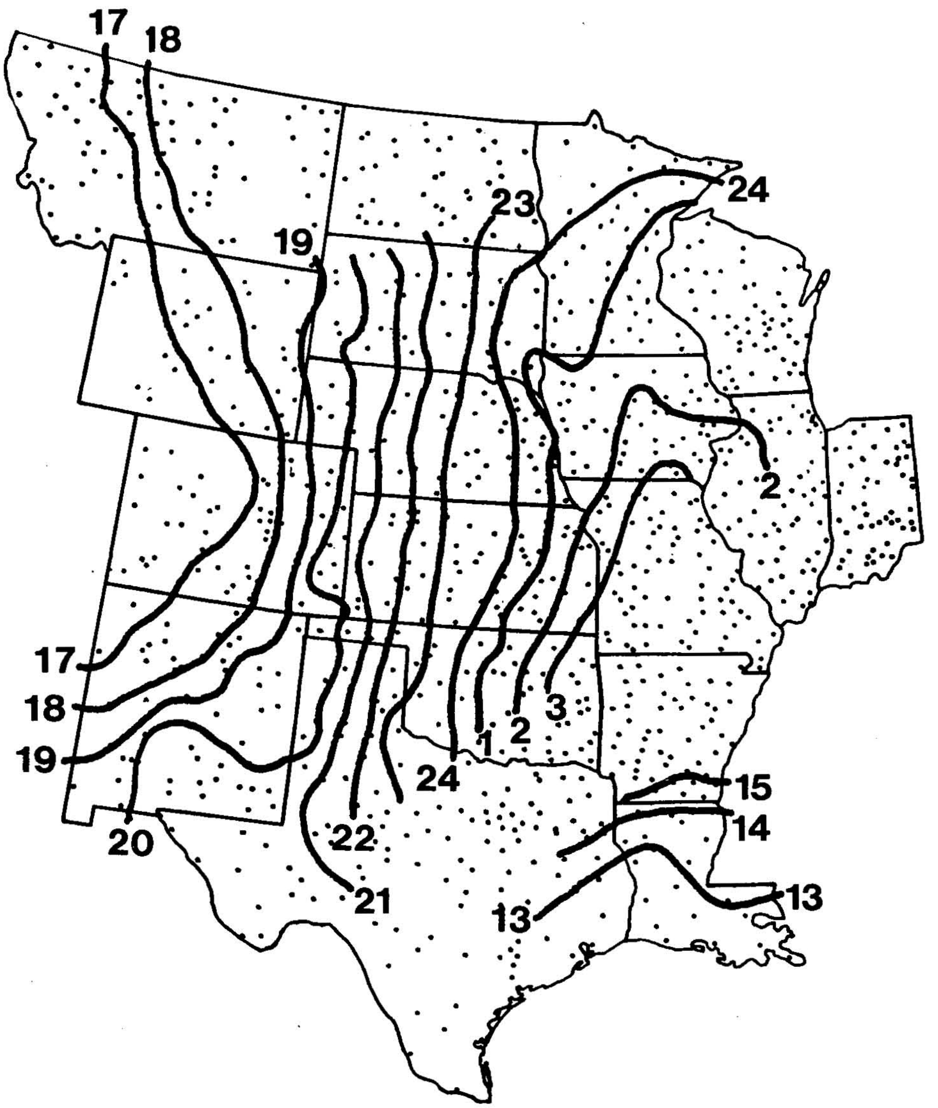

Figure 7. First-harmonic time (TST) of maximum rainfall frequency for the larger events.

5. RESULTS: INTERMONTHLY PATTERNS

The spatial and temporal patterns presented for the combined six months of the warm season may mask substantial changes that take place through the period. In this section, results are presented for the three 2-month sub-periods in the warm season.

Analyses of the April and May data reveal the strongest diurnal modulations in the southwestern portion of the study area (Fig. 8). The central Plains generally have slightly more than 55% of their rainfall at night (2000-0800 TST); only a few stations in southwestern Texas show more that 60% of their rainfall at night in these months (Fig. 9). Western New Mexico displays a similar propensity for daytime storms, but most of the study area shows a near-even split between daytime and nighttime frequencies. The time of maximum (Fig. 10) for the area with standardized amplitudes $\geqslant$ 0.10 displays a consistent longitudinal gradient from 1700 TST in central New Mexico to 0200 in eastern Kansas.

June and July appear to be the two months with the strongest modulations in the precipitation frequency data. Nearly all the study area shows a standardized amplitude greater than 0.10 (Fig. 11); a few stations in Colorado and Kansas exceed the 0.50 level. A core area extending from northern Texas through western Oklahoma, central Kansas, and southeastern Nebraska exceeds 65% nighttime precipitation frequency (Fig. 12).

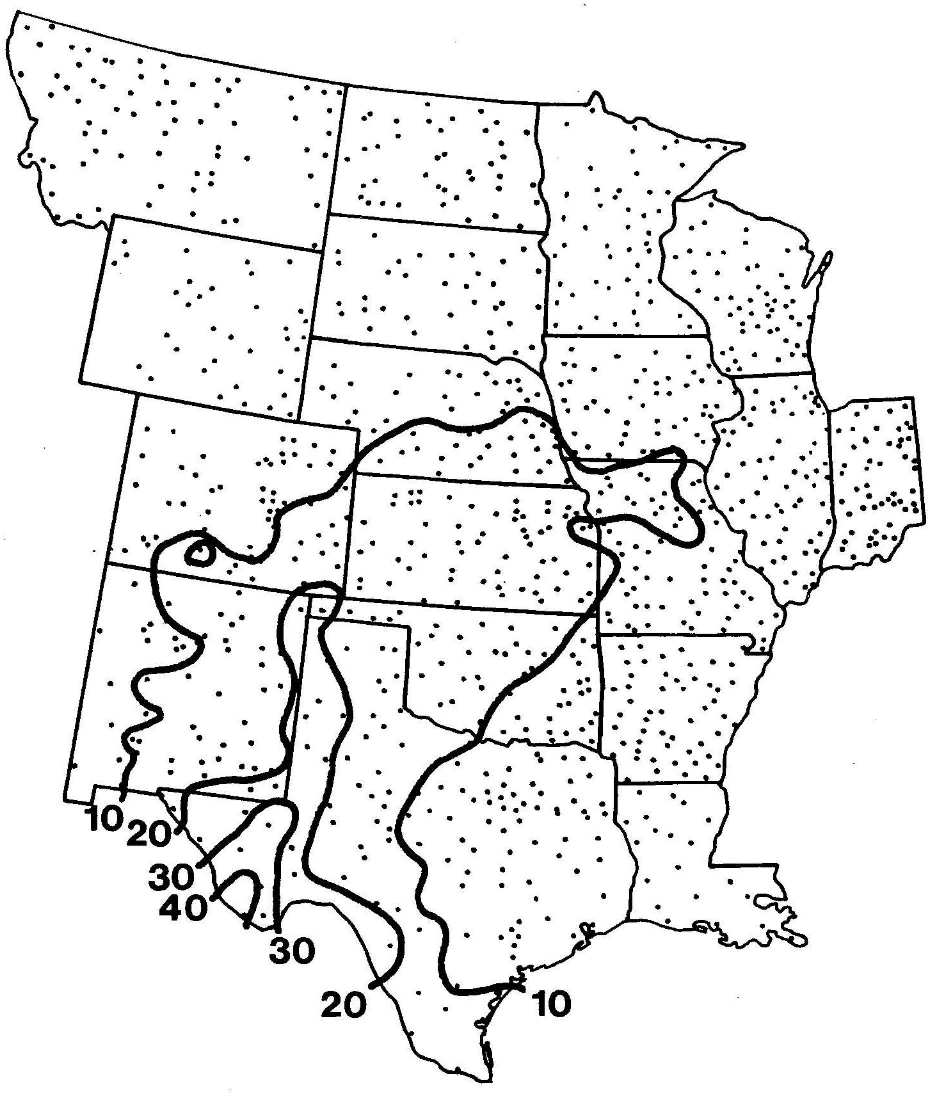

Figure 8. First-harmonic standardized amplitudes (x10^{2}) for April and May events.

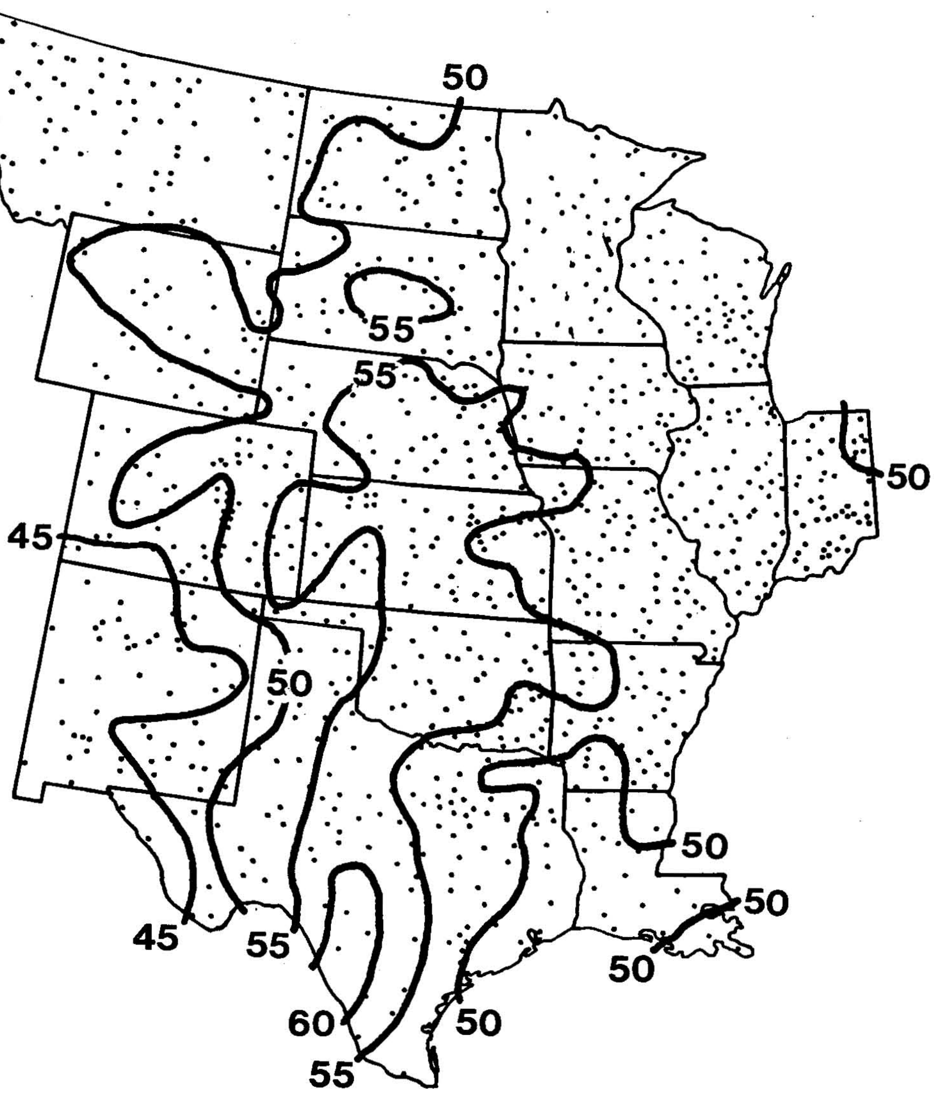

Figure 9. Nocturnal precipitation frequencies (percent) for April and May events.

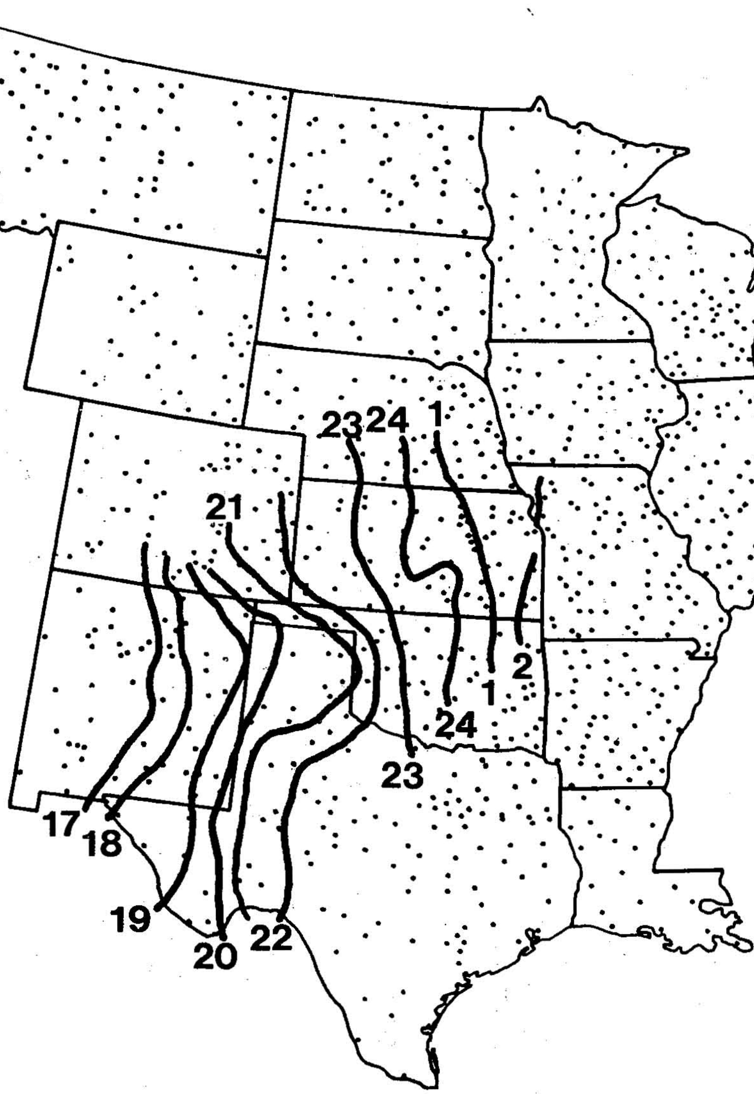

Figure 1Ø. First-harmonic time (TST) of maximum for April and May events.

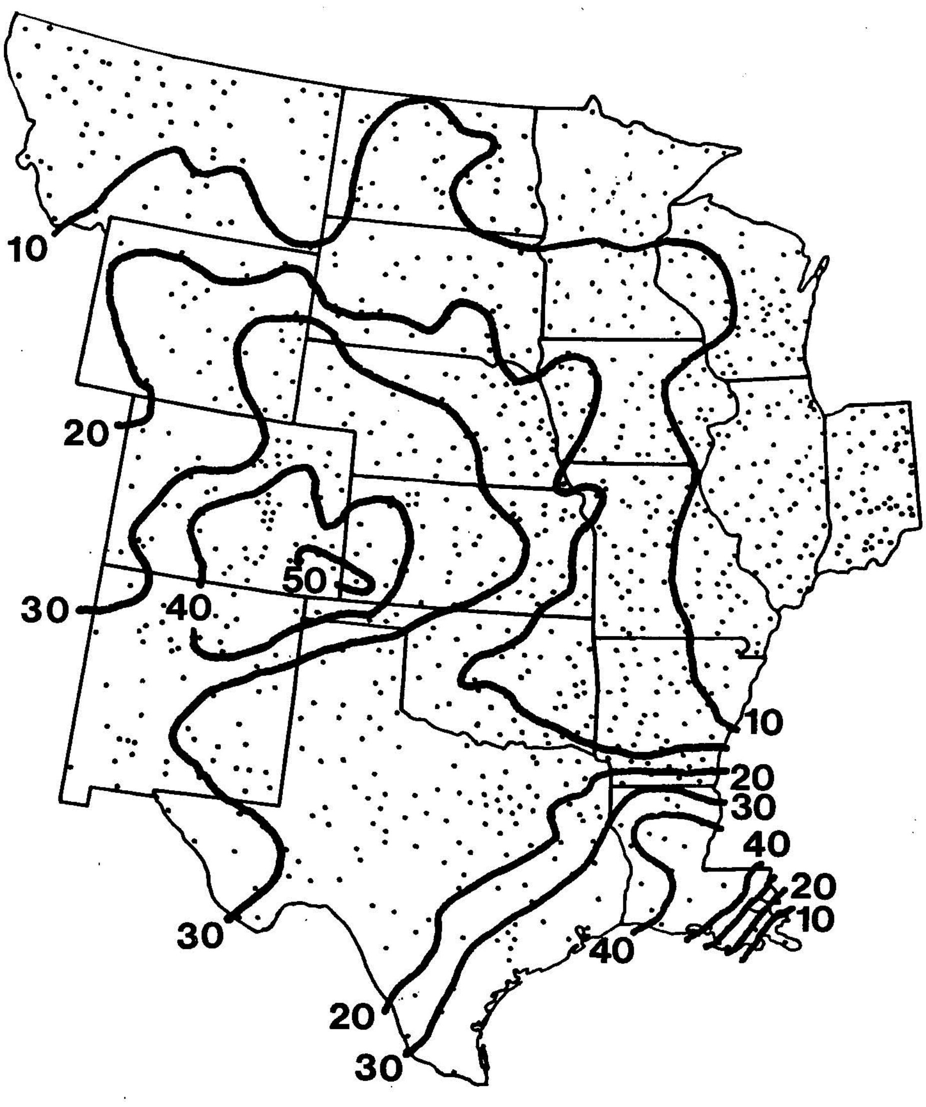

Figure 11. First-harmonic standardized amplitudes (x10^2) for the June and July events.

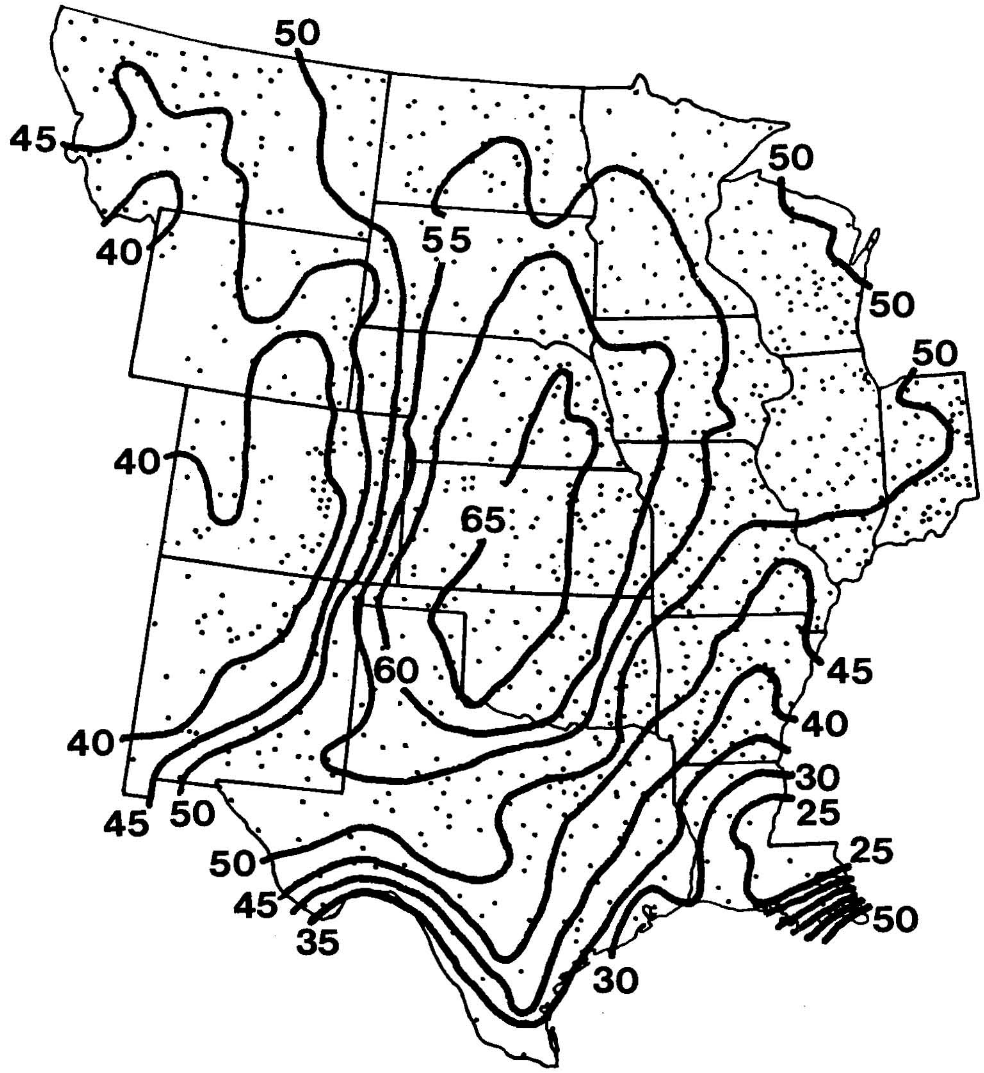

Figure 12. Nocturnal precipitation frequencies (percent) for the June and July events.

The steepest gradients extend away from this core area to the west where less than 40% of the rain occurs at night in western Colorado and New Mexico. Gradients to the south lead to nighttime rainfall frequencies less than 35% in southern Texas, and less than 25% in eastern Louisiana.

The phase angles associated with the first harmonic curves reveal a consistent longitudinal gradient and a maximum that occurs near 1800 TST along the Front Range to 0400 TST along a diagonal from central Iowa through central Oklahoma (Fig. 13). A sharp break between the Great Plains rainfall regime and a Gulf Coast regime extends across central Texas, southeastern Oklahoma, northwestern Arkansas, and into southern Missouri. South of the discontinuity the coastal regime dominates with, morning rainfall along the coast and early afternoon storms at the more inland stations.

The patterns so firmly established for June and July deteriorate during August and September. The area of 65% nocturnal rainfall in the Great Plains begins to shrink, and the distinctive afternoon shower pattern of the Rockies is lost (Fig. 14). The area of 0.10 standardized amplitudes is reduced, and the levels of the standardized amplitudes are lower than those in June and July (Fig. 15). In a large area in central Texas, the amplitudes fall below 0.10.

Several interesting features appear on the map showing the hour of maximum precipitation frequencies (Fig. 16). The central Plains continue to be dominated by the familiar longitudinal pattern of approximately 1 h per 100 km. However, the Gulf Coast

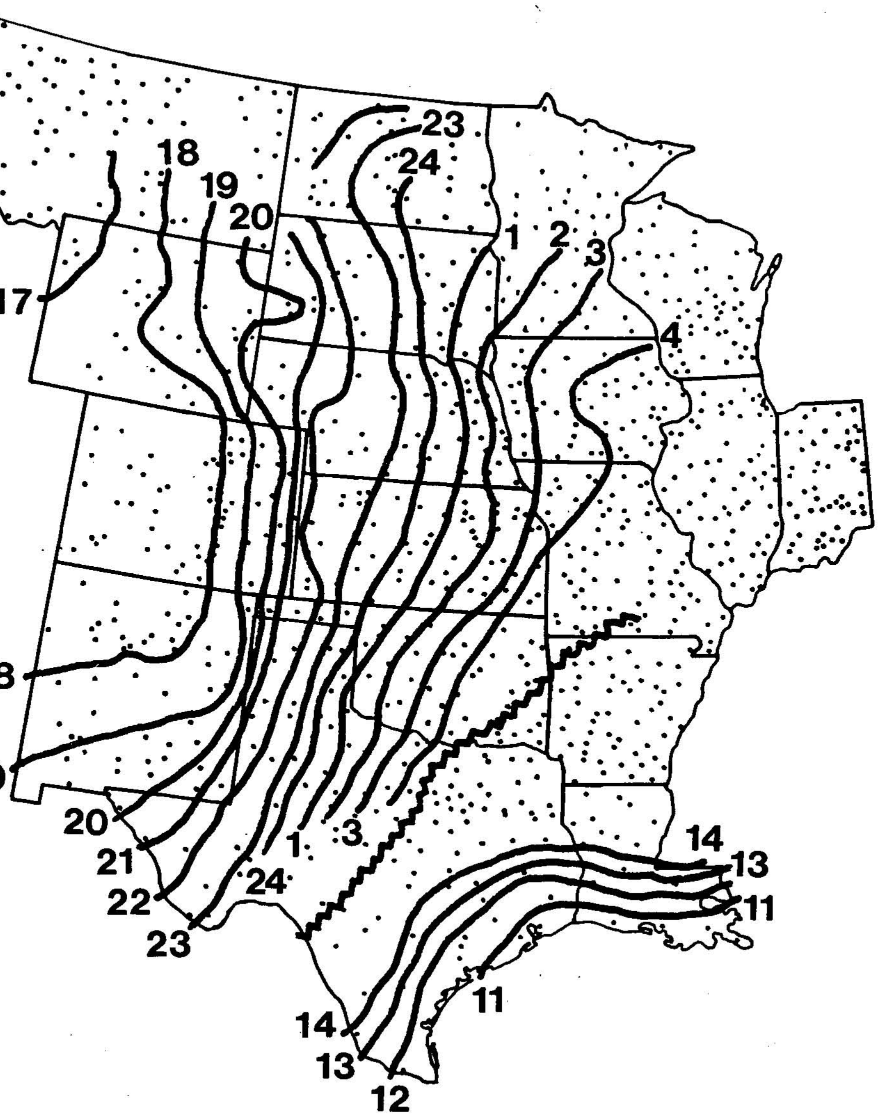

Figure 13. First-harmonic time of maximum (TST) for the June and July events.

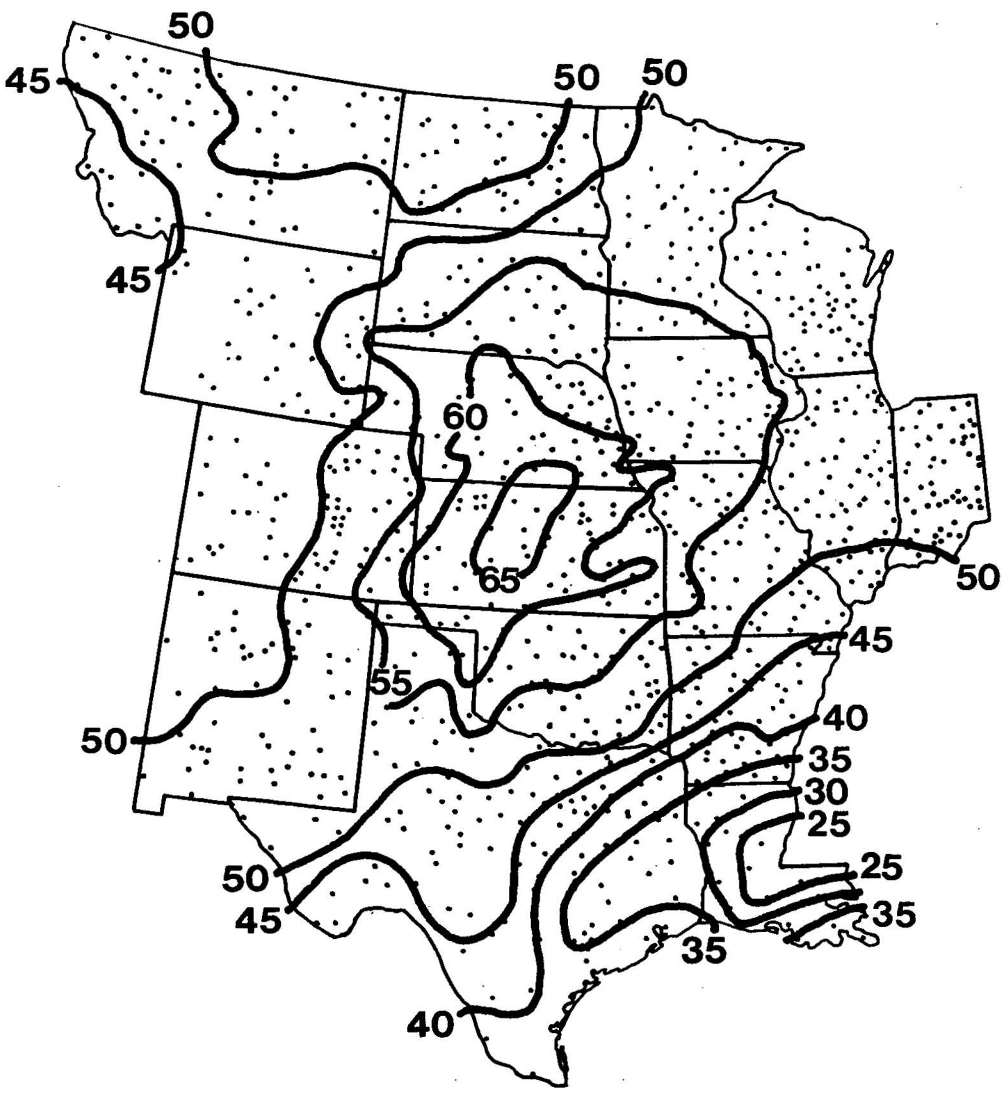

Figure 14. Nocturnal precipitation frequencies (percent) for the August and September events.

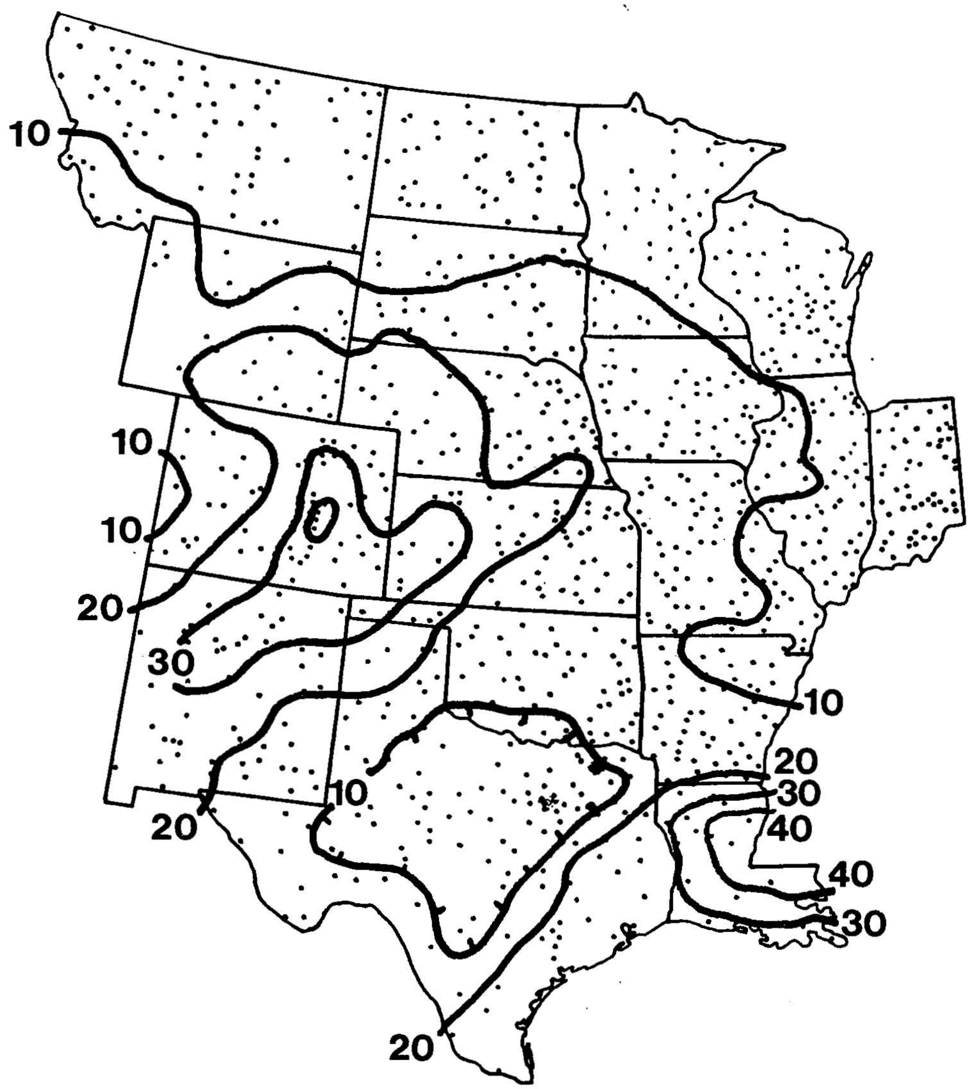

Figure 15. First-harmonic standardized amplitudes (x10^2) for the August and September events.

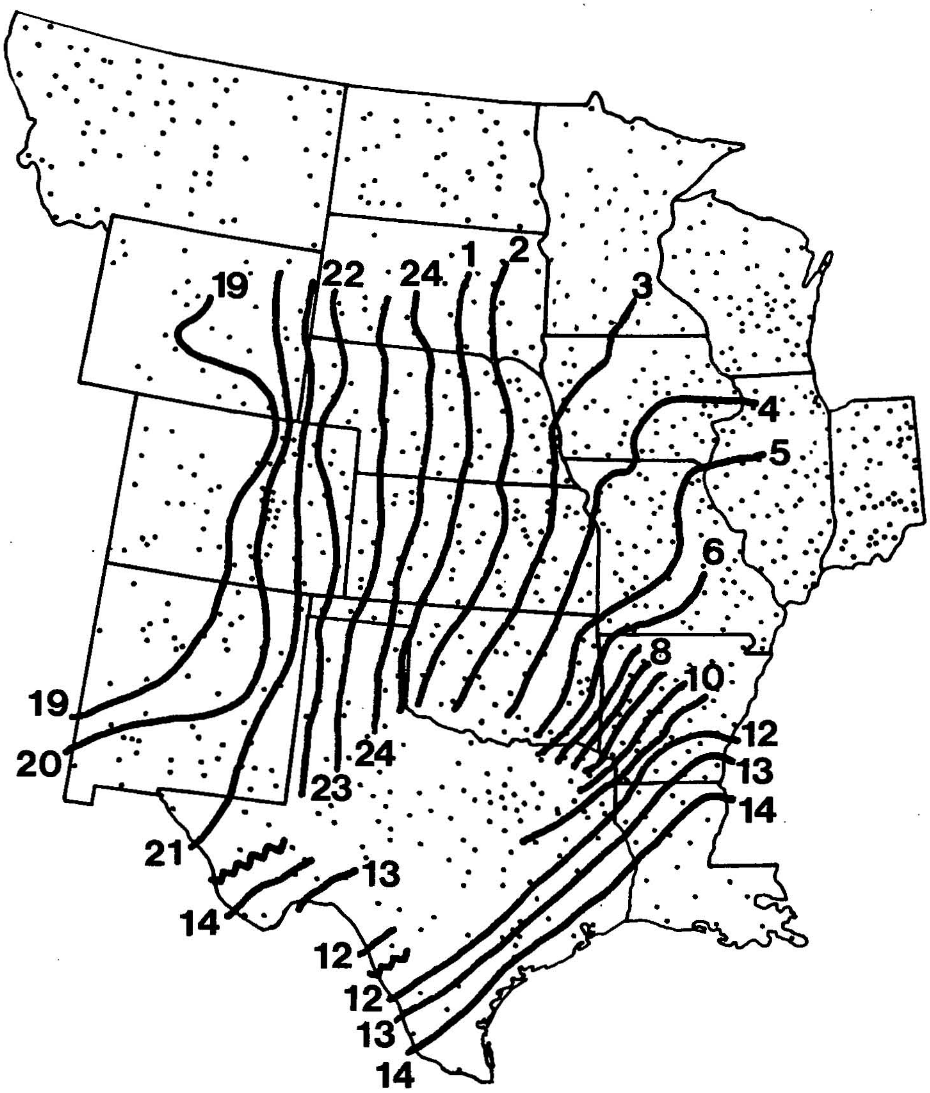

Figure 16. First-harmonic time of maximum (TST) for the August and September events.

pattern is now inverted, and rainfall events occur later nearer the coastal stations. A strong gradient across Arkansas suggests a climatic connection between the regime of the Plains and the regimes of the coastal area. Southwest Texas reveals a relatively small area that appears to operate independently of the regimes to the southeast and northwest.

6. APPLICATIONS

The purpose of this study was to identify more clearly the time and space patterns in warm season precipitation frequencies in the central United States. Percentages of nocturnal precipitation events, times of maximum rainfall frequency, and standardized amplitudes from first-harmonic curves are generated for the combined six-month warm season and for the three two-month subperiods. The 15 maps displaying the spatial patterns in these statistics may serve a variety of useful functions including the following:

(1) The spatial patterns presented in this study may be used in evaluating theories of nocturnal rainfall in the central United States. Any of the theories of this phenomenon should be capable of explaining the spatial and temporal patterns presented in this report.

(2) The climatological patterns in the diurnal precipitation variations may be useful in the analyses of individual precipitation events. An event may be placed into some climatological context by comparing the timing and movement of the individual case with the long-term patterns presented in this report.

(3) As more sophisticated numerical models are constructed for the precipitation processes in the central United States, the results of this study may prove valuable in model verification. Numerical models of summertime rainfall in the Plains should be capable of simulating the general time and space patterns

revealed in the precipitation frequencies.

(4) At the operational weather forecasting level, the results of this investigation may be immediately useful to meteorologists in preparing precipitation probabilities for different times of day.

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REFERENCES

Astling, E. G., J. Paegle, E. Miller, and C. J. O'Brien, 1985: Boundary layer control of nocturnal convection associated with a synoptic scale system. Mon. Wea. Rev., 113, 540-552.

Balling, R. C., Jr., 1985: Warm season nocturnal precipitation in the Great Plains of the United States. J. Clim. Appl. Meteor., 24, 1383-1387.

Bleeker, W., and M. J. Andre, 1951: On the diurnal variation of precipitation, particularly over the 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.

Bonner, W. D., 1968: Climatology of the low-level jet. Mon. Wea. Rev., 96, 833-850.

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

Easterling, D. R., and P. J. Robinson, 1985: The diurnal variation of thunderstorm activity in the United States. J. Clim. Appl. Meteor., 24, 1048-1058.

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.

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.

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.

Landin, M. G., and L. F. Bosart, 1985: Diurnal variability of precipitation in the northeastern United States. Mon. Wea. Rev., 113, 989-1014.

Maddox, R. A., 1980: Mesoscale convective complexes. Bull. Am. Meteor. Soc., 61, 1374-1387.

Maddox, R. A., 1983: Large-scale meteorological conditions associated with midlatitude mesoscale convective complexes. Mon. Wea. Rev., 111, 1475-1493.

Maddox, R. A., C. F. Chappell, and L. R. Hoxit, 1979: Synoptic and meso-α aspects of flash flood events. Bull. Am. Meteor. Soc., 60, 115-123.

Maddox, R. A., and C. A. Doswell, III, 1982: An examination of jet stream configurations, 500 mb vorticity advection and the low level thermal advection patterns during periods of intense convection. Mon. Wea. Rev., 110, 184-197.

Means, L. L., 1944: The nocturnal maximum occurrence of thunderstorms in the midwestern states. University of Chicago, M. S. Thesis.

Means, L. L., 1954: A study of the mean southerly wind maximum in low levels associated with a period of summer precipitation in the Middle West. Bull. Am. 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, Technical Note 71-4, U.S. Air Force Environmental Technical Applications Center, Washington.

Sangster, W. E., 1957: An investigation of nighttime thunderstorms in central United States. University of Chicago, M. S. Thesis.

Schwartz, B. E., and L. F. Bosart, 1979: The diurnal variability of Florida rainfall. Mon. Wea. Rev., 107, 1535-1545.

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

Wallace, J. M., and F. R. Hartranft, 1969: Diurnal wind variations, surface to 30 kilometers. Mon. Wea. Rev., 97, 446-455.

NATIONAL SEVERE STORMS LABORATORY

The NSSL Technical Memoranda, beginning at No. 28, continue the sequence established by the U.S. Weather Bureau National Severe Storms Project, Kansas City, Missouri. Numbers 1-22 were designated NSSP Reports. Numbers 23-27 were NSSL Reports, and 24-27 appeared as subseries of Weather Bureau Technical Notes. These reports are available from the National Technical Information Service, Operations Division, Springfield, Virginia 22151, a microfiche version for $4.00 or a hard copy, cost depending upon the number of pages. NTIS numbers are given below in parenthesis.

No. 1 National Severe Storms Project Objectives and Basic Design. Staff, NSSP. March 1961. 16 p. (PB-168207)

No. 2 The Development of Aircraft Investigations of Squall Lines from 1956-1960. Brent B. Goddard. 34 p. (PB-168208)

No. 3 Instability Lines and Their Environments as Shown by Aircraft Soundings and Quasi-Horizontal Traverses. Dansey T. Williams. February 1962. 15 p. (PD-168209)

No. 4 On the Mechanics of the Tornado. J. R. Fulks. February 1962. 33 p. (PD-168210)

No. 5 A Summary of Field Operations and Data Collection by the National Severe Storms Project in Spring 1961. Jean T. Lee. March 1962. 47 p. (PB 165095)

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