HYDROMETEOROLOGICAL REPORT NO. 41

Probable Maximum and TVA Precipitation over the Tennessee River Basin above Chattanooga

U.S. DEPARTMENT OF COMMERCE
WEATHER BUREAU
Washington
June 1965

HYDROMETEOROLOGICAL REPORTS

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*No. 10. Maximum possible rainfall over the Arkansas River Basin above Caddoa, Colo. 1939. Supplement, 1939.
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*No. 21. A hydrometeorological study of the Los Angeles area. 1939.
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*No. 25A. Representative 12-hour dewpoints in major United States storms east of the Continental Divide. 2d edition. 1949.
*No. 26. Analysis of winds over Lake Okeechobee during tropical storm of August 26–27, 1949. 1951.
*No. 27. Estimate of maximum possible precipitation, Rio Grande Basin, Fort Quitman to Zapata. 1951.
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No. 35. Meteorology of hypothetical flood sequences in the Mississippi River Basin. 1959.
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No. 37. Meteorology of hydrologically critical storms in California. 1962.
No. 38. Meteorology of flood-producing storms in the Ohio River Basin. 1961.
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U.S. DEPARTMENT OF COMMERCE
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WEATHER BUREAU
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For
The Tennessee Valley Authority
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FOREWORD

This report continues a series of estimates of probable maximum precipitation made by the Hydrometeorological Branch, Office of Hydrology of the Weather Bureau. The major previous studies by the Branch have been funded by the Corps of Engineers, Department of the Army, primarily to meet needs associated with their river basin projects. These reports have been made available to all interested engineers and other citizens through publication.

The present report is funded by the Tennessee Valley Authority in support of a new appraisal of the potential for high flows on the Tennessee River near Chattanooga. This report draws on the techniques and experience of the former studies and in turn advances the state of the art, particularly regarding hydrometeorological procedures for larger basins in the south-central and southeastern states.

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Chapter I

INTRODUCTION

Purpose of report

The maximum flood potential at Chattanooga, Tenn. can be evaluated using extreme upstream rainfall. This report provides estimates of extreme rainfall for the total 21,400-sq. mi. Tennessee River drainage above Chattanooga and for a 7980-sq. mi. sub-basin. These basins are outlined on figures 1-1 and 1-2.

Authorization

The authorization for this study is an agreement between the Tennessee Valley Authority and the U. S. Weather Bureau. Excerpts from the agreement are found in appendix A.

Scope

Two categories of extreme precipitation, namely probable maximum precipitation (PMP) and a standardized less extreme rainfall, called "TVA precipitation" are included in this report. These categories are discussed in chapter II.

Emphasis is given to two general types of storms, the cool-season winter-type and the warm-season hurricane-type. The month-to-month variation in the values of extreme rainfall, including characteristic within-basin areal distribution, are developed for the March through September season. The intense, small-area, summer thunderstorm type is not of concern for the 21,400- and 7980-sq. mi. basins dealt with in this report.

The report also provides storm conditions that could be antecedent and subsequent to each of the extreme rainfall categories.

Organization of report

The report consists of seven chapters. The final chapter is a resume of storm criteria including all necessary information and recommendations for use. The figures and tables of chapter VII give twelve 6-hr. increments of probable maximum and TVA precipitation with isohyetal patterns that provide within-basin depth-area relations.

An appraisal of the overall problems is made in chapter II. Chapter III deals with the meteorology of important storms including both cool-season and summer types. Topographic effects on distribution and on volume of rainfall in the Tennessee Basin above Chattanooga are discussed in chapter IV. Chapter V presents the probable maximum and TVA precipitation estimates including month-to-month variations. Antecedent and subsequent rainfall conditions are presented in chapter VI.

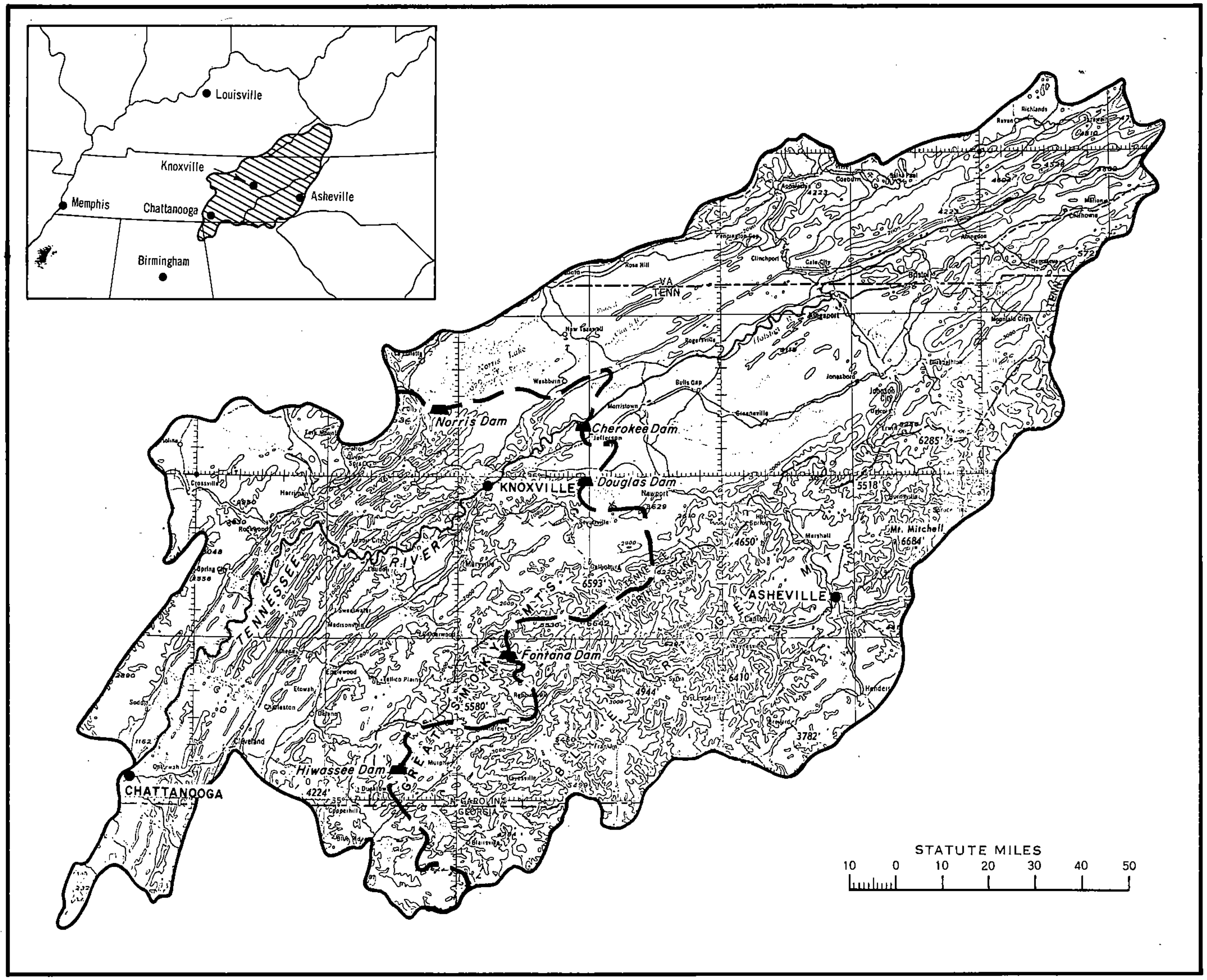


Figure 1-1. Basin boundaries and topography, Tennessee River Basin above Chattanooga

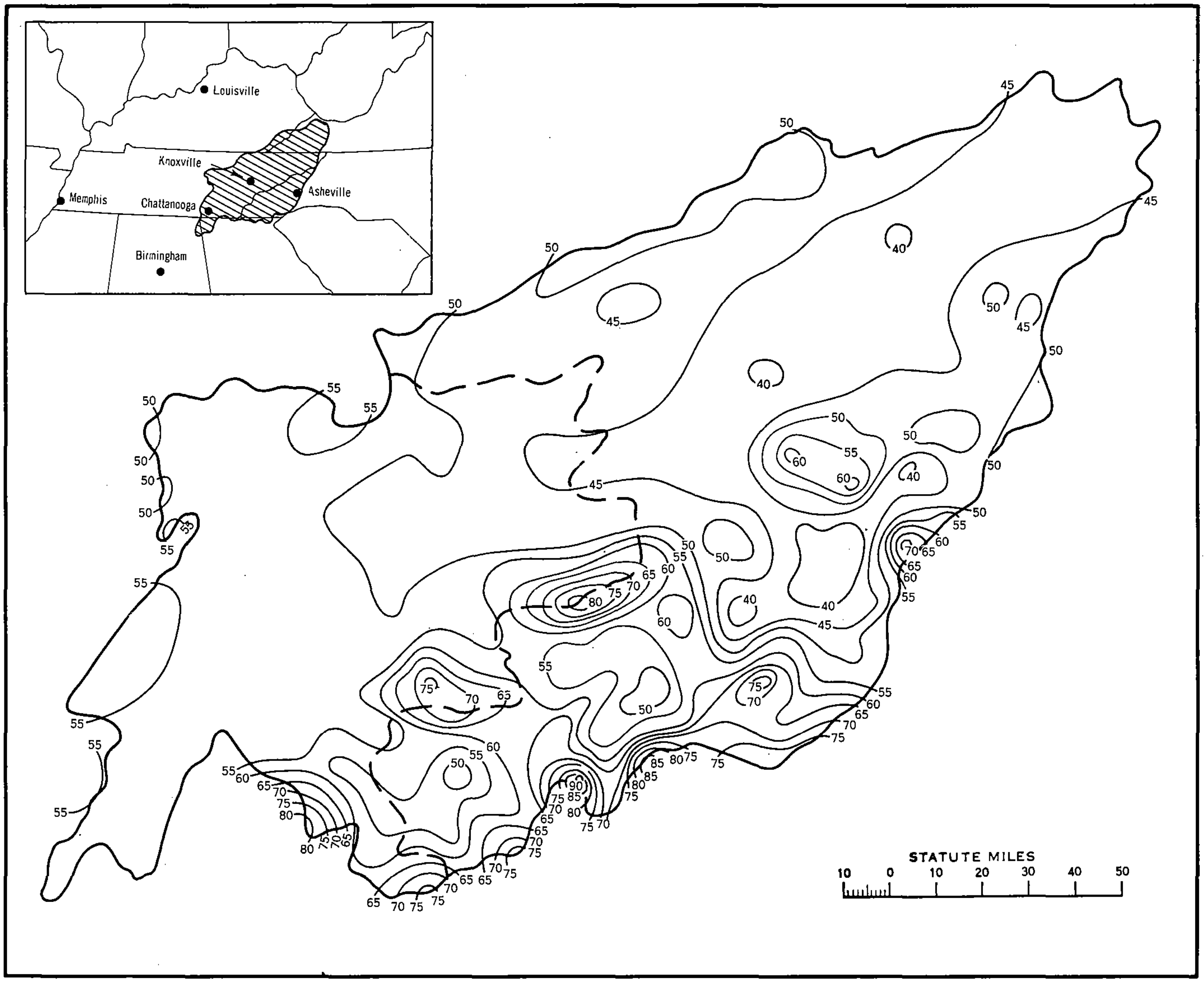


Figure 1-2. Mean annual precipitation (in.) Tennessee River Basin above Chattanooga (From TVA analysis Ref. 4-1)

The figures most important to understanding the report are placed in the body of the report. Additional complementary figures are shown in appendix B. A list of references begins on page 117 and are numbered according to their order of occurrence by chapter.

Chapter II

THE PROBLEM OF ESTIMATING EXTREME PRECIPITATION - AN APPRAISAL

The purpose of this chapter is twofold. The first is to clarify the character of and the relationship between the two categories of extreme precipitation presented in this report. The second is to present Tennessee Basin characteristics important for estimating extreme precipitation.

Concept of probable maximum precipitation (PMP)

There is no universal agreement on a single precise meaning of PMP. It is reasonable to assume that a physical upper limit to the rate of rainfall does exist. Physical limitations on the joint occurrence of the various rain-favoring meteorological parameters impose limits on the rainfall magnitude.

The definition of PMP that is used in this report is the rainfall depth (for a particular size basin) that approaches the upper limit that the present climate can produce.

Development of PMP values

Observed storms must influence greatly the estimate of PMP. In regions of high, elongated, topographic barriers theoretical models of air flow may help substantially. For the complicated topography of the Tennessee River drainage the use of theoretical flow models is not feasible. The existing topographic effects need to be considered, however, for making any necessary adjustments to basic PMP values derived from storm experience.

Storms that have occurred in the basin provide the starting point. These give rainfall values we know can occur in the basin. A better estimate of an upper limit to rainfall in a basin results through making allowance for the occurrence in the basin of appropriate storms removed or transposed from their actual place of occurrence. This introduces the accepted hydrometeorological principle of storm transposition. Application of the storm transposition principle requires mature meteorological judgment on the nature of storm types and, in turn, on the establishment of transposition limits.

An additional important ingredient in estimating the PMP is a maximizing of observed storms (both those occurring within the basin and those transposed to the basin). This maximizing step is accomplished by increasing the depth-duration-area rainfall values by applying a higher water vapor content of the air than actually existed. The higher water vapor values however, are no greater than maximum observed flowing to the basin.

Finally, an interpretation is required of the composite of all the resulting rainfall values from transposed and maximized storms. If PMP estimates have been made for similar-sized nearby basins, consistency checks with these estimates are made. Recognition should also be given to the amount and quality of the available storm data. The adopted PMP values - whether resulting from a liberal or close envelopment of the data - depend upon such factors.

Relation of probable maximum to TVA precipitation

Most users of PMP estimates apply an additional level of possible rainstorm experience. The Tennessee Valley Authority uses a TVA storm* which is defined as a storm "resulting from transposition and adjustment to the Tennessee Basin without maximization of appropriate storms which have occurred elsewhere." Thus, the TVA precipitation is less conservative than the PMP by virtue of elimination of the maximization-for-moisture step.

In the development of separate estimates of PMP and TVA precipitation in this report (chapter V) this maximization distinction is retained in the methods applied to cool-season storm types. However, for the warm-season storm type a distinction based on storm maximization-for-moisture is tenuous and rather meaningless. Important tropical storms and/or hurricanes nearly always occur with high moisture charge; in fact, this must be so for storms that derive the bulk of their energy from the latent heat of condensation. This contrasts to the extratropical winter-type storm where significant kinetic energy derives from the conversion of potential energy existing in strong thermal gradients. For summer, therefore, a distinction of PMP from TVA precipitation is based on a less liberal envelopment of observed data in the TVA precipitation case compared to the PMP case (chapter V).

Significant basin features

Enumerated below are features of the Tennessee Basin that are important to estimates of extreme rain.

1. The basin is sufficiently far north to come under the influence of major mid-latitude storms especially from November through March.

2. The basin is sufficiently close to the Atlantic Ocean and Gulf of Mexico to be affected by decadent hurricanes and/or tropical storms.

3. The major axis of the basin has approximately the same orientation as many of the rainfall patterns of major storms.

4. The flow of the Tennessee River is opposite to the prevailing westerly flow in the atmosphere.

5. There are topographic features in the basin that affect rainfall distribution patterns. The most direct flow of moisture from the Gulf or the warm Atlantic source must pass over barriers in reaching the northeastern portion of the basin.

*See footnote, attachement A of appendix A (p. 121).

Chapter III

METEOROLOGY OF MAJOR STORMS

Introduction

The major flood season in the Tennessee Basin is late November through mid April. During this season the basin experiences the frontal or cyclone storm-type that accounts for most of the important rains in the Southeastern United States in the cool season. The salient meteorological features of these storms are summarized in the second part of this chapter, (B).

Hurricanes, while rare, are the principal large-area threats in summer. These storms are discussed in the third part of this chapter, (C).

The meteorology of major storms in any basin is best appreciated by an examination of the climate which has prevailed in that area. The chapter begins therefore with a synopsis of the rainfall climate, (A).

3-A. CLIMATIC FEATURES OF TENNESSEE BASIN

The rainfall climate of the Tennessee Basin is summarized by considering rainfall for durations ranging from a day to a year. Particular emphasis is given to the extremes. Annual precipitation provides a benchmark.

Mean annual precipitation. The mean annual precipitation over the Tennessee Basin above Chattanooga is shown on figure 1-2. Portions of the Great Smokies and Blue Ridge are the rainiest spots in the United States east of the Rocky Mountains with annual rainfall amounts in excess of 80 inches. In contrast, the more sheltered portion of the nearby Upper French Broad River Valley has some of the lowest mean annual rainfall amounts both in the basin and in the eastern half of the United States. The less rugged remaining portion of the basin west of the Great Smokies shows relatively minor variations in mean annual precipitation.

There is a gradual decline in annual precipitation northeastward along the Tennessee and Holston River Valleys. The decline in precipitation can be attributed to two factors. One is the increasing distance from the moisture source. The other and more important factor is the sheltering of the area above Knoxville by the higher ridges of the Great Smokies and Blue Ridge from direct inflow of Gulf moisture. There is also some shielding by the Cumberland Plateau (Ref. 3-1).

Monthly and shorter duration precipitation

To obtain a picture of the rainfall regimes in the Tennessee Basin, mean monthly, maximum monthly and 24-hr. maximum rainfalls are summarized for Chattanooga and Knoxville, Tenn. and Asheville, N. C. A tie-in with surrounding areas is accomplished by summarizing similar data for Birmingham, Ala., Louisville, Ky., and Memphis Tenn., (see inset, fig. 1-1). The data for the six stations are shown on figures 3-1 through 3-6. Most of the rainfall statistics are from Local Climatological Data (Ref. 3-2). Data from Technical Paper No. 15 (Ref. 3-3) were used for extending the 24-hr. rainfall records to earlier years.

Rain data for 3- and 10-day durations that were already processed in another study were summarized. The averages of the highest five 3- and 10-day rains are shown on figure 3-7 for Memphis and on figure 3-8 for Asheville. These are for a 50-yr. period of record (1912-1961). The single highest with its year of occurrence is also shown on these figures.

Assuming Chattanooga and Knoxville most typical as indicators of winter-type storm capability, the evidence of a springtime maximum suggests that this be given the greatest emphasis in developing estimates of extreme precipitation for the basins. Likewise, the hurricane needs to be given serious consideration in estimating summertime precipitation capabilities. The unusual hurricane rainfall of July 1916 at Birmingham (fig. 3-5) reverses the seasonal trend suggested by the remaining data for this station.

The data of figures 3-1 through 3-8 have some additional application to month-to-month variation and to antecedent rainfall, discussed in chapters V and VI.

3-B. METEOROLOGY OF COOL-SEASON STORMS

Large-scale controls

Major rainfall floods over large basins do not occur unless important large-scale weather features are favorable. Studies of major storms in the Ohio and Mississippi River Valleys (Refs. 3-4, 3-5) have demonstrated the importance of (1) large troughs of low pressure above the surface, (2) frontal zones at the surface, (3) a rich and continuing moisture supply.

A recent study (Ref. 3-6) relates the position of the trough aloft, at about 10,000 feet, to concurrent 5-day precipitation. When such a trough aloft moves but little, then the concurrent surface feature is often a frontal zone that also moves little. This quasi-stationary character of weather features provides a favorable setting for flood-producing rains by virtue of successive bursts of rainfall falling in approximately the same area. This of course also requires that the axis of moisture inflow remain relatively fixed.

Moisture transport from the Gulf of Mexico concentrates around 1500 to 2000 feet above the ground (Ref. 3-7). Usually the 850-mb chart (approximately 5000 ft.) can be used as an indicator of the prevailing rain-producing moisture inflow for storms in Eastern United States. High values of moisture transport at the 850-mb level are nearly always associated with heavy rain situations. Therefore, in the following discussions of recent storms the 850-mb chart is emphasized in addition to the weather charts for the surface and for 500 mb (approximately 18,000 ft.).

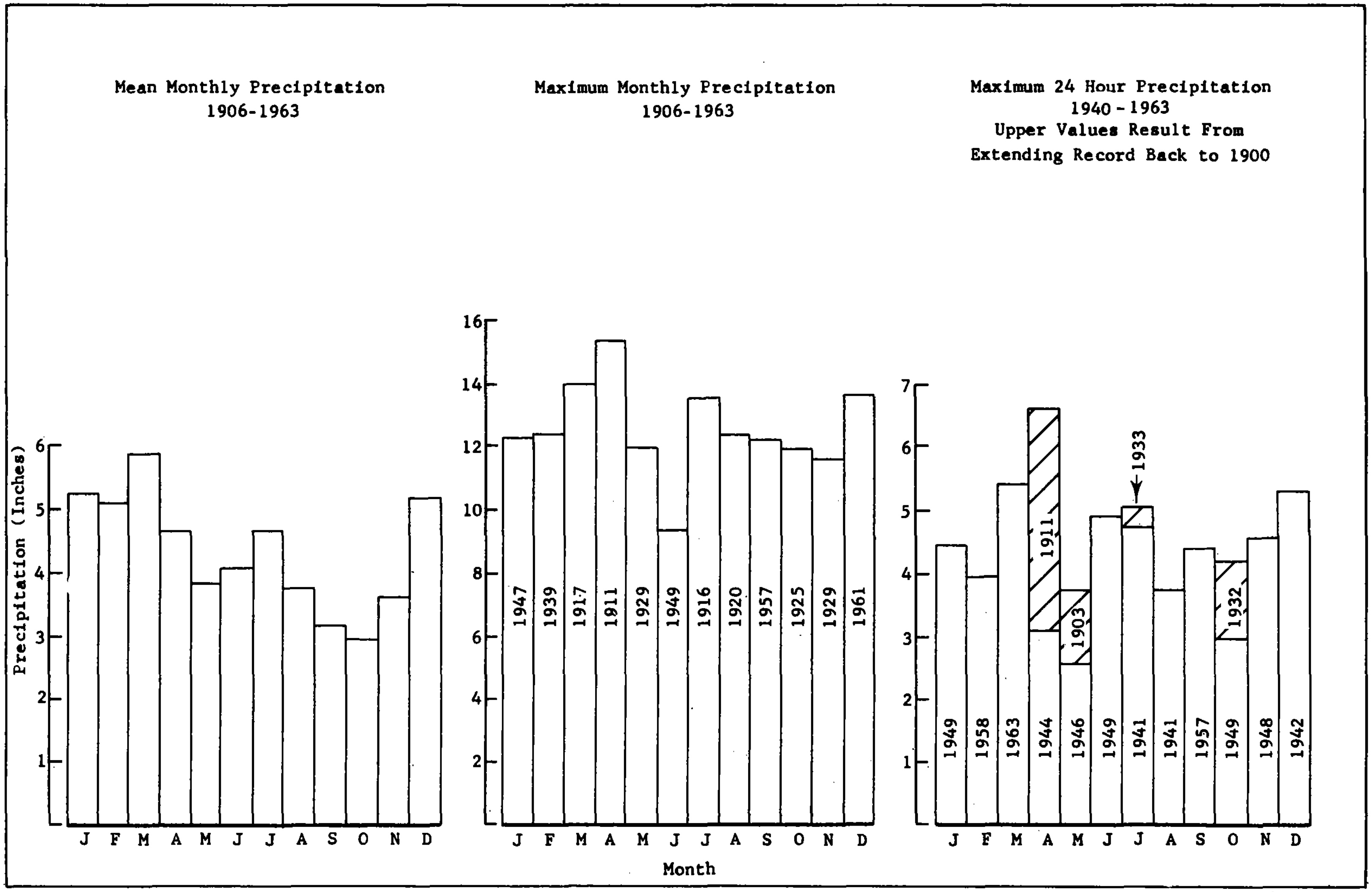


Figure 3-1. Mean and extreme rainfall - Chattanooga

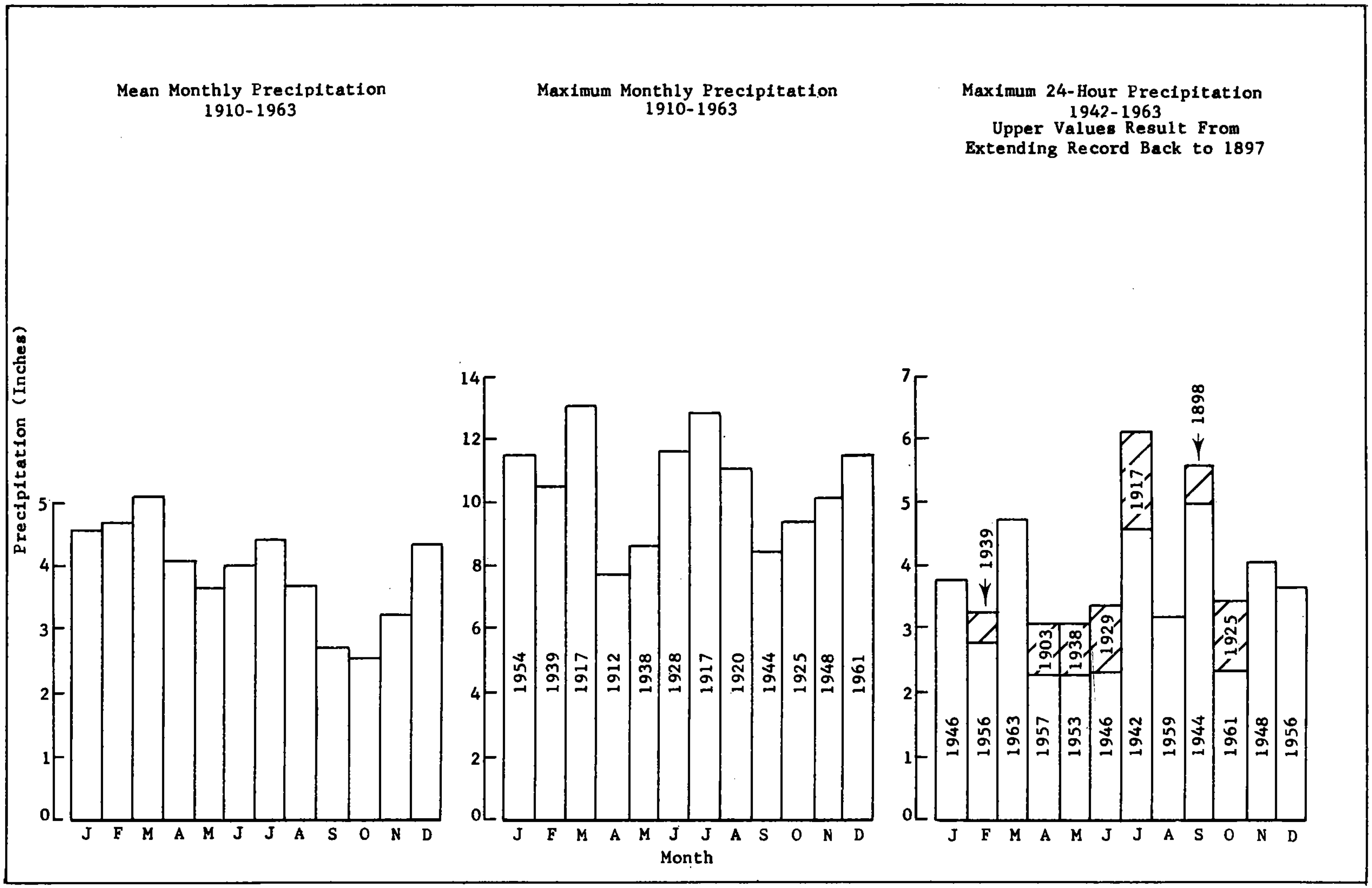


Figure 3-2. Mean and extreme rainfall - Knoxville

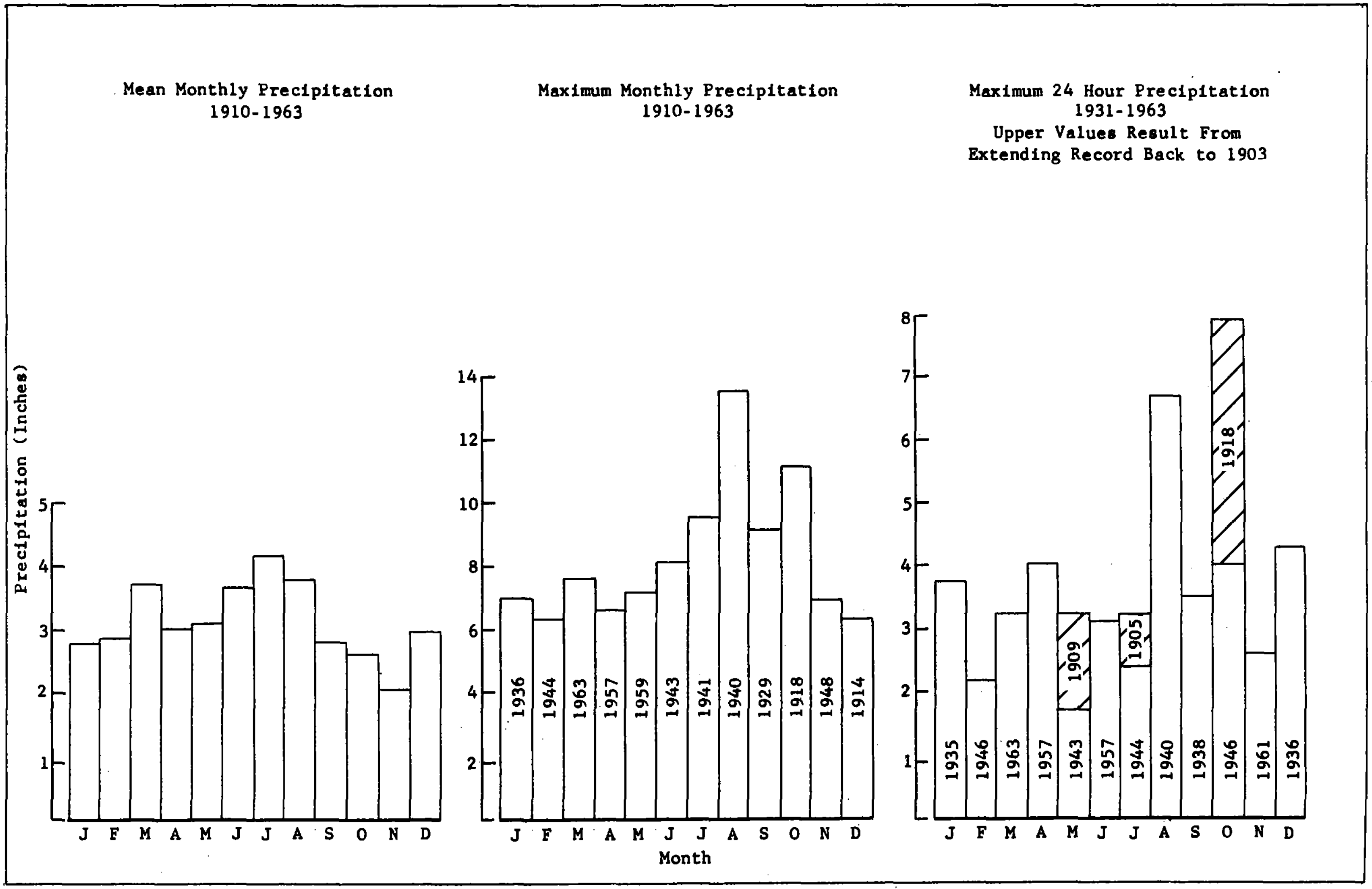


Figure 3-3. Mean and extreme rainfall - Asheville

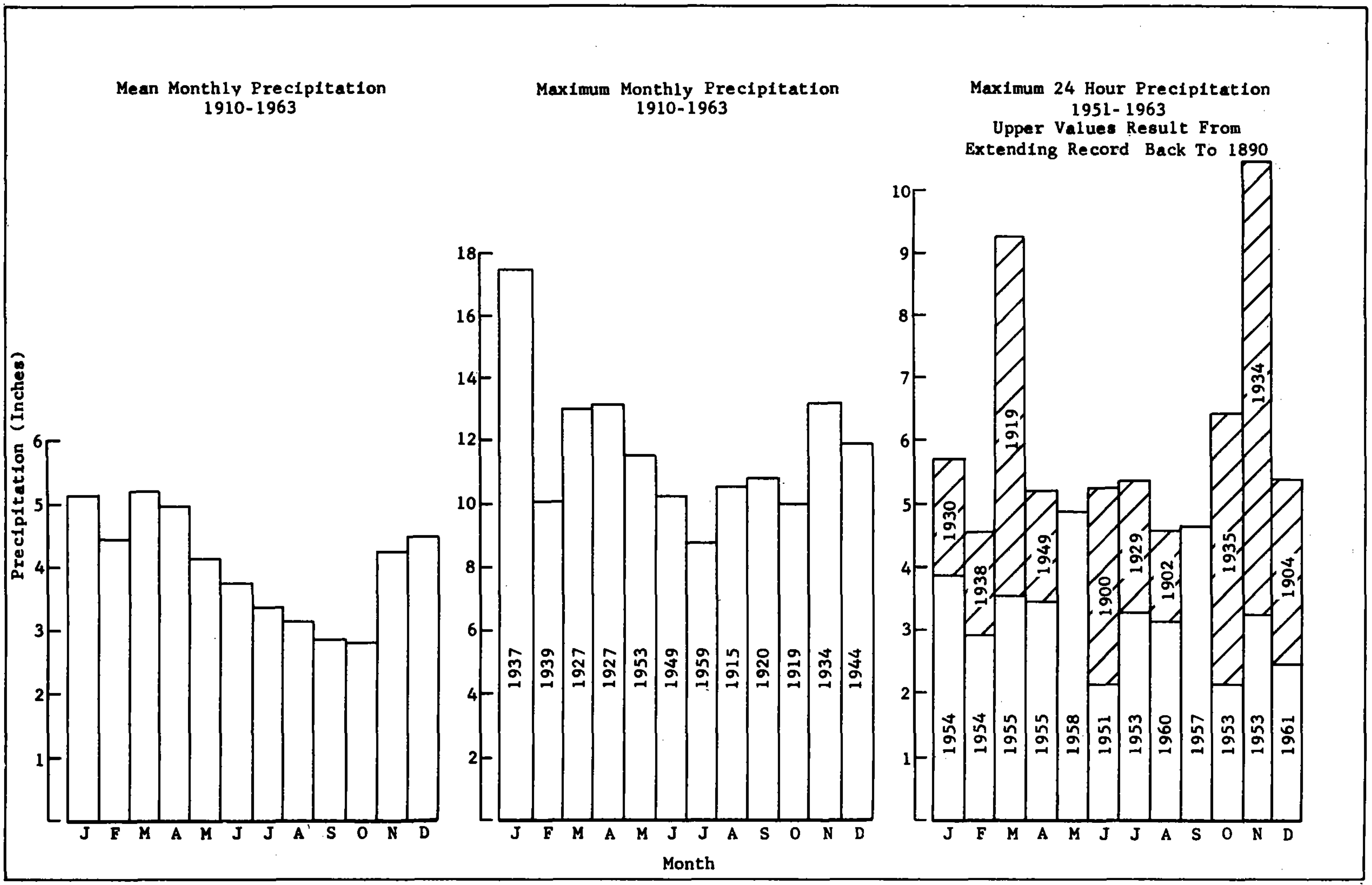


Figure 3-4. Mean and extreme rainfall - Memphis

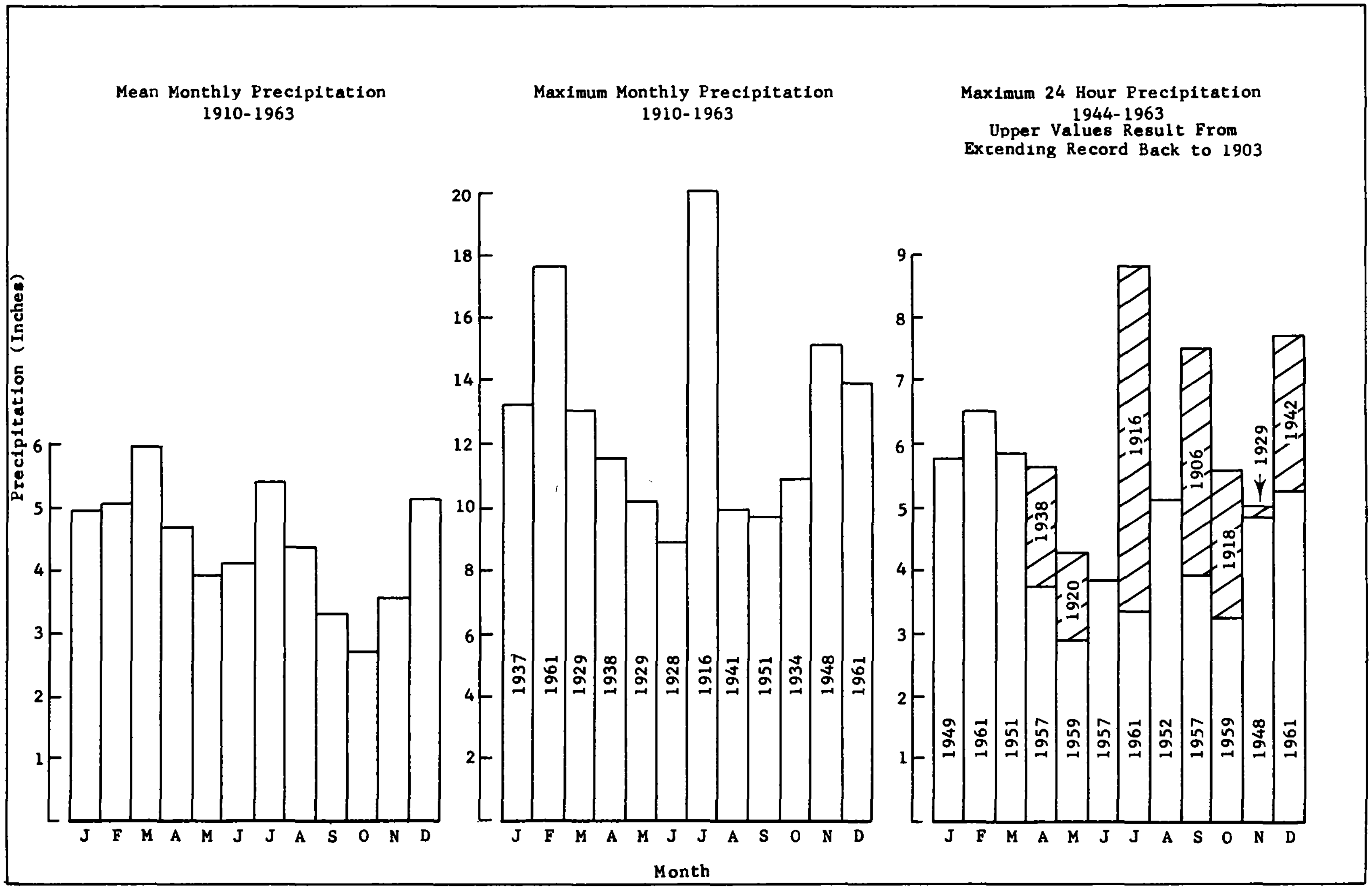


Figure 3-5. Mean and extreme rainfall - Birmingham

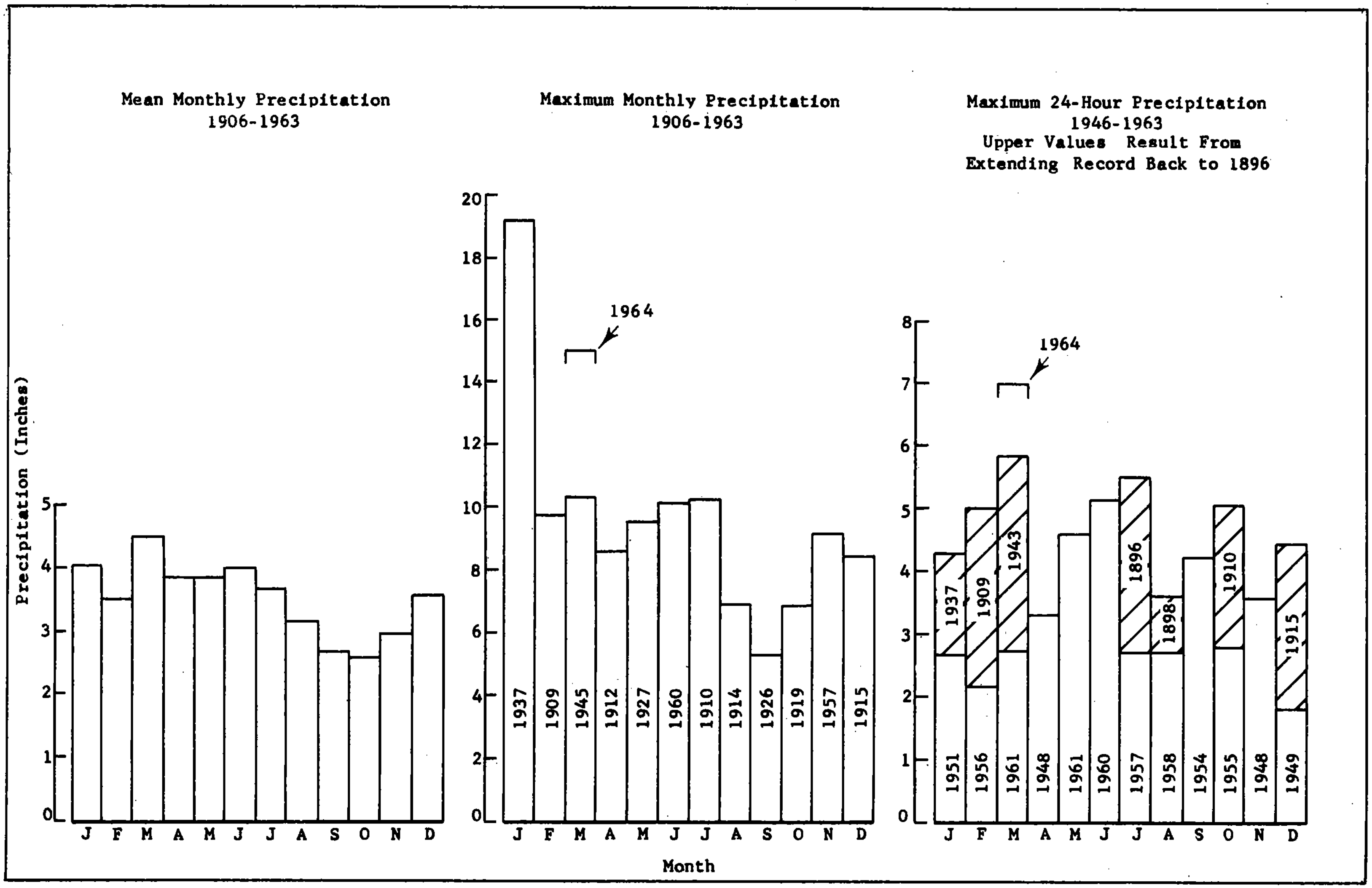


Figure 3-6. Mean and extreme rainfall - Louisville

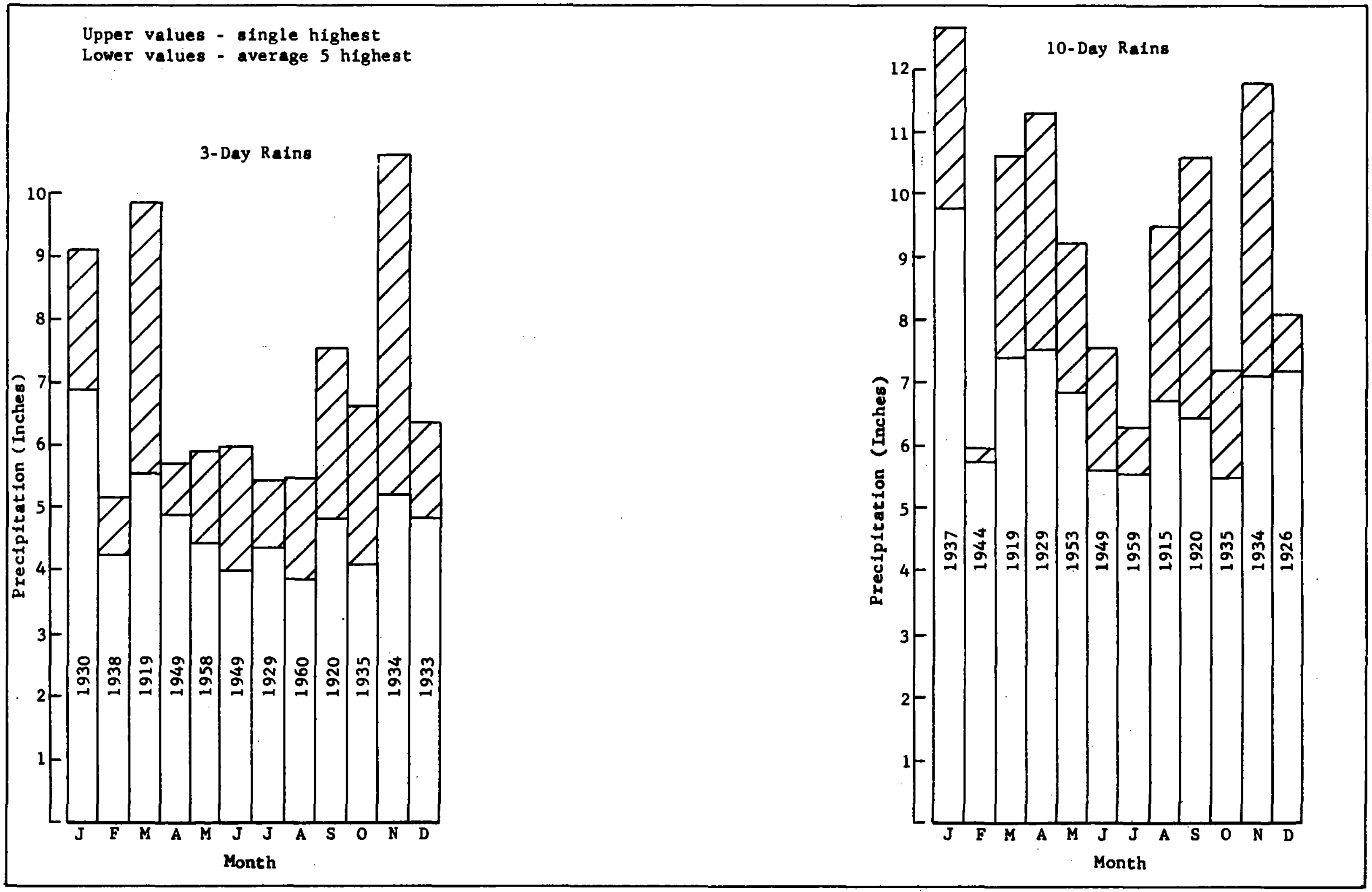


Figure 3-7. Extreme 3- and 10-day rains - Memphis (1912-1961)

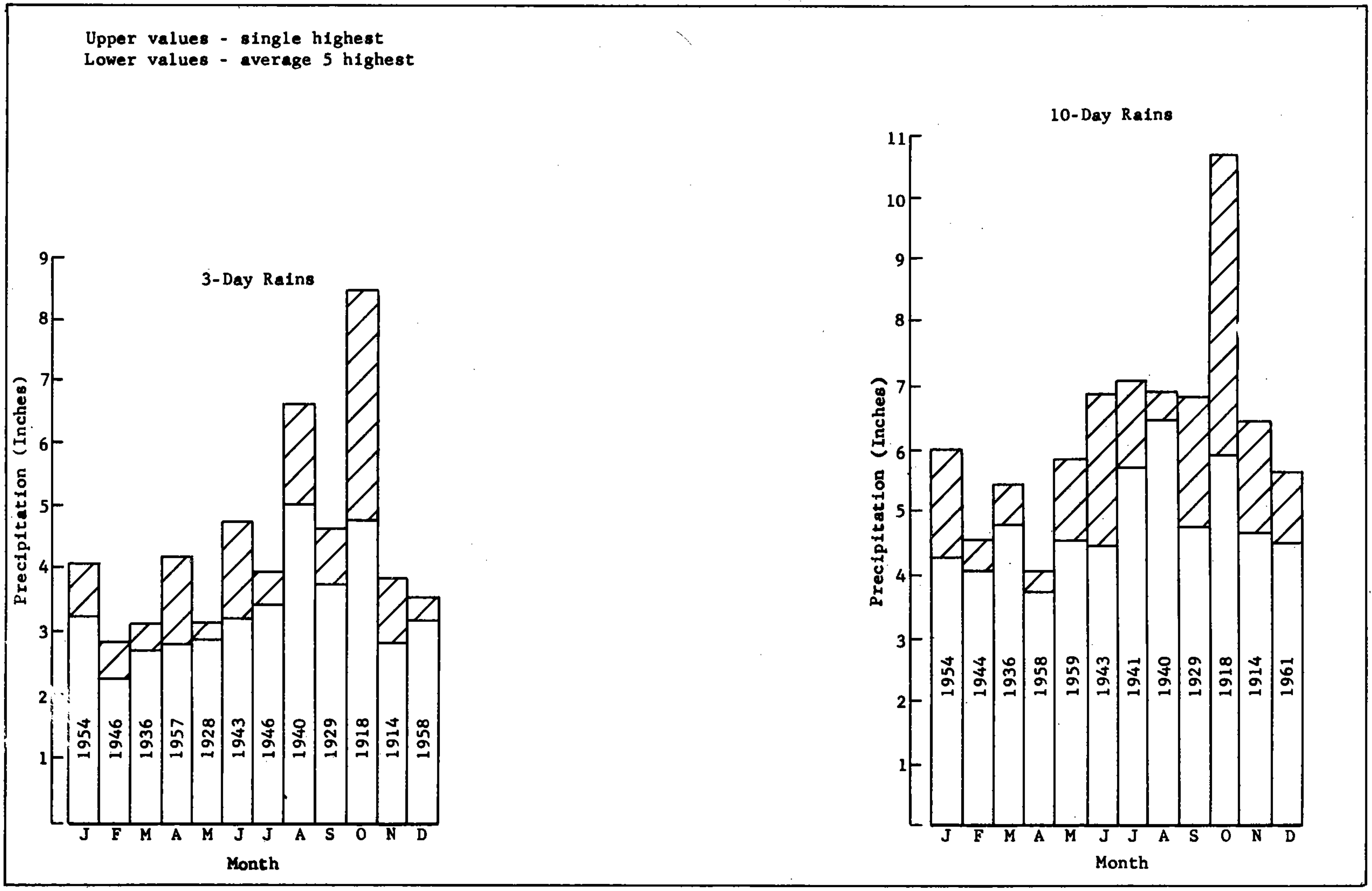


Figure 3-8. Extreme 3- and 10-day rains - Asheville (1912-1961)

Meteorology of past Tennessee Valley storms

The meteorological features of past flood-producing storms in the Valley are summarized below. Flood occurrences are divided into three categories:

(1) Outstanding floods prior to 1900
(2) Selected floods 1900-1936 (table 3-1)
(3) Floods since 1950 (table 3-2)

In category (2), situations are selected to obtain some cases of high flood flows in the warmer months even though the magnitude of flow was lower than many of the cooler-season floods not considered.

Outstanding storms prior to 1900. Three outstanding flood-producing storms prior to 1900 were: (1) March 1-7, 1867; (2) February 23-25, 1875; and (3) March 26-April 1, 1886.

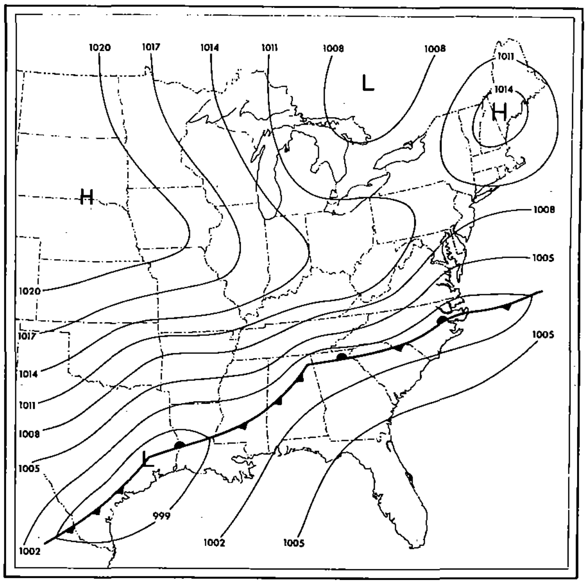
The March 1867 storm is classified primarily as the quasi-stationary frontal type with waves. This storm produced the highest stage of record at Chattanooga. Limited rainfall measurements point to a total storm rainfall of 12 inches or more extending from southwest of Chattanooga across the headwaters of the Hiwassee and Little Tennessee drainages.

The "Clingmans Dome" storm of February 23-25, 1875 was an intense concentration of rainfall resulting from convergence within warm moist air as low pressure systems intensified west of the Appalachians. The rainfall centered well to the southeast of the path of the primary low-pressure disturbance in the manner of the April 15-18, 1900 Eutaw, Ala. storm (see discussion of transposed storms in chapter V). The 1875 storm had an elongated southwest-to-northeast oriented isohyetal pattern - typical of many of the storms transposable to the Tennessee Basin (see fig. 5-1). A rainfall center of nearly 8 inches was located at Knoxville, Tenn.

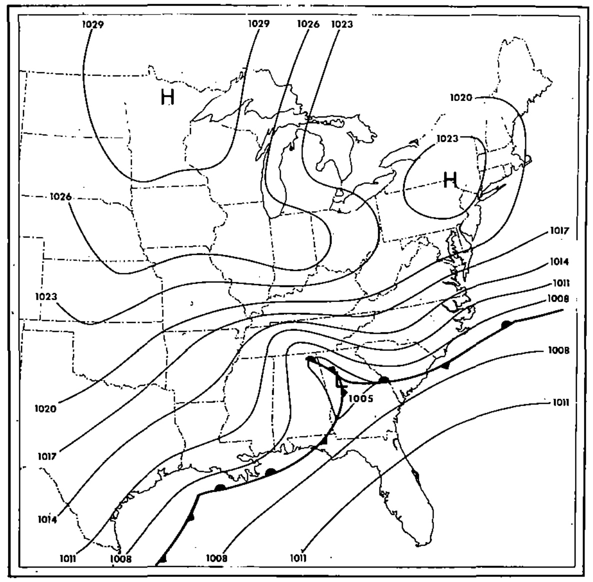
Surface weather charts for the 1867, 1875 and 1886 storms are shown in figures 3-9 through 3-11. These were adapted from original analyses made by Kleinsasser.

The "Pink Beds" storm of March 26 to April 4, 1886 resulted in the third highest discharge at Chattanooga for the period 1867 to 1937. This storm is best classified as the quasi-stationary frontal type. The quasi-stationary stage was accompanied by a wave disturbance. Finally, a northward moving low-pressure system brought an end to the rainy spell.

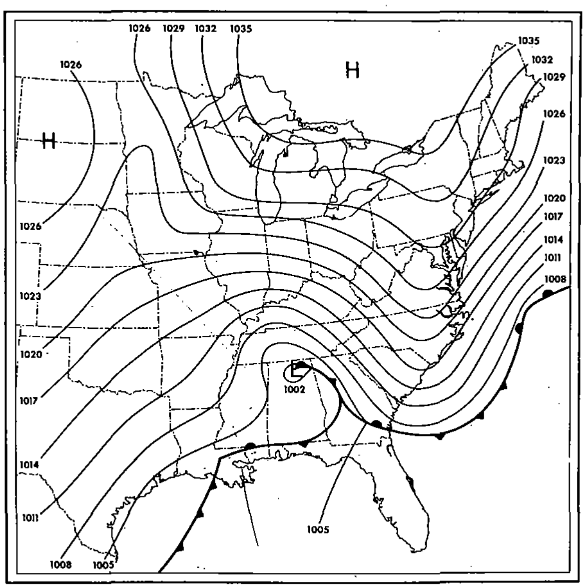
Selected storms since 1900. The highest flow at Chattanooga for each of seven months is shown in table 3-1. These data are taken from Geological Survey Water Supply Paper 1676 (Ref. 3-8). The period through 1936 is considered most appropriate since increased regulation of flow by reservoirs was introduced in subsequent years. The meteorological characteristics of these storms are similar to those of later storms as discussed following table 3-2. Table 3-2 (computed natural flows with stages at Chattanooga greater than 35 ft.) summarizes recent cases (1950-1963) of high flow abstracted from data supplied by the TVA.



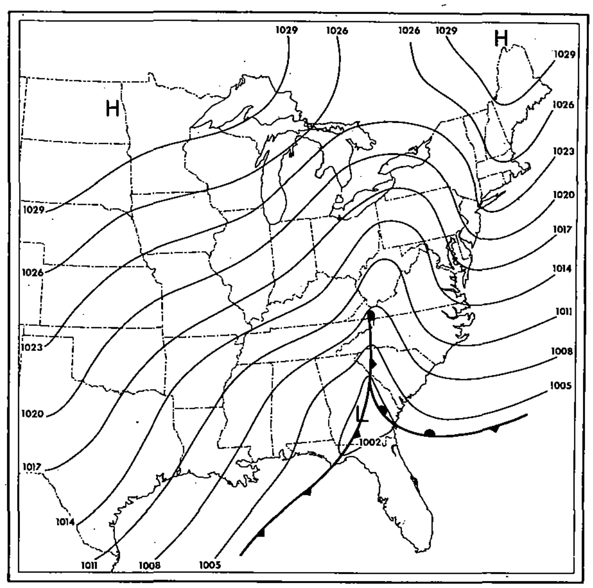
March 4, 1867



March 5, 1867

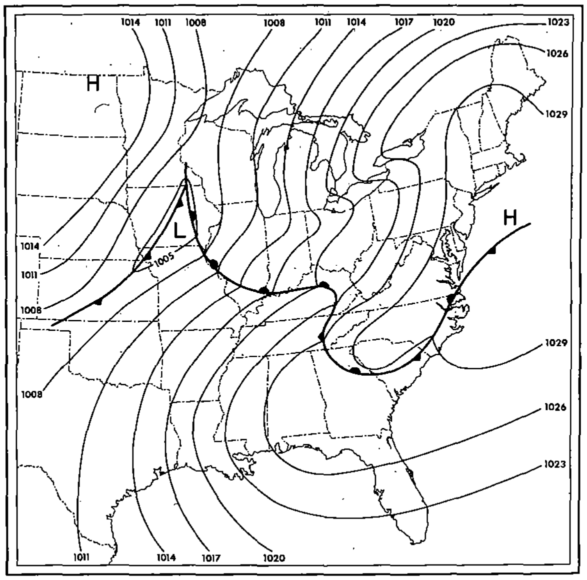


March 6, 1867

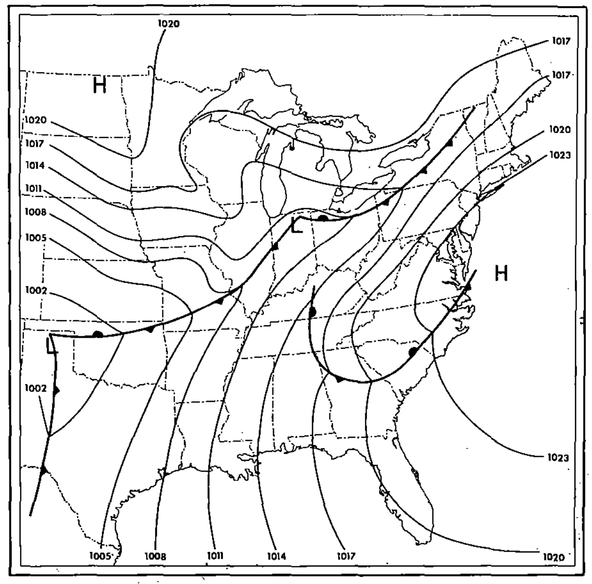


March 7, 1867

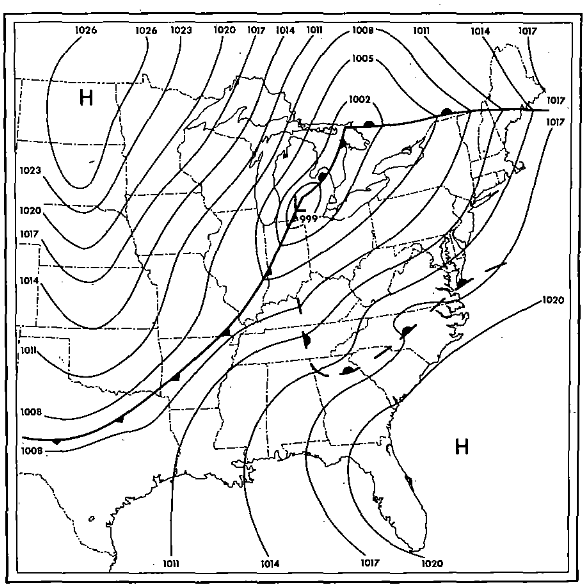
Figure 3-9. Surface weather maps (A.M.) for March 1-7, 1867 storm



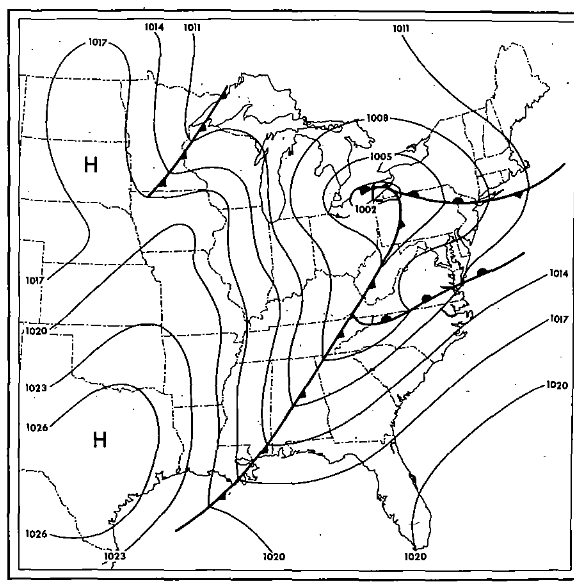
February 22, 1875



February 23, 1875

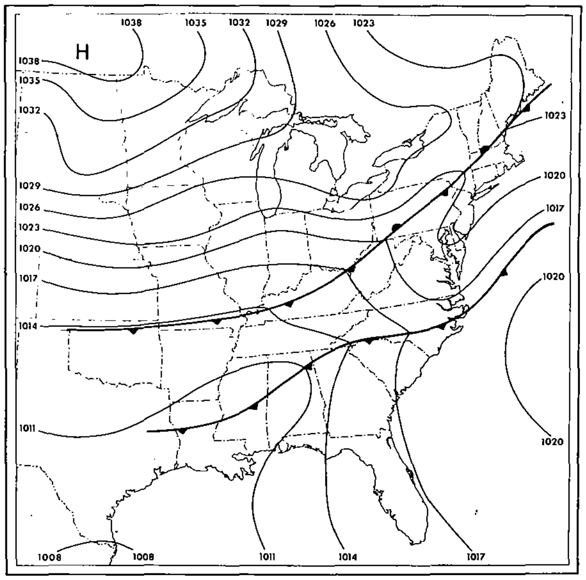


February 24, 1875

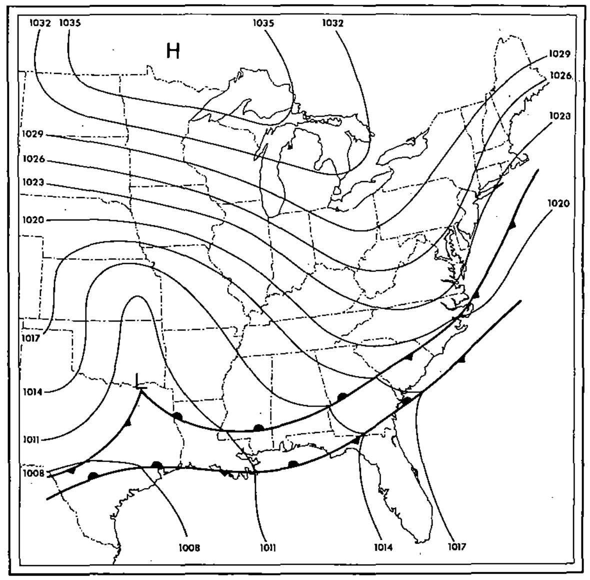


February 25, 1875

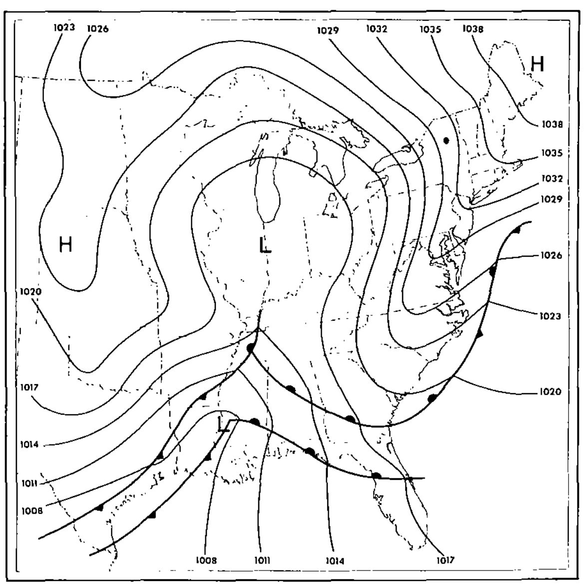
Figure 3-10. Surface weather maps (A.M.) for February 23-25, 1875 storm



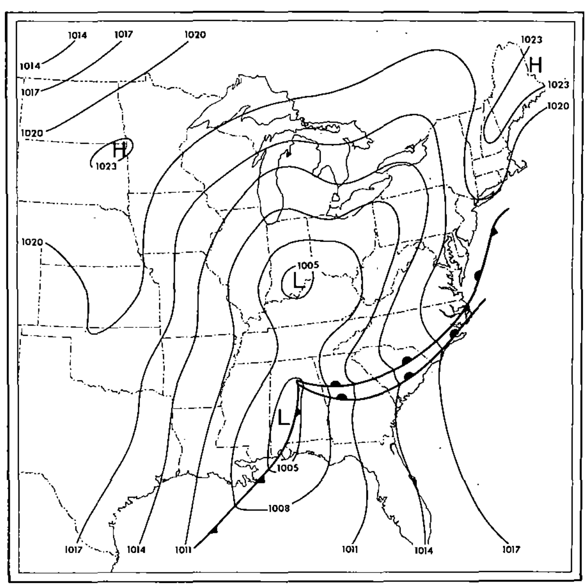
March 27, 1886



March 28, 1886



March 29, 1886



March 30, 1886

Figure 3-11. Surface weather maps (A.M.) for March 26-April 1, 1886 storm

Table 3-1

HIGHEST FLOWS BY MONTHS AT CHATTANOOGA (1900-1936)

Date of High Flow	Flow (Second Feet)	Stage (Feet)
January 2, 1902	271,000	40.8
February 2, 1918	270,000	42.4
March 7, 1917	341,000	47.7
April 5, 1920	275,000	43.6
May 25, 1901	221,000	33.2
June 6, 1909	163,000	25.3
November 22, 1906	222,000	33.4

Table 3-2

COMPUTED NATURAL MAXIMUM FLOW AT CHATTANOOGA (1950-1963)

Date of High Flow	Flow (Second Feet)	Stage (Feet)
February 3, 1957	412,000	54.0
March 15, 1963	347,000	48.3
January 24, 1954	275,000	41.3
February 4, 1950	258,000	39.6
February 26, 1962	252,000	39.0
December 19, 1961	249,000	38.6
November 20, 1957	232,000	36.8
January 29, 1962	230,000	36.6
February 26, 1961	229,000	36.4
March 23, 1955	223,000	35.8
March 30, 1951	221,000	35.6

Meteorological discussions of some of these high flow storms are found in recent TVA publications (Refs. 3-9, 3-10, 3-11, 3-12). Surface weather charts for the cases of table 3-1 and for some of the recent storms are shown in appendix B, figures 3B-1 through 3B-10b.

The highlights of these significant storms are enumerated:

(1) quasi-stationary fronts with wave developments of varying intensity.
(2) southwesterly flow aloft.

(3) strongly contrasting temperatures. One example of the role of contrasting temperatures during heavy convergence rain in the warm air occurred on January 20, 1954,in connection with a southward-moving cold air mass. Kleinsasser (Ref. 3-9), in discussing the rainfall of January 20, 1954, states,

> "studies of past storms indicate that such a field of convergence remains active over an area as large as the Tennessee Valley as long as the cold air continues its active southward surge, frequently lasting 12 to 24 hours and seldom exceeding 30 hours."

(4) Much thundershower activity and strong southerly low-level flow from the Gulf of Mexico. It is noteworthy that these two features are associated with most of the outstanding large-area cool-season storms in the Eastern United States. This is true of the Elba, Ala. storm of March 1929. The Elba storm is one of the more important storms instrumental in establishing the magnitude of the probable maximum rainfall resulting from the cool-season type storm (chapter V).

Resume of March 1963 storm

A recent TVA publication (Ref. 3-12) presents rainfall statistics for the storms of March 5-6, 1963 and March 11-12, 1963. Precipitation of March 5-6 was heaviest in the mountainous southeastern section of the Tennessee Basin with some amounts in excess of six inches occurring mostly in a 24-hr. period. The average over the 21,400-sq. mi. area above Chattanooga was 3.22 inches.

Rainfall of March 11-12, 1963 in the area above Chattanooga averaged 4.49 inches, with 3.34 inches in 24 hours, highest 24-hr. average in the last 20 years. This compares with 4.0 inches, the statistically-computed March daily value with a 100-yr. return period, based on extrapolation from the 20-yr. record (1944-1963).

The heavy rain periods are best understood in terms of the prevailing weather features. The important feature of a low-pressure trough in the upper levels shows up clearly in figure 3-12. This is a composite chart showing the flow of air and prevailing temperatures that resulted from averaging observational data from four successive upper-air observations on March 4-5, 1963. It shows conditions at 500 mb, or approximately 18,000 ft. above the surface.

Surface weather features were characterized by slow or restricted motions of the prevailing fronts. Figure 3-13 demonstrates this for both rain periods in March 1963. The approximate 2-in., 24-hr. isohyetal patterns and the tracks of low pressure centers are shown in figures 3-14 and and 3-15. Primary tracks of low pressure for March (fig. 3-16) show that disturbances move in a northeastward direction west of the basin (Ref. 3-13). With just the right motion a strong influx of moisture may affect the basin as in March 1963.

A composite chart (fig. 3-17a) shows prevailing moisture conditions at the 850-mb level for March 4-5, 1963. A tongue of moist air with a dew point of 8°C extends northeastward from the Gulf of Mexico to Tennessee. Another 850-mb moisture composite chart is shown as figure 3-17b. This is based on 54 winter moist tongue cases separated into three rainfall categories. The rainfall categories are simple station averages over 15,000 square miles. The outline of the mean 5°C dew point is shown in figure 3-17b for each rainfall category. The accompanying legend shows dew point values at specific latitudes along the axes in each category. The similarity of the March 1963 situation to the composite winter heavy rain case (category C) is evident.

Resume of January-February 1957 storm

Without TVA flood regulation it is estimated (Ref. 3-10, p. 1) that accumulated runoff from tributary basins into the Tennessee River from this storm would have resulted in a flood at Chattanooga second only to that of March 1867. It is important therefore to consider the meteorological features of this storm. The TVA report (Ref. 3-10) highlights the following:

(1) The frontal zone remained quasi-stationary in the vicinity of the Tennessee River Basin for the major portion of the January 20-February 10, 1957 period.

(2) Heaviest rain fell from midnight of January 26 into February 1 (62 percent of the 21-day total fell over the basin during this period).

(3) From January 21 through February 8 a combination of a Gulf of Alaska ridge aloft and a West Coast upper trough remained relatively fixed.

(4) During the periods of heavy rains there were no developments of intense low-pressure disturbances. Instead, numerous wave disturbances moved over approximately the same region.

(5) A reversal of the controlling large-scale regime aloft brought an end to the rainy period.

The unusual January circulation features of 1957 are similar to those of 1937, 1949 and 1950--months of serious floods. Weather maps for the January-February 1957 storm are shown in figures 3-18a through 3-18d. Noteworthy of the January 1957 rains compared to those of March 1963 was the absence of vigorous low-pressure developments. This kind of situation permits a continuing influx of moisture into approximately the same region. The rainfall in January-February 1957 was generally less intense but more persistent than that of the March 1963 rainy periods. Comparison of rainfall intensities for these storms is shown in table 3-3 in the form of depth-duration-area data supplied by the TVA for these two important storms.

Conclusions

The March 1963 and January-February 1957 storms, like many other large Tennessee Basin storms of earlier years, emphasize the importance of the

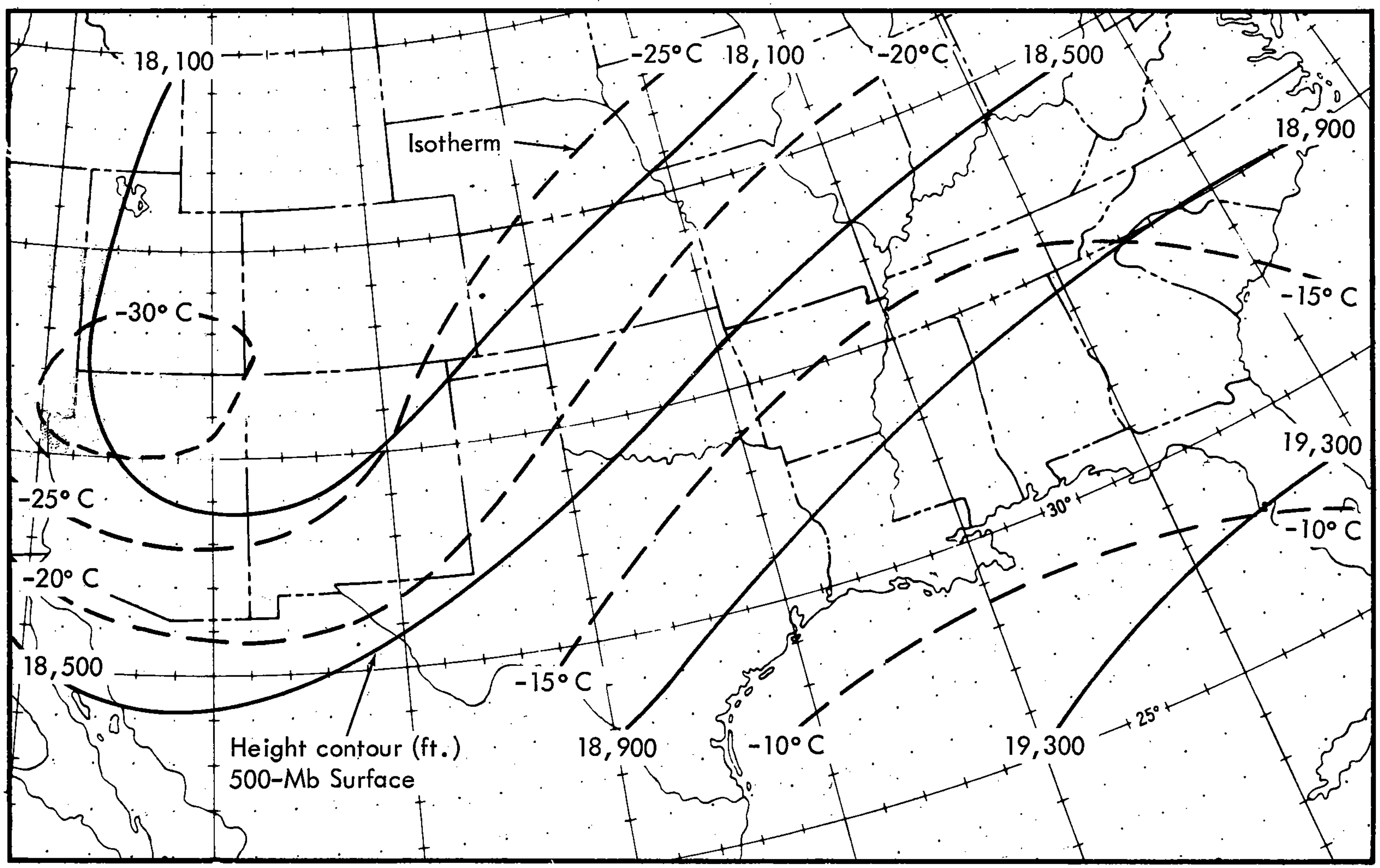


Figure 3-12. Mean 500-mb flow for March 4-5, 1963

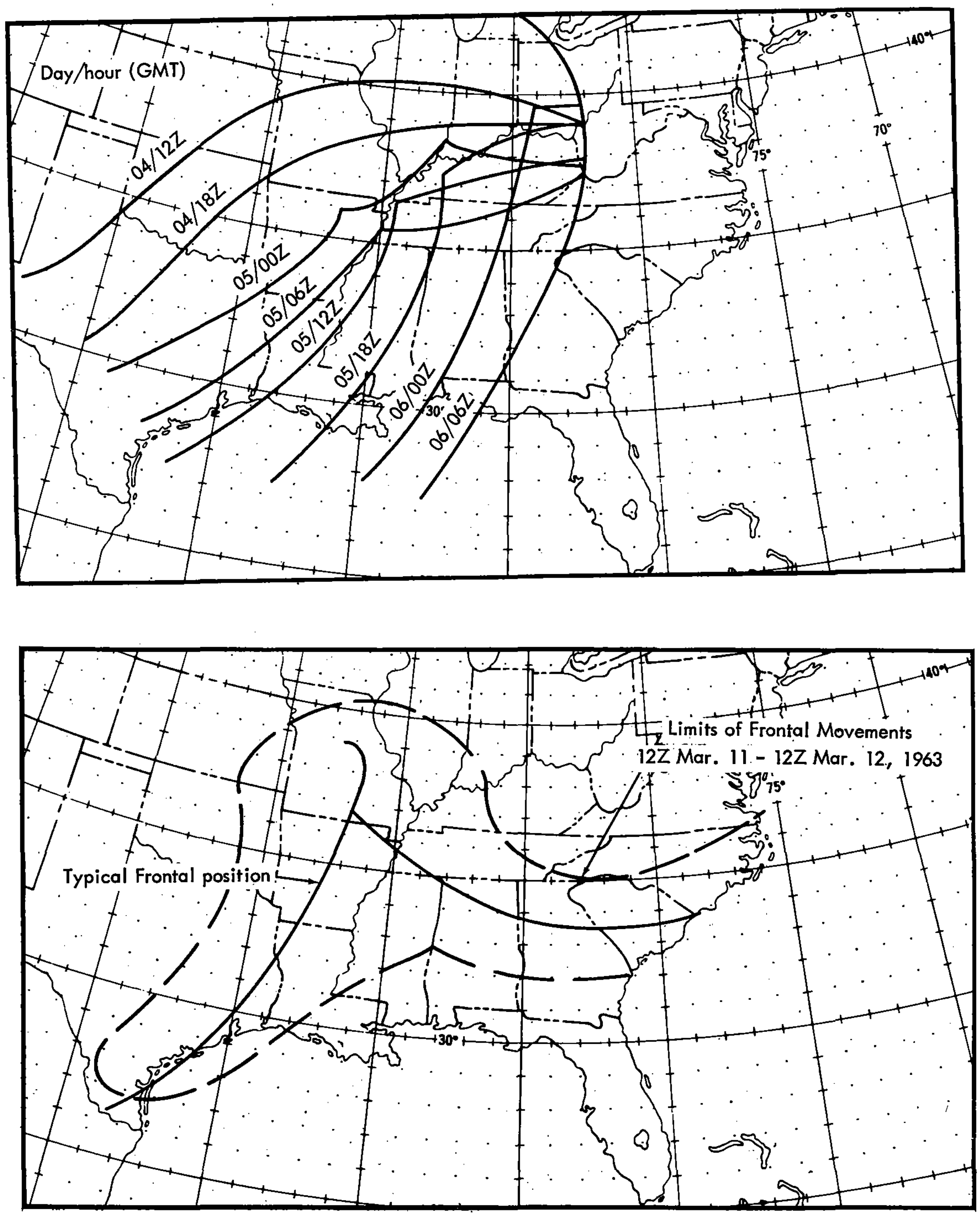


Figure 3-13. Surface frontal positions for March 1963 storm

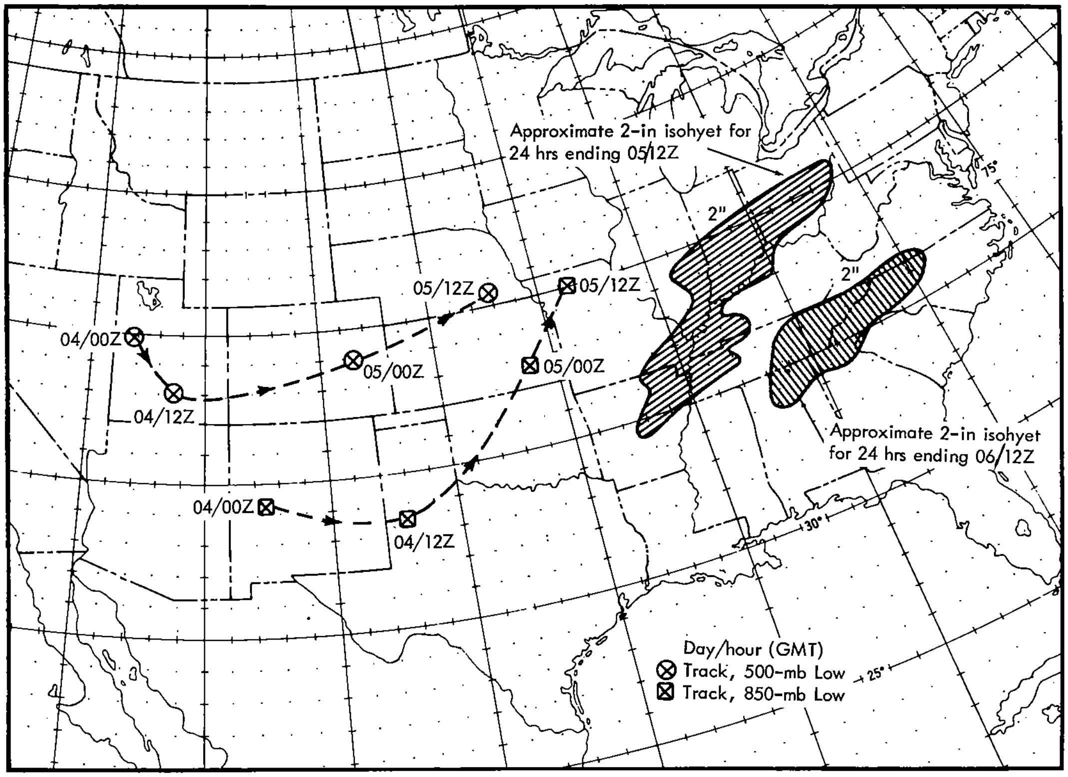


Figure 3-14. Low tracks and rain pattern - March 5-6, 1963

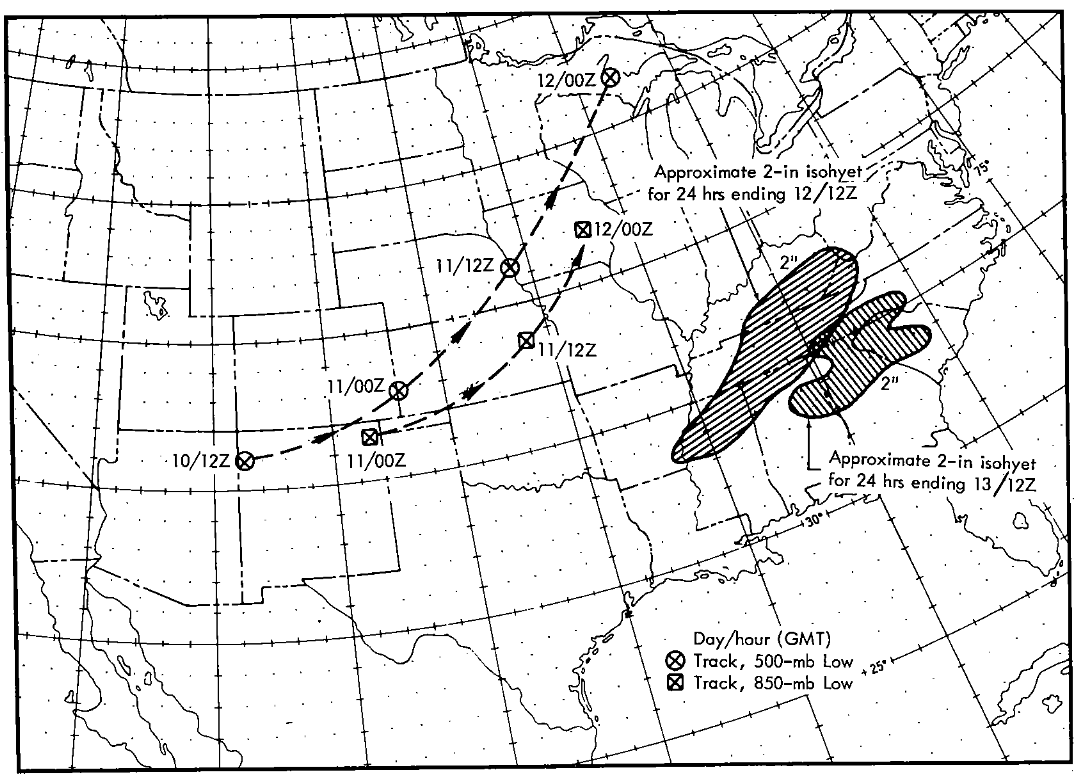


Figure 3-15. Low tracks and rain pattern - March 11-12, 1963

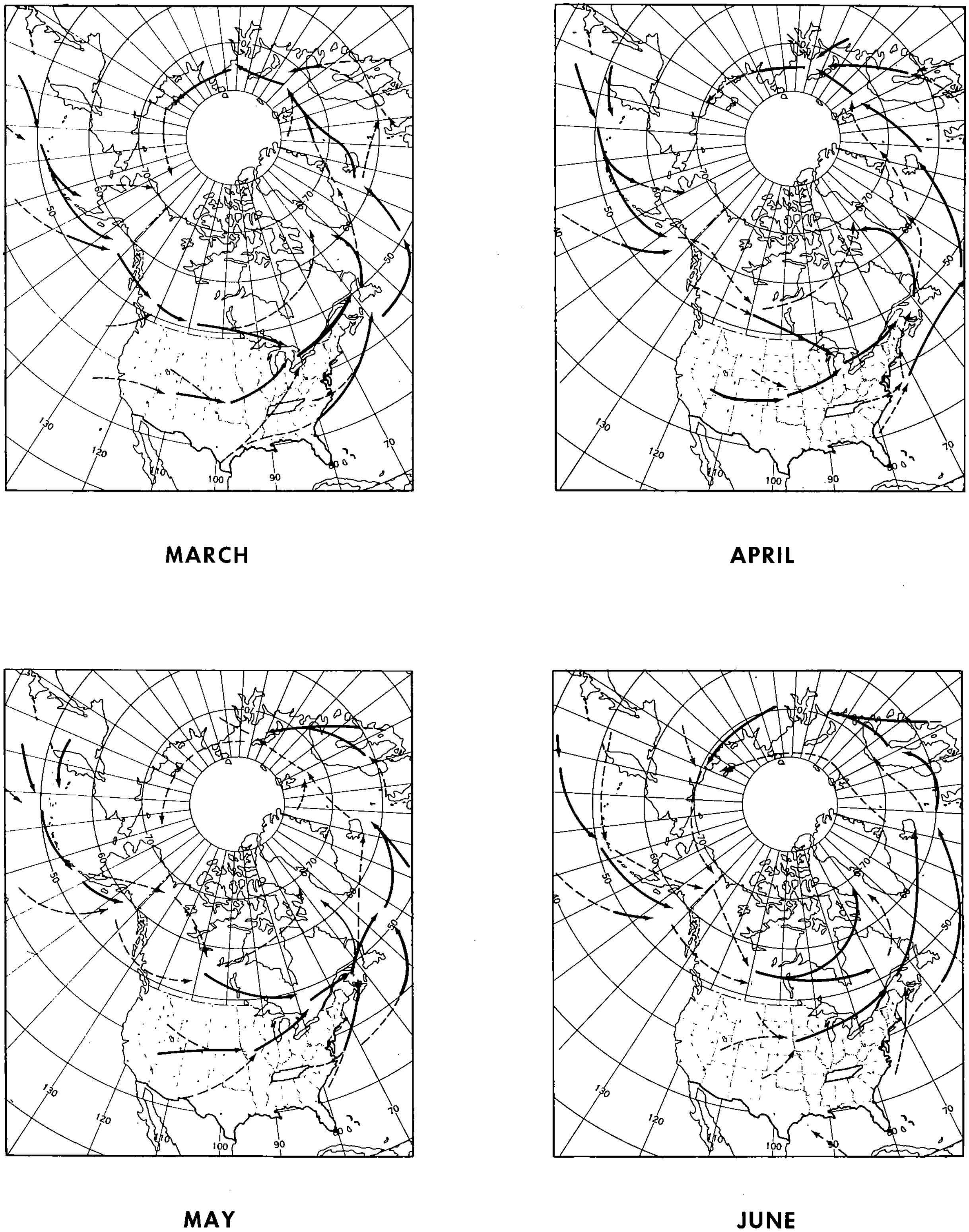


Figure 3-16. Primary (solid) and secondary (dashed) tracks of Lows (From Ref. 3-13)

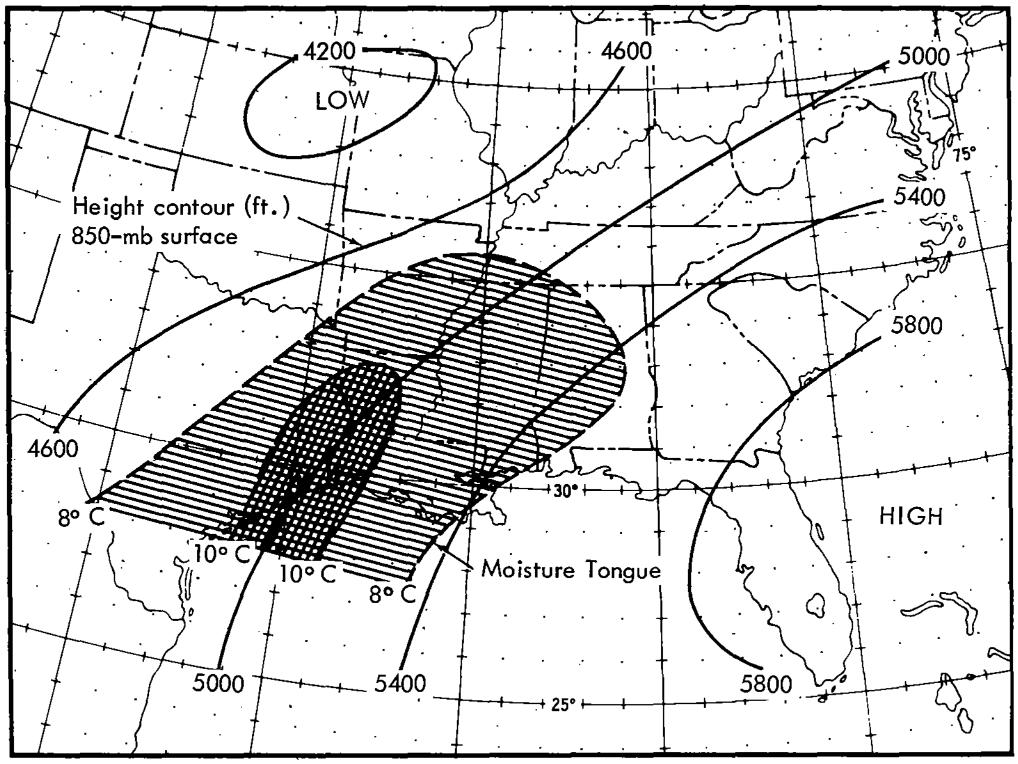
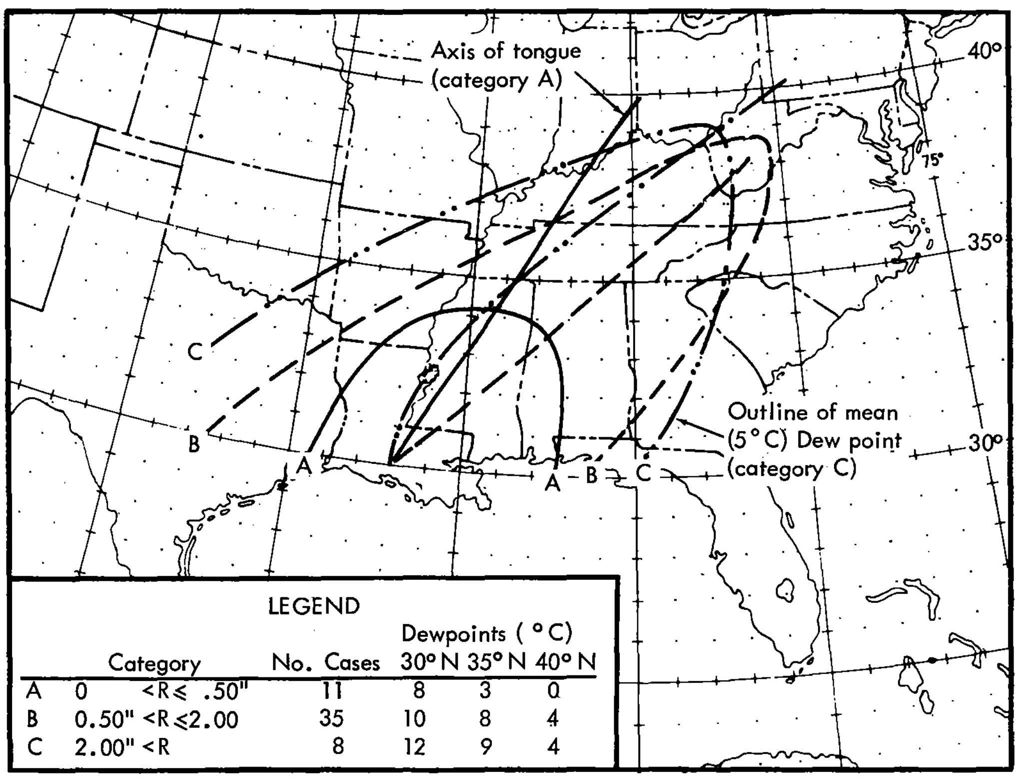


Figure 3-17a. Mean 850-mb flow for March 4-5, 1963



Category		No. Cases	Dewpoints (°C) 30° N	35° N	40° N
A	0 <R≤ .50"	11	8	3	0
B	0.50" <R≤2.00	35	10	8	4
C	2.00" <R	8	12	9	4

Figure 3-17b. Mean moisture tongue for January rain cases

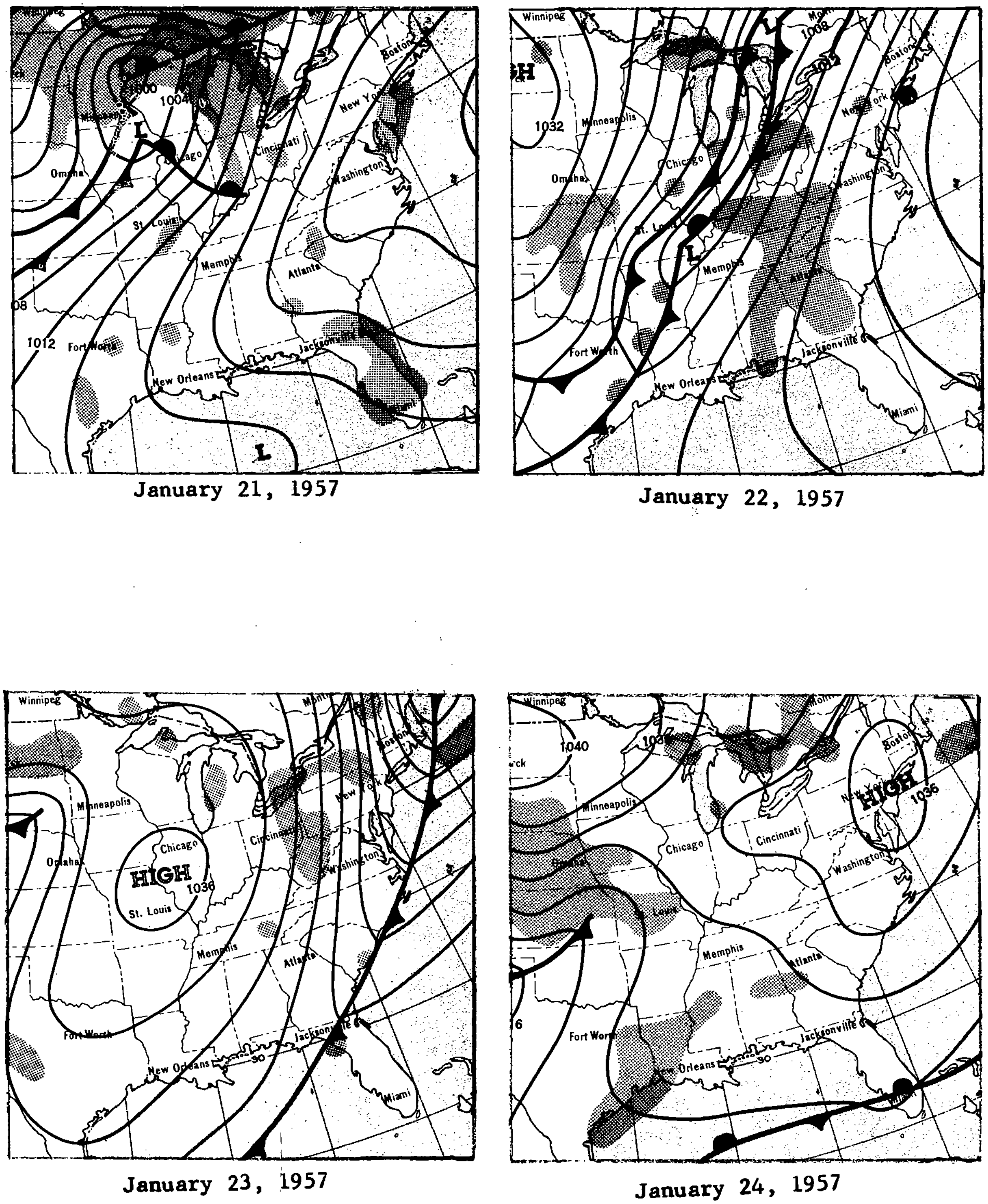
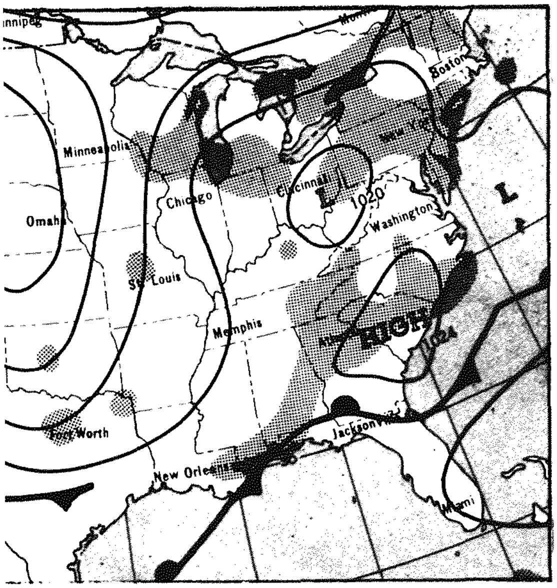
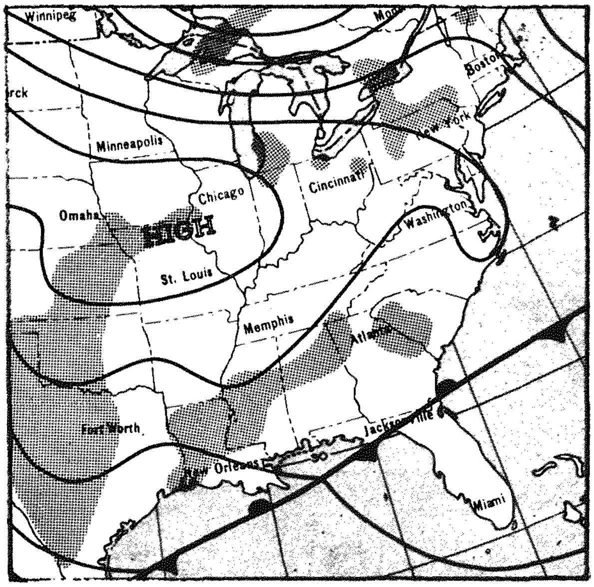


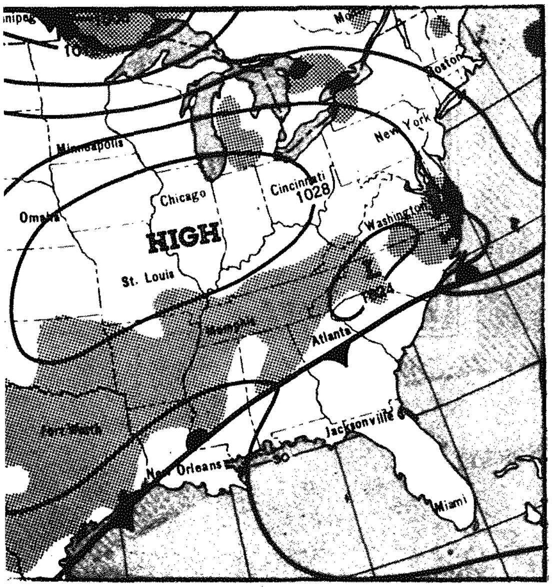
Figure 3-18a. Surface weather maps (1800 GMT) for January 1957 storm



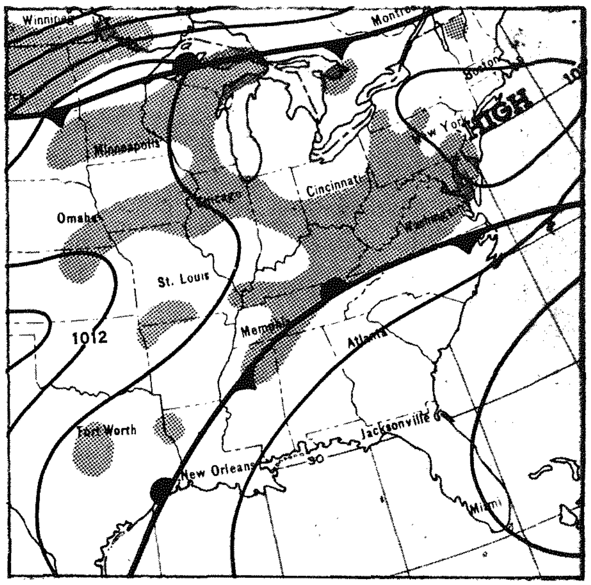
January 25, 1957



January 26, 1957

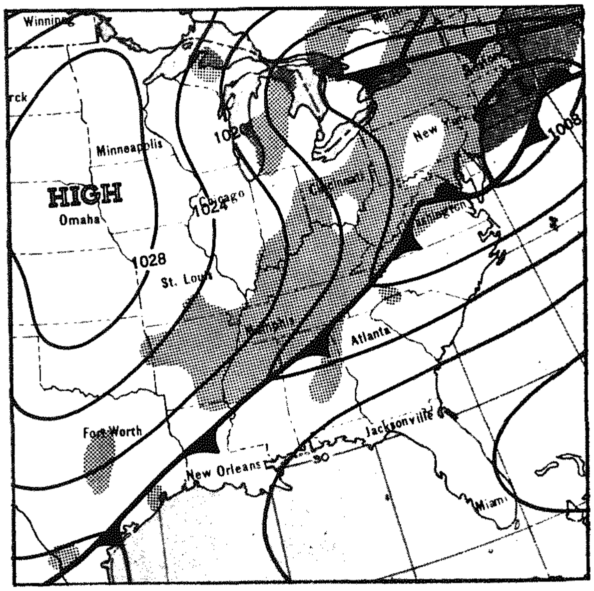


January 27, 1957

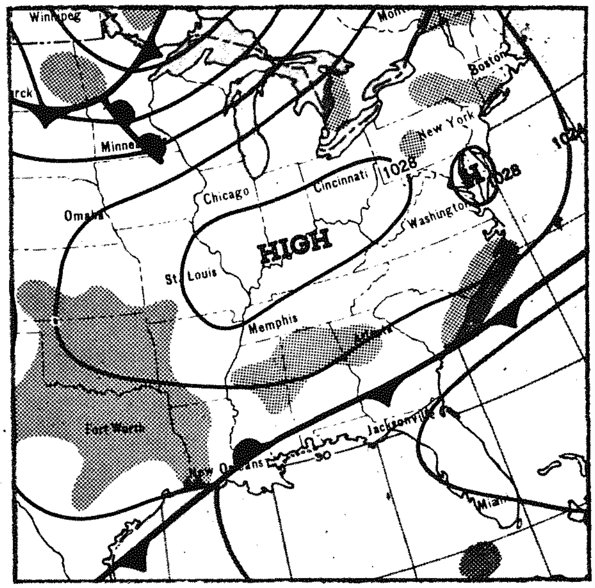


January 28, 1957

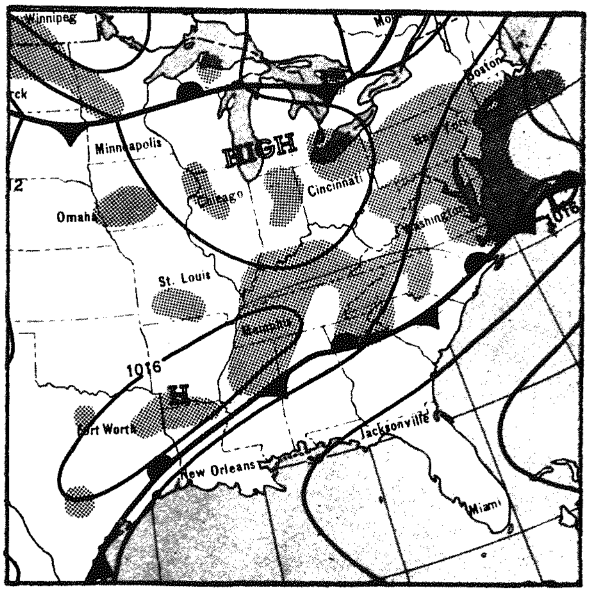
igure 3-18b. Surface weather maps (1800 GMT) for January 1957 storm



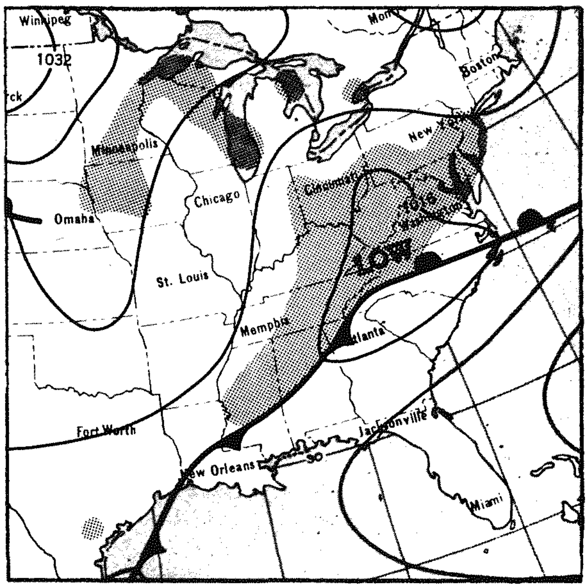
January 29, 1957



January 30, 1957

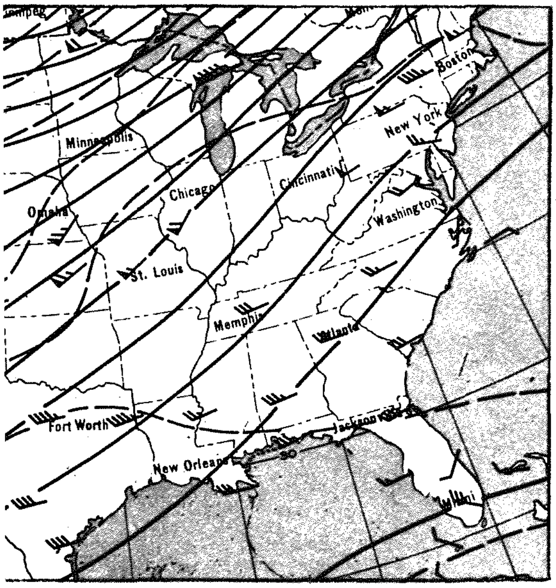


January 31, 1957

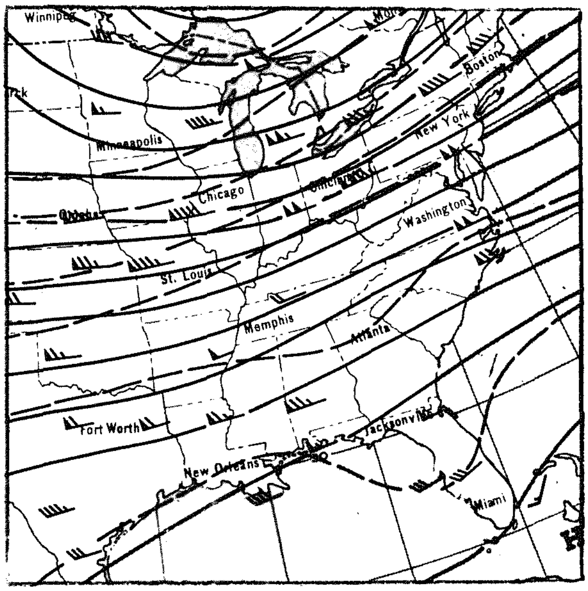


February 1, 1957

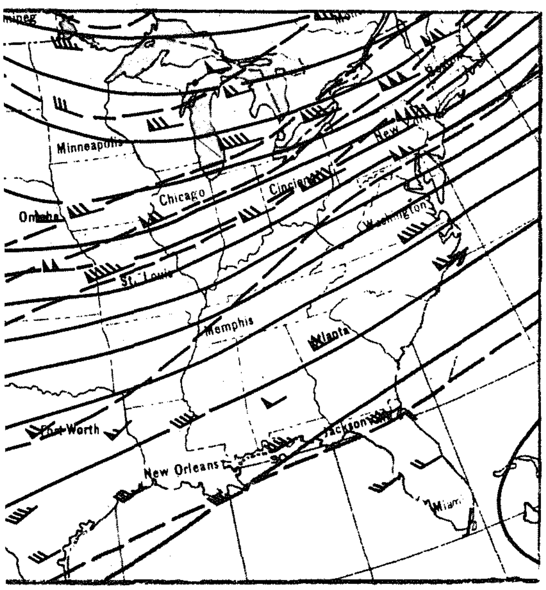
Figure 3-18c. Surface weather maps (1800 GMT) for January 1957 storm



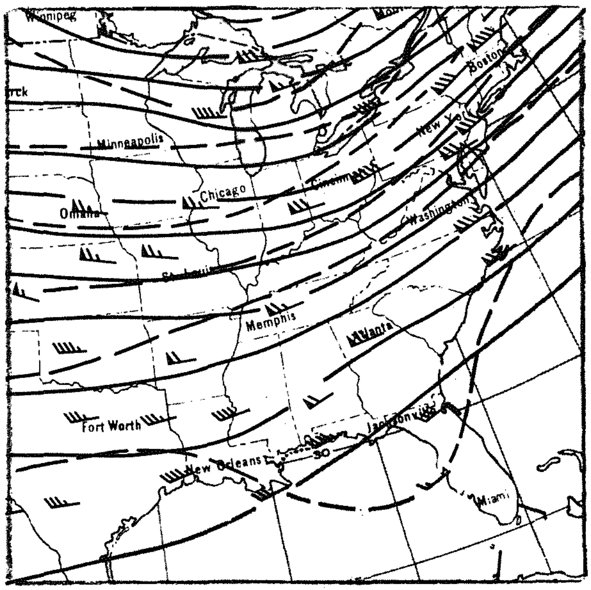
(500 mb)
January 21, 1957



(500 mb)
January 25, 1957



(500 mb)
January 29, 1957



(500 mb)
February 1, 1957

igure 3-18d. Upper-air weather maps (0300 GMT) for January 1957 storm persistence, or persistent recurrence, of the broadscale rain-favoring features. Within the framework of the broadscale weather controls, a variety of day-by-day weather developments may take place. The severity of a resulting flood is a function not only of such meteorological developments but also of other factors. Thus a less intense, but more persistent rain, as in the 1957 storm, may produce a more critical large-basin flood than the more intense but less persistent type like that of March 1963.

Table 3-3

MAXIMUM DEPTH-AREA DATA

STORM OF JANUARY 27-FEBRUARY 2, 1957

Centers at Shelbyville, Tenn., and Clingmans Dome, N. C. Depth-area data are for the area enclosed by the 7-in. isohyet.

MAXIMUM AVERAGE DEPTH OF RAINFALL IN INCHES

Area	Duration of Rainfall in Hours										
(Square Miles)	6	12	18	24	30	36	48	72	96	120	138
100	2.5	4.4	5.8	6.8	7.5	7.6	8.0	8.3	9.5	10.1	11.5
500	2.2	3.6	4.8	5.6	6.0	6.3	7.1	7.3	8.4	9.1	10.4
1,000	2.0	3.3	4.5	5.1	5.5	5.8	6.8	6.9	8.1	8.8	10.0
2,000	1.8	3.0	4.2	4.7	5.1	5.4	6.5	6.6	7.8	8.5	9.7
5,000	1.6	2.6	3.8	4.3	4.7	5.0	6.1	6.3	7.4	8.2	9.4
10,000	1.4	2.3	3.4	4.0	4.4	4.7	5.8	5.9	7.0	8.0	9.1
20,000	1.2	2.0	3.0	3.6	4.0	4.3	5.4	5.5	6.6	7.7	8.7
40,000	1.0	1.6	2.5	3.0	3.5	3.7	4.8	4.9	6.1	7.3	8.2

STORM OF MARCH 11-12, 1963

Center at Signal Mountain, Tenn. Depth-area data are for area west of Appalachian Divide enclosed by the 3-in. isohyet.

MAXIMUM AVERAGE DEPTH OF RAINFALL IN INCHES

Area	Duration of Rainfall in Hours						
(Square Miles)	6	12	18	24	30	36	42
100	5.1	6.4	7.2	7.7	8.1	8.4	8.5
500	4.8	5.8	6.7	7.2	7.6	7.9	8.0
1,000	4.5	5.5	6.4	6.9	7.3	7.6	7.7
2,000	4.1	5.1	6.1	6.6	7.0	7.2	7.4
5,000	3.2	4.4	5.4	6.0	6.3	6.6	6.8
10,000	2.4	3.5	4.4	5.0	5.4	5.7	5.9
20,000	2.0	3.0	3.8	4.4	4.7	5.0	5.2
45,000	1.8	2.8	3.5	3.9	4.3	4.5	4.7

3-C. METEOROLOGY OF WARM-SEASON STORMS

Introduction

Many of the world's extreme rainfall records have been associated with hurricanes.* The most extreme rains have occurred over islands or close to the coasts of large land masses. For example, Hurricane Easy of September 3-7, 1950 produced most of the maximum observed United States rainfall values for areas up to 5000 square miles and durations to 72 hours. The importance of this storm and others of tropical origin, as producers of maximum U. S. rainfalls, is shown in table 3-4. Values resulting from hurricanes, including residual tropical storms, are underlined in the table.

Table 3-4

MAXIMUM OBSERVED U. S. RAINFALL (in.)

(Revised June 1960)

Area (Square Miles)	Duration (hours) 6	12	18	24	36	48	72
10	24.7 a	<u>29.8 b</u>	<u>36.3 c</u>	<u>38.7 c</u>	<u>41.8 c</u>	<u>43.1 c</u>	<u>45.2 c</u>
100	<u>19.6 b</u>	<u>26.3 c</u>	<u>32.5 c</u>	<u>35.2 c</u>	<u>37.9 c</u>	<u>38.9 c</u>	<u>40.6 c</u>
200	<u>17.9 b</u>	<u>25.6 c</u>	<u>31.4 c</u>	<u>34.2 c</u>	<u>36.7 c</u>	<u>37.7 c</u>	<u>39.2 c</u>
500	<u>15.4 b</u>	<u>24.6 c</u>	<u>29.7 c</u>	<u>32.7 c</u>	<u>35.0 c</u>	<u>36.0 c</u>	<u>37.3 c</u>
1000	<u>13.4 b</u>	<u>22.6 c</u>	<u>27.4 c</u>	<u>30.2 c</u>	<u>32.9 c</u>	<u>33.7 c</u>	<u>34.9 c</u>
2000	<u>11.2 b</u>	<u>17.7 c</u>	<u>22.5 c</u>	<u>24.8 c</u>	<u>27.3 c</u>	<u>28.4 c</u>	<u>29.7 c</u>
5000	<u>8.1 bj</u>	<u>11.1 b</u>	<u>14.1 b</u>	<u>15.5 c</u>	18.7 d	20.7 d	24.4 d
10,000	<u>5.7 j</u>	7.9 k	10.1 e	12.1 e	15.1 d	17.4 d	21.3 d
20,000	<u>4.0 j</u>	6.0 k	7.9 e	9.6 e	11.6 d	13.8 d	17.6 d
50,000	2.5 eh	4.2 g	5.3 e	6.3 e	7.9 e	8.9 e	<u>11.5 f</u>
100,000	1.7 h	2.5 ih	3.5 e	4.3 e	5.6 e	<u>6.6 f</u>	<u>8.9 f</u>

*All references to hurricanes in this section will imply storms of tropical origin regardless of intensity.

Table 3-4 (cont'd.)

Storm		Location of Center	Storm Rainfall No.#
a	July 17-18, 1942	Smethport, Pa.	OR 9-23
b	**Sept. 8-10, 1921	Thrall, Tex.	GM 4-12
c	*Sept. 3-7, 1950	Yankeetown, Fla.	SA 5-8
d	June 27-July 1, 1899	Hearne, Tex.	GM 3-4
e	March 13-15, 1929	Elba, Ala.	LMV 2-20
f	*July 5-10, 1916	Bonifay, Fla.	GM 1-19
g	April 15-18, 1900	Eutaw, Ala.	LMV 2-5
h	May 22-26, 1908	Chattanooga, Okla.	SW 1-10
i	Nov. 19-22, 1934	Millry, Ala.	LMV 1-18
j	**June 27-July 4, 1936	Bebe, Tex.	GM 5-6
k	April 12-16, 1923	Jefferson Parish, La.	LMV 4-8

* hurricanes
** residual tropical storms
\# (Ref. 3-14)

The threat of heavy hurricane rainfall over the Tennessee Basin is real. The inland location of the basin cannot be considered a protection against this hazard, and a study (Ref. 3-15) made for an area as far north as the inland Province of Ontario, Canada underscores this fact.

This section assesses the hurricane rainfall threat to the Tennessee Basin by doing the following:

(1) summarizing observed hurricane rainfall in the United States
(2) summarizing observed hurricane tracks and speeds
(3) developing the hurricane prototype

Hurricane rainfall

A summary of hurricane rainfall in the United States (Ref. 3-16) is shown in table 3-5. From depth-duration-area analyses rainfall values are shown for areas of 5000, 10,000 and 20,000 square miles and durations of 24 and 72 hours. The largest of these values are used in developing a distance-from-coast rainfall relation in chapter V.

Table 3-5

HURRICANE RAINFALL FOR SELECTED SIZED AREAS AND DURATIONS

Rainfall (In.)

Storm Date	5000-sq. mi. 24-hr	5000-sq. mi. 72-hr	10,000-sq. mi. 24-hr	10,000-sq. mi. 72-hr	20,000-sq. mi. 24-hr	20,000-sq. mi. 72-hr	Storm Rainfall No.#	Rainfall Center Lat.	Rainfall Center Long.	State
9/16-19/1901	7.2	8.6	6.2	7.7	5.2	6.8	SA 2-5	32°04'	84°13'	Ga.
10/7-11/1903	9.0	10.2	7.7	8.9	6.1	7.6	GL 4-9	40°55'	74°10'	N. Y.
9/12-15/1904	5.4	5.5	4.9	5.0	4.5	4.6	NA 1-9	39°38'	75°25'	N. J.
7/26-8/2/1908	7.4	11.2	5.5	9.0	3.5	6.6	LMV 3-14	29°47'	91°30'	La.
7/28-31/1908	4.7	8.1	4.0	7.4	3.2	6.2	SA 5-23	35°07'	77°03'	N. C.
9/19-22/1909	7.4	7.8	6.2	6.6	5.0	5.4	LMV 3-16	30°46'	91°22'	La.
8/28-31/1911	8.0	10.7	6.1	8.9	4.5	7.1	SA 3-11	30°30'	82°02'	Ga.
8/16-21/1915	7.3	17.1	6.4	15.3	5.4	12.3	LMV 1-10	31°31'	94°07'	Tex.
9/28-30/1915	9.9	10.1	8.6	8.9	7.1	7.5	LMV 2-13	30°51'	90°10'	La.
8/1-3/1915	7.9	9.5	6.7	8.3	M	M	SA 4-15	27°47'	82°38'	Fla.
7/5-10/1916	12.0	16.5	9.8	15.4	7.4	14.0	GM 1-19	30°49'	86°19'	Fla.
7/13-17/1916	10.9	13.8	8.6	11.0	5.9	8.4	SA 2-9	35°53'	82°01'	N. C.
9/14-15/1919	8.8	9.5	8.1	8.7	6.9	7.5	GM 5-15A	28°21'	98°07'	Tex.
9/8-10/1921	15.0	16.3	10.7	12.2	M	M	GM 4-12	30°35'	97°18'	Tex.
9/14-17/1924	9.4	11.6	8.1	10.6	6.3	9.4	SA 3-16	34°44'	76°39'	N. C.
8/23-26/1926	9.1	9.6	7.8	8.4	6.3	7.1	LMV 4-5	30°06'	90°58'	La.
9/17-21/1926	11.0	12.7	9.8	11.6	8.4	10.3	SA 4-28	30°53'	87°47'	Fla.
8/7-12/1928	6.9	9.3	5.8	8.0	4.0	6.7	SA 4-24	28°14'	81°17'	Fla.
8/10-12/1928	7.0	9.3	6.0	8.3	4.9	7.0	NA 1-18	38°44'	76°51'	Md.
8/10-11/1928	6.0	6.5	5.3	5.8	4.4	4.9	SA 2-12	36°01'	80°46'	N. C.
8/13-17/1928	7.3	9.3	6.3	8.4	5.2	7.4	SA 2-13	35°07'	82°38'	S. C.
9/16-19/1928	9.4	11.0	8.5	10.4	7.3	9.6	SA 2-15	34°17'	79°52'	S. C.
9/23-28/1929	9.8	14.3	7.6	12.5	5.8	10.5	SA 3-20	31°56'	81°56'	Ga.
9/29-10/3/1929	8.0	10.5	7.2	9.5	6.4	8.9	SA 3-23	30°38'	85°43'	Fla.

#(Ref. 3-14)

M Not available for this storm

Table 3-5 (Cont'd.)

HURRICANE RAINFALL FOR SELECTED SIZED AREAS AND DURATIONS

Rainfall (In.)

Storm Date	5000-sq. mi. 24-hr	5000-sq. mi. 72-hr	10,000-sq. mi. 24-hr	10,000-sq. mi. 72-hr	20,000-sq. mi. 24-hr	20,000-sq. mi. 72-hr	Storm Rainfall No.#	Rainfall Center Lat.	Rainfall Center Long.	State
9/16-17/1932	7.9	8.2	6.9	7.5	M	M	NA 1-20	41°22'	71°50'	R. I.
10/14-18/1932	6.4	7.9	6.1	7.6	5.6	7.1	SA 5-11B	33°14'	87°37'	Ala.
10/15-18/1932	6.9	8.0	6.4	7.5	5.8	7.0	SA 5-11A	37°00'	79°54'	Va.
7/22-27/1933	10.5	16.8	8.5	14.9	6.5	12.4	LMV 2-26	31°58'	94°00'	La.
8/20-24/1933	7.0	9.8	6.4	9.0	5.6	8.1	NA 1-24	41°56'	74°23'	N. Y
6/12-17/1934	7.0	11.8	5.6	10.2	4.2	8.7	SA 5-1	28°21'	82°17'	Fla.
9/5-9/1934	6.4	7.9	5.4	6.7	M	M	SA 5-12	34°44'	76°39'	N. C.
8/31-9/6/1935	9.8	12.7	8.8	11.6	7.2	9.9	SA 1-26	38°46'	76°01'	Md.
6/27-7/4/1936	10.0	11.9	8.0	10.2	6.1	8.5	GM 5-6	29°24'	97°39'	Tex.
7/29-8/2/1936	5.8	7.3	5.3	6.7	4.7	6.1	SA 3-22	30°26'	85°02'	Fla.
9/14-18/1936	8.7	16.5	6.7	13.2	4.9	10.4	GM 5-7	31°47'	100°50'	Tex.
8/12-15/1938	8.6	9.4	6.8	7.6	4.7	5.8	LMV 4-23	30°20'	92°45'	La.
9/16-21/1938	4.8	7.0	4.1	6.3	3.2	5.6	SA 5-16	35°33'	76°38'	N. C.
9/17-22/1938	6.3	12.0	5.7	10.9	4.9	9.6	NA 2-2	41°40'	72°40'	Conn.
8/6-9/1940	12.3	22.9	8.5	17.2	5.5	12.6	LMV 4-24	29°45'	92°10'	La.
8/11-17/1940	7.5	12.3	6.4	11.0	5.0	9.3	SA 5-19A	37°03'	78°30'	Va.
10/17-22/1941	11.2	15.0	8.1	11.8	4.2	7.6	SA 5-6	29°48'	82°57'	Fla.
10/11-17/1942	7.2	11.8	5.7	9.8	3.9	7.5	SA 1-28A	38°31'	78°26'	Va.
7/27-29/1943	10.4	15.7	7.7	12.5	5.4	9.3	GM 5-21	30°02'	94°35'	Tex.
9/12-15/1944	4.8	9.3	4.4	8.3	3.9	7.2	NA 2-16	40°29'	74°27'	N. J.
8/26-29/1945	10.8	13.3	9.1	11.7	6.8	9.5	GM 5-23	30°02'	95°09'	Tex.
9/1-7/1950 (Easy)	15.5	21.0	10.6	16.4	7.5	13.5	SA 5-8	29°09'	83°02'	Fla.
6/24-28/1954 (Alice)	8.9	14.3	5.7	10.5	3.6	7.2	SW 3-22	30°22'	101°23'	Tex.
8/11-15/1955 (Connie)	5.0	8.7	4.5	8.0	3.9	7.2	NA 2-21A	42°01'	74°25'	N. J.
8/17-20/1955 (Diane)	9.5	13.0	8.0	10.8	6.3	8.5	NA 2-22A	43°07'	72°45'	Mass.

\# (Ref. 3-14)

M Not available for this storm

Climatology of hurricane tracks and speeds

The climatology of hurricane tracks and speeds is useful in establishing the prototype of extreme summer rainfall. Summaries of mean and extreme speeds and directions are presented. One summary taken directly from Hurricane Forecasting (Ref. 3-17) is shown as figure 3-19a. It presents a frequency distribution of hurricane direction of motion at grid points for 5° latitude-longitude squares. Median speeds are plotted alongside the direction arrows whenever a direction was based on five or more cases.

A somewhat different summation of tropical storm movements is shown in figure 3-19b, taken from data in NHRP Report No. 42 (Ref. 3-18). Maximum and minimum speeds, with storm motion direction to 8 points, are shown for the months of June through October. The data for the 35°-40° latitude zone are for 15 degrees of longitude rather than for 5 degrees because of a lesser frequency of storms at the higher latitudes. Indicated directions, such as NE, means hurricane moving toward the northeast.

The climatology of tropical storm motion in relation to the Tennessee Basin shows that:

(1) A northeastward track and higher speeds are more likely at the latitude of Tennessee than at more southerly latitudes.

(2) Movement to higher latitudes does not necessarily require accelerating motion.

(3) The minimum speed near the latitude of Tennessee averages about twice that at latitudes about 5 degrees farther south.

Examples of specific storm paths

The primary source of information for hurricane tracks was Technical Paper No. 36 (Ref. 3-19). Tracks for more recent years (since 1958) were obtained from Climatological Data (Ref. 3-20). Sixteen tracks of storms are depicted (figs. 3-20 through 3-23). The grouping is in generalized categories based primarily on direction of approach to the basin. Dates on the figures differ in some cases from those in the text. This is due to differences in days of identifiable storm centers compared to days of significant storm rainfall. The more important of these storms are discussed in chapter V.

Hurricane tracks from the Atlantic. Hurricanes that move northwestward from the South Atlantic coastal region are significantly affected by the mountainous terrain of the eastern portion of the basin. The two outstanding storms in this category are the "Altapass" storm of July 13-17, 1916 and the storm of August 10-17, 1940. The tracks (No. I and No. IV) of these two important storms are shown in figure 3-20. The other two are shown to demonstrate the possible extreme variations in storm tracks. Storms numbered II and III with minor changes could also have affected the basin.

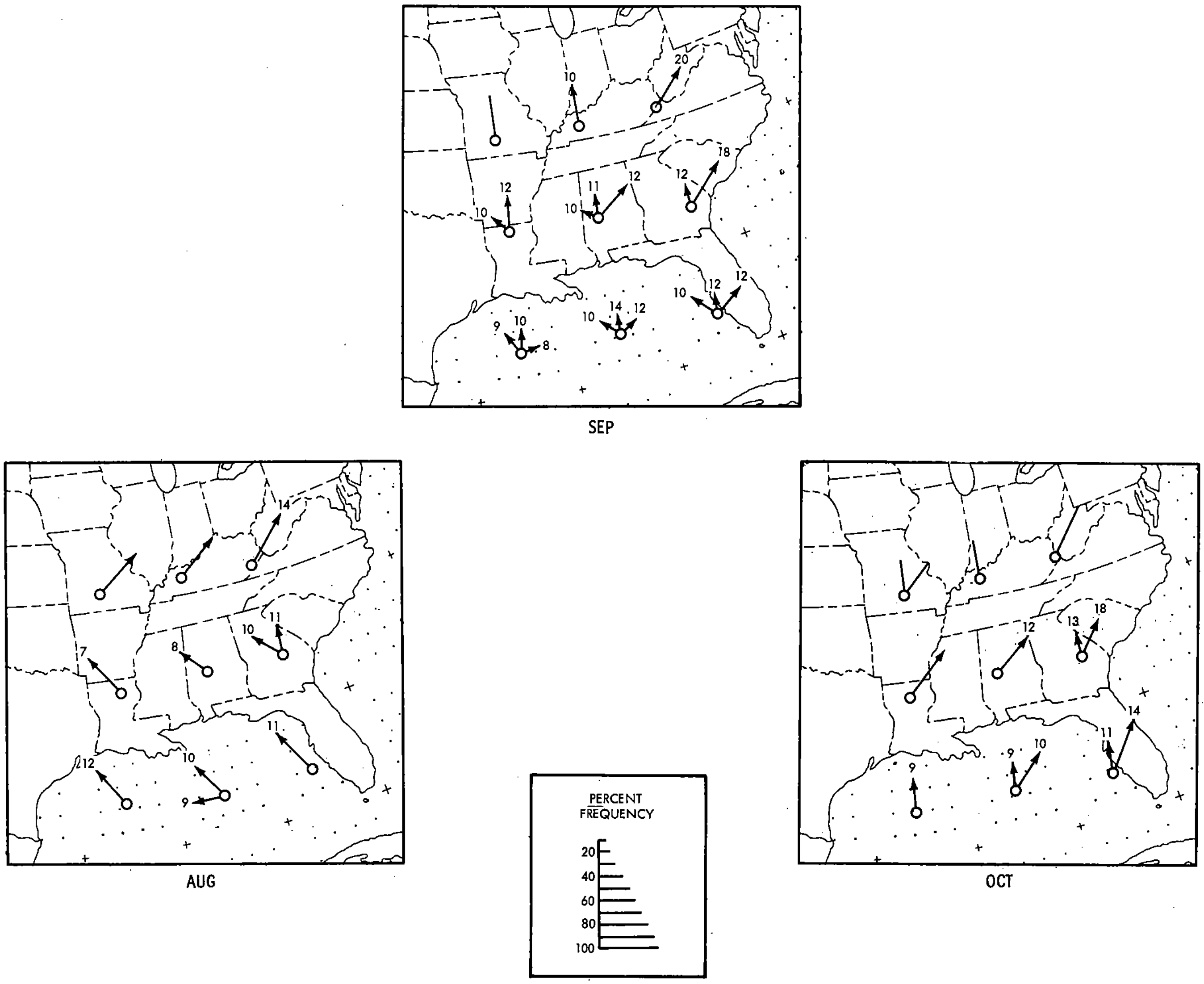


Figure 3-19a. Most frequent directions and median speed (kt.) of tropical storm movements (after Ref. 3-17)

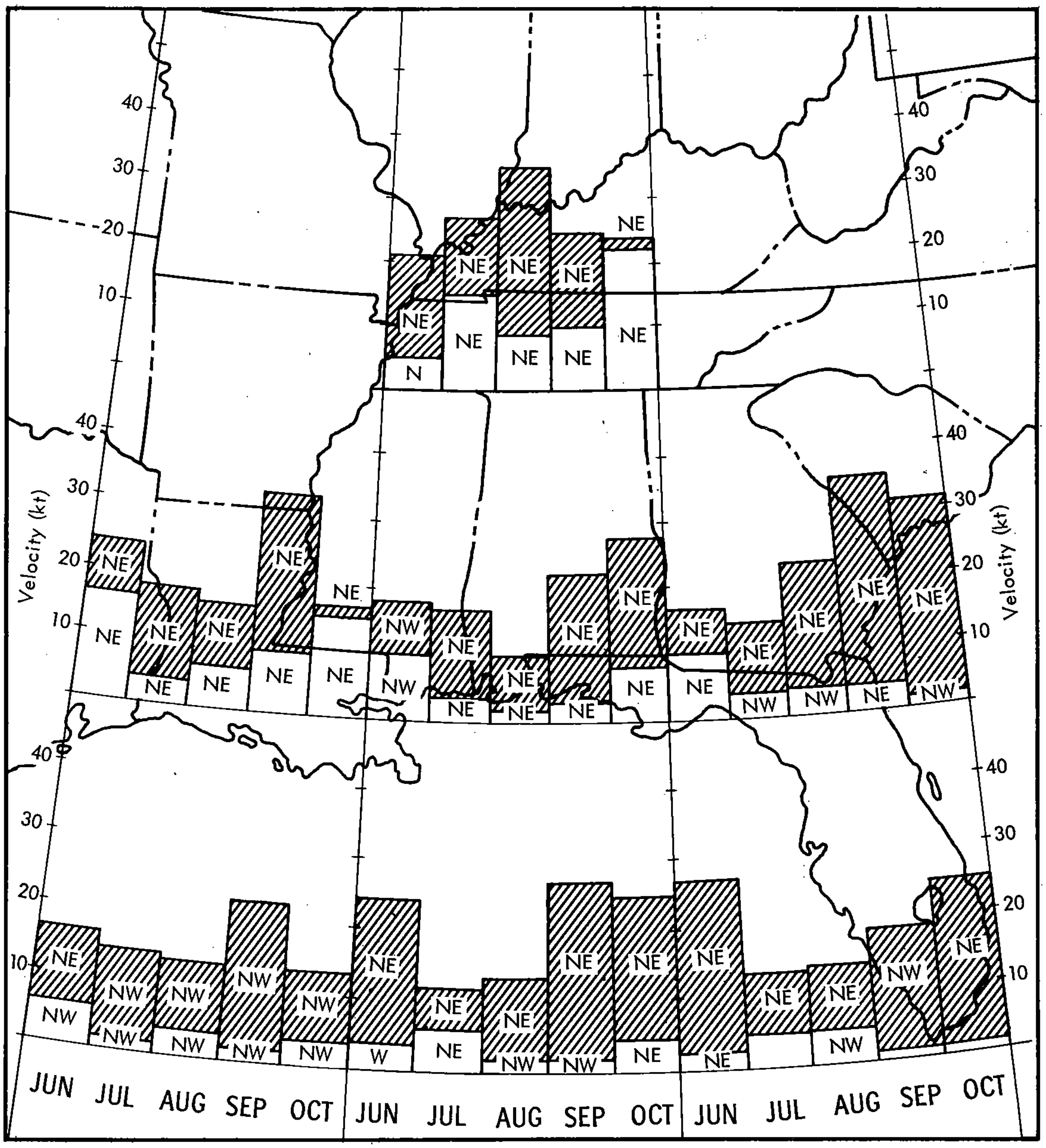


Figure 3-19b. Maximum and minimum speed (kt.) of tropical storm movement (1886-1958) in a 5-deg. lat.-long. box (after Ref. 3-18)

Hurricane tracks from the south (Gulf). Figure 3-21 shows six storms with tracks extending northward across or very near Tennessee. Of these the July 5-10, 1916 storm (VI) is a famous one that gave record-breaking rains near the Gulf Coast. The August 1901 storm (III) resulted in the highest summertime flow of record on the Tennessee River at Chattanooga.

The irregular and relatively slow motion of the July 5-10, 1916 storm singles it out as the best model for summertime extreme rain over the Tennessee River Basin above Chattanooga. This storm is instrumental in development of a distance-from-coast relation (chapter V).

Hurricane tracks from the southwest. Six storms with movements mainly toward the northeast are shown in figures 3-22 and 3-23. Figure 3-22 shows two storms which crossed the State of Tennessee on a northeasterly track while another northeastward-moving storm is shown passing to the south of the basin. Typical of such tracks are either fast motion or accelerating motion, both of which usually reduce rainfall at any location. A large volume of rain may be produced but it doesn't ordinarily concentrate over a particular region. Climatologically such fast or accelerated motion toward the northeast is most probable with either early or late-season storms. These are the seasons when the storms are more apt to come under the influence of upper-level winds with a pronounced eastward component of motion.

However, on occasion, relatively slow motion is definitely possible while a storm moves in a northeasterly direction. Such was the case in June 1960 when rather heavy rains were produced from eastern Texas into Kentucky by a northeastward-moving decadent tropical storm. This storm produced excessively heavy rains in Texas at a time when the storm was moving slowly. Surface maps for this storm and for the August 1915 storm are shown in appendix B (figs. 6B-2 and 6B-3). The track of the famous early-season storm "Audrey" of June 26-29, 1957 is also shown in figure 3-23. The remnants of this storm produced important rains and winds as far north as the Province of Ontario, Canada, pointed out by Thomas (Ref. 3-21) who said,

> "... no early season tropical disturbance prior to Audrey had passed over southern Ontario in the past 47 years, although four had done so in the 14 years prior to 1910."

Thus, a long period without storm experience of a particular type does not assure a region continued immunity from such a storm occurrence.

Hurricanes with loops. A storm such as that of July 5-10, 1916 (track No. VI-fig. 3-21) could have produced more rain in latitudes northward to Tennessee if the forward motion had been slower and particularly if the storm had executed a loop. Figure 3-24, taken from National Hurricane Research Project Report No. 42 (Ref. 3-18) shows examples of tropical cyclones that executed loops. Looping hurricanes are most probable in lower latitudes but figure 3-24 shows they have occurred as far north as Tennessee.

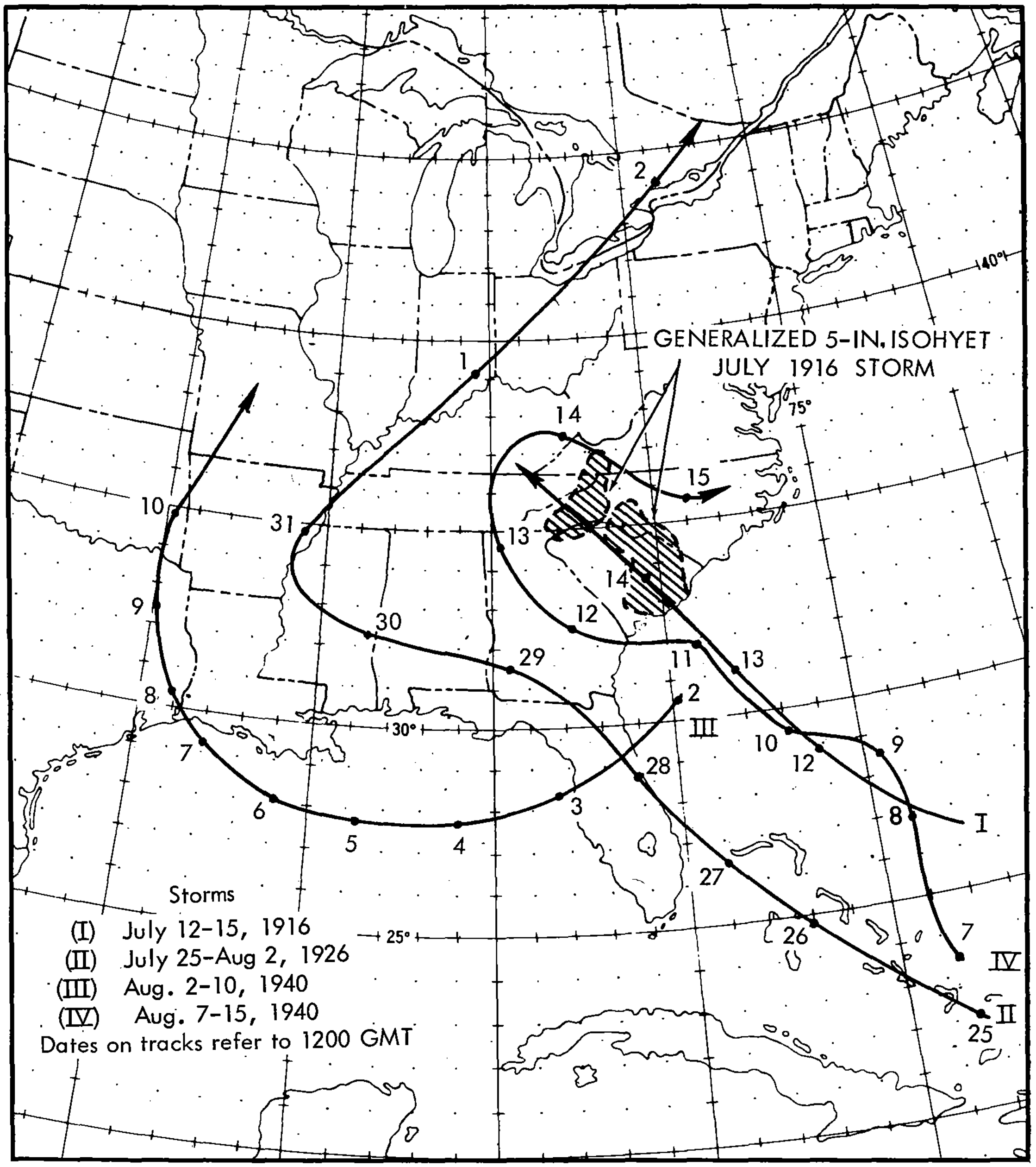


Figure 3-20. Hurricane tracks from the Atlantic

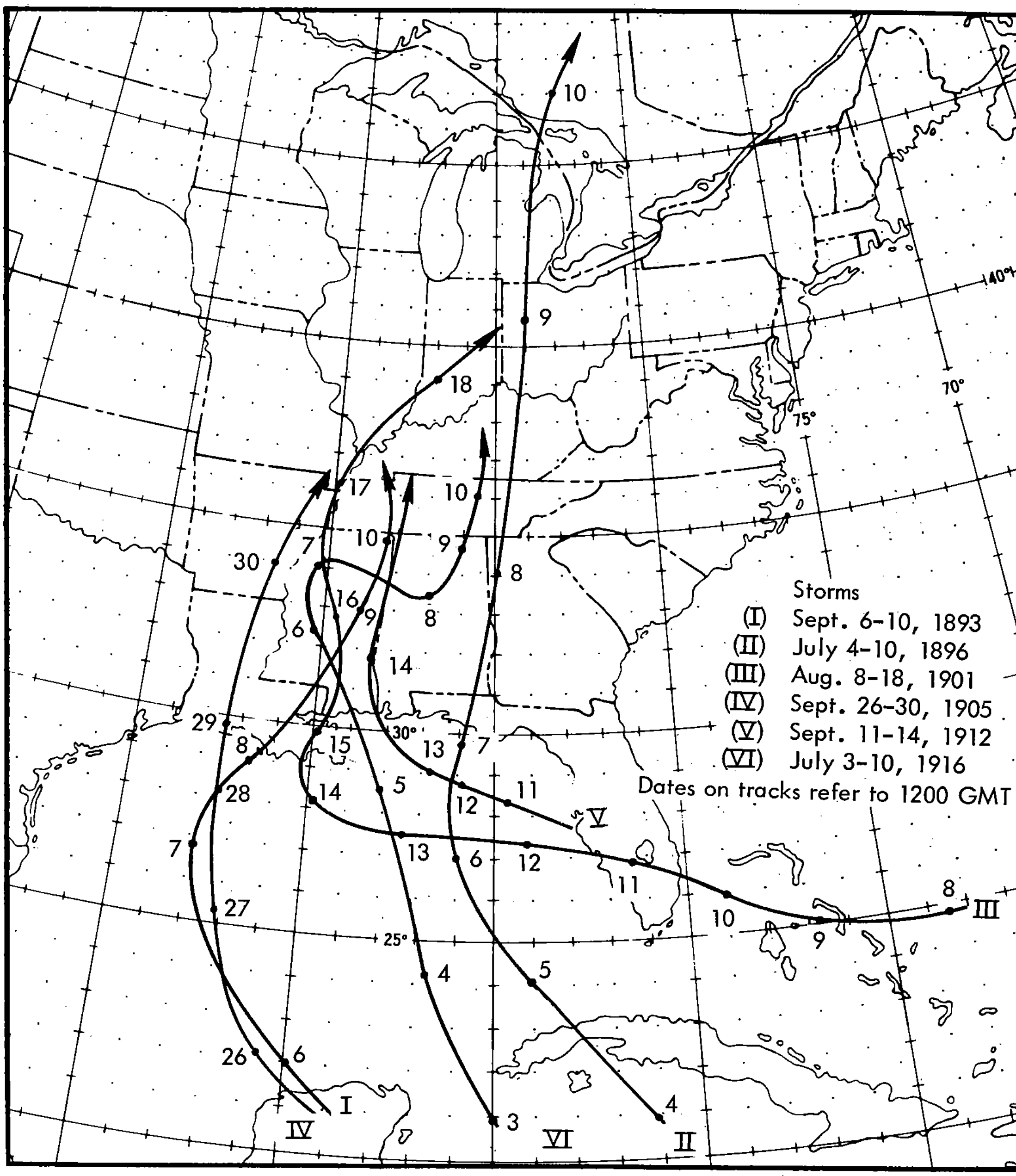


Figure 3-21. Hurricane tracks from the south

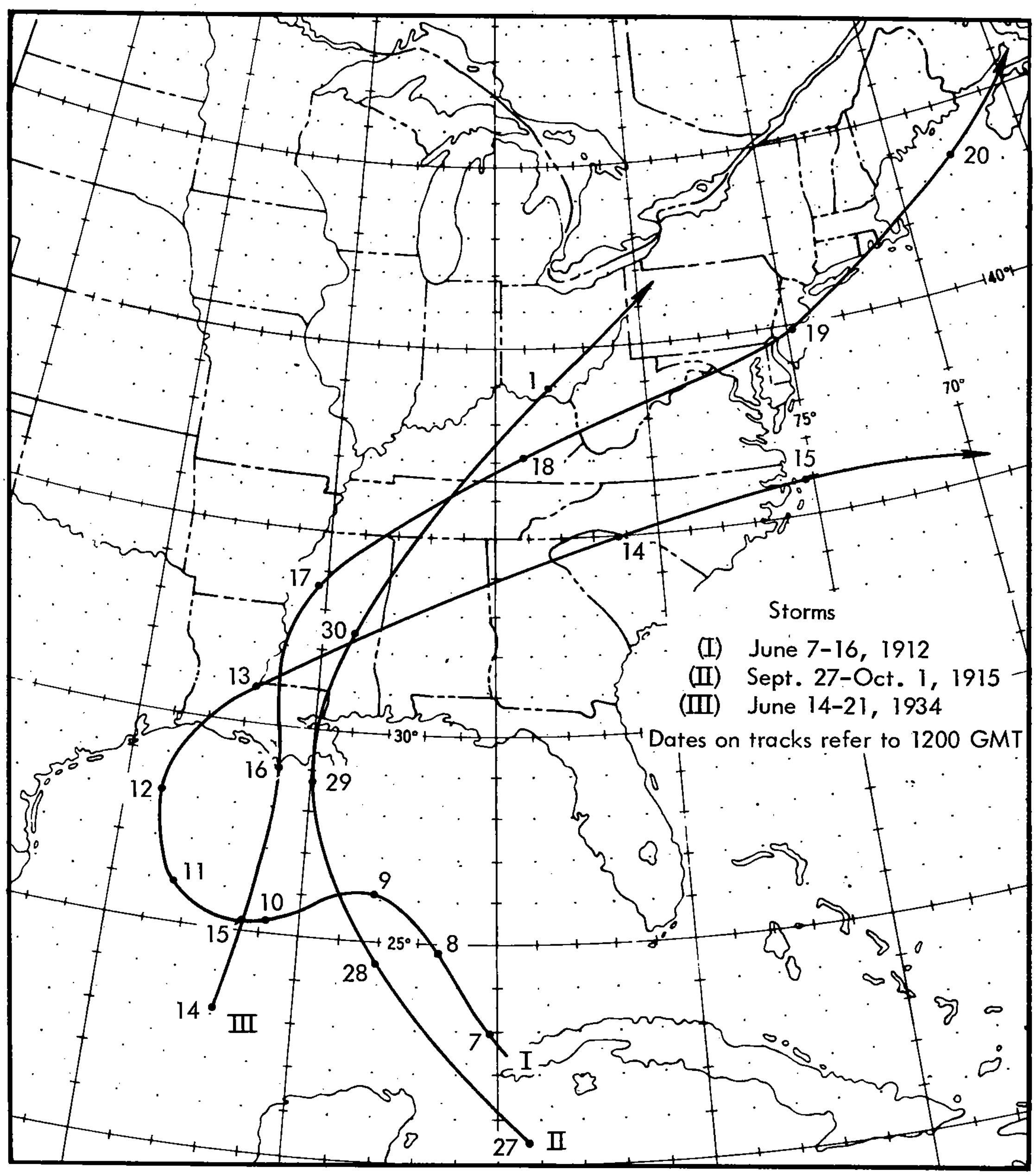


Figure 3-22. Hurricane tracks from the southwest

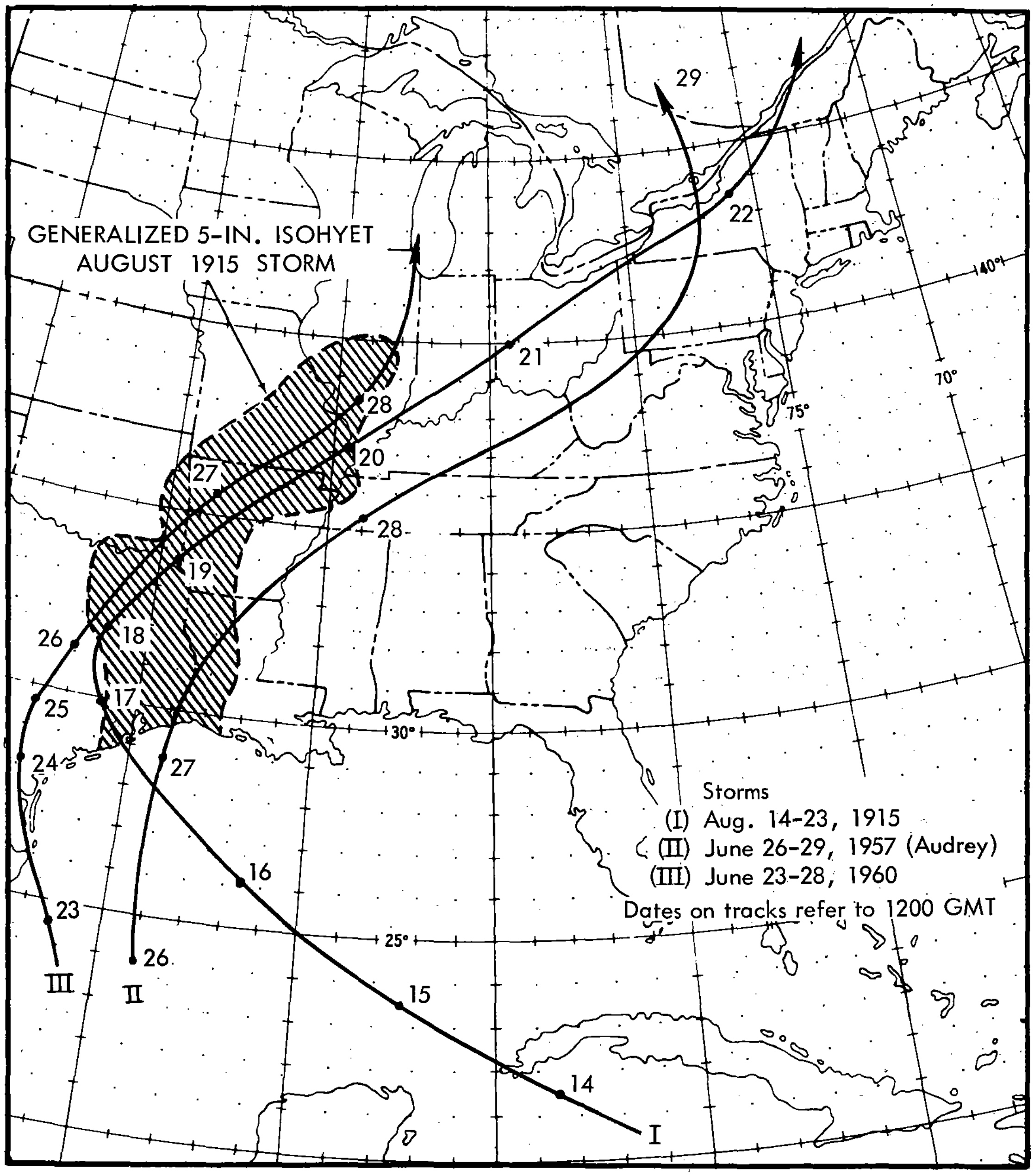


Figure 3-23. Hurricane tracks to west of basin

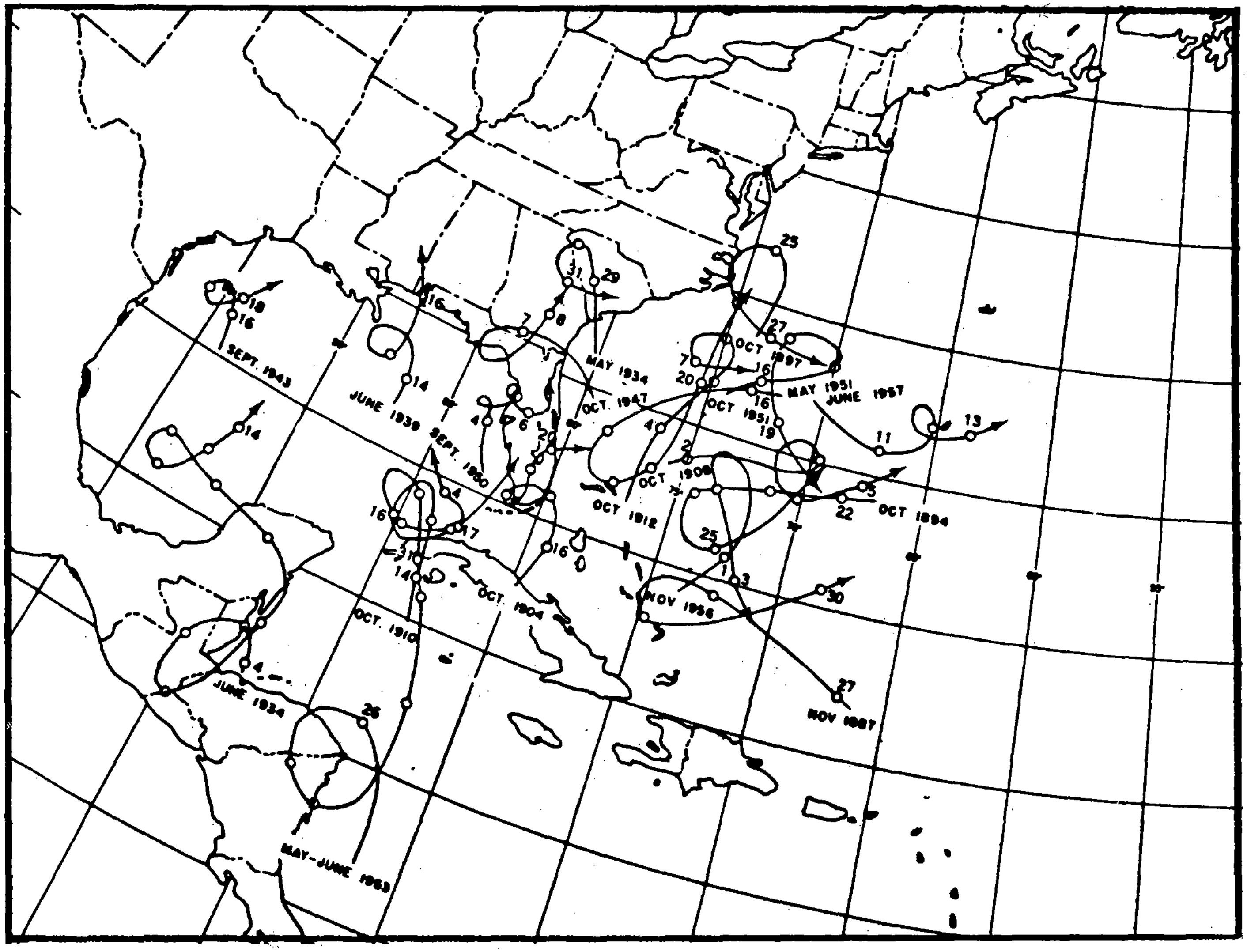


Figure 3-24. Tropical cyclone tracks with counterclockwise loops (from Ref. 3-18)

The famous Yankeetown, Fla., hurricane of September 1950, discussed in the introduction to this chapter, is an outstanding one of the slow-moving, looping variety.

Conclusions on summer storm prototype

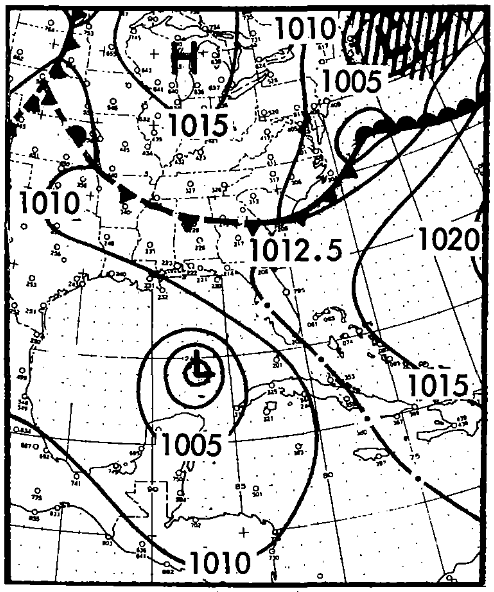
Hurricanes provide maximum potential for summer rainfall important for the 7980 and 21,400-sq. mi. basins. Two factors important for hurricane-derived rainfall are:

(1) The storm should move quite slowly, stalling or "looping" in the area. Such slow motion or looping would be most appropriate for giving maximum rains for durations up to 3 days.

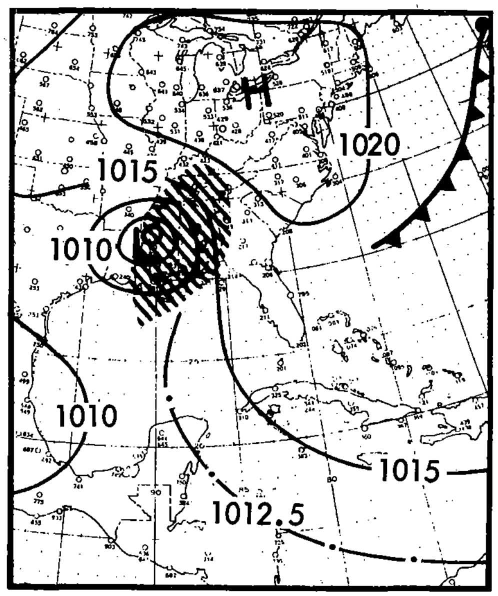
(2) The storm should pass across the basin in a manner that will result in a minimum of moisture depletion from intervening terrain.

The July 5-10, 1916 storm, appropriately modified for a more direct movement from the Gulf, is a prototype for summertime TVA precipitation in the Tennessee Basin above Chattanooga. Surface weather maps for this storm are shown in figure 3-25. Another storm with desirable prototype characteristics is that of August 11-18, 1901. Figure 3-26 shows the surface weather maps for this storm. The tracks of both of these model storms are shown in figure 3-21.

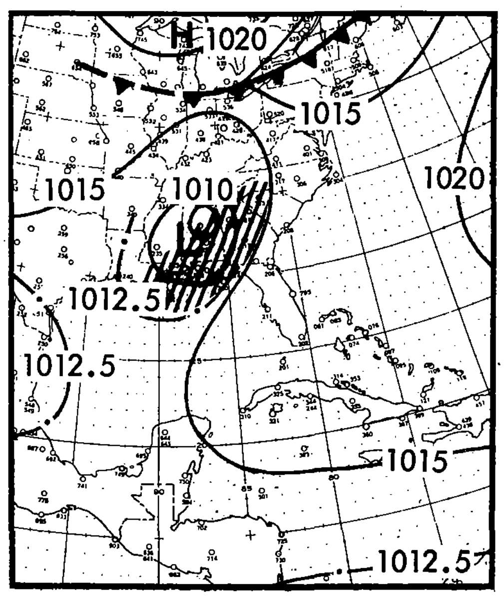
At the beginning of this section we stressed the outstanding rainfall associated with the hurricane of September 3-7, 1950. Slow motion, loops and full hurricane intensity while still near the coast combined in this storm to produce precipitation which approaches PMP depths for the Gulf Coast region for areas of 5000 square miles or less for some durations.



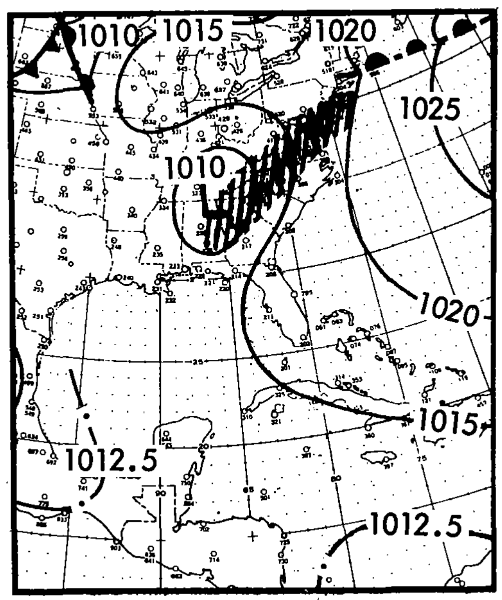
July 4, 1916



July 6, 1916

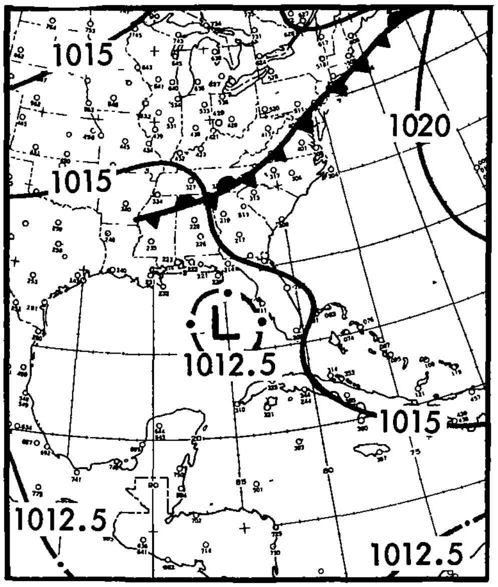


July 8, 1916

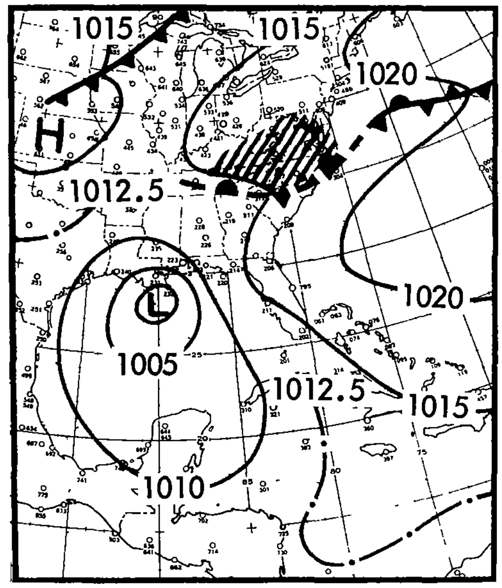


July 10, 1916

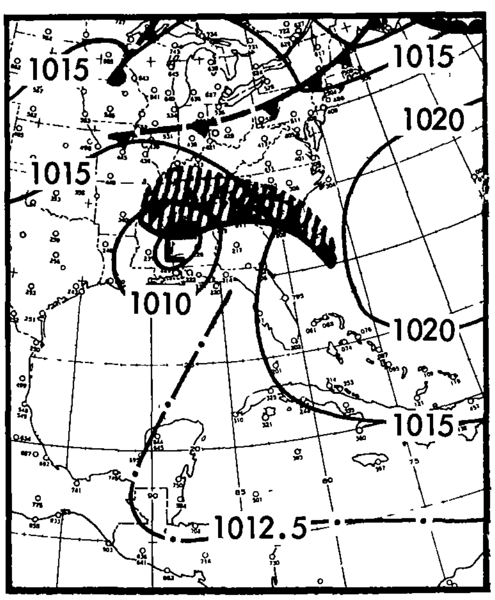
Figure 3-25. Surface weather maps (1300 GMT) for July 4-11, 1916 storm



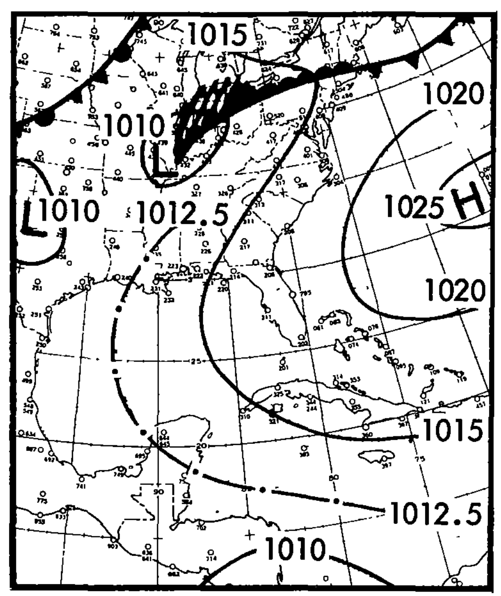
August 12, 1901



August 14, 1901



August 16, 1901



August 18, 1901

Figure 3-26. Surface weather maps (1300 GMT) for August 11-18, 1901 storm

Chapter IV

BASIN TOPOGRAPHY - ITS EFFECT ON DISTRIBUTION AND VOLUME OF RAINFALL

Introduction

The central Appalachians shed their waters into the Tennessee. The river then courses through a broad valley. The purpose of this chapter is to evaluate the twofold effects of this varied topography, (1) distribution of rainfall within the basin, discussed in Part A, and (2) the total volume of rainfall, discussed in Part B.

Inflow direction for large storms

Determination of the low-level inflow direction of moist air in large rainstorms is the first step in assessing the effects of topography on rainfall distribution and volume. A very useful and readily available tool in this regard is the system of surface isobars on weather maps. Using surface isobars to approximate low-level moisture inflow, several groups of heavy rain situations were investigated. These were:

(1) Fifteen cases with rainfall averaging two inches or more in 24 hours over the 21,400-sq. mi. basin above Chattanooga during a 20-yr. period, as tabulated in table 4-1.

(2) Two periods of heavy rain in March 1963 over the Tennessee River Basin.

(3) The heavy rain period in the Tennessee Basin of January 27-31, 1957.

(4) The five highest March and the five highest August 3-day rains at Asheville, N. C.

Typical surface isobars for the 15 heavy daily rain cases of table 4-1 and also for the various other heavy rain cases are shown in figure 4-1. The surface isobars are usually representative of the wind 1000 to 2000 feet above the surface. At the surface, the wind tends to cross the isobars at an angle; when the surface isobars run from the south the surface winds are most likely from a more easterly direction. Representative surface winds are also shown in the examples of figure 4-1 providing a more complete picture of the low-level winds.

The following characteristics of flow are used in evaluating the topographic effects on maximum rainfall:

(1) The low-level wind has a strong southerly component in virtually all heavy rains over the basin.

(2) For heaviest total basin rainfall a wind from west of south is favorable (fig. 4-1a-d).

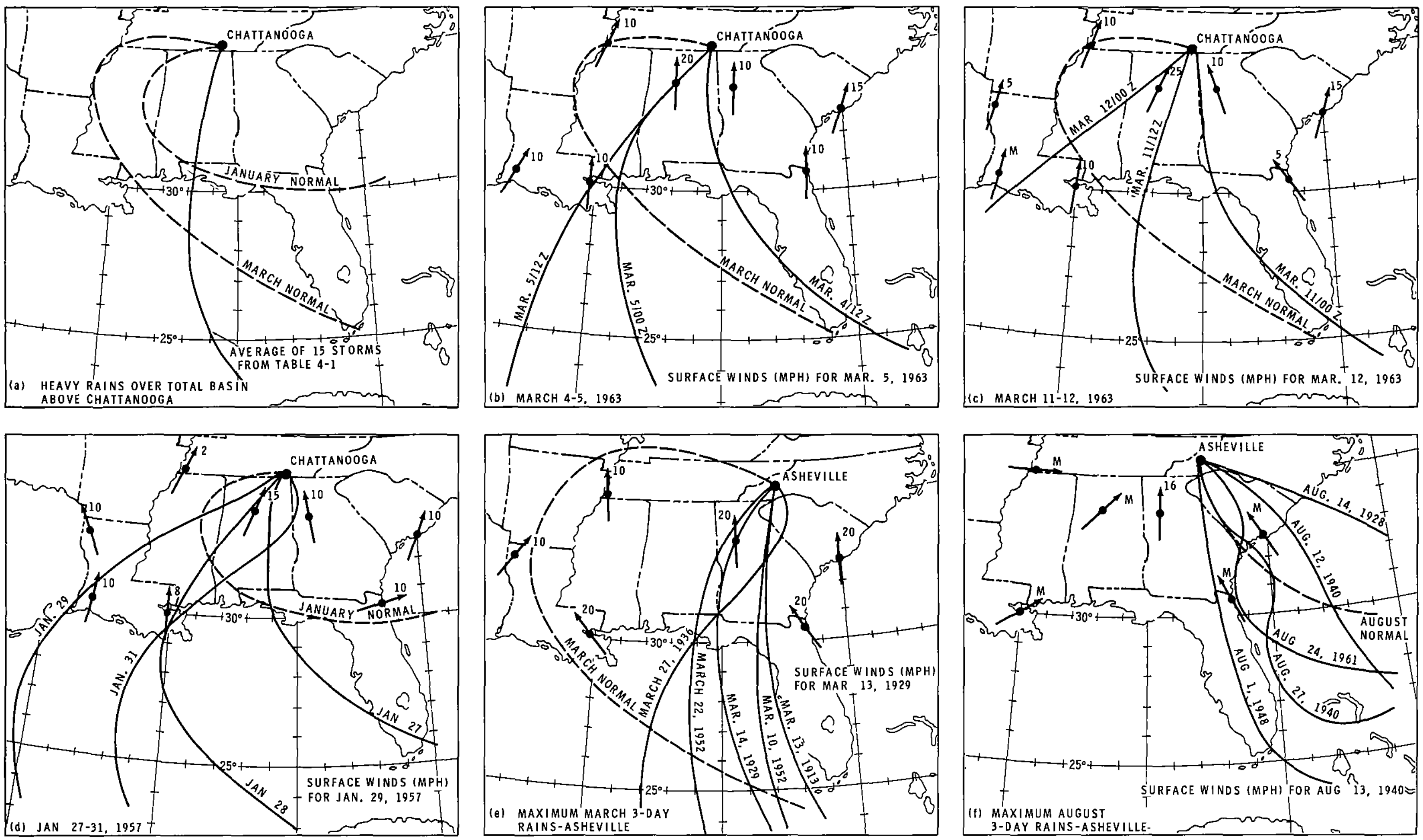


Figure 4-1. Surface isobars through Chattanooga and Asheville for heavy rain

(3) For heaviest rain in the mountainous southeast portion of the basin some wind from east of south is favorable (fig. 4-1e-f).

Table 4-1

DAILY RAINS OF MORE THAN 2 INCHES OVER 21,400 SQUARE MILES ABOVE CHATTANOOGA

(1944-63)

Case No.	Date	Rainfall (in.)
1	9/30/44	2.17
2	2/13/45	2.11
3	1/8/46	2.18
4	10/30/49	2.41
5	3/29/51	2.30
6	11/1/51	2.11
7	3/11/52	2.12
8	2/21/53	2.06
9	1/15/54	2.82
10	4/15/56	2.48
11	1/31/57	2.15
12	4/4/57	2.67
13	12/11/61	2.41
14	3/11/63	3.34
15	3/5/63	2.74

4-A. TOPOGRAPHIC EFFECTS ON RAINFALL DISTRIBUTION

Topographic effects on rainfall distribution in the Tennessee Basin were evaluated from observed rainfall patterns. These included mean and extreme rainfall occurrences for durations ranging from a day to a season. The areas of strongest and most consistent topographic augmentation and depletion of precipitation were singled out and compared. This involved deciding which topographic features produced important and consistent effects, due consideration being given to the adopted storm prototypes and wind directions. Two orographic rainfall patterns were developed to allow the user some variety of possibilities - the downstream-centered pattern and the upstream-centered pattern. These patterns are discussed below and in chapter VII.

Method and results

Annual, monthly mean and monthly extreme precipitation patterns, since they are more stable than the shorter durations, provide the most useful information.

Using such data and comparing precipitation at gage sites in the orographically-controlled areas of rainfall excess and deficiency with values in the relatively non-orographic western portion of the basin around Chattanooga, topographically-controlled rainfall patterns were developed. These included points of greatest augmentation and depletion. The patterns from observed rains were subjectively modified somewhat by studying the topography. This was to provide patterns that would not be dependent upon the chance location of rain gages. Modifications concerned two situations - one with winds with some southwest component; the other with winds with some southeast component. One of the resulting charts (southwest winds) is shown in figure 4-2. Figure 4-2 is called the downstream pattern. To give some idea of relative intensities of centers of maximum orographic influence, these are marked with approximate ratios (subjectively averaged from all the data) of rain intensity at these points to that in parts of the basin with little orographic effect. The other pattern, not shown, but discussed below, is the upstream pattern.

Chapter VII describes how these two charts (downstream and upstream) of the orographically-patterned rainfall are provided with isohyetal labels by applying rainfall concentration characteristic of the basin. Resulting isohyetal patterns are shown in figures 7-3 through 7-6. For example, figures 7-3 and 7-4 derive from figure 4-2 such that the maximum 6-hr. (chapter V) adopted TVA precipitation volume (fig. 7-3) and PMP volume (fig. 7-4) respectively occur over the 21,400-sq. mi. basin.

Downstream pattern. In the downstream pattern (figs. 7-3 and 7-4) the non-orographic rainfall is centered in the low-lying area to the north of the Great Smokies. Such a centering of the rainfall is consistent with winds sufficiently from a southwesterly direction to bring in a rich supply of moisture around the southern periphery of the Appalachians. Such a weather situation is conducive to significant centers of orographically intensified rainfall not only along the southern periphery of the Appalachians but also along the Great Smokies.

Upstream pattern. In the upstream pattern (figs. 7-5 and 7-6), the centering of the rainfall in the mountains favors southeast-facing slopes with low-level winds assumed from the south to southeast for part of the storm. Therefore, these regions are allowed proportionally more orographic increase than in the downstream-centered pattern. Some areas of orographic rainfall increase are still allowed for in the Great Smokies since low-level winds to the east of south would not persist for the full three days in the situation that would produce PMP or TVA precipitation over the total basin. Furthermore, even with southeast winds some orographic intensification exists along the Smokies. This is accounted for by the additional lifting of the air after it has been partially depleted of moisture by the Blue Ridge. April 1957 is an example of a heavy rain month along the southern and southeastern edges of the basin. This and other such heavy rain months provided the bases for the shaping of the upstream pattern.

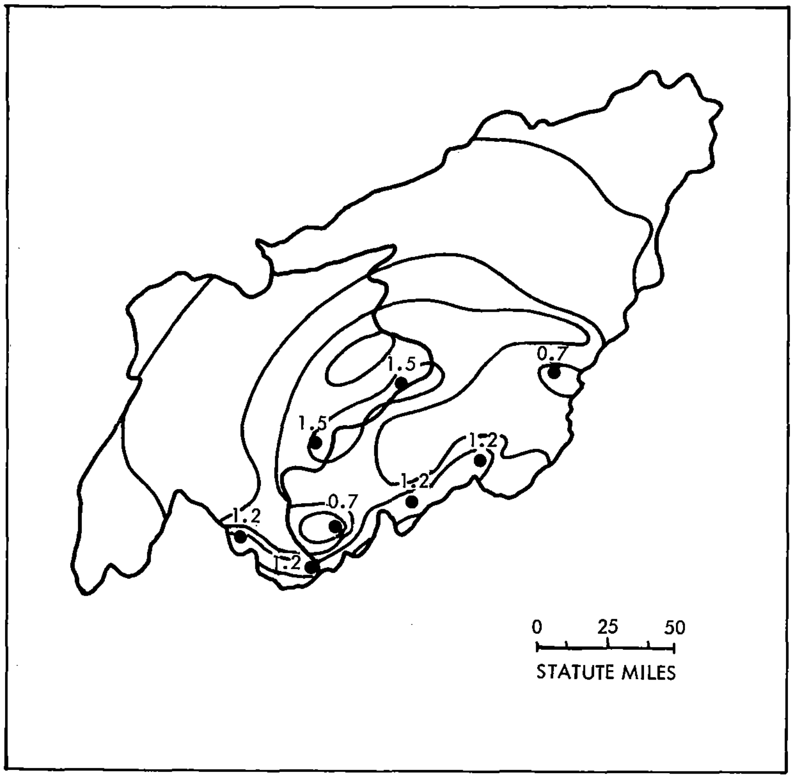


Figure 4-2. Typical orographic rain pattern (downstream)

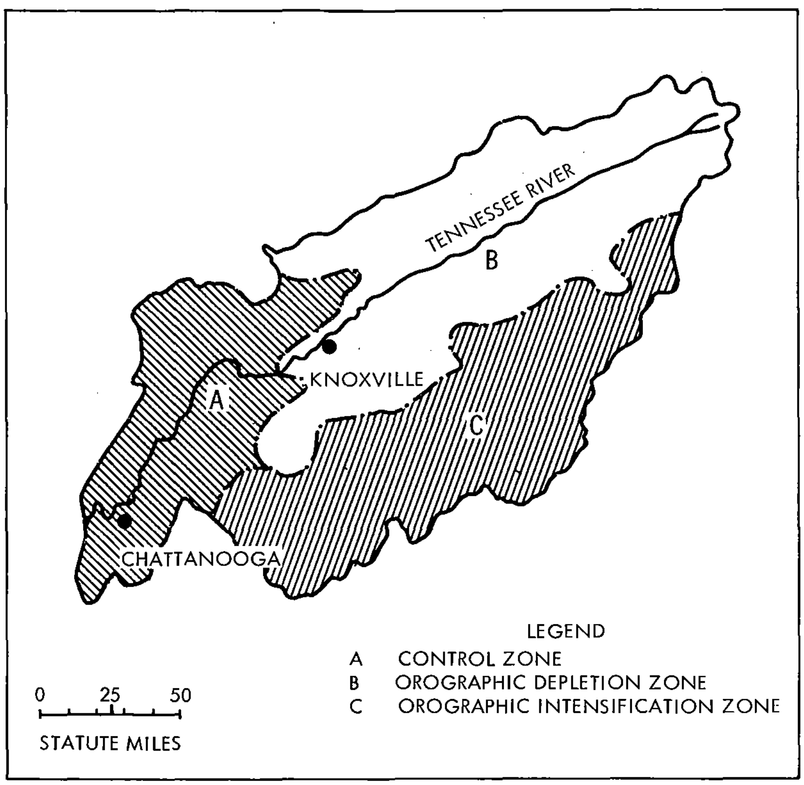


Figure 4-3. Zones for orographic volume check

4-B. TOPOGRAPHIC EFFECTS ON RAINFALL VOLUME

With the topographic effects on rainfall within the basin now assessed, the next question is, do the mountains add to or subtract from what the total rainfall would be in the basin if there were no mountains. In other words, is a readjustment of the total basin volume necessary because of the presence of the mountains? This question is important because the PMP and TVA precipitation volumes are derived primarily from data outside the basin. Any net effect of topography on total basin rainfall is then a correction to this. In some parts of the basin the mountains cause a forced lifting of the air and thereby increase rainfall; in other parts of the basin mountains provide a sheltering effect and thereby decrease the rainfall. Do these effects compensate each other?

To answer this question durations of rainfall ranging from a day to a year were evaluated. The samples of data used resulted in small but conflicting indications. A conclusion of no net topographic effect was adopted.

Topographic effects on mean annual rainfall

Estimates were made independently, by five meteorologists, of the non-orographic mean annual precipitation over the basin above Chattanooga. They were based on extrapolation over the basin of mean annual precipitation lines surrounding the basin, assuming the non-existence of the Appalachians. Estimated values ranged from 45 to 52 inches, with a mean of 47 inches. This range in estimated values results from differing judgment as to the role of the Appalachians in affecting the rainfall distribution in surrounding areas.

To accept this estimated mean annual non-orographic rainfall of 47 inches would mean that topographic effects result in a net increase of precipitation of 8 to 9 percent since the long-term actual mean annual precipitation over the basin above Chattanooga as given in a recent TVA publication (Ref. 4-1), is 50.99 inches.

Topographic effects on mean monthly rainfall

The months of February, March and August were selected for evaluating net topographic effects on the volume of monthly rainfall. The drainage basin was divided into three zones of approximately equal size. These were a control zone of minimal topographic effects, (A); an orographic depletion zone, (B); and an orographic intensification zone, (C). These zones are shown in figure 4-3. The demarcation between zones B and C is based on the main divide provided by the Great Smokies. TVA sub-basins were used for the precise demarcation and are chosen so as to make the division as reasonable as possible. Mean monthly rainfall maps were planimetered to obtain average rainfall values for each of the three zones. The control values were assigned 100 percent and the corresponding percents were determined for other zones. Table 4-2 summarizes the results.

The zone B depletion in February and March suggests a net orographic depletion greater than the zone C augmentation in winter. From August, a net orographic increase in summer is suggested.

Table 4-2

AVERAGE DEPTHS OF MEAN MONTHLY RAINFALL BY ZONES

(1935-1959)

Month	Zone A (control) Amount (In.)	Zone A Percent	Zone B (depletion) Amount (In.)	Zone B Percent	Zone C (intensification) Amount (In.)	Zone C Percent
February	5.5	100	4.3	78	5.9	107
March	5.7	100	4.5	79	6.2	109
August	3.7	100	4.1	111	4.8	130

Topographic effects - rainy months

In order to evaluate net orographic effects in "rainy months" seven winter or spring months with rainfall 50 percent or more above normal were selected from TVA data (Ref. 4-1). These months are from the ten-year period 1954 to 1963 for February, March and April.*

Table 4-3

AVERAGE DEPTHS FOR RAINY MONTHS BY ZONES

Case No.	Month	Zone A (control) Amount (In.)	Zone A Percent	Zone B (depletion) Amount (In.)	Zone B Percent	Zone C (intensification) Amount (In.)	Zone C Percent
1	Feb. 1956	10.1	100	8.4	83	8.9	88
2	Jan. 1957	7.9	100	8.6	109	6.6	84
3	Feb. 1957	8.5	100	7.3	86	8.7	102
4	Apr. 1958	7.1	100	6.1	86	6.7	94
5	Feb. 1961	8.5	100	6.5	76	7.4	87
6	Feb. 1962	8.7	100	7.2	83	6.4	74
7	Mar. 1963	10.9	100	9.9	91	10.4	95
	Mean (cases 1-7)	8.8	100	7.7	88	7.9	90
8	Jan. 20, 1957- Feb. 10, 1957	12.3	100	12.5	102	11.8	96

*Criteria used (150% of normal):
February, precipitation 7.01 inches or more; March, precipitation 7.95 inches or more; April, precipitation 6.29 inches or more.

Average rainfall was determined over the three zones of figure 4-3 for these seven heavy rain months. In addition, similar computations were made for the heavy rain period of January 20-February 10, 1957. Two of the "rainy months" included the effect of this extended rainy period. The results of the computations are summarized in table 4-3. Figure 4-4, showing the March 1963 rainfall distribution, is reproduced from a TVA report (Ref. 4-2).

In comparing the values in table 4-3 with the winter values in table 4-2, the conclusion is that in the heavy rain months the orographic depletion zone, (B), gains rainfall, while the orographic intensification zone, (C), loses rainfall.

Topographic effects on extreme daily rains

Maximum daily rains averaged over the Tennessee Basin above and below Chattanooga were used as an auxiliary indicator of net orographic effects. The area above Chattanooga can be likened to zones B and C topographically and the area below Chattanooga to zone A. The data consisted of 20 years of daily rainfall averaged separately over the portions of the basin above and below Chattanooga. The statistic taken from these sub-basin averages and used for this comparison is the mean of the monthly series. This is a statistically computed monthly value that approximates the 2-year return period daily rainfall. A summary of these values is shown in table 4-4.

Table 4-4

MAXIMUM DAILY RAINFALL ABOVE AND BELOW CHATTANOOGA

(Mean of Monthly Series)

(Inches)

Month	Above Chattanooga	Below Chattanooga	Ratio (above/below)
January	1.29	1.44	0.90
February	1.21	1.47	0.82
March	1.47	1.53	0.96
April	1.14	1.13	1.01
May	0.77	0.95	0.81
June	0.78	0.82	0.95
July	0.76	0.77	0.99
August	0.64	0.71	0.90
September	1.01	1.03	0.98
October	0.91	0.79	1.15
November	1.09	1.25	0.87
December	1.21	1.47	0.82
Average			0.93

These data show a net deficit totaled for the year of about 7 percent for the basin above Chattanooga over that for the basin below Chattanooga.

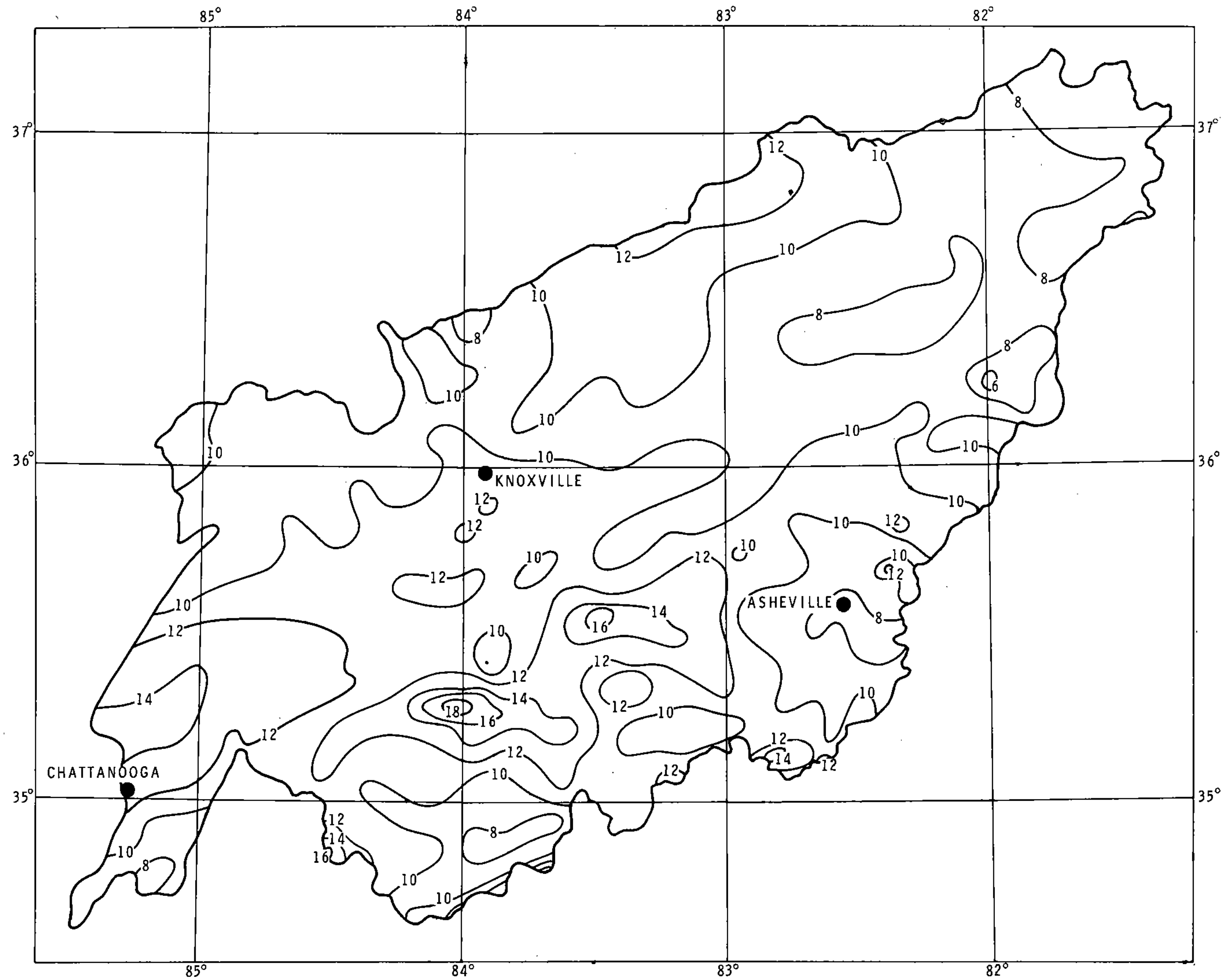


Figure 4-4. Tennessee River Basin precipitation - March 1963

This compares with -2 percent using mean annual data. (50.99 in./52.09 in. = .98). The former statistic is more representative of extreme rains than is the mean annual.

Summary of topographic effects on rainfall volume

The effects for the various categories of rainfall are as follows:

1. Mean annual-- an estimated net topographic increase of 8 to 9 percent in basin above Chattanooga.

2. Mean monthly rainfall-- net topographic depletion for winter months based on the depletion zone B decrease overcompensating for the orographic zone C increase. (Table 4-2.)

3. Rainy months-- mean of 7 rainy months shows no significant difference in rainfall in depletion zone B compared to intensification zone C. Therefore, in the rainy month the depletion zone gains at the expense of the intensification zone. (Table 4-3.)

4. Extreme daily rainfall-- net topographic deficit for the basin above Chattanooga compared to the basin below Chattanooga.

Although mean annual precipitation data suggest a modest orographic intensification of rainfall, more extreme rainfall data point to a negation of any such orographic intensification. In any case, the data suggest net effects are small. The working assumption of no net topographic effect on volume is therefore used in this report.

Chapter V

DERIVATION OF PROBABLE MAXIMUM AND TVA PRECIPITATION

Introduction

This chapter explains the methods used in estimating probable maximum and TVA precipitation for the 7980- and 21,400-sq. mi. basins. The adopted values, including month-to-month variations, are shown in table 5-1, for a 7980-sq. mi. area and in table 5-2 for a 21,400-sq. mi. area centered upstream or downstream.

The method used in deriving rainfall values for winter-type storms consisted of adjustment and transposition of record storms of this type. For estimating summer rainfall capabilities a distance-from-coast variation of hurricane rainfall was developed. Both of these procedures were applied primarily to 24-hr., 10,000-sq. mi. rainfall. Rainfall depth-area and depth-duration ratios and various indices of month-to-month variations were then used in arriving at the smoothed set of values shown in tables 5-1 and 5-2. The 21,400-sq. mi. values shown in table 5-2 are appropriately adjusted for occurrence over the total basin above Chattanooga.

5-A. COOL-SEASON TYPE ESTIMATES

Methods

Various facts and deductions give a glimpse at that climatic characteristic we are seeking - the probable maximum precipitation over the upper Tennessee Basin. And likewise the TVA level of precipitation. The facts we use, the basic ingredients and underpinning for the rest, are the maximum known rainfall values in storms in the Eastern United States, as listed from Storm Rainfall (Ref. 3-14) in table 5-3.

If we look at enough rainstorms, ultimately we will find a few approaching the maximum which nature has to offer. If by "enough" rainstorms we mean all cool-season storms detected by the moderately good rain gage network in the eastern two-fifths of the United States during one-half to three-quarters of a century, then experience seems to say that a few storms will approach within 30 percent, or perhaps even closer to the PMP.

There are two techniques by which these record storms can be made to reveal information about PMP in Tennessee. Both are variants on transposition. The most direct is to transpose each storm to the basin, after a relocation adjustment and a maximization adjustment. This is a suitable technique when the transpositions are modest and the relocation adjustments are clear-cut.

The technique chosen here is to maximize and plot on a map each of the candidate storms in its native location, for a particular duration and size

Table 5-1

PMP AND TVA PRECIPITATION VALUES OVER
7980-SQ. MI. BASIN

Category	Duration (hrs.)	Rainfall by Months (in.)						
		Mar.	Apr.	May	June	July	Aug.	Sept.
TVA	6	4.47	4.13	3.74	3.59	3.64	3.75	4.06
	24	8.93	8.26	7.48	7.18	7.27	7.50	8.11
	72	12.95	11.98	10.85	10.41	10.54	10.88	11.76
PMP	6	7.02	6.97	6.87	6.74	6.58	6.58	7.00
	24	14.04	13.93	13.74	13.47	13.15	13.15	14.00
	72	20.36	20.20	19.92	19.53	19.07	19.07	20.30

Table 5-2

PMP AND TVA PRECIPITATION VALUES OVER
21,400-SQ. MI. BASIN

Category	Duration (hrs.)	Rainfall by Months (in.)						
		Mar.	Apr.	May	June	July	Aug.	Sept.
TVA	6	3.20	2.91	2.50	2.20	2.15	2.24	2.53
	24	7.11	6.46	5.54	4.90	4.76	4.98	5.62
	72	10.67	9.70	8.31	7.36	7.14	7.48	8.42
PMP	6	5.03	4.83	4.58	4.22	3.87	3.93	4.48
	24	11.18	10.73	10.18	9.39	8.61	8.73	9.95
	72	16.78	16.11	15.27	14.09	12.92	13.09	14.92

of area. The chosen dimensions here are 24 hours and 10,000 square miles. Enveloping isolines are then drawn to fit one or a few of these values but exceed the lesser storm values. The complexities of relocation adjustment are not ignored; rather, they are taken into account in constructing the gradients of the isolines. The main considerations are the location and influence of mountain chains, location and distance of the moisture-releasing sea, and the known climate in general.

Selection of storm data

A thorough survey was made of storms in Eastern United States, from Storm Rainfall (Ref. 3-14) in TVA reports and from other sources. A list of storms transposable to the Tennessee Basin and/or surrounding areas, is shown in table 5-3.

Features of transposable storms

Surface weather charts for three of the transposed storms are shown in appendix B as figures 5B-1 through 5B-3. Detailed isohyetal patterns for some of the storms are shown in figure 5-1. The southwest-to-northeast orientation of most of the rainfall patterns is noteworthy. It reflects large-scale control by southwesterly flow aloft (chapter III). Thus, although the meteorological developments in large-area rains vary considerably in the Eastern United States, the prevailing winds aloft stretch out the large-area long-duration isohyetal patterns along a southwest- to-northeast axis.

A brief discussion follows of some of the more important transposed storms with emphasis on the causes of flood-producing rains in the basin (chapter III).

December 16-20, 1895 storm. This storm, with typical southwest- to-northeast isohyetal pattern, featured a quasi-stationary front with wave activity. Finally, as in the March 25-27, 1913 Ohio storm, a developing low-pressure disturbance increased the rainfall intensity prior to an influx of drier air.

April 15-18, 1900 storm (fig. 5B-1). This storm is one of several with a common outstanding transposable rain-producing feature, namely a pronounced flow of converging Gulf of Mexico air into the rain area. Yet there is considerable variation in details of the synoptic development in these storms. In the January 1954 storm, for example, such a convergence area occurred ahead of a slowly moving front separating air of strongly contrasting temperatures.

The April 1900 storm was centered at Eutaw, Ala. A strong southerly flow developed between a ridge of high pressure off the East Coast (fig. 5B-1) and a slowly moving N-S trough in the Plains. It was in this converging moist flow that the heavy rain occurred, intensified by approach of a cold front on the morning of the 17th. Most of the rain fell in an 18-hr. period from noon of the 16th. Rains from such a situation tend to be more intense but less persistent than from other types. An example of this storm type giving heavy rains within the basin is the storm of April 4-5, 1920.

March 23-27, 1913 storm (fig. 5B-2). This storm has been described in other reports and classified as the storm most typical of the quasi-stationary frontal type (Ref. 3-4). It is considered most typical in that a series of waves or low-pressure developments ends with a more vigorous storm. This general type is important as a heavy rain producer over most of the Eastern United States. The final developing low-pressure disturbance brought an end to the rainy period in this storm.

November 15-17, 1928 storm. The most important precipitation in this storm occurred in connection with a quasi-stationary front with weak low-pressure disturbances moving along it. The quasi-stationary frontal situation was preceded and followed by occluding Lows which moved northeastward into the Great Lakes area.

Table 5-3

STORMS TRANSPOSABLE TO TENNESSEE AND/OR BORDERING STATES

No.	Storm Assignment No. (from Ref. 3-14)	Date	Location Rainfall Center (Lat.	Long.)	State
1	MR 1-1	12/16-20/95	37°33'	92°47'	Mo.
2*	LMV 2-5	4/15-18/00	32°47'	87°50'	Ala.
3	LMV 2-7	3/25-29/02	34°42'	88°57'	Miss.
4*	OR 1-15	3/23-27/13	40°22'	83°46'	Ohio
5	LMV 2-22	1/6-11/30	34°07'	93°03'	Ark.
6	LMV 1-19	1/18-21/35	34°50'	90°00'	Miss.
7	OR 5-6	1/5-24/37	36°07'	88°33'	Tenn.
8	SW 2-20	5/6-12/43	35°29'	95°18'	Okla.
9	SW 2-21	5/12-20/43	35°52'	96°04'	Okla.
10	UMV 2-5	6/9-10/05	40°42'	91°48'	Iowa
11	MR 2-13	1/26-31/16	37°37'	90°38'	Mo.
12	GL 4-14	3/21-27/16	41°17'	91°41'	Iowa
13	MR 6-15	6/10-13/44	41°57'	97°14'	Neb.
14	OR 5-11	2/2-17/83	36°58'	86°26'	Ky.
15	UMV 2-4	3/24-26/04	36°59'	91°59'	Mo.
16	LMV 1-5	1/1-3/07	34°22'	92°49'	Ark.
17	OR 4-8	10/3-6/10	37°22'	88°29'	Ill.
18	LMV 1-9	1/10-11/13	35°27'	92°24'	Ark.
19	UMV 3-20b	9/30-10/7/41	40°58'	90°23'	Ill.
20	LMV 5-3	4/23-5/4/53	31°04'	93°12'	Iowa
21	LMV 2-18	6/1-5/28	31°55'	87°45'	Ala.
22	GM 2-25	4/5-9/38	32°08'	88°02'	Ala.
23*	LMV 2-20	3/11-16/29	31°25'	86°04'	Ala.
24	LMV 5-4	5/11-19/53	31°46'	91°49'	La.
25	MR 3-20	11/15-17/28	37°55'	95°26'	Kan.
26	SW 3-5	3/28-4/2/45	32°20'	95°42'	Tex.
27	Pink Beds	3/26-4/1/86	35°22'	82°47'	N. C.
28	Clingmans Dome	2/23-25/75	35°33'	83°30'	N. C.
29	LMV 3-7	1/4-6/99	32°38'	90°02'	Miss.
30	LMV 1-4	11/17-21/06	34°39'	90°28'	Miss.
31	LMV 1-18	11/19-21/34	31°38'	88°19'	Ala.
32	OR 7-15	3/21-23/29	35°48'	85°38'	Tenn.
33	LMV 1-12	3/15-17/19	35°25'	88°39'	Tenn.

*Surface maps shown in appendix B.

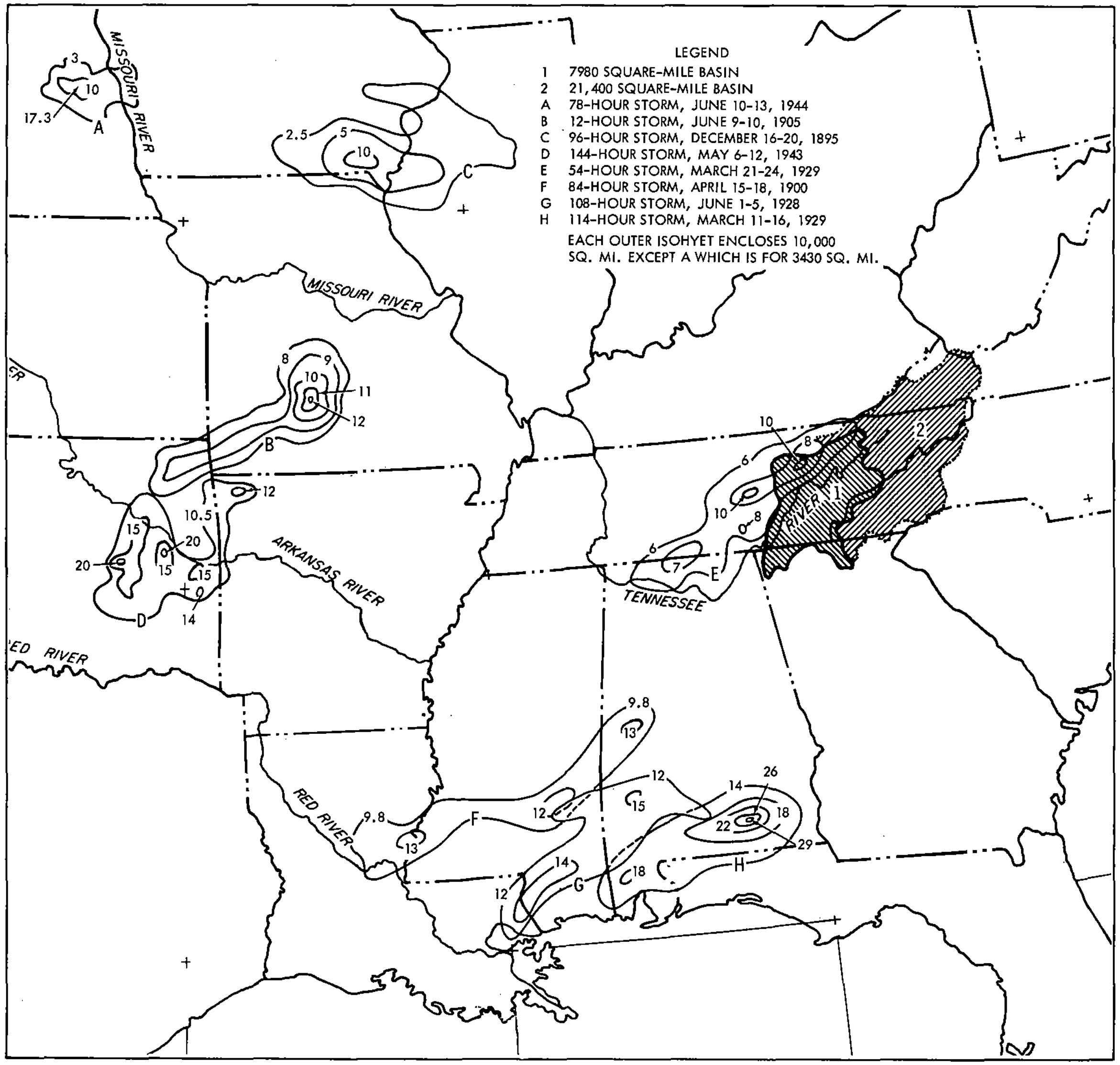


Figure 5-1. Isohyetal patterns of important storms

March 11-16, 1929 storm (fig. 5B-3). This outstanding storm centered at Elba, Ala. produced rainfall of 12.1 inches in 24 hours over 10,000 square miles. Lott (Ref. 5-1) singles out the strong warm air advection of unstable air as an important synoptic feature in this storm. Such a strong flow of air from a far southerly latitude typifies heavy rains in the Tennessee Basin also (see fig. 4-1).

May 6-12, 1943 storm. Hydrometeorological Report No. 34 (Ref. 3-5) discusses thoroughly this outstanding storm. A 24-hr. rainfall averaging nearly 12 inches over 20,000 square miles occurred in this storm. The persistence of a quasi-stationary front together with a strong inflow of moist air from the south were the two governing factors in this long-duration heavy rainstorm.

Basis for cool-season transposition

Many historically-important storms over widely separated areas in the Eastern United States have common meteorological characteristics. One common to the Tennessee Basin and much of the Eastern United States is that of having waters far to the south as the primary source of moisture. When a situation arises that is characterized by a strong influx of moisture in lower levels from latitudes far to the south, heavy rains result. The site of the rainfall in relation to this flow is dictated by concomitant factors such as the location and movement of the upper trough and of frontal or non-frontal convergence patterns. When such rain-favoring features persist or persistently reoccur in large basins, such as the Tennessee, severe floods may result.

This similarity of major storm features over wide areas of the Eastern United States is the basis for the transposition technique applied to these cool-season storms.

Probable maximum and TVA generalized estimates

Adopted generalized March TVA precipitation values for 10,000 square miles and 24 hours are shown in figure 5-2. Similarly, figure 5-3 shows March PMP values. The distinction is attributed directly to maximization for moisture for PMP but not for TVA values. This moisture maximization is based on precipitable water content appropriate to the maximum 12-hr. dew point for the month and place of storm. On both basic generalized charts (figs. 5-2 and 5-3), appropriate rainfall values are shown for the more important storms. Those on the PMP chart (fig. 5-3) have been maximized for moisture.

Near the Gulf of Mexico the Elba, Ala. storm of March 11-16, 1929, controls. To the north, the March storm of most importance is the Bellfontaine, Ohio storm of March 23-27, 1913. While not a controlling PMP storm for 24 hours, it is important for durations longer than the basic 24 hours used in the generalized charts. In addition to the influence of various durations, the degree of envelopment at 24 hours is also influenced by extreme rains of other months.

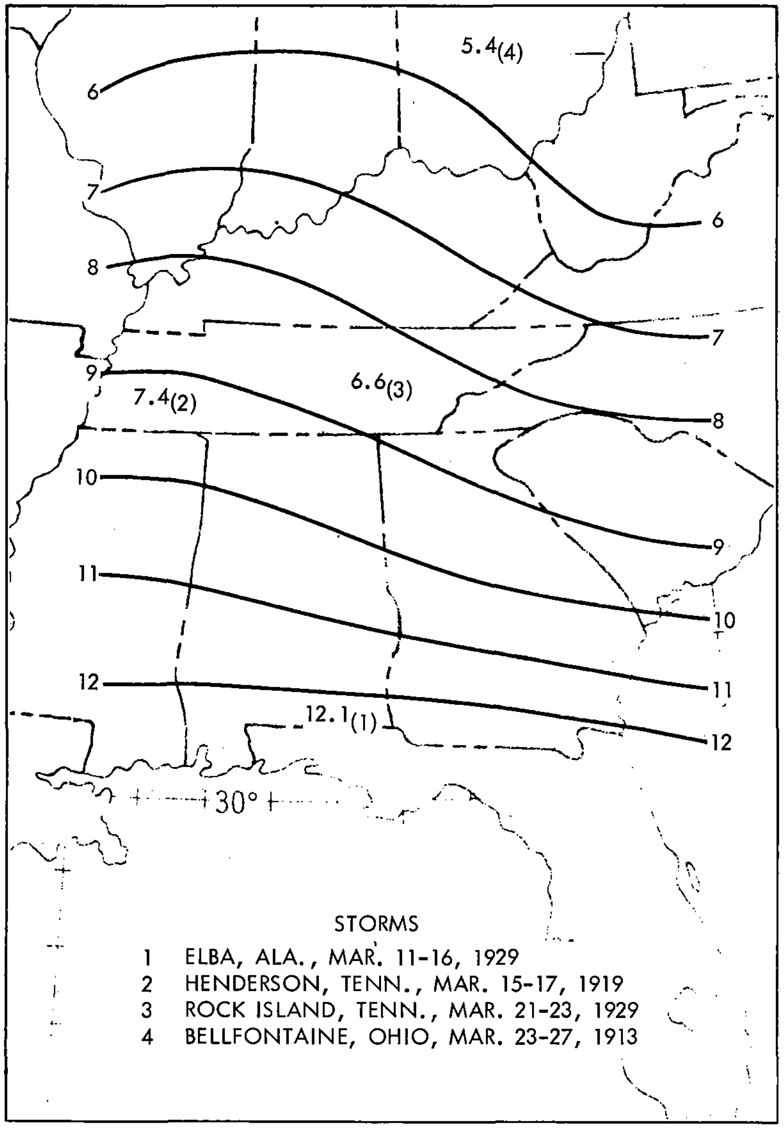


Figure 5-2. March 24-hr. 10,000-sq.mi. TVA precipitation (in.)

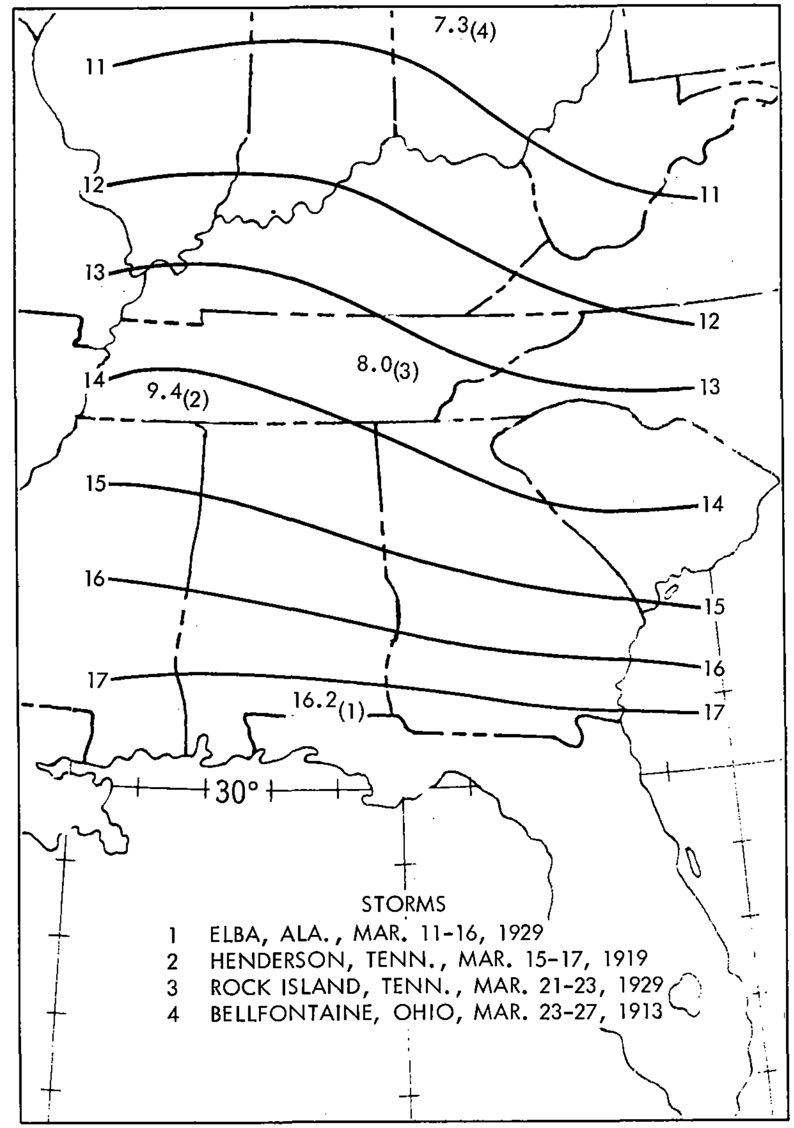


Figure 5-3. March 24-hr. 10,000-sq. mi. PMP (in.)

Rainfall values for two additional storms occurring in March 1919 and March 1929 are shown. These two storms produced significant rain amounts in Tennessee.

5-B. WARM-SEASON ESTIMATES

The Tennessee Basin is too far from the Atlantic Ocean or the Gulf of Mexico to experience a full-fledged hurricane. Yet rather substantial rains from decadent hurricanes have occurred. For example, the largest summertime flow of record at Chattanooga, in August 1901, resulted from the remnants of a hurricane.

Observed hurricane rainfall values were used to derive a distance-from-coast variation of hurricane rainfall. Conforming to the cool-season approach to generalized rainfall estimates, emphasis is on a 24-hr. warm-season rainfall over a 10,000-sq. mi. area. This is a parallel to the generalized chart approach of the previous section. The distance-from-coast is a framework for applying the various facts and deductions to space the lines on the summer generalized charts.

Data sources. Storms with suitable tracks, as given in Weather Bureau Technical Paper No. 36 (Ref. 3-19), formed the basis of search for hurricane rainfall dates. For most of the heavy rain-producing cases selected, rainfall values (for selected basin sizes and durations) were available from either of two sources--Storm Rainfall (Ref. 3-14) or National Hurricane Research Project Report (NHRP) No. 3 (Ref. 3-16). Additional rainfall values were determined for important hurricane-connected rains not included in the above sources. Two such cases are for September 21, 1947 in Missouri and for June 28-29, 1960 in Kentucky. However the bulk of the rainfall data were from NHRP Report No. 3 (Ref. 3-16) and selected data from this source are shown in chapter III, table 3-5.

Features of important storms

Table 5-4 lists the storms which produced rainfall amounts most influential in development of a distance-from-coast relation. Two of these storms gave large amounts well inland into the Middle Mississippi Valley: August 1915 and June 1960. The tracks were quite similar (see fig. 3-23), yet the sequence of weather events was markedly different. In the 1960 storm, the tropical circulation faded away at the surface, but not until a rich supply of moisture had been transported into the area. This moisture later became involved in extensive thunderstorm activity. In the August 1915 storm, the remnants of the residual tropical circulation were transformed into a vigorous, heavy-rain-producing, middle-latitude storm. Surface weather maps for the 1915 and 1960 storms are shown in appendix B, figures 6B-2 and 6B-3.

Table 5-4

IMPORTANT SUMMER RAINFALL INDIRECTLY OR DIRECTLY RELATED TO TROPICAL STORMS

Code No.	Date	Rainfall Center
1	9/10-13/78	Jefferson, Ohio
2	8/20/15	Missouri
3	7/5-10/16	Bonifay, Fla.
4	7/13-17/16	Altapass, N. C.
5	9/8-10/21	Thrall, Tex.
6	9/21/47	Shelbyville, Mo.
7	9/3-7/50	Yankeetown, Fla.
8	10/14-16/54	Ontario, Canada
9	6/28-29/60	Kentucky

This relatively common redevelopment of a pronounced circulation (by transformation into a middle-latitude disturbance) allows the residual rich moisture supply of a tropical disturbance to become productive of extreme rainfall well inland. Such transformation characterized three other storms with significant inland rainfall. One such transformation followed the penetration inland of a hurricane in Louisiana on September 19, 1947 after crossing southern Florida from the Atlantic. Another was that of the famous hurricane "Hazel" of October 1954, which brought record-breaking rains to the Province of Ontario in Canada. Both the September 1947 and October 1954 storms had a pronounced trough of low pressure aloft "pick-up" the remnants of their hurricane circulation. Petterssen (Ref. 5-2) states that Hazel became "absorbed in a regular extratropical cyclone of very great intensity." Figure 5B-4 in appendix B shows this development. The third example, the unusual September 1878 storm, brought record rains to Ohio.

In contrast to the above examples of redevelopment, the Yankeetown, Fla. storm of September 1950 typifies a heavy-rain-producing, slow-moving hurricane.

Assumptions and working hypotheses. The final determination of the variation of hurricane rainfall with distance-from-coast is aided by certain assumptions and working hypotheses:

(1) The assumption is made that the potential for hurricane rainfall remains constant for the first 50 miles inland from the coast. This is based on the fact that the terrain is relatively flat and the assumption that the record to the contrary is biased by greater storm frequency at the coast.

(2) Beyond 50 miles a marked decrease in rainfall potential begins. The basis for this is the pronounced decrease in width of continued inflow of moisture, essential to heavy rain continuing over basins of the order of 10,000 square miles or larger.

(3) The intensity of tropical storm rainfall should level off at large distances inland as middle-latitude storm characteristics become more predominant. This is suggested by both Hazel (October 1954) and the August 1915 storm discussed above.

(4) As with the cool-season estimates, summer basin rainfall estimates are assumed to be non-orographic values. For this reason observed storms in the Atlantic Coast drainage, with its complicated topographic effects, were less useful in defining a distance-from-coast relation there than storms in flatter areas.

Adopted summer estimates

The storm data presented and the assumptions made above lead to the adopted summer TVA precipitation and probable maximum precipitation shown on figures 5-4 and 5-5, respectively. The TVA intensity at the coast is equal to that observed in the July 5-10, 1916 storm. The TVA adopted values undercut such outstanding storms as the Jefferson, Ohio storm of September 1878. The rainfall for this rare storm is instrumental, however, in setting the level of the PMP in that general area (fig. 5-5). The adopted PMP lines (fig. 5-5) over-envelop the Yankeetown, Fla. rainfall value for a duration of 24 hours and an area as large as 10,000 square miles. The envelopment is less for somewhat smaller areas and longer durations. The smooth isohyetal lines on figures 5-4 and 5-5 are considered non-orographic rainfall values.

Relationship of generalized winter and summer estimates

While the cool-season generalized charts were keyed to March data (figs. 5-2 and 5-3) consideration of month-to-month variation aided in such features as the degree of envelopment and shaping.

The generalized warm-season charts (figs. 5-4 and 5-5) utilized hurricane rainfall data without consideration of month-to-month variation per se. These variations are introduced in section C of this chapter by means of month-to-month ratios. The mid-basin values from figure 5-4 are to be considered approximate midsummer TVA depths in table 5-1 after appropriate adjustments from 10,000 to 7980 square miles.

5-C. MONTH-TO-MONTH, DURATIONAL AND BASIN-SIZE VARIATION

The chapter thus far develops PMP and TVA precipitation for 24 hours and 10,000 square miles for two seasons. This last section is concerned with defining the following:

(1) Month-to-month variation of 24-hr. PMP and TVA precipitation values (in percent of March) for the entire area above Chattanooga, 21,400 square miles.

(2) Adjustment of these relations to an area of 7980 square miles.

(3) Durational variation to 72 hours, based on storm rainfall data.

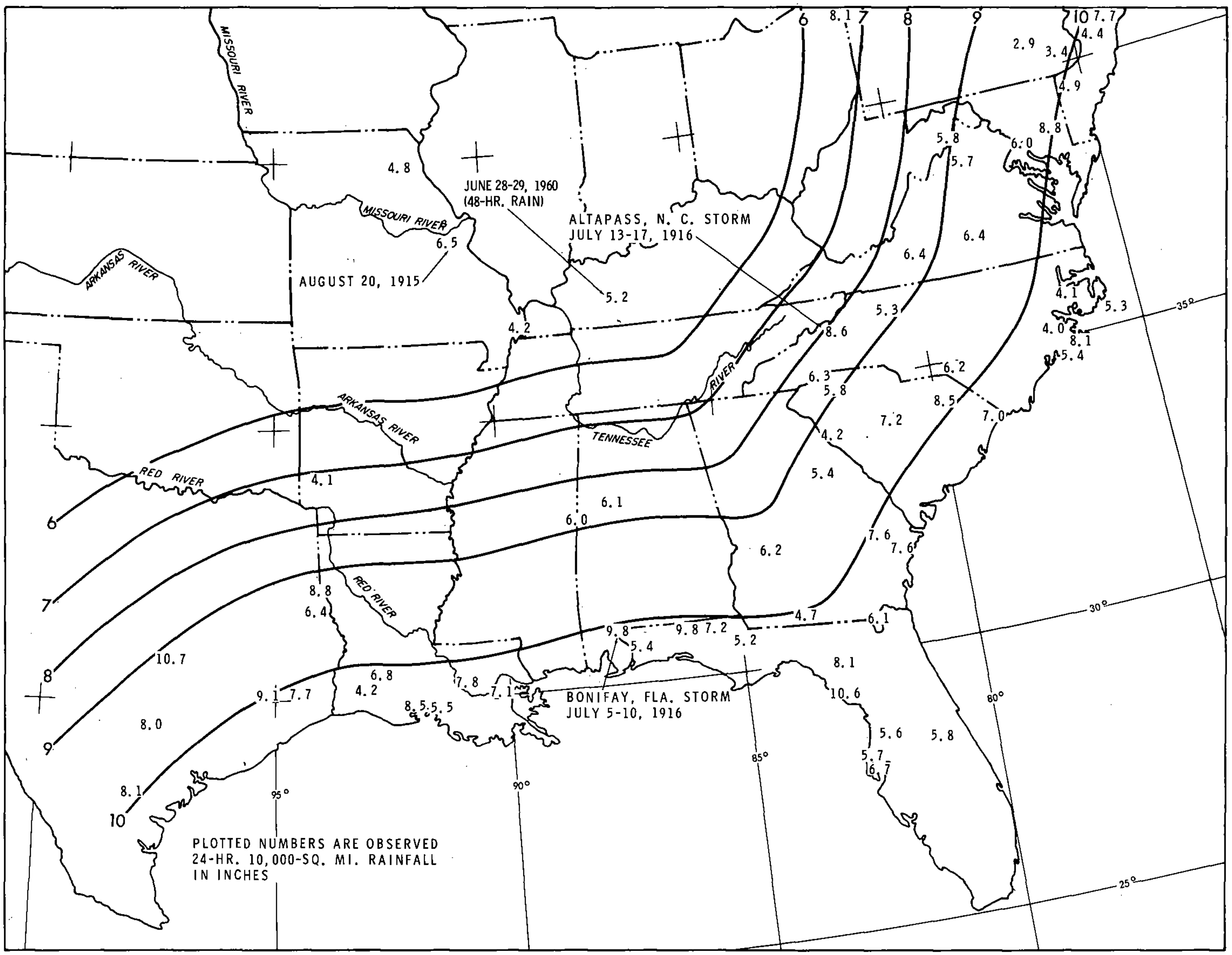


Figure 5-4. Distance-from-coast variation of summer TVA precipitation (non-orographic)

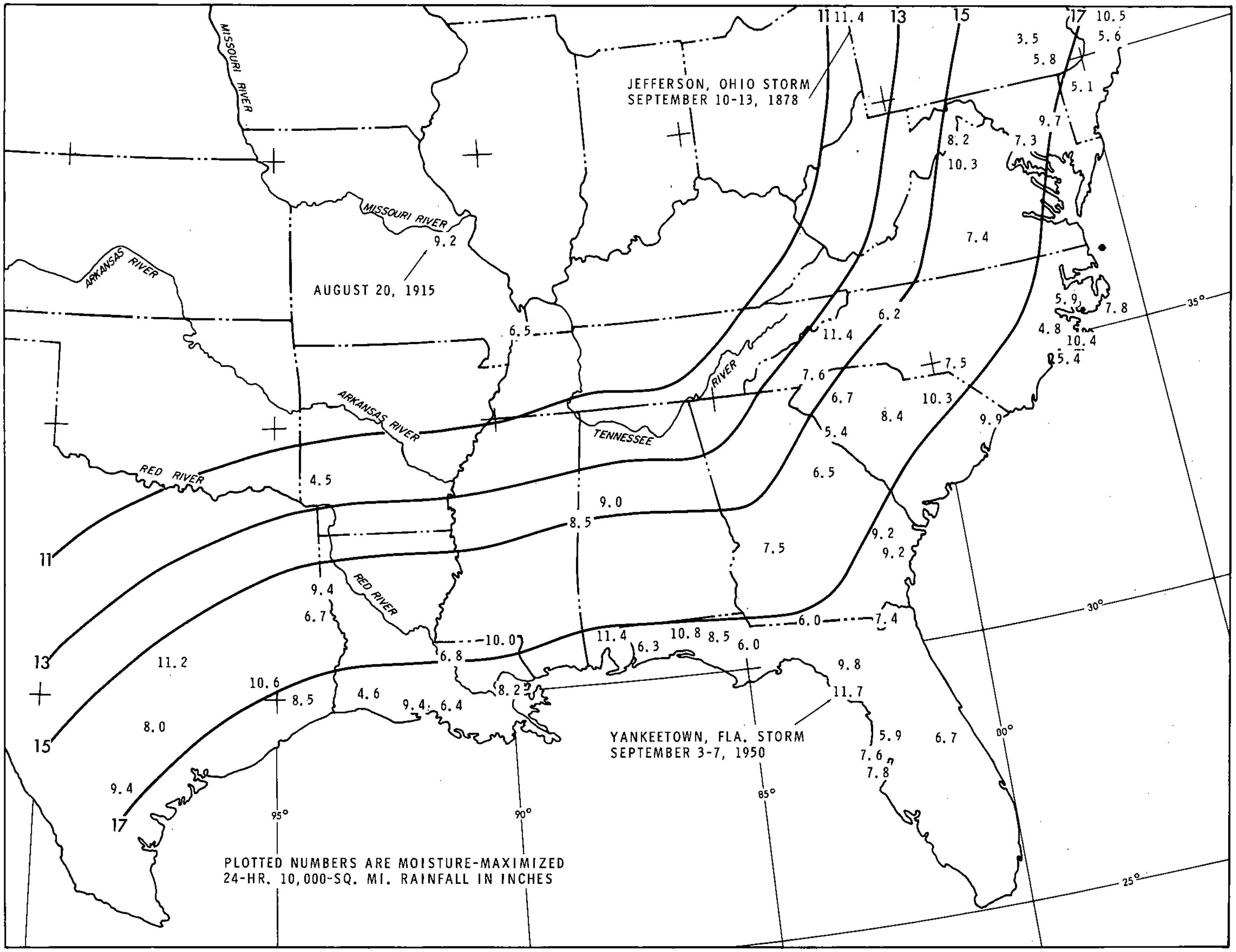


Figure 5-5. Distance-from-coast variation of summer PMP (non-orographic)

Month-to-month variation for 21,400 square miles

Adopted relations. The adopted PMP and TVA precipitation variation (percent of March) for 21,400 square miles is shown in two curves in figure 5-6. Many considerations and much data are involved in the shaping of these curves. More evidence than shown in figure 5-6, too involved to present in this report, bears on the shape of the adopted curves.

The following information about month-to-month variations in rainfall is shown in figure 5-6:

(1) A smoothed envelopment of unpublished 20,000-sq. mi. estimates for zone 7 of HMR 33 (Ref. 5-3), centered over Tennessee.

(2) A curve from Schloemer (Ref. 5-4) which approximately envelops both weekly average precipitation and that for shorter durations over basins in the eastern two-thirds of the United States averaging approximately 20,000 sq. mi. in size.

(3) A curve drawn to average of five highest 7-day rains by months at Memphis 1912-1961.

(4) The 2-year and 100-year return-period values derived from statistical analyses of 20 years of daily rainfall over the 21,400-sq. mi. area above Chattanooga, shown in more detail in figure 5-7.

(5) 100-year return-period data similar to (4) for 3-day rains.

Further evidence of seasonal variation

Early summer extreme rainfall events hold up the top curve of figure 5-6. This fact raises the question as to how far the rare storm with winter-type characteristics may extend into the warmer season. Examples of such winter-type storms that occurred well into the warm season are (1) the June 20-21, 1935 storm centered at Greenville, Ky., and (2) the Clinton, Tenn. storm of June 28-30, 1928. Figures 5-8 and 5-9 show features of the surface charts for these two storms. Smoothed total storm isohyets show their relationship to frontal patterns and tracks of Lows. The Eutaw, Ala. storm of April 15-18, 1900 (section A and fig. 5B-1) suggests only a slight decline in PMP capability from March to April.

Support for a lower value of PMP and especially of TVA precipitation in summer than in March is given below:

1. The flood record suggests a sharp decline during April.
2. A marked decline of maximum daily rainfall into the warm season is shown by 20 years of daily precipitation above Chattanooga (fig. 5-7).
3. A winter-type storm provides the highest observed rainfall in the United States averaged over large areas. Table 3-4 shows the

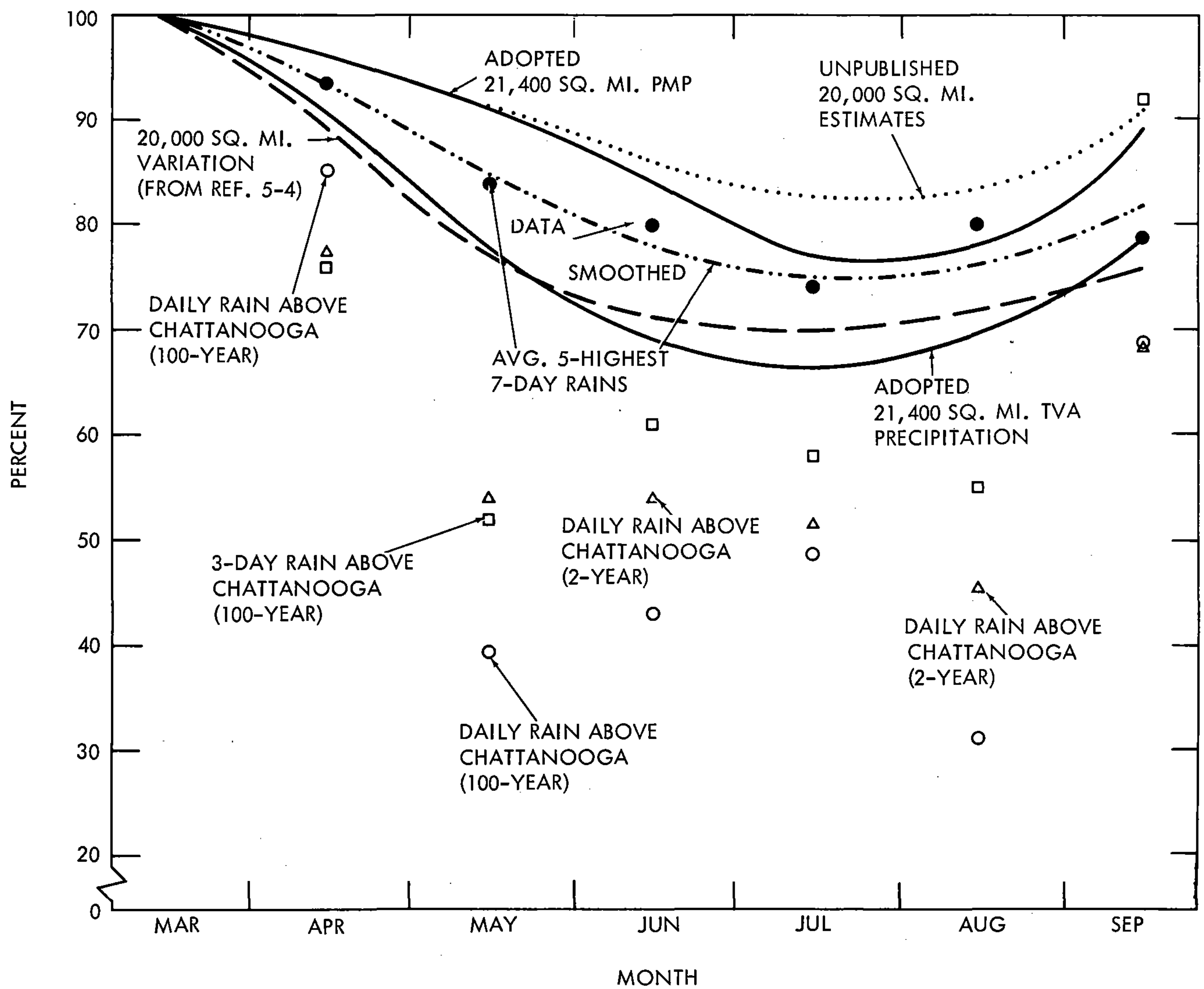


Figure 5-6. Seasonal variation of rainfall over the upper Tennessee River Basin (in percent of March)

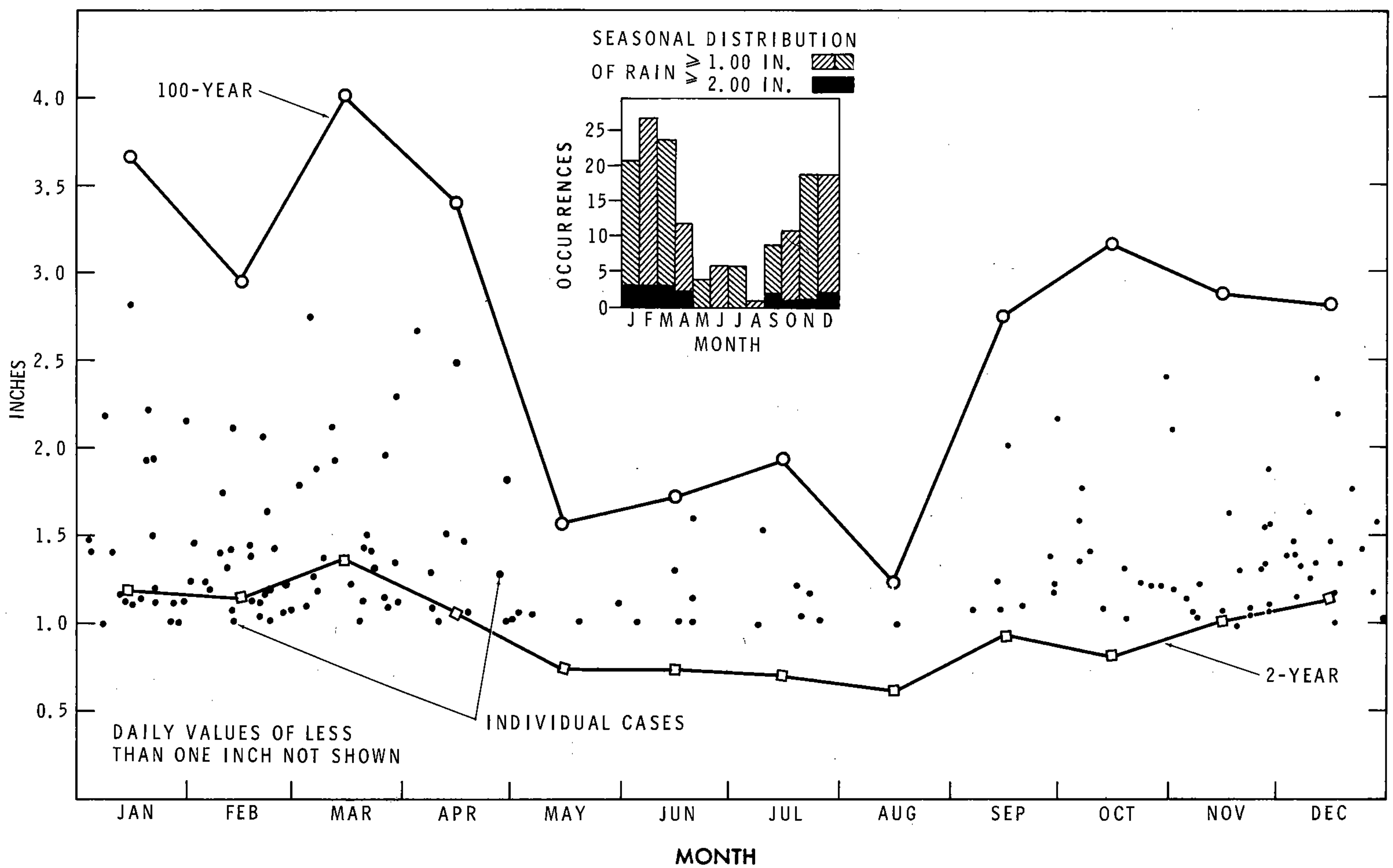


Figure 5-7. Daily rains of one inch or more above Chattanooga (1944-1963)

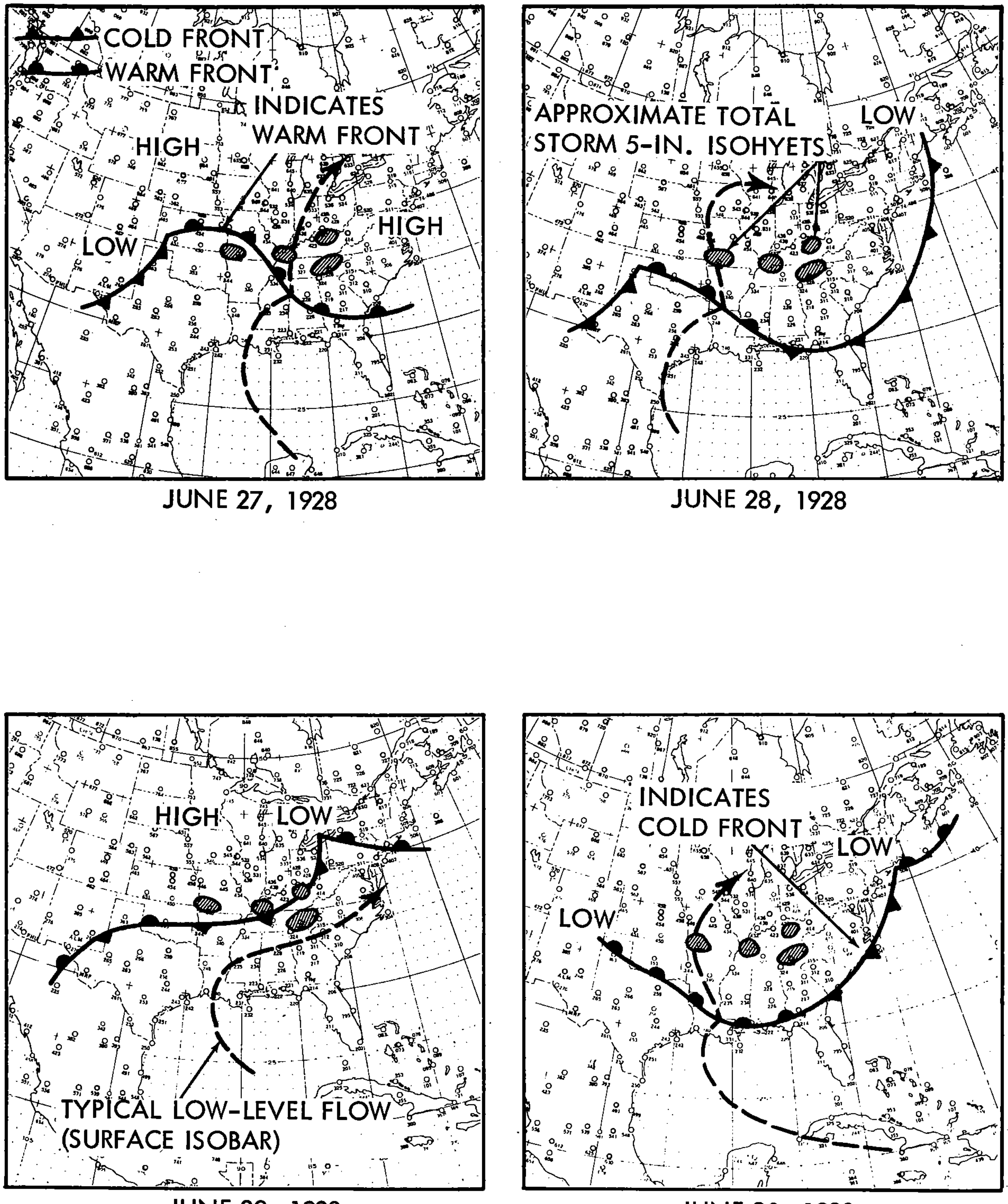


Figure 5-8. Surface weather features (1300 GMT) for June 28-30, 1928 storm

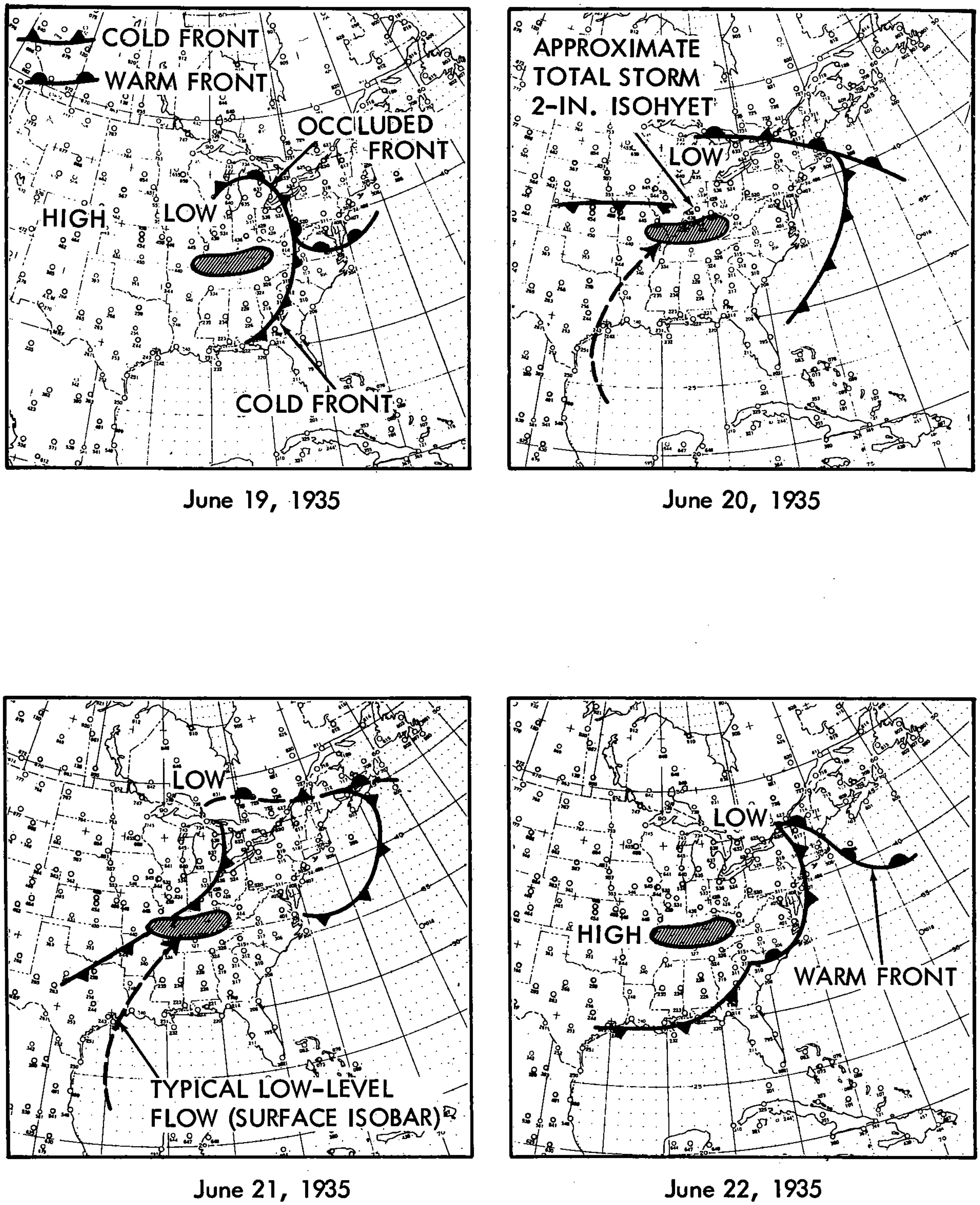


Figure 5-9. Surface weather features (1300 GMT) for June 20-21, 1935 storm

control of highest observed U. S. rain values by the winter-type Elba, Ala. storm and the summer-type Yankeetown, Fla. hurricane, each of which is considered as similar to the rare (PMP) type for its season. A ratio of rainfall observed in these storms is related to area in figure 5-10. This figure shows the winter storm (Elba) predominating for areas above 7000 square miles.

4. Large-area rainstorms in the interior of the Eastern United States are considerably greater in magnitude and more numerous in March than in the warmer season. Figure 5-11 shows all important March through June rainfall values from Storm Rainfall (Ref. 3-14) within 400 miles of the center of the basin.
5. Evidence from the May 6-12, 1943 Warner, Okla. storm. It occurred in an area favoring maximum rains in May (Ref. 5-5). This suggests that those factors causing the phenomenal May 1943 storm at Warner would act less effectively in Tennessee in May, and thus that the May PMP should not be as high as the March PMP.
6. Ranking by months the area within a given isohyet for 167 storms (data supplied by the TVA) places May and June low compared to March and April.
7. Independent estimates of rainfall capabilities by the differing methods discussed in sections A and B, show summer capabilities below winter.

<u>PMP and TVA precipitation for 7980 square miles</u>

The goal of internal consistency required that much rainfall data (Ref. 3-14) from the Eastern United States be summarized to determine smooth month-to-month variations of depth-area ratios. These variations of depth-area relations with area were then compared as ratio curves. To aid in deriving smooth relations areas as large as 50,000 square miles were considered.

The adopted 20,000- to 10,000-sq. mi. curve and the supporting data are shown in figure 5-12. Data are monthly mean ratios of much Eastern United States depth-area rainfall values involving many storms. Particular guidance comes from important storms. The overall similarity of storms in Eastern United States supports the use of mean data to obtain the most meaningrul relations.

Since interest is primarily in basin sizes of 7980 and 21,400 square miles, an additional ratio curve was developed relating these size areas. Such a ratio curve, in addition to the 20,000 to 10,000 ratio curve copied from figure 5-12, is shown in figure 5-13. Some of the more important data support for the ratio curve relating the 7980 and 21,400-sq. mi. areas are shown on figure 5-13. A greater quantity of Eastern United States data, as mentioned above, were most instrumental in obtaining internal consistency among the various ratio curves.

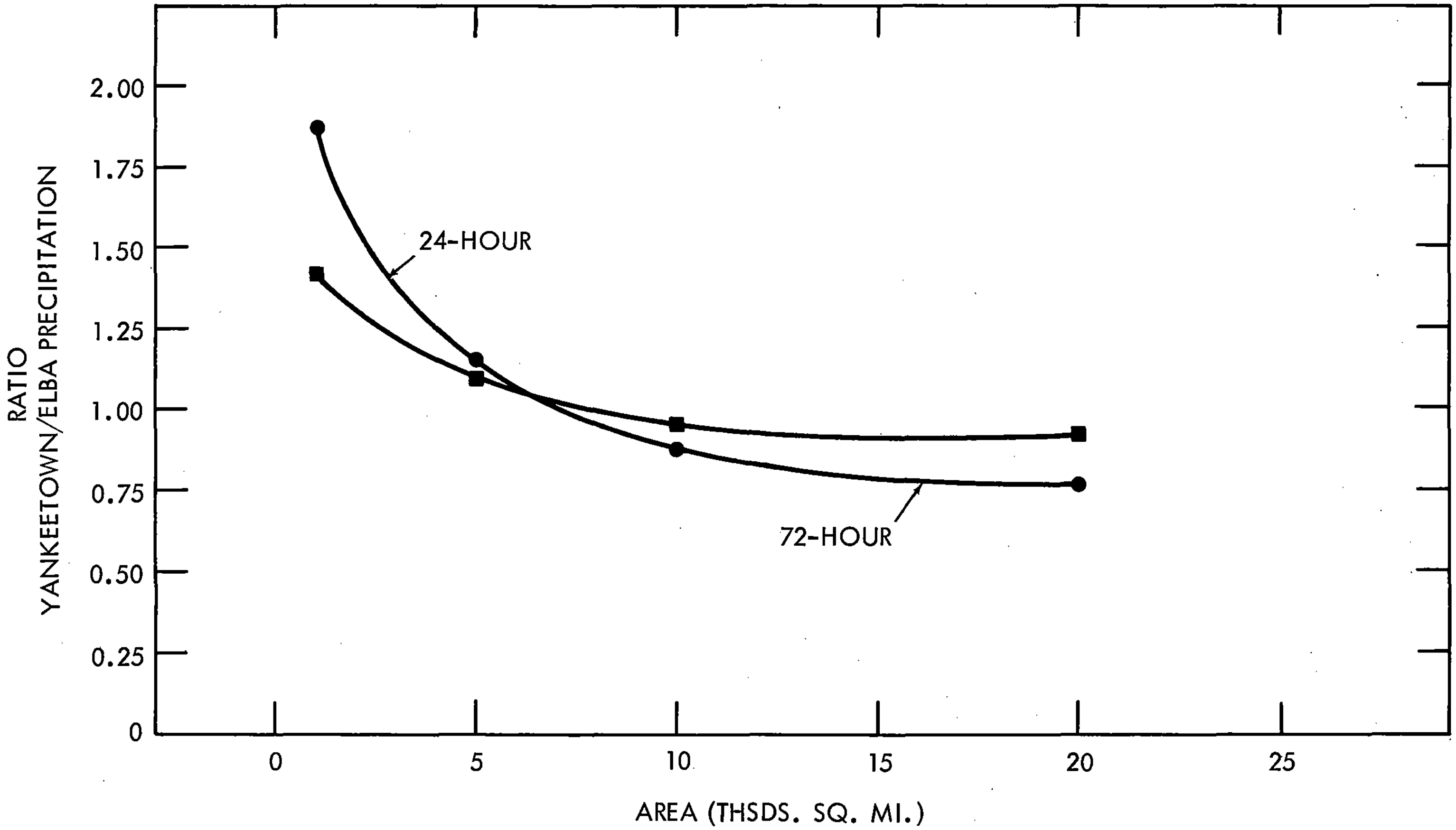


Figure 5-10. Seasonal variation of precipitation related to area

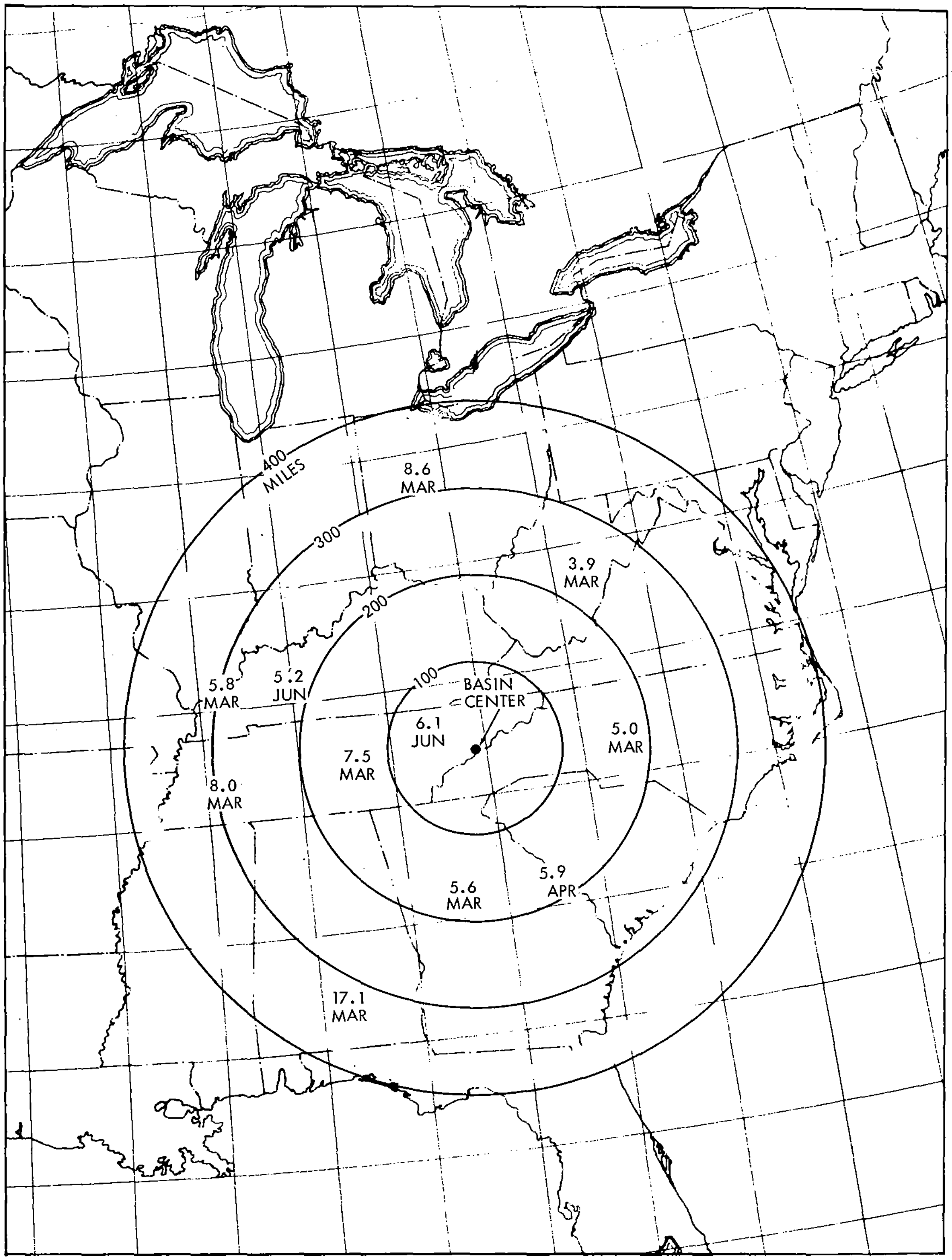


Figure 5-11. 10,000-sq. mi. 72-hr. rains within 400 miles of basin center

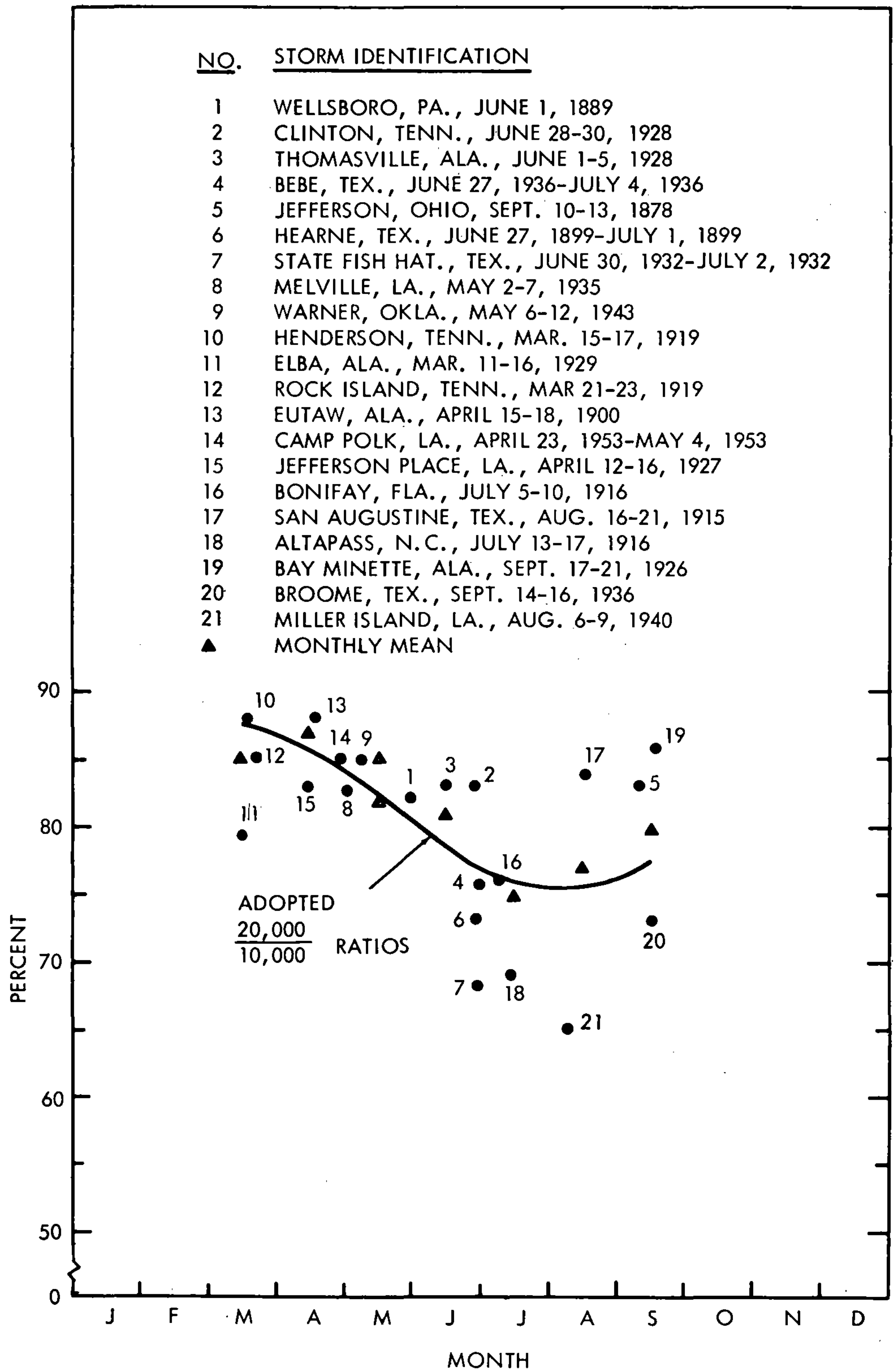


Figure 5-12. Depth-area ratio (20,000/10,000-sq. mi.) for 24-hr. rainfall

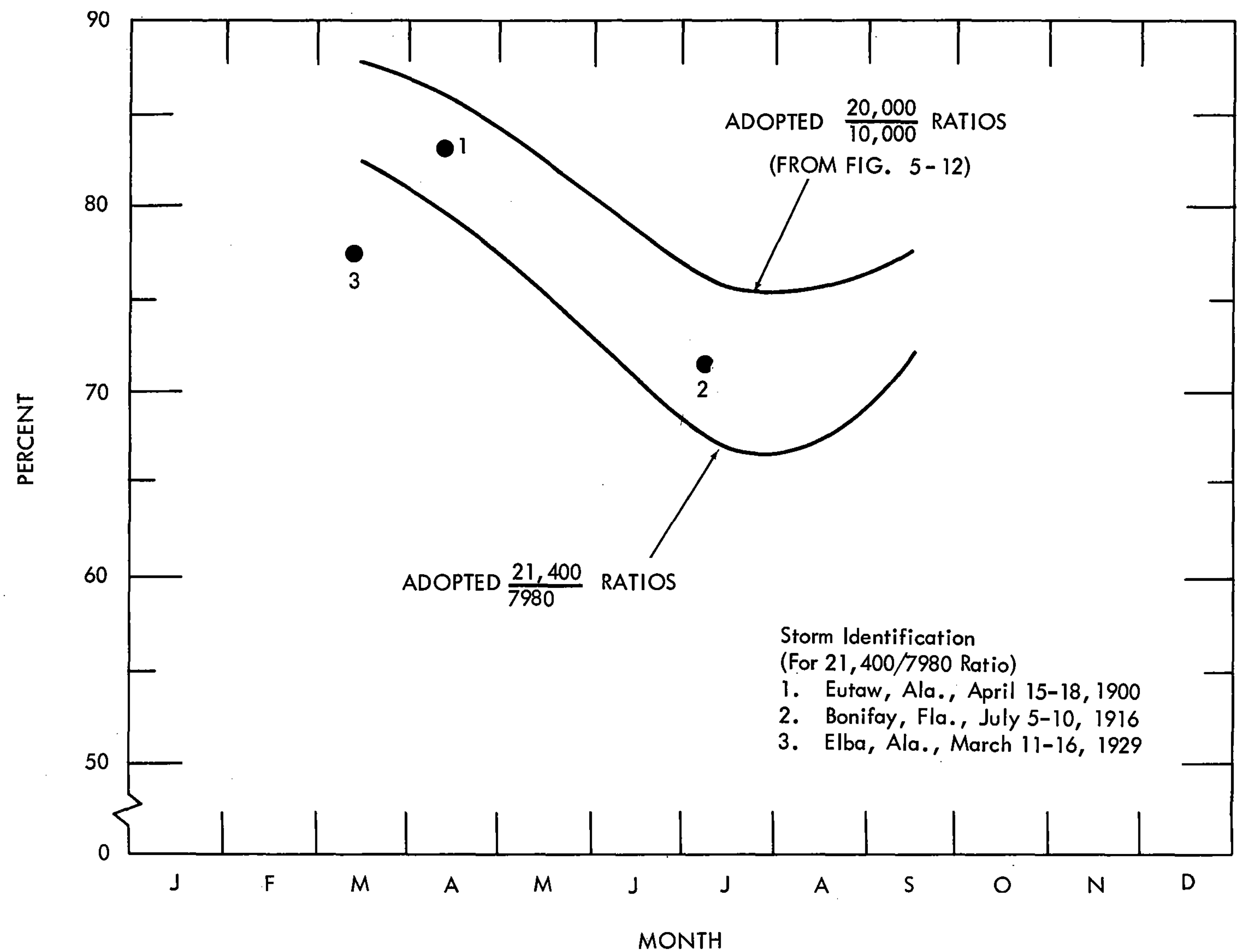


Figure 5-13. Depth-area ratios (21,400/7980-sq. mi.) for 24-hr. rainfall

Depth-duration relations

Storm Rainfall data (Ref. 3-14) for Eastern United States, particularly 6/24- and 72/24-hr. ratios, were used as indicators of duration ratios for TVA and probable maximum rainfall in the Tennessee Basin. These data include mean storm ratios by months and individual ratios for important storms. They show no clear-cut seasonal trends for the two sizes of areas considered. Figures 5-14 and 5-15 show the data and the adopted 10,000- and 20,000-sq. mi. duration relations, respectively.

The adoption of mean curves with no seasonal trend is supported by an important factor, convergence of the data toward their mean value with increasing rain intensity. This convergence of ratios was found in much storm data for both area sizes, for both 6/24- and 72/24-hr. ratios. One example of this convergence, for 6/24-hr. ratios and 10,000-sq. mi. area for the month of April, is given in figure 5-16.

Additional evidence of lack of a consistent seasonal trend of ratio is found in 3-day to 1-day station rainfall ratios. Figure 5-17 shows 72/24-hr. ratios for four locations. The values are based on the five highest 72-hr. rains for a 50-yr. period of record (1912-1961).

The adopted ratios for the basic 10,000- and 20,000-sq. mi. areas and for the two basin areas of 7980 and 21,400 square miles are shown in table 5-5. Smooth depth-area curves were drawn to obtain the extrapolated basin values.

Table 5-5

DURATION RAINFALL RATIOS

Area (Square Miles)	Ratio 6/24 Hrs.	Ratio 72/24 Hrs.
7,980	0.50	1.45
10,000	0.48 (from fig. 5-14)	1.48 (from fig. 5-14)
20,000	0.46 (from fig. 5-15)	1.50 (from fig. 5-15)
21,400	0.45	1.50

Figure 5-18 compares, for an area size of 10,000 square miles, the adopted depth-duration relation with observed storm cases.

Application of seasonal and depth-area-duration relations

The adopted monthly array of TVA precipitation and PMP (tables 5-1 and 5-2) result from the application of the above adopted monthly depth-area and all-season depth-duration ratios to March 10,000-sq. mi. 24-hr. rainfall values developed in sections A and B of this chapter, with slight modifications to obtain smooth depth-duration-area relations. The midsummer values were compared with those derived by the distance-from-coast approach. The differences were small so additional adjustments were not considered necessary. Figure 5-6 shows adopted 21,400-sq. mi. PMP and TVA precipitation curves in percent of March values.

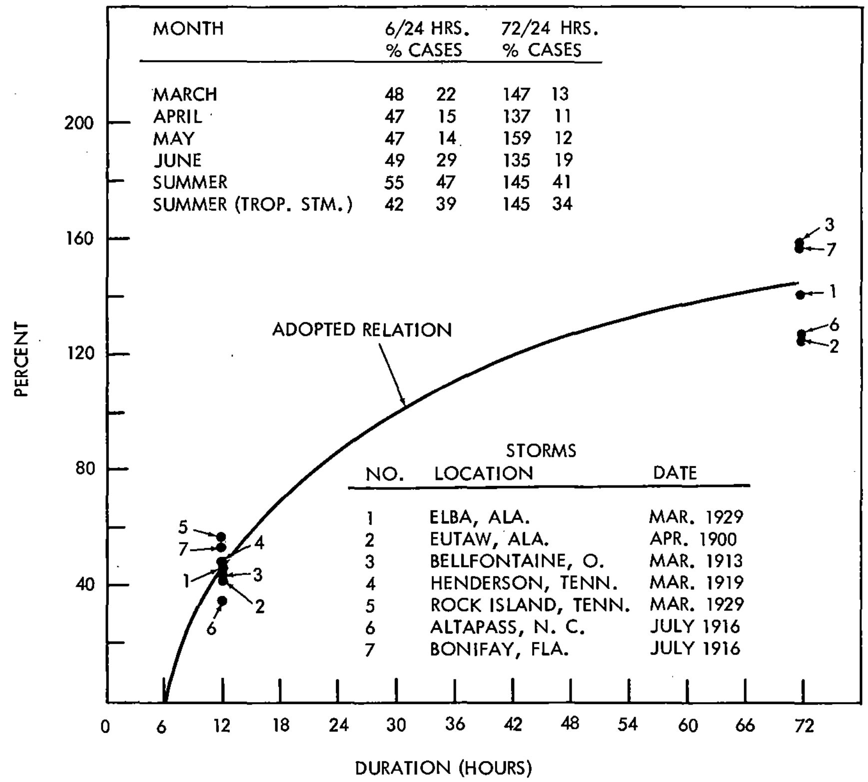


Figure 5-14. Depth-duration in percent of 24 hours (10,000 sq. mi.)

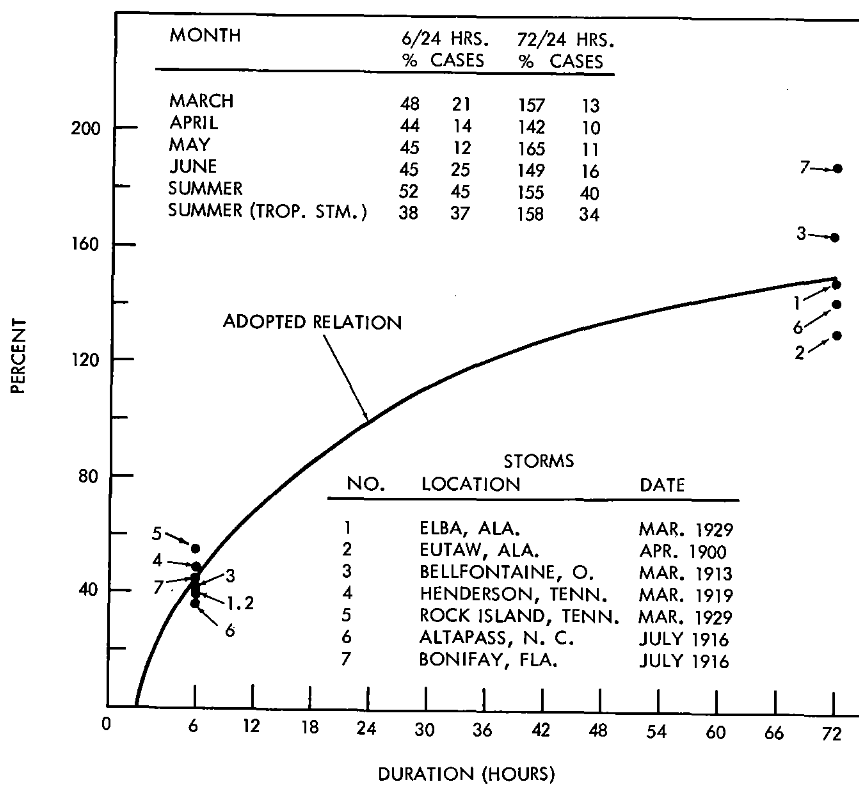


Figure 5-15. Depth-duration in percent of 24 hours (20,000 sq. mi.)

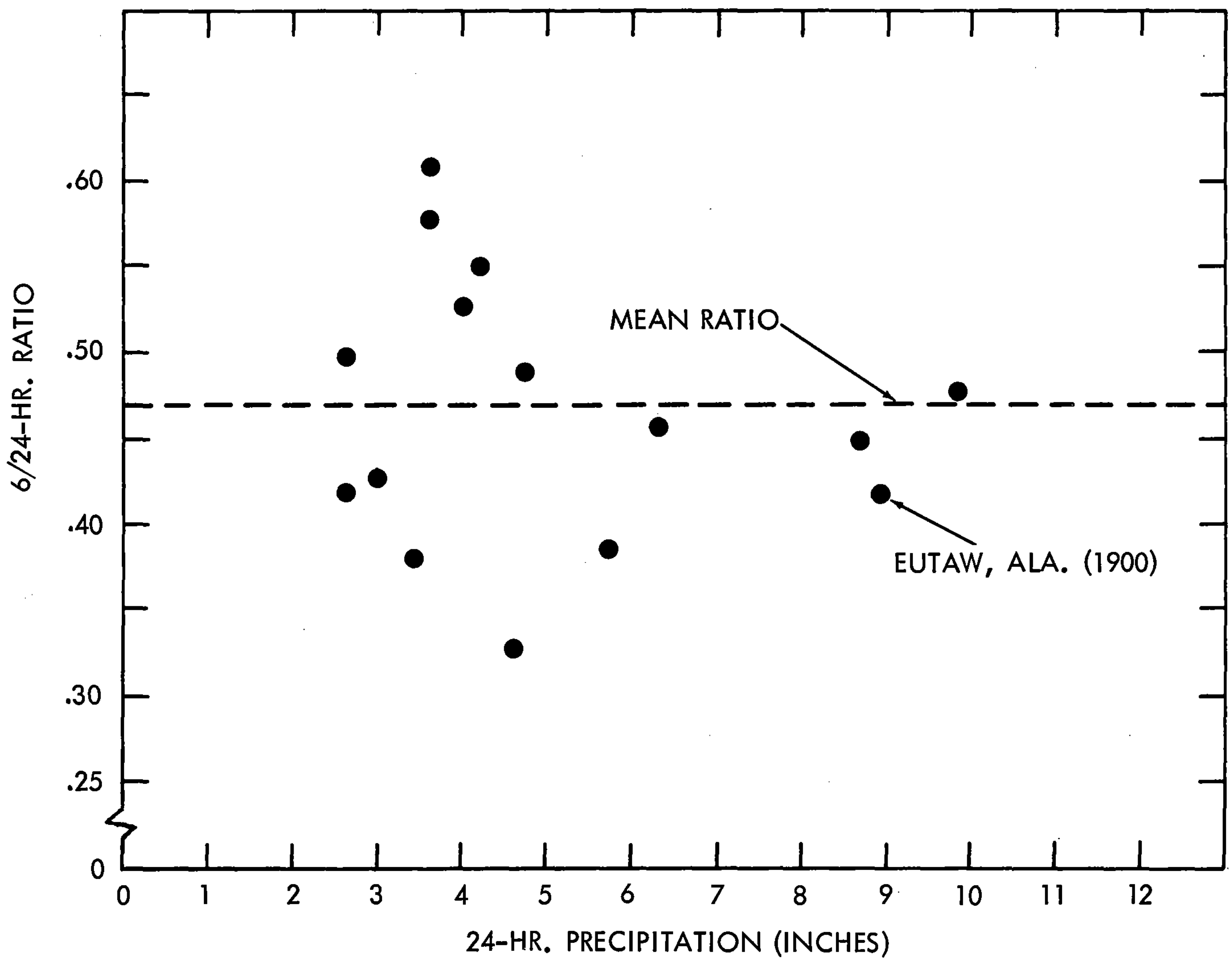


Figure 5-16. 10,000-sq. mi. 24-hr. 6/24-hr. ratio (April)

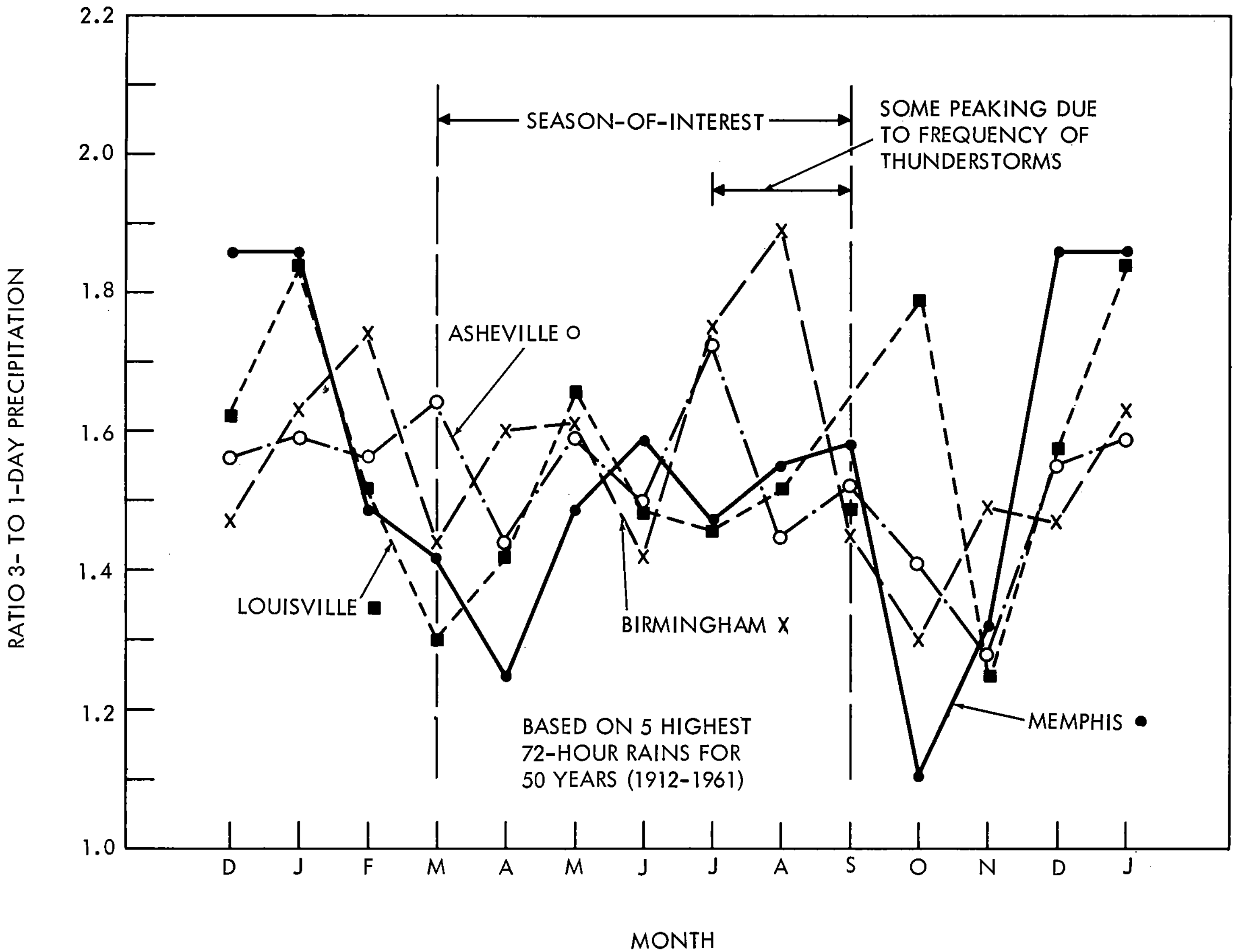


Figure 5-17. Seasonal variation of point 72/24-hr. ratios

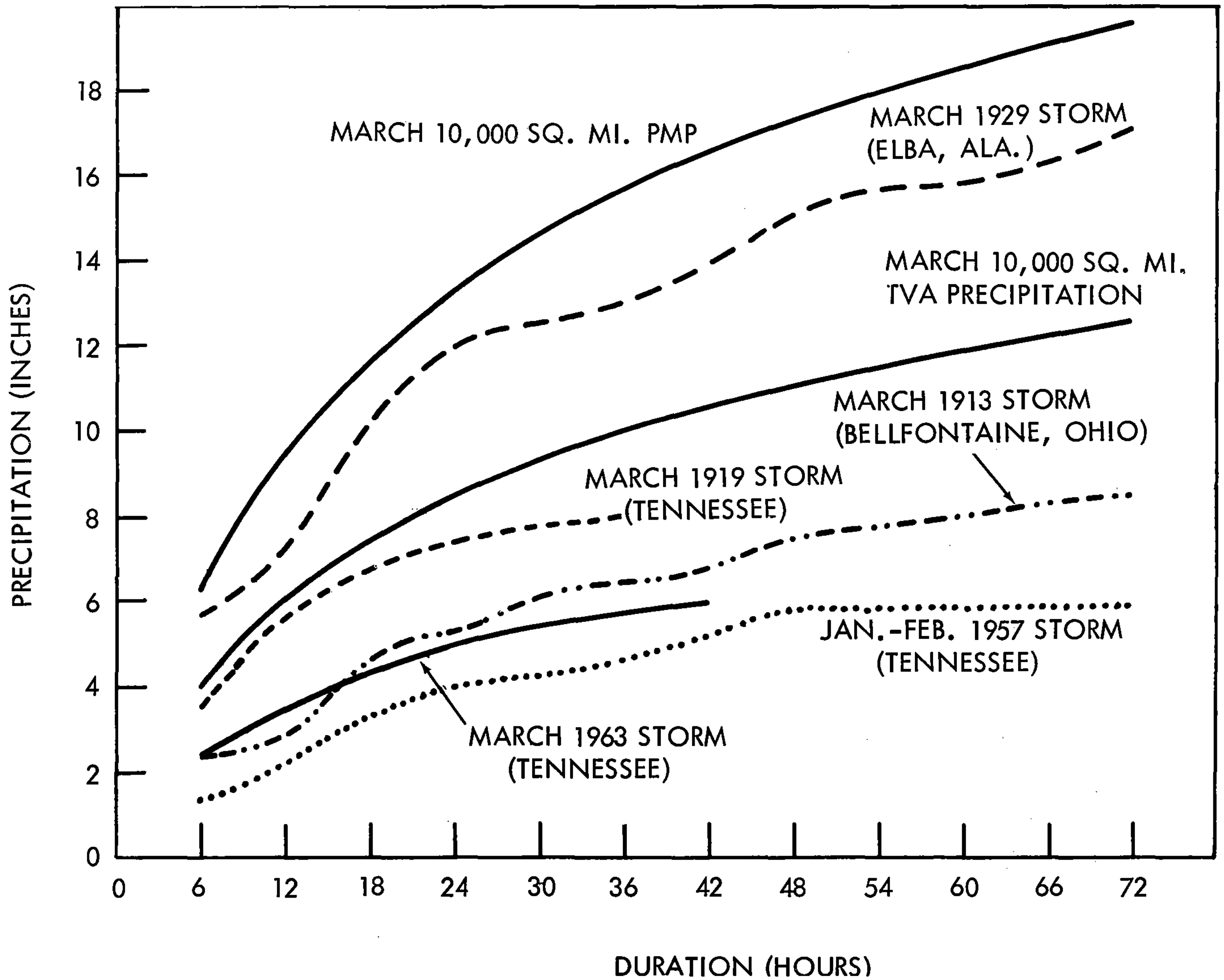


Figure 5-18. Depth-duration rainfall comparisons

Chapter VI

ANTECEDENT AND SUBSEQUENT CONDITIONS

Introduction

The flood-producing capabilities of a large 3-day rain depend upon many factors. Antecedent and subsequent rainfall may play important roles. Many large floods on sizeable basins have resulted from the recurrence of periods of rainfall as the broad-scale meteorological controls persist. An excellent (and rather extreme) example is that of the extended period of recurring rainfall in January 1937. This persistent rain period has been discussed thoroughly in previous reports (Ref. 3-4).

The purpose of this chapter is to present rainfall criteria that could readily occur prior to and following the 3-day TVA precipitation and 3-day PMP. The adopted rainfall amounts and number of rainless days are presented in tables 6-1 (antecedent) and 6-2 (subsequent). The method used is discussed in subsequent paragraphs. Recommendations for application of the values in tables 6-1 and 6-2 are covered in chapter VII.

Sources of data and method

Guidelines for setting rainfall antecedent and subsequent to the main storm are two kinds. Both are relied on. The first is rainfall in storms and at stations for various durations. These are examined to determine characteristic ratios, for example, of total 10-day rain to the heaviest 3-day rain within the 10 days. Some of the data reviewed are:

(1) Observed maximum 3- to 10-day precipitation for stations in and around the basin.

(2) Computed average basin precipitation for durations of 1 to 10 days for the 21,400-sq. mi. drainage above Chattanooga.

(3) Depth-area-duration relations from "Storm Rainfall" (Ref. 3-14).

(4) Statistical station estimates of precipitation for durations of 1 to 10 days for Memphis, Louisville, Asheville and Birmingham (Refs. 6-1 and 6-2).

The second kind of guidance is obtained primarily from weather maps. Many storm sequences are reviewed to find what happens to such features as fronts, Lows and currents of moist air as one storm ends and another approaches. This guidance is the primary one for setting the dry interval between storms. Some reviewed data of these kind include:

(1) Observed meteorological sequences in the storms of March 1963 in Tennessee and of June 1960 in Kentucky, adopted as model storms for this purpose.

(2) Sequence of meteorological features associated with maximum 1- to 10-day rains of record in and around Tennessee.

(3) Hypothetical flood sequences of observed storms found to be meteorologically reasonable in other reports (Refs. 3-4 and 3-5).

Table 6-1

ANTECEDENT RAINFALL

Month	Antecedent Ratio to Main Storm (percent)	Antecedent (Inches) 7980-sq. mi. basin	Antecedent (Inches) 21,400-sq. mi. basin	Dry Interval Before PMP or TVA storm (days)	3-Day PMP or TVA Pcpn. (Inches) 7980-sq. mi. basin	3-Day PMP or TVA Pcpn. (Inches) 21,400-sq. mi. basin
			PMP			
Mar.	40	8.14	6.71	3	20.36	16.78
Apr.	40	8.08	6.44	3	20.20	16.11
May	40	7.96	6.10	3	19.92	15.27
June	40	7.81	5.63	3	19.53	14.09
July	30	5.72	3.87	2-1/2	19.07	12.92
Aug.	30	5.72	3.87	2-1/2	19.07	13.09
Sept.	30	6.09	4.47	2-1/2	20.30	14.92
			TVA Precipitation			
Mar.	40	5.18	4.26	4	12.95	10.67
Apr.	40	4.79	3.88	4	11.98	9.70
May	40	4.34	3.32	4	10.85	8.31
June	40	4.16	2.94	4	10.41	7.36
July	30	3.16	2.14	3	10.54	7.14
Aug.	30	3.26	2.24	3	10.88	7.48
Sept.	30	3.52	2.52	3	11.76	8.42

Table 6-2

SUBSEQUENT RAINFALL TO FOLLOW SEQUENCE OF TABLE 6-1

Month	3-Day PMP or TVA Pcpn. (Inches) 7980-sq. mi. basin	21,400 sq. mi. basin	Dry Interval After PMP or TVA Storm (days)	Ratio to Main Storm (percent)	Subsequent (Inches) 7980-sq. mi. basin	21,400-sq. mi. basin
			PMP			
Mar.	20.36	16.78	2	20	4.07	3.35
Apr.	20.20	16.11	2	20	4.04	3.22
May	19.92	15.27	2	20	3.98	3.05
June	19.53	14.09	2	20	3.90	2.81
July	19.07	12.92	2-1/2	15	2.86	1.89
Aug.	19.07	13.09	2-1/2	15	2.86	1.96
Sept.	20.30	14.92	2-1/2	15	3.04	2.23
			TVA Precipitation			
Mar.	12.95	10.67	3	20	2.59	2.13
Apr.	11.98	9.70	3	20	2.39	1.94
May	10.85	8.31	3	20	2.17	1.66
June	10.41	7.36	3	20	2.08	1.47
July	10.54	7.14	3	15	1.58	1.07
Aug.	10.88	7.48	3	15	1.63	1.12
Sept.	11.76	8.42	3	15	1.76	1.26

Summary of meteorological features important in long-duration rains

The above model storms, the 7- and 10-day rains at Memphis, Tenn. and Asheville, N. C., and the hypothetical storm sequences highlight meteorological conditions important to antecedent and subsequent rainfall. The two cities were chosen so as to detect any significant differences between the mountainous east (represented by Asheville) vs. the less rugged western part of the Tennessee drainage above Chattanooga. Storm features for the Tennessee Basin below Chattanooga (represented by Memphis) are similar to those of the western part of the Tennessee drainage above Chattanooga. Three situations that lead to important long-duration rains are:

(1) Winter-type quasi-stationary front with waves. The heaviest 7-day rain of record at Memphis for the month of May (May 10-16, 1953) is an example of this type, which typically has a persistent upper level low pressure trough over the western United States, as shown in figure 6-1b. With this

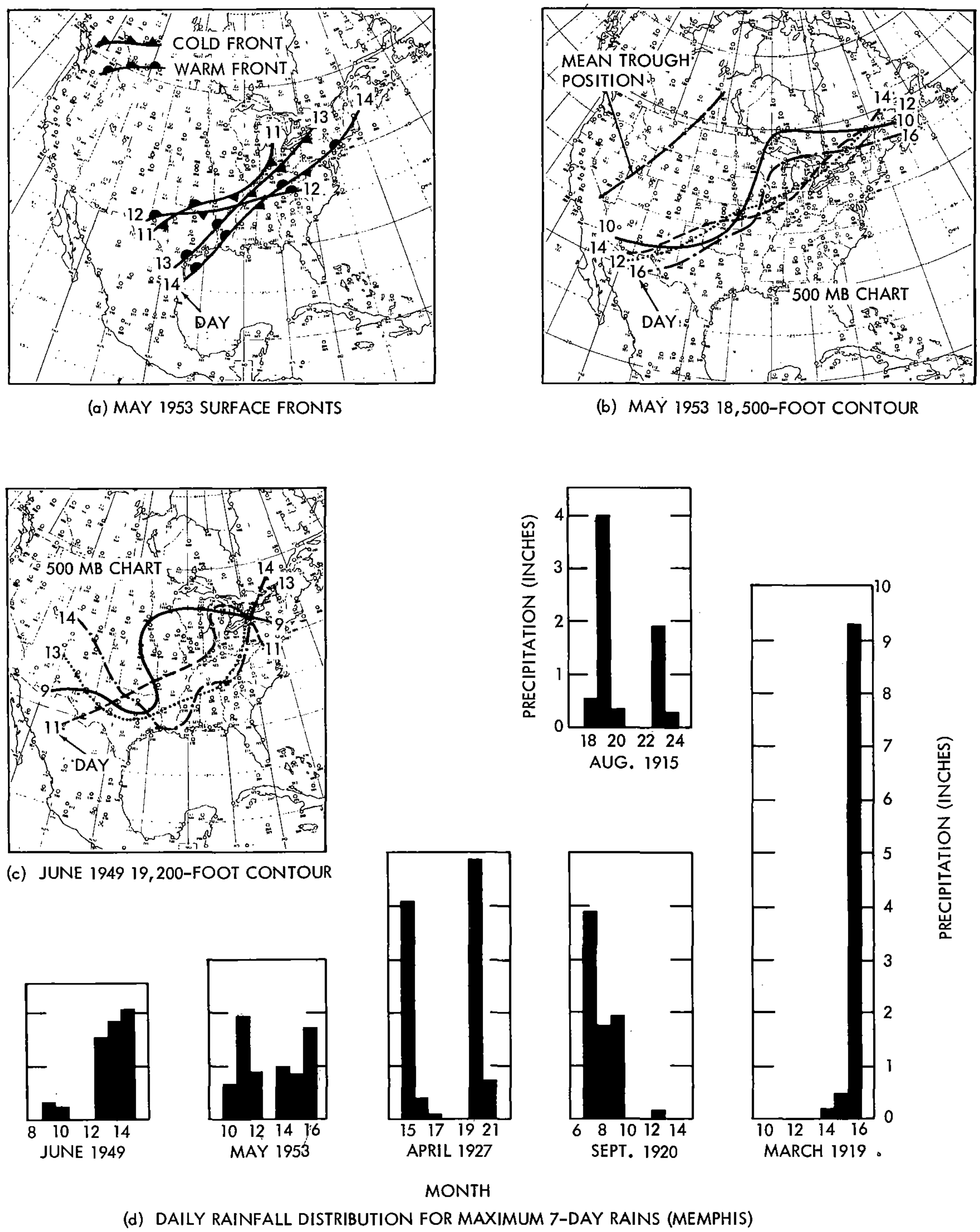


Figure 6-1. Characteristics of heavy long-duration rains in Tennessee

trough controlling, maximum 7-day rains result from a persistence of rainy days as in the May 1953 storm (fig. 6-1d). No such persistence is noted on maps of March 1919 in which a 1-day rain (fig. 6-1d) contributed most of the large March 7-day amount.

(2) Decadent tropical storms. The heaviest 10-day rain of record (1912-1961) for August (Aug. 18-27, 1915) at Memphis was due primarily to the remnants of a tropical disturbance. Figure 6-1d shows the daily rainfall at Memphis in this storm. The highest August (1940) and second highest July (1916) 10-day rains at Asheville also resulted primarily from the effects of two tropical disturbances within 10-day periods.

(3) Convergence in warm air. Intense thunderstorms may result from convergence within the warm moist air. Although often closely related to advancing fronts and/or low-pressure systems, much rain may occur well in advance of the fronts and Lows. The common denominator is pronounced horizontal convergence often associated with an increased flow of moist air from southerly latitudes. Convergence in the warm air was a factor in both of the heavy Memphis rains of March 16, 1919 and April 15, 1927.

Concluding remarks on meteorology. Figure 6-1 highlights some of the above-mentioned meteorological features. Note the quasi-stationary character of the May 1953 surface systems (fig. 6-1a) and the general southwest-to-northeast upper-level flow implied in figure 6-1b for this storm period. Figure 6-1c shows similar persistence of upper-level flow for the heavy rain of June 1949. Figures 6-2a and 6-2b show the important surface weather features associated with the heavy rains at Memphis of April 1927. Two important rain periods at Memphis for this storm are shown in figure 6-1d.

Several additional figures in appendix B emphasize important weather features in other long-duration heavy rain situations. Figures 6B-1a through 6B-1c show meteorological features associated with Asheville's record 10-day rain (1912-1961). Figures 6B-2a and 6B-2b show weather maps during important rains preceding tropical storm rainfall and figures 6B-3a and 6B-3b show weather maps during important rains following tropical storm rainfall. These situations demonstrate that fronts can be important in varying ways for warm season rains.

The variety of meteorological developments contributing to heavy rainfall suggests that a rigid meteorological pattern of development need not be specified in hypothesizing antecedent or subsequent rainfall. Although specific models (March 1963 and June 1960) are part of the data evaluated, the results are of general applicability in the sense of not being dependent upon any specific meteorological sequence.

Dry interval preceding 3-day storm

Previous work with storm sequences for regions well inland suggests that the realistic interval of little or no rain separating major storms is three

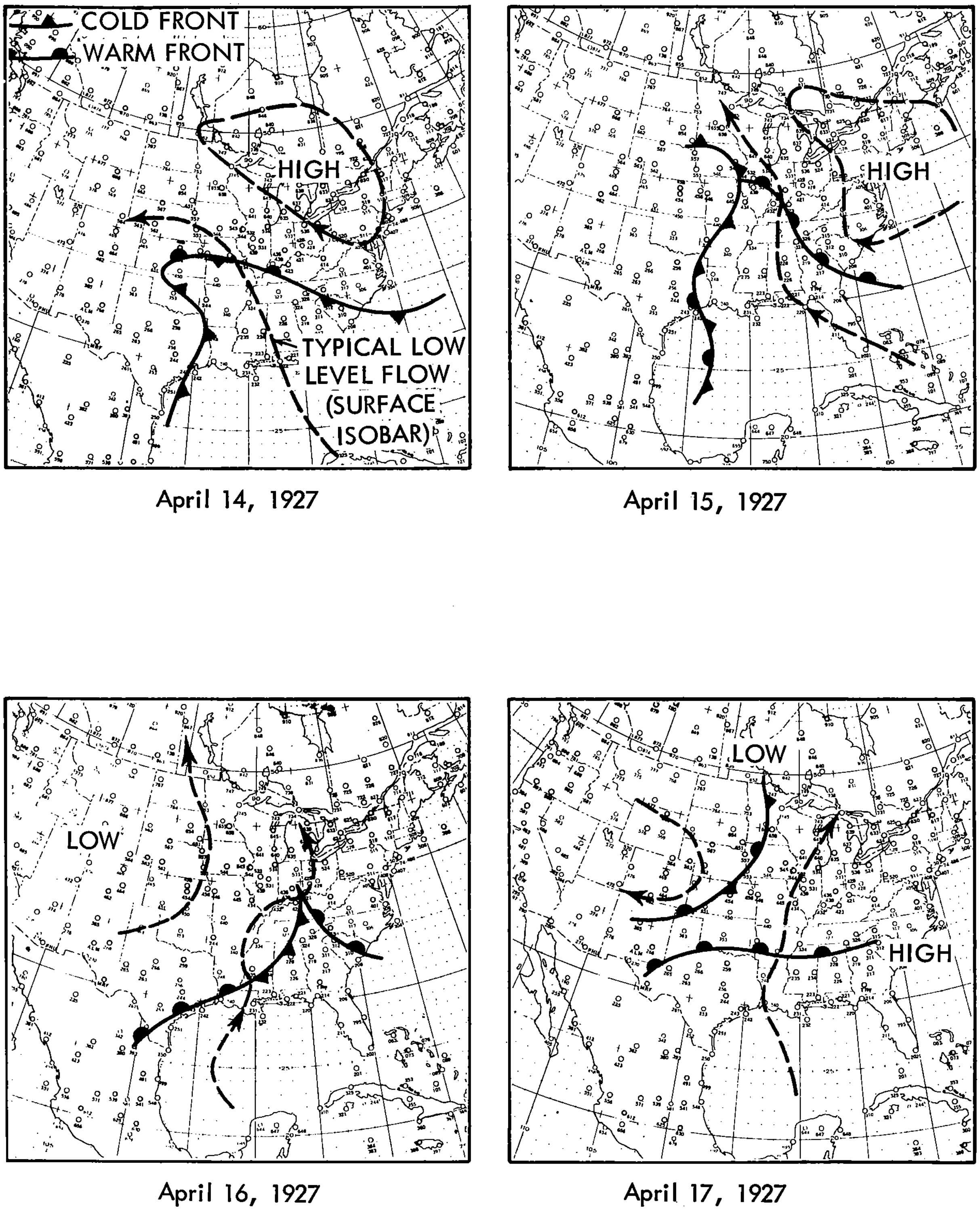


Figure 6-2a. Surface weather features (1300 GMT) for maximum Memphis April 7-day rain

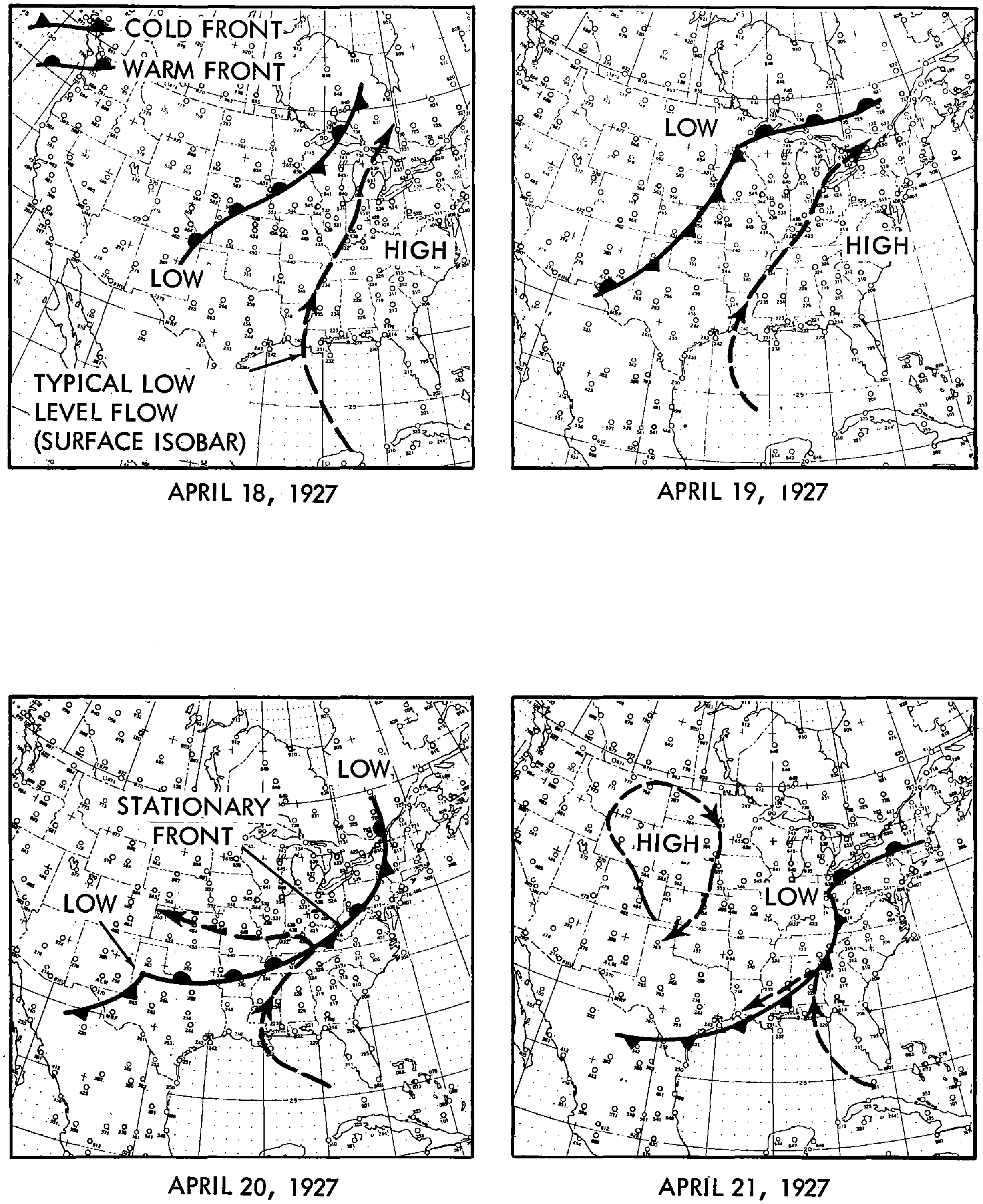


Figure 6-2b. Surface weather features (1300 GMT) for maximum Memphis April 7-day rain

days (Refs. 3-4 and 3-5). This is true even when the Gulf of Mexico moisture source is effectively cut off by the influx of drier air reaching to Yucatan. March examples of quick return of moisture after being effectively cut off are found in the years 1923, 1927 and 1956.

A specific storm that helps in differentiating the PMP from the TVA precipitation antecedent dry days is that of March 11-12, 1963. The heavy rain in this storm was preceded by approximately 4-1/2 dry days (Ref. 3-12). A 4-day dry interval was adopted for the TVA antecedent winter-type storm situation.

An additional dry interval problem concerns a month-to-month variation (or summer-type vs. winter-type distribution). Toward this end a study was made of antecedent rains at Memphis and Asheville. These data indicated greater liklihood of rain occurring sooner than three days prior to maximum 3-day rains in summer as compared to winter. A small seasonal difference was therefore adopted to make allowance for the tendencies in the data.

Relative magnitude of long-duration rain

Rainfall both preceding and following the major 3-day storm is required. To provide this primary emphasis is given to the ratio of the total rainfall during three rain periods, interspersed by two dry intervals, to the rainfall in the 3-day primary storm. This led to a selection of situations involving ratios of 13-day rains to 3-day rains. The 13-day duration was chosen simply because of the type and form of readily available data. These ratios are listed with brief discussions below:

(1) In May of 1943 two major storms occurred in close geographical proximity with about five days of little or no rain in between the two major rain periods. These storms were those of May 6-12, 1943 centered near Warner, Okla. and May 12-20, 1943 centered at nearby Mounds, Okla. In this May 1943 storm sequence, a 13/3-day ratio, allowing for transposition of rain centers, was nearly 2 for areas between 10,000 and 20,000 square miles.

(2) The January 1937 storm, for areas of 10,000 to 20,000 square miles, also provided rainfall over a 13-day period that was nearly twice the maximum 3-day rainfall. This ratio derives from the rainfall as it occurred and does not involve any transposition.

(3) Previously accepted hypothetical sequences of storms result in some estimated 13/3-day rain ratios of 2 or a little greater. These ratios allow for transposition of storm centers.

(4) Point 100-yr. return-period rain values for durations through 13 days result in 13/3-day rain ratios of near 1.6. The 13-day values are extrapolations of values through ten days, read from smooth isohyets in recent reports (Refs. 6-1 and 6-2).

The use of observed rainfall data for long durations provides ratios which involve both antecedent and subsequent rainfall in addition to rainless intervals. Before discussing the adopted criteria some indications of seasonal variation are needed.

Seasonal variation. The following data help to define the seasonal variation of the magnitude of long-duration rains. The exceedances of 10-day rains over 3-day amounts for Asheville, N. C., Memphis, Tenn., and Birmingham, Ala. were computed by months. These exceedances are the average difference between the five greatest 3-day rains and the five greatest 10-day rains each month for these stations. The monthly average exceedances in inches are plotted on figure 6-3 for each station. Considered jointly, the 10- to 3-day exceedances suggest that warm-season antecedent rainfall ought to be 70 to 80 percent of March values. These percents, based on point rainfall data, are probably too high for rainfall over large areas. The exceedances in inches from figure 6-3 are reproduced as averages for the 3 stations and plotted in figure 6-4 as a percent of the March value which is set equal to 100 percent. Other symbols are used to denote the adopted antecedent rainfall values in percent of corresponding adopted 3-day PMP and TVA precipitation values from table 6-1. These adopted data from table 6-1 represent 8- to 10-day exceedances over the main 3-day storm values.

Adopted antecedent and subsequent criteria

The data discussed above suggest the possibilities of 13/3-day rain ratios of about 2. In the adopted antecedent criteria (table 6-1) and subsequent criteria (table 6-2) a total increase of 60 percent over the PMP and TVA magnitudes is allowed in a period of 14 to 16 days. This adopted ratio (1.6) is about equal in magnitude to the estimated 13/3-day ratios from station rainfall data. However, the adopted criteria of tables 6-1 and 6-2 do allow the extra one to three days in realizing this 60 percent increase. The 60 percent total increase in precipitation is well below the 100 percent increase in 13 days suggested by some of the data where rainfall from widely separate portions of the Eastern United States are considered. This is in accordance with the desire to present criteria that are realistic.

The excess of the long-duration rainfall over the 3-day storm is apportioned so that two thirds of the amount is hypothesized as antecedent rainfall and the remaining one-third is subsequent rainfall. For example, in the winter-type storm 40 percent is antecedent to, and 20 percent is subsequent to, the PMP rain.

Comparisons with maximum monthly rains of record

In order to provide the user with some additional basis for judging the severity of the criteria presented, table 6-3 summarizes the total long-duration rain given in this report (for 21,400-sq. mi.) compared to maximum observed monthly precipitation (Refs. 4-1, 6-3, 6-4, 6-5, 6-6).

Table 6-3

MAXIMUM OBSERVED PRECIPITATION ABOVE CHATTANOOGA COMPARED WITH REPORT CRITERIA

(21,400 sq. mi.)

	PMP*		TVA*		Maximum Monthly (1890-1963)		
Month	Rain (In.)	Duration (Days)	Rain (In.)	Duration (Days)	Amount (In.)	Year	Rain Days#
Mar.	26.84	14	17.06	16	11.40	1917	17
Apr.	25.77	14	15.52	16	7.49	1911	10
May	24.42	14	13.29	16	7.95	1929	13
June	22.53	14	11.77	16	8.67	1909	11
July	18.68	14	10.35	15	11.07	1916	16
Aug.	18.92	14	10.84	15	13.33	1901	17
Sept.	21.62	14	12.20	15	7.69	1957	13

*Includes 3-day main storm plus antecedent (table 6-1) and subsequent (table 6-2).

#Days with 0.04 inches or more of rain at Chattanooga, Tenn.

Snowfall as an antecedent

Significant snow cover over the Tennessee Basin above Chattanooga is possible at least as late as the middle of March. However, the antecedent rainfall criteria presented in this study are judged capable of producing a flow far greater than that possible from snowmelt. This is particularly true when one considers that conditions cold enough to produce a maximum snow cover would necessitate an extra day or two for a return flow of air warm and moist enough to produce the 3-day probable maximum or TVA precipitation.

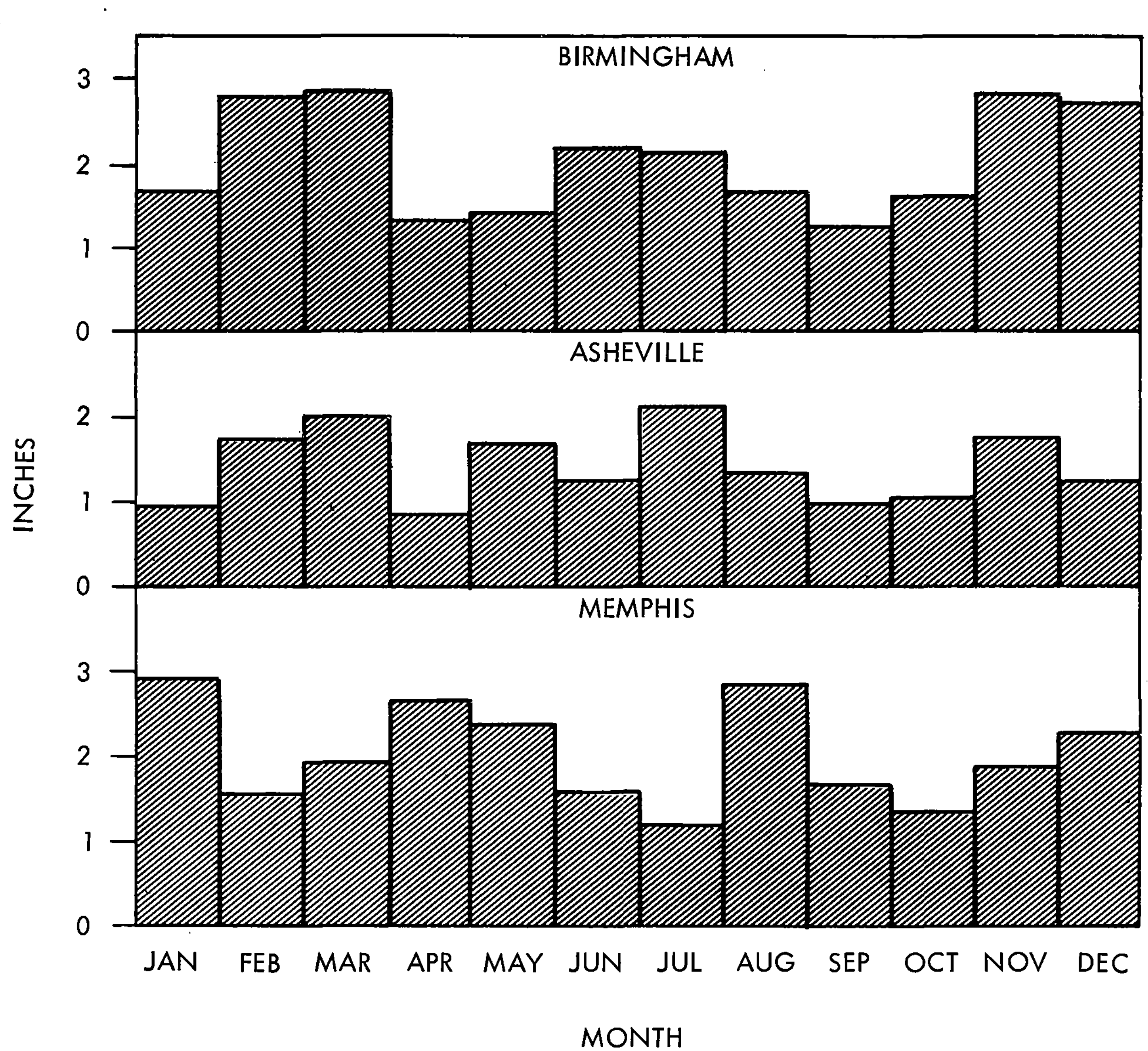


Figure 6-3. Exceedance of 10-day over 3-day rain (mean of 5 highest rains, 1912-1961)

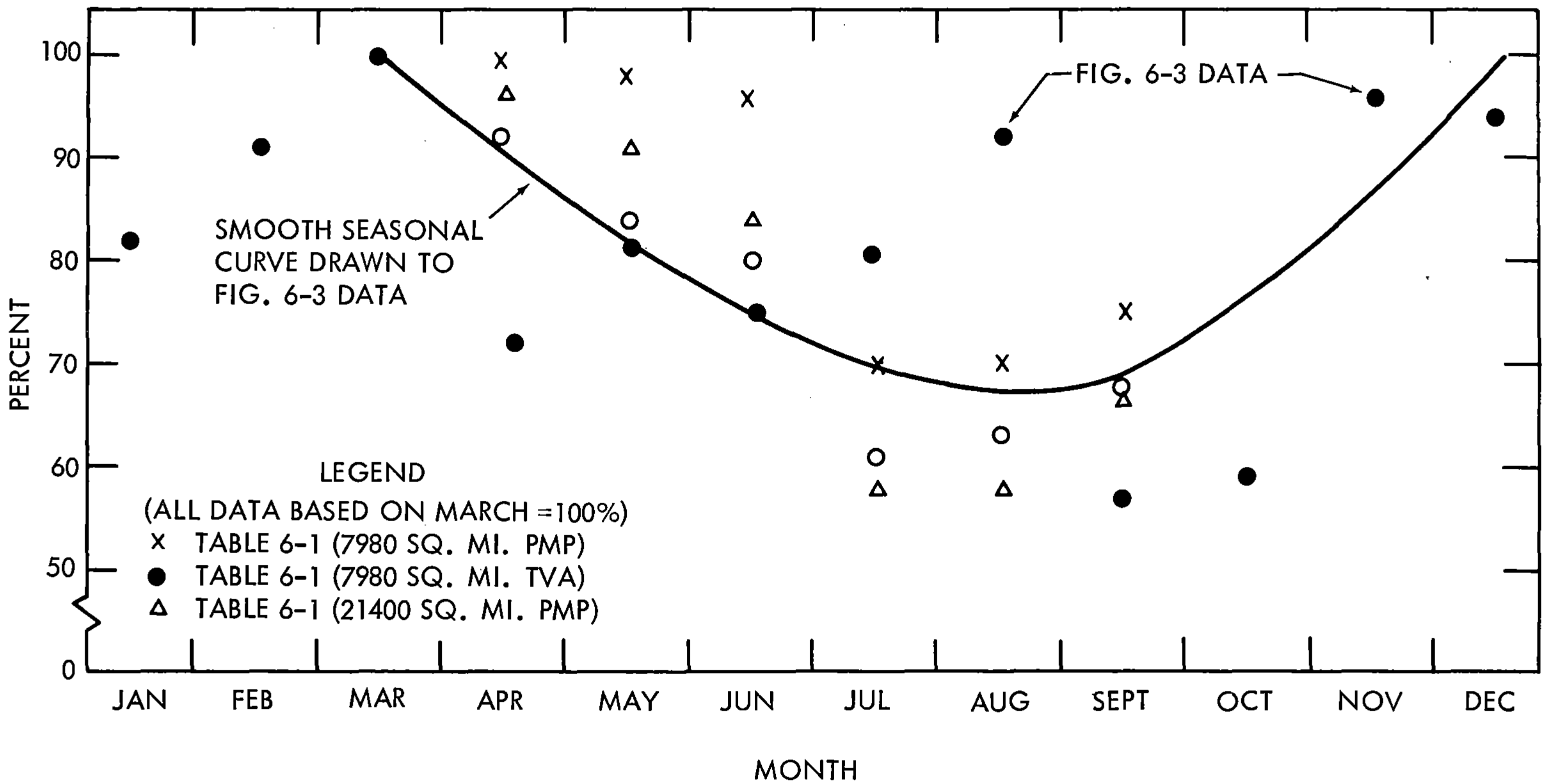


Figure 6-4. Exceedance of 10-day over 3-day rain compared to adopted criteria

Chapter VII

APPLICATION OF PRESENTED CRITERIA

Introduction

Chapter VII summarizes the data necessary to compute 3-day PMP and TVA precipitation and explains the use of the data. Prior to this there is a discussion of within-basin rainfall concentration.

Rainfall concentration

Depth-area relations define the concentration of rainfall within a basin. The shape, orientation and placement of the isohyets of PMP and TVA precipitation were discussed in chapter IV with references to figures 7-3 through 7-6. We now direct our attention to assigning labels (or magnitude) to the isohyets thereby defining the rainfall concentration or depth-area relations in the basins. The isohyetal labels must meet two requirements. First, the resulting concentration must be characteristic of storms of the region. Second, the rainfall over the basin must average out to the PMP or TVA precipitation depth that has already been specified.

Susquehanna method. Depth-area curves of important storms in and around the Tennessee Basin were compared to the depth-area curves of storms transposable to another basin in the Appalachian system, the 24,400-sq. mi. Susquehanna Basin above Harrisburg, Pa. The depth-area curves of these two regions are sufficiently similar so that detailed within-basin depth-areal relations worked out for PMP over the Susquehanna Basin in a recent Hydrometeorological Report (Ref. 7-1) can be applied directly to the Tennessee Basin.

The depth-area relations in the Susquehanna Report are expressed as ratios of the labels of the various isohyets over a basin to the basin-average PMP. Nomograms give these ratios for isohyets encompassing various areas, and placed over a range of basin sizes, separately by 6-hr. time-increments of the PMP storm. Ratios were scaled from the nomograms for the two basin sizes of interest here, 7980 square miles and 21,400 square miles, and for the areas encompassed by the isohyets of figures 7-1 through 7-6. Multiplying the March PMP and March TVA precipitation of tables 5-1 and 5-2 by these ratios yields the complete set of March probable maximum and TVA isohyetal labels in tables 7-1 through 7-6, the use of which is discussed below. The labels for the maximum 6-hr. duration also appear in figures 7-1 through 7-6.

The Susquehanna method meets the two stated requirements for isohyetal labels: The depth-area nomograms are based on storms with depth-area curves similar to Tennessee storms. Basin-average PMP or TVA precipitation from the isohyets equals the predetermined average (within computational tolerances) because the ratio nomograms are constructed so that the basin-average ratio is always 1.0.

Time distribution (depth-duration relation)

The time distribution of the probable maximum and TVA storm precipitation involves two separate problems. One is the time concentration of rainfall (e.g., how much of the 24-hr. PMP is concentrated in 6 hours), which is implicit in the depth-duration ratios used in obtaining the precipitation criteria (chapter V and figs. 5-14 and 5-15). Tables 5-1 and 5-2 present rainfall depths for three durations. All 6-hr. increments or incremental percentages to 72 hours are included in tables 7-1 through 7-6.

The other aspect of the time-distribution problem, the sequential arrangements, is discussed under "recommendations for use of presented data."

Resume of presented criteria

The basic maps, tables and charts needed to obtain storm rainfall estimates for the 7980- and 21,400-sq. mi. basins are listed below.

(1) Figures 7-1 through 7-6 show adopted isohyetal patterns. The isohyets are labeled alphabetically and on each map is shown the corresponding mid-March highest 6-hr. rainfall period of the 72-hr. storm.

The six maps represent three isohyetal patterns. The pattern of figures 7-1 and 7-2 provides the 7980-sq. mi. TVA precipitation and 7980-sq. mi. PMP. This pattern extends beyond the 7980 square miles to provide precipitation estimates during the storm for areas lying outside the 7980-sq. mi. center. The second pattern (figs. 7-3 and 7-4) is a topographically-adjusted pattern which gives the 21,400-sq. mi. TVA precipitation and PMP with a downstream centering. The third pattern (figs. 7-5 and 7-6) allows for concentration of more rainfall at upstream locations.

(2) Six tables, one for each storm situation, are included (tables 7-1 through 7-6) which give precipitation values for all isohyets and rainfall centers for incremental 6-hr. durations covering the 3-day storm. Values in the six tables apply to the six maps, all of which are for the month of March. Depths for the first four 6-hr. periods are given directly in the tables. For the second and third days, total daily values are presented. Percentages are given for obtaining the four 6-hr. increments in the second and third days.

To illustrate the use of the tabular daily values, reference is made to table 7-2. The four 6-hr. increments (for each isohyet) for the second day of the March PMP storm are obtained by taking 30 percent (highest 6-hr. increment), 27 percent (second highest 6-hr. increment), 23 percent (third highest 6-hr. increment), and 20 percent (fourth highest 6-hr. increment) of each of the second day March PMP values which are (in inches), 5.6, 5.0, 4.2, 3.8, 3.4, 3.0, 2.6, 2.2, and 1.9. The resulting values provide the respective labels for isohyetal lines (or points) A, B, C, D, E, F, G, H, and I of the generalized pattern of figure 7-2. For example, isohyet "D" for the third highest 6-hr. period on the second day of the PMP March storm would be labeled 0.9 in. (3.8 x 23%).

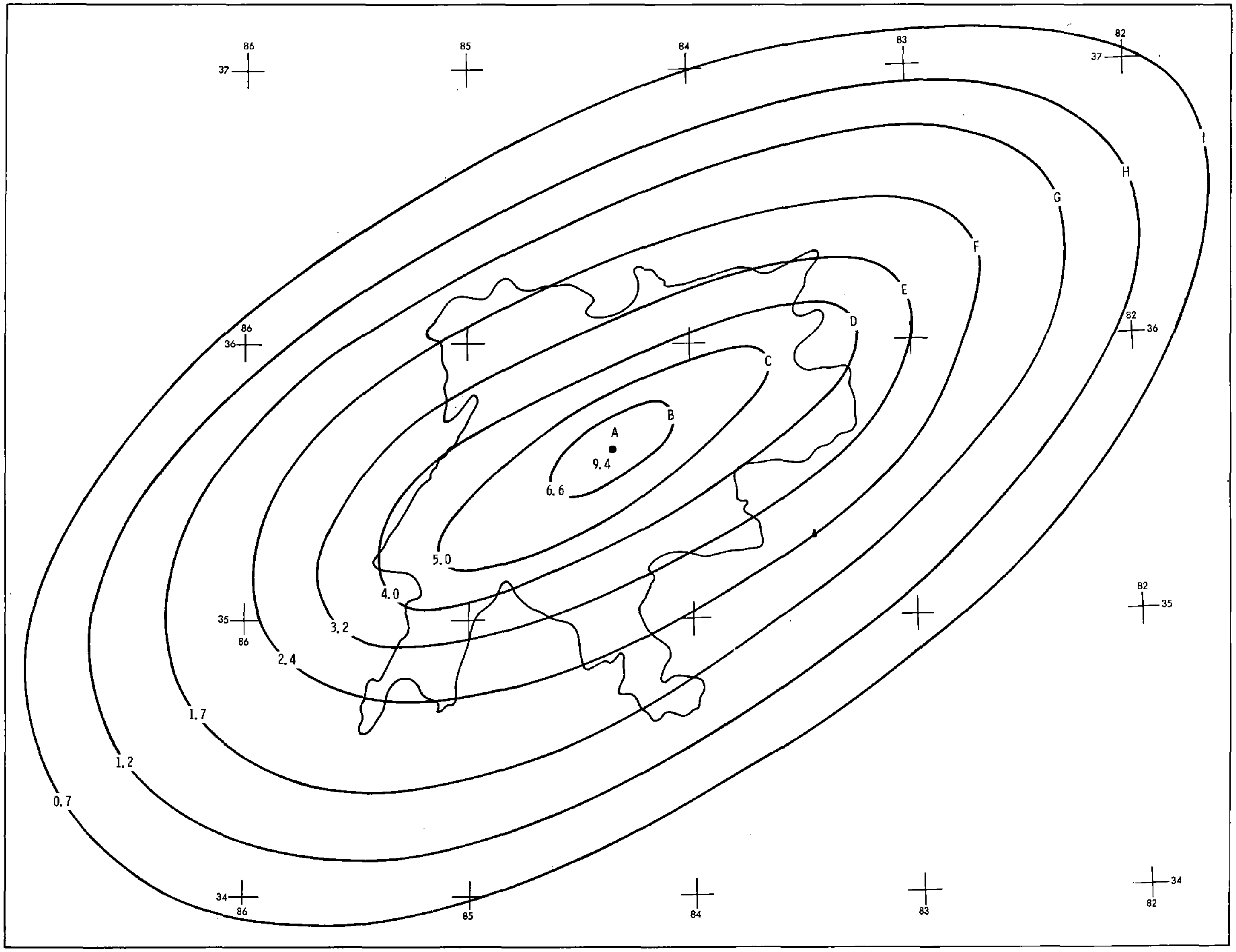


Figure 7-1. TVA March isohyets (7980 sq. mi.), 1st 6 hours

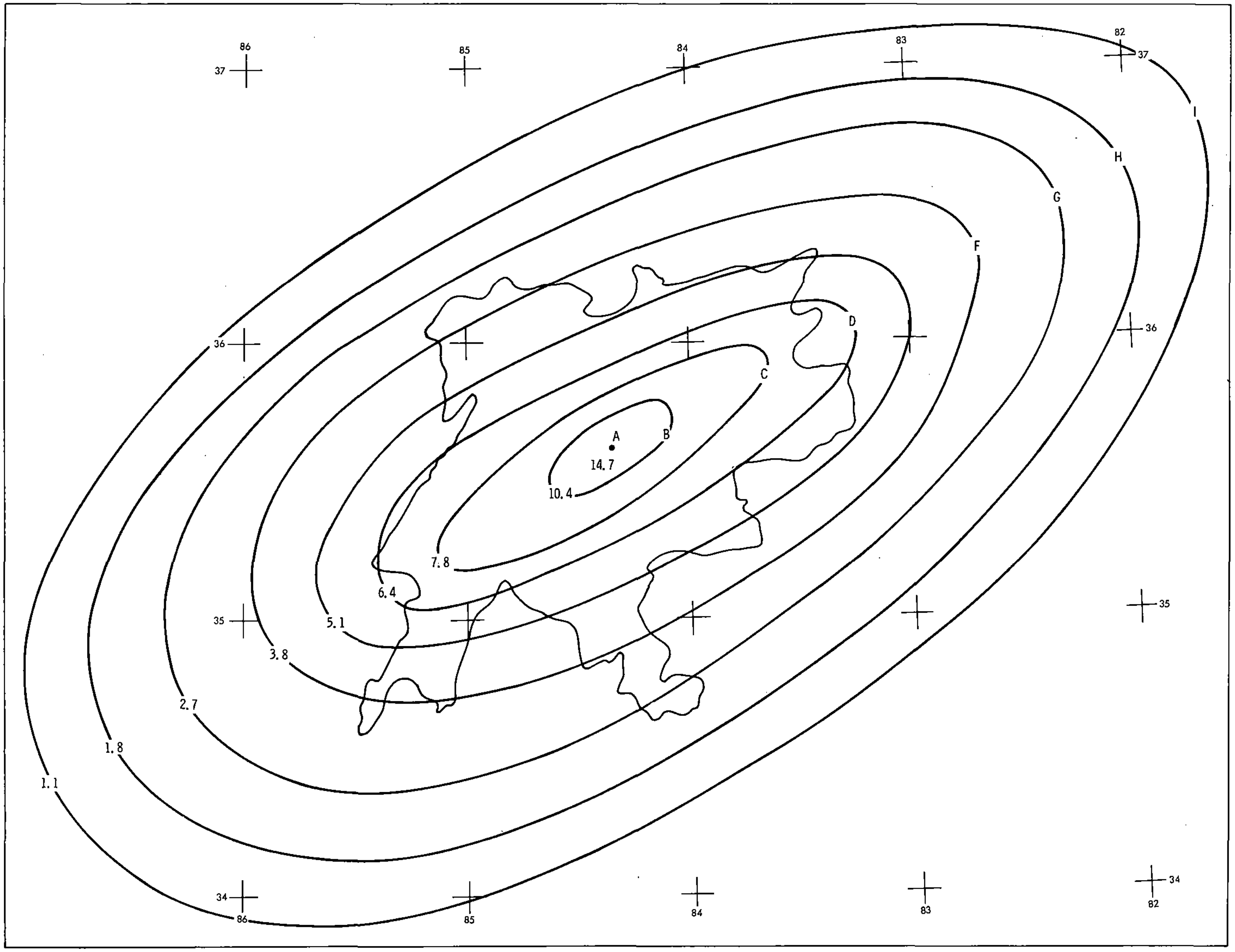


Figure 7-2. Probable maximum March isohyets (7980 sq. mi.), 1st 6 hours

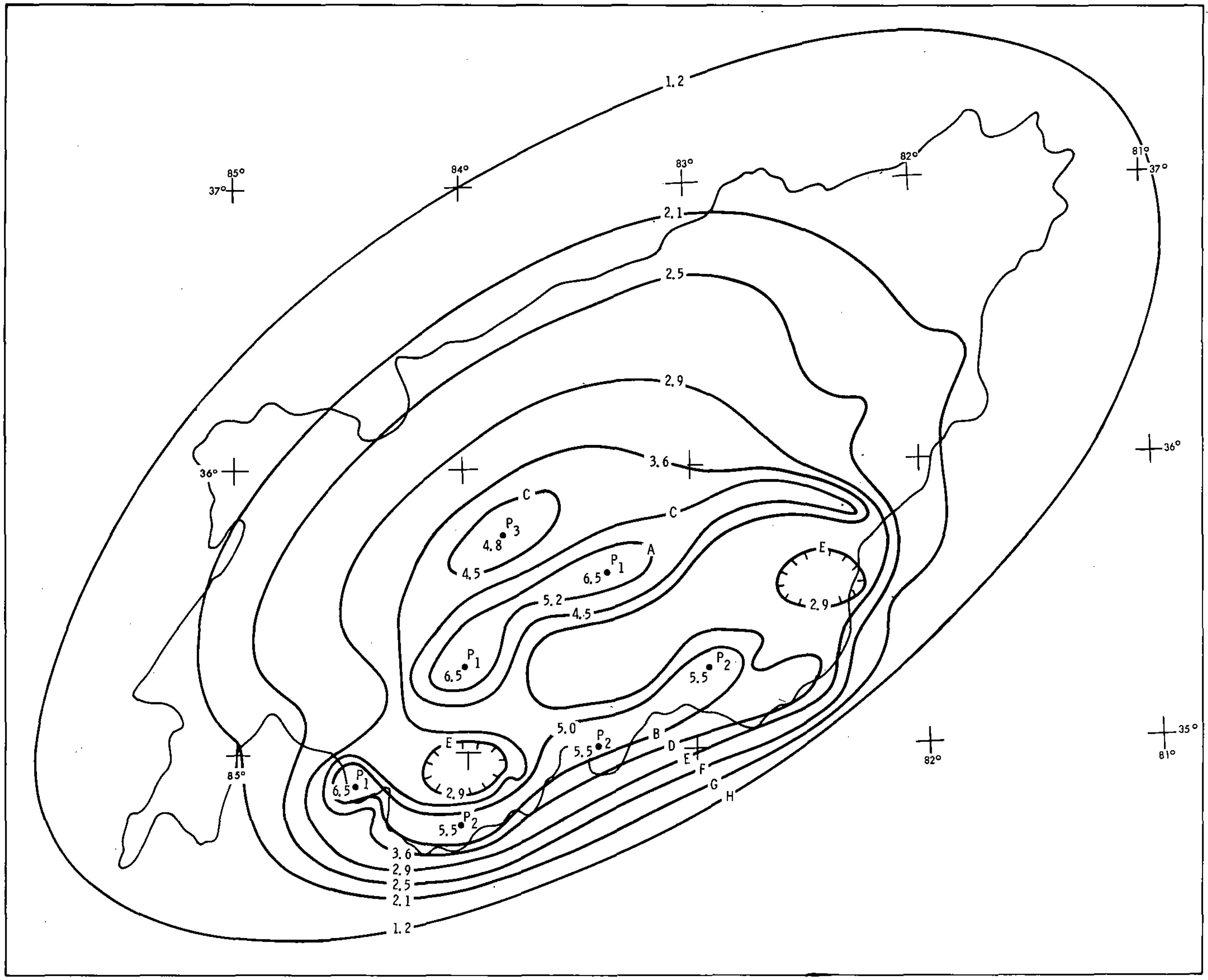


Figure 7-3. TVA March isohyets (21,400-sq. mi. downstream), 1st 6 hours

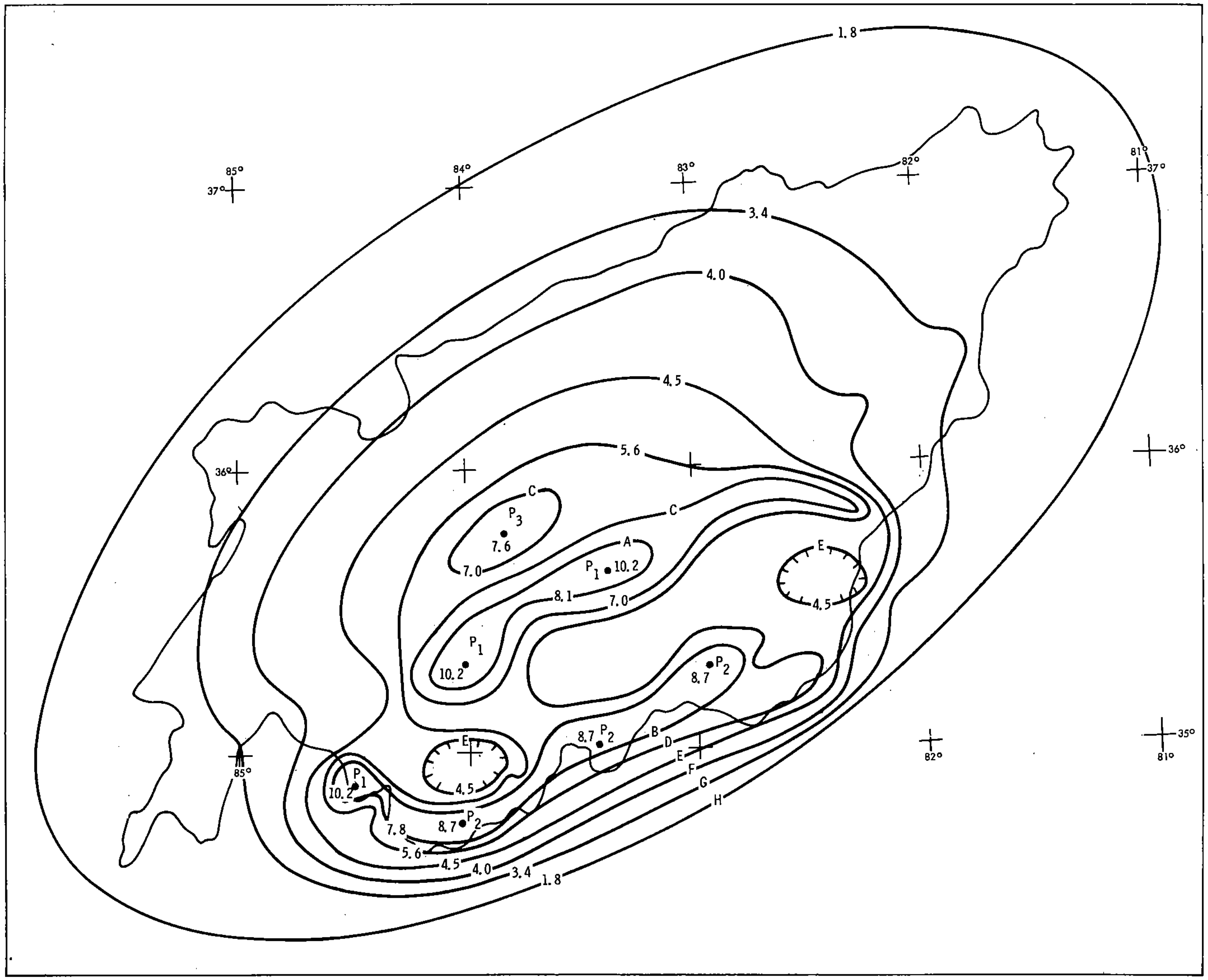


Figure 7-4. Probable maximum March isohyets (21,400-sq. mi. downstream), 1st 6 hours

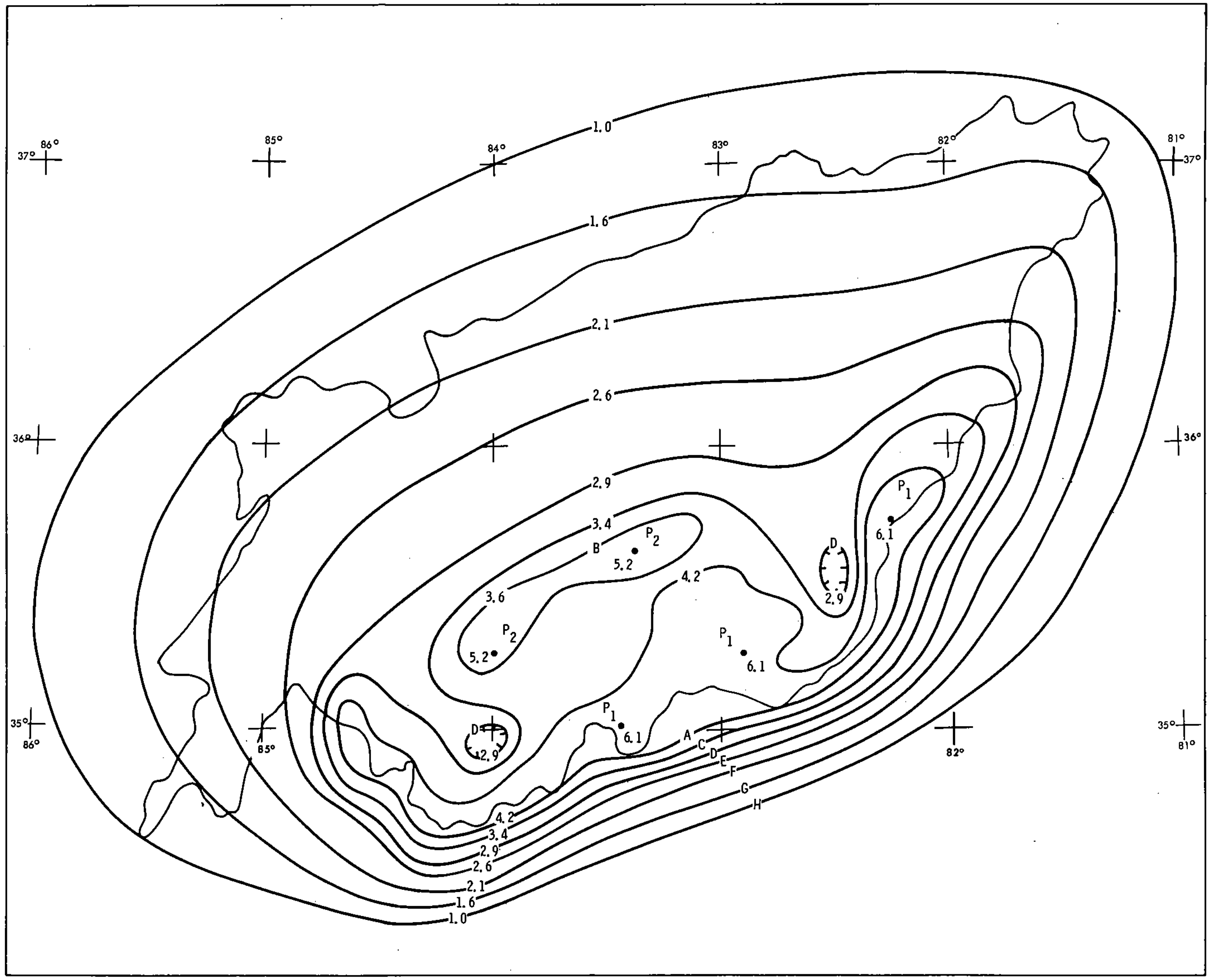


Figure 7-5. TVA March isohyets (21,400-sq. mi. upstream), 1st 6 hours

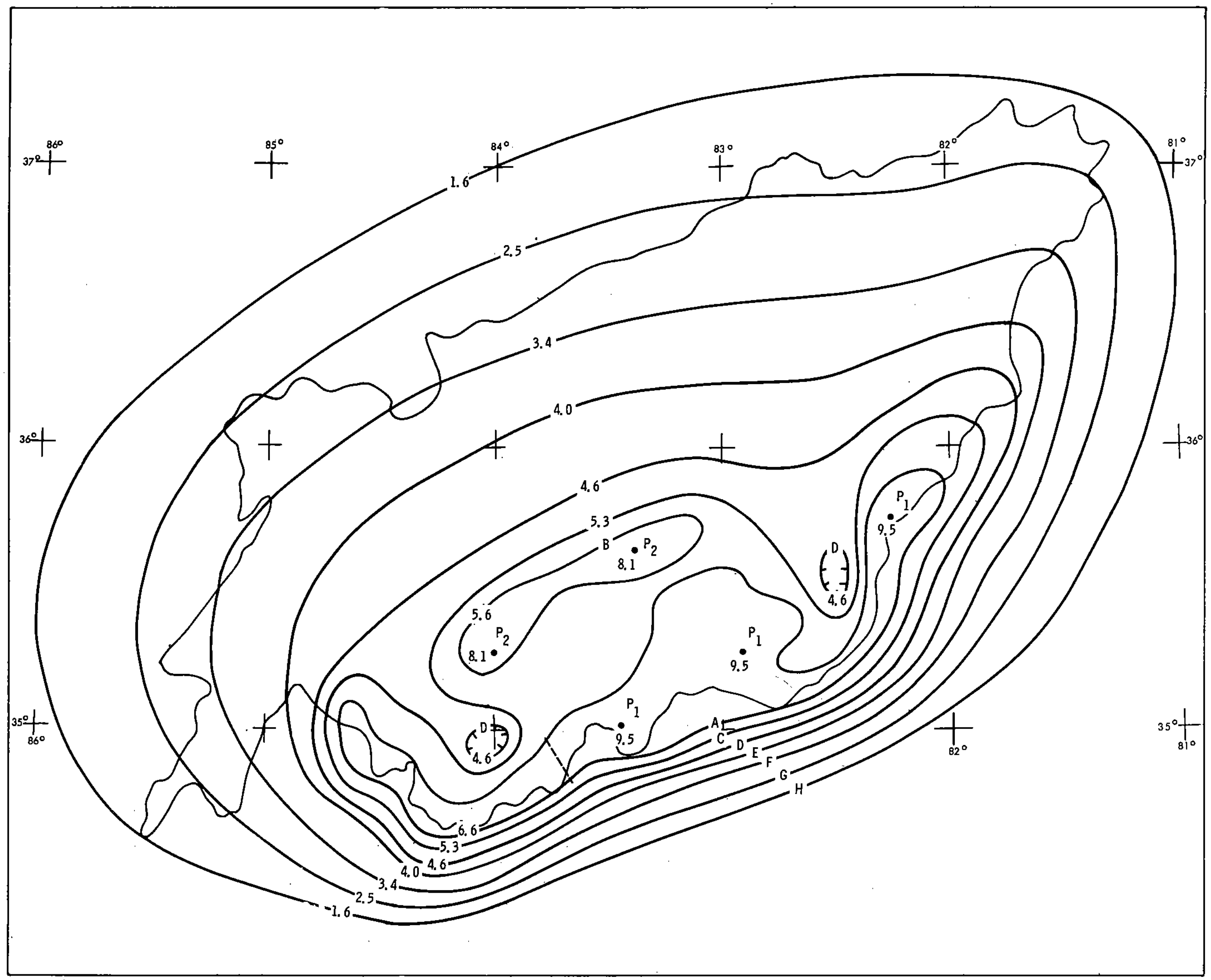


Figure 7-6. Probable maximum March isohyets (21,400-sq. mi. upstream), 1st 6 hours

(3) Table 7-7 gives monthly ratios in terms of 1.0 in March to obtain rainfall values for other months. For example, to obtain the TVA upstream 21,400-sq. mi. rainfall for the month of June the array of values in table 7-5 are multiplied by 0.689.

Table 7-7

SEASONAL VARIATION RATIOS

Area (sq. mi.)	Category	Mar.	Apr.	May	June	July	Aug.	Sept.	Use with Table No.
7980	TVA	1.000	.925	.838	.804	.814	.840	.908	7-1
7980	PMP	1.000	.992	.979	.959	.937	.937	.997	7-2
21,400	TVA	1.000	.909	.779	.689	.669	.700	.790	7-3 and 7-5
21,400	PMP	1.000	.959	.911	.840	.770	.781	.890	7-4 and 7-6

(4) Antecedent criteria are provided in tables 6-1 and 6-2.

Recommendations for use of presented data

Placement of pattern (7980-sq. mi. basin). The elliptical pattern of figures 7-1 and 7-2 may be used as shown, centered over the basin. The user may also move the isohyetal pattern parallel to the long axis of the 7980-sq. mi. basin.

Placement of pattern (21,400-sq. mi. basin). Both the upstream (figs. 7-5 and 7-6) and downstream (figs. 7-3 and 7-4) isohyetal patterns are geographically fixed and cannot be moved.

Time distribution (sequential arrangements). For a given month and basin, the user has 6-hr. incremental values (or maps) for the 12 periods in the 3-day storm. The question is how should these 6-hr. increments of rainfall be arranged in a time sequence? Storm experience provides the guidelines for reasonable time sequences; it shows a strong tendency for several "bursts" of rainfall. Within a typical "burst" of rainfall the highest two or three 6-hr. increments generally occur adjacent to each other. With these thoughts in mind, the following rules are formulated.

1. Group the four heaviest 6-hr. increments of the 72-hr. PMP in a 24-hr. sequence, the middle four increments in a 24-hr. sequence, and the smallest four increments in a 24-hr. sequence.

2. Within each of these 24-hr. sequences arrange the four increments with the second highest next to the highest, the third highest adjacent to these, and the fourth highest at either end.

3. Arrange the three 24-hr. sequences with the second highest 24-hr. period next to the highest with the third at either end. Any of the possible combinations of the three 24-hr. periods is acceptable with the exception of placing the lightest 24-hr. period in the middle.

Recommendations for use of antecedent and subsequent criteria

Rainfall and dry intervals preceding and following the main 3-day storm are given in tables 6-1 and 6-2. The same percentages of main storm rainfall are used for probable maximum and TVA antecedent precipitation. This results in a greater magnitude of antecedent rainfall in the PMP case. This is a maximizing step but the resulting total long-duration rainfall is not considered to be an excessively remote event.

Time distribution. The 3-day antecedent and subsequent rainfall amounts may be apportioned with time similar to the apportionment of the 3-day PMP or TVA precipitation.

Area distribution. For simplicity of application and to avoid unnecessary compounding of probabilities, with coincident rain centers, uniform areal distribution of the antecedent and subsequent rainfall is recommended.

Alternate antecedent criteria. Other suitable antecedent conditions are found in actual flood-producing situations of record. As an alternate to the criteria presented, depending on specific requirements, the user may select a reasonably severe flood of record as antecedent to the PMP. For example, if an extended period of wet conditions is desired, the January-February 1950 storm rainfall could serve for the rare winter antecedent and the August 1901 storm rainfall for the rare summer antecedent.

Table 7-1

VALUES OF TVA-MARCH PATTERN STORM ISOHYETS (FIGURE 7-1) FOR DRAINAGE AREA ABOVE CHATTANOOGA, TENN.

Basin Size: 7980 Sq. Mi.

	A	B	C	D	E	F	G	H	I
				Isohyet Values (inches)					
72 hours	21.5	17.3	14.1	12.2	10.5	8.8	7.1	6.0	4.8
1st 6 hours	9.4	6.6	5.0	4.0	3.2	2.4	1.7	1.2	0.7
2nd 6 hours	3.1	2.6	2.2	2.0	1.7	1.5	1.3	1.2	1.0
3rd 6 hours	2.0	1.8	1.5	1.4	1.2	1.1	0.9	0.8	0.7
4th 6 hours	1.4	1.2	1.1	1.0	0.9	0.8	0.6	0.6	0.5
2nd day*	3.5	3.2	2.7	2.4	2.2	1.9	1.6	1.4	1.2
3rd day**	2.1	1.9	1.6	1.4	1.3	1.1	1.0	0.8	0.7
Total Area Enclosed by Isohyet (sq. mi.)	10	403	1973	4331	8168	14094	22982	32108	42678

*For successive 6-hour values use 30, 27, 23, and 20% of 2nd day values.

**For successive 6-hour values use 28, 26, 23, and 23% of 3rd day values.

Table 7-2

VALUES OF PMP-MARCH PATTERN STORM ISOHYETS (FIGURE 7-2) FOR DRAINAGE AREA ABOVE CHATTANOOGA, TENN.

Basin Size: 7980 Sq. Mi.

	A	B	C	D	E	F	G	H	I
				Isohyet Values (inches)					
72 hours	33.8	27.2	22.1	19.1	16.5	13.9	11.3	9.3	7.7
1st 6 hours	14.7	10.4	7.8	6.4	5.1	3.8	2.7	1.8	1.1
2nd 6 hours	4.9	4.0	3.5	3.1	2.7	2.4	2.1	1.8	1.6
3rd 6 hours	3.1	2.8	2.4	2.1	1.9	1.7	1.4	1.3	1.1
4th 6 hours	2.2	2.0	1.7	1.5	1.4	1.2	1.0	0.9	0.8
2nd day*	5.6	5.0	4.2	3.8	3.4	3.0	2.6	2.2	1.9
3rd day**	3.3	3.0	2.5	2.2	2.0	1.8	1.5	1.3	1.2
Total Area Enclosed by Isohyet (sq. mi.)	10	403	1973	4331	8168	14094	22982	32108	42678

*For successive 6-hour values use 30, 27, 23, and 20% of 2nd day values.
**For successive 6-hour values use 28, 26, 23, and 23% of 3rd day values.

Table 7-3

VALUES OF TVA-MARCH PATTERN STORM ISOHYETS (FIGURE 7-3) FOR DRAINAGE AREA ABOVE CHATTANOOGA, TENN.
Basin Size: 21,400 Sq. Mi.
(DOWNSTREAM PLACEMENT)

	A	B	C	D	E	F	G	H	P_1	P_2	P_3
					Isohyet Values (inches)						
72 hours	14.5	13.9	12.5	11.6	10.2	9.2	8.4	6.3	18.7	15.8	13.8
1st 6 hours	5.2	5.0	4.5	3.6	2.9	2.5	2.1	1.2	6.5	5.5	4.8
2nd 6 hours	2.2	2.1	1.9	1.9	1.7	1.6	1.5	1.1	2.9	2.4	2.1
3rd 6 hours	1.5	1.4	1.3	1.3	1.2	1.1	1.0	0.8	2.0	1.7	1.5
4th 6 hours	1.2	1.1	1.0	1.0	0.9	0.8	0.8	0.7	1.5	1.3	1.1
2nd day*	2.8	2.7	2.4	2.4	2.2	2.0	1.9	1.6	3.7	3.1	2.7
3rd day**	1.6	1.6	1.4	1.4	1.3	1.2	1.1	0.9	2.1	1.8	1.6
Total Area enclosed by Isohyet (sq.mi.)	532	903	1806	5667	11003	15810	21653	39676	1	1	1

*For successive 6-hour values use 32, 27, 22, and 19% of 2nd day.
**For successive 6-hour values use 29, 26, 23, and 22% of 3rd day.

Table 7-4

VALUES OF PMP-MARCH PATTERN STORM ISOHYETS (FIGURE 7-4) FOR DRAINAGE AREA
ABOVE CHATTANOOGA, TENN.
Basin Size: 21,400 Sq. Mi.
(DOWNSTREAM PLACEMENT)

	A	B	C	D	E	F	G	H	P_1	P_2	P_3
					Isohyet Values (inches)						
72 hours	22.9	21.7	19.6	18.0	15.8	14.5	13.2	9.8	29.3	24.9	21.8
1st 6 hours	8.1	7.8	7.0	5.6	4.5	4.0	3.4	1.8	10.2	8.7	7.6
2nd 6 hours	3.5	3.3	3.0	2.9	2.7	2.5	2.3	1.7	4.5	3.8	3.3
3rd 6 hours	2.4	2.2	2.0	2.0	1.8	1.7	1.6	1.3	3.1	2.6	2.3
4th 6 hours	1.9	1.8	1.6	1.6	1.4	1.3	1.2	1.0	2.4	2.1	1.8
2nd day*	4.4	4.2	3.8	3.7	3.4	3.2	3.0	2.5	5.8	4.9	4.3
3rd day**	2.6	2.4	2.2	2.2	2.0	1.8	1.7	1.5	3.3	2.8	2.5
Total Area Enclosed by Isohyet (sq.mi.)	532	903	1806	5667	11003	15810	21653	39676	1	1	1

*For successive 6-hour values use 32, 27, 22, and 19% of 2nd day.
**For successive 6-hour values use 29, 26, 23, and 22% of 3rd day.

Table 7-5

VALUES OF TVA-MARCH PATTERN STORM ISOHYETS (FIGURE 7-5) FOR DRAINAGE AREA ABOVE CHATTANOOGA, TENN.

Basin Size: 21,400 Sq. Mi.
(UPSTREAM PLACEMENT)

	A	B	C	D	E	F	G	H	P_1	P_2
				Isohyet Values (inches)						
72 hours	12.5	11.7	11.0	10.2	9.4	8.4	7.2	6.0	17.3	14.7
1st 6 hours	4.2	3.6	3.4	2.9	2.6	2.1	1.6	1.0	6.1	5.2
2nd 6 hours	2.0	1.9	1.8	1.7	1.6	1.5	1.3	1.0	2.6	2.2
3rd 6 hours	1.3	1.3	1.2	1.2	1.1	1.0	0.9	1.0	1.8	1.5
4th 6 hours	1.0	1.0	1.0	0.9	0.9	0.8	0.7	0.6	1.4	1.2
2nd day*	2.5	2.5	2.3	2.2	2.0	1.9	1.7	1.5	3.4	2.9
3rd day**	1.5	1.4	1.3	1.3	1.2	1.1	1.0	0.9	2.0	1.7
Total Area Enclosed by Isohyet (sq. mi.)	2749	633	7093	10630	15181	21575	30114	41680	1	1

*For successive 6-hour values use 32, 27, 22, and 19% of 2nd day.
**For successive 6-hour values use 29, 26, 23, and 22% of 3rd day.

Table 7-6

VALUES OF PMP-MARCH PATTERN STORM ISOHYETS (FIGURE 7-6) FOR DRAINAGE AREA ABOVE CHATTANOOGA, TENN.
Basin Size: 21,400 Sq. Mi.
(UPSTREAM PLACEMENT)

	A	B	C	D	E	F	G	H	P_1	P_2
				Isohyet Values (inches)						
72 hours	19.6	18.5	17.3	14.9	14.6	13.1	11.4	9.5	27.1	23.0
1st 6 hours	6.6	5.6	5.3	4.6	4.0	3.4	2.5	1.6	9.5	8.1
2nd 6 hours	3.1	3.0	2.8	2.7	2.5	2.3	2.1	1.6	4.2	3.5
3rd 6 hours	2.1	2.1	2.0	1.8	1.7	1.6	1.4	1.5	2.8	2.4
4th 6 hours	1.6	1.6	1.5	1.4	1.4	1.2	1.1	1.0	2.2	1.9
2nd day*	3.9	3.9	3.6	2.4	3.2	2.9	2.7	2.4	5.3	4.5
3rd day**	2.3	2.3	2.1	2.0	1.8	1.7	1.6	1.4	3.1	2.6
Total Area Enclosed by Isohyet (sq. mi.)	2749	633	7093	10630	15181	21575	30114	41680	1	1

* For successive 6-hour values use 32, 27, 22, and 19% of 2nd day.
**For successive 6-hour values use 29, 26, 23, and 22% of 3rd day.

ACKNOWLEDGMENTS

The author appreciates the guidance and many helpful suggestions of Vance A. Myers, Head of the Hydrometeorological Branch, and other colleagues in the Branch. Mr. Bob Buehler and Mr. Donald Newton of the Flood Control Branch of the Tennessee Valley Authority at Knoxville, Tenn. contributed valuable advice in conferences and in review of the report. The Tennessee Valley Authority is also to be thanked for providing useful data. Timely advice on the rainfall-topography problem was provided by Mr. Russell Younkin of the Quantitative Precipitation Forecasting Section of the Weather Bureau. Sydney Molansky of the Hydrometeorological Branch is cited for being responsible for the editing and general organizing of the report for publication.

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APPENDIX A

Appendix A consists of a copy of attachment A to an agreement made between the Tennessee Valley Authority and the U. S. Weather Bureau in December 1963. This document outlines the details of the work to be performed by the Hydrometeorological Section* of the Weather Bureau by virtue of a transfer of funds from the Tennessee Valley Authority. Such cooperative effort was earlier authorized under terms of a Tennessee Valley Authority Memorandum of Agreement (Contract TV-29342A) dated January 22, 1963 and as provided for in item b on page 6 of the Work Plan for Fiscal Year 1964 dated December 10, 1963.

*Now the Hydrometeorological Branch, Office of Hydrology.

ATTACHMENT A

CHATTANOOGA STORM STUDIES

The storm studies are to be divided into two broad parts.

Part 1 will cover the 7,980-square-mile watershed lying upstream from Chattanooga, Tennessee, but downstream from the 5 large tributary storage reservoirs, Norris, Cherokee, Douglas, Fontana, and Hiwassee. This part of the study is to be conducted first and completed within 3 months but portions of the study useful to TVA in its hydrologic analysis will be furnished as completed.

For part 1 the Weather Bureau is expected to provide:

a. Recommended probable maximum and TVA storm[1] precipitation for winter-type storms.

b. Recommended probable maximum and TVA storm precipitation for hurricane-type storms.

c. Recommended time and areal distribution and antecedent storm conditions suited to each of these four situations.

Part 2 of the study will cover the entire 21,400-square-mile watershed lying upstream from Chattanooga, Tennessee. This part of the study is to commence as soon as manpower requirements for part 1 permit and is to be completed within the 6-month period specified for the total study. Those portions of the study useful to TVA in its hydrologic analysis will be furnished as completed.

For part 2 the Weather Bureau is expected to provide:

a. Recommended probable maximum and TVA storm precipitation for winter-type storms with particular attention to the seasonal variation during the March to June period.

b. Recommended probable maximum and TVA storm precipitation for hurricane-type storms.

c. Time and areal distribution and antecedent storm conditions suited to each of these four situations in a form to be determined in future conferences.

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1. For this agreement the TVA storm is defined as one resulting from transposition and adjustment to the Tennessee Basin without maximization of appropriate storms which have occurred elsewhere. It is the level of expected rainfall used to define the TVA maximum probable flood.

APPENDIX B

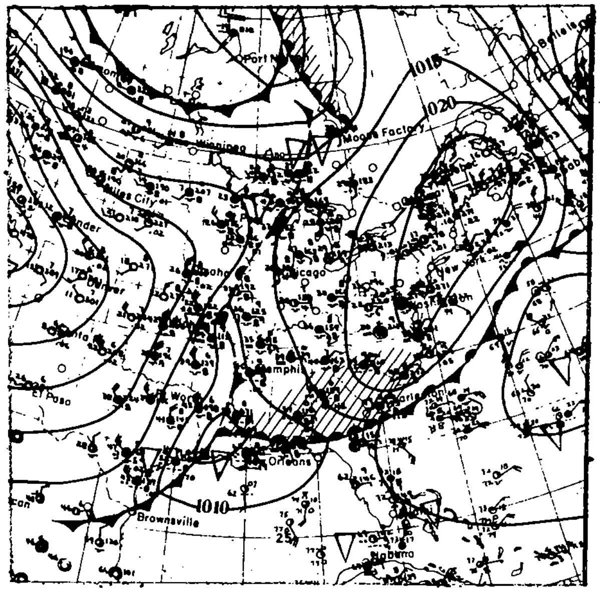
SELECTED WEATHER MAPS

Appendix B consists of charts shown to depict the primary weather features for storms discussed in the text. Most are surface weather maps. For the more recent storms some upper-air maps are included.

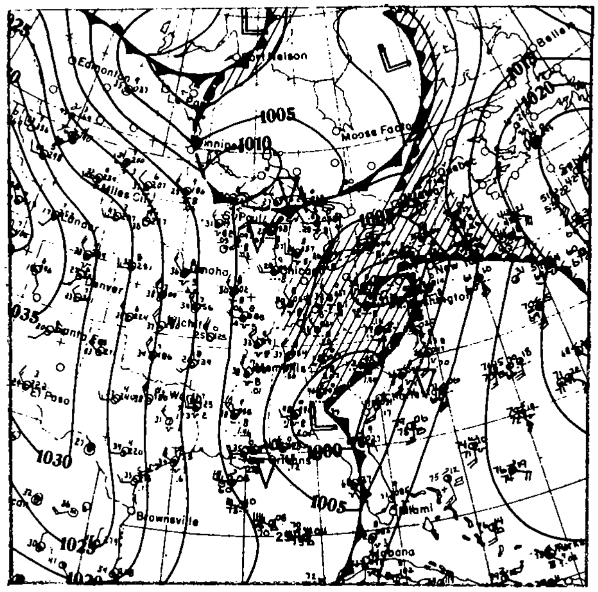
The time of day for taking primary weather observations has changed through the years. The earlier charts (through 1929) are for 0800 EST (1300Z). Later (e.g. figure 6B-1) the charts are for 0730 EST (1230Z). In 1954 the surface maps are for 1330 EST (1830Z) while the upper-air maps are for 1000 EST (1500Z).* For the storms beginning in 1960, the surface maps are for 1300 EST (1800Z) while the upper-air maps are for 1900 EST (0000Z).

The sources of the charts shown are the United States Weather Bureau Historical and Daily Weather Map series.

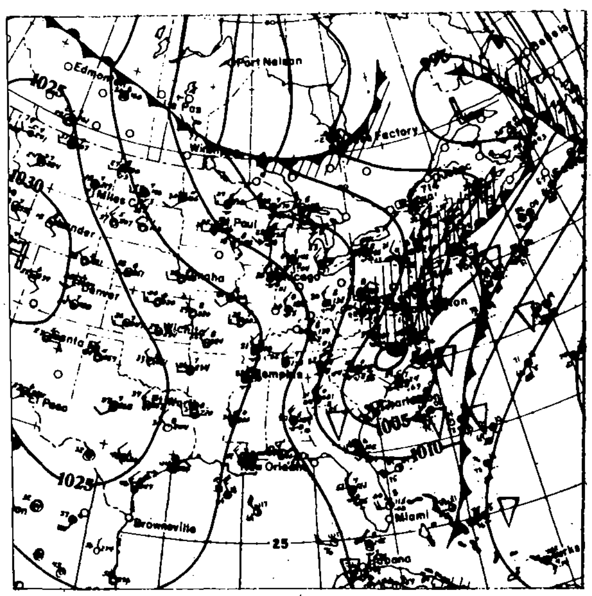
*Changed to 2200 EST (0300Z) by October 1954.



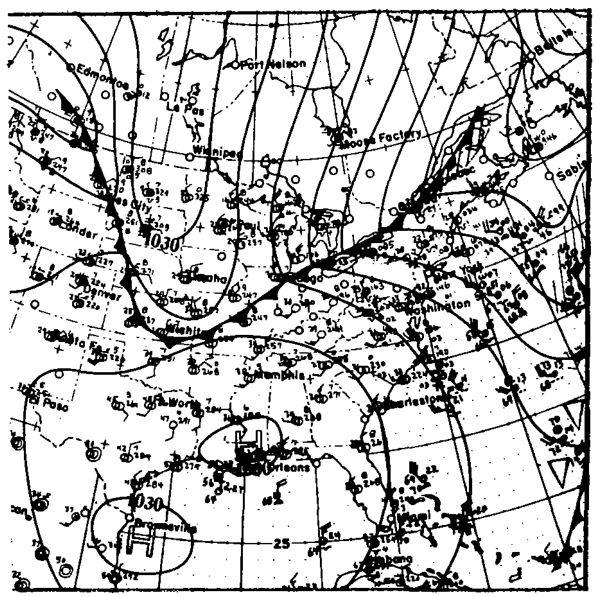
December 28, 1901



December 29, 1901

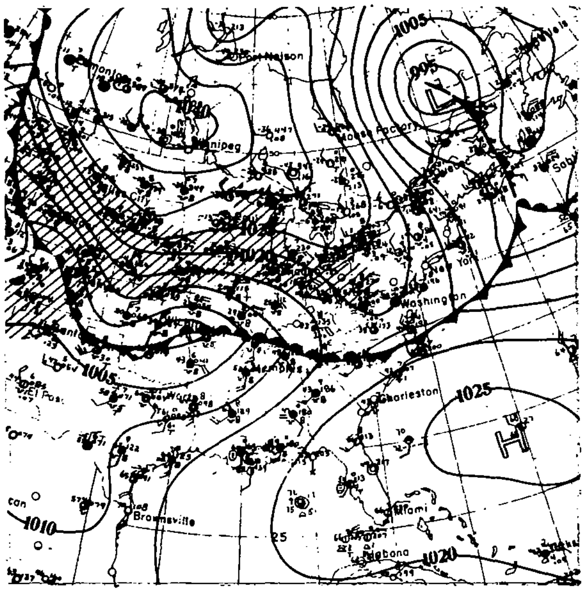


December 30, 1901

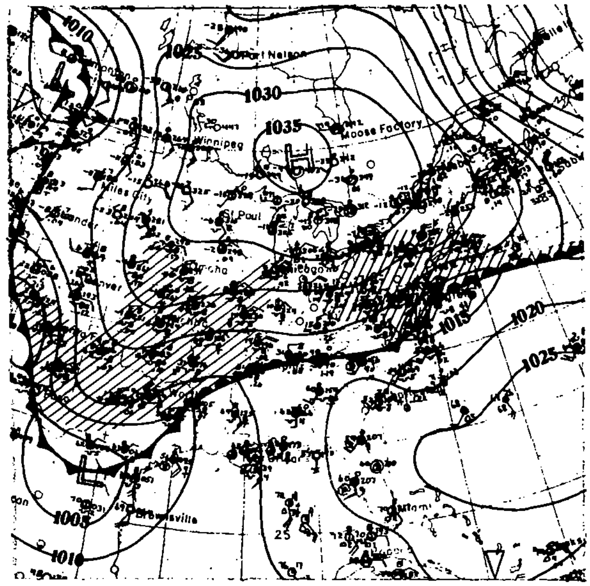


December 31, 1901

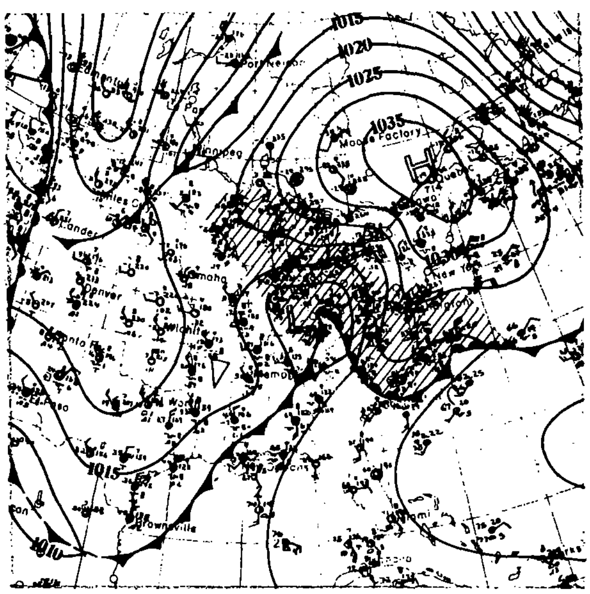
Figure 3B-1. Surface weather maps for January 2, 1902 flood



January 26, 1918

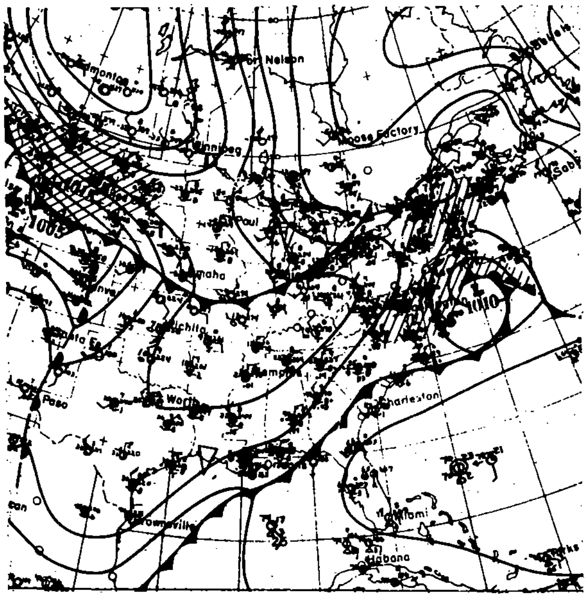


January 27, 1918

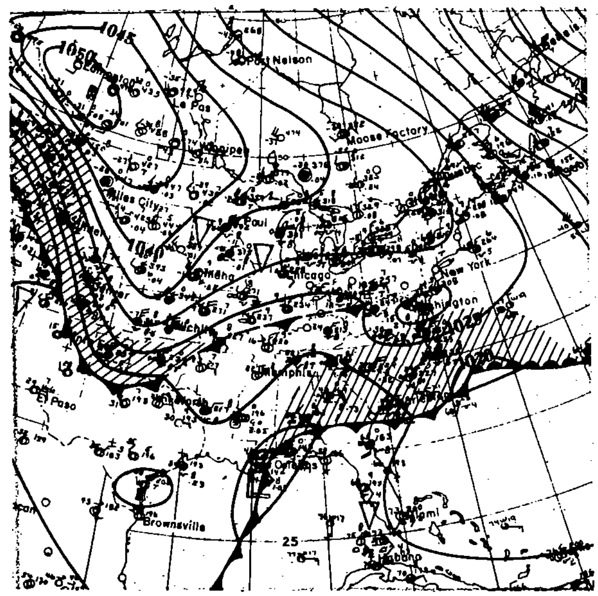


January 28, 1918

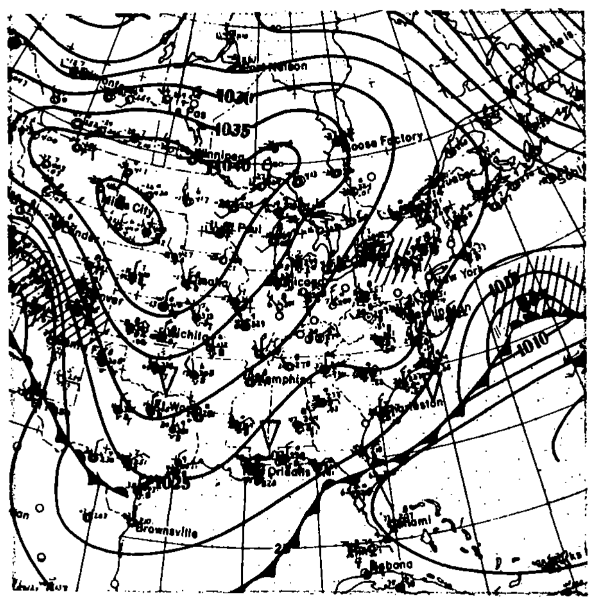
Figure 3B-2a. Surface weather maps for February 2, 1918 flood



January 29, 1918

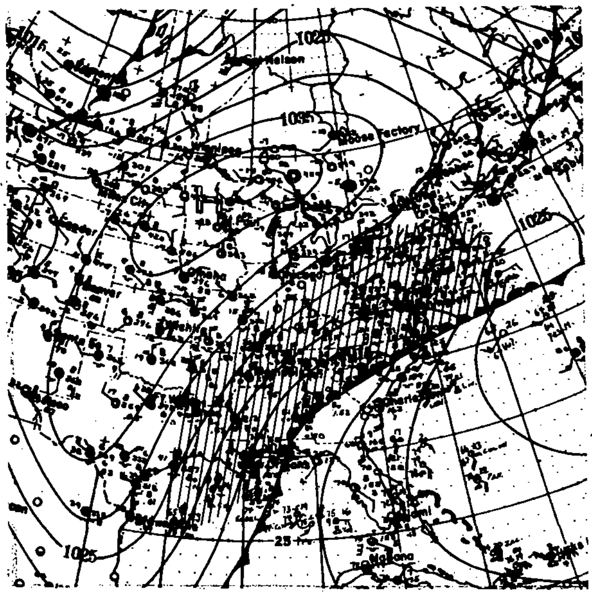


January 30, 1918

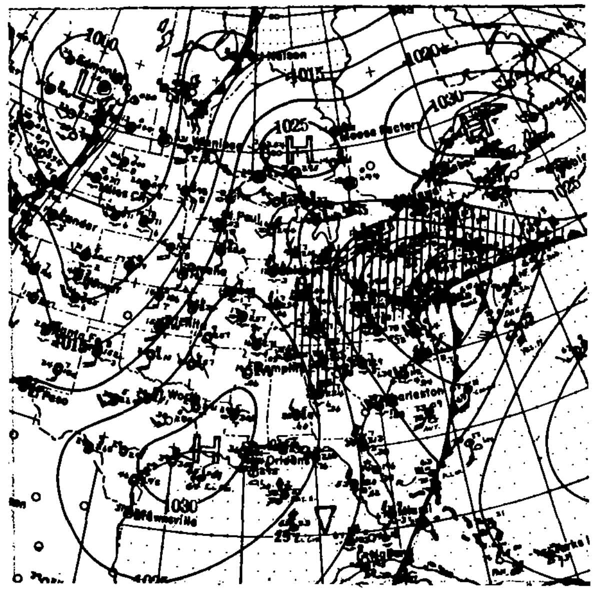


January 31, 1918

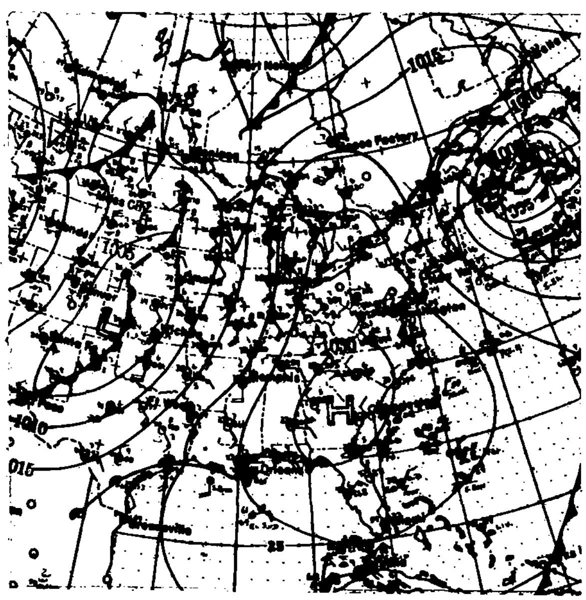
Figure 3B-2b. Surface weather maps for February 2, 1918 flood



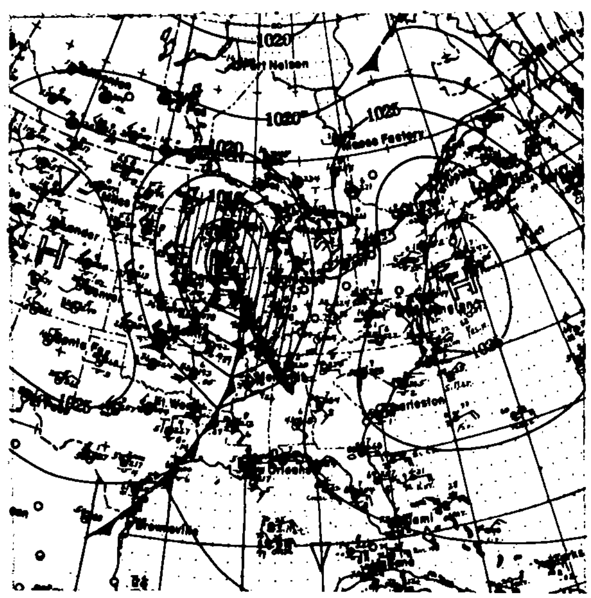
March 4, 1917



March 5, 1917

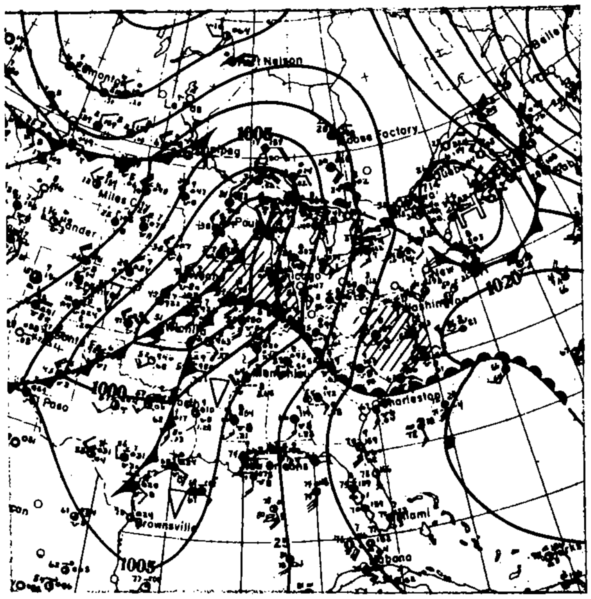


March 6, 1917

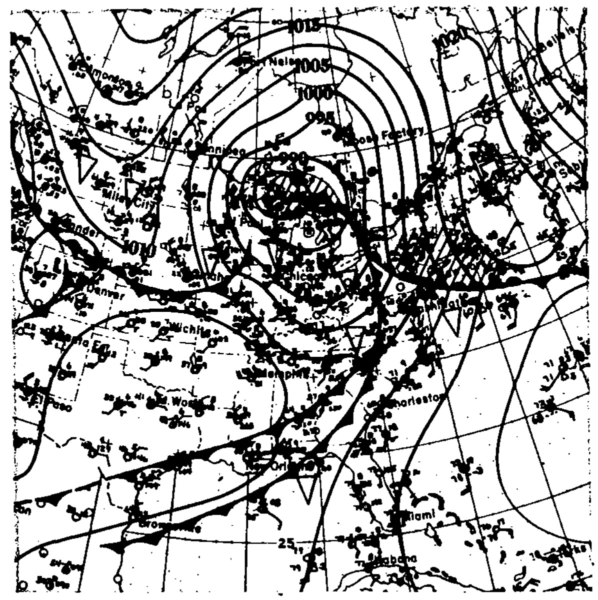


March 7, 1917

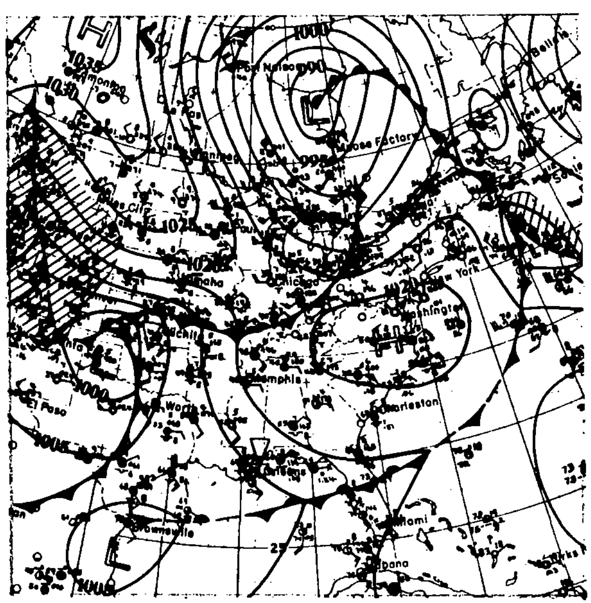
Figure 3B-3. Surface weather maps for March 7, 1917 flood



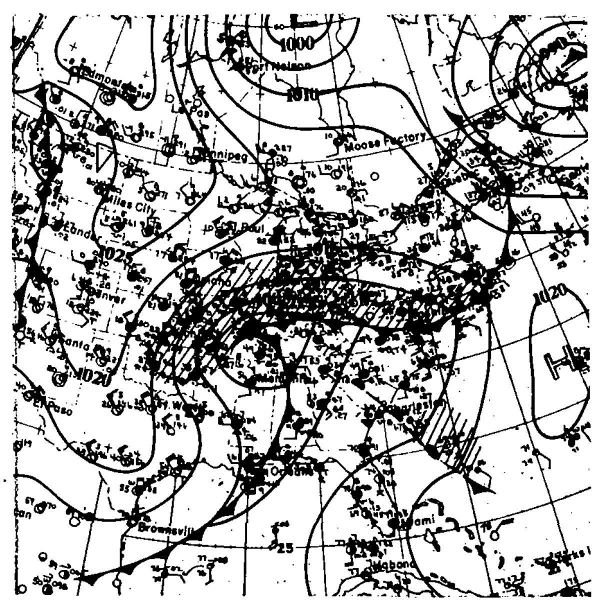
April 1, 1920



April 2, 1920

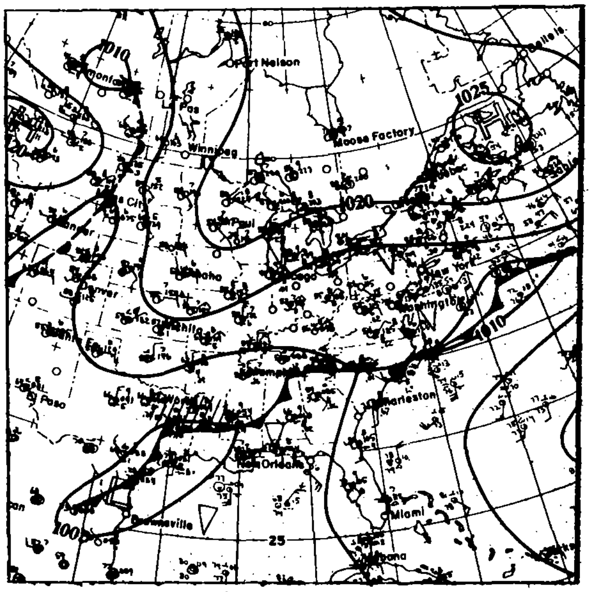


April 3, 1920

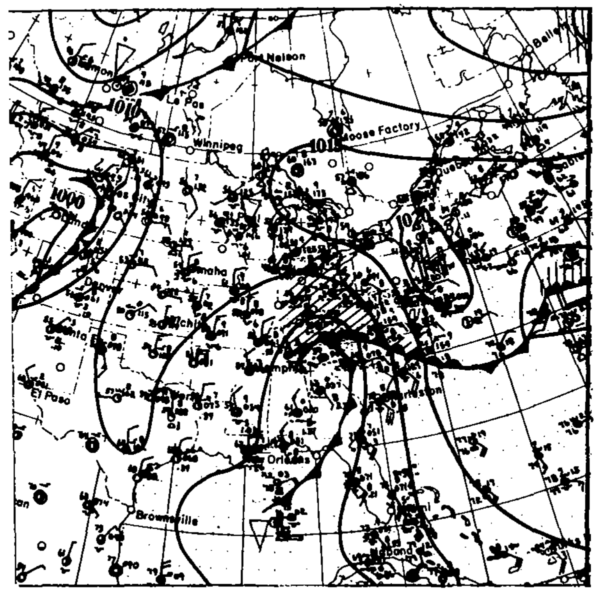


April 4, 1920

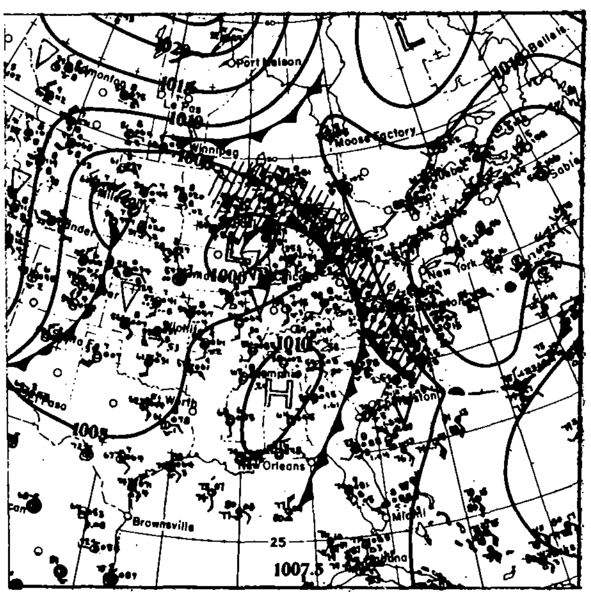
Figure 3B-4. Surface weather maps for April 5, 1920 flood



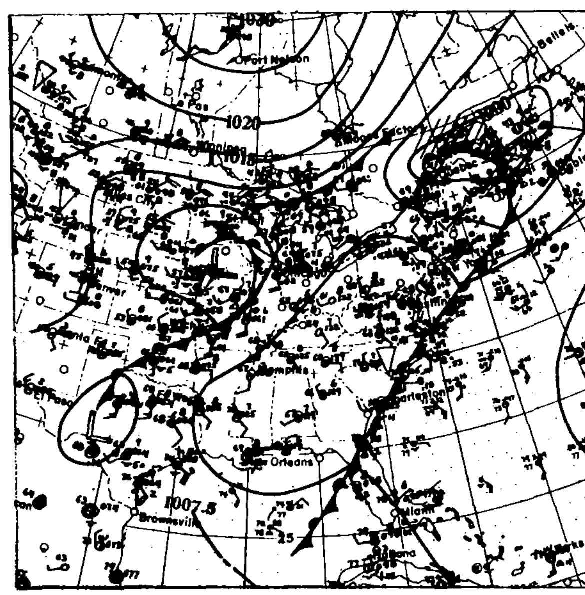
May 20, 1901



May 21, 1901

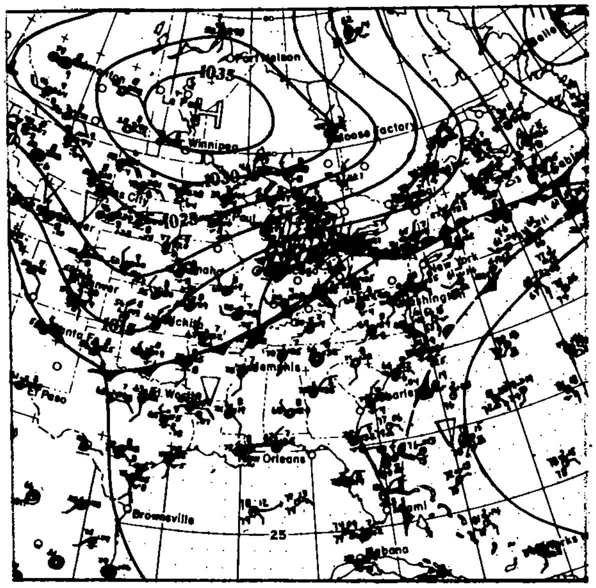


May 22, 1901

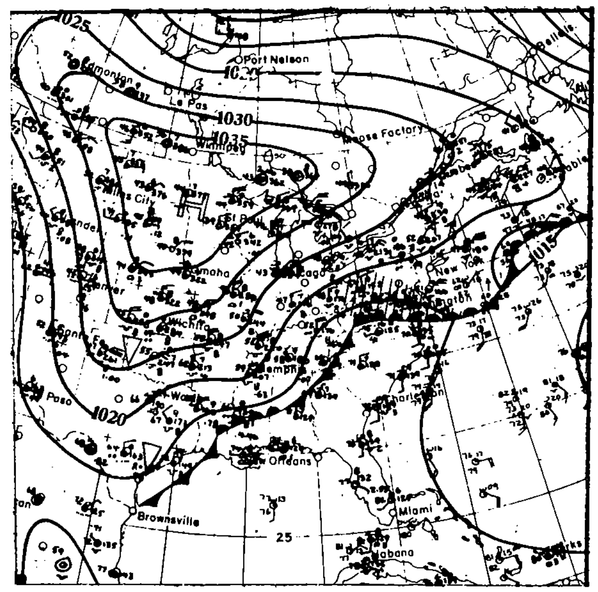


May 23, 1901

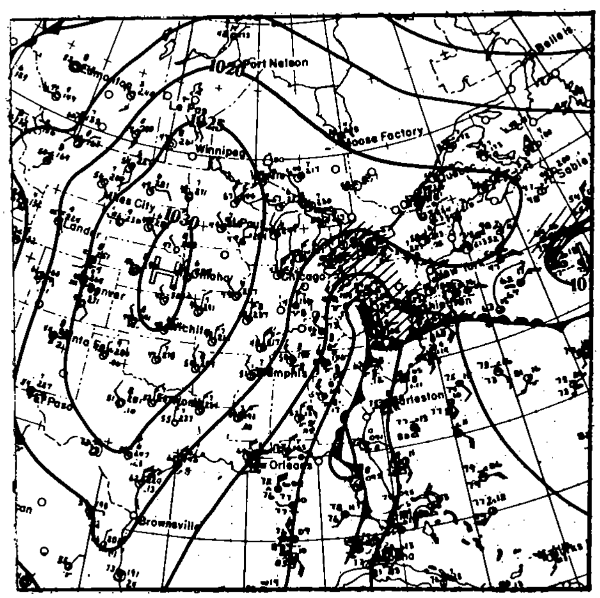
Figure 3B-5a. Surface weather maps for May 25, 1901 flood



May 24, 1901

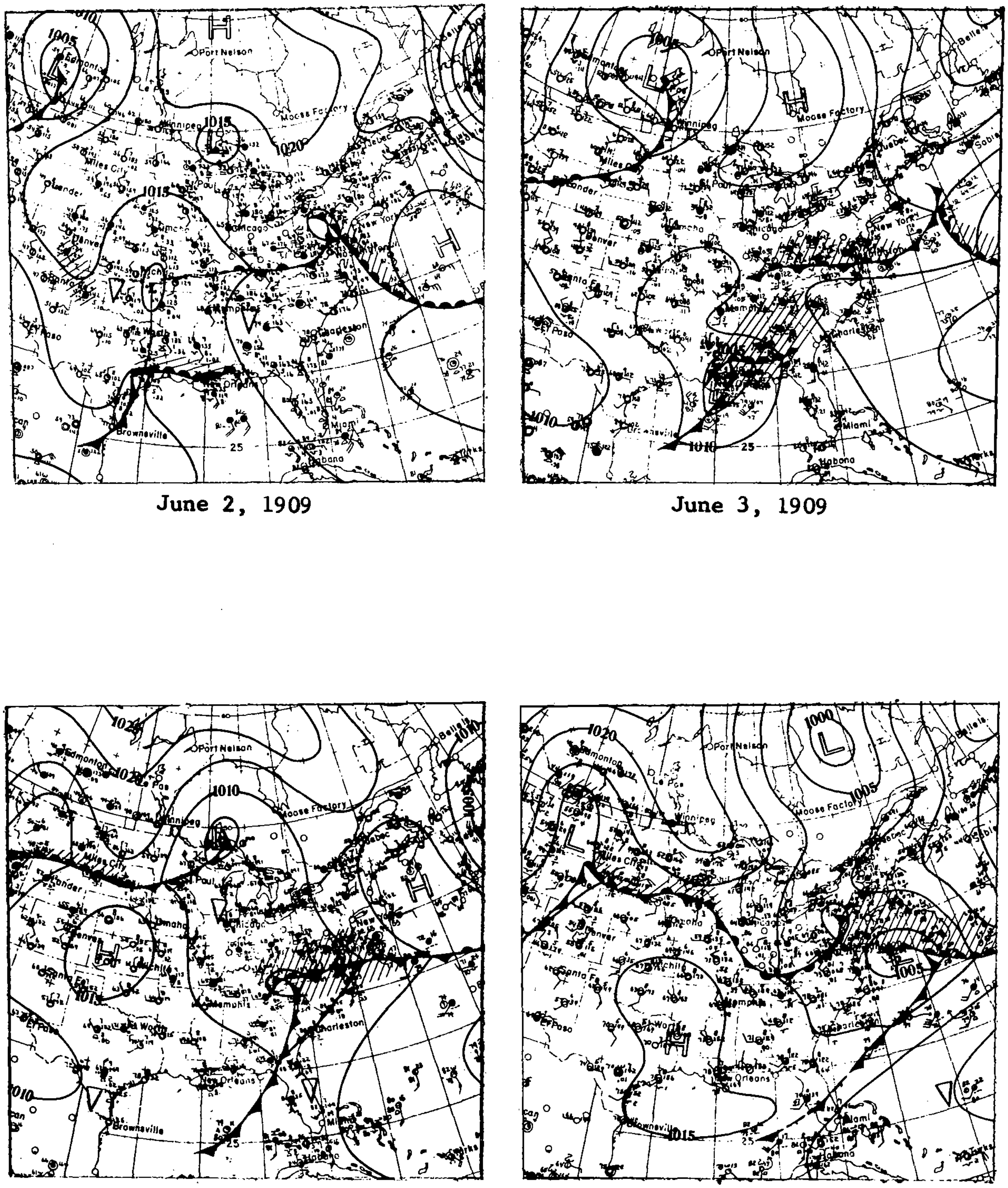


May 25, 1901



May 26, 1901

Figure 3B-5b. Surface weather maps for May 25, 1901 flood



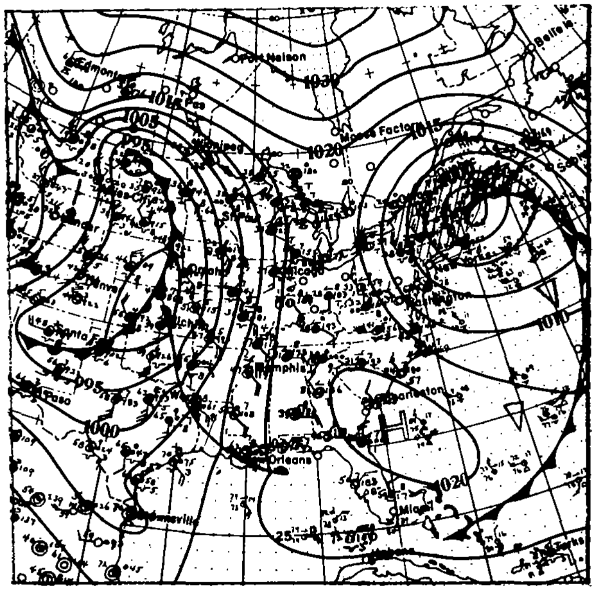
June 2, 1909

June 3, 1909

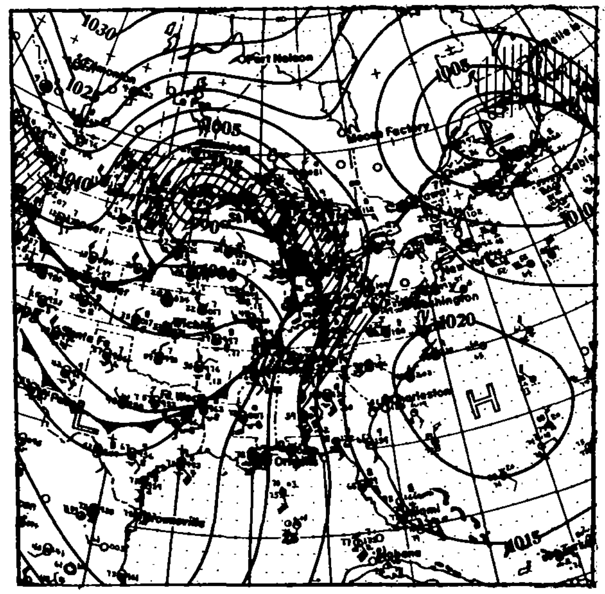
June 4, 1909

June 5, 1909

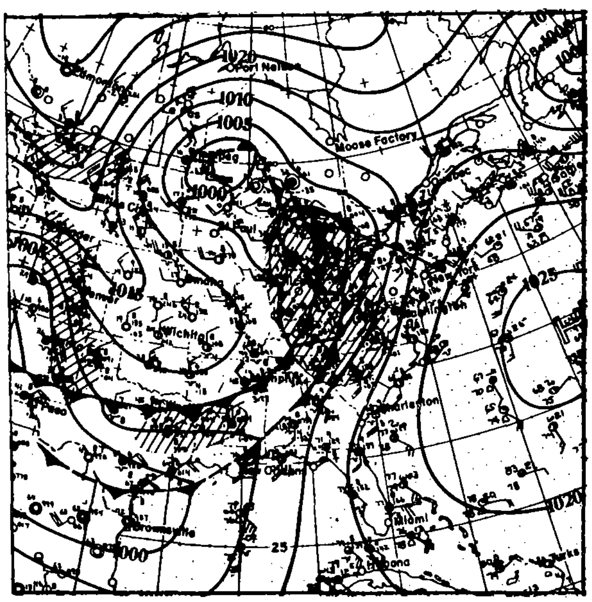
Figure 3B-6. Surface weather maps for June 6, 1909 flood



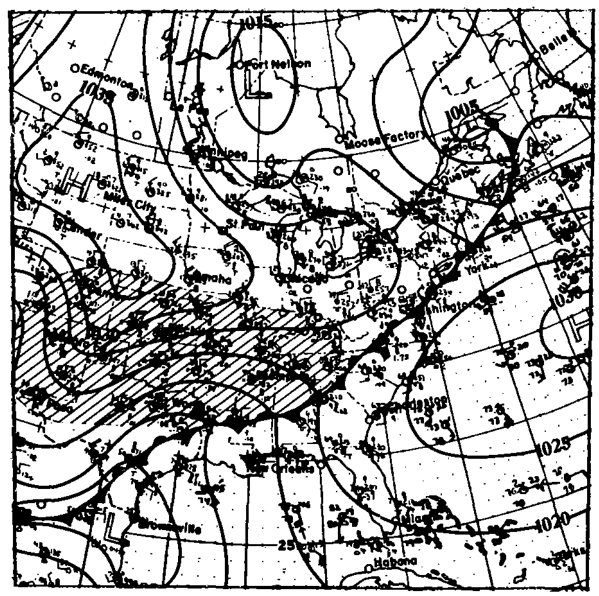
November 16, 1906



November 17, 1906



November 18, 1906



November 19, 1906

Figure 3B-7. Surface weather maps for November 22, 1906 flood

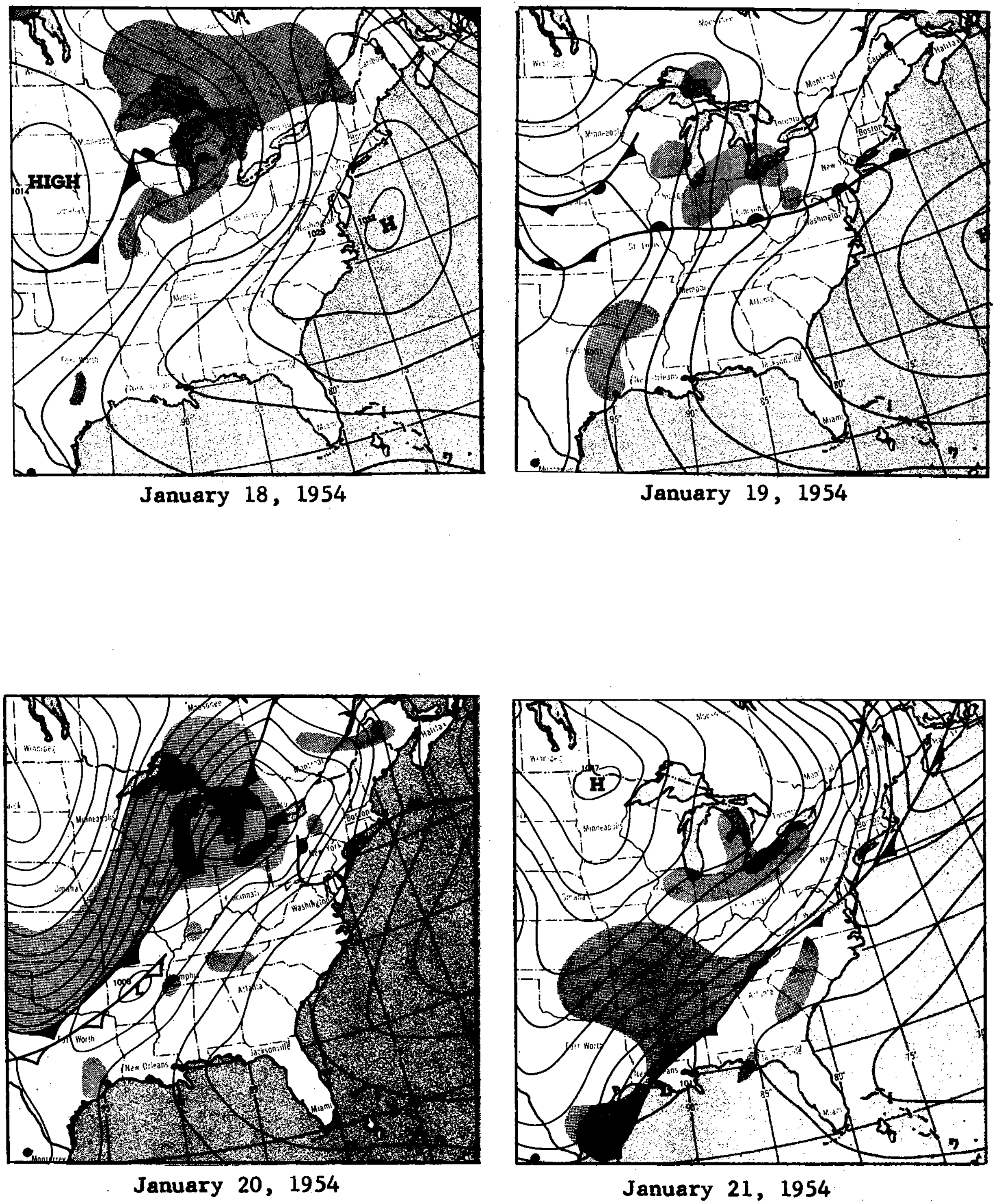
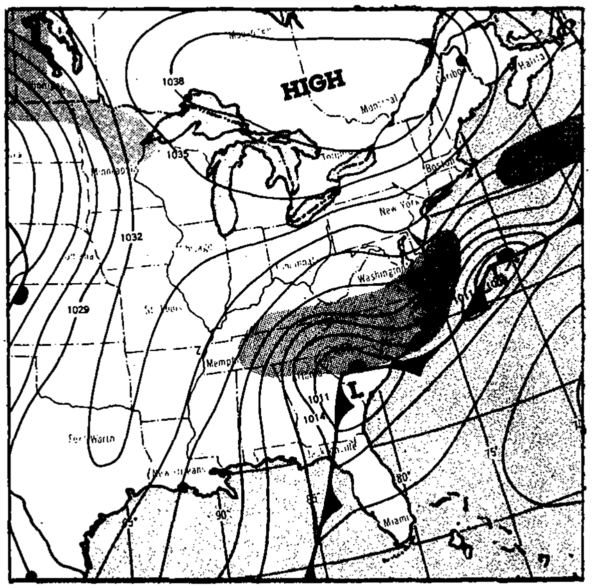
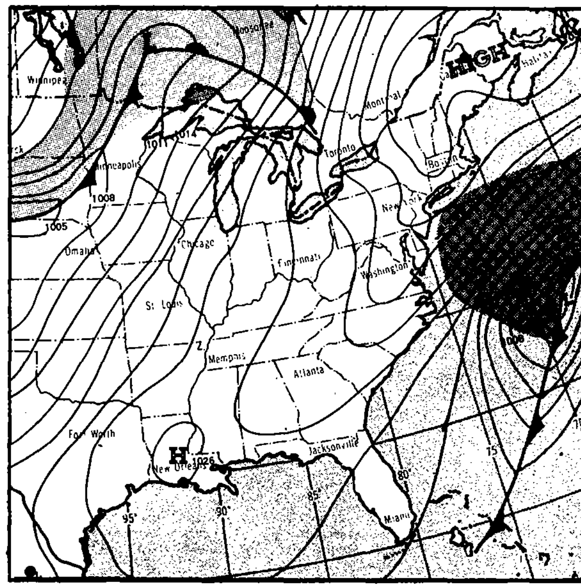


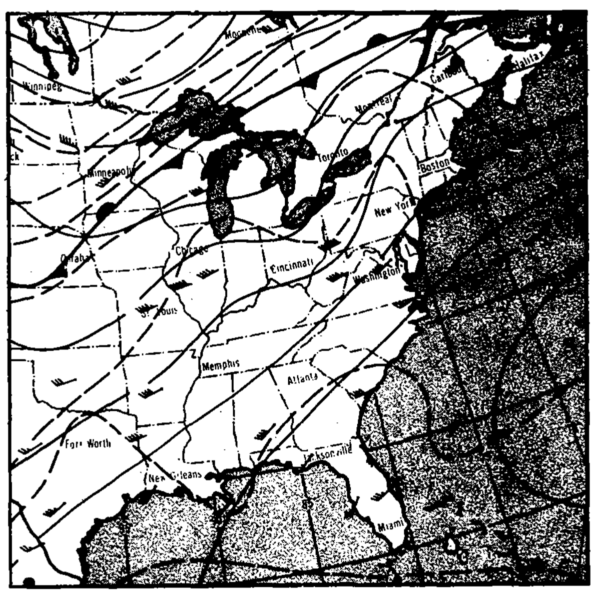
Figure 3B-8a. Surface weather maps for January 24, 1954 flood



January 22, 1954

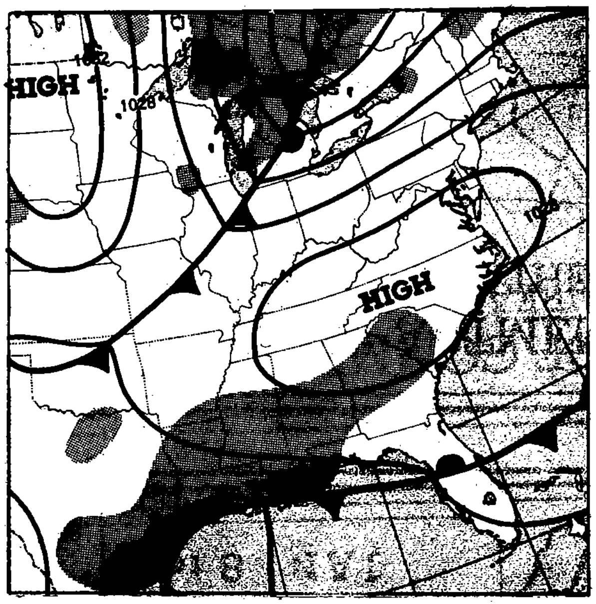


January 23, 1954

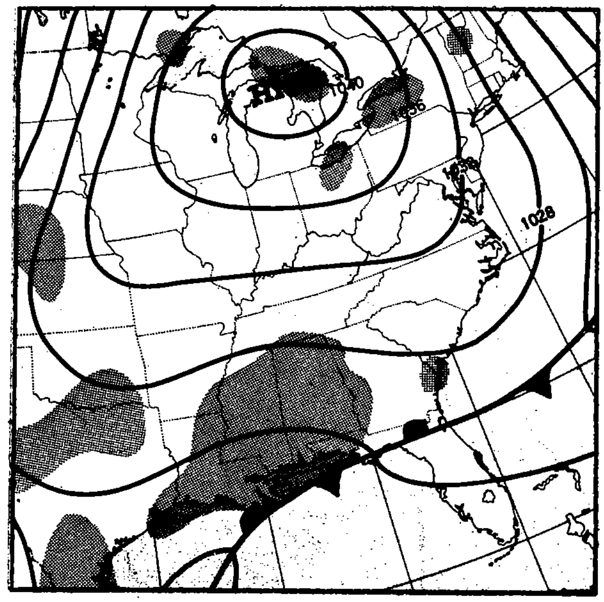


(700 mb)
January 20, 1954

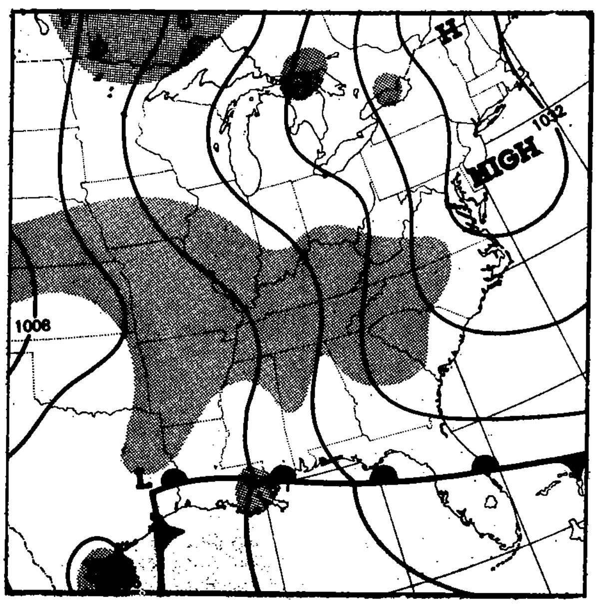
Figure 3B-8b. Surface and upper-air weather maps for January 24, 1954 flood



December 14, 1961



December 15, 1961

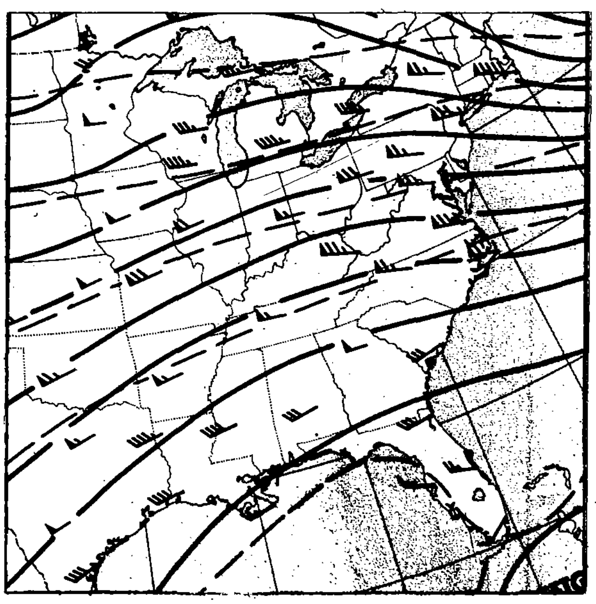


December 16, 1961

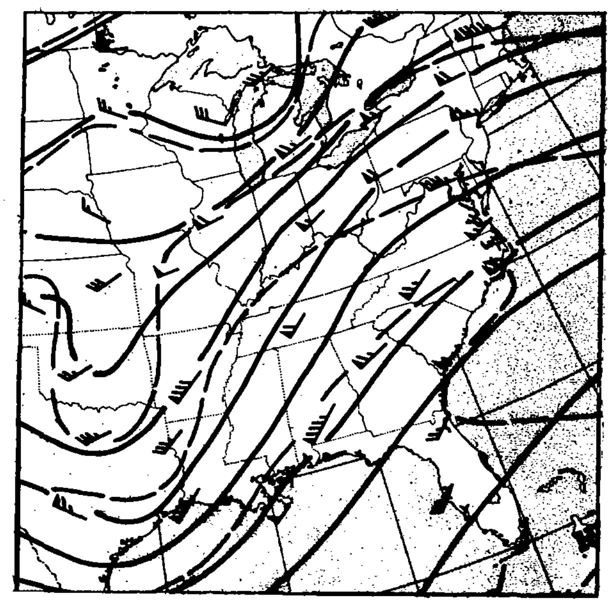
December 17, 1961

Figure 3B-9a. Surface weather maps for December 19, 1961 flood

December 18, 1961

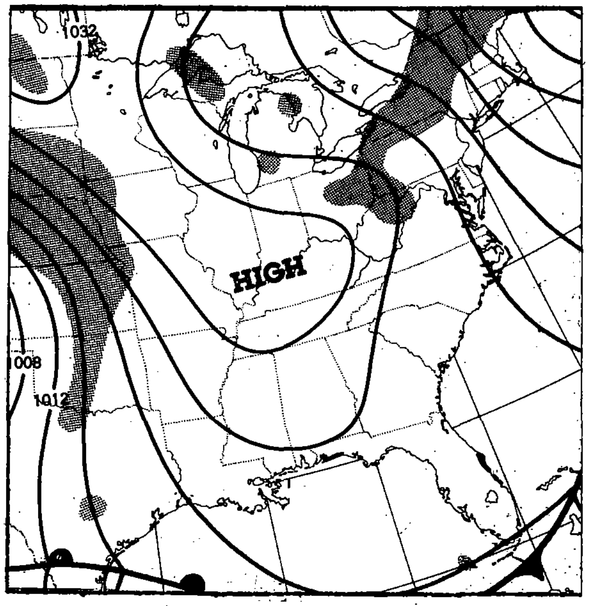


(500 mb)
December 15, 1961

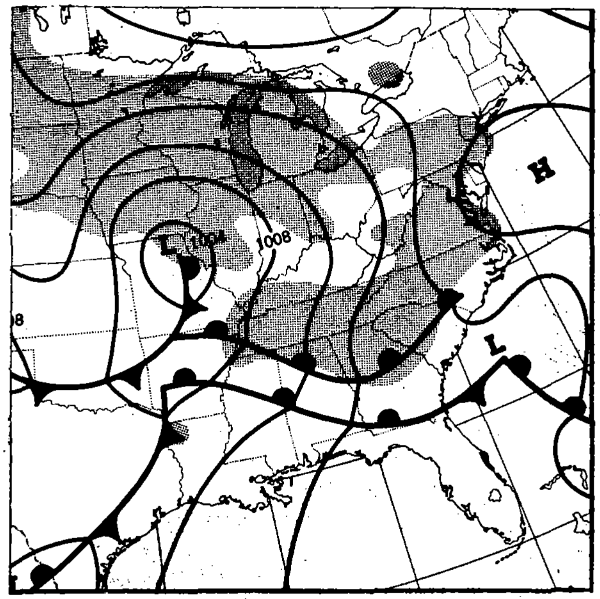


(500 mb)
December 17, 1961

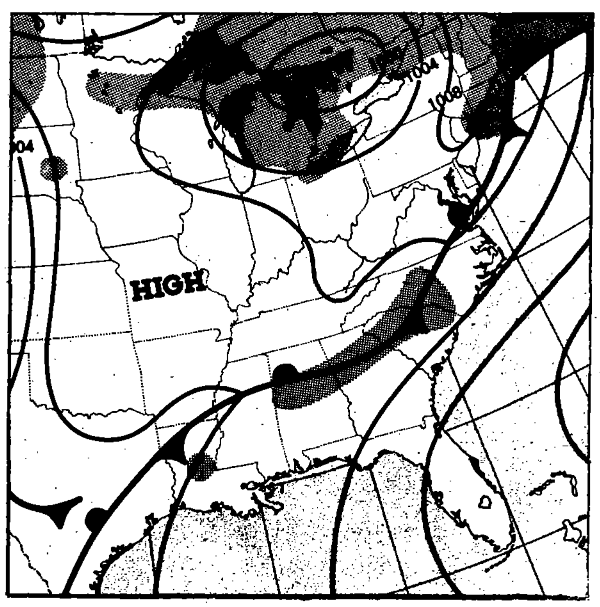
Figure 3B-9b. Surface and upper-air weather maps for December 19, 1961 flood



February 20, 1962

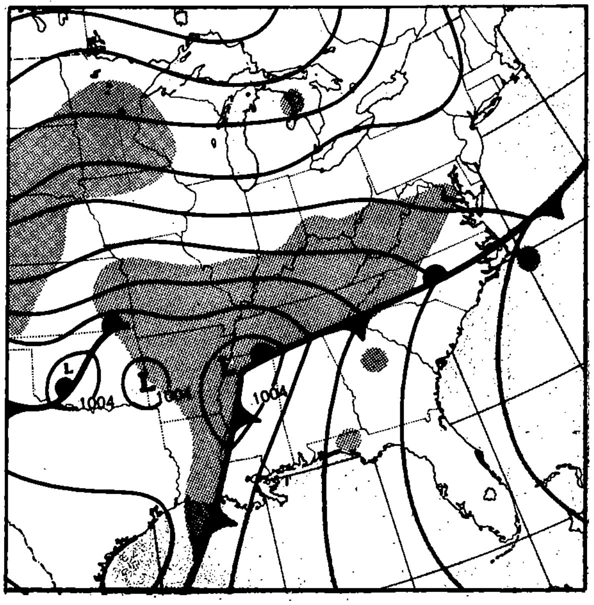


February 21, 1962

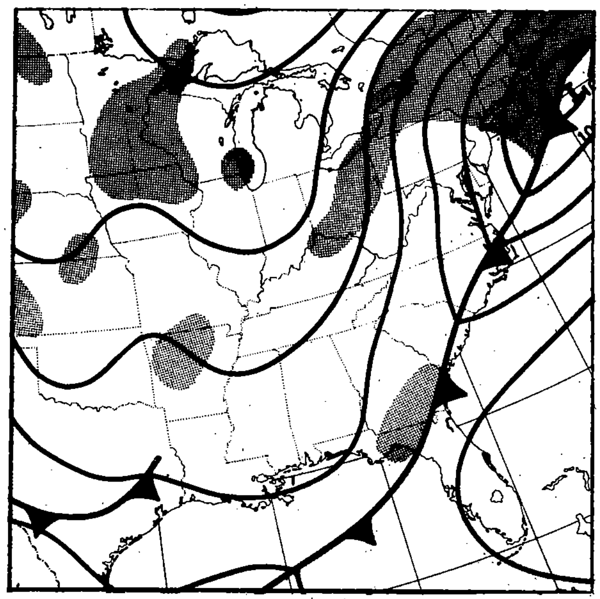


February 22, 1962

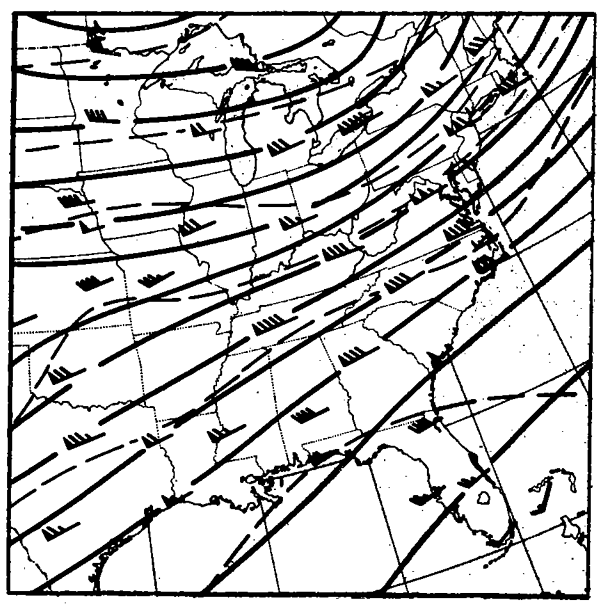
Figure 3B-10a. Surface weather maps for February 26, 1962 flood



February 23, 1962

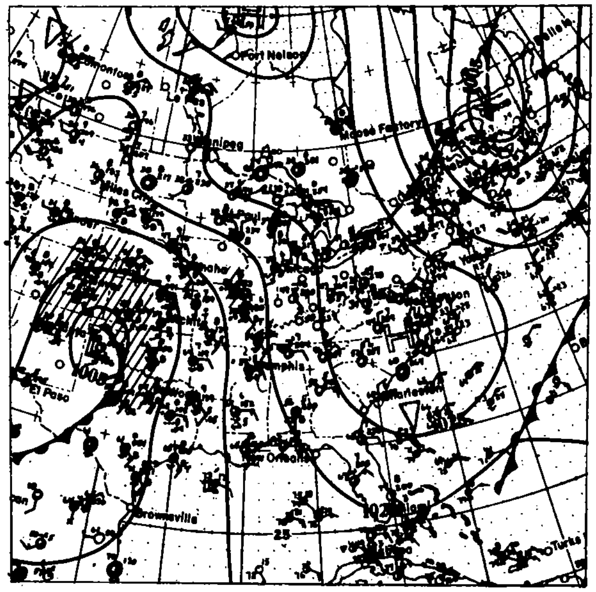


February 24, 1962

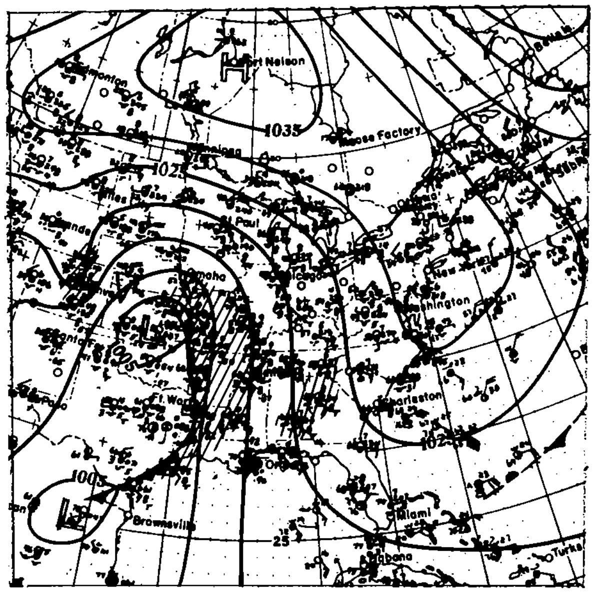


(500 mb)
February 22, 1962

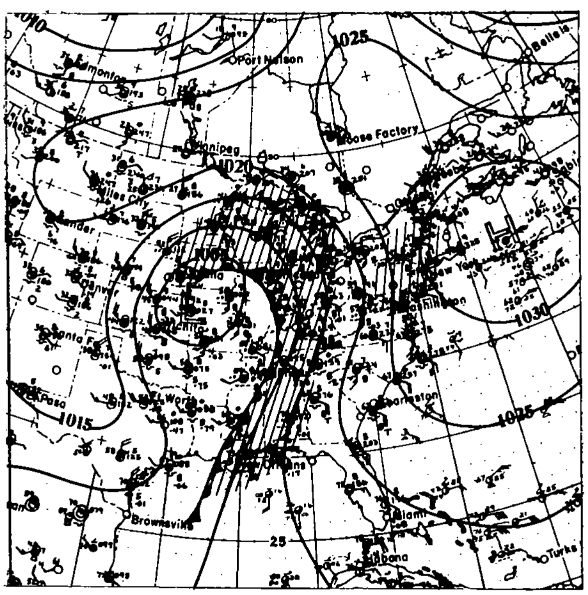
Figure 3B-10b. Surface and upper-air weather maps for February 26, 1962 flood



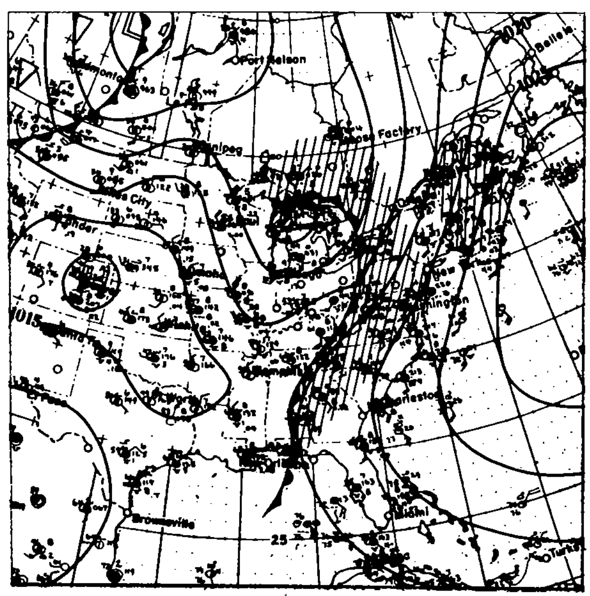
April 15, 1900



April 16, 1900

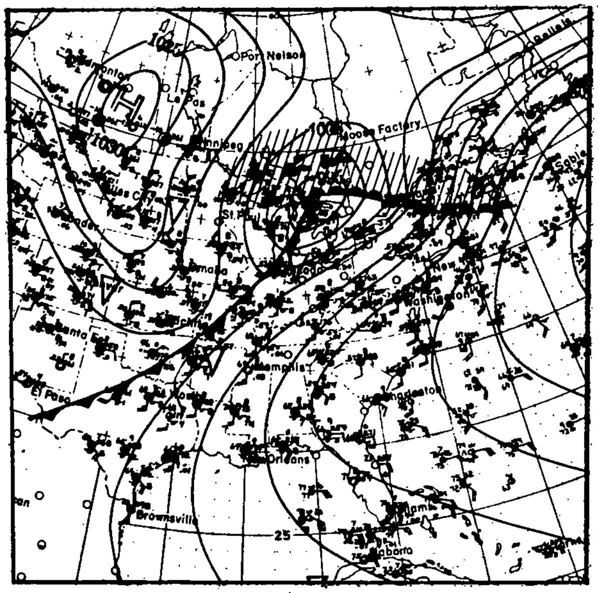


April 17, 1900

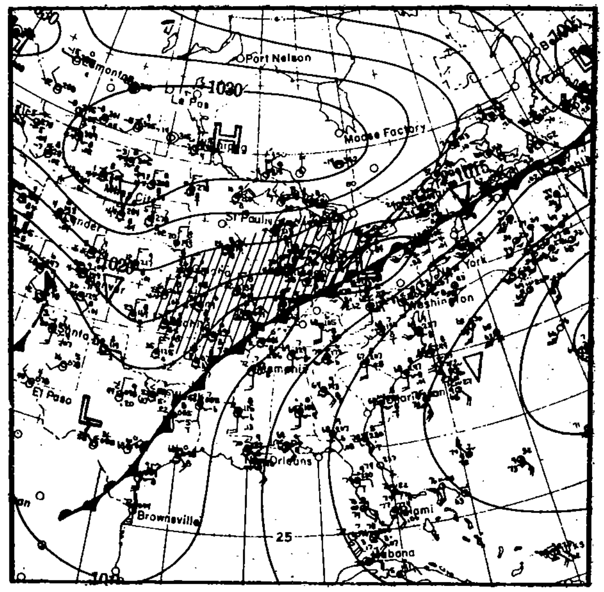


April 18, 1900

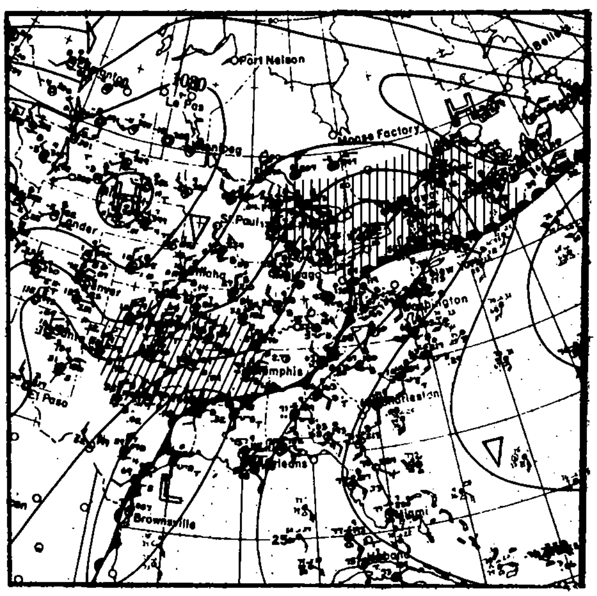
Figure 5B-1. Surface weather maps for April 15-18, 1900 storm



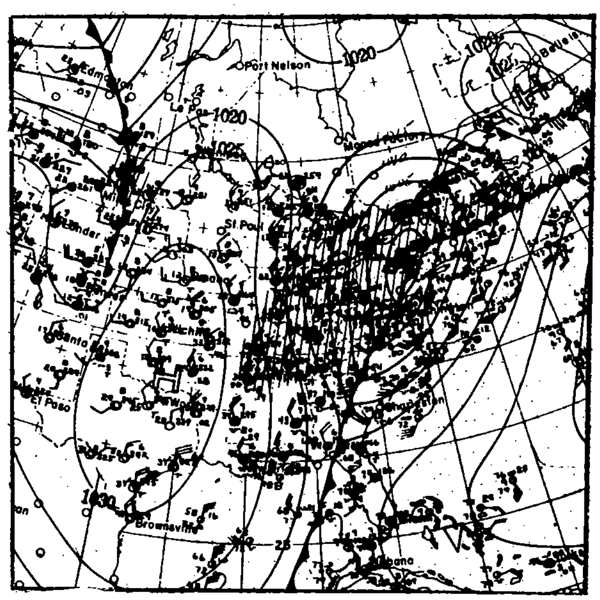
March 24, 1913



March 25, 1913

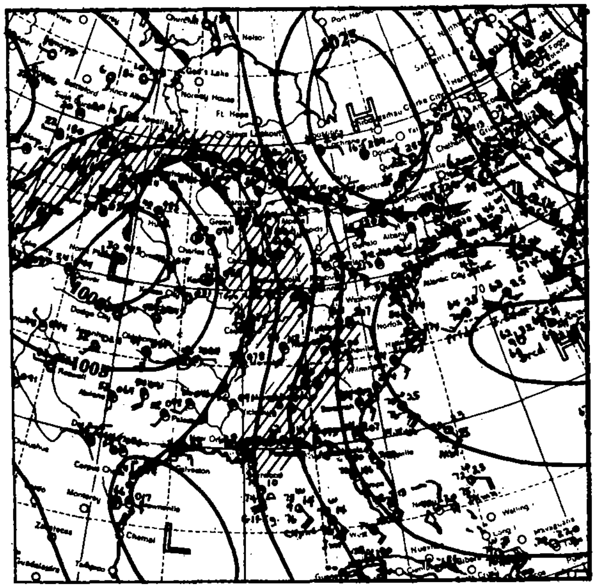


March 26, 1913

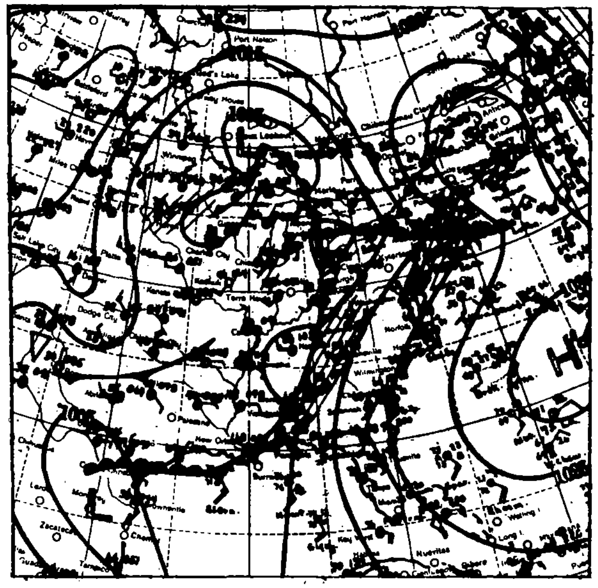


March 27, 1913

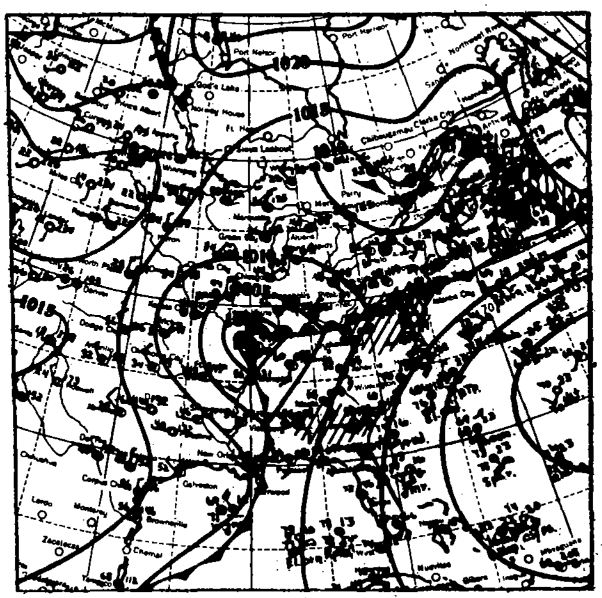
Figure 5B-2. Surface weather maps for March 24-27, 1913 storm



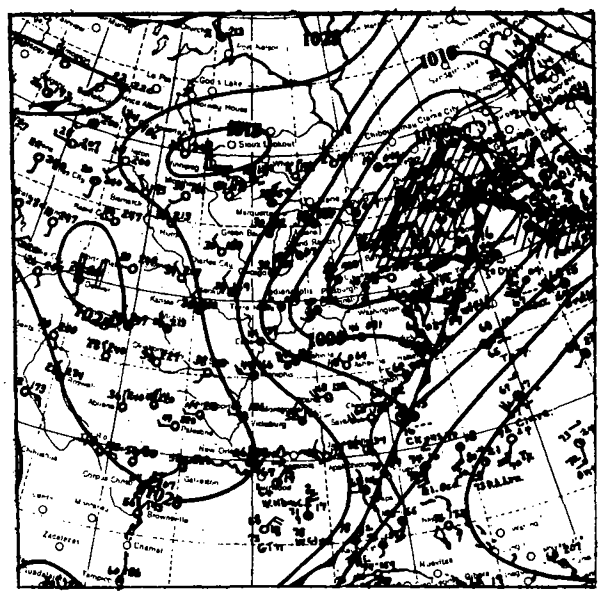
March 13, 1929



March 14, 1929

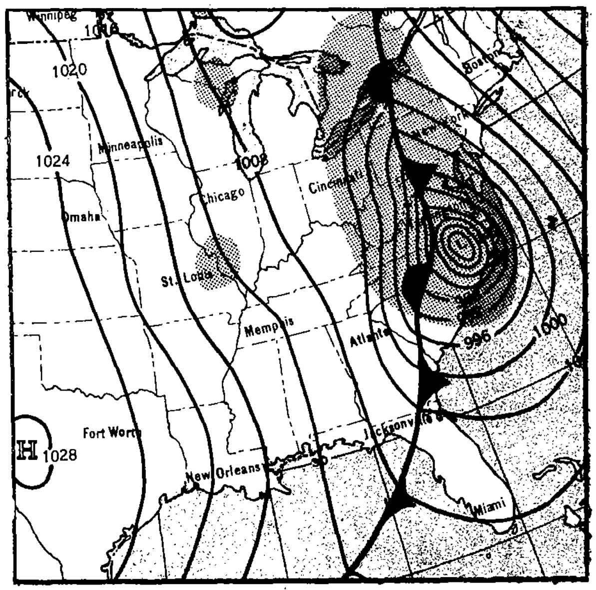


March 15, 1929

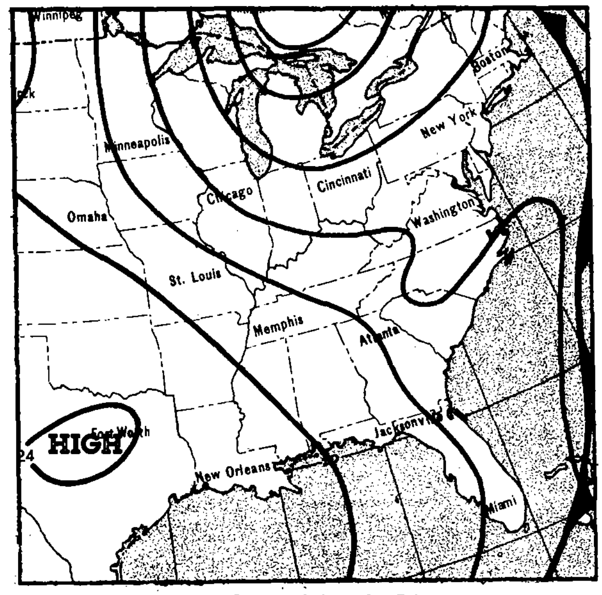


March 16, 1929

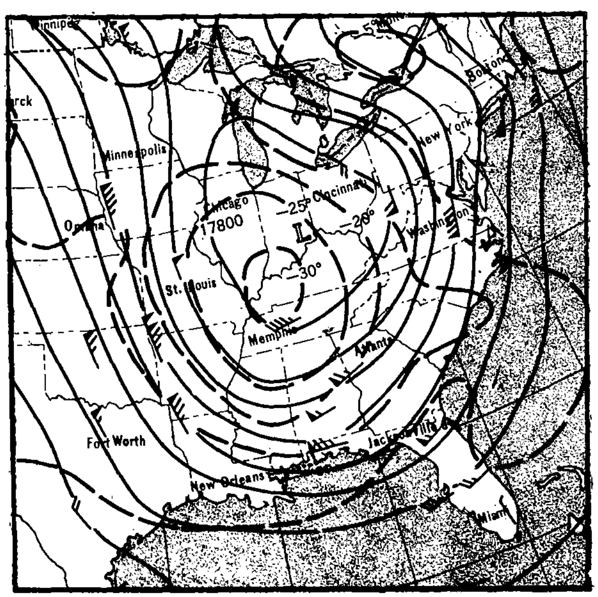
Figure 5B-3. Surface weather maps for March 13-16, 1929 storm



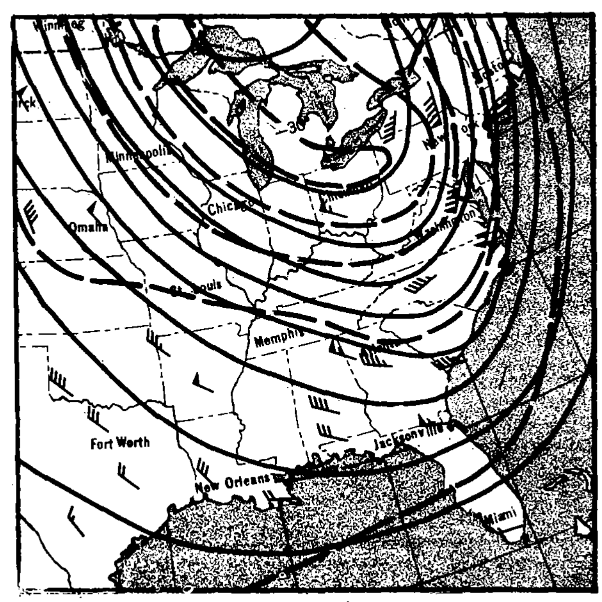
October 15, 1954



October 16, 1954

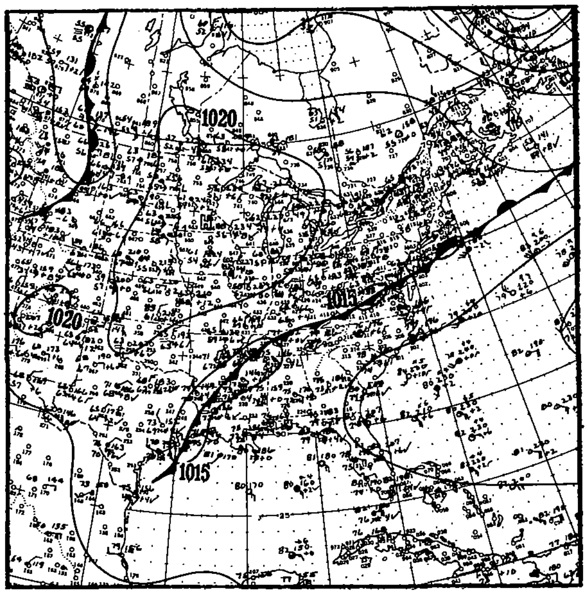


(500 mb)
October 15, 1954

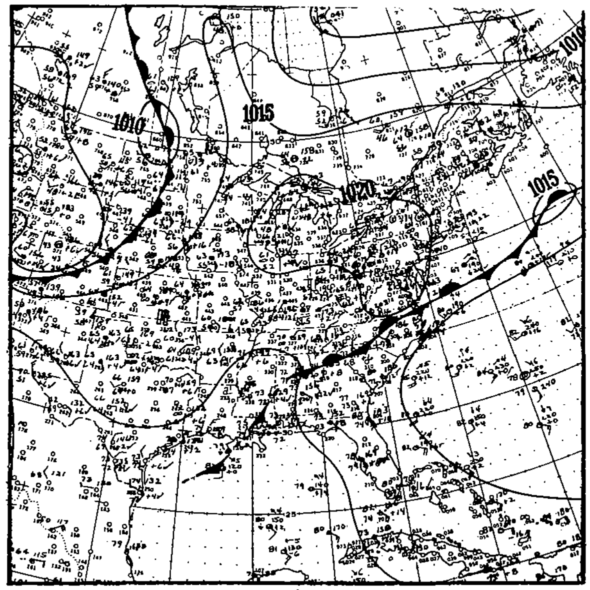


(500 mb)
October 16, 1954

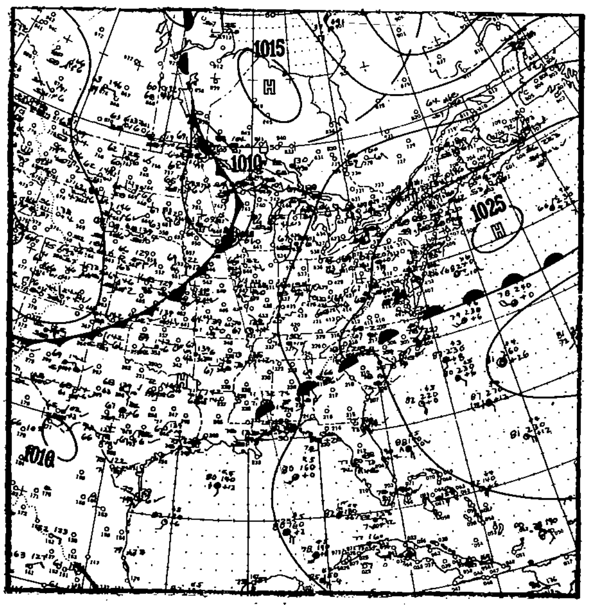
Figure 5B-4. Surface and upper-air weather maps for October 15-16, 1954 storm



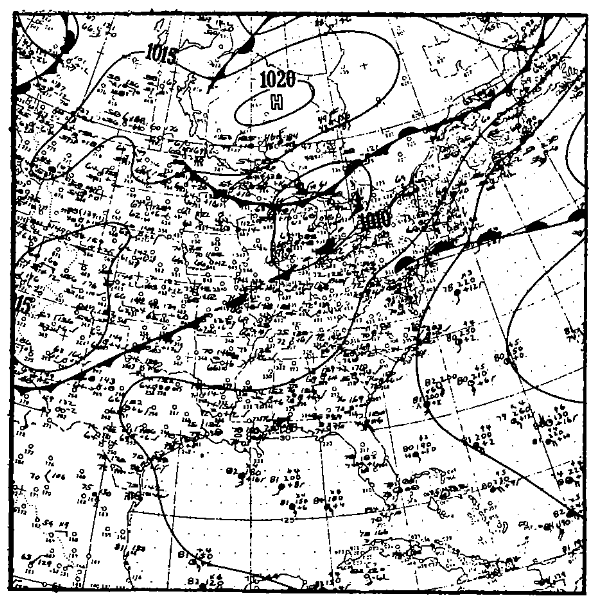
July 4, 1941



July 5, 1941

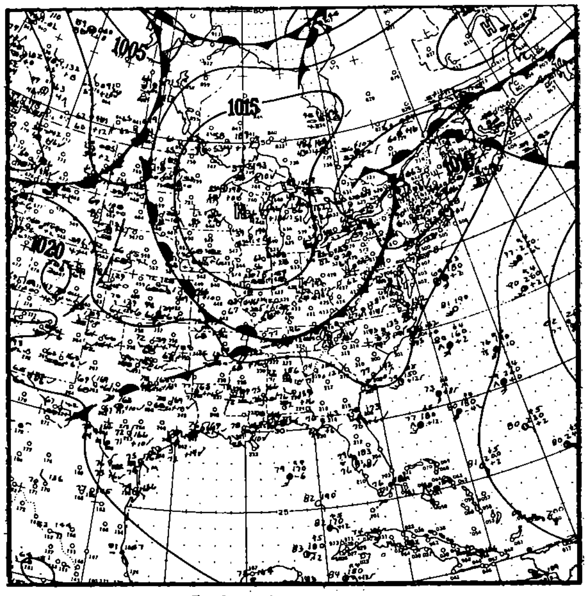


July 6, 1941

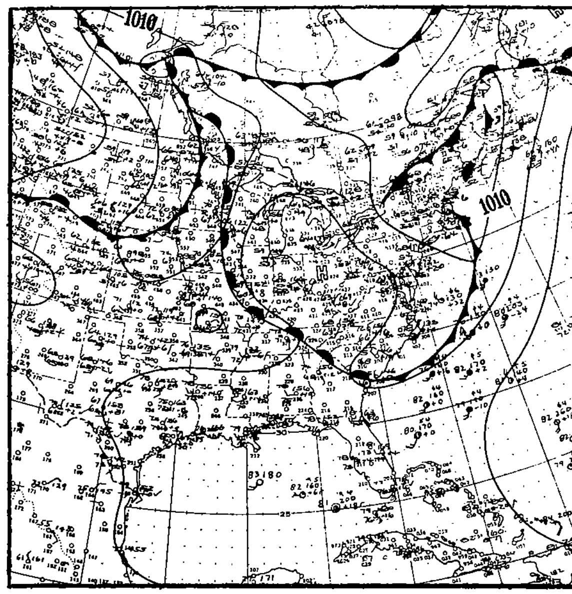


July 7, 1941

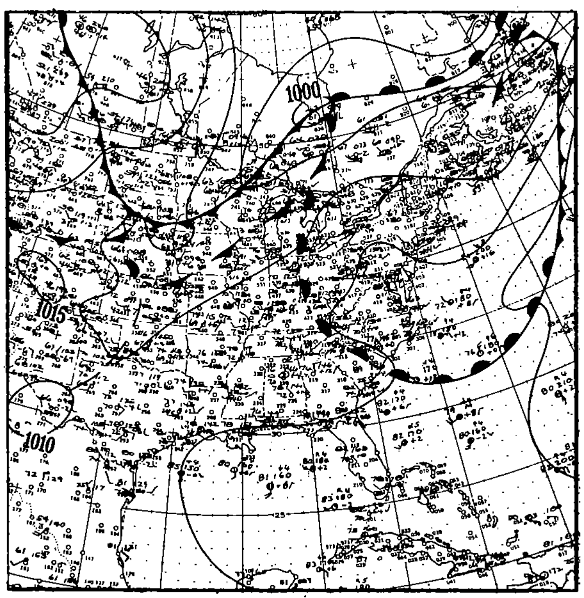
Figure 6B-1a. Surface weather maps for largest summer 10-day rain at Asheville (1912-1961)



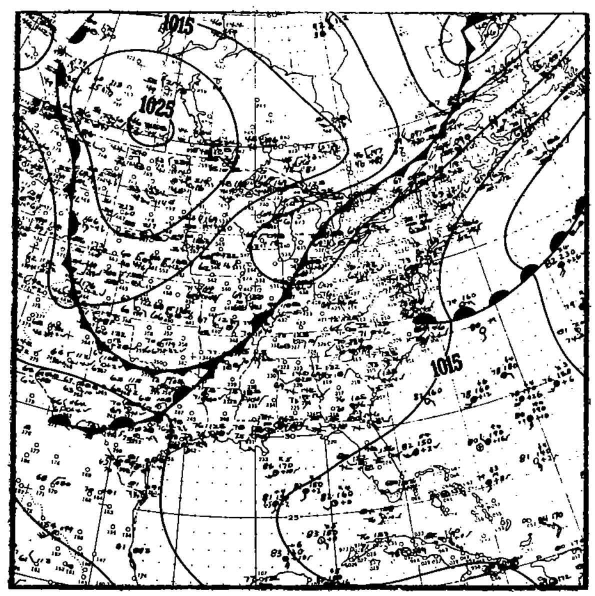
July 8, 1941



July 9, 1941

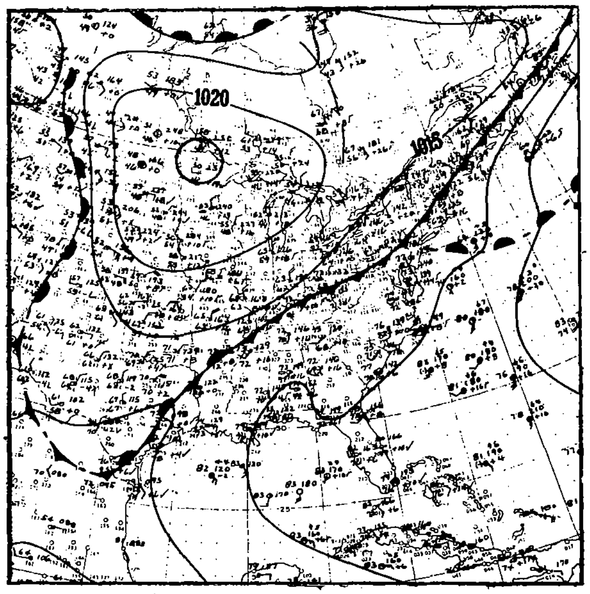


July 10, 1941

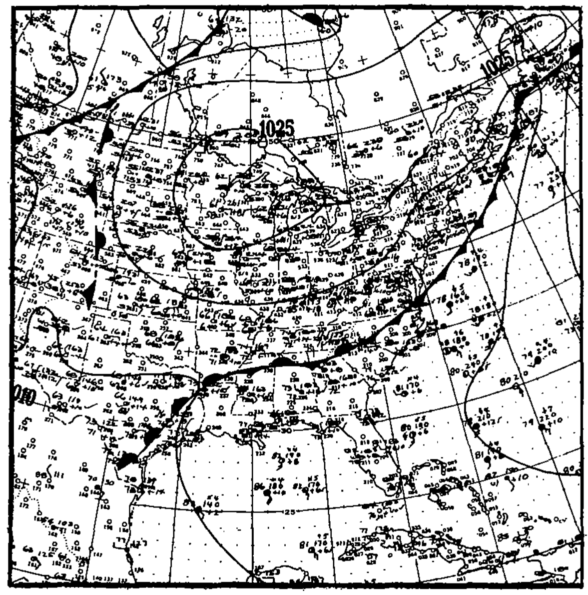


July 11, 1941

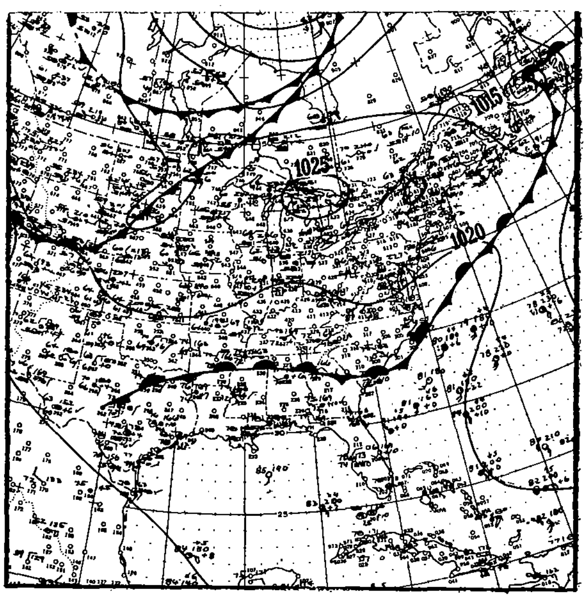
Figure 6B-1b. Surface weather maps for largest summer 10-day rain at Asheville (1912-1961)



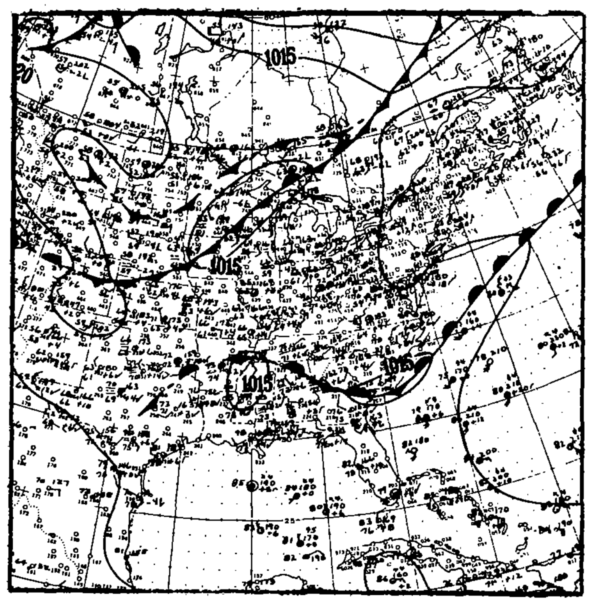
July 12, 1941



July 13, 1941

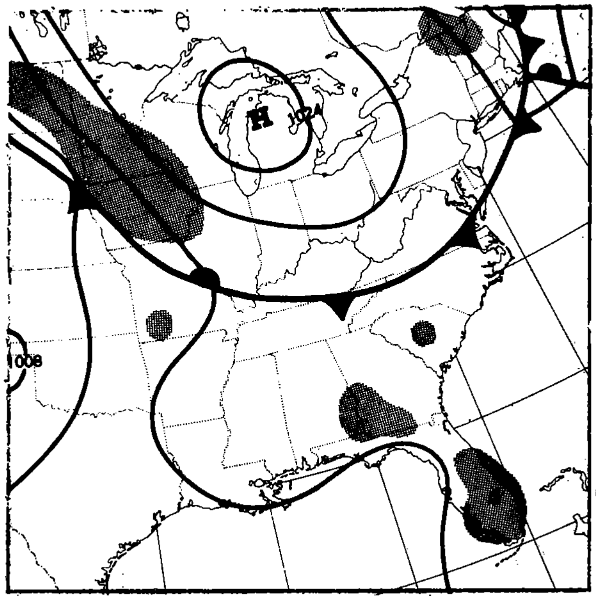


July 14, 1941

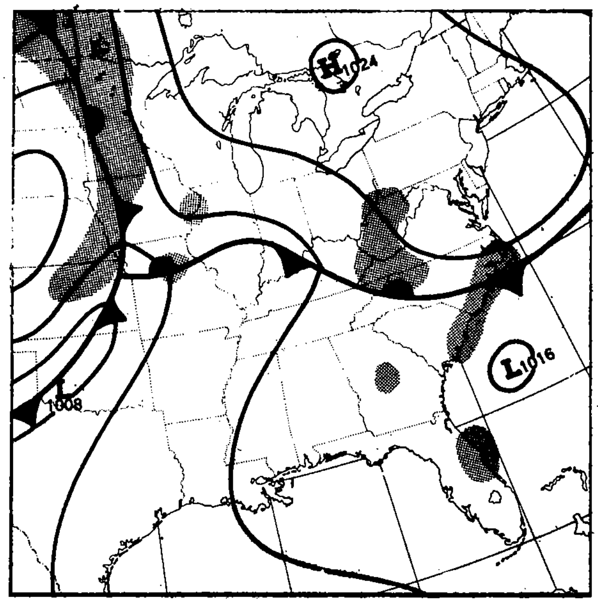


July 15, 1941

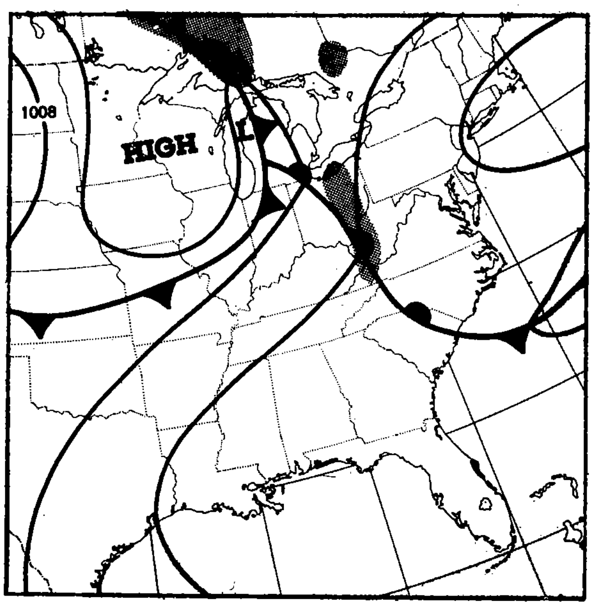
Figure 6B-1c. Surface weather maps for largest summer 10-day rain at Asheville (1912-1961)



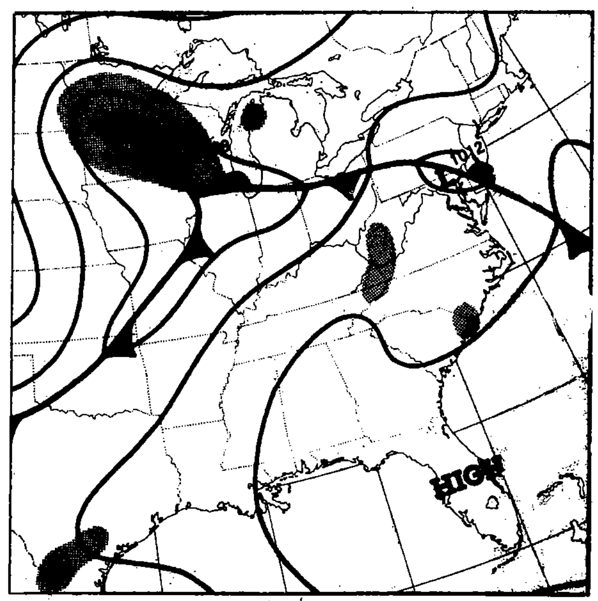
June 20, 1960



June 21, 1960

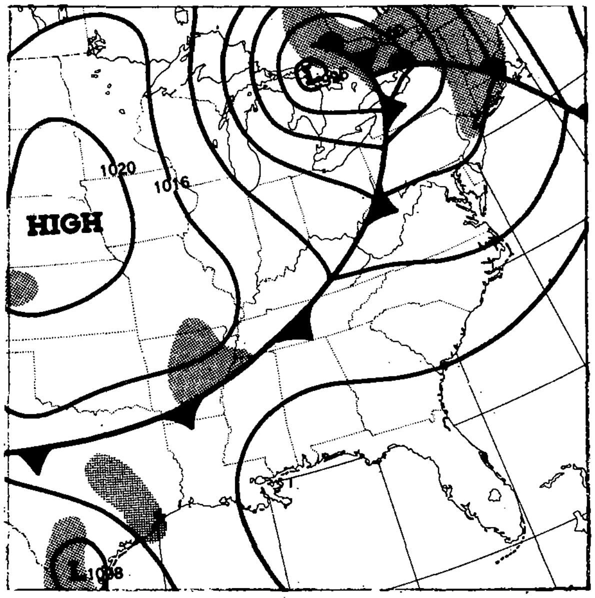


June 22, 1960

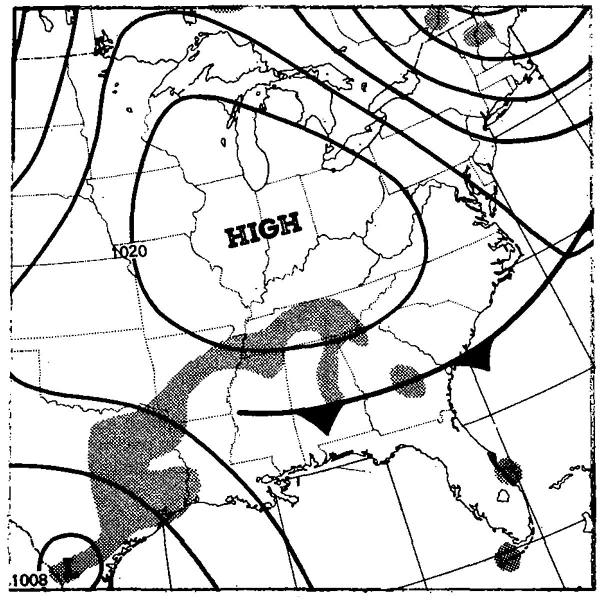


June 23, 1960

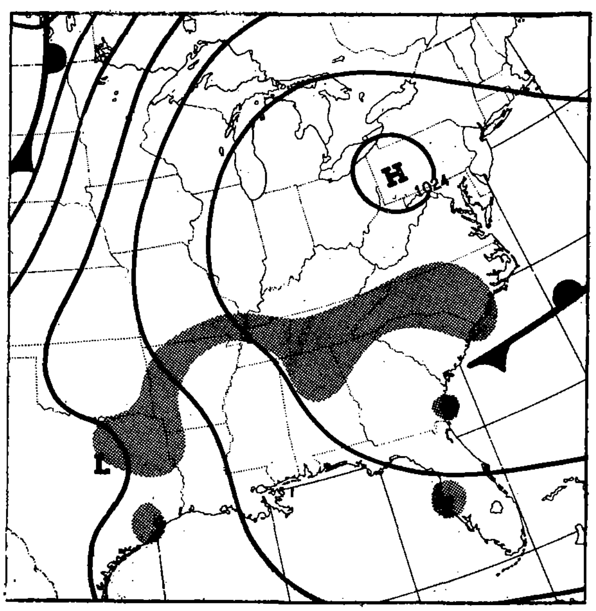
Figure 6B-2a. Surface weather maps for June 1960 Kentucky rain



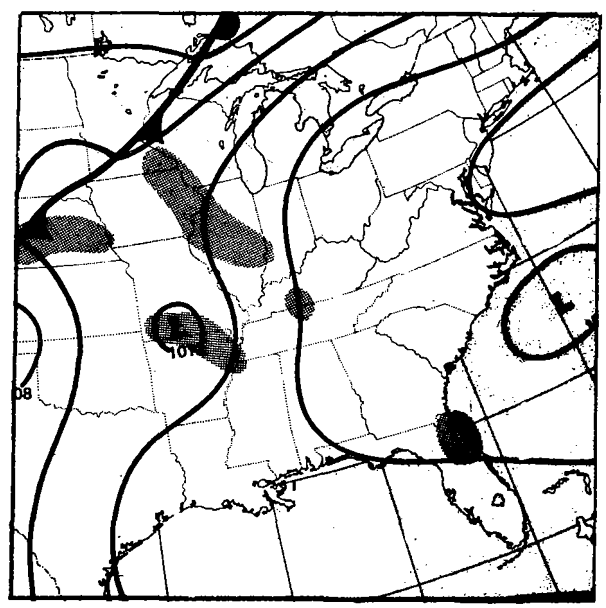
June 24, 1960



June 25, 1960

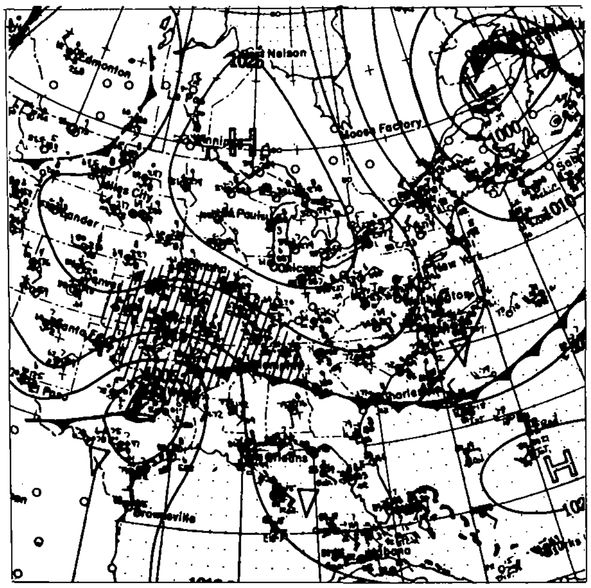


June 26, 1960

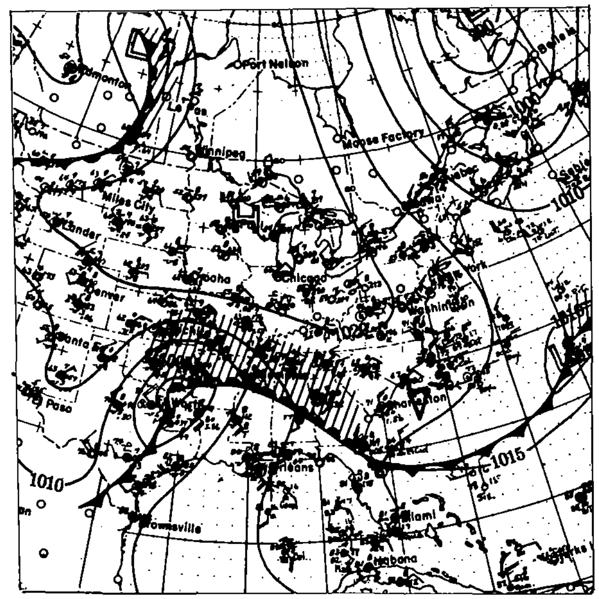


June 27, 1960

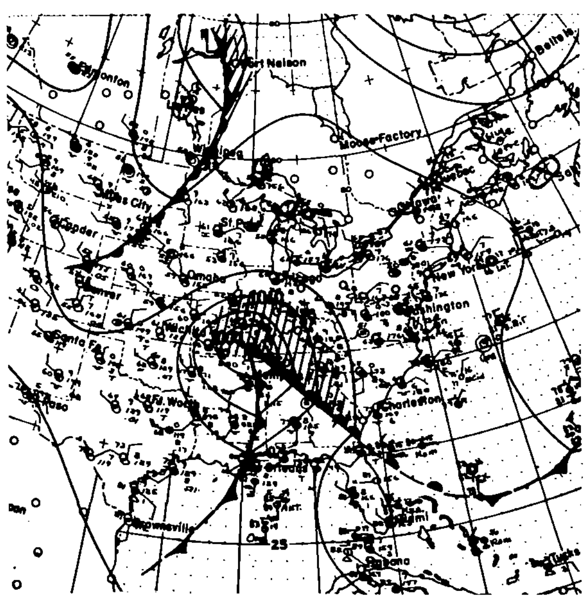
Figure 6B-2b. Surface weather maps for June 1960 Kentucky rain



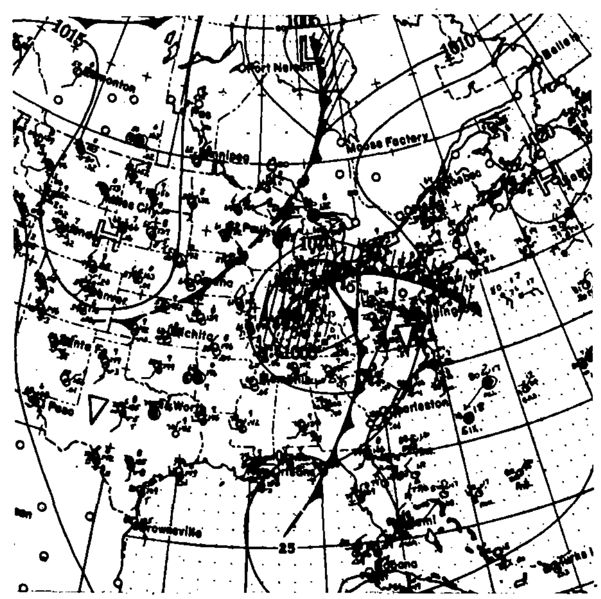
August 18, 1915



August 19, 1915

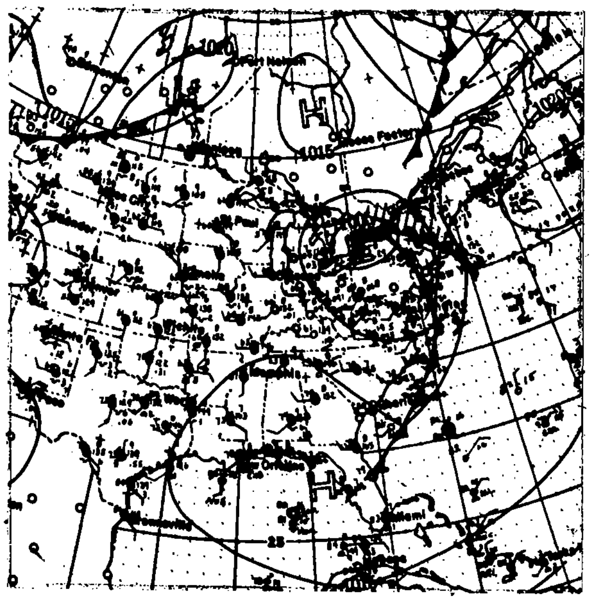


August 20, 1915

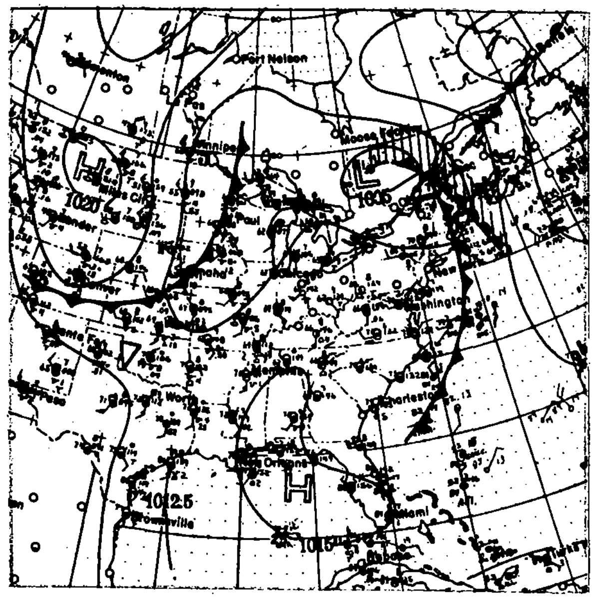


August 21, 1915

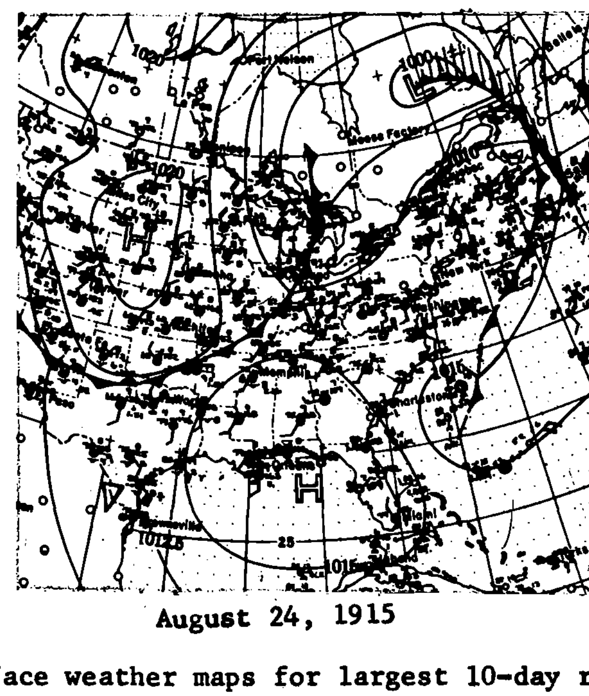
Figure 6B-3a. Surface weather maps for largest 10-day rain at Memphis (1912-1961)



August 22, 1915



August 23, 1915



August 24, 1915

Figure 6B-3b. Surface weather maps for largest 10-day rain at Memphis (1912-1961)

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