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Meteorology of Important Rainstorms in the Colorado River and Great Basin Drainages

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Silver Spring, MD

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16. ABSTRACT

This report is a companion to Hydrometeorological Report No. 49, "Probable Maximum Precipitation Estimates, Colorado River and Great Basin Drainages." The report covers some of the pertinent meteorological features of important general and local storms and of moisture climatology for the southern portion of the intermountain region. This information was used as background for the development of Probable Maximum Precipitation estimates for the region. A hypothetical extreme tropical cyclone related event is also discussed. (Author)

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Meteorology of Important Rainstorms in the Colorado River and Great Basin Drainages

U.S. DEPARTMENT OF COMMERCE
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
U.S. DEPARTMENT OF ARMY
CORPS OF ENGINEERS

Silver Spring, Md.
December 1981

HYDROMETEOROLOGICAL REPORTS

*No. 1. Maximum possible precipitation over the Ompompanoosuc Basin above Union Village, Vt. 1943.
*No. 2. Maximum possible precipitation over the Ohio River Basin above Pittsburgh, Pa. 1942.
*No. 3. Maximum possible precipitation over the Sacramento Basin of California. 1943.
*No. 4. Maximum possible precipitation over the Panama Canal Basin. 1943.
*No. 5. Thunderstorm rainfall. 1947.
*No. 6. A preliminary report on the probable occurrence of excessive precipitation over Fort Supply Basin, Okla. 1938.
*No. 7. Worst probable meteorological condition on Mill Creek, Butler and Hamilton Counties, Ohio. 1937. (Unpublished.) Supplement, 1938.
*No. 8. A hydrometeorological analysis of possible maximum precipitation over St. Francis River Basin above Wappapello, Mo. 1938.
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*No. 14. The frequency of flood-producing rainfall over the Pajaro River Basin in California. 1940.
*No. 15. A report on depth-frequency relations of thunderstorm rainfall on the Sevier Basin, Utah. 1941.
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*No. 24. Maximum possible precipitation over the San Joaquin Basin, California. 1947.
*No. 25. Representative 12-hour dewpoints in major United States storms east of the Continental Divide. 1947.
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*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. 29. Seasonal variation of the standard project storm for areas of 200 and 1,000 square miles east of 105th meridian. 1953.
*No. 30. Meteorology of floods at St. Louis. 1953. (Unpublished.)
*No. 31. Analysis and synthesis of hurricane wind patterns over Lake Okeechobee, Florida. 1954.
*No. 32. Characteristics of United States hurricanes pertinent to levee design for Lake Okeechobee, Florida. 1954.
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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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No. 40 Probable maximum precipitation, Susquehanna River drainage above Harrisburg, Pa. 1965.
No. 41. Probable maximum and TVA precipitation over the Tennessee River Basin above Chattanooga. 1965.
No. 42. Meteorological conditions for the probable maximum flood on the Yukon River above Rampart, Alaska. 1966.
No. 43. Probable maximum precipitation, Northwest States. 1966.
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U.S. DEPARTMENT OF COMMERCE
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Meteorology of Important Rainstorms in the Colorado River and Great Basin Drainages

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Office of Hydrology
National Weather Service

Silver Spring, Md.
December 1981

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METEOROLOGY OF IMPORTANT RAINSTORMS IN THE COLORADO RIVER AND GREAT BASIN DRAINAGES

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ABSTRACT. This report is a companion to Hydrometeorological Report No. 49, "Probable Maximum Precipitation Estimates, Colorado River and Great Basin Drainages." The report covers some of the pertinent meteorological features of important general and local storms and of moisture climatology for the southern portion of the intermountain region. This information was used as background for the development of Probable Maximum Precipitation estimates for the region. A hypothetical extreme tropical cyclone related event is also discussed.

1. INTRODUCTION

1.1 Purpose of Report

The purpose of this report is to describe significant meteorological characteristics of storms, both general and local, and moisture sources that contribute to the understanding of extreme precipitation in the Colorado River and Great Basin drainages and to the development of probable maximum precipitation (PMP) estimates. As a companion report to Hydrometeorological Report No. 49, "Probable Maximum Precipitation Estimates, Colorado River and Great Basin Drainages" (Hansen et al. 1977), hereafter referred to as HMR 49, this volume concentrates on the meteorology of important rain-producing storms in the region. HMR No. 49, on the other hand, applies what we have learned about these important storms toward estimating the PMP in the region.

1.2 Authorization

Authorization for these PMP studies was given in a July 8, 1971 memorandum from the Office of the Chief of Engineers, U.S. Army, Corps of Engineers. In subsequent conferences it was agreed that the bulk of the meteorological studies would be published separately.

1.3 Scope of the Report

The region covered in this study is shown in figure 1.1. The unstippled portion of figure 1.1 is the region of study for both general and local storm PMP and the stippled portion is included only for the study of local storm PMP. Some of the major river systems are also shown in this figure. In numerous places in this study we refer to the study region as the Southwestern States or the Southwest.

In chapter 2, we discuss and classify by synoptic type, or group, major large-area storms that have affected portions of the Southwestern States. In some cases, such as the December 1955 storm, Colorado River or Great Basin drainages were affected, although the major affect was on the areas draining into the

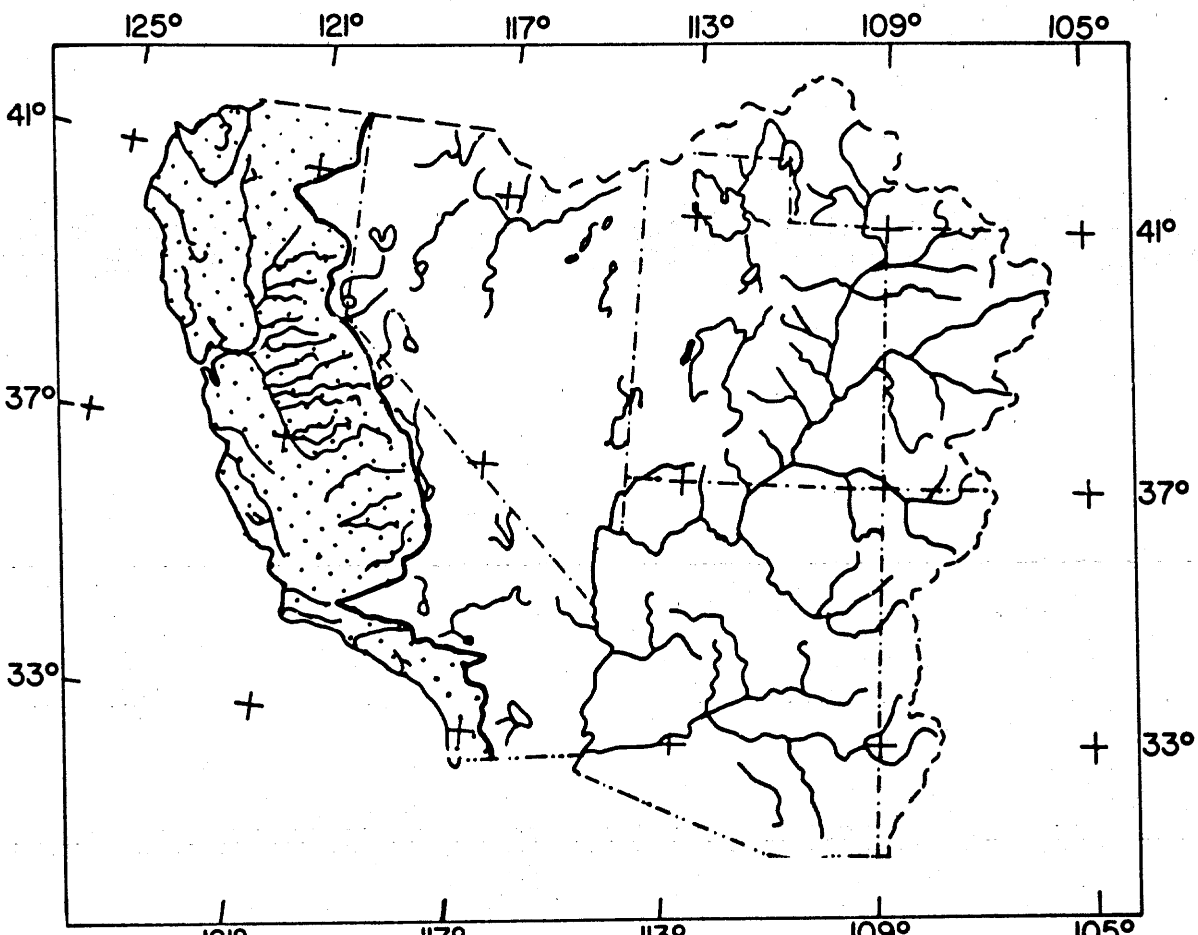


Figure 1.1.--Colorado River, Great Basin, and Western California study area showing major river systems.

Pacific. Since the December 1955 storm, and others like it, are discussed at length in "Meteorology of Hydrologically Critical Storms in California" (Weaver 1962), we do not report the meteorological aspects of these storms in this report.

In addition to the discussion of the major storms of record that have affected the study region we have developed a hypothetical extreme tropical cyclone event. This hypothesized storm composites and optimizes features of various tropical cyclone related storms of the past to a degree believed meteorologically possible. The development of this hypothesized storm helped in the evaluation of the general level of PMP and in the definition of the area over which a tropical cyclone would control PMP.

Chapter 3 discusses the meteorological characteristics of intense local rain storms. Such storms formed the basis for setting the general level of PMP for small drainages (local storm PMP) in HMR No. 49. The most extreme events of record are emphasized, although some lesser storms are also discussed.

With the availability of detailed rainfall-frequency values (Miller et al. 1973), we have expressed station rainfalls as percentages of point 100-yr precipitation. This helps in judging the magnitude of the rainfall relative to a common base. For this purpose, observed depths and percentages of 100-yr 24-hr precipitation are given in tables. In chapter 2, most 1- and 3-day rains have been expressed as a percent of the 100-yr 24-hr value. In chapter 3, most local storm rains are expressed as a percent of the 100-yr 6-hr value. In the discussions of rainfall amounts in the text the percents of 100-yr 6- or 24-hr precipitation (except when noted otherwise) are given in brackets after the precipitation amount.

Chapter 4 deals with the climatology of moisture, both at low and high altitudes. For months when both local and general storm types could be hydrologically critical (April through October) two sets of maximum moisture charts were developed -- one applicable to the general storm, the other applicable to the local storm.

Since HMR No. 49 was published in early 1977 there have occurred a number of general and local storms within the Southwest. Although it may appear logical to include information on these more recent storms in this report, it was the author's decision to maintain this present study as the originally planned companion volume to HMR No. 49. Thus, we have included only such storms and background meteorological discussion as was considered at the time of that report. Of the more recent large general storms, tropical storm Kathleen (September 7-10, 1976), and the cool season storms of October 6-9, 1977, February 27-March 3, 1978, December 17-19, 1978 and February 13-22, 1980 are particularly noteworthy and support many of the conclusions made in this report. It may be added, however, that none of these or other more recent storms were of such magnitude as to have resulted in changes to HMR No. 49.

1.4 Appendices

For convenience, three appendices have been added to this study. Appendix A contains two sets of monthly normal weather charts (U.S. Weather Bureau 1952). One set represents sea level pressure charts, and the second represents the 500-mb surface (approximately 18,000 ft). These charts are useful in making comparisons with synoptic weather patterns presented for some of the major rainfall events described in this study.

Appendix B is a glossary of selected geographical and meteorological terms used in this report. Many of the definitions contained in this glossary have been extracted from the Glossary of Meteorology (American Meteorological Society 1959). The inclusion of geographical descriptions was made where the usage of a term in this report may be unclear or somewhat different from accepted usage.

Appendix C provides dimension equivalents for converting English units in this report to metric units in accordance with efforts to adopt the metric system. Presentation in English units was recognized in this report, however, in consideration of the users, most of whom have not yet adopted the metric system, with the following exceptions. In meteorology, it is common to refer to pressure surfaces in millibars (mb), and to mixing ratios in terms of the dimensionless unit, g/kg.

2. GENERAL STORMS

2.1 Introduction

By general storm, we mean a storm that produces significant precipitation over at least several hundred square miles and lasts at least a day. The significant general storms for this report can be classified into two groups: (a) tropical storms, and (b) extratropical storms. To judge significance, we compared observed precipitation to 100-yr 24-hr amounts from NOAA Atlas 2 (Miller et al. 1973).

In the course of investigating general storms of record, we concluded that a hypothetical more extreme tropical cyclone, e.g., optimizing moisture and movement compared to extreme storms of record, could be the most extreme rain-producer over a large portion of the Southwestern States during August or September.

For some regions the PMP-producing storms are associated with low-pressure systems that form generally in the middle latitudes (rather than the tropics). These are called extratropical storms. They ordinarily involve an interplay of large contrasts in temperature and strong inflows of moisture. When moisture values are large and the various precipitation-producing factors operate in an optimum manner, large amounts of precipitation may result. The extratropical storms, in addition to being the controlling storm type for some portions of the Southwest, are also important for producing maximum precipitation in all areas of the Southwest for months other than those when tropical storms control.

Since in most major storms a large component of the moisture flow is from the south or southwest in the lower few thousand feet, the heaviest general rains usually occur along the first extensive upslopes encountered approximately normal to these inflow directions. These upslopes are in the coastal mountains of southern California and near central Arizona.

One area of our study region that we believe could not receive general storm PMP from either the extratropical storm with a moisture source from west of the Continental Divide or from the hypothetical tropical cyclone related PMP storm type, is in the vicinity of southwest Wyoming. The general storm PMP for this area is most likely a storm with moisture from the Gulf of Mexico. An example of this storm type occurred in northern Montana in June 1964, producing record rainfall. This storm is discussed in section 2.3.8.

The following sections describe pertinent meteorological factors of the important general storms that have occurred in the region. Table 2.1 lists locations of rainfall amounts mentioned in the text. Figure 2.1 is a map showing the locations of sites listed in table 2.1.

Throughout this report we have used small charts of the surface and 500-mb analyses to illustrate the meteorological conditions prevailing before and during the time of the major storms being discussed. For the most part these charts

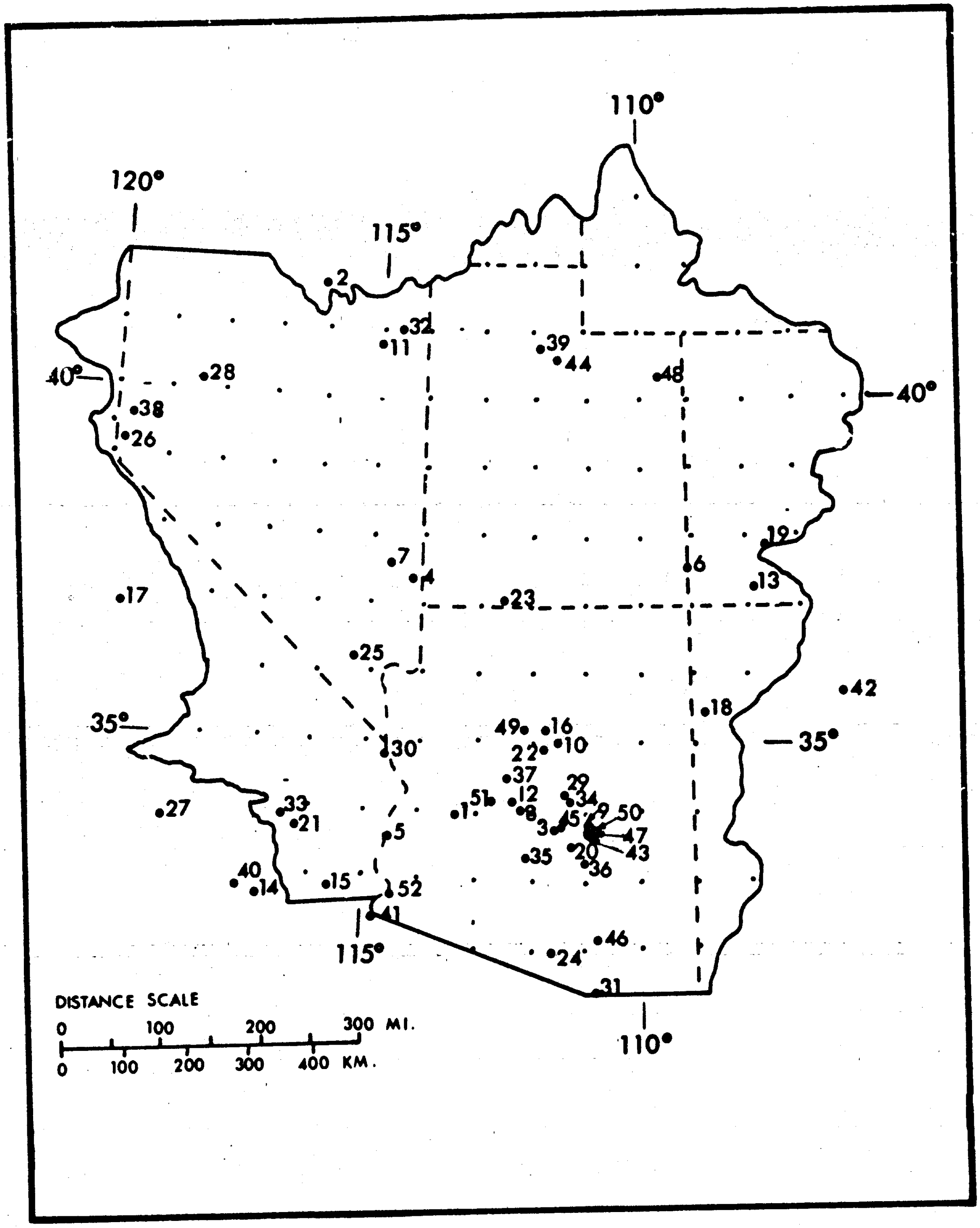


Figure 2.1.--Index map of Colorado River and Great Basin Drainages showing places referred to in chapter 2. Stations identified in table 2.1.

Table 2.1.—Identification of places referred to in text (see figure 2.1)

Index number	Station name	Latitude (°)	Latitude (')	Longitude (°)	Longitude (')
1	Aguila, Ariz.	33	56	113	11
2	Aura, Nev.	41	38	116	05
3	Bartlett Dam, Ariz.	33	49	111	38
4	Beaver Dam St. Park, Nev.	37	25	114	07
5	Blythe, Calif.	33	37	114	36
6	Bug Point, Utah	37	39	109	04
7	Caliente, Nev.	37	37	114	31
8	Canon, Ariz.	34	03	112	10
9	Carr Ranch, Ariz.	33	50	110	59
10	Casa Grande Ruins, Ariz.	33	00	111	32
11	Clover Valley, Nev.	40	53	115	03
12	Crown King, Ariz.	34	12	112	20
13	Durango, Colo.	37	17	107	53
14	El Cajon, Calif.	32	48	116	55
15	El Centro, Calif.	32	47	115	34
16	Flagstaff, Ariz.	35	12	111	40
17	Fresno, Calif.	36	47	119	42
18	Gallup, N.M.	35	31	105	43
19	Gladstone, Colo.	37	49	107	40
20	Hackberry R.S., Ariz.	33	35	111	18
21	Indio, Calif.	33	43	116	15
22	Junipine, Ariz.	34	58	111	45
23	Kanab, Utah	37	03	112	31
24	Kitt Peak, Ariz.	31	58	111	36
25	Las Vegas, Nev.	36	05	115	10
26	Lewers Ranch, Nev.	39	14	119	51
27	Los Angeles, Calif.	33	56	118	23
28	Lovelock, Nev.	40	11	118	29
29	Natural Bridge, Ariz.	34	19	111	27
30	Needles, Calif.	34	50	114	36
31	Nogales, Ariz.	31	20	116	56
32	Oasis Ranch, Nev.	41	02	114	30
33	Palm Springs, Calif.	33	50	116	30
34	Payson R.S., Ariz.	34	14	111	20
35	Phoenix, Ariz.	33	27	112	04
36	Pinal Ranch, Ariz.	33	21	111	00
37	Prescott, Ariz.	34	32	112	29
38	Reno, Nev.	39	30	119	47
39	Salt Lake City, Utah	40	46	111	58
40	San Diego, Calif.	32	47	117	04
41	San Luis, Mex.	32	28	114	48
42	Santa Fe, N.M.	35	37	106	05
43	Sierra Ancha, Ariz.	33	48	110	58
44	Silver Lake Brighton, Utah	40	36	111	35
45	Sunflower, Ariz.	33	52	111	28
46	Tucson, Ariz.	32	08	110	57
47	Upper Parker Creek, Ariz.	33	48	110	57
48	Vernal, Utah	40	27	109	31
49	Williams, Ariz.	35	15	112	11
50	Workman Creek, Ariz.	33	49	110	55
51	Yarnell, Ariz.	34	13	112	45
52	Yuma, Ariz.	32	40	114	36

present only broadscale features, i.e., pressure centers, fronts, and upper-level temperature patterns. In the surface charts, isobars of pressure are shown in millibars. The 500-mb charts have been adjusted to give temperatures in °F and heights in feet. Because temperatures in the original Weather Bureau analyses were given in °C and some heights were given in meters, this conversion has resulted in labels at uncommon intervals. Although a consistent set of charts is desirable, it was judged prohibitively laborious to reanalyse the charts.

2.2 Tropical Cyclones

Tropical cyclones, originating at low latitudes, have produced significant rainfall in the Southwest States. Figure 2.2 shows tracks for selected tropical cyclones. The storms selected were those that produced heavy rains in some portion of the Southwestern States or contributed information from which we have developed the hypothesized extreme tropical cyclone event. In most cases, the tropical cyclone circulation is still far removed from the study region at the time of much of the heaviest precipitation. The moist air flow in advance of this circulation is triggered by some other precipitation-producing mechanism. The northward transport of warm moist air into this normally dry region is one of the most important features of this storm type. The largest and most intense rainfalls will occur where some other mechanism does not trigger a precipitation event early and the storm retains its identity into the region. To obtain the 3-day PMP event associated with a tropical cyclone, some rain well in advance of the storm center must be supplemented significantly by a storm circulation retaining its identity into the region. This is the basis for consideration of a hypothetical extreme tropical cyclone.

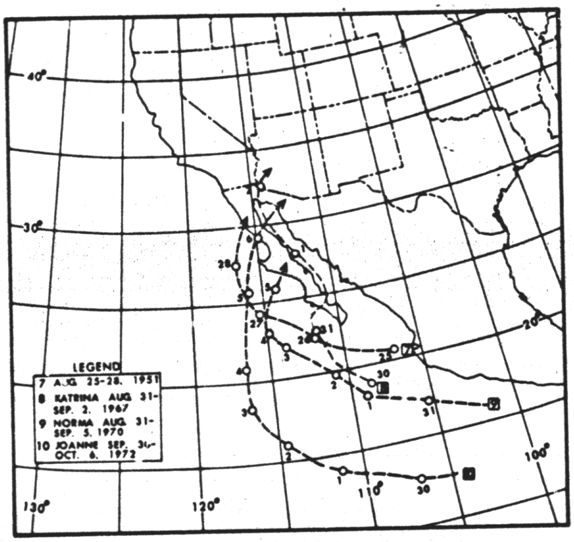
Three of the tropical cyclones shown on figure 2.2 are discussed immediately below. Others are discussed in connection with the hypothesized extreme tropical cyclone related event covered in section 2.4.5.

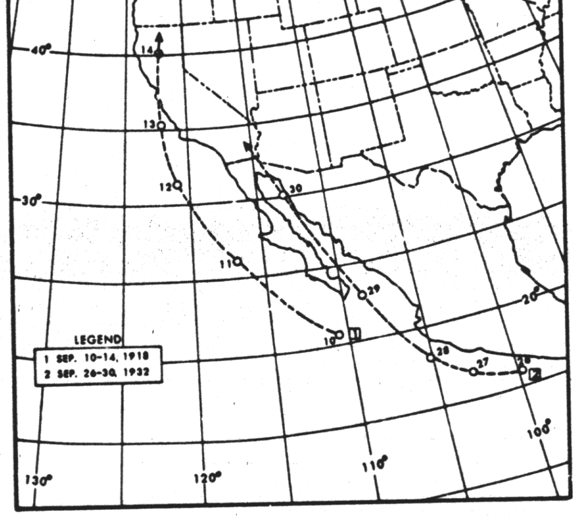
2.2.1 September 4-7, 1970 (Norma)

This storm is important in establishing the general level of all-season PMP over much of the Southwest for durations of up to about 1 day. A generalized isohyetal pattern for this storm is shown in figure 2.3.

2.2.1.1 Important Meteorological Features. Figures 2.4 and 2.5, surface and upper-air weather maps, show the broadscale synoptic features associated with this important storm. Beginning on September 2nd, a substantial flow of moist tropical air headed north from the eastern Pacific Ocean, south of the Gulf of California, toward the southern border of Arizona. At this time, the center of the tropical cyclone was still about 200 miles south-southwest of the southern tip of Baja California. The storm continued northwestward for two more days before curving toward the northeast on the 4th. The dissipating storm center crossed the coast of Baja California on the morning of the 5th. During this period, a northeast-southwest cold front moved from the Pacific Ocean across Nevada and through Arizona. The frontal system and associated upper-air systems were accompanied by unusually cold air for so early in the season. The interaction of the warm moist air moving northward as a result of the tropical cyclone with this mid-latitude system caused the heavy precipitation.

The extensiveness both horizontally and vertically of the moisture influx to this storm is demonstrated by cross sections that vary with time in figure 2.6 as drawn by May (1971). The shaded areas show dew point depressions (temperature





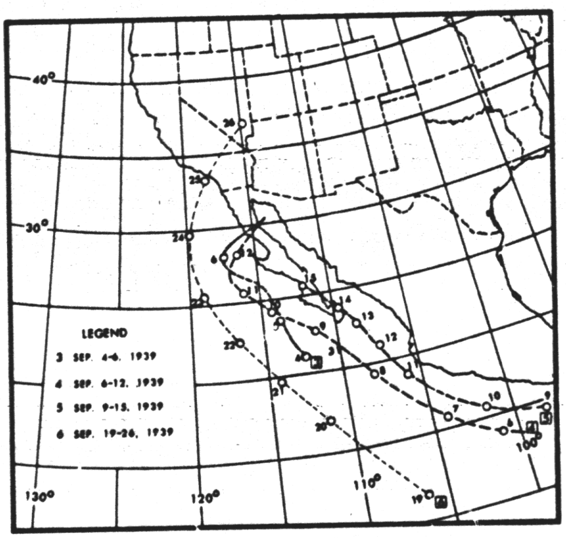


Figure 2.2.--Tropical storm tracks.

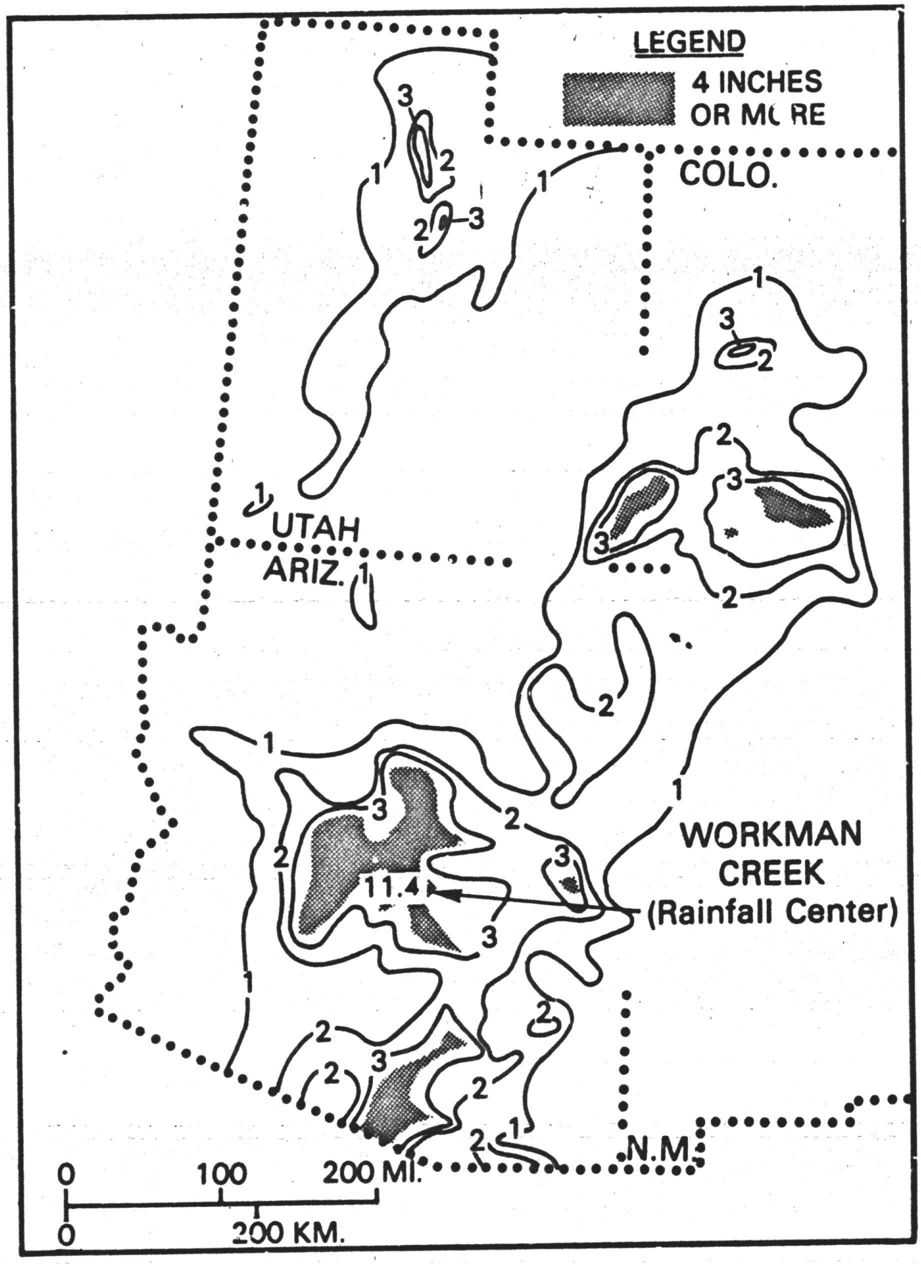


Figure 2.3.--Generalized isohyetal pattern for tropical storm (Norma), September 4-7, 1970,

minus dew point temperature) of 9°F or less. Winds are shown by arrows, pointed toward the direction of flow, where a full barb depicts 10 kt.

Of the four sets of cross sections shown in figure 2.6, those from YUM (Yuma, Ariz.) to MAF (Midland, Tex.) and from LAS (Las Vegas, Nev.) to AMA (Amarillo, Tex.) show the air over Arizona. The correspondence between the component of

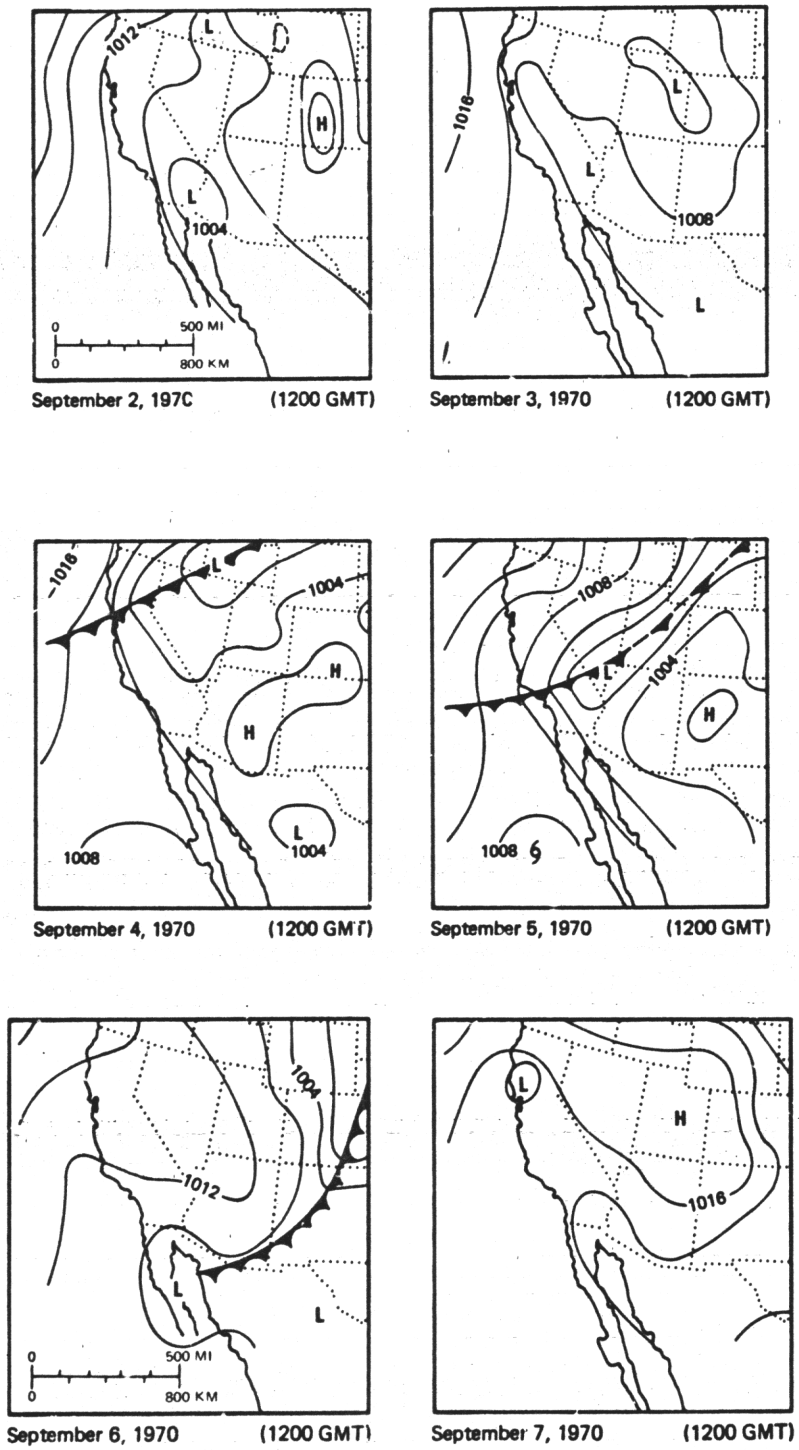


Figure 2.4.--Surface weather maps for September 2-7, 1970.

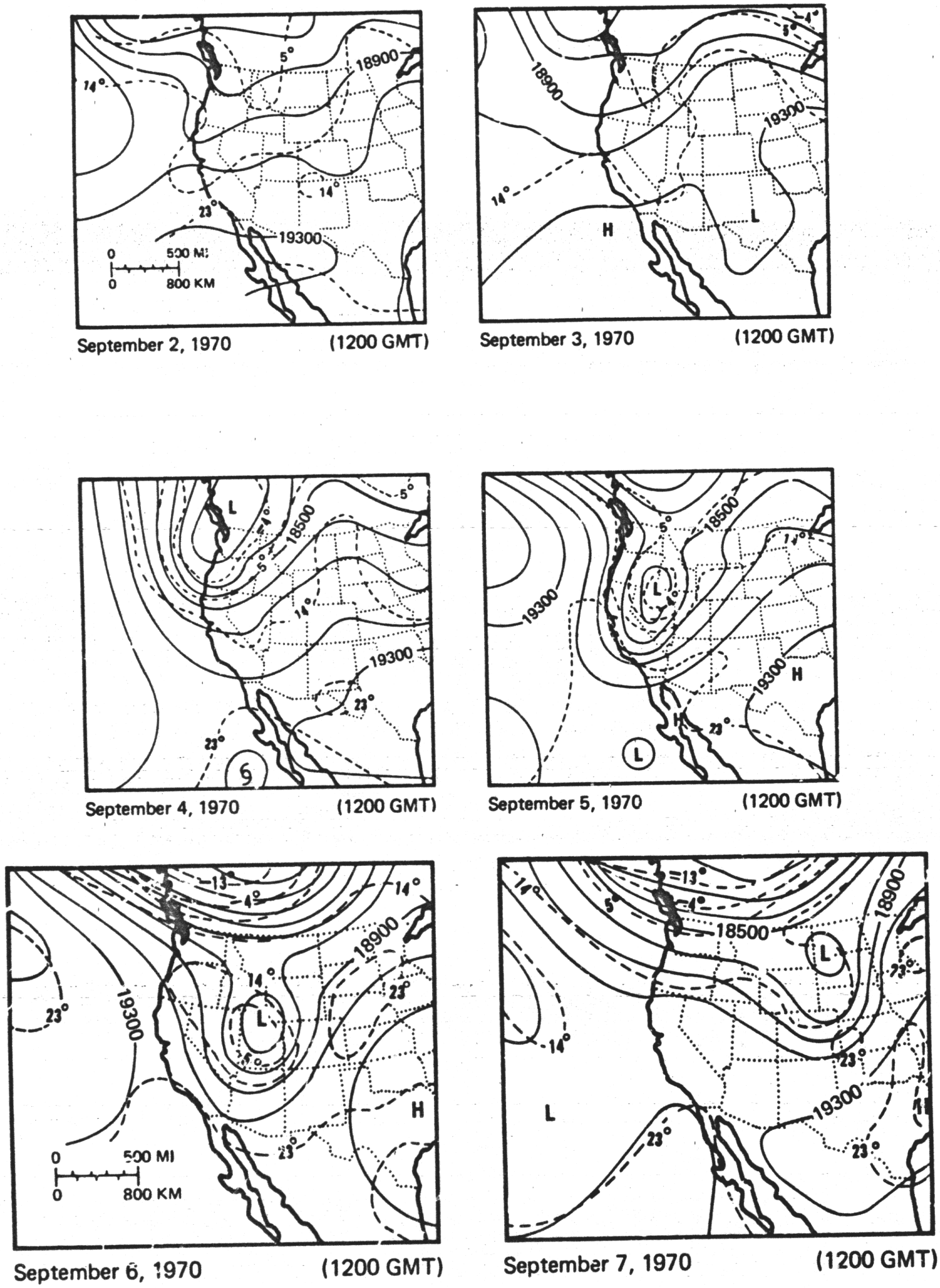


Figure 2.5.--500-mb charts for September 2-7, 1970

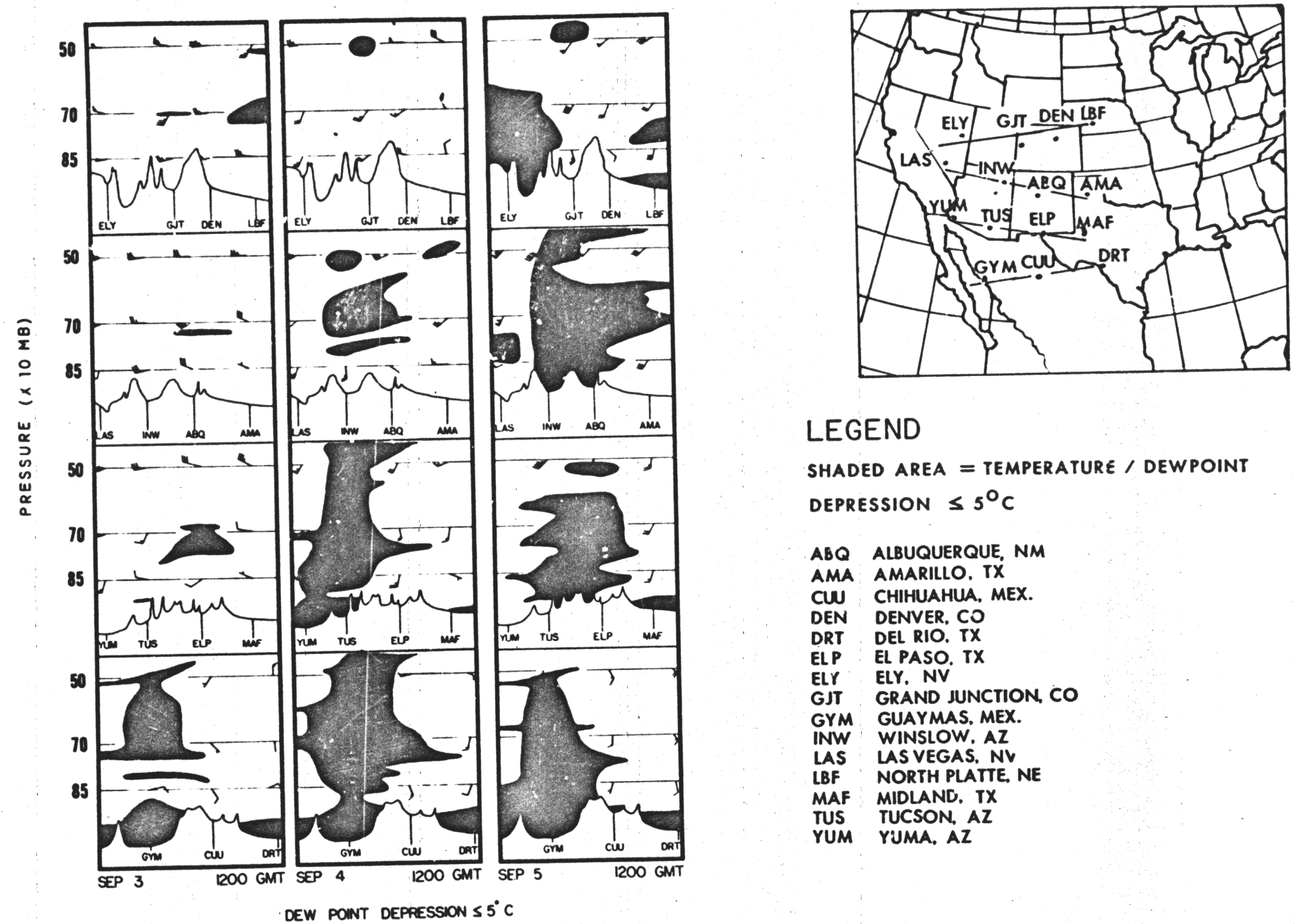


Figure 2.6.--Vertical distribution of moisture over Southwest during the period September 2-7, 1970, from May (1971)

upper-air wind from the south with height and the increase in vertical extent of the near-saturated air (i.e., darkened areas on the cross sections) is evident. Between September 3 and 5, significant depths of moist air appear, first over central Arizona (Tucson) and then drifting eastward.

2.2.1.2 Significant Rains. Scattered thundershowers began in southern Arizona the afternoon of September 3. This early shower activity is apparent in the mass curve of rainfall for Kitt Peak, Ariz. (fig. 2.7). The more widespread and intense rainfall farther north did not occur until the late afternoon and night of September 4 (see mass curves for Workman Creek 1 and Sunflower, Ariz. in fig. 2.7).

From 2300 MST on September 4 to 2300 MST on September 5, 1970 (0600 GMT of the 5th to 0600 GMT of the 6th), 11.40 in. [163%]* was measured at Workman Creek 1, Ariz. (Kangieser 1972). This nearly doubled the previous Arizona record 24-hr rain of 6 in. [86%] observed at Crown King on December 19, 1967.

In addition to the Workman Creek 1 record rain, new daily records were set at many other Arizona stations. Two of these, Bartlett Dam with 4.50 in. [96%] and Sierra Ancha with 4.77 in. [71%], had their previous records set in the August 1951 storm (section 2.2.2). A new daily record of 6.20 in. [118%] was established at Payson R.S., where records began prior to 1900.

Another downpour also occurred on September 5, at Bug Point, Utah at an elevation of 6,530 ft (see mass curve on fig. 2.7) giving 6.0 in. in 12 hr [257% of the 100-yr 12-hr value].

2.2.1.3 Importance of Mid-Latitude Influence. The outstanding feature of the September 1970 storm is the strong interaction of tropical cyclone related moisture with an unusually strong and cold mid-latitude low-pressure trough or low-pressure system.

The intense 500-mb Low that developed within the upper trough and dipped southeastward into Nevada was one of the major factors in causing the intense rainfall over central Arizona where the tongue of tropical cyclone related moisture was crossing the State. In order to supplement extreme temperature summaries already available and to quantitatively evaluate the severity of the September 1970 situation, 500-mb charts were surveyed for a 10-yr period (1961-1970) that included the 1970 storm. All cases for either August or September involving closed circulations (Lows) at 500 mb over or in the vicinity of the Southwestern States were noted and evaluated.

The 9 cases found in this survey (all in September) are tabulated in table 2.2 which also lists the height of the innermost closed isoline (a measure of intensity of circulation on the 500-mb chart) and the closed isotherm with the lowest temperature.

From table 2.2 we note that only two cases occurred earlier in the season than the September 1970 case and both of these (1961 and 1964) had the cold air centered farther north than the center in the 1970 storm. In addition to the

*Value given in brackets is percent of 100-yr 24-hr rainfall. Unless otherwise noted, this format will apply to other discussions of rainfall amounts in this chapter.

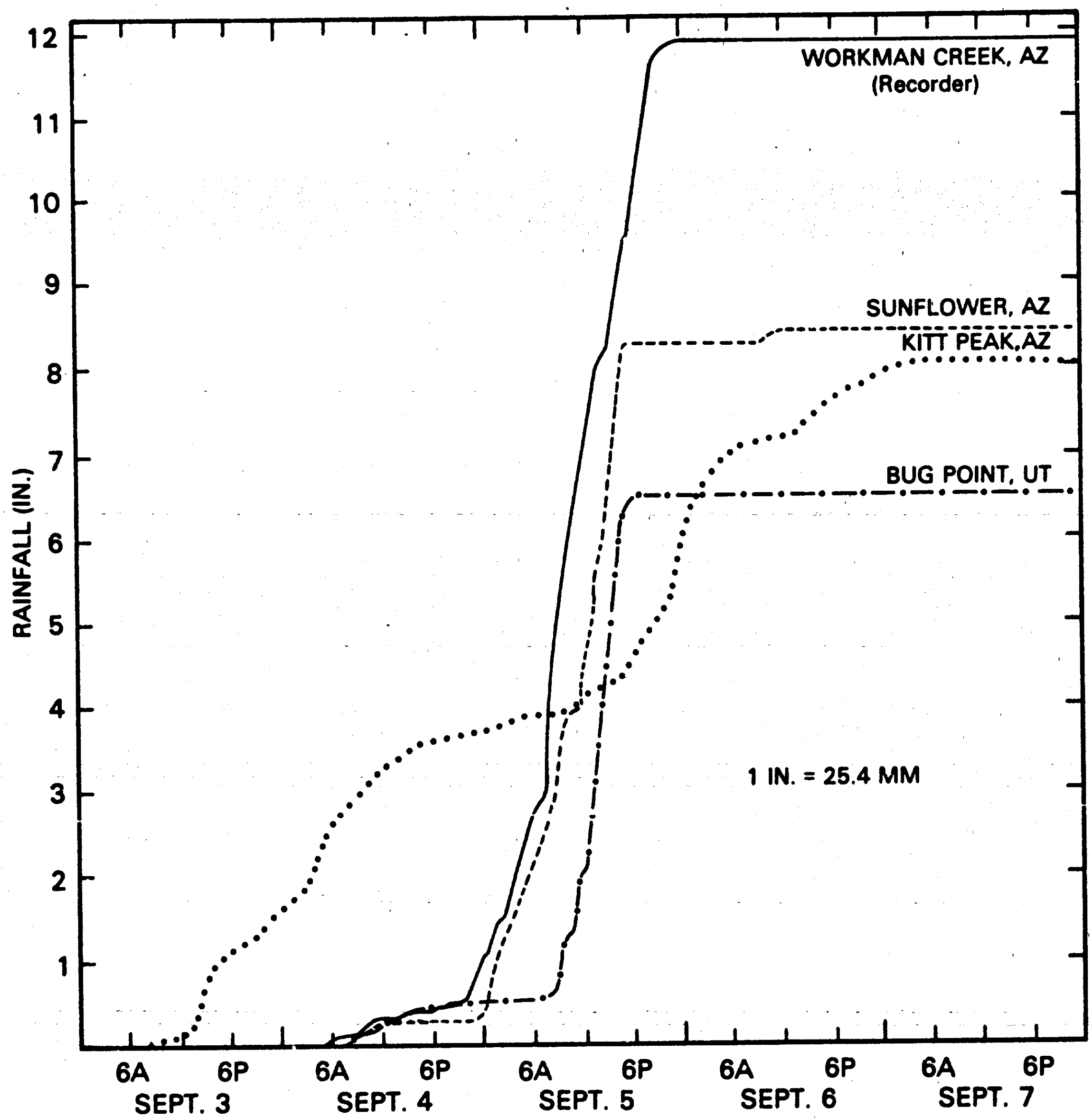


Figure 2.7.--Mass curves of rainfall at selected stations for storm of September 2-7, 1970.

early 1964 case, the September 1968 storm had a lower temperature, but again, this occurred at a higher latitude.

A study of record 500-mb low temperatures in and around the Southeast States was made by Ratner (1958). This study provides a basis for measuring extreme values. During September 17-19, 1971, the average temperatures were lower than the extremes cited by Ratner. A comparison can be made between the center of cold air in the September 1970 storm and record cold temperatures at 500 mb as shown in figure 2.8. In this figure, mean isotherms (°F) for the period September 17-19, 1971 are shown as solid lines and the -4°F closed isotherm for the September 1970 situation by the dashed line. The severity of the September 1970 air at 500 mb can be judged as near record low levels for this time period and location.

Table 2.2.—Record closed 500-mb Lows in September over the Southwestern States (1961-1970)

Date	Height of innermost isoline (ft)	Lowest isotherm (°F)	General location of 500-mb Low
9/04/61	18,000	5	Colorado
9/18/61	18,000	5	N. Nevada
9/01/64	18,300	-13	N. California
9/22/64	18,300	-4	N. Arizona
9/14/66	18,500	-4	N. Nevada
9/19/66	18.500	-4	Off S. Calif.
9/27/66	18,900	14	W. Arizona
9/21/68	18,100	-13	Utah-Idaho border
9/06/70	18,200	-4	S. Nevada

2.2.2 August 26-29, 1951

The track of this storm (fig. 2.2) was more northerly than the September 1970 storm. Many stations in the August 1951 storm had record rainfalls for durations of up to 3 days. This contrasts with the September 1970 storm where the rainfalls for durations longer than 1 day were less important.

The August 1951 tropical cyclone first intensified as it moved on a northwesterly then northeasterly track off the Baja California coast from August 26 to 28, 1951. The remnants of the storm moved onshore August 29 and continued on a northeastward track across northern Baja California into the Colorado River Valley during the next 24 hrs.

2.2.2.1 Important Meteorological Features. The stage was set for the August 1951 storm rainfall since shower activity had already occurred in the area from August 19 to 25 leaving a residual of moisture. Surface and upper-air weather maps for the August 26-29, 1951 storm are shown in figures 2.9 and 2.10.

Following the development and intensification of the tropical cyclone on the 25th, the southward extension of a mid-latitude trough aloft off the California coast provided the necessary southerly component of wind for the continued transport of moisture well to the north of the storm center.

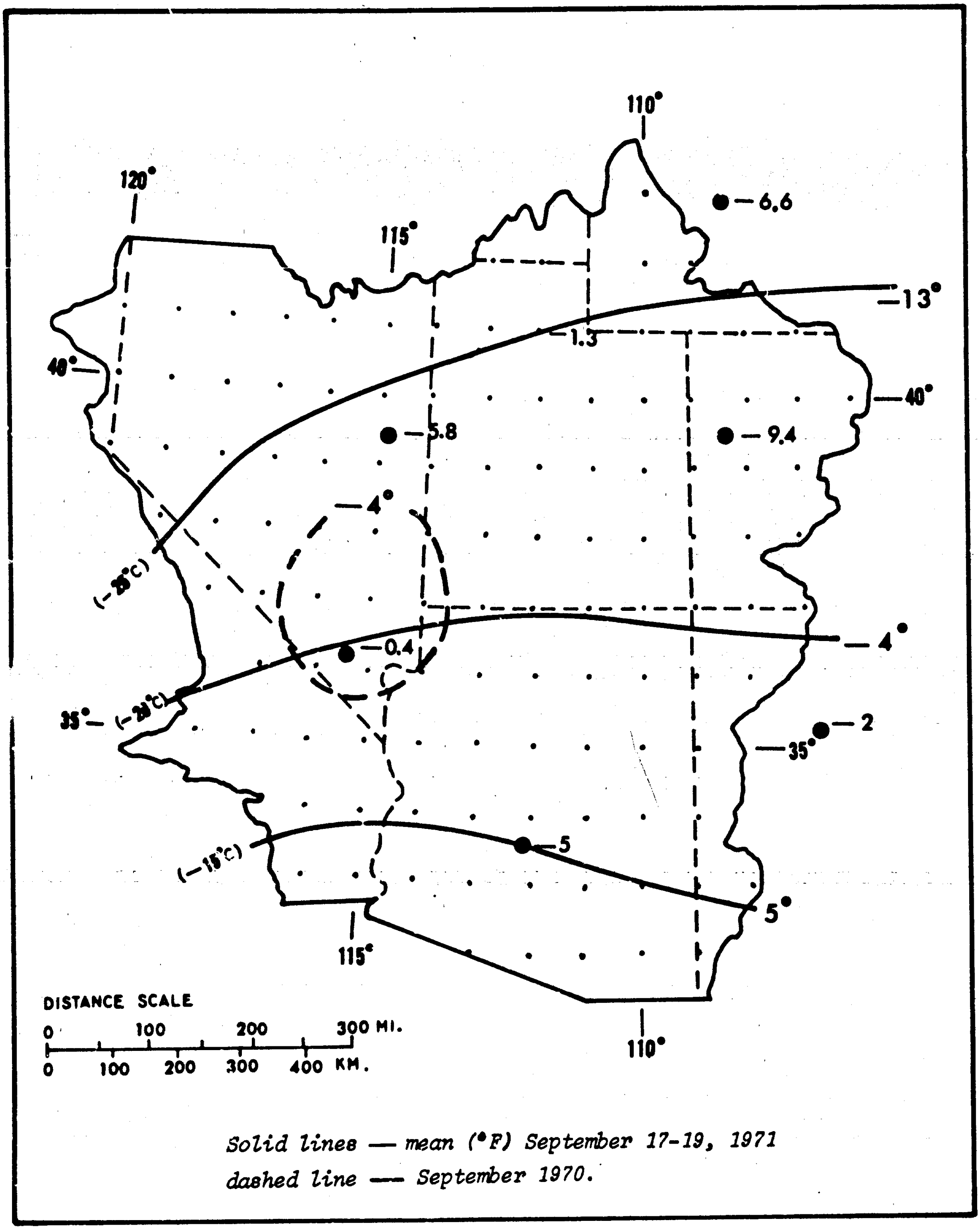
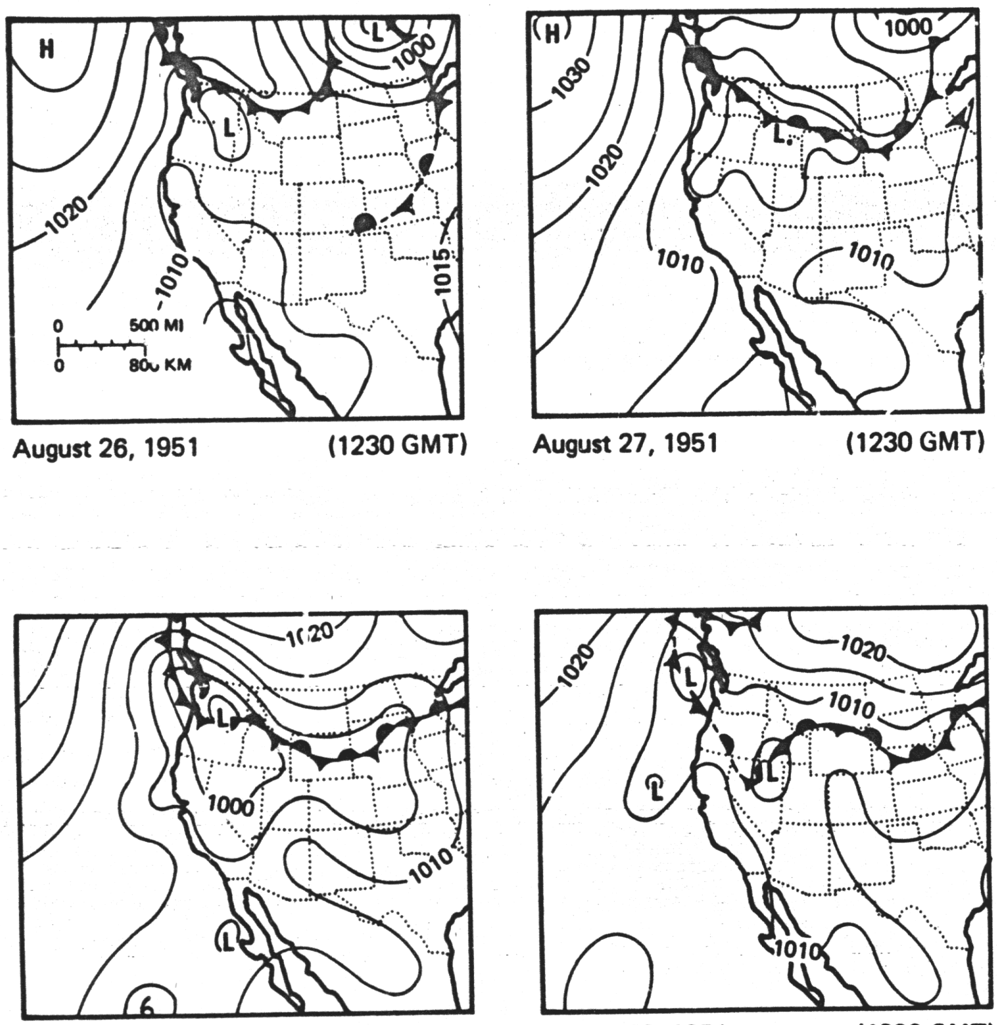


Figure 2.8.--Record 500-mb low temperatures for September.



August 26, 1951 (1230 GMT)
August 27, 1951 (1230 GMT)
August 28, 1951 (1230 GMT)
August 29, 1951 (1230 GMT)

Figure 2.9.--Surface weather maps for August 26-29, 1951.

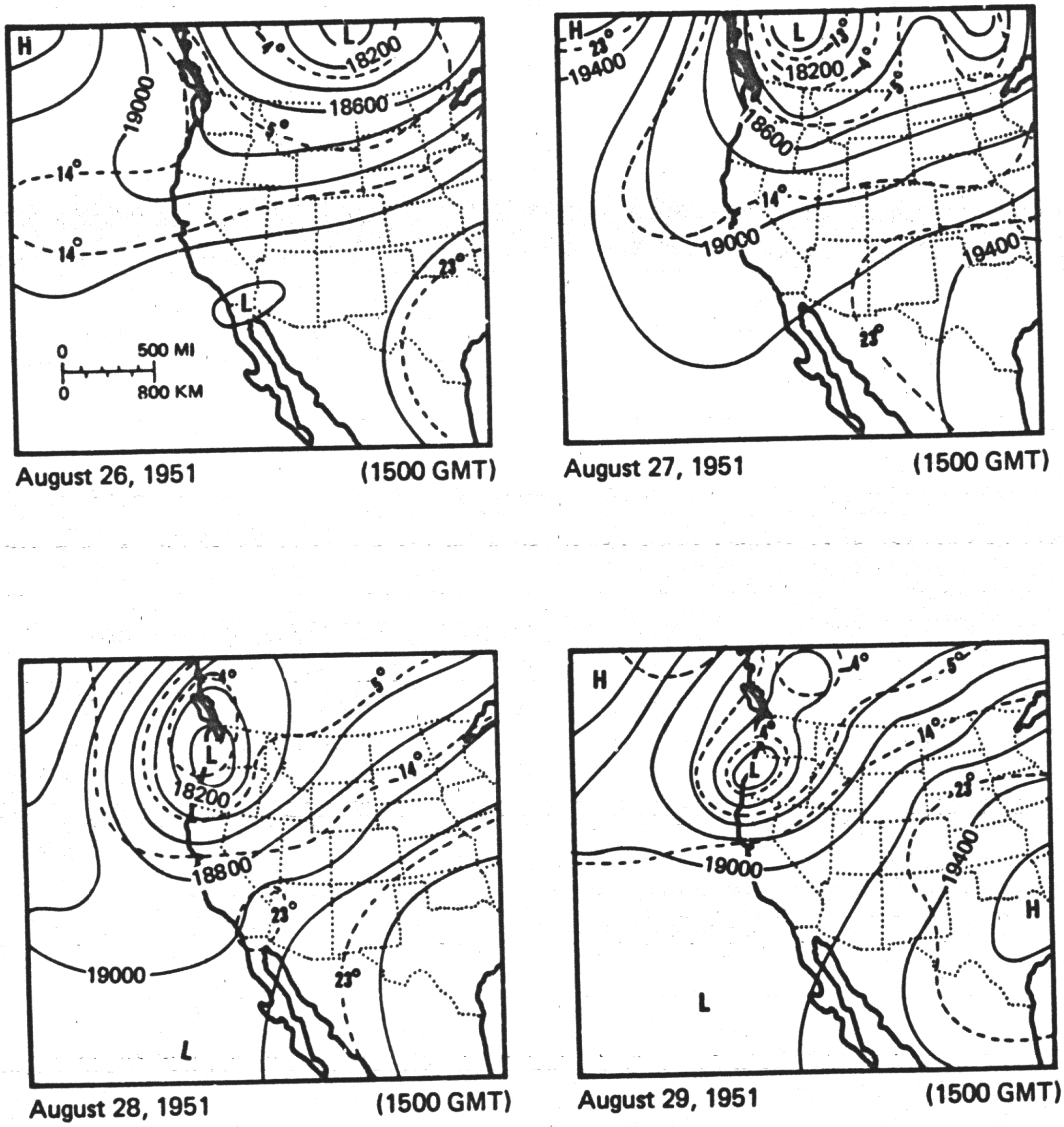
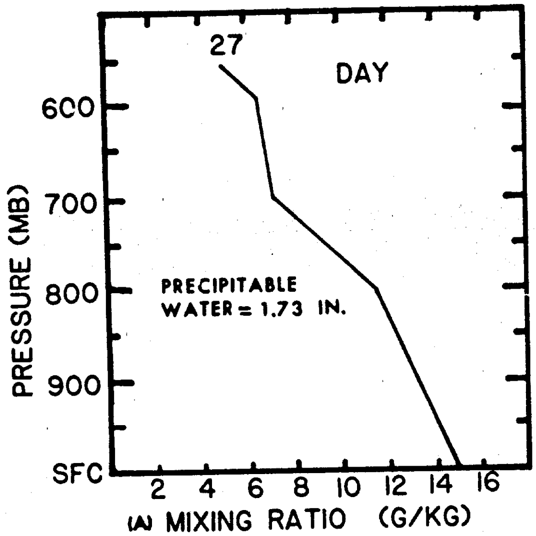
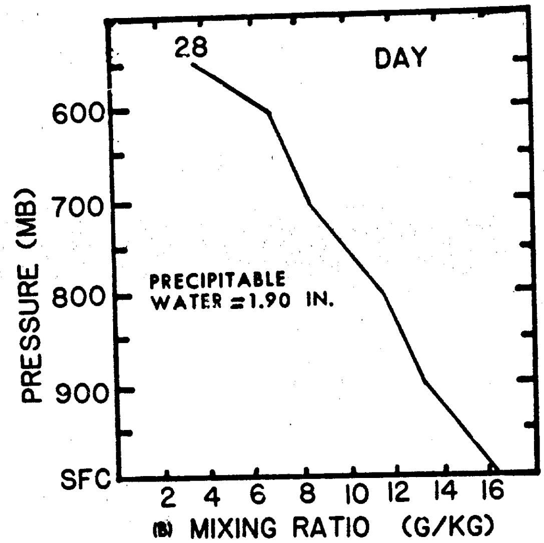


Figure 2.10.--500-mb charts for August 26-29, 1951.

With the tropical cyclone centered still far to the south, moisture increased substantially over Arizona on August 26 and 27, remaining at unseasonably high values until August 30. Precipitable water values (twice-a-day observations, surface to 500 mb) were determined for days of greatest rainfall. The highest precipitable water at Phoenix was 1.90 in. at 2000 MST on both August 27 and 28 (0300 GMT of 28th and 29th). These soundings are shown on figure 2.11. Mixing ratio, shown on figure 2.11, is a measure of atmospheric moisture in the air and





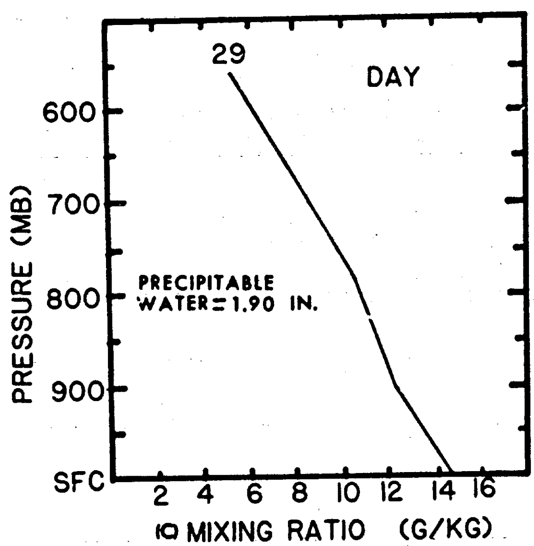


Figure 2.11.--Vertical profiles of mixing ratios on August 27-29, 1951 at Phoenix, Ariz. Metric units are customarily used to describe mixing ratio.

is defined as the mass of water vapor to the mass of dry air (in g/kg, we have chosen to leave these measurements in metric units which are normally used in meteorology). The value 1.90 in. is close to 2 standard deviations above the mean precipitable water for Phoenix for August (Lott 1976). The maximum precipitable water for August for Phoenix (Ho and Riedel 1979) was 2.02 in. at 2000 MST on August 20, 1955 (0300 GMT of 21st).

Figure 2.12 relates dew points (representing moisture) and winds (representing inflow) at the 850-mb and 700-mb levels at Phoenix during the August 1951 storm to 3-hr rains at Phoenix and Upper Parker Creek (Carr 1951). Although some pertinent data are missing (M), the combination of greater moisture with greater southwesterly inflow appears to be related to heavier overall rainfall. Also of interest in this figure, is the fact that the precipitation increase occurs almost simultaneously at both locations but continues over a longer period of time at the Upper Parker Creek site.

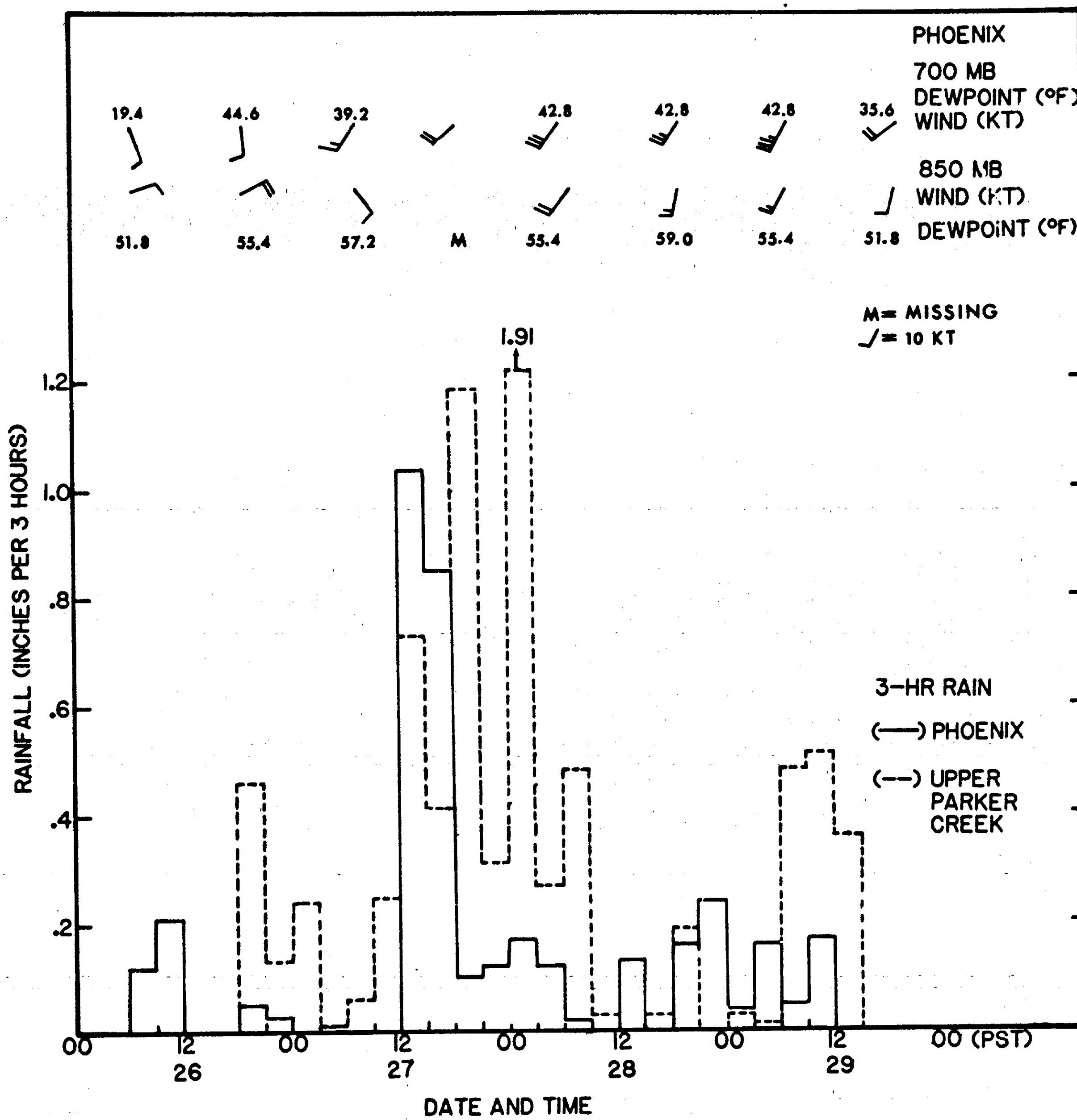


Figure 2.12.--Comparison of dew points and winds at Phoenix, Ariz. with 3-hr precipitation increments at Phoenix and Upper Parker Creek, Ariz., August 20-29, 1951.

2.2.2.2 Significant Rains. The storm isohyetal map for August 26-30, 1951 over Arizona is shown in figure 2.13. Phoenix (elev. 1,109 ft) received 4.18 in. [110%] of rain for the 4-day period. Similar amounts were observed to the southwest of Phoenix over generally nonorographic terrain, and represent convergence rainfall along the inflow track of maximum moisture. Thus, we conclude for this storm the rain at Phoenix primarily results from convergence activity. Almost half (1.9 in.) of the total-storm rainfall at Phoenix occurred during a 6-hr period centered about 1600 MST (2300 GMT). At Upper Parker Creek (elev.

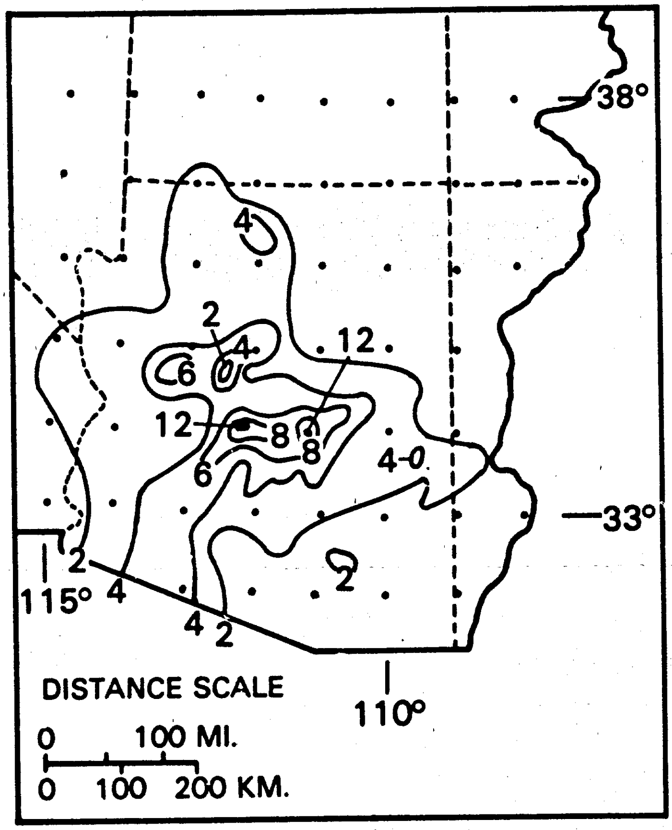


Figure 2.13.--Generalized isohyetal map for storm of August 26-30, 1951.

4,420 ft), heavy rains, 8.47 in. [121%] in 4 days, appear to come from three approxiimately 3-hr bursts that occur between 1300 MST (2000 GMT) on the 27th and 0400 MST (1100 GMT) on the 28th. These discontinuous short bursts of rain shown in figure 2.12 are typical of convective showers superimposed on the general level of orographic and convergence rain in the region of maximum rainfall shown in figure 2.13.

Mass curves of rainfall are shown in figure 2.14 for three stations (Crown King, Sunflower and Workman Creek) with the largest total rainfalls in this storm. Locations of these stations are shown in figure 2.1. Although isohyetal centers in figure 2.13 show mountain areas to be favored, heavy convergence rain was also an important feature of this storm.

2.2.3 September 4-7, 1939

This storm was noteworthy for having a track (fig. 2.2) that enabled it to bring unusually heavy rains to normally very dry nonmountainous regions of interior California and parts of west-central Arizona. The discussion of this and the following two storms show how tropical storm related events can produce large rain amounts well inland from the coast.

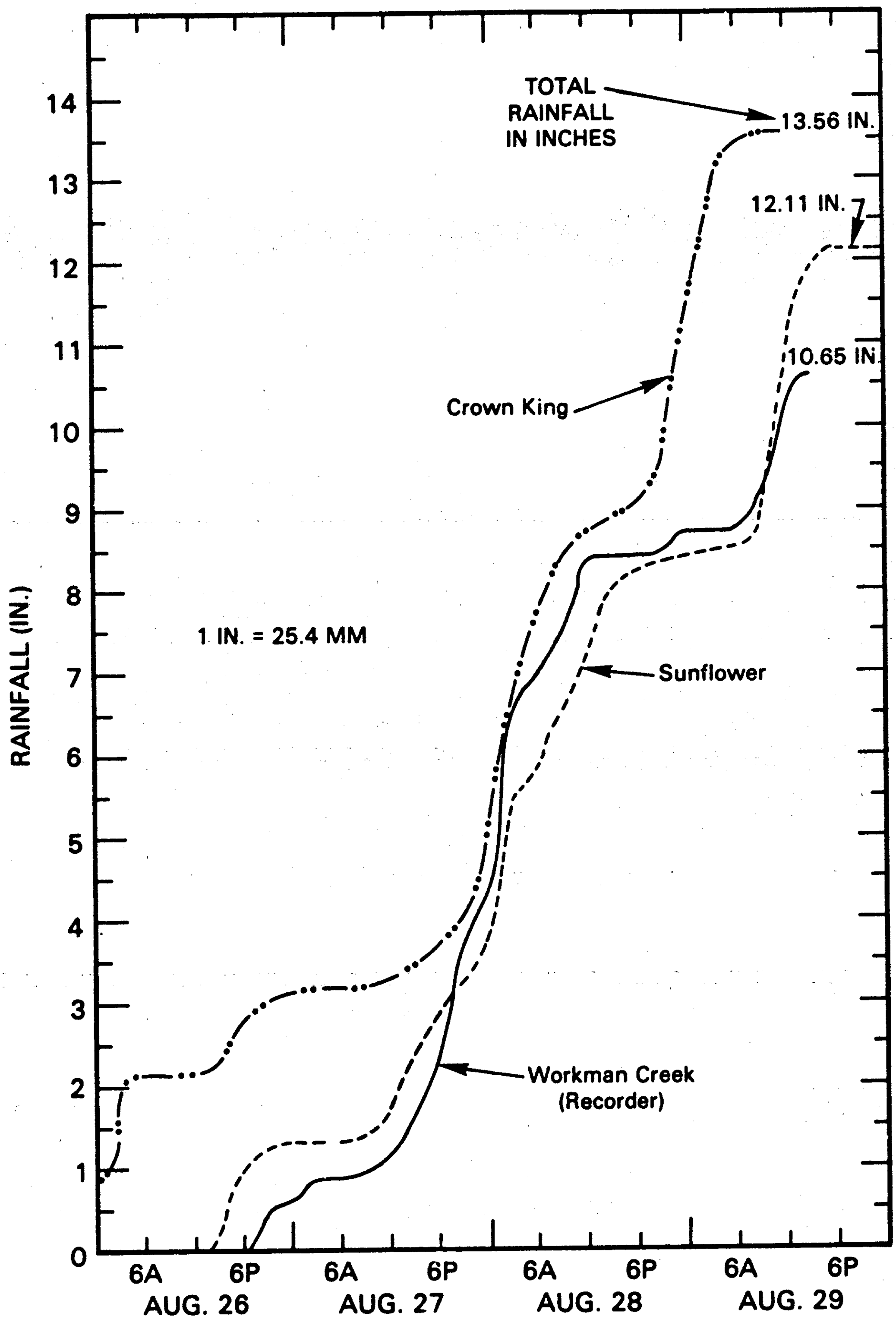
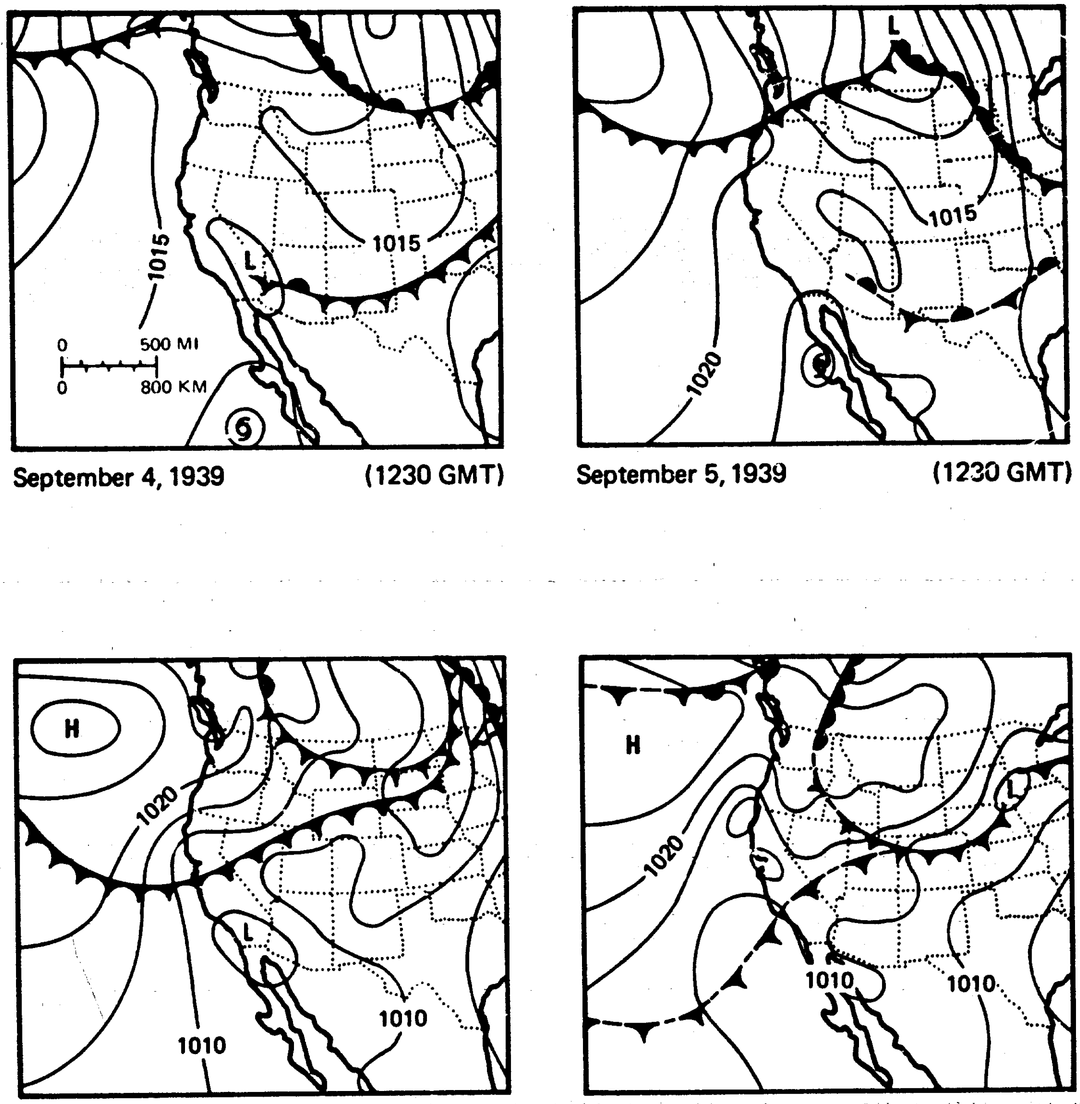


Figure 2.14.--Mass curves of rainfall at selected stations for storm of August 26-30, 1951.



September 4, 1939 (1230 GMT)

September 5, 1939 (1230 GMT)

September 6, 1939 (1230 GMT)

September 7, 1939 (1230 GMT)

Figure 2.15.--Surface weather maps for September 4-7, 1939.

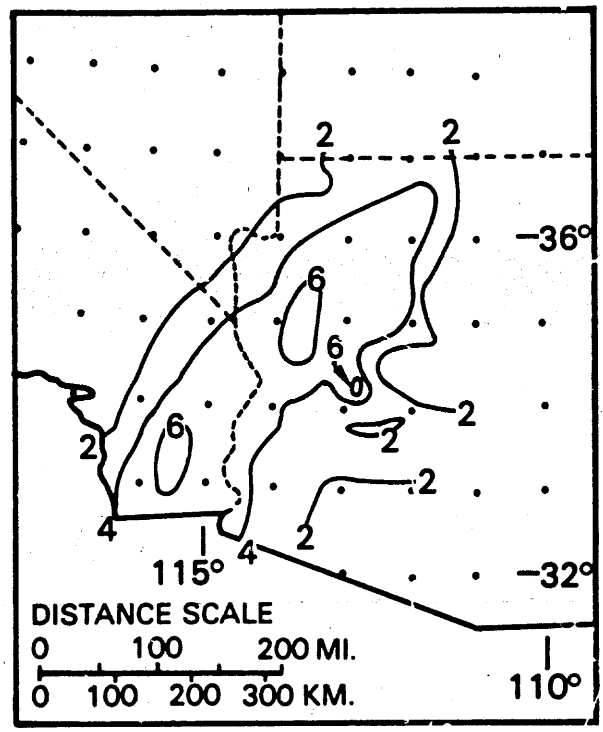


Figure 2.16.--Generalized isohyetal map for storm of September 4-7, 1939.

2.2.3.1 Important Meteorological Features. Surface weather maps are shown in figure 2.15. The two main synoptic scale features of this storm were a tropical cyclone that moved northward west of Baja California (see track in fig. 2.2), and a cold front that moved south and east across California that apparently helped to turn the remnants of the tropical cyclone to the northeast and across the coast.

The tropical cyclone disappeared as a discernable entity at the surface in southeastern California the morning of September 6. However, motion of a southeastward-moving mid-latitude front effectively utilized the moisture from the tropical cyclone and extended the precipitation well into northwestern Arizona as shown in figure 2.16.

2.2.3.2 Significant Rains. The rain was fairly general, following the storm track of the tropical cyclone's remnant circulation, in an elongated pattern oriented from southwest to northeast across southeastern California and western Arizona. Rain amounts showed less dependence on topography or elevation than in either the September 1970 or August 1951 storms. This is most evident on large detailed isohyetal charts (not shown).

Typical of many of the tropical cyclone related rains that affect the Southwestern States, the rain in Arizona began while the tropical Low was still far to the south. However, the heaviest rains at places like Needles and El Centro, Calif. were associated with the passage of the remnant tropical cyclone center on September 6. The rains across southeastern Utah, where several stations had 2.0 in. or more, were associated with the continued movement of the moisture after the morning of September 6. Rain exceeding 6 in. [143%] occurred in the Arizona mountains on both September 5 and 6, showing an orographic effect on these days.

2.2.4 October 4-5, 1925

In this storm, rain amounts in coastal and southeastern California were less than in the September 1939 storm just discussed. However, moderate to heavy rain was reported as far inland as northeastern Utah.

2.2.4.1 Important Meteorological Features. Figure 2.17 shows the surface weather maps for this storm. The upper-level trough or Low position (center positions shown in upper left-hand diagram in fig. 2.17) for this storm which predates upper air observations are estimated on the basis of relations of surface movements of Lows and troughs to upper-air Lows in more recent storms.* Until the morning of October 5, a tropical cyclone was moving slowly northward along the Baja California coast. A rapid increase in forward motion after that was apparently associated with a trough or Low aloft picking up the remnants of the tropical cyclone.

2.2.4.2 Significant Rains. An isohyetal chart for the October 1925 storm is shown in figure 2.18. Rain amounts were moderate along the western Arizona border, becoming slightly less in eastern Utah and Colorado. Although the rain occurred prior to midnight October 4 along the southern California coast, it did not begin until October 5 in Utah. The rain, as in the September 1939 storm, did not favor mountain stations. No hail or thunderstorms were reported within this isohyetal pattern. However, an isolated observation at Fresno, on the western periphery of the pattern, reported heavy hail on the 5th. Some examples of the larger total storm amounts and the corresponding percent of 100-yr 24-hr precipitation (Miller et al. 1973) are given in table 2.3.

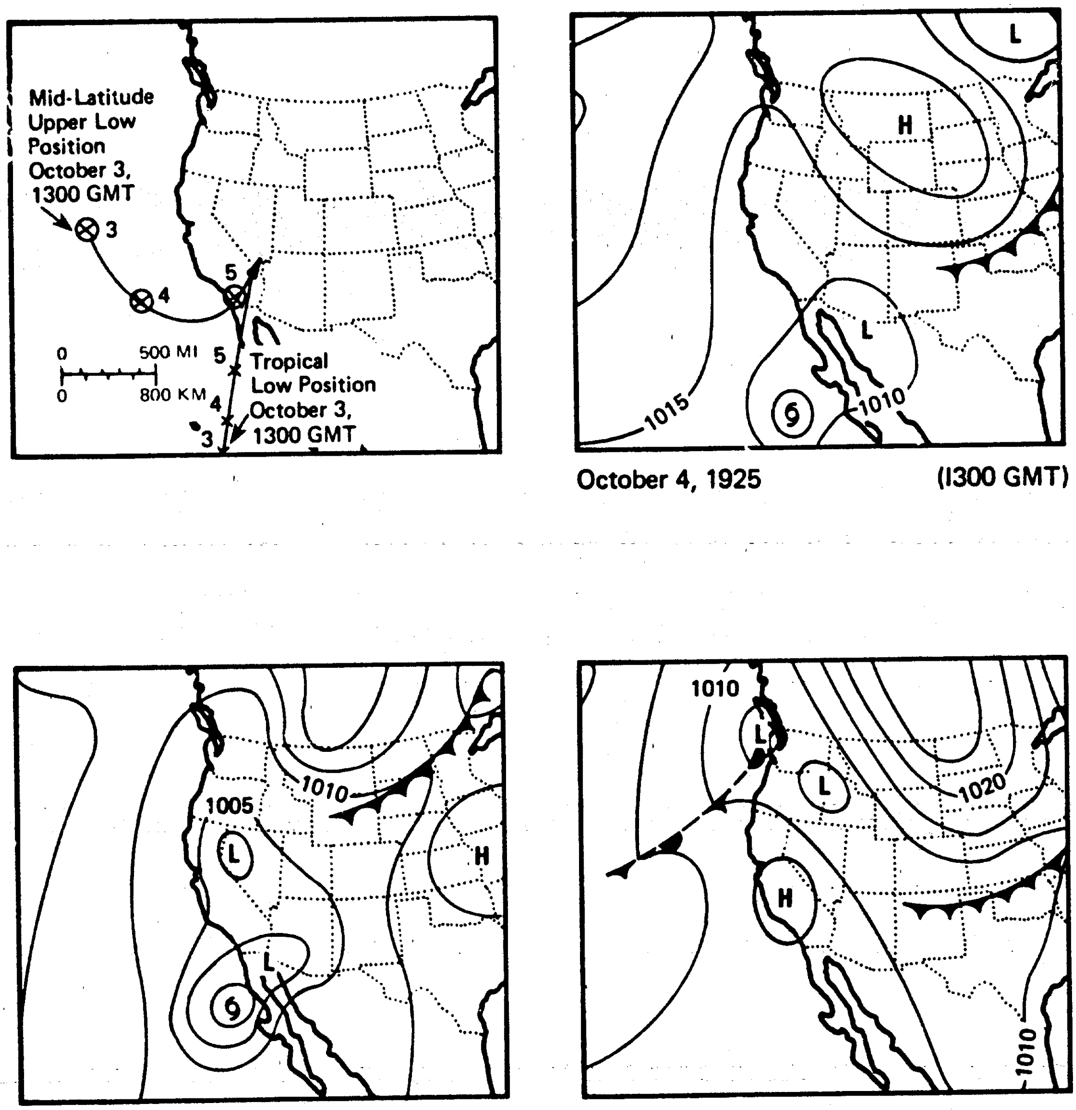
Table 2.3.--Precipitation at selected stations in October 4-5, 1925 storm

Station	Amount (in.)	Percent of 100-yr 24-hr rainfall
Needles, Calif.	2.4	67
Las Vegas, Nev.	1.9	66
Leeds, Utah (near)	2.8	100
Kanab, Utah	2.8	80
Sunnyside, Utah	2.9	97
Grand Junction, Colo.	1.8	72

2.2.5 October 4-5, 1911

A primary factor in this storm, as in the two storms just discussed, was the tropical storm that originated over the Pacific Ocean south of Baja California. This storm was unusual in that the heaviest rains were observed well inland as a result of rapid interaction with an active frontal system.

*Estimation of upper-air conditions has been made for a number of the synoptic events prior to December 1944 considered in this study and is based upon observed relations for more current storms.



October 4, 1925 (1300 GMT)

October 5, 1925 (1300 GMT)

October 6, 1925 (1300 GMT)

Figure 2.17.--Surface weather maps for October 4-6, 1925 and schematic diagram showing estimated upper level trough positions.

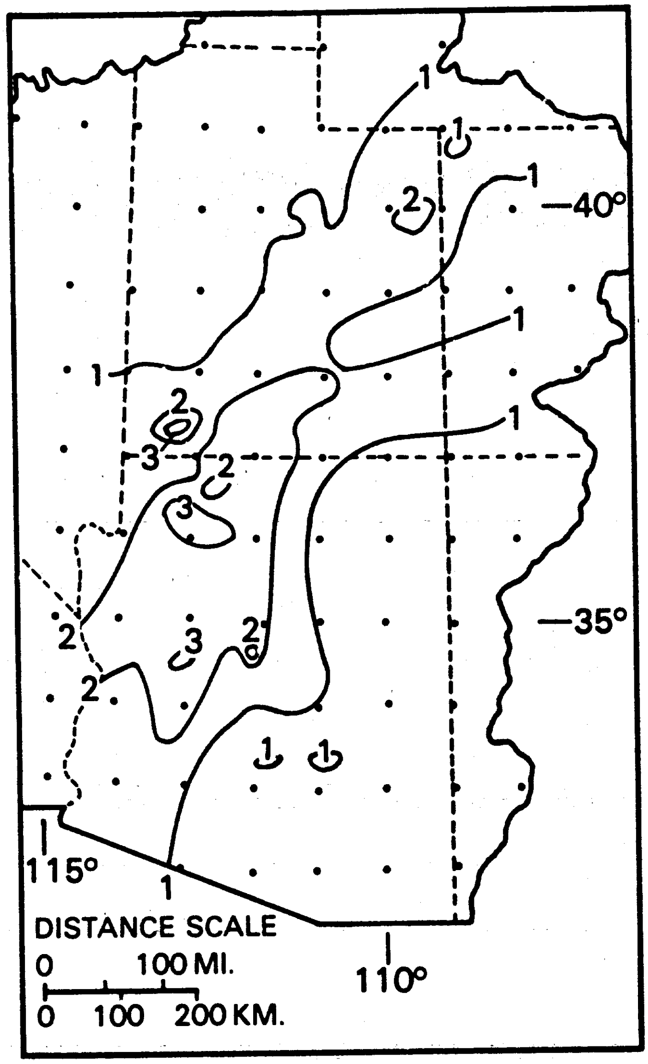


Figure 2.18.--Generalized isohyetal map for the storm of October 4-5, 1925.

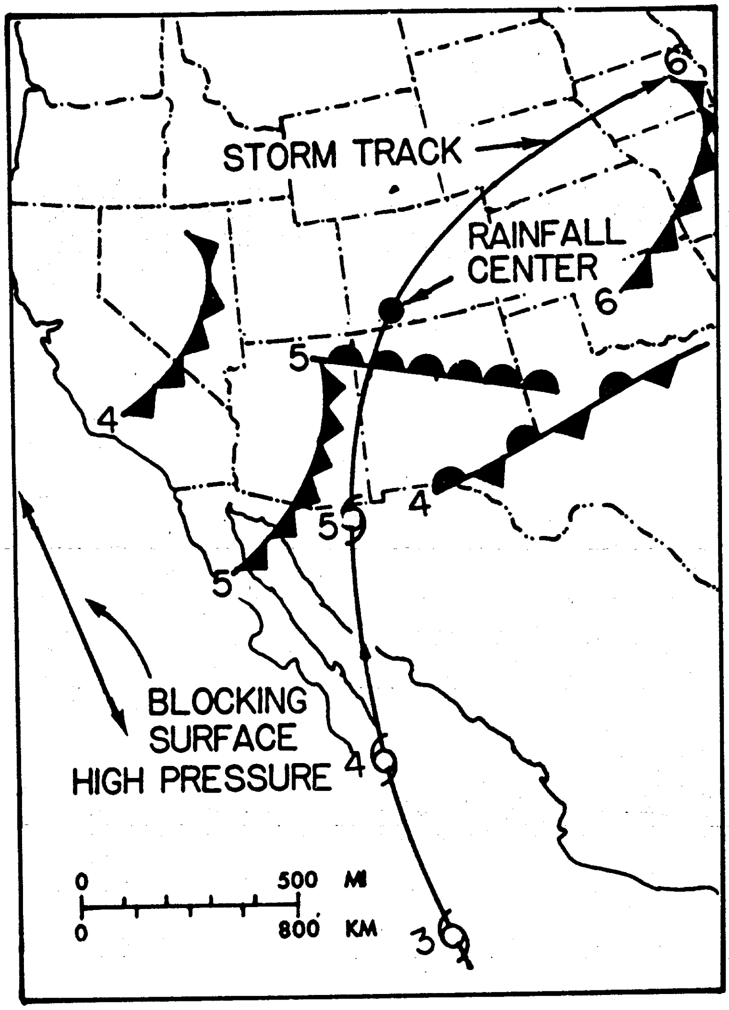


Figure 2.19.--Storm track and significant weather features for storm of October 4-6, 1911.

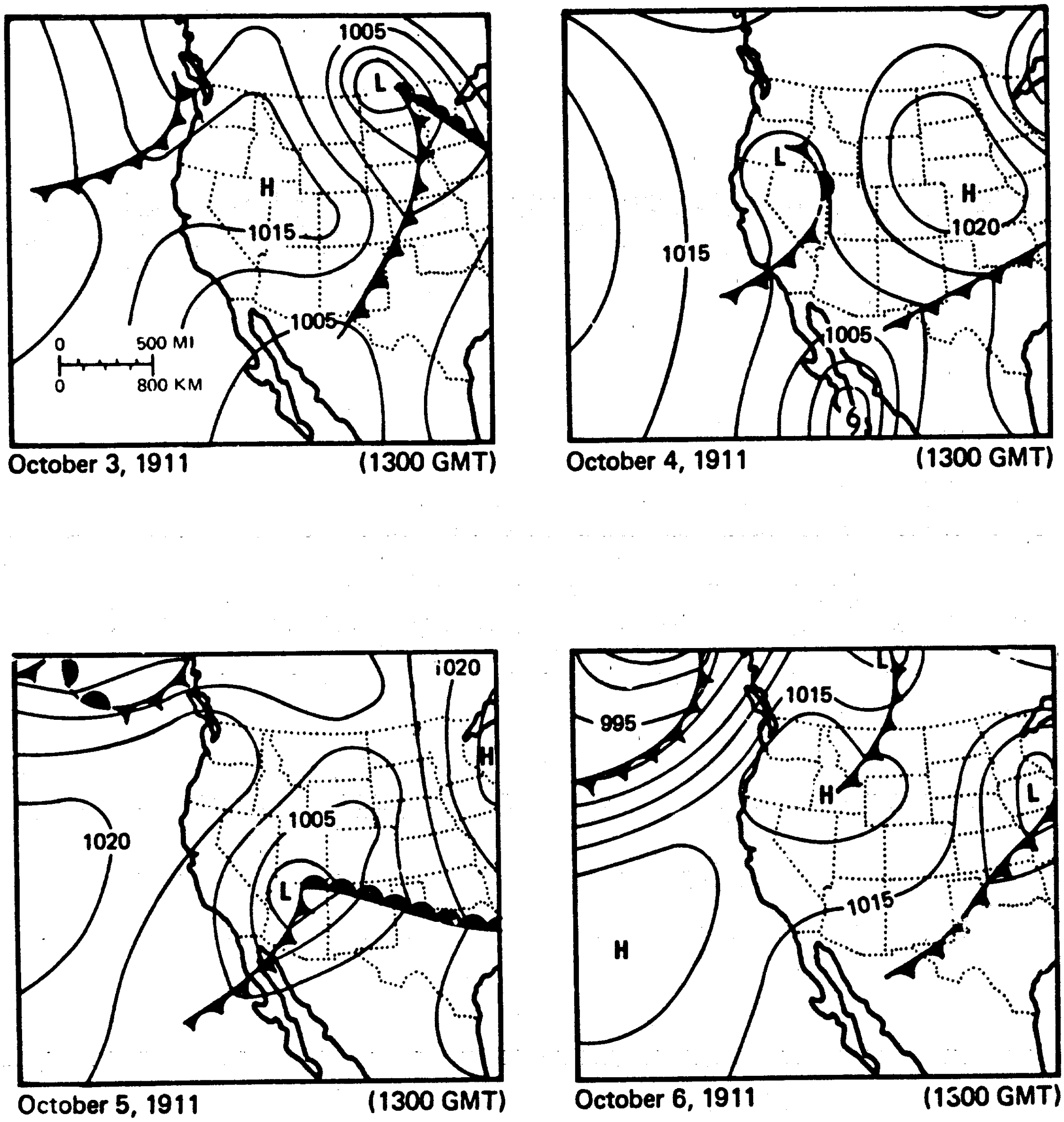


Figure 2.20.--Surface weather maps for October 3-6, 1911.

2.2.5.1 Important Meteorological Features. Figure 2.19 shows the track of this tropical cyclone with other features portrayed schematically, while figure 2.20 shows the surface weather maps. The main feature was the remnant moisture of a tropical cyclone (fig. 2.19) that moved first northward through the Gulf of California and southeastern Arizona and then, combined with an extratropical Low, northeastward through central Colorado. This track was aided by the southwestward movement into Arizona of a cold front oriented generally southwest to northeast. By noon of October 4, a warm moist flow extended from the tropical cyclone well into New Mexico. The rapid northeastward movement (fig. 2.19) of the tropical Low on October 4 and 5 and its merging with the deepening extratropical low-pressure system October 5 accounted for the concentration of rainfall observed. Southeast winds over the Colorado rain center on the morning of October 4 gave way to strong southerly winds following the warm front passage on the 5th. The winds veered to the west and northwest by the evening of October 5 as the Low moved rapidly northeastward. High moisture is indicated by the 1000-mb 0600 MST (1300 GMT) surface dew point temperatures of 71°F at Phoenix and Flagstaff, Ariz., Durango, Colo., and Santa Fe, N.M.

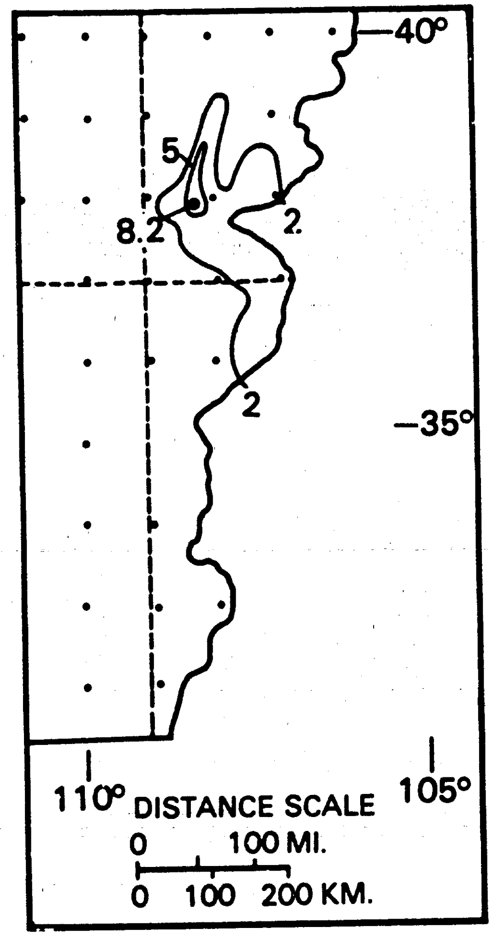


Figure 2.21.--Generalized isohyetal map for storm of October 4-5, 1911.

2.2.5.2 Signficant Rains. The period of heavy rain lasted about 24 hours, beginning during the afternoon of October 4, with the heaviest falls during the night. Precipitation was heaviest on the steep upslope areas of the San Juan mountains that were open to a strong, moist, southerly flow with a low upwind barrier nearby. Figure 2.21 shows an isohyetal map of the rain area of 2 in. or more over Colorado and New Mexico west of the Continental Divide. Highest recorded rainfall was 8.2 in. at Gladstone, Colo. [164%] (50 mi north of Durango), at an elevation of 10,800 ft. Here, steep slopes rise above Gladstone in all directions except to the southsoutheast. This storm demonstrates that tropical cyclone moisture interacting with mid-latitude affects can result in heavy rain far inland, and at relatively high elevations under optimum exposure.

2.2.6 September 23-26, 1939

This is one of the two tropical storms within the region that in addition to producing significant precipitation over an area of several hundred square miles produced some intense rainfall over a relatively small area. At Indio, Calif., the September 24, 1929 total rainfall was measured by the Weather Bureau observer as 6.45 in. [306% of 100-yr 6-hr rain] in the 6-hr period between 0500 and 1100 PST (1300-1900 GMT). The total storm precipitation at Indio during September 23-26 was 6.78 in.

Pyke (1975a) made a study of the 3-hr storm and concluded that the September 24, 1939 storm was more than merely a local convective thunderstorm. He suggests that the Indio rain may have been related to a surge of moisture that moved northward from the Gulf of California ahead of the center of the tropical cyclone. Once this surge progressed northward and encountered a narrowing valley, the result was the efficient use of the moisture through a combination of orographic and convergence lifting, mountain vs. valley circulation, and convection along heated east-facing slopes. Figure 2.22 shows the total storm isohyetal pattern (Gatewood 1945).

The tropical cyclone crossed the southern California coast near Los Angeles on the 25th and brought most of the general-storm rains to the region during the 24th to 26th. Heavy 3-day rainfalls exceeding 11 in. were observed in the mountains surrounding Los Angeles as the storm was generally caught by the upper-level trough and moved off toward the northeast.

2.2.7 July 31 - August 2, 1906

At Casa Grande Ruins on August 1, 1906 the cooperative observer's record shows 5.40 in. of rain fell between 0100 and 0730 MST (0800 and 1430 GMT). This was the heaviest shower of many reported during the period between the evening of July 31st and the afternoon of August 2nd, throughout much of the central and southeastern portions of Arizona.

Figure 2.23 shows surface weather maps covering the period of this storm. A thermal Low pressure center developed over Sonora, Mexico, on July 30. By the 31st, the system had expanded to the north and was absorbed by a cold frontal system that moved into the Southwest on August 1st. Not shown on July 30th is the position of an apparent tropical cyclone at latitude 15°N off the western coast of Mexico. It is presumed that the shift northward of the Sonoran Low was indicative of a surge of moisture through the Gulf of California and into south-central Arizona by the 1st. The moisture surge may have had its origin in the unstable air ahead of the weakening tropical disturbance. Between the 1st and the 2nd, the surge of moisture encountered the trailing end of the cold frontal system resulting in release of extensive heavy showers through the south-facing slopes of the Mogollon Rim. No precipitation was reported west of the 114th meridian from this storm.

2.3 Extratropical Storms

We have classified extratropical storms that are important to the Southwest States into six groups as follows:

2.3.1 Storm Classification

a. Cut-off Lows - The phrase cut-off Lows refers to the 500-mb circulation where a low-pressure system separates from the main trough. Cut-off Lows generally move slowly. In general, these storms involve surface low-pressure systems that initially move in a southeasterly direction into the Southwestern States. The low-pressure system becomes organized near the latitude of northern California and is

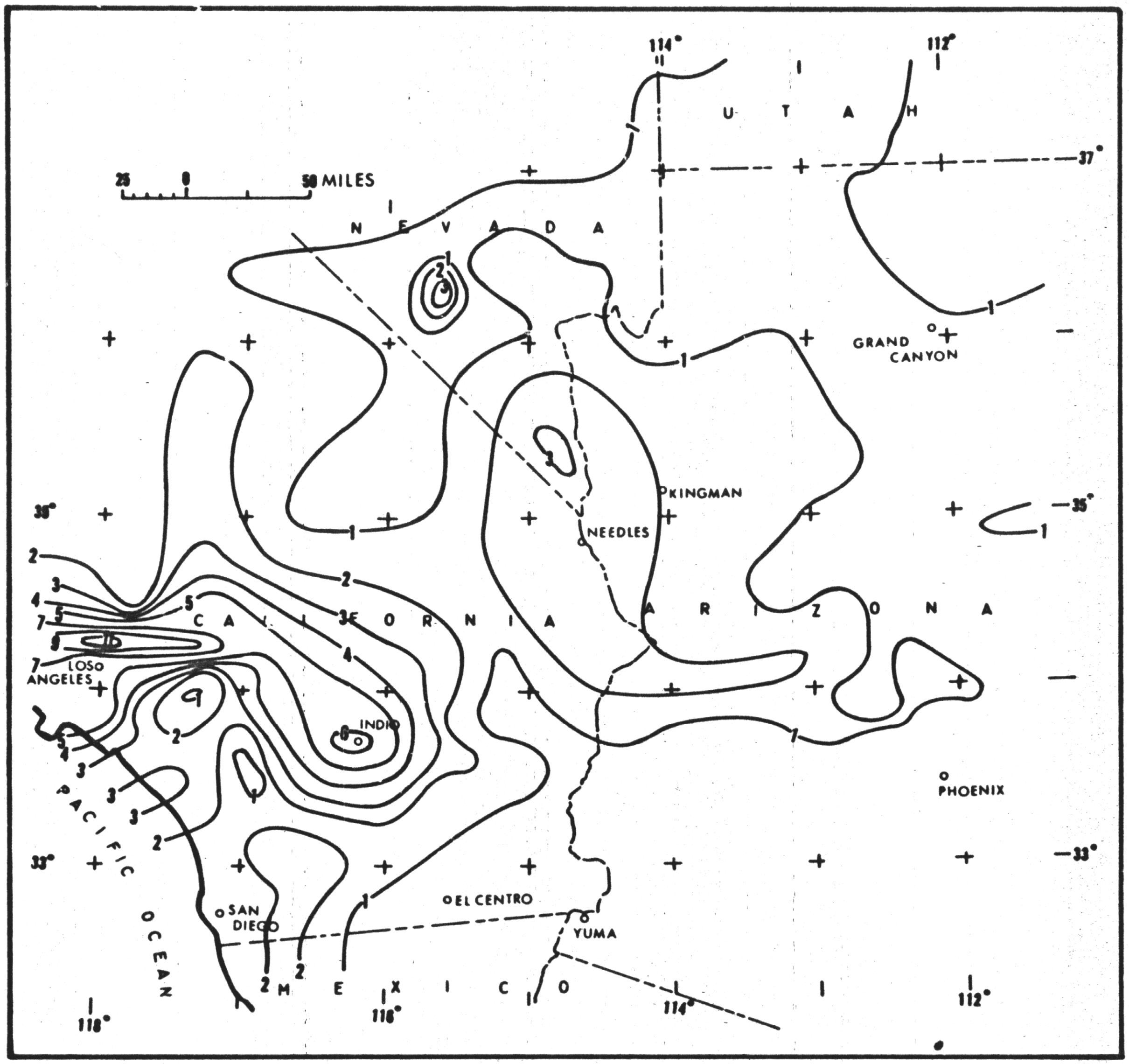


Figure 2.22 Generalized isohyetal map for storm of September 13-15, 1939.

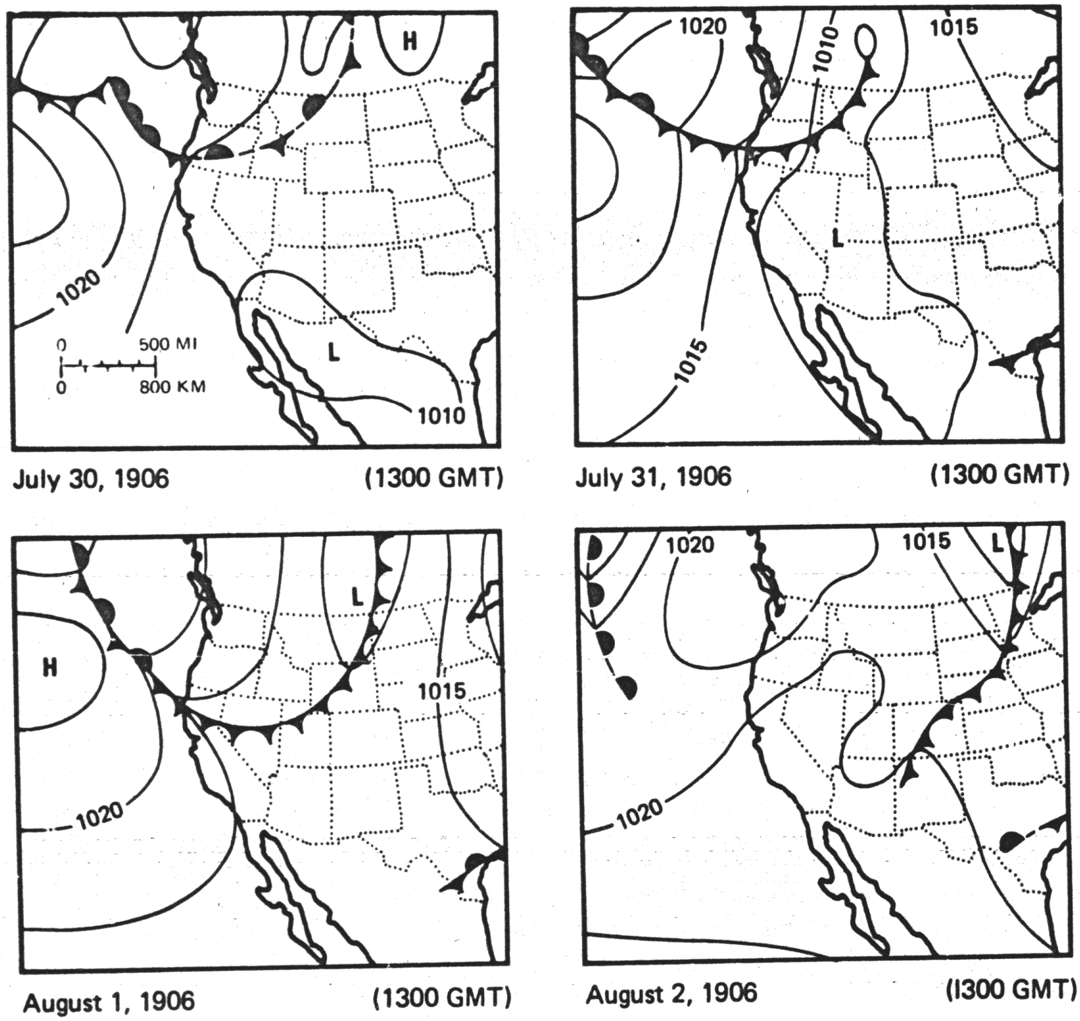


Figure 2.23.--Surface weather maps for July 30 to August 2, 1906.

surrounded by high pressure in a crescent-shaped pattern, leaving the south side open as supply. Cut-off Lows may form or intensify in the great basin and tend to drift slowly toward the southeast. The upper left diagram in figure 2.24 is a schematic drawing of this storm type.

b. High-latitude Lows - This group is quite similar to the first group except that a break appears in the surface high pressure ridge to the north or northwest. This permits the surface low-pressure system to move into the Southwest from a location farther to the north than in group a. The number of Lows or storms in this group usually ranges from 1 to 3. They tend to move faster than those in the first group. Figure 2.24 shows a schematic of this storm type in the upper right diagram.

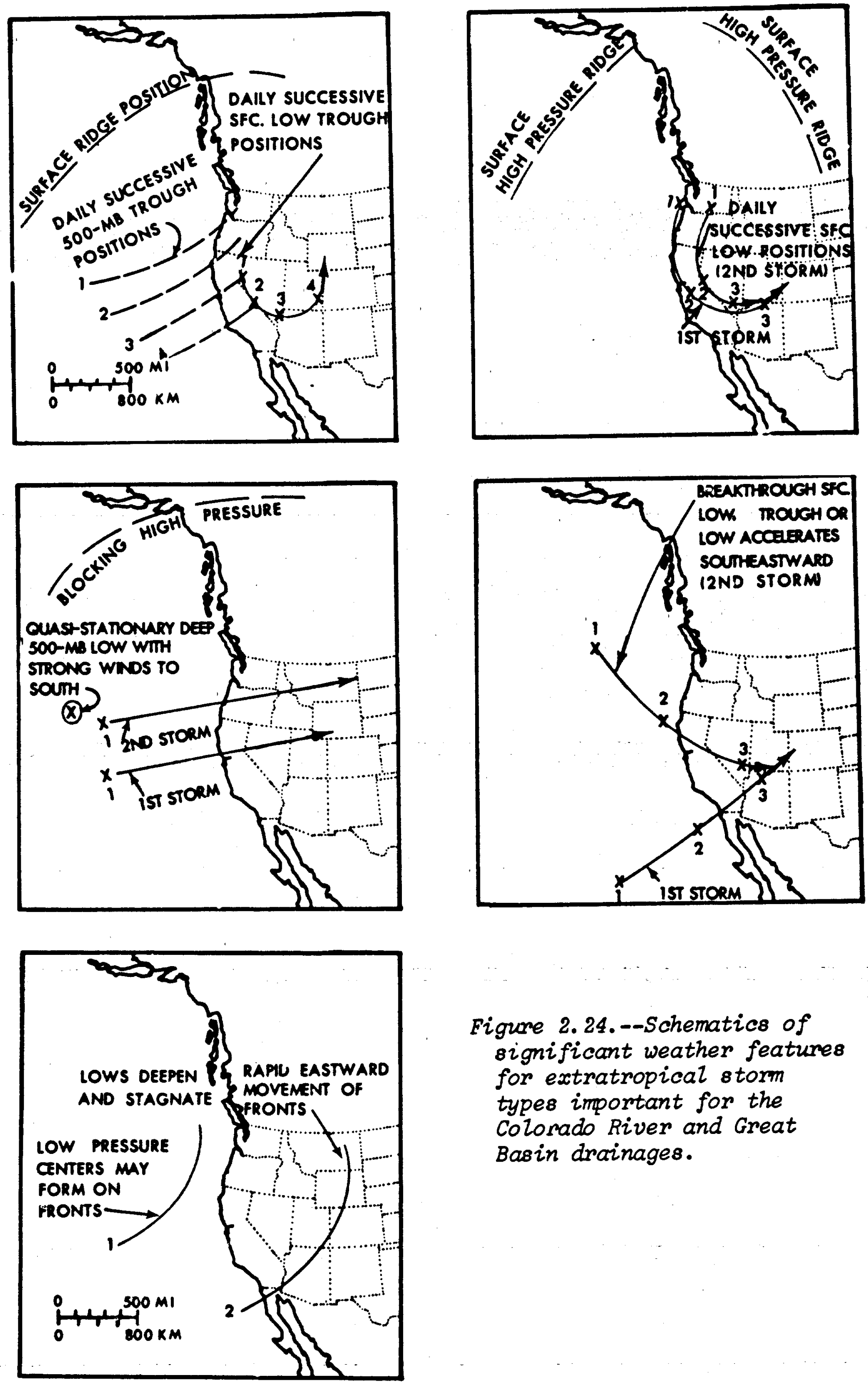


Figure 2.24.--Schematics of significant weather features for extratropical storm types important for the Colorado River and Great Basin drainages.

c. Low-latitude Lows - This group generally involves movement of surface Lows into the region from the Southwest. Frequently, however, organization of a Low over the Southwest is an important characteristic. A blocking surface high-pressure ridge extends across to the north. A determining common feature of the low-latitude storm group is offshore blocking at high- and mid-latitudes, forcing the storm to enter along low-latitude tracks. Aloft, a deep quasi-stationary Low is present over the Pacific, at about the latitude of northern California. Figure 2.24 shows a schematic of this type in the middle left panel.

d. Low-latitude Lows with breakthrough - This group is similar to group c, except that there is only partial blocking by high pressure to the north. This allows passage of secondary fronts or surface low-pressure systems into the Southwest in a storm sequence. The sequence of events begins with a surface Low approaching from the southwest at about the latitude of California. It is followed by a southeast-eastward moving Low breaking through the Gulf of Alaska ridge and moving into the Arizona-Utah-Nevada region. Figure 2.24 shows a schematic of this type at the middle right panel.

e. Mid-latitude Lows - These Lows move into the study area from the west. Strong westerly flow aloft (i.e., high zonal index) promotes rapid west-to-east motion of occluded fronts at mid-latitudes. This usually results in repeated periods of precipitation with only short intervals between with lesser or no rain. Usually, mid-latitude Lows are also characterized by orographic precipitation amounts over the central and northern Arizona mountains. The fast motion of individual fronts or Lows in this group makes it difficult to prolong precipitation over a fixed region. Hence, the number of storms contributing significant rain in this group are small as special conditions are needed to concentrate the rainfall. Figure 2.24 shows a schematic of this group in the lower left panel.

f. Lows using the Gulf of Mexico moisture - This group is of importance for rainfall east of the Continental Divide where low-level moisture is drawn primarily from the Gulf of Mexico. For our study area, this group is of consequence only where there is enough of an opening in the Continental Divide to allow greater rainfall potential to enter the region from the east side of the Divide. In other words, the opening in the Divide produces a lower barrier to moisture than the barrier effect on winds from a Pacific moisture source.

Subsequent sections beginning with 2.3.2 will involve discussions of individual storms that represent examples of each of the groups just described.

2.3.2 Cut-Off Lows

Two significant storms in this group are those of October 27-29, 1946, and November 26-27, 1967.

2.3.2.1 October 27-29, 1946. This storm is included as an example of a storm that brought heavy rains into Nevada rather than concentrating in the mountains of Arizona. Figure 2.25 shows surface weather maps for this storm period. High pressure persisted well off the coast of the Pacific Northwest as deepening of a Low over Nevada and Utah took place on October 26. There was little surface movement of the Low until October 28 when it was apparently picked up by a deeper upper-level trough (charts not shown) that moved southeastward and affected the area. Low-level moisture inflow from the south occurred during the slow movement of the Low through southern Nevada. Often characteristic of the cut-off Low type, the surface weather maps show that the Low organized over the study region. Some large rainfall amounts for this storm are shown in table 2.4.

Table 2.4.--Precipitation at selected stations in October 27-29, 1946 storm

Station	Amount (in.)	Duration	Percent of 100-yr 24-hr rainfall
Beaver Dam State Pk., Nev.	3.0	6 hr	86
	7.5	1 day	214
Caliente, Nev.	2.1	1 day	70
	2.8	3 days	93

2.3.2.2 November 24-27, 1967. At 500 mb, (fig. 2.26) a cut-off Low was centered about 500 mi southwest of San Diego at 0500 MST (1200 GMT) on November 25. By 0500 MST (1200 GMT) of November 27, the Low had moved over land and was decreasing rapidly in intensity. Surface weather maps (fig. 2.27) show that a quasi-stationary front became established by 0500 MST (1200 GMT) on November 26 between cool, dry continental air north of a line from southern California and Nevada into central Colorado and warm, moist maritime tropical air to the south. During the following 24 hours the front moved southward to a more east-west position extending from near Los Angeles to southern New Mexico. This brought it just to the north of the location where the heaviest rain occurred south of Yuma, Ariz. at San Luis, Mexico (figure 2.1).

Low-level moisture in the vicinity of the mouth of the Colorado River along with unstable air led to shower activity beginning about 0800 MST (1500 GMT) on November 26. The region of showers increased in size, and numerous thunderstorms were reported at San Luis by 1700 MST on November 26 (0000 GMT on November 27). Three hours later, moderate, continuous rain was reported at Yuma, Ariz. and at Blythe, Calif., with lighter rain at San Diego, Calif. In the next 3 hours the rain had ceased, leaving only scattered showers that continued over the next 15 hours. Six-hourly analyses of rainfall (maps not shown) indicated that the rain center moved from near El Centro, Calif. at 0200 MST (0900 GMT) on November 26 to the vicinity of Gallup, N. M. at 1300 MST (2000 GMT) on November 27. The maximum 24-hr rainfall was 7.64 in. [100-yr 24-hr rainfall not available for Mexico] at San Luis, Mexico.

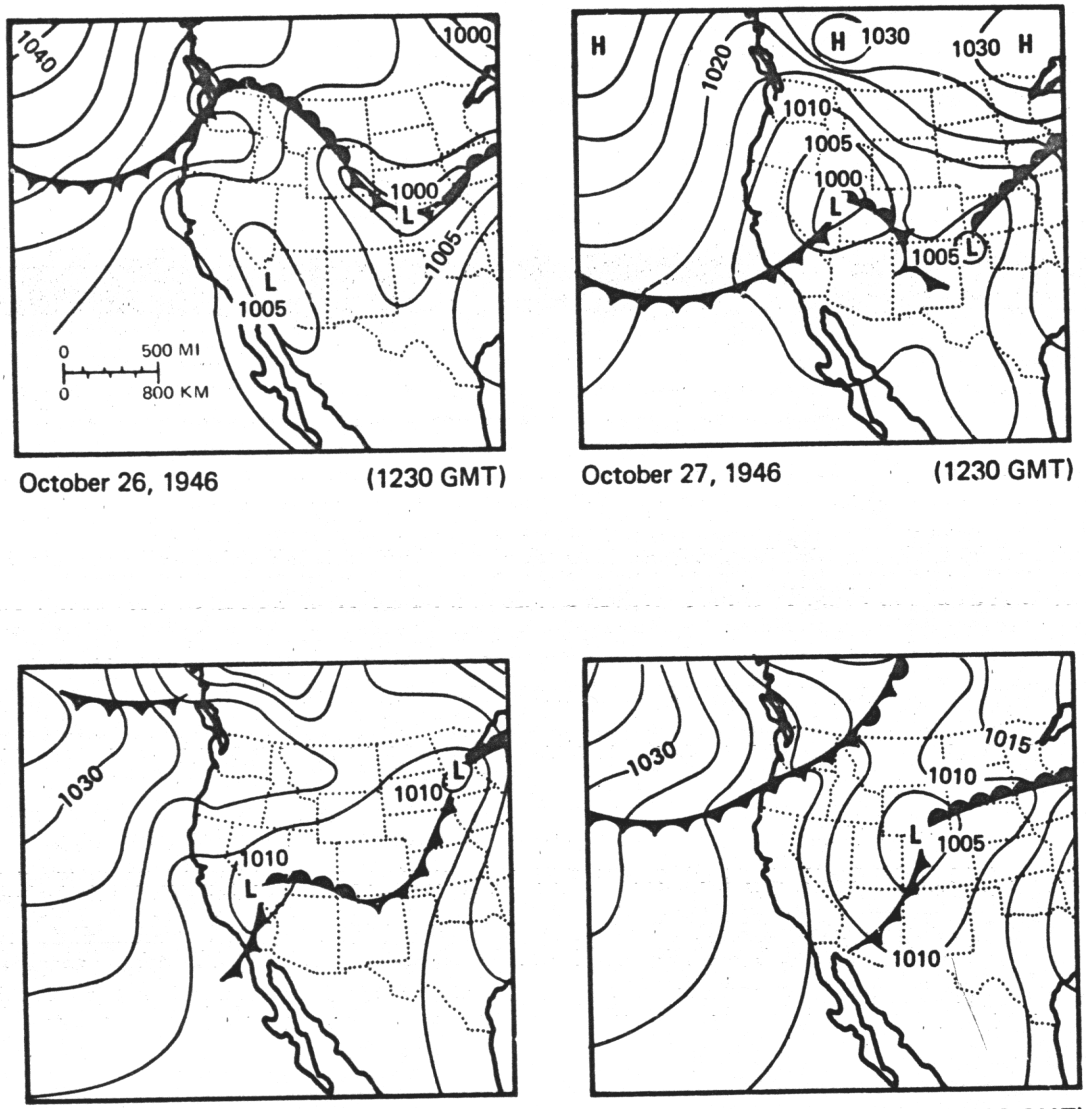


Figure 2.25.--Surface weather maps for October 26-29, 1946.

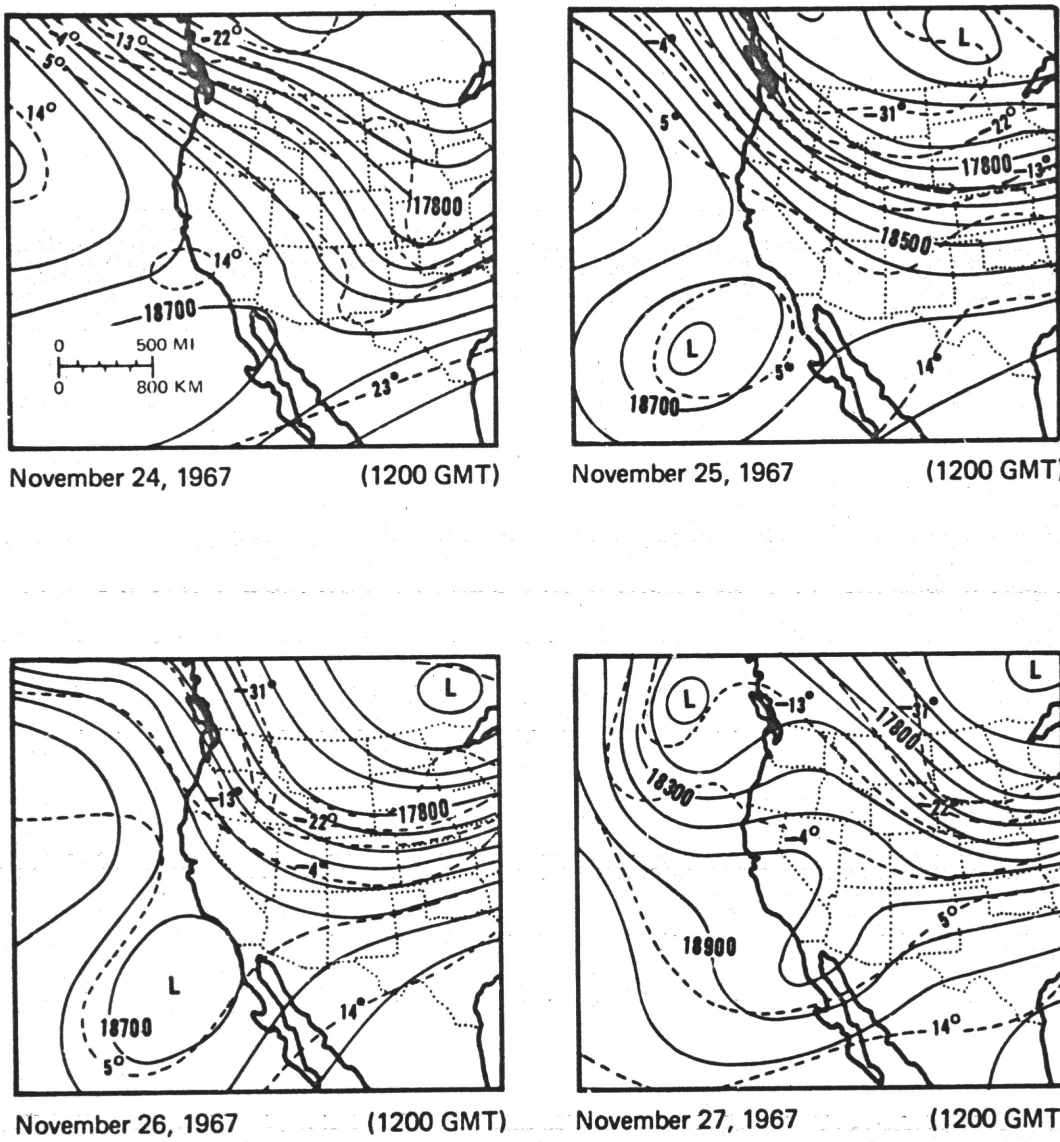


Figure 2.26.--500-mb charts for November 24-27, 1967.

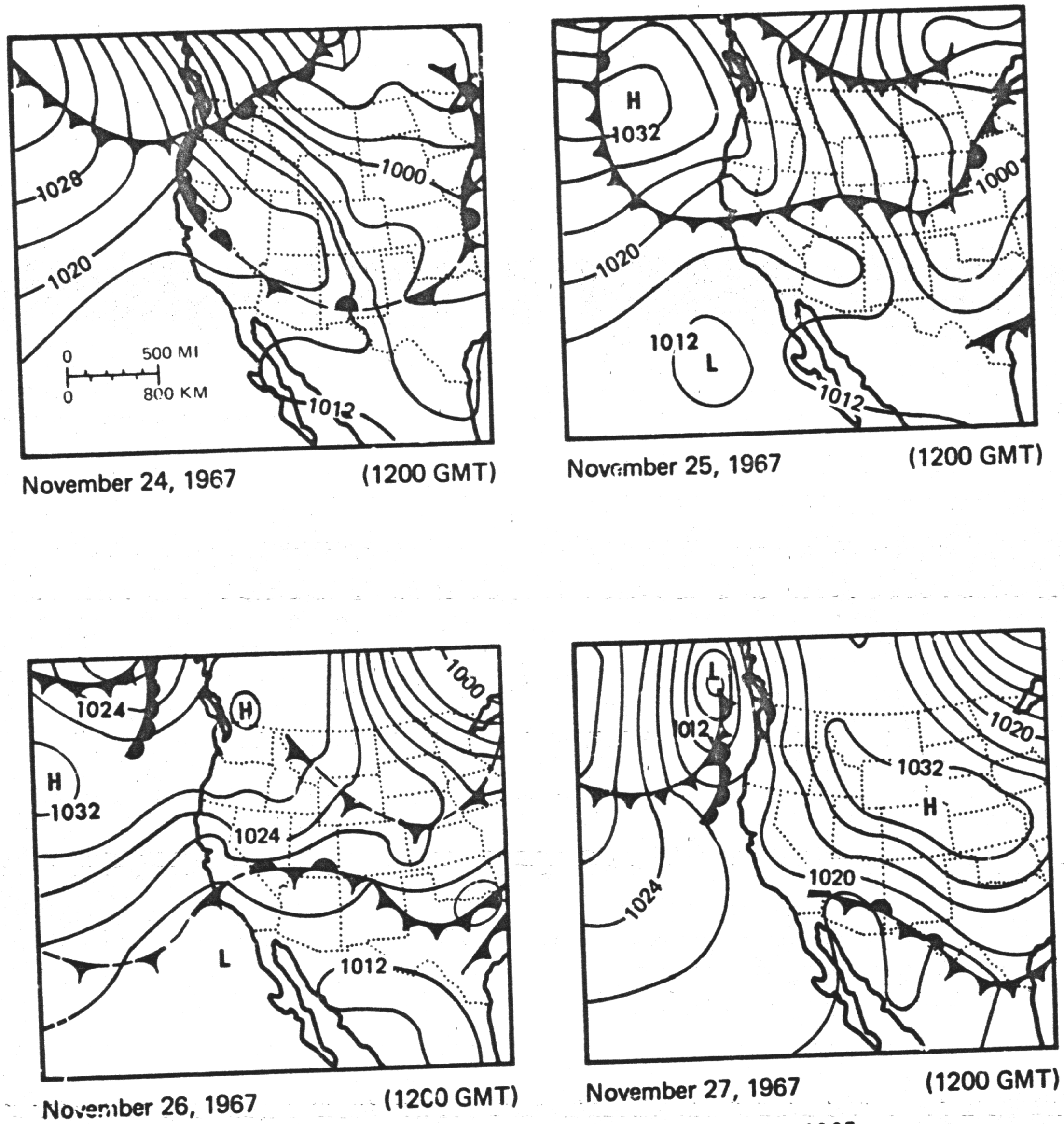


Figure 2.27.--Surface weather maps of November 24-27, 1967.

2.3.3 High-Latitude Lows

Seven storms that fit into this classification are discussed. Of the seven, only the storm of January 25-30, 1916 had a path far enough south to allow air with high moisture content to become involved.

2.3.3.1 November 26-28, 1905. This storm is an important cool-season rain-producer for that portion of the Southwest most often frequented by heavy rains -- the mountains of central Arizona to the north and east of Phoenix. Figure 2.28 shows the surface weather maps for this storm whose precipitation was concentrated in about 1.5 days. The storm's rapid motion limited the duration of rain at specific locations.

The storm involved a single but complex Low which took a course from southwestern Canada on November 26 generally southward to southwestern Idaho on the morning of the 27th. The storm turned eastward late on the 27th and by the morning of the 28th was well east of the region. The significant precipitation in this storm occurred mostly in Arizona with passage of the Low through Utah on November 27, but some precipitation continued in mountainous areas on November 28 in the northwesterly flow behind the Low. Table 2.5 summarizes some of the larger precipitation amounts for this storm.

Table 2.5.--Precipitation at selected stations in November 26-28, 1905 storm

Station	Amount (in.)	Duration	Percent of 100-yr 24-hr rainfall
Pinal Ranch, Ariz.	4.4	1 day	69
Yarnell, Ariz.	4.8	1 day	104
Williams, Ariz.	3.6	1 day	77
Natural Bridge, Ariz.	3.7	1 day	126

2.3.3.2 January 16-19, 1916. Rain from this storm concentrated in the interior drainage somewhat to the south of the mountainous areas that most often intercept the heaviest rains. Figure 2.29 shows the surface weather maps for this storm. A series of Lows formed off the coast and moved through California, dissipating against a strong blocking high pressure system centered along the Continental Divide from British Columbia to Texas. Late on January 17, the axis of the trough and path of Lows shifted from northwest-southeast to southwest-northeast. This change permitted passage of occluding waves across Arizona from the southwest on January 18 and 19.

The low-level southerly inflow was quite substantial in this storm. Compare, for example, the surface map for January 18, 1916 with the normal January sea-level chart (fig. A-1 in appendix A). This storm was helpful in the determination of seasonal variation of convergence PMP rainfall in HMR No. 49. Some of the more important rainfall amounts are shown in table 2.6.

2.3.3.3 January 25-30, 1916. Figure 2.30 shows weather maps for this storm which was less severe but more prolonged than the storm of about 10 days earlier (section 2.3.3.2). Three-day rains were important in this storm. A northwest-to-southeast track of low-pressure systems prevailed. Following movement of the first Low from offshore through Oregon and then through northern Utah on January 26, a second Low entered Utah on January 28 after pronounced deepening near the central California coast on the day before. This second system caused most of

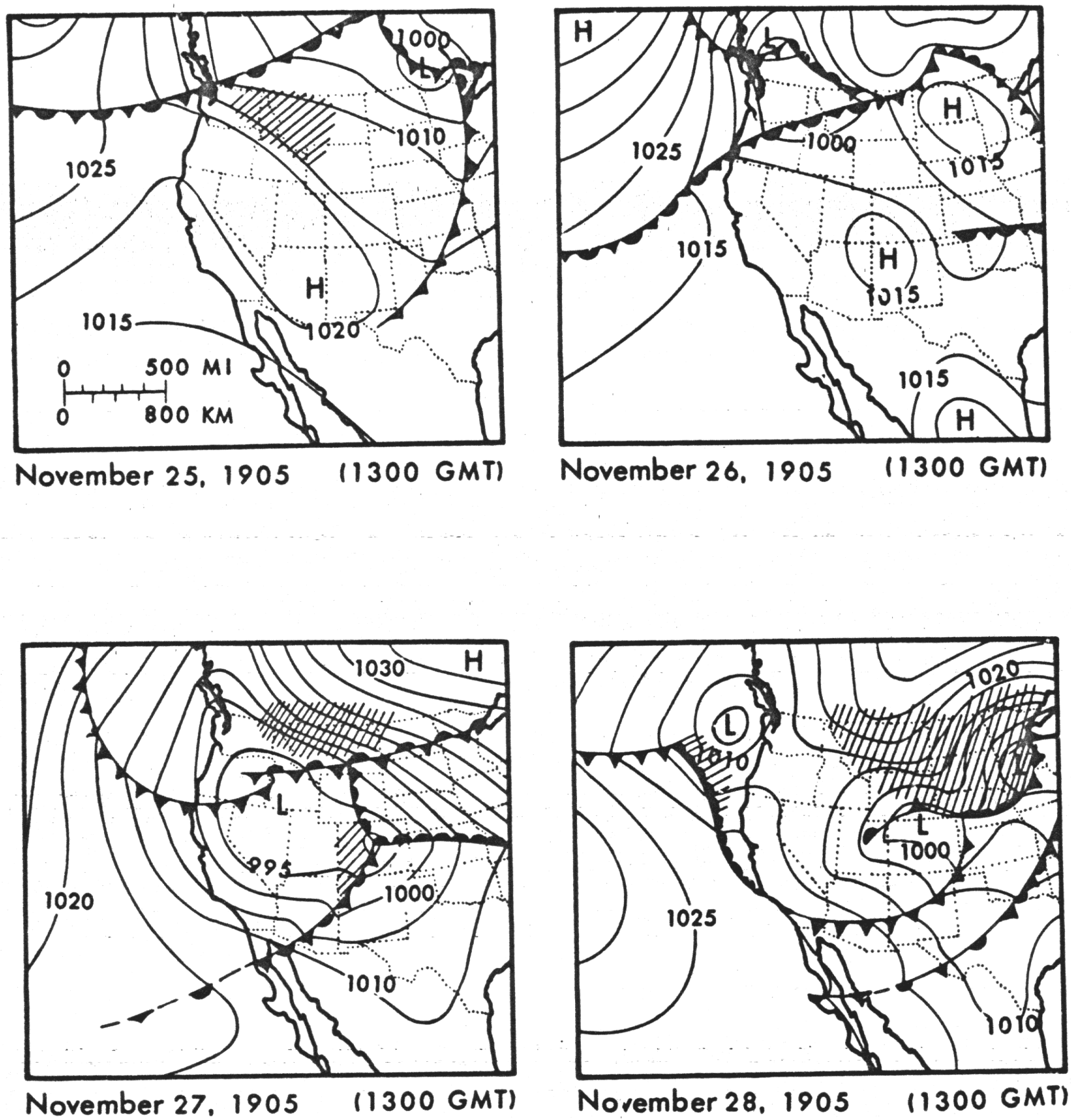


Figure 2.28.--Surface weather maps for November 25-28, 1905.

Table 2.6.--Precipitation at selected stations in January 16-19, 1916 storm

Station	Amount (in.)	Duration	Percent of 100-yr 24-hr rainfall
Nogales, Ariz.	3.8	1 day	84
Tucson, Ariz.	2.6	1 day	57
Hackberry R.S., Ariz.	2.7	1 day	49
	7.7	4 days	140

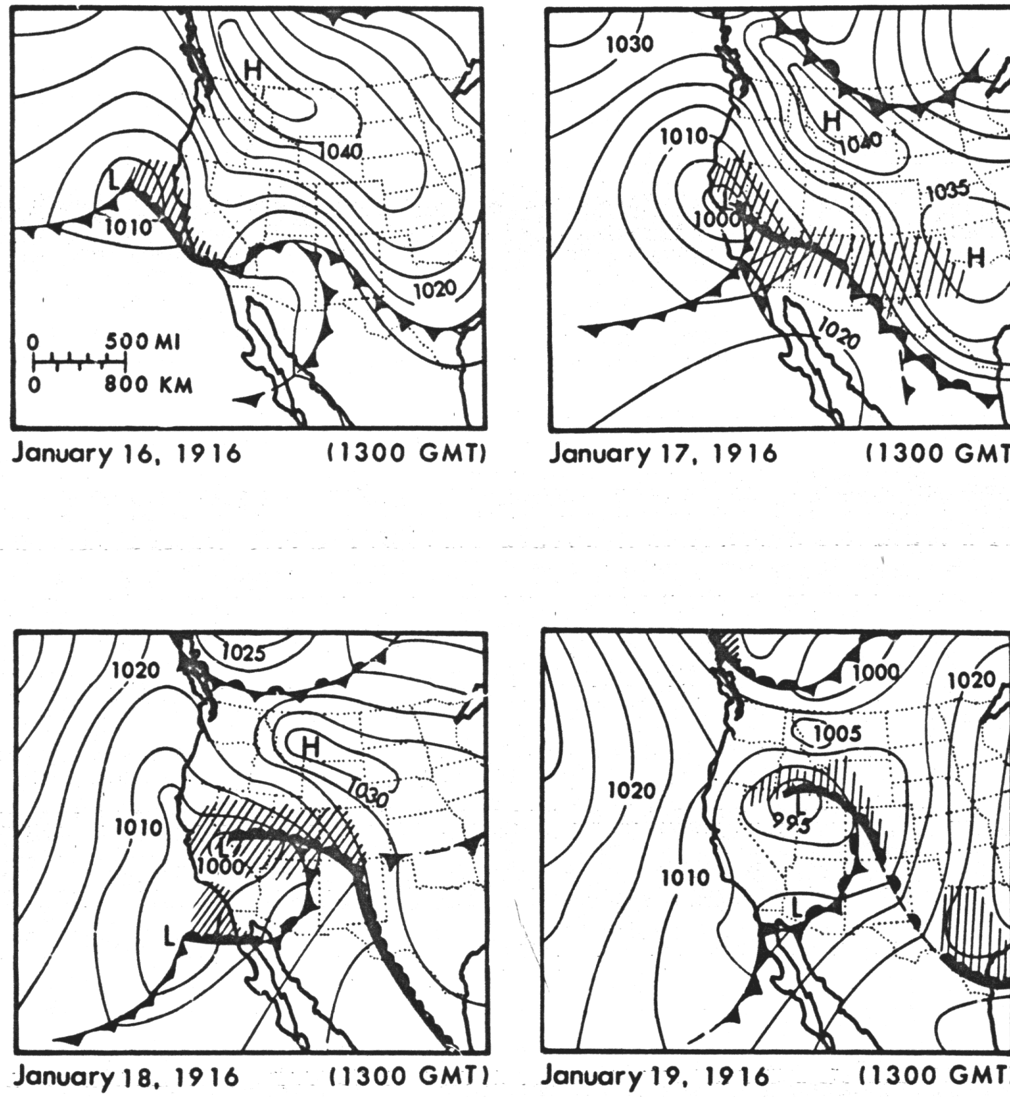


Figure 2.29.--Surface weather maps for January 16-19, 1916.

the precipitation. A third, much weaker Low (not shown), moved across southern Utah late on January 30 with only light precipitation.

Most of this storm's precipitation was along the mountains to the north and northeast of Phoenix. Figure 2.31 shows a generalized isohyetal map for this storm. Some of the more important rainfall amounts are shown in table 2.7.

2.3.3.4 April 16-17, 1917. This is an example of a late-season storm. Figure 2.32 shows the surface weather maps. With the northwest-southeast ridge-trough combination, Lows deepened in the vicinity of the Nevada-Utah border (or moved there from the northwest). After an initial offshore Low deepened in Nevada on April 14 and moved into Colorado on April 15 (maps not shown), a new center formed in southern Nevada by April 16, which joined over Utah a second breakthrough Low from the northwest. The combined Low then pushed southeastward into New Mexico by April 18, bringing an end to the precipitation.

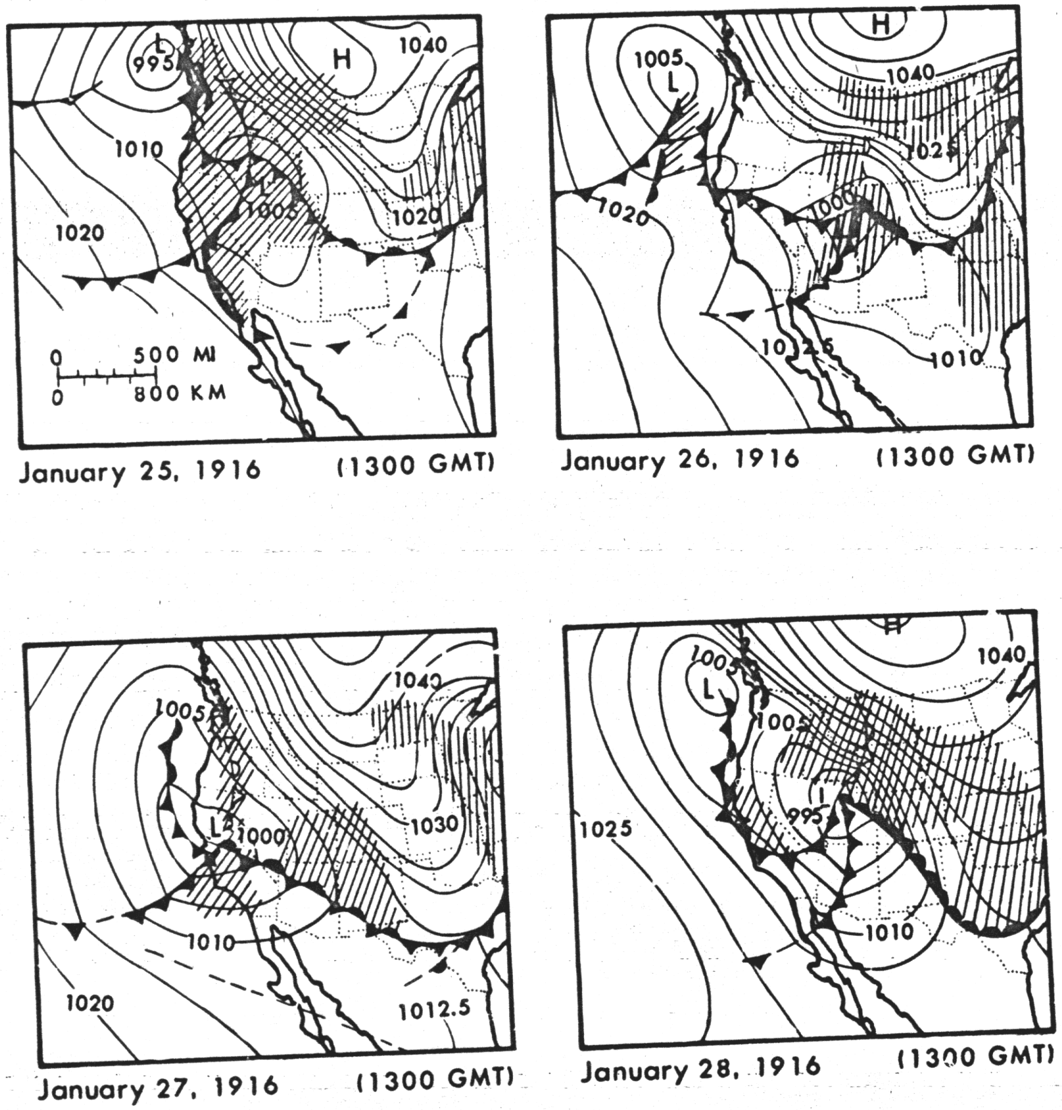


Figure 2.30.--Surface weather maps for January 25-28, 1916.

Table 2.7.--Precipitation at selected stations in January 25-30, 1916 storm

Station	Amount (in.)	Duration	Percent of 100-yr 24-hr rainfall
Carr Ranch, Ariz.	6.0	3 days	92
Flagstaff, Ariz.	6.3	3 days	52
Canon, Ariz.	4.0	3 days	83

Precipitation from this storm centered in the orographically-prone rainfall area of north-central Arizona where Crown King reported a 3-day total of 8.16 in. [132%]. A number of stations reported 3-day rains around 5 in.

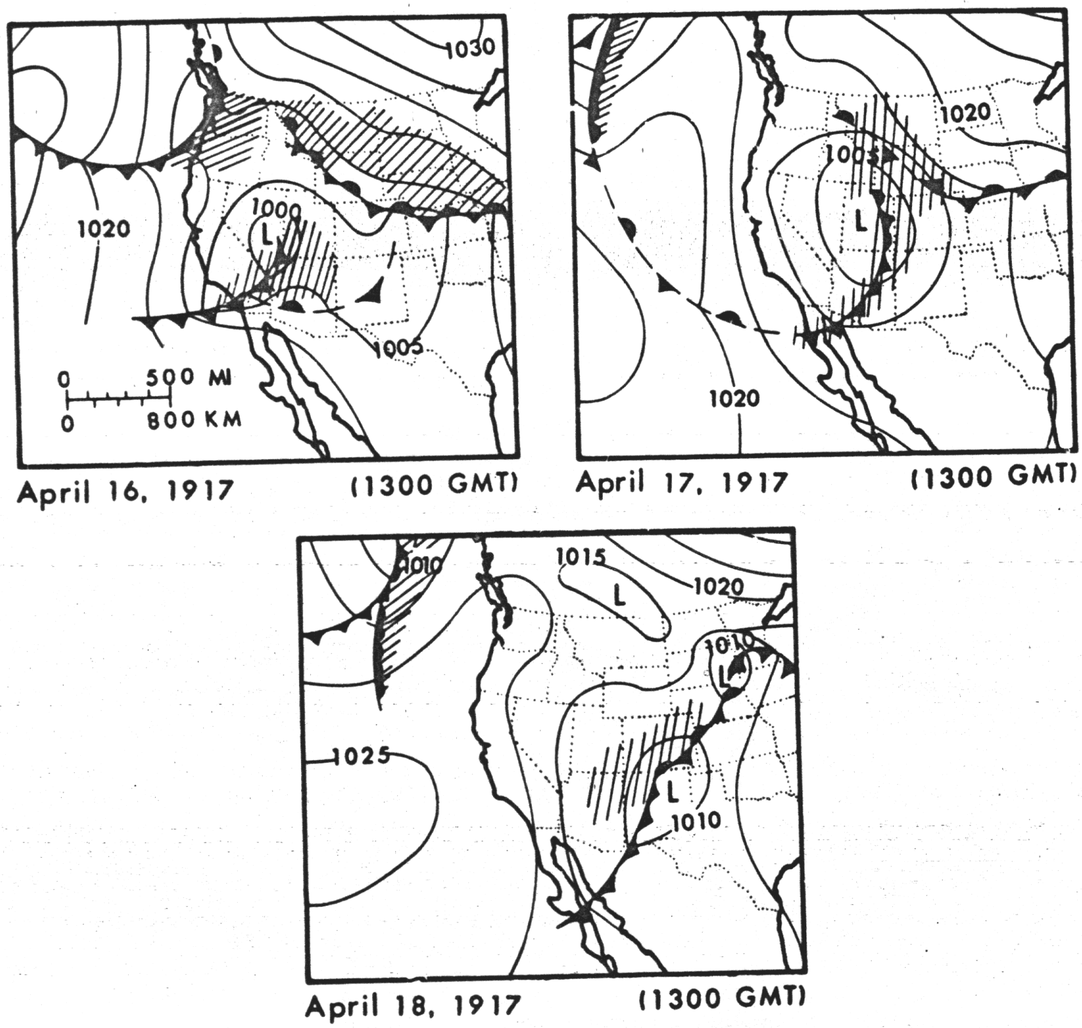


Figure 2.32.--Surface weather maps for April 16-17, 1917.

(U.S. Weather Bureau 1953). The maximum measured storm total was 4.73 in. [106%] at Lewers Ranch, Nev. at an elevation of 5,200 feet.

2.3.3.7 May 31 - June 5, 1943. This late season storm produced unusual rain in the northeastern part of the study region near Salt Lake City, Utah. The surface weather maps for this storm are shown in figures 2.35a and b. When a surface front and Low moved east of the Continental Divide on June 2, a secondary trough of low pressure intensified over the Great Basin so that by the morning of June 4, a low-pressure center with a central pressure of less than 1000 mb was positioned near the junction of Nevada, Utah, and Arizona. From the period of May 31 through June 5, Silver Lake Brighton experienced 6.75 in. [160%] of rain, with a 24-hr maximum of 3.12 in. [74%] ending the morning of June 1. This was a record 24-hr June precipitation for this station.

2.3.4 Low-Latitude Lows

2.3.4.1 January 9-11, 1905. Figure 2.36 shows surface maps for this storm. A high-pressure ridge stretching across the Pacific Northwest acted as a block to

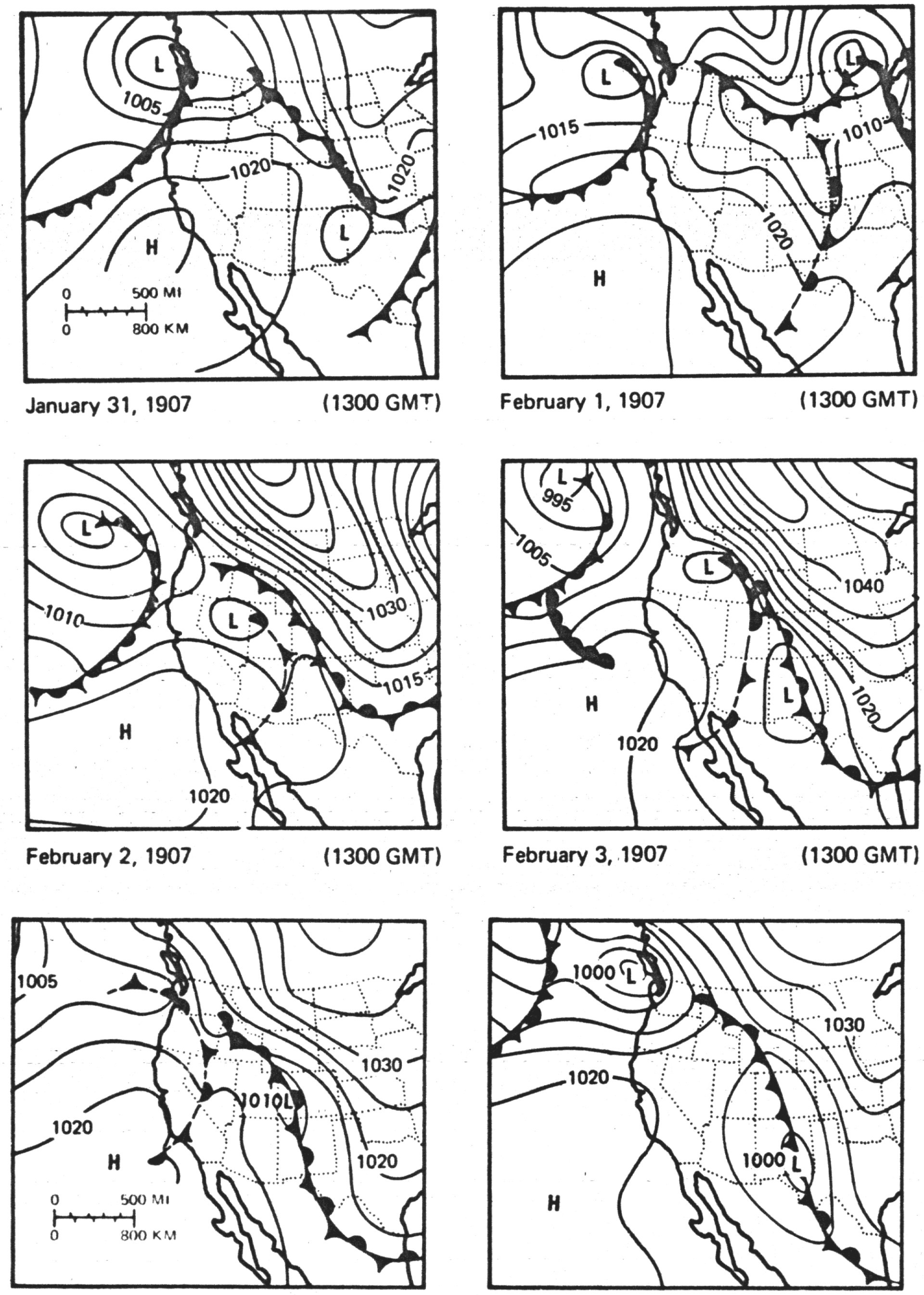


Figure 2.33.--Surface weather maps for January 31 to February 5, 1907.

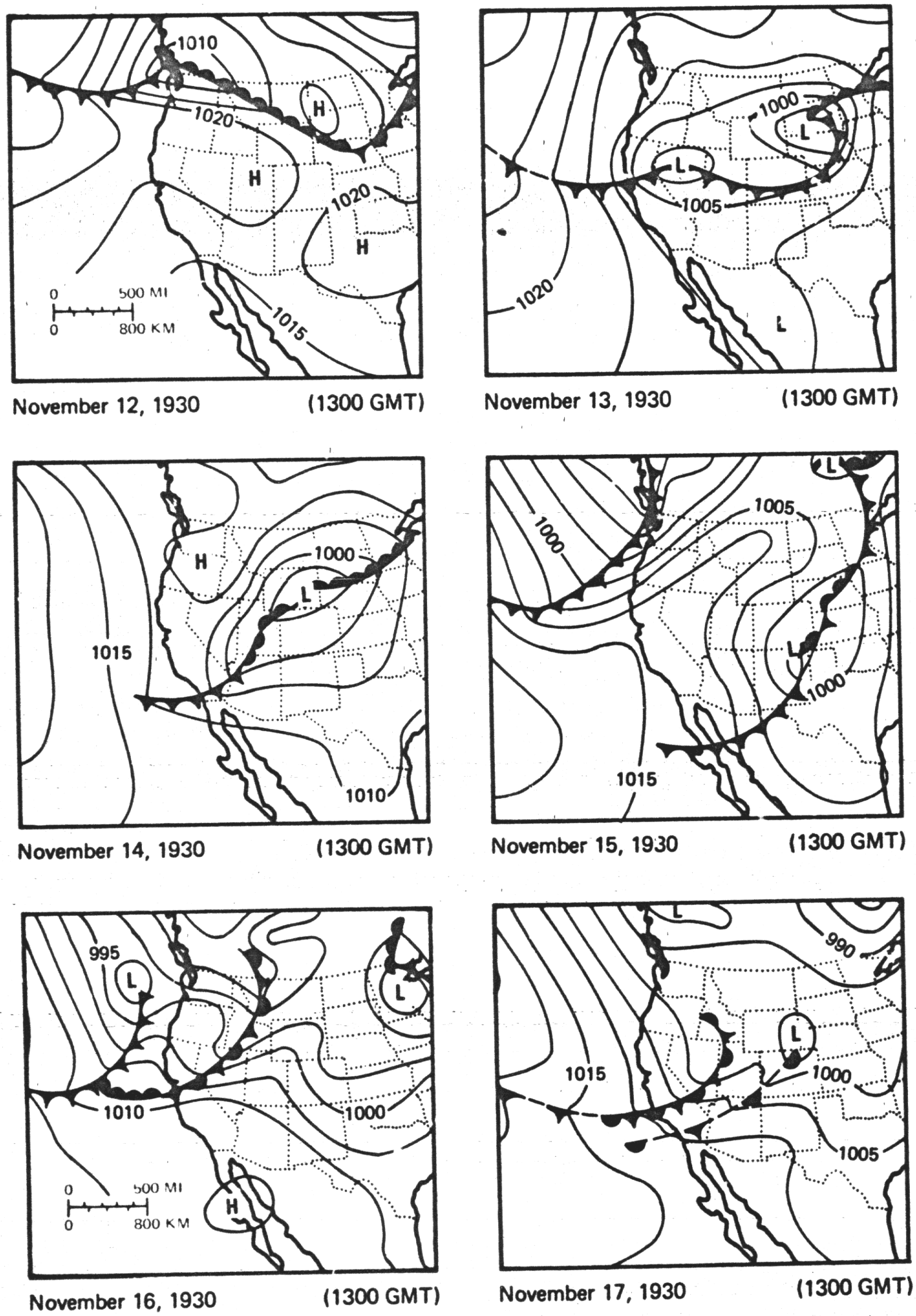


Figure 2.34.--Surface weather maps for November 12-17, 1930.

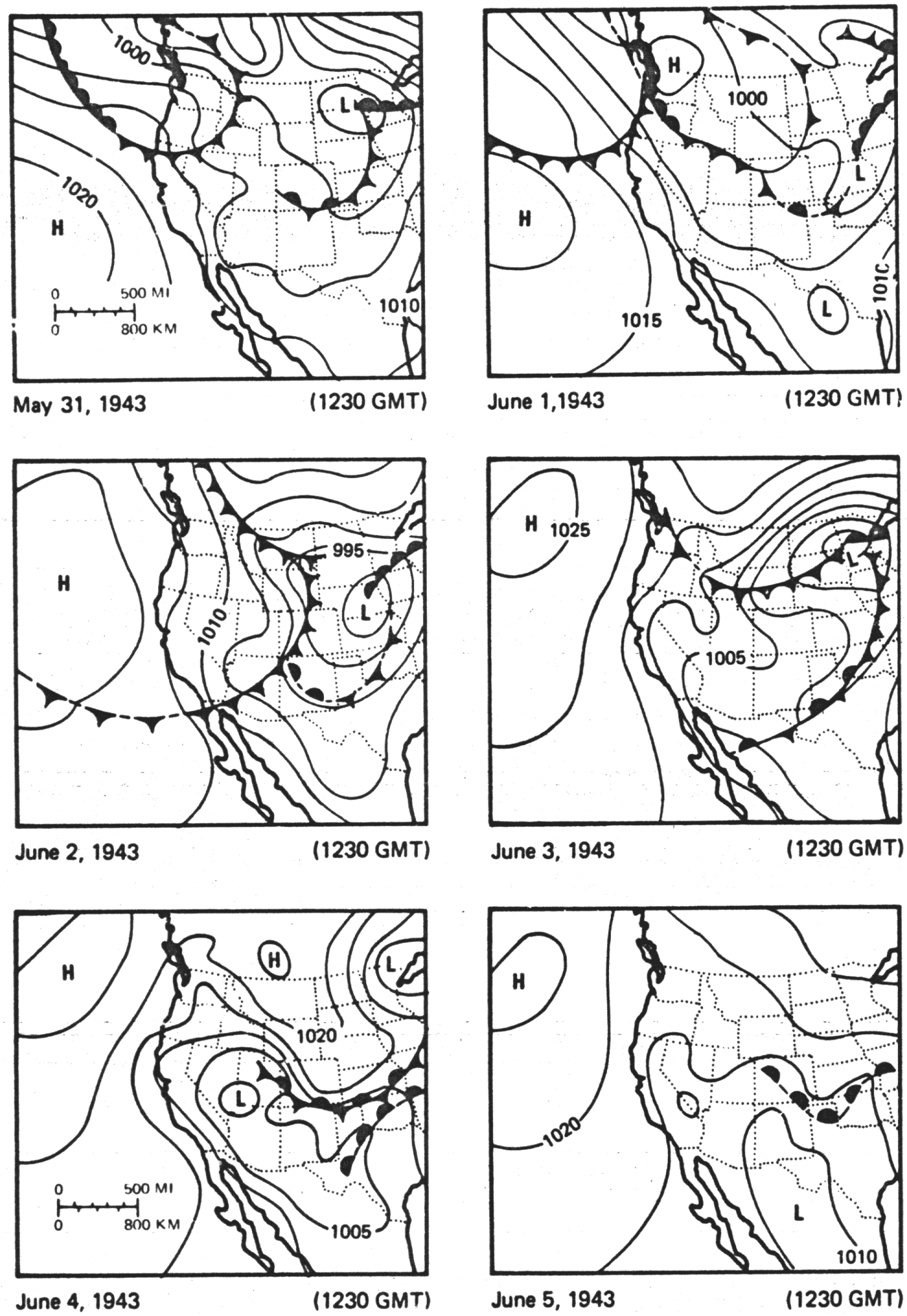


Figure 2.35a.--Surface weather maps for May 31 to June 5, 1943.

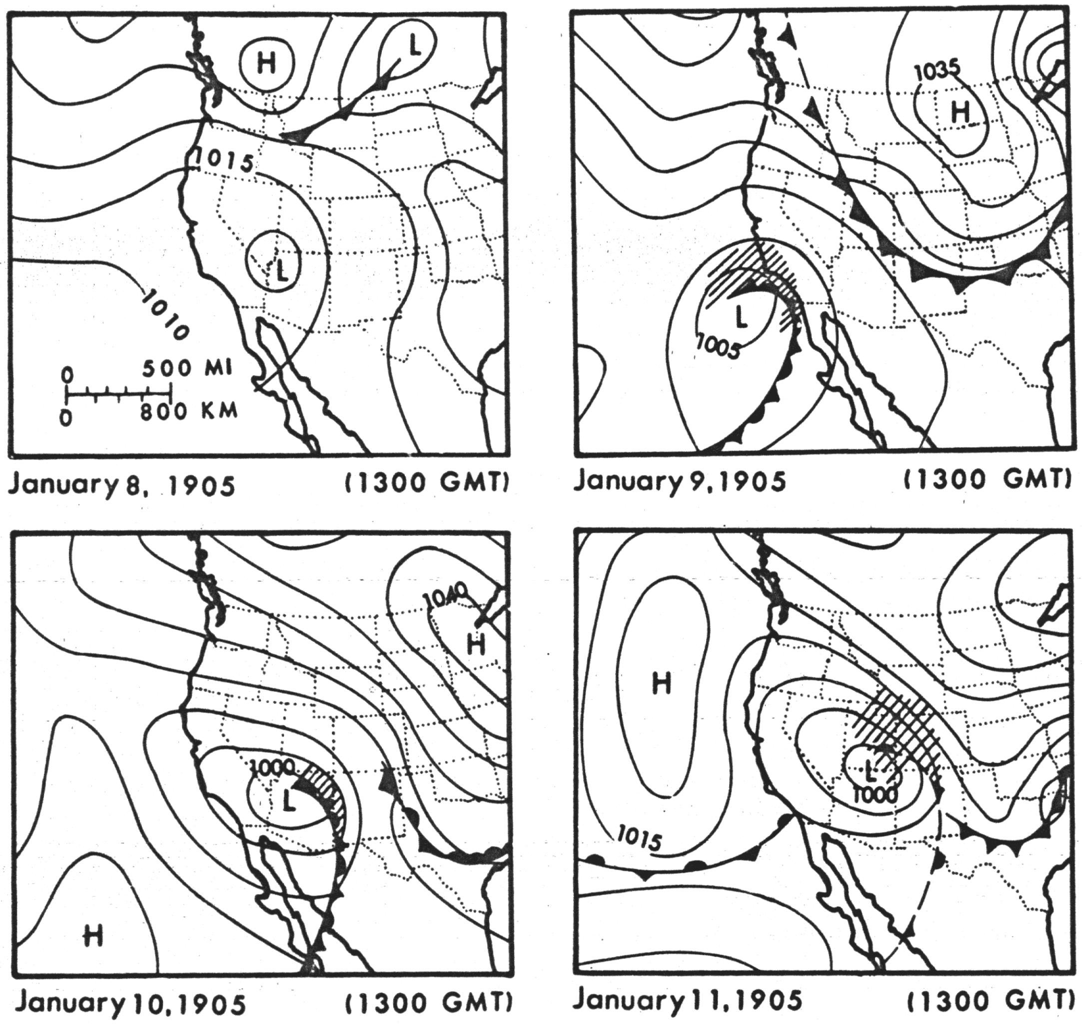


Figure 2.36.--Surface weather maps for January 8-11, 1905.

this type demonstrates the importance of low level southerly flow for areas well inland even though the low-level flow must follow a tortuous route to reach the affected area.

Rapid motion of the weather features was characteristic of this 1963 storm. Convergence rain occurred in the vicinity of a semi-stationary front lying east-west through northern Utah beginning January 29 (fig. 2.38). Rainfall was intensified by two waves that traveled rapidly along the quasi-stationary front. Reno, Nev. received 1.41 in. [53%] in this storm.

2.3.5 Low-Latitude Lows With High-Latitude Breakthrough

Just one storm, February 2-6, 1905, is discussed in this group.

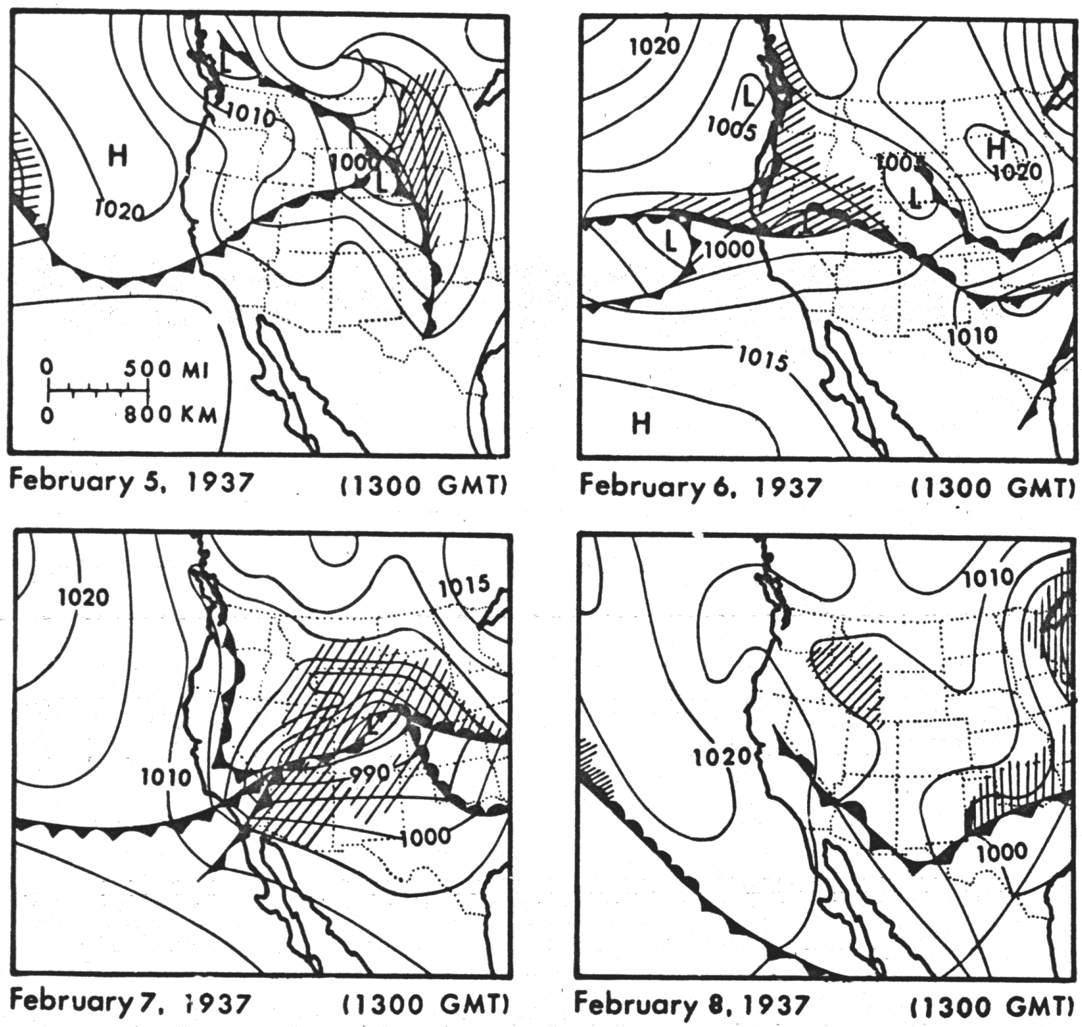


Figure 2.37.--Surface weather maps for February 5-8, 1937.

2.3.5.1 February 2-6, 1905. The main feature of this storm was the breakthrough Low from the northwest (fig. 2.39) that moved to an offshore moisture source region and stagnated before moving inland.

On February 2, 1905, a Low had moved into Utah and the associated occluded front had moved over eastern Arizona. By February 3, the breakthrough Low from the northwest approached the coast and stagnated and then, while still offshore absorbed the initial Low. Moving into northern Arizona by February 4, this intensified Low was blocked by the High to the east. It was followed by a third wave that was west of the southern California coast on February 4. This deepened and the frontal system occluded as it moved slowly across Nevada on February 5 and 6 and into Colorado on February 7.

Heaviest precipitation amounts came during the night of February 3 with rapid movement (and associated convergence) of the breakthrough Low across Arizona.

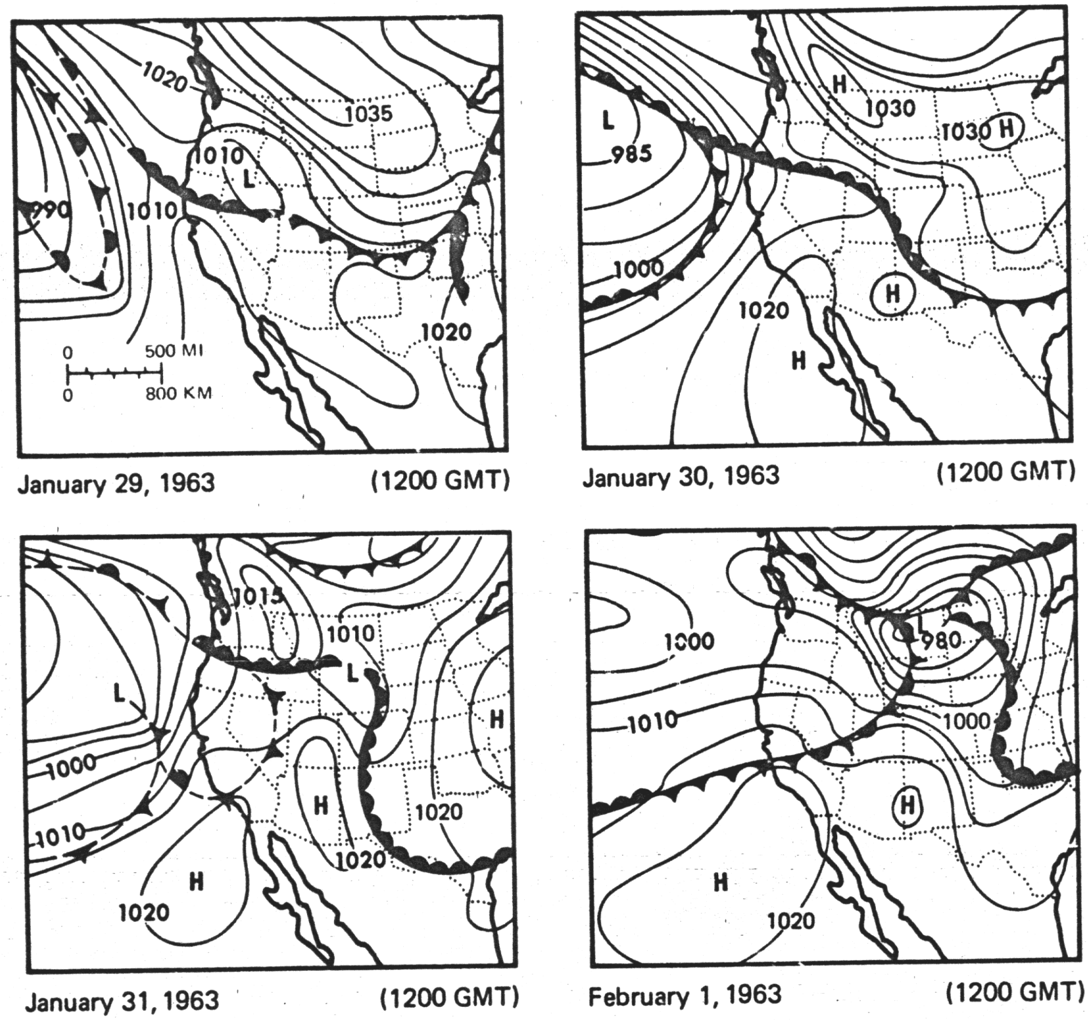


Figure 2.38. Surface weather maps for January 29 to February 1, 1963.

Pinal Ranch had 1-and 3-day rains of 2.3 and 6.9 in. [36 and 108%], respectively. These compare with 5.95 in. and 8.45 in. in the low-latitude January 1905 storm (table 2.9). The February 1905 storm was influential in determining seasonal variation of convergence PMP.

2.3.6 Mid-Latitude Lows

2.3.6.1 February 14-17, 1927. This storm was one of two February storms helpful in defining the winter convergence PMP. Rapid passage of north-south occlusions from the Pacific across the western states (in response to strong west-east flow), as seen in the surface weather maps of figure 2.40, was the main feature of this storm. Paths of Lows were far to the north through Washington and Idaho. On February 15, the northern part of the first occlusion had already passed across Colorado while the southern section was lagging through Arizona. The second and third occlusions, shown offshore on February 15, passed through

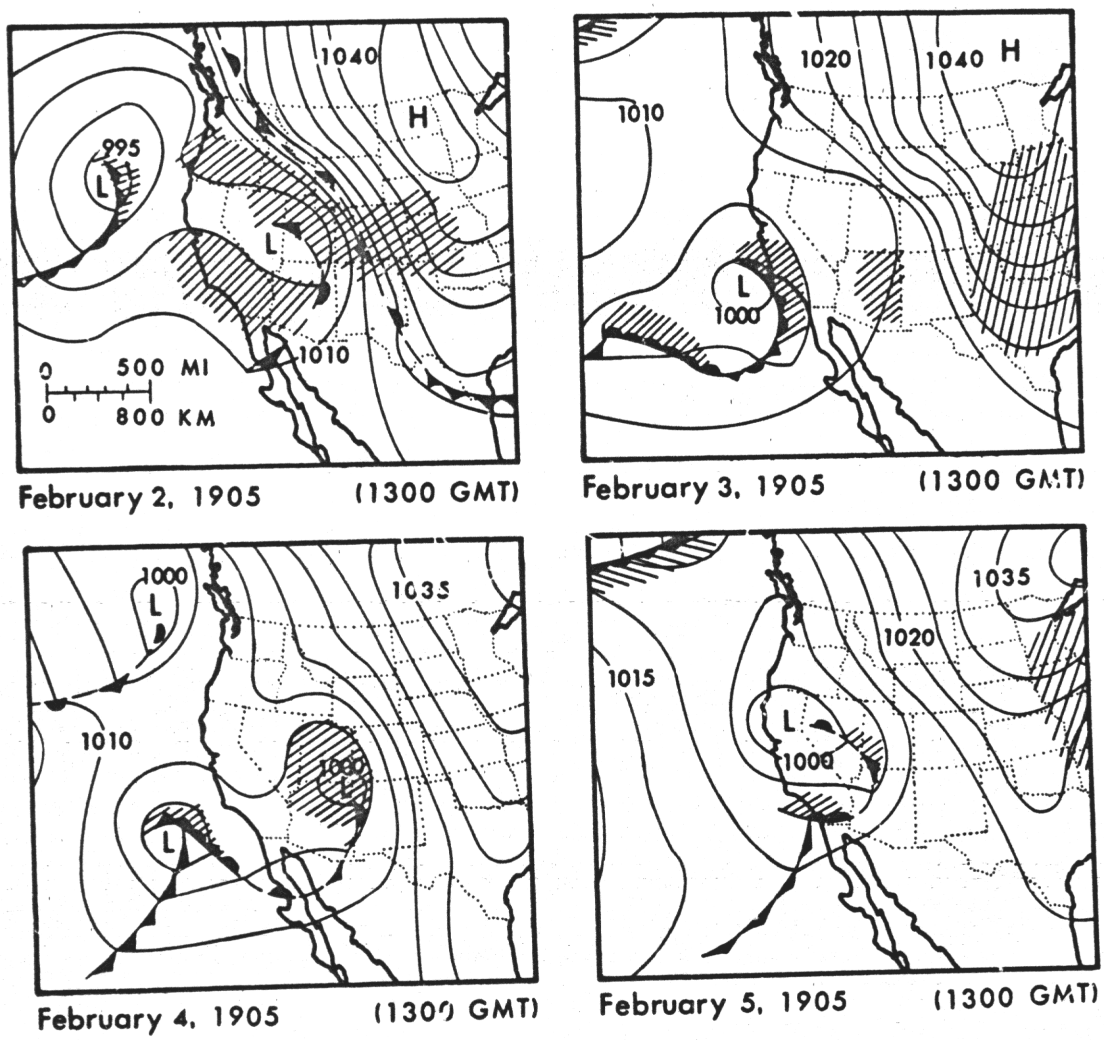


Figure 2.39.--Surface weather maps for February 2-5, 1905.

Arizona in a similar manner on February 16. The third occlusion is shown east-west through southern Arizona on the morning of February 17, with the Low far to the east. A fourth occlusion, which lies across central California and northwestern Nevada on the 17th, weakens in Nevada during the 17th and 18th as a ridge builds across the Great Basin.

Precipitation favored the northern Arizona mountains facing into the strong southwest flow at low levels. For example, Prescott had 3.0 in. [67%] in one day and 8.1 in. [180%] in 3 days. For comparison, the record 1-day rain at Prescott is 4.6 in. [102%].

2.3.6.2 **March 1-3, 1938.** Surface weather maps for this storm are shown in figure 2.41. Two occluded fronts passed through Arizona; the first, early on March 1, and the second just a little over 24 hr later. Almost all the rain fell with the passage of the second (and much stronger) occlusion. The second frontal

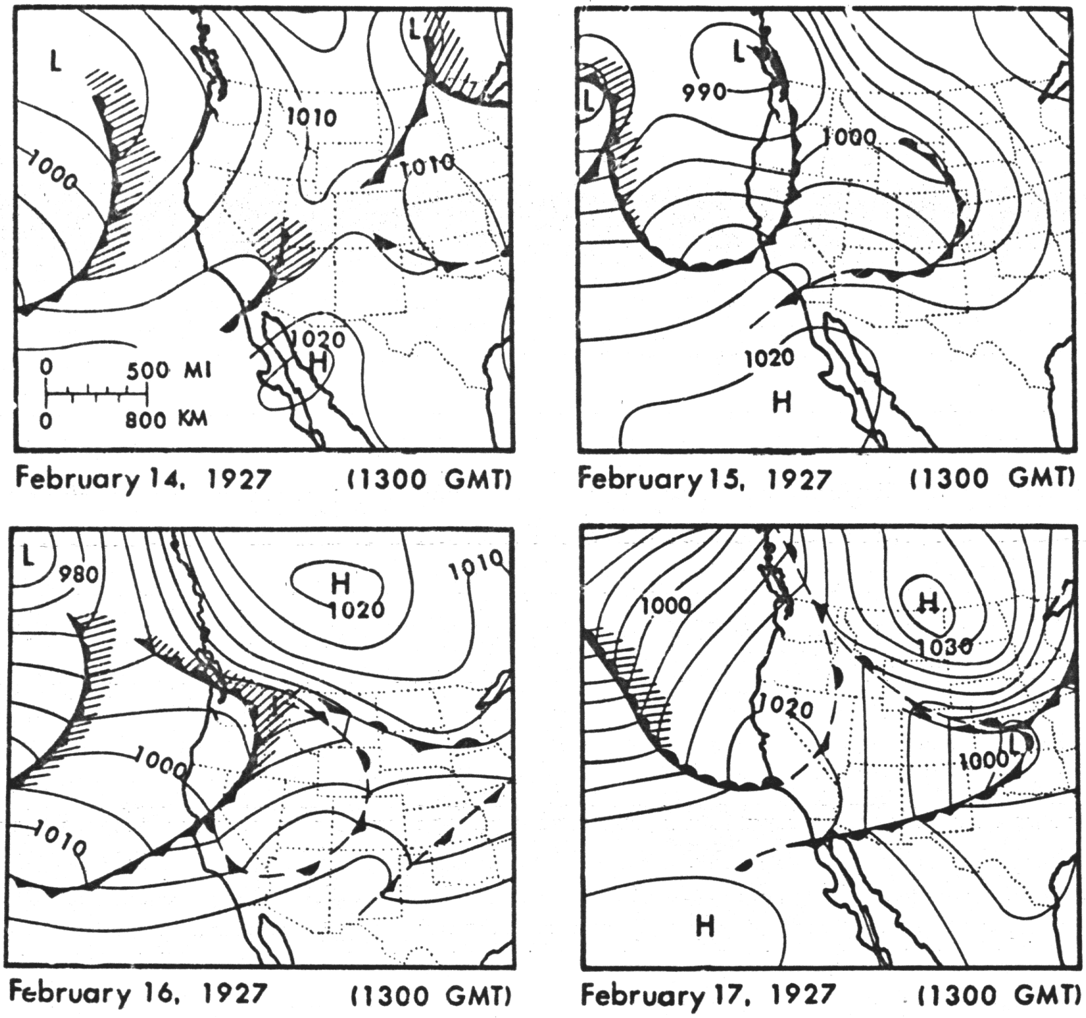


Figure 2.40.--Surface weather maps for February 14-17, 1927.

system occluded slowly while moving to the coast and then continued to move inland between the 2nd and 3rd leaving an intense Low offshore west of the State of Washington. This caused the southwesterly flow to continue and brought a strong inflow of near-tropical air from low latitudes to central Arizona as the front moved inland. Thus, in spite of rapid frontal motion which is characterristic of this storm group, the intensity of the Low and continued southwesterly flow counteracted the depleting effect of the eastward movement of the front on the rainfall amounts. Thus, the rainfall-producing capacity was brought about through the vigorous influx of moist air and convergence associated with rapid pressure changes.

The more extreme 1- and 3-day rainfall amounts in this storm for Arizona are shown in table 2.10.

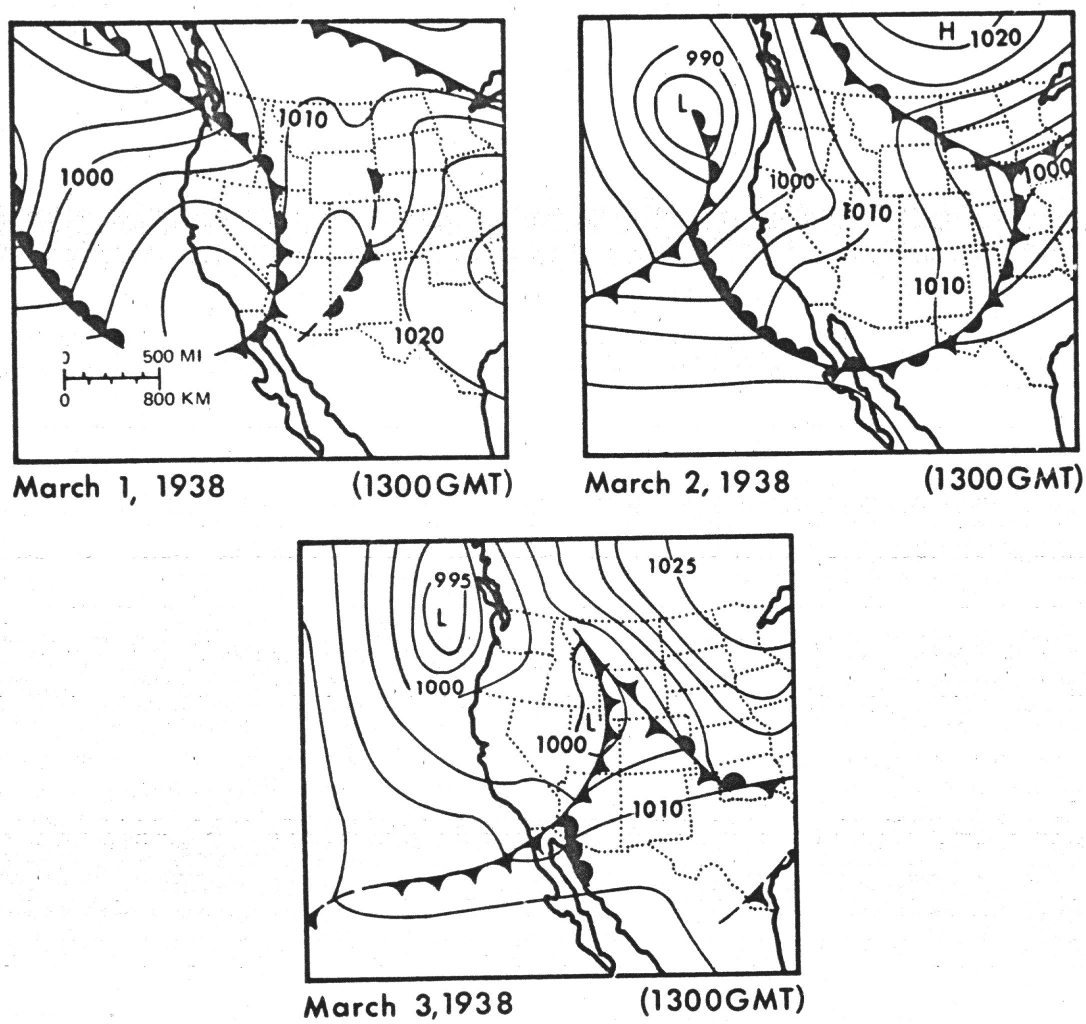


Figure 2.41.--Surface weather maps for March 1-3, 1938.

For an area size of 1,000 mi^2 for durations of 6 to 12 hours, this storm's rainfall amounts were within about 30 percent of the PMP in central Arizona and southern Utah (see table 5.1 in HMR No. 49). The lower percentage of the 100-yr 24-hr rain at the strongly orographic station, Pinal Ranch, compared to larger percentages at less orographic stations, indicates that the convergence component of rainfall in this storm was important.

Table 2.10.--Precipitation at selected stations in March 1-2, 1938 storm

Station	Amount (in.)	Duration	Percent of 100-yr 24-hr rainfall
Junipine, Ariz.	5.5	1 day	95
	6.0	3 day	103
Prescott, Ariz.	3.2	1 day	71
Pinal Ranch, Ariz.	3.3	1 day	52

2.3.7 West Coast Drainage Storms Producing Large Rains East of the Sierra Nevada Ridge

Some storms that were outstanding rain-producers in California west of the Sierra Nevada Ridge are also important in areas to the east of this Ridge. General storm PMP for portions of northern Nevada results from spillover from such storms. The December 21-23, 1955 storm was thoroughly discussed in HMR No. 37 (Weaver 1962), and will be simply highlighted here emphasizing the rain amounts east of the ridge.

2.3.7.1 December 21-23, 1955. A Corps of Engineers' report of the December flood (U.S. Corps of Engineers 1956) gives rainfall depths for stations and river drainages (the Truckee, Carson, and Walker Rivers) east of the Sierra crestline. Drainage outlines for portions of the basins over which rainfall was assessed and some stations pertinent to these drainages are shown in figure 2.42.

For the Truckee River drainage, some of the 3-day station rainfall amounts included 14.0 in. [140%] at Meyers Inspection Station, Calif., 7.0 in. [159%] at Boca, Calif., 5.0 in. [159%] at Reno, Nev., and 2.0 in. [91%] at Fernley, Nev., near the eastern edge of the Truckee basin. The estimated 3-day average precipitation for the Truckee basin above Reno was 13.5 in. In the Carson River drainage, the rain at stations varied from about 16 in. [133%] at the Sierra crest, near Twin Lakes, to 10.5 in. [150%] at Woodfords, Calif. to 7.5 in. [197%] at Topaz Lake, Calif. For the West Carson River basin above Woodfords, the 3-day basin-average depth was estimated to be 13.5 in. while over the East Carson River basin, above Gardnerville (see fig. 2.42), the estimate was 12.5 in.

2.3.8 Lows Involving Gulf of Mexico Moisture

One of the closest approaches to the general storm PMP in the Northwestern States (U.S. Weather Bureau 1966; see Nyack Creek Basin data for Montana in table 7.3, p. 216) resulted from a June 1964 storm in Montana that was fed by low-level moisture from the Gulf of Mexico pushing northward across the Great Plains east of the Continental Divide. On June 7, 1964 (fig. 2.43) a Low deepened over northern Colorado and southern Wyoming. Strong easterly winds prevailed to the north of the Low center on June 7. The flow from the east extended through a deep layer to near 20,000 ft, (see 500-mb charts fig. 2.44). A thorough treatment of the meteorology of the June 1964 Montana storm may be found in U.S. Geological Survey Water Supply Paper 1840B (Bonner and Stermitz 1967). We judge this June 7-8, 1964 Montana storm to be the outstanding example of the storm type that would produce the general storm PMP across the Continental Divide into southwest Wyoming and nearby areas for a wide spectrum of basin sizes.

The ruggedness and the steepness of the upwind slopes (in this case east-facing slopes at the storm location) were necessary to bring out the strong orographic components of precipitation evident in this storm. For a similar storm to occur in the southwestern portion of Wyoming, the large scale weather features need to be modified to give an optimum moisture inflow direction relative to orography in the new area. Also, since the slopes are not as pronounced as in western Montana, the orographic effect would be less. The mean June surface flow is directed upslope in the Colorado area (fig. A.1 in appendix A). The shifting of the Low's position and its intensification are needed for increased upslope flow in this area in the extreme rainfall case.

That moisture from an easterly direction will be effective in bringing PMP rains to southwest Wyoming and extreme northeast Utah is supported by the fact

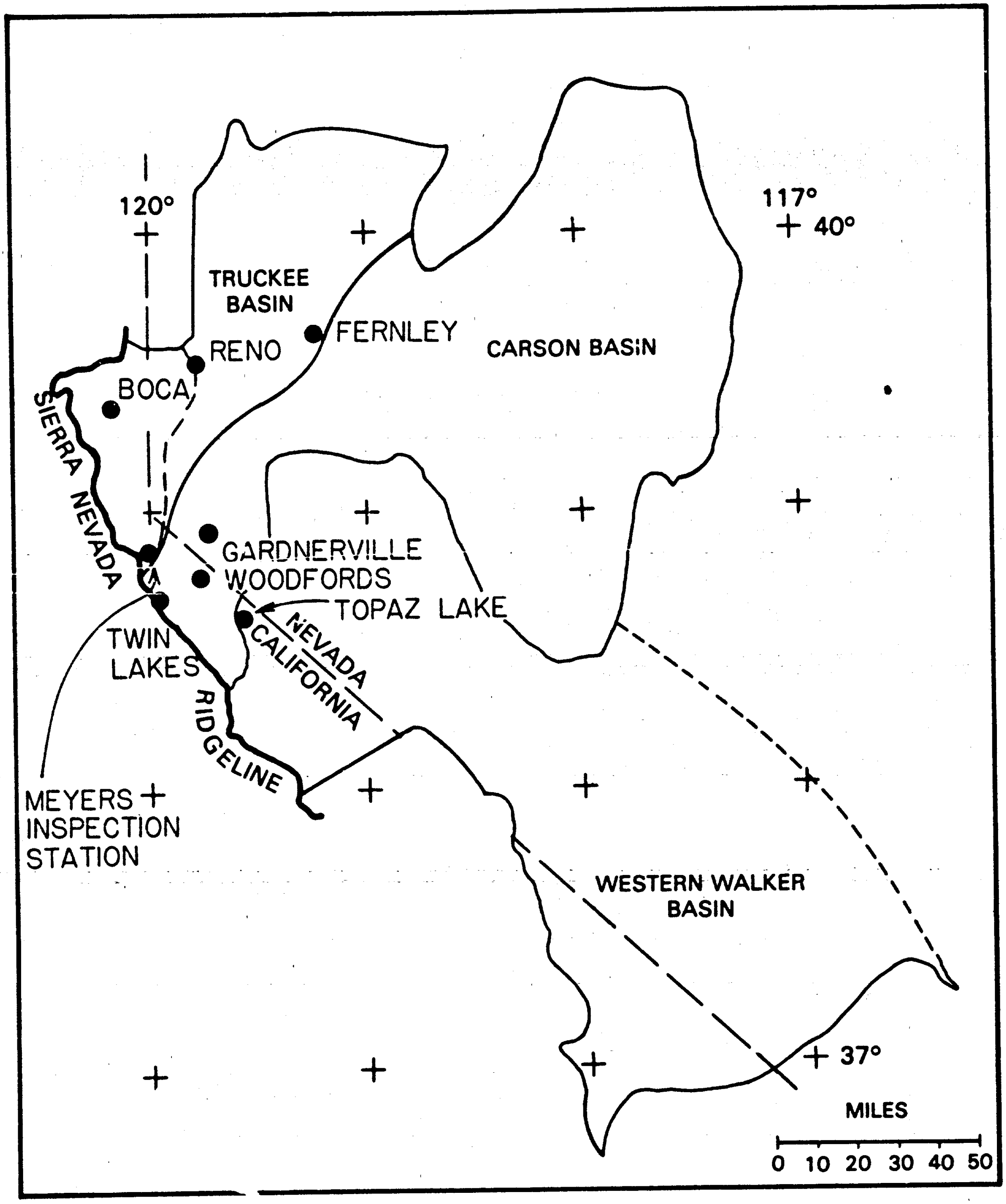


Figure 2.42.--Location map for Truckee, Carson and Walker River drainages.

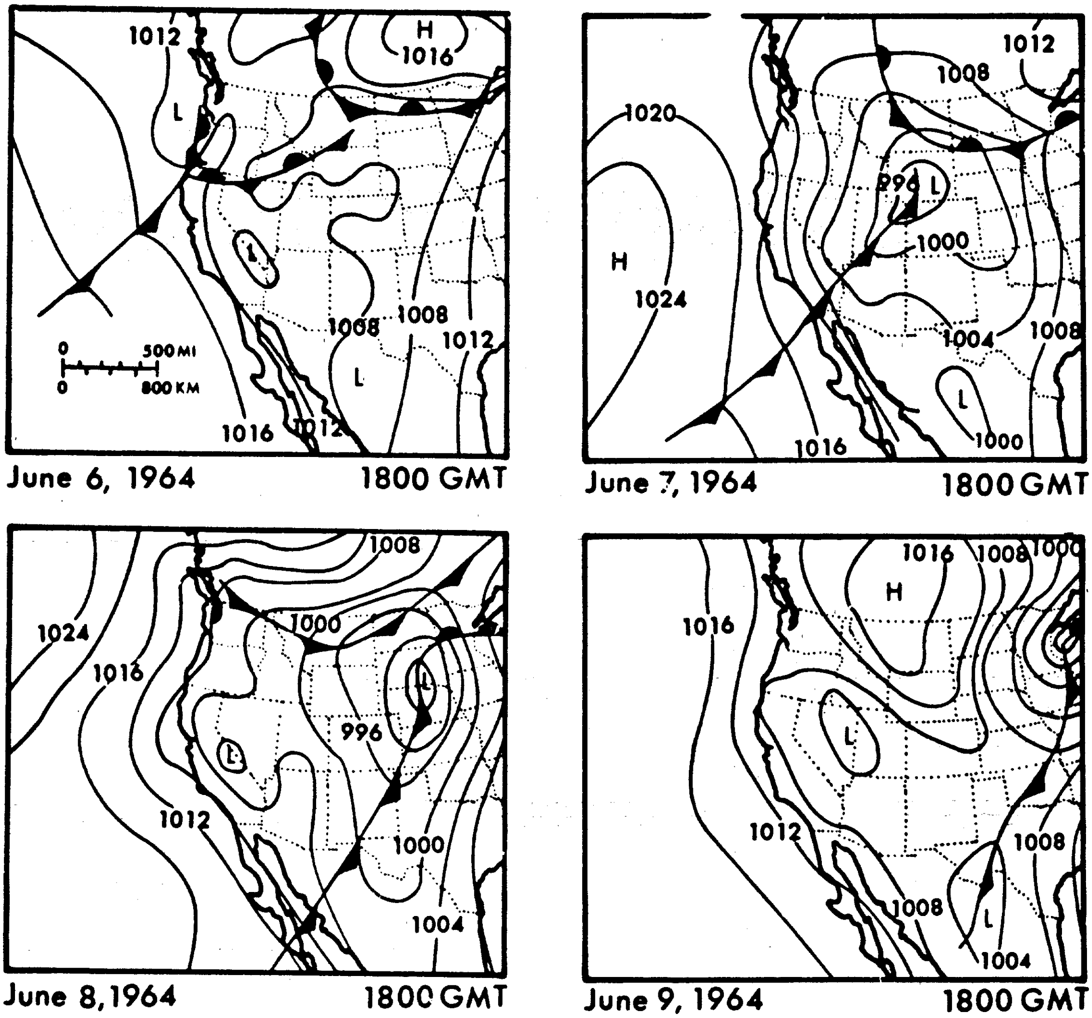


Figure 2.43.--Surface weather maps for June 6-9, 1964.

that a weather pattern with such a flow brought in Gulf of Mexico moisture and produced the maximum flow of record on some drainages in the eastern extremities of the Uinta Mountains on June 11, 1965. These basins included the 101 mi^2 Ashley Creek drainage near Vernal, Utah, (U.S. Geological Survey 1973).

2.4 A Hypothetical Extreme Tropical Cyclone Event

2.4.1 Introduction

In Section 5.9 of HMR No. 49, the general level of convergence PMP over much of the study area is checked by comparison with rainfall from a hypothesized extreme tropical cyclone. We transposed and adjusted eastern United States 24-hr PMP at

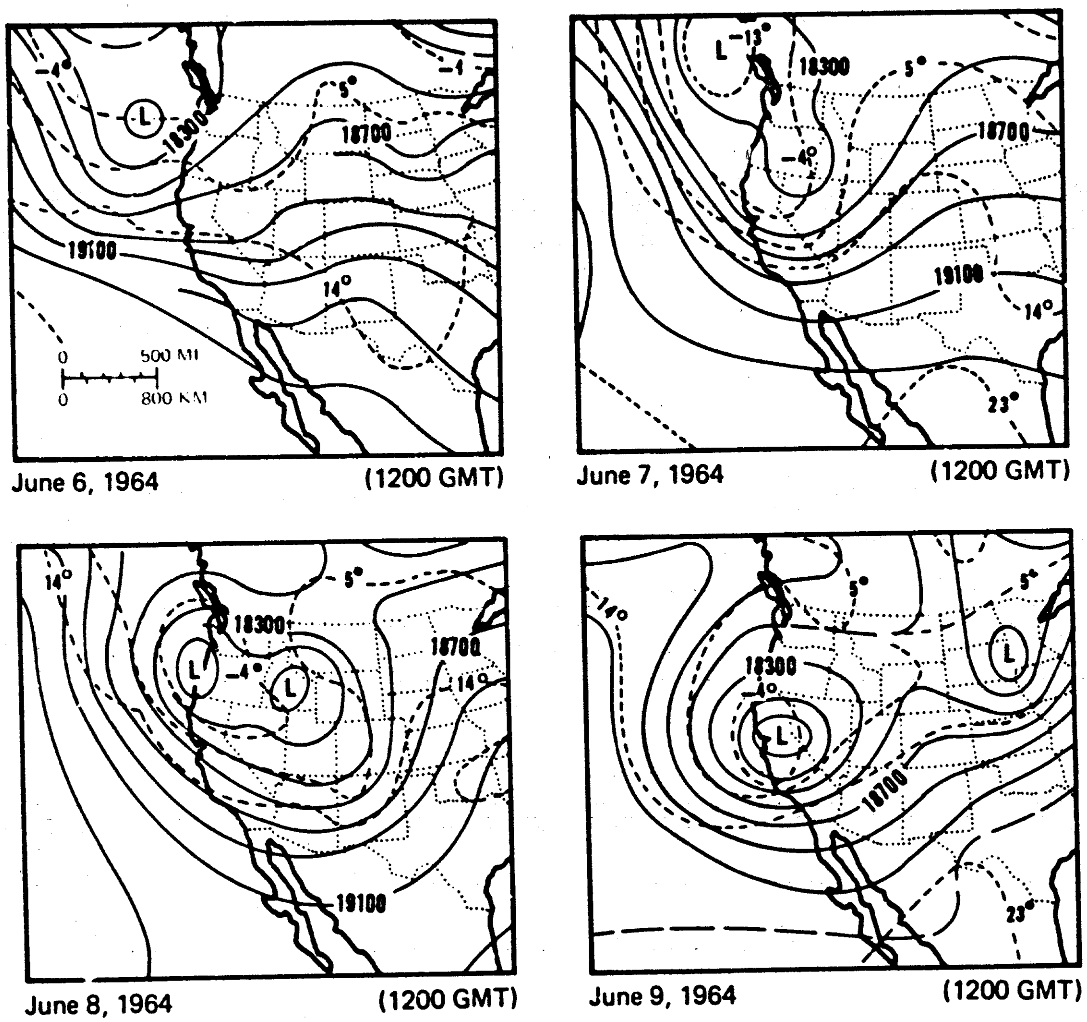


Figure 2.44.--500-mb charts for June 6-9, 1964.

Yankeetown, Fla., (which is based upon the September 5-6, 1950 storm centered at this location) to a point off the Baja California coast. The adjustment was based upon maximum moisture through depth determined from extreme surface dew points related to extreme sea surface temperatures (SST)* near where the storm occurred as compared to those at the transposed location. After applying an additional adjustment for distance-from-the-moisture source, the resulting general level agrees quite well with convergence PMP from HMR No. 49.

Further discussion concerning high moisture (or the basis for high moisture, i.e., high SST) and other factors which influence the magnitude of tropical cyclone-related rainfall is the purpose of this section. These factors are based

*Hereafter SST will be used to denote sea surface temperature(s).

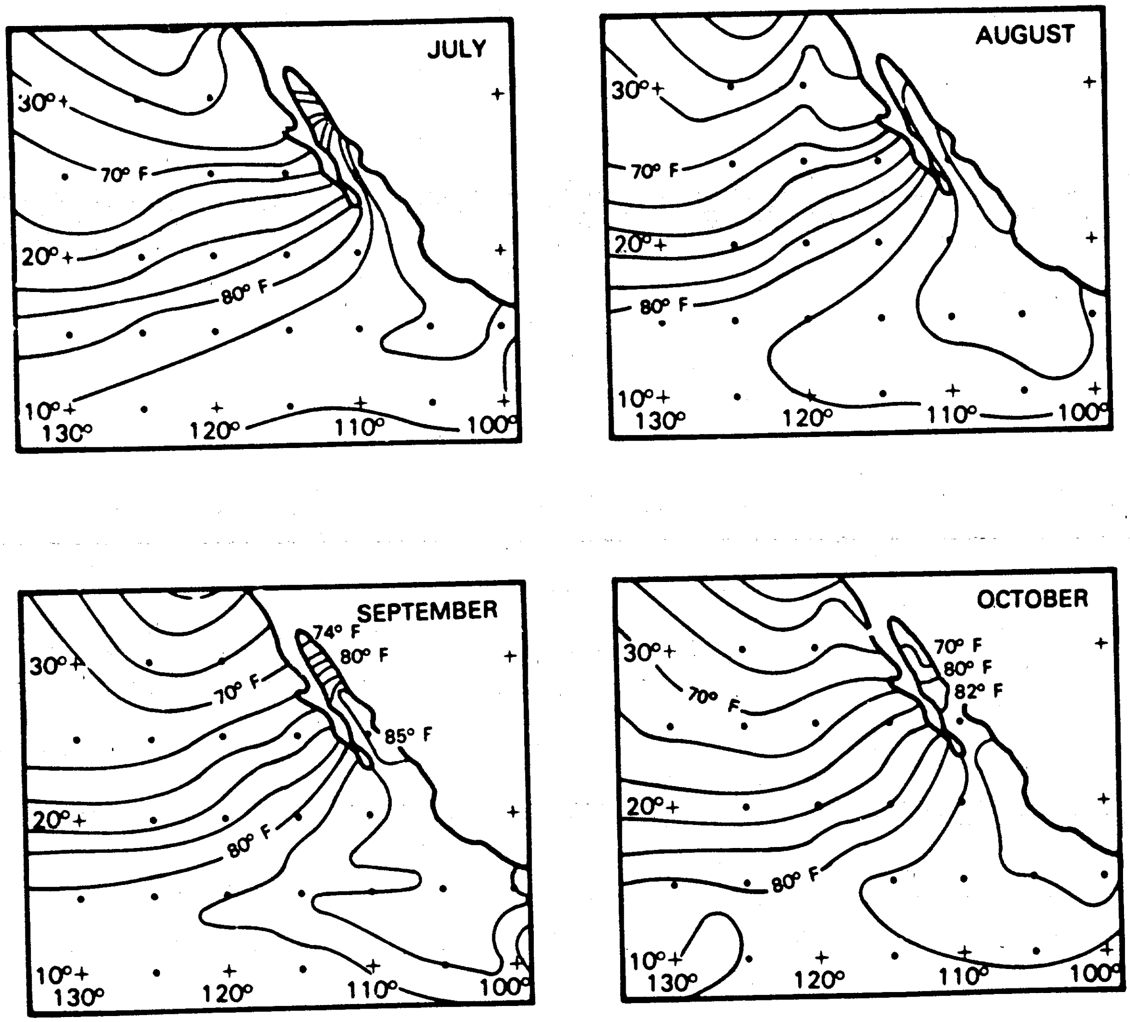


Figure 2.45.--Mean sea-surface temperature charts for the tropical Pacific for July, August, September and October (Laviolette and Seim 1969).

largely on experience with tropical cyclones and their associated rainfall off the Pacific coast as well as in other regions, such as the U.S. Gulf of Mexico and Atlantic coasts.

2.4.2 Climatology of SST

Figure 2.45 shows mean SST (°F) for the months of July through October (the season of tropical cyclones affecting the Southwest) for the eastern Pacific Ocean off the Mexican and Central American coasts. Figure 2.46 shows maximum SST for the same region and season. These charts, after Laviolette and Seim (1969), are based on summaries and analyses of data for one degree latitude-longitude areas. Both mean and maximum SST show a very pronounced decrease northward along Baja California. For the same latitude, the Gulf of California waters are considerably warmer than those of the Pacific Ocean.

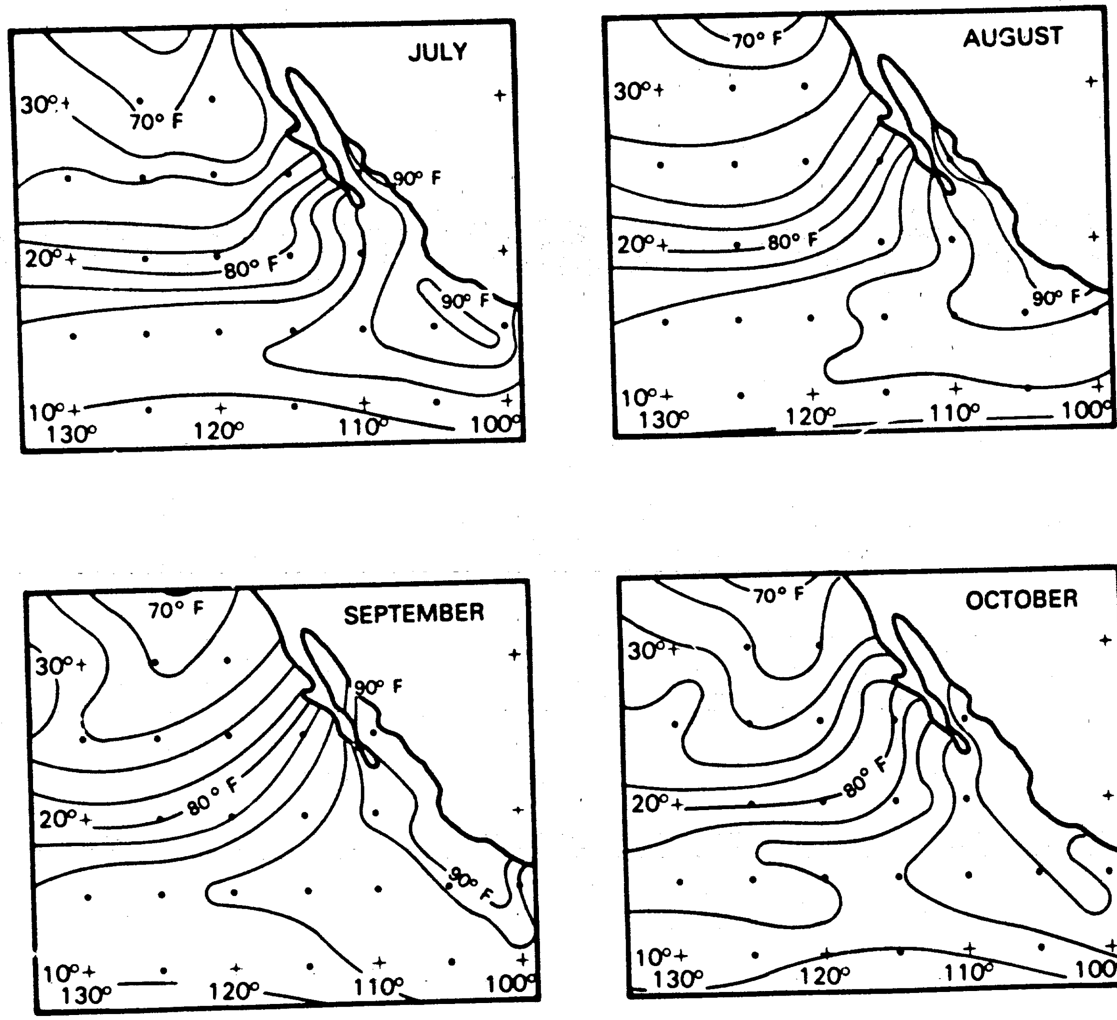


Figure 2.46.--Maximum sea-surface temperature charts for the tropical Pacific for July, August, September and October (Laviolette and Seim 1969).

The importance of the magnitude of SST relevant to tropical cyclones and subsequent rainfall is emphasized in a study by Pyke (1972). Pyke concludes that SST anomalies are quite important in the determination of the amounts of precipitation which fall over various regions of the Southwest.

Development and maintenance of tropical cyclones are dependent on magnitude and extent of SST. Even though the Gulf of California waters are considerably warmer than those of the Pacific Ocean off the Baja California coast, the areal extent of the gulf is limited, and therefore, the total effect of these warmer waters is limited. Gilman and Peterson (1958) estimated that a circular sea area with a diameter of about 400 mi is required for sustaining a tropical cyclone. Accepting such an estimate, the narrow Gulf of California can play only a secondary role in the maintenance of a tropical cyclone circulation.

2.4.3 Climatology of Eastern North Pacific Tropical Cyclones

Douglas and Fritts (1972) used the period 1947-1971 to summarize tropical cyclone occurrences off the Pacific coast by month and direction of motion within 5° latitude-longitude areas. Some results, taken from this study (reproduced with permission of the authors), are shown in figure 2.47. Direction of motion is indicated to eight points of the compass with the length of each vector giving the percentage frequency of storms moving in that direction, from the center of the grid. The number in each grid represents the storms observed.

In figure 2.47, the gradual shifting of the tropical cyclones toward more northerly latitudes from June through September is apparent. The consequence of this shift is that the greater the number of tropical cyclones that reach latitudes north of 20°N, the greater is the likelihood of encounter with a mid-latitude trough that will carry the storm into the Southwest. In addition, the mid-latitude trough may contribute to the intensification of the tropical cyclone related rainfall (see section 2.2.1.3).

2.4.4 Factors Important to the Magnitude of Tropical Cyclone Rainfall in the Southwest

We have briefly discussed the climatology of SST in the eastern Pacific Ocean. The prevailing SST have an important bearing on the magnitude of both the tropical cyclone rainfall intensity and the related rainfall in the Southwestern States. Two features of SST that are particularly important to subsequent rainfall are the prevailing SST over and in the vicinity of the area in which the tropical cyclone develops, and the prevailing SST over the path followed by the tropical cyclone to the Southwestern States.

The higher the prevailing SST over and near the area over which the tropical cyclone develops, the greater the potential rainfall. This comes about because the tropical cyclone is fueled by the latent heat released by the lifting of moist air. Once formed over warm SST, the tropical cyclone must not move over SST that are too low, in reaching the Southwest, or its intensity will be too diminished to produce PMP caliber rainfall. Although a precise value for too low is difficult to define, experience indicates that SST significantly less than 75°F requires an increased rate of travel by a tropical cyclone if it is to maintain its rain potential. The New England hurricane of September 1938 is a good example of an intense fast-moving storm at a high latitude. Apparently, in this case, fast movement was at least partially responsible for the retained intensity insofar as it shortened the time for colder ocean temperatures to adversely affect the storm's intensity.

Assuming other factors are equal, and like that of other storm systems, the slower the movement of a tropical cyclone over a target drainage, the greater the rainfall intensities. The rain is more concentrated in space and therefore results in higher extremes. Taking into account this and the effects of SST, an optimum condition would be a well-developed tropical cyclone traveling rapidly over lower SST, and then slowly (consistent with other factors) over a target drainage.

Mountainous terrain or extensive land masses upwind of the study region will reduce rain potential of the tropical cyclone over the study area. Two effects are involved. One is that mountains or land masses encountered prior to reaching the target area will reduce the cyclonic circulation through obstruction and friction and thus affect the ability of the system to efficiently import moist

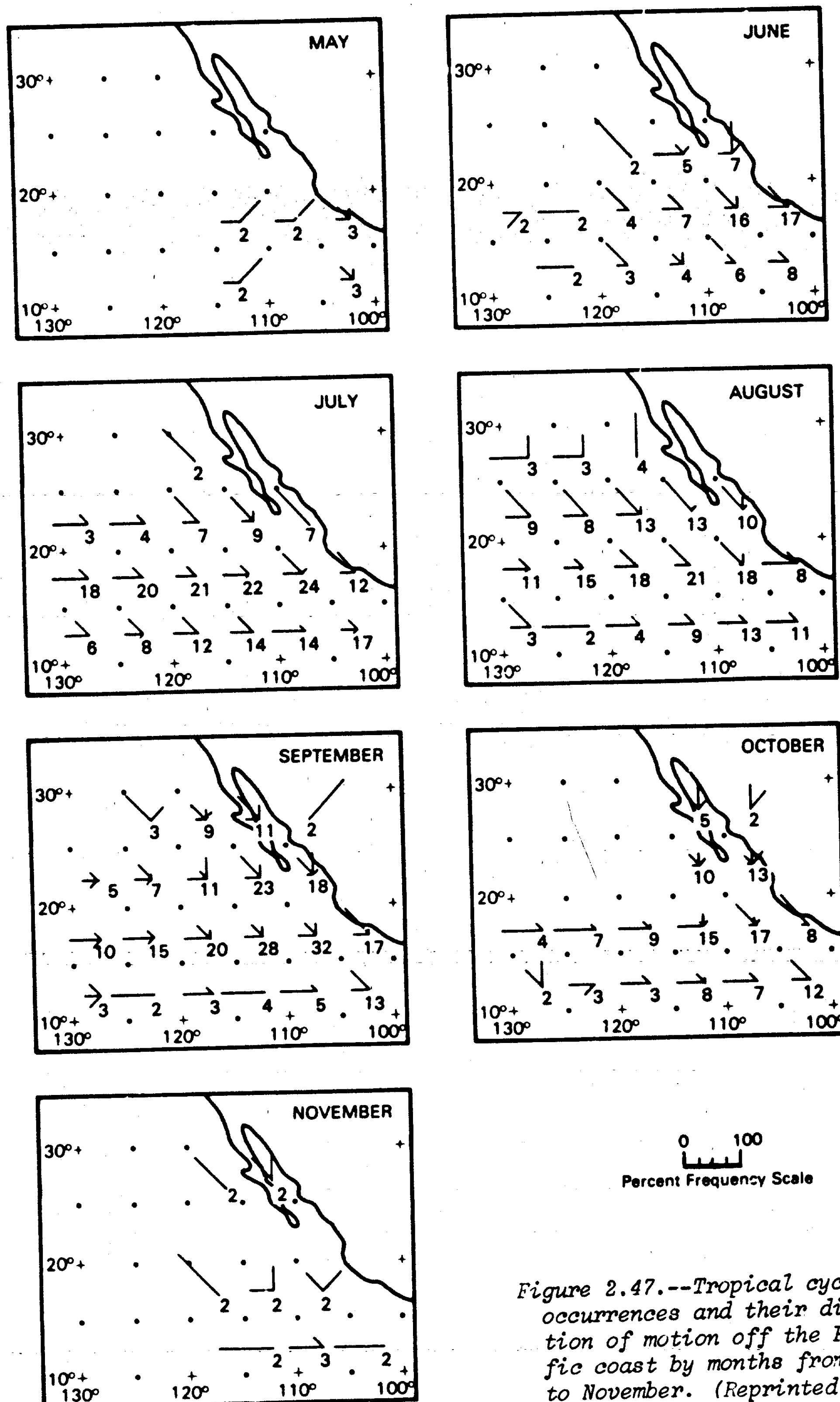


Figure 2.47.--Tropical cyclone occurrences and their direction of motion off the Pacific coast by months from May to November. (Reprinted with permission of Douglas and Fritts 1972).

air from its source. The other is that windward-facing slopes will trigger rainfall, preventing it from reaching a target drainage to the lee.

For a region like the Southwest, where full-fledged (or intensive) hurricane circulations are not likely because of upwind terrain effects, rainfall potential for 24 hr or less may be enhanced by an efficient interaction with an extratropical circulation. The extratropical system that provides greatest storm potential is a pronounced mid-latitude trough of low pressure accompanied by unseasonably cold air.

2.4.5 Discussion of Features of Tropical Cyclones Affecting the Southwest

A number of tropical cyclones in the eastern Pacific have impacted the Southwest and California. Figure 2.2 shows tracks of storms selected from this sample. These storms will be discussed individually in the framework of providing clues to rain-enhancing factors of the hypothetical tropical cyclone related PMP event for the Southwestern States. The factors discussed in section 2.4.4 are a part of this framework. The two most important storms in this study are the September 1970 and August 1951 storms. The hypothetical storm is a composite of these storms, modified by factors from other tropical cyclones that are discussed subsequently.

2.4.5.1 September 4-6, 1970. This storm is noteworthy for its record-breaking 1-day rains (see section 2.2.1). The storm center crossed the Baja California coast near 27°N (fig. 2.2) where mean SST are near 75° (fig. 2.45). Pyke (1975b) has shown that SST were probably not much above normal for this month. The most important aspect of this storm in its latter stages was the interaction of tropical moisture with cold mid-latitude air, which helped in the efficient production of rainfall (see section 2.2.1).

In the September 1970 storm we believe there are at least two factors that could have produced even greater rainfall. One of these would be SST significantly above normal. Rainfall would also have been increased by a well-defined cyclonic system of winds reaching inland at least to the southern edge of Arizona.

2.4.5.2 August 26-29, 1951. Significantly prolonged rains for durations of about 3 days were characteristic of this storm. As in the September 1970 storm, Pyke (1975b) has shown the August 1951 storm also occurred without high SSTs along its track (fig. 2.2), which, if present would almost certainly have increased the total rainfall.

A significant feature of the August 1951 storm was the efficient use of the moisture that advanced northward in advance of the parent tropical cyclone. Such a feature combined with a more concentrated and intense 1-day rain (characteristic of the September 1970 storm) helped in formulating a hypothetical tropical cyclone related event that could produce PMP for durations out to 3 days.

2.4.5.3 September 12-14, 1918 and September 24-26, 1939. Pyke (1975a) determined that the September 1939 storm was associated with well above normal SST. This may have been true also in the September 12-14, 1918 storm, although supporting data are not available. Both storms produced tropical cyclone related rainfall far to the north of most other storms (fig. 2.2). The September 1918 storm produced record rainfall at Red Bluff, Calif. (see section 3.3.3.1).

The rains in the September 24-26, 1939 storm were both more intense and more widespread than in September 1918. The relative importance of the rains can be gleaned from comparing Red Bluff's 4.70 in. [98%] in 3 hr (table 4.1, HMR No. 49) for the September 1918 storm to the 6.45 in. [190%] in 6 hr at Indio, Calif. in September 1939 (fig. 2.2, HMR No. 49). The fact that the September 1918 storm moved over increasingly cooler waters could account for the lesser rainfall.

2.4.5.4 September 28-30, 1932. This storm demonstrates that if all other factors are assumed equal, a tropical cyclone track (fig. 2.2) restricted to the Gulf of California results in a net loss in potential for heavy rain production. We believe this is caused by two factors: a) the small size of the Gulf of California which limits the amount of energy to be gained from its warm waters and b) the terrain along both east and west coasts of the gulf acts to diminish the circulation. We therefore expect that the least net loss (or possibly a net gain) would be for a storm that crosses the extreme northern portion of the Gulf of California. Relative to the northern Gulf of California, the offshore Pacific waters are as much as 10° cooler and therefore have a diminishing effect on tropical cyclone circulation. We assume the September 1932 storm's path over the lower portion of the Gulf of California sacrificed the optimum use of the greater expanse of warm Pacific waters at these low latitudes. We postulate that the hypothetical extreme storm should remain over the Gulf of California for only a short time. This is in contrast with tropical cyclone Joanne (section 2.4.5.6) whose short-lived but timely movement over the northern gulf apparently resulted in a net gain in intensity.

2.4.5.5 September 30 - October 6, 1972 (Joanne). Remnants of this tropical cyclone's circulation entered Arizona between Yuma and Tucson on October 6, 1972 (fig. 2.2). Ingram and Kangieser (1973) state, "What is unique about this storm is that it is believed to be the first time that a tropical storm, as such, has entered Arizona with its circulation intact!" What remained of the tropical cyclone at the time was producing winds of 35 to 45 mph.

At sea, while still classified as a hurricane, Joanne had sustained winds of about 85 kt with gusts to 105 kt (Ingram and Kangieser 1973). Upon nearing 19°N, the colder Pacific water began taking its toll and Joanne's sustained winds near the center were reduced to about 65 kt. Crossing the 3,000- to 5,000-ft saddle of the Baja California peninsula failed to dissipate the circulation. Crossing higher elevations undoubtedly would have had a greater effect. Thus, crossing Baja California at a favorable location is another important factor in maintaining a storm's circulation. As the storm crossed over the Gulf of California on October 6, sustained winds of 40 kt with gusts to 55 kt were observed. Just before entering Arizona, Joanne may have had a small gain in energy from the Gulf of California which helped sustain its circulation while moving into Arizona. Joanne's track was such that the limited supply of warm Gulf of California moisture added energy to partly counteract the negative effect of the mountains of Baja California on the circulation. In this regard, Joanne followed a track recommended for the hypothetical tropical cyclone.

2.4.5.6 August 31 - September 2, 1967 (Katrina). The track of Katrina is an example of a track somewhat modified from that of Joanne (fig. 2.2). Katrina crossed the Baja California peninsula roughly 5° farther south than Joanne. Although the terrain elevations at crossing were about the same, Katrina moved somewhat faster than Joanne, but still suffered a loss in storm intensity. However, the cyclone then moved over the warm Gulf of California and was able to regain some of its lost intensity from these warm waters. The remnants of this storm produced more than 2 in. of rain at Yuma, Ariz.

Joanne and Katrina illustrate that we do not as yet have a record of sufficient varients of storm movement to know the optimum track of a tropical cyclone crossing the Baja California peninsula and moving over the northern portion of the Gulf of California so that the net result would be a maximum storm circulation and maximum moisture upon making landfall in Arizona.

2.4.6 Conclusions on Hypothesized Tropical Cyclone Events

Using the factors in secton 2.4.4 supported by clues from storm experience discussed in section 2.4.5, we synthesized hypothetical conditions that could lead to extreme tropical cyclone rainfall concentrating in Arizona. The remnant tropical cyclone's circulation must track into the State. For rains to be concentrated in other areas of the Southwest, certain variations are required. Hypothesized conditions are:

a. Antecedent synoptic scale weather features that permit the accumulation and transport of significant moisture into the southwest well ahead of a tropical cyclone circulation. The moisture is necessary for the rainfall to be of long duration. The August 1951 storm that gave the greatest long duration rainfall of record had such an antecedent weather feature. This feature allows for substantial rainfall prior to that associated with the hypothesized tropical-cyclone circulation.

b. A part of the necessary synoptic conditions are the southward development of a mid-latitude cold trough aloft to help accelerate the storm as it turns northward and/or north-northeastward and crosses the Baja California coast and its mountainous backbone at the lowest elevation (near 29°N latitude) consistent with these requirements, particularly (e), and also with (a) above. The accelerated speed decreases the time the storm spends over land and therefore minimizes loss of intensity. In the optimum case, the tropical cyclone should regain some of its intensity as it moves over the small area of warmer waters of the northern portion of the Gulf of California.

c. Maximum or near maximum SST off the west coast of Baja California. This permits an offshore tropical cyclone to remain fully developed farther north than under normal SST conditions. This apparently was the case with the September 24-26, 1939 storm. Tropical storm Joanne in October 1972 (section 2.4.5.5) was also fed by above-normal SST, (Pyke 1975b).

d. A well formed tropical cyclone, gaining intensity well south of Baja California and moving slowly northwest or northward so as to permit the optimum realization of the antecedent tropical cyclone rainfall.

e. A tropical cyclone track which, after reaching the latitude of Baja California, parallels the coast at just the right distance offshore so that, in addition to having a good supply of energy from Pacific Ocean waters, the outer fringes of the massive storm circulation also draws from the very warm waters of the Gulf of California.

f. Entrance into southwestern Arizona with a circulation of greater strength than any produced in the limited record, after which the remnant storm should interact with a significant mid-latitude frontal system associated with the extremely cold trough or low pressure aloft, as occurred in the disastrous storm of September 1970.

3. LOCAL STORMS

3.1 Introduction

This chapter provides information on the meteorological character of significant short-duration, small-area storms (local storms). In the previous chapters, the stipled region in figure 1.1, and west of the dotted line in figure 3.1, were not considered. This portion of California, which contains the Pacific Ocean drainages, is referred to as Western California in this chapter.

The chapter surveys the data of local storms in the region, and describes the distribution of observed storms with regard to elevation, moisture, and terrain. Brief meteorological descriptions are given for some of the more important local storms considered in the development of local storm PMP. A total analysis of these storms would require a detailed mesoscale analysis, and this is not possible for the older storms and even for many of the more recent storms in the Western United States, because the network of observing stations is too widely scattered. The descriptions are followed by a summary of characteristics observed in extreme local storms such as moisture, instability, precipitation efficiency, inflow direction and storm movement, and the phenomenon of cloud mergers.

3.1.1 Definition of a Local Storm

In this study, we have chosen to define a local storm as unusually heavy rains exceeding 3.0 in. in 3.0 hr or less, that are reasonably isolated from surrounding rains. Some authors refer to storms of this nature as air mass thunderstorms. Because the area of rainfall observed in a storm is a function of both the horizontal extent of the storm and the density of observing stations in the vicinity of the storm, we find that some local storm events are represented by only one observation. Others are broad enough and occur over a region with a sufficient gage density that approximate isohyets can be analyzed.

The degree of isolation for each storm varies from those with no rainfall reported in the vicinity of the exteme local storm to those with scattered amounts at surrounding locations. A decision to include a particular storm as an isolated storm was based on a somewhat subjective determination that the surrounding scattered rains were not associated with any organized meteorological system; i.e., low-pressure center, front, closed upper-level Low or trough, etc. Since upper-level data are available only since 1945 for stations even more scattered (approximately 200 miles apart), only surface features can be used for storms prior to this date.

In the storms considered in this study, it is unlikely that the maximum rainfall listed represents the largest value in the storm. Precipitation in storms is highly variable and the probability of the maximum amount occurring

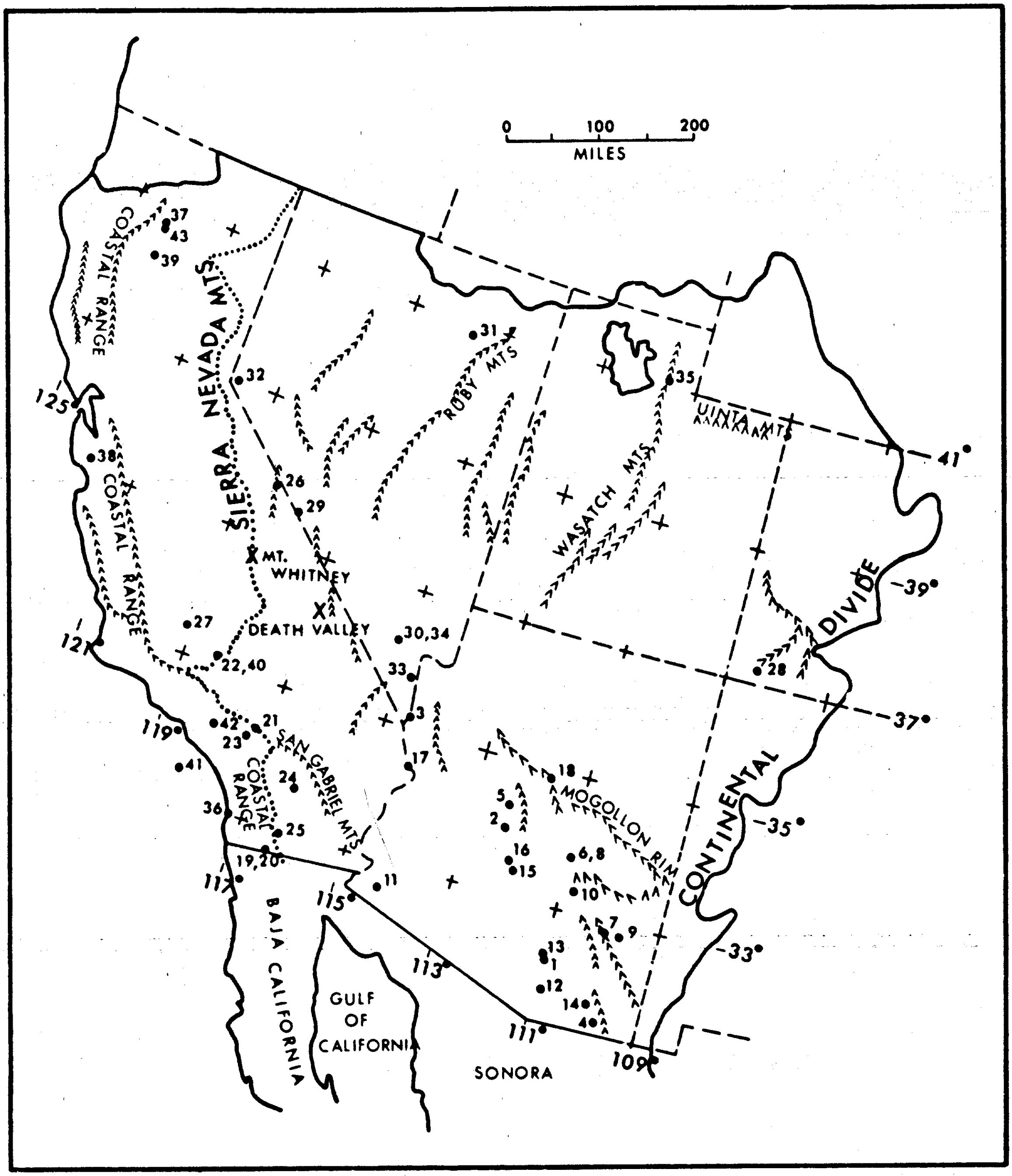


Figure 3.1.--Region for which local storm PMP is given in HMR No. 49 showing location of extreme local storm rains.

over a rain gage is extremely small. For this reason, field investigations are conducted after most known intense rains to find supplementary measurements that might more truly measure the maximum rainfall amounts. In many cases, particularly in the Western United States where the population density is low, the maximum value obtained is still less than the maximum amount of rain that fell.

3.1.2 Data Sample

The storms of record that were considered in the initial development of the local storm PMP in HMR No. 49 are listed in table 3.1, according to the State in which the extreme point rainfall occurred. In this list, the rainfalls at La Quinta, Calif., and Las Vegas, Nev. (7/3/75), had durations that exceeded our criterion by one-half hour. These limited exceptions to the definition were considered acceptable.

It was noted early in our study that only four storms (Campo 1891, Campo 1922, Cucamonga, and Bakersfield) listed in table 3.1 occurred in Western California. Squirrel Inn and Tehachapi, Calif. lie on the boundary between regions. Therefore, in the development of local storm PMP, it was decided that additional data would be needed in Western California. A simple reduction in the 3.0 in. depth criteria did not point to any additional storms.

The decision was made to consider additional intense storms, in California only, which met the 3.0 in. criterion, but which may have been associated with an organized meteorological system involving tropical moisture. Some of the bases for this decision may become more clear by the discussions of meteorological characteristics in section 3.5. Under this exception, the storms in table 3.2 were included in the local storm PMP analysis. In two instances (Encinitas and Kennett), durations of 8 hours were accepted, while in two other storms (Tehachapi (9/30/32) and Newton) 6-hr durations were accepted.

In tables 3.1 and 3.2, the information is listed according to station, date, location, elevation (approximate for maximum point rainfall location), maximum point amount (both in inches and as a percentage of the 100-yr 6-hr rainfall), duration, time of onset of heavy rain (U = unknown), and a reference to the source where the rainfall amount was first reported, or to another discussion of the event. Not all of the reference material is readily available, but can be provided upon request.

The number of significant figures used to represent each rainfall is that given in the original report of the event and gives some feel for the accuracy of the observed point rainfall amounts in table 3.1 and table 3.2. The 6 in. observation at Wellton 15 WSW, Arizona (8/23/55) is considered less accurate than the 5.02 in. amount observed at Sierra Ancha, Ariz. (8/5/39). No adjustment was made for this variation in accuracy.

The reliability of the reported rainfalls for three of the events in tables 3.1 and 3.2 have been questioned in this study. The 8.8 in. rainfall amount reported at Palmetto, Nev. (8/11/1890) has already been judged doubtful (U.S. Weather Bureau 1960) on the basis of detailed study. Another indicator that the Palmetto amount may be questionable comes from the fact that it has the highest percentage of 100-yr 6-hr value, 463%, larger than the next highest percentage by 80%. A second doubtful report was an estimate of 7 in. obtained in the Morgan, Utah event (8/16/58). This maximum was based on an amount caught in a milk can hung on a fence post. The position of the container relative to incident

Table 3.1.--Local storms considered in Southwest, listed chronologically by state. Index numbers refer to locations in figure 3.1. (Refer to end of table for legend).

Index no.	Station	Date	Lat. (°)	Lat. (')	Long. (°)	Long. (')	Elev. (ft)	Amount (in.)	Amount (%)	Dur. (min)	Time began (LST)	Reference+
	ARIZONA											
1	Tucson	7/11/78*	32	13	110	58	2360	5.10	142	105	1645	MWR 7/78*
2	Farley's Camp	8/28/91*	34	02	112	18	2600	3.10	91	90	U	MWR 8/91*
3	Ft. Mohave	8/28/98*	35	03	114	36	540	8	258	45	U	CCSB 8/98*
4	Bisbee	7/22/10	31	27	109	55	5500	4.25	118	70	U	Green & Sellers 1964
5	Crown King	8/11/27	34	12	112	29	6000	4.90	109	170	U	Leopold 1943
6	Sierra Ancha	9/10/33	33	48	110	58	5100	4.28	95	105	U	#1
7	Pima	8/02/39	32	51	110	02	4230	3.10	103	60	U	Langhein 1941
8	Sierra Ancha	8/05/39	33	48	110	58	5100	5.02	112	140	U	USCE 1961a
9	Thatcher	9/16/39	32	51	109	46	2800	4.1	146	90	U	USCE 1961a
10	Globe	7/29/54	33	20	110	43	3540	3.5	106	40	1810	#2
11	Wellton 15 WSW	8/23/55	32	37	114	20	2800	6	167	180	1700	#3
12	Santa Rita	6/29/59	31	45	110	51	4400	4.5	113	60	1645	#4
13	No. Tucson	9/06/64	32	18	110	00	2450	5	132	120	1400	#5
14	Walnut Gulch	9/10/67	31	42	110	05	1600	3.45	108	70	1600	Osborn & Renard 1965
15	Tempe	9/14/69	33	22	111	58	1150	3.52	110	60	1800	#6
16	Phoenix	6/22/72	33	27	112	04	1120	5.25	164	120	0600	USCE 1972
17	Lk. Havasu City	7/19/74	34	26	114	20	48	4.5	141	60	U	#7
18	Sedona	7/14/75	34	53	111	46	4320	3.5	103	60	1630	Selvidge 1975
	CALIFORNIA											
19	Campo	8/12/91*	32	36	116	28	2590	11.5	383	80	1140	USWB 1960
20	Campo	7/18/22	31	42	110	05	1600	3.45	108	70	1600	Osborn & Renard 1965
21	Squirrel Inn	7/18/22	34	14	118	15	5240	5.01	76	90	1000	CD 7/22
22	Tehachapi	10/06/45	35	08	118	27	3990	3.17	127	80	U	#8
23	Cucamonga	9/29/46	34	05	117	25	1650	3.2	91	91	U	#9
24	LaQuinta	7/22/47	33	40	116	19	50	3	107	210	U	USCE 1957
25	Vallecito	7/18/55	32	58	116	21	1430	7.1	237	70	1440	#10
26	Chiatovich Flat	7/19/55	37	44	118	15	10320	8.25	330	150	U	Kesseli & Beaty 1959
27	Bakersfield	6/07/62	35	45	119	03	475	3.5	206	75	1430	Bryant 1972
	COLORADO											
28	Mesa Verde Pk.	8/03/24	37	12	108	29	6960	3.50	152	45	U	CD 8/24

Table 3.1.--Local storms considered in Southwest, listed chronologically by state. Index numbers refer to locations in figure 3.1. (Refer to end of table for legend). Continued

Index no.	Station	Date	Lat. (°)	Lat. (')	Long. (°)	Long. (')	Elev. (ft)	Amount (in.)	Amount (%)	Dur. (min)	Time began (LST)	Reference+
	NEVADA											
29	Palmetto	8/11/90*	37	27	117	42	6700	8.8†	463	60	U	USWB 1960
30	Las Vegas	6/13/55	36	11	115	11	2030	3.4	179	35	1710	#11
31	Elko	8/27/70	40	50	115	47	5080	4.13	258	120	1135	CD 8/70
32	Genoa	8/07/71	38	59	119	50	4700	3.50	140	58	U	#12
33	Nelson	9/14/74	35	43	114	49	3500	3.25	105	45	1445	Glancy & Harmsen 1975
34	Las Vegas	7/03/75	36	11	115	11	2030	3	158	210	1130	Randerson 1975
	UTAH											
35	Morgan	8/16/58	41	03	111	38	5159	6.75	321	60	1600	Peck 1958

Legend of symbols, abbreviations, and references used in table.

* - Storm date prior to 1900.
† - Questionable amount, see text.
U - Unknown.
ST - Local standard time.
% - Percent of 100-yr 6-hr rainfall.
+ - Reference identification.

MWR - Monthly Weather Review, National Weather Service, Washington, D. C.
CCSB - Climate & Crop Service Bulletin, Dept. of Agriculture (early volumes published by state).
USCE - U.S. Army Corps of Engineers, Washington, D.C.
USWB - U.S. Weather Bureau, Washington, D.C.
USGS - U.S. Geological Survey, Washington, D.C.

Unpublished material (copies available from authors of this report).

1. Letter from USCE, Los Angeles District (LAD), April 27, 1944.
2. Report from USCE, LAD, August 24, 1954.
3. Report from USCE, LAD, September 15, 1955.
4. Letter from U.S. Dept. of Agriculture, Exp. Stn., August 21, 1959.
5. Communication from U.S. Geological Survey, Tucson, Ariz., (undated).
6. Letter from Flood Control District of Maricopa County, Ariz., October 8, 1969.
7. Communication from USCE, LAD, (undated).
8. Joint review of Flood Damage, Excerpts Kern and Inyo County, Calif., January 17, 1946.
9. Report from San Bernardino, County Flood Control District, Calif., October 4, 1946.
10. Report from USCE, LAD, August 5, 1955.
11. Report from USCE, LAD, July 6, 1955.
12. Communication from USGS, Carson City, Nev. (undated)

Table 3.2--Supplemental short duration storms considered in Western California. (See table 3.1 for legend, index numbers refer to locations in figure 3.1).

Index no.	Station	Date	Lat. (°)	Lat. (')	Long. (°)	Long. (')	Elev. (ft)	Amount (in.)	Amount (%)	Dur. (min)	Time began (LST)	Reference+
	CALIFORNIA											
36	Encinitas	10/12/89*	32	59	117	15	100	7.58	303	480	2200	MWR 10/89*
37	Kennett	5/09/15	40	45	122	24	730	8.25	156	488	1200	Weaver 1962
38	Wright	9/12/18	37	08	121	55	1600	3.5	64	60	U	Weaver 1962
39	Red Bluff	9/14/18	40	09	122	15	320	4.7	181	180	U	Weaver 1962
40	Tehachapi	9/30/32	35	08	118	27	3960	6.2	248	300	1500	CD 10/32
41	Avalon	10/21/41	33	21	118	19	10	5.53	-	210	0700	Weaver 1962
42	Los Angele	3/02/43	34	11	118	01	1500	3.32	60	180	2100	USCE 1958
43	Newton	9/18/59	40	42	122	22	700	10.6	236	300	1700	Weaver1962

rainfall could not be determined in a follow-up review (summary report by National Weather Service hydrologist, 5/19/64, and also in Butler and Marsell 1972), and therefore the accuracy of the catch could not be fixed. The amount given in table 3.1 for this storm is the next highest rainfall reported, 6.75 in., which was measured in an upright garbage can. The third report that is regarded as questionable is that for the storm at Wrights, Calif. (9/12/18). Wrights reported 8.75 in. for this date, and Weaver (1962) estimated a 1-hr value of 3.5 in. by subtracting an average daily rainfall of 5.25 in. obtained from nearby surrounding stations. His study of this storm was based on his conclusion that the intense rainfall at Wrights was not observed at these other surrounding locations. Weaver's 1-hr estimate is listed in table 3.1, however.

We chose not to consider the three local storm maxima at Palmetto, Morgan, and Wrights equally with the other events in tables 3.1 and 3.2, during the development phase of PMP in HMR No. 49, but have included brief comments in this report regarding available synoptic weather descriptions.

3.2 Physiographic Distribution of Local Storms

In developing a regional pattern of PMP, relations between storm rainfall amounts and specific physiographic characteristics sometimes provide guidance. The rains in table 3.1 were considered with regard to their distribution with elevation, moisture sources, and terrain roughness. The intent here is to point out any relationships characteristic of extreme local storms in the region.

3.2.1 Distribution Relative to Elevation

A wide range of elevation is found in the Southwest, varying between a low of 280 ft below sea level (Death Valley, Calif.) and a high of 14,495 ft (Mt. Whitney, Calif.). These are the lowest and highest points in the contiguous United States, although they are located less than 100 mi apart (see fig. 3.1).

Elevations for the locations of point rainfall extremes in table 3.1 were plotted against the corresponding rainfall amounts, as shown in figure 3.2. There is a restrictive distribution of observing stations since few stations are located on rugged slopes or ridges in the remote areas that dominate the Southwest. All but three (Chiatovich Flat, Mesa Verde, and Palmetto) of the storms in this figure occurred over locations that were at or below 6,000 ft. The scatter of points does not suggest any obvious correlation between rainfall amount and elevation, either collectively or within individual states. Nevertheless, there appears to be some slight trend in an envelope curve or an eye fitted trend line through the mass of data to suggest a decrease with elevation. Another reason that could support a limit to extreme rains with elevation is the decrease in moisture with increasing elevation.

The information in figure 3.2 was used as a guidance in developing the concept in HMR No. 49 (see p. 109) that maximum precipitation could occur without reduction throughout a 5,000 ft range in elevation.

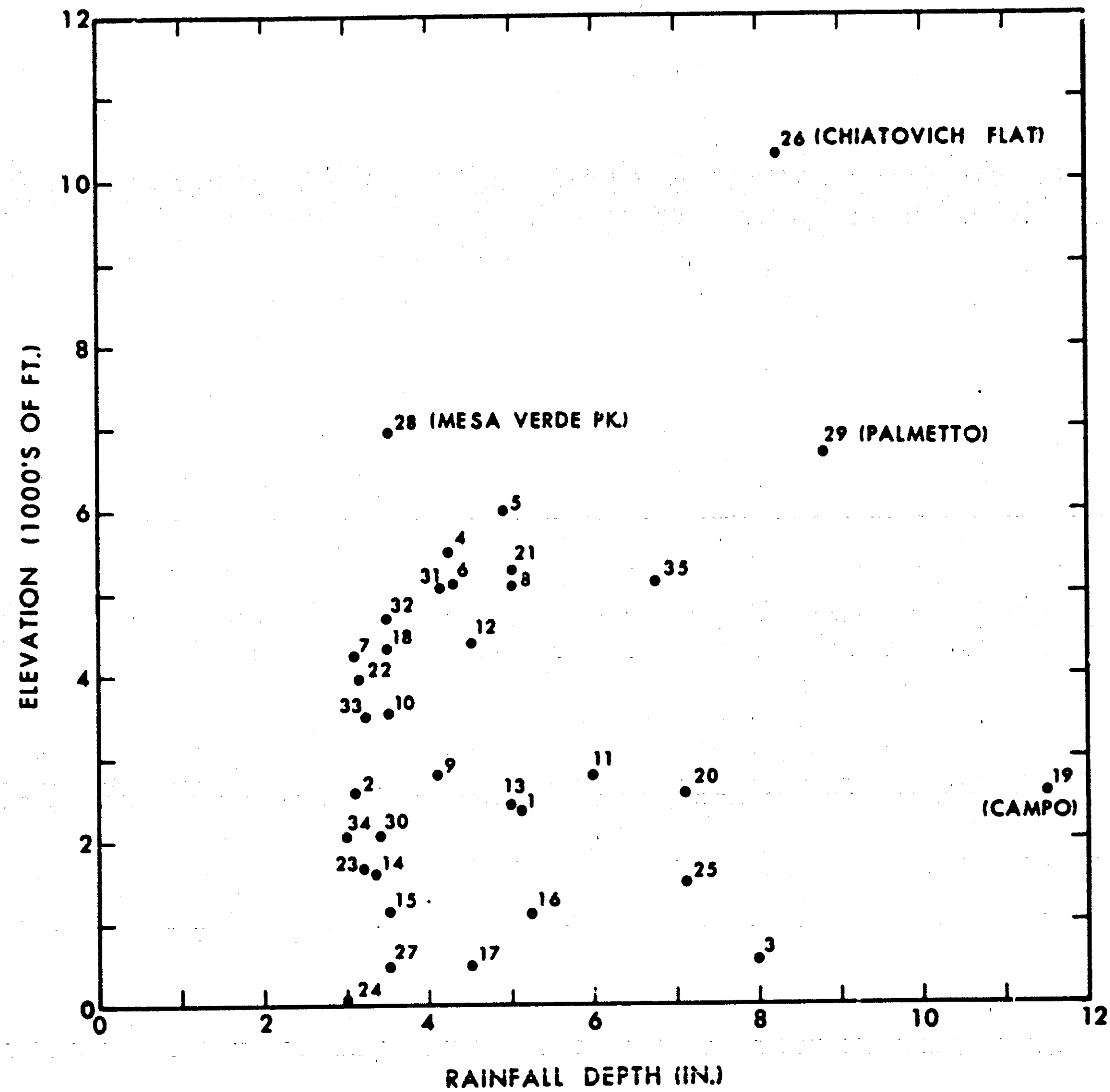


Figure 3.2.--Point rainfall extremes for local storms vs. elevation at which the data were observed. Refer to table 3.1 for storm identification.

3.2.2 Distribution Relative to Moisture Sources

The sources of moisture available to storms affecting the Southwest are the Gulf of Mexico, the tropical Pacific Ocean and the Gulf of California*, and the eastern Pacific Ocean at latitudes north of about 30°N. The Gulf of Mexico lies over 1,000 mi from the nearest major storm occurrence in the Southwest (Bisbee, Ariz.). Between the Gulf of Mexico and the Southwest, the terrain rises, gradually, and numerous ridges of 4,000-5,000 ft force moist air to higher levels or to the northeast of the Continental Divide. Moist air from the Gulf of Mexico that may arrive over the Southwest occurs at elevations in excess of 5,000 ft. The actual height of Gulf of Mexico moisture in the Southwest may be considerably above this level (closer to 9,000 or 10,000 ft) because moisture trajectories in the absence of convection tend to follow along isentropic surfaces. From the Gulf of Mexico, there is a general rise in height of an isentropic surface in the direction that would bring moisture from this source to the Southwest at these altitudes.

Moisture from the tropical Pacific Ocean via the Gulf of California has more or less direct access at low levels into the southern portion of the Southwest, since the northernmost part of the gulf is separated by a distance of about 50 mi from the southern Arizona border. Sea surface temperatures in the upper Gulf of California are on the order of 80 to 90°F in the warm season. These high temperatures provide an immediate source of high moisture to the surrounding vicinity, but since the areal extent of this source region is small, its influence is undetermined. How this moisture is drawn into the Southwest will be discussed in section 3.5.1.

The eastern Pacific Ocean provides most, if not all the moisture to California slopes that drain into the Pacific, and contributes considerable moisture to the Great Basin region in association with the eastward passage of major weather systems. To do so, Pacific moisture must pass over substantial barriers (the Sierra Nevada is the most prominent), although a limited amount may enter at low levels around the southern end of the Sierra Nevada-Tehachapi Mountain chain.

In figure 3.1, almost all the local storms (except Elko, Morgan and Mesa Verde Park) occur within 300 mi of the Pacific coastline, although this does not imply that moisture to these storms followed the most direct route in reaching the storm location. Moisture from the Gulf of California and the tropical Pacific contributes to major local storms at Phoenix (6/22/72), Elko (8/27/70), and Morgan (8/16/58), according to a study by Hansen (1975b). These sources are the most probable contributors to at least an additional 20 extreme storms listed in tables 3.1 and 3.2. The remaining 20 storms listed here have not been studied in detail, primarily because of lack of data for the storms before 1950. Additional discussion of moisture sources is given in the review of individual storms in sections 3.3 and 3.4 and in section 3.5.1.

*In the remainder of this chapter, reference to moisture sources as the Gulf of California implicitly mean moisure channelled through the gulf from the tropical Pacifc Ocean. We have no information to distinguish moisture moving through this channel from that which may originate within this narrow water body.

3.2.3 Distribution Relative to Terrain Roughness

The location of each major rainfall relative to terrain features such as mountain ridges was considered. The terrain throughout the Southwest is generally rough as compared to the Great Plains. Since the terrain in the Southwest is so complex, it is difficult to determine a generalized relationship between the observed local storms and terrain. As will be described in sections 3.3 and 3.4, many of the storms occurred on the slopes of ridges generally facing inflow from southerly directions. Others however occurred over valleys where the effect of terrain was less clear.

3.3 Meteorology of Specific Extreme Local Storms

As indicated in HMR No. 49 the present report includes meteorological analyses of the synoptic weather surrounding most of the significant storms considered in developing local storm PMP. In the finalized version of HMR No. 49, a majority of the storms listed in table 3.1 were considered not significant to the study in that they were exceeded by nearby controlling storms amounts. Controlling storms are those most closely enveloped in drawing PMP analyses for the area sizes and durations of interest. Four of the storms in table 3.1 (Campo 1891, Ft. Mohave, Chiatovich Flat, and Morgan) were considered controlling. In table 3.2, Avalon and Newton were judged controlling for part of Western California.

We have chosen not to give a meteorological description for all the storms listed in table 3.1. The basis for including those that have been described was the percentage the observed rainfall is of the 100-yr 6-hr amount. Storms for which this percentage exceeded 150 are described (listed in table 3.3). Since the storms in table 3.2 are considered important supplements to local storm PMP in Western California, a meteorological discussion is given for each of these storms. Macroscale pressure maps have been included in the discussions to illustrate the likely influence or lack thereof by organized synoptic weather systems on the reported rainfall. Comparisons can also be made between these observed conditions and the normal weather patterns given in appendix A.

Table 3.3.—Storms in table 3.1 for which meteorological description is included

Index number (see table 3.1)	Location	Date
3	Ft. Mohave, Ariz.	8/28/1898
11	Wellton 15 WSW, Ariz.	8/23/1955
16	Phoenix, Ariz.	6/22/1972
19	Campo, Calif.	8/12/1891
20	Campo, Calif.	7/18/1922
25	Vallecito, Calif.	7/18/1955
26	Chiatovich Flat, Calif.	7/19/1955
27	Bakersfield, Calif.	6/07/1972
28	Mesa Verde Park, Colo.	8/03/1924
29	Palmetto, Nev.	8/11/1890
30	Las Vegas, Nev.	6/13/1955
31	Elko, Nev.	8/27/1970
34	Las Vegas, Nev.	7/03/1975
35	Morgan, Utah	8/16/1958

3.3.1 Ft. Mohave, Arizona 8/28/1898

An extreme rainfall of 8 in. [258%]* fell in about 45 minutes at Ft. Mohave, Ariz., 75 mi southsoutheast of Las Vegas, Nev. (National Oceanic and Atmospheric Administration 1897-). The observer reported;

> "On the 28th, we had the biggest rain in 10 or 15 years, and to my regret, between the rain and the furious wind, my rain guage was upset. To give an idea of the amount of rain that fell, and which lasted only 45 minutes, I had a wash tub set out on the mesa clear of everything, and the water after the rain measured 8 inches."

Ft. Mohave is situated on a plateau, averaging about 550 ft in elevation, just to the east of the north-south flowing Colorado River which cuts through the valley. About 10 mi to the east and west the valley rises to ridges of more than 2,000 ft, with one peak of 5,000 ft.

The surface pressure maps in figure 3.3 for August 28 and 29, 1898 have been drawn from widely scattered data, and provide only a rough sketch of the conditions at the time of this event. These maps indicate a broad region of low pressure consistent with the normal position of the thermal low.

For this date, the maximum temperature of 90°F and 1000-mb dew point temperatures** of 72°F at Yuma, Ariz. represent the closest surface data to Ft. Mohave. The Climatological Data Summary (National Oceanic and Atmospheric Administration 1897-) indicated that only 12 out of 59 stations in Arizona reported rainfall for the 28th. Similar sparseness of rainfall reports was given for stations nearby in Nevada and Calif. However, the period between August 18 and 27 showed more than half the Arizona stations reported rainfall (Ft. Mohave reported only a trace prior to the 28th).

Although we are unable to make a specific analysis from these data that would point to the likely source of moisture or cause of extreme rainfall, we can provide some educated speculation that will gain some support from the discussions of more recent events to follow. It is possible that the Ft. Mohave local storm developed in a situation of extreme surface heating that may have resulted from clearing skies. Low-level moisture evaporated from a surface wet by showers to the south of Ft. Mohave during the previous few days may have provided much of what was needed for this unusual local storm.

3.3.2 Wellton 15 WSW, Arizona 8/23/55

At the Texas Hill Farm, about 15 mi WSW of Wellton, an estimated 6 in. [167%] of rain fell between 1700 and 2000 MST (0000 - 0300 GMT August 24). "This storm

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*Value given in bracket is percent of the 100-yr 6-hr rainfall amount.

**In this chapter we make reference to 1000-mb dew points that represent a singular maximum observation or instantaneous value, and are given as a means of comparison among the events discussed. These dew points are therefore somewhat larger than the 12-hr persisting dew points used to moisture maximize observed precipitation in HMR No. 49.

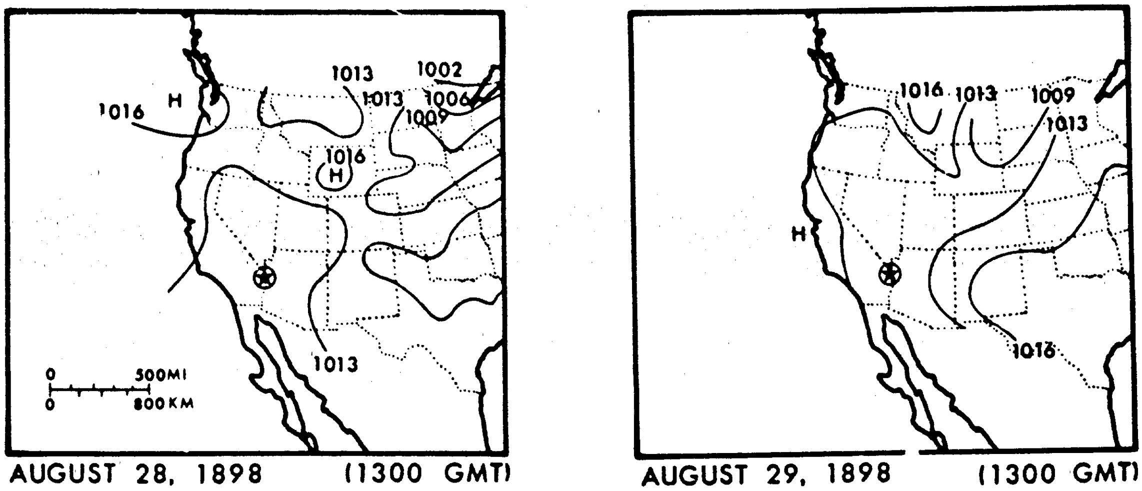


Figure 3.3.--Surface weather maps for August 28-29, 1891.

was the largest that occurred in southwest Arizona over a period of daily thunderstorms between the 12th and 24th" (Unpublished report, U.S. Corps of Engineers 1955, see table 3.1). This storm is described as "...centered over the Gila Mountain, moving from southeast to northwest....Precipitation commenced about 1730 MST (0030 GMT August 24) in the Wellton-Mohawk area and continued for about 2 hours." Yuma, Arizona (approximately 18 mi to the west) received only 0.54 in. between 1700 and 2100 MST (0000 and 0400 GMT of the 24th) for this date.

The Gila Mountains are a ridge of 2,000- to 3,000 ft peaks about 50 mi in length oriented roughly southeast-northwest in the southwest corner of Arizona. The base elevation to the east of the mountains is approximately 500 to 1,000 ft, and slightly lower to the west.

Surface pressure maps for August 23 and 24, 1955 (fig. 3.4) show a small Low centered in southern California. Yuma 1000-mb dew points had increased from 69°F on the 22nd to 75°F on the 23rd and 24th, while the wind was from the south to southeast. Since dew points remained unchanged at El Paso, Tex. and Tucson, Ariz. it is concluded that moisture arrived at the Gila Mountains-Yuma vicinity from the Gulf of California. Heavy runoff was reported on both sides of the Gila Mountains, so it is difficult to determine the direction of moisture inflow to these rains. The observers report of storm clouds moving to the northwest (i.e. along the axis of the mountains) does not resolve this detail.

Aloft at 500 mb (maps not shown) a large high-pressure system was centered over northeastern Arizona on the 23rd. Circulation around this system produced easterly winds over Yuma that brought dry continental air from the Great Plains.

3.3.3 Phoenix, Ariz. 6/22/72

Heavy local storms brought rainfall to northeastern Phoenix the evening of June 21 and again about 12 hr later (U.S. Corps of Engineers 1972). The second storm that began about 0600 MST (1300 GMT) on the 22nd resulted in the greater rainfalls. A maximum of 5.25 in. [164%] was reported for a 2-hr period estimated as between 0600 and 0800 MST (1300 to 1500 GMT) in this storm.

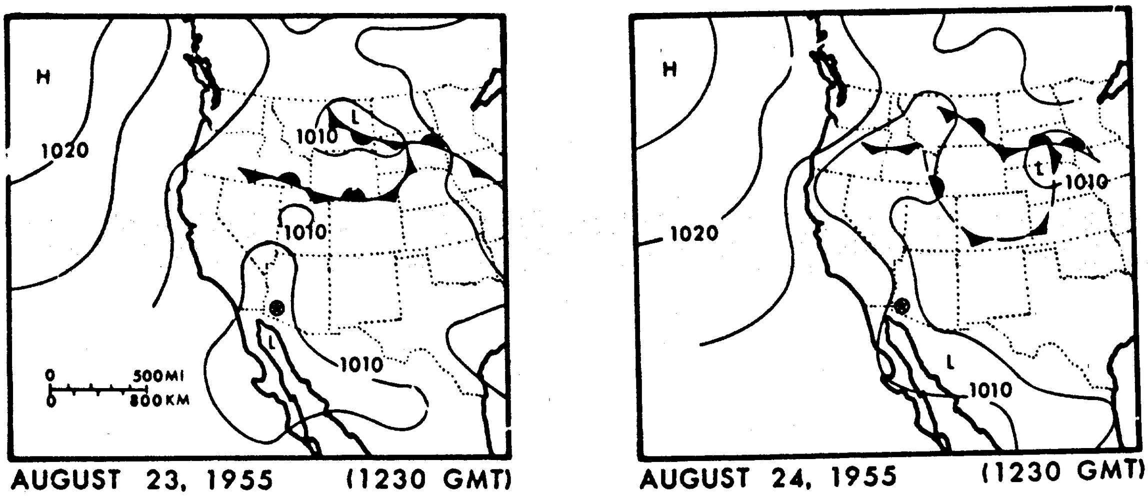


Figure 3.4.--Surface weather maps for August 23 and 24, 1955.

The Corps of Engineers performed a post storm survey of rainfall amounts in this storm. The area within the 0.5 in. isohyet (fig. 3.5) of their analysis was about 310 mi^2 and resulted from a complex multicelled storm that lasted roughly 6 hr, 0600 to 1200 MST (1300-1900 GMT). Orientation of the isohyetal pattern is 010°/190°.

The Phoenix rain was unusual in that it followed several months of below normal precipitation, and occurred in a region only minimally affected by orography. An extensive ridge of mountains rising to peaks exceeding 8,000 ft lies some 50 mi to the north and east, while numerous small ridges (heights of 3,000-4,000 ft and 10-20 mi in length) occur in the general plains to the south and west of Phoenix.

Of interest is the time of onset of heavy rain, 0600 MST (1300 GMT), a time of usually minimum convective activity. The Corps of Engineers report (1972) describes the moisture source for this storm as "...a deep flow of very moist, unstable tropical air that invaded the southwestern United States from the Gulf of California and the Pacific Ocean west of Baja California."

Figure 3.6 shows the surface analyses for 0500 MST (1200 GMT) on June 22 and 23. A small thermal Low is centered in southeastern California and a High is situated in northeastern Arizona. Phoenix lies between these two centers, and the combined circulation about these two systems was favorable for moisture inflow from the region of the Gulf of California into southwestern Arizona.

Hansen (1975b) made an analysis of 1000-mb dew points at 6-hr intervals for California and Arizona during this storm period which showed an influx of low-level moisture (1000-mb dew points >68°F) northward from the Gulf of California to the Phoenix locale beginning 12 hr before the heavy rains (fig. 3.7). This is consistent with the reported rains the evening of the 21st.

A subsequent increase in convective activity is shown in figure 3.8 by the increase in radar echoes (from Air Route Traffic Control Center [ARTCC] summary charts) beginning at 0600 MST (1300 GMT). Table 3.4 lists some of the symbols on these diagrams. The numerous echoes that appear in these figures in northern

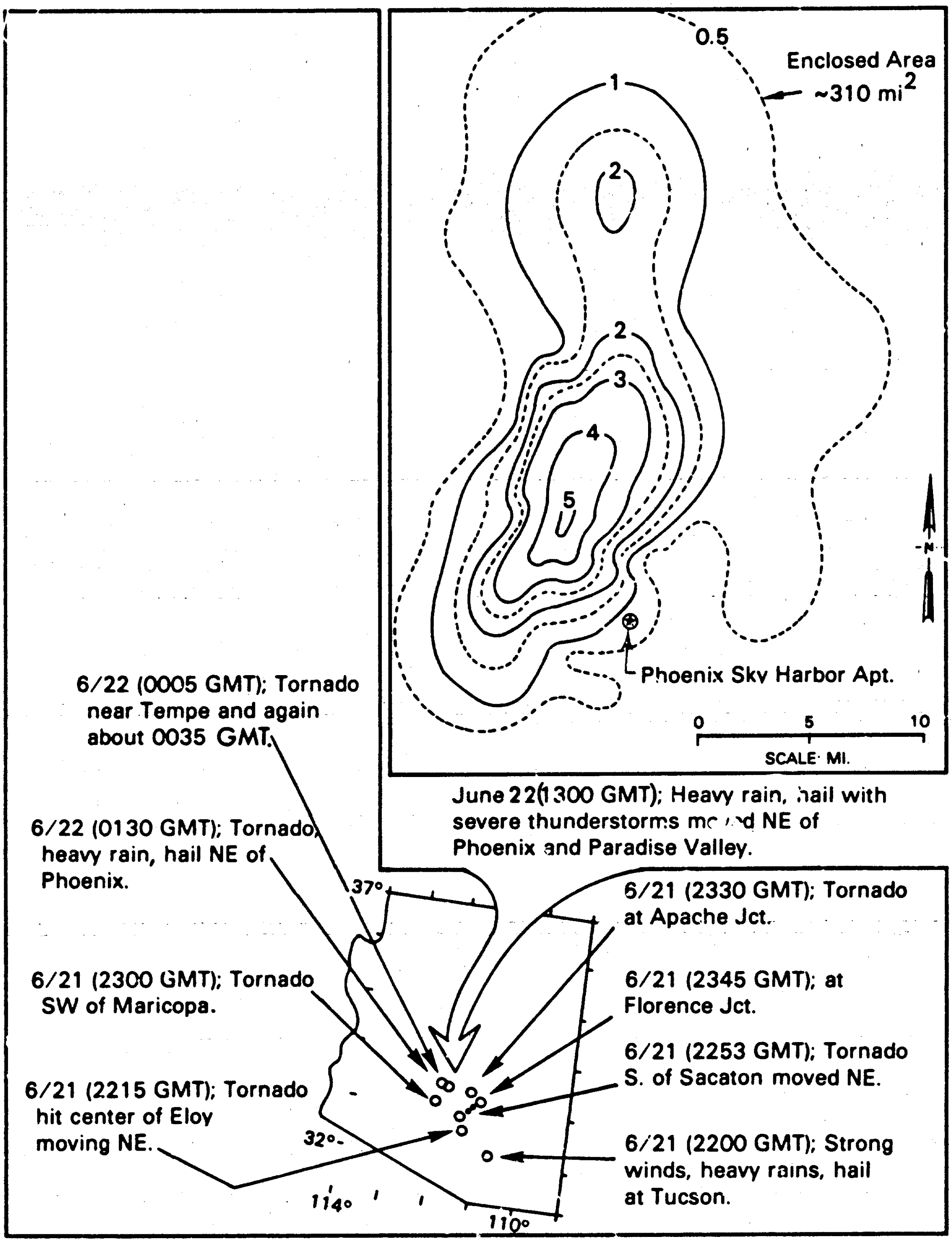
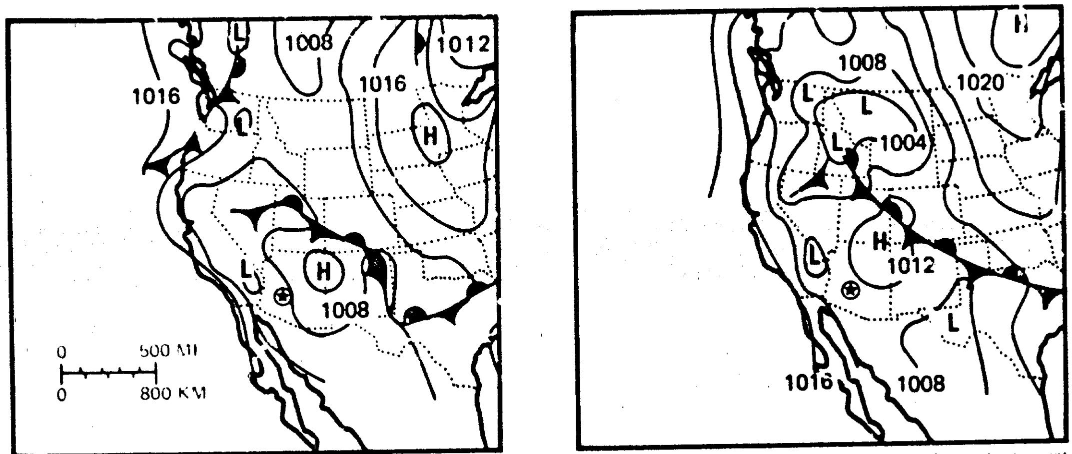


Figure 3.5.--Isohyetal analysis for storm of June 22, 1972.



June 22, 1972 (1200 GMT) June 23, 1972 (1200 GMT)

Figure 3.6.--Surface weather maps for June 22 and 23, 1972.

Arizona and to the north are related to a stationary front shown in figure 3.6, and are separate from the convective echoes near Phoenix.

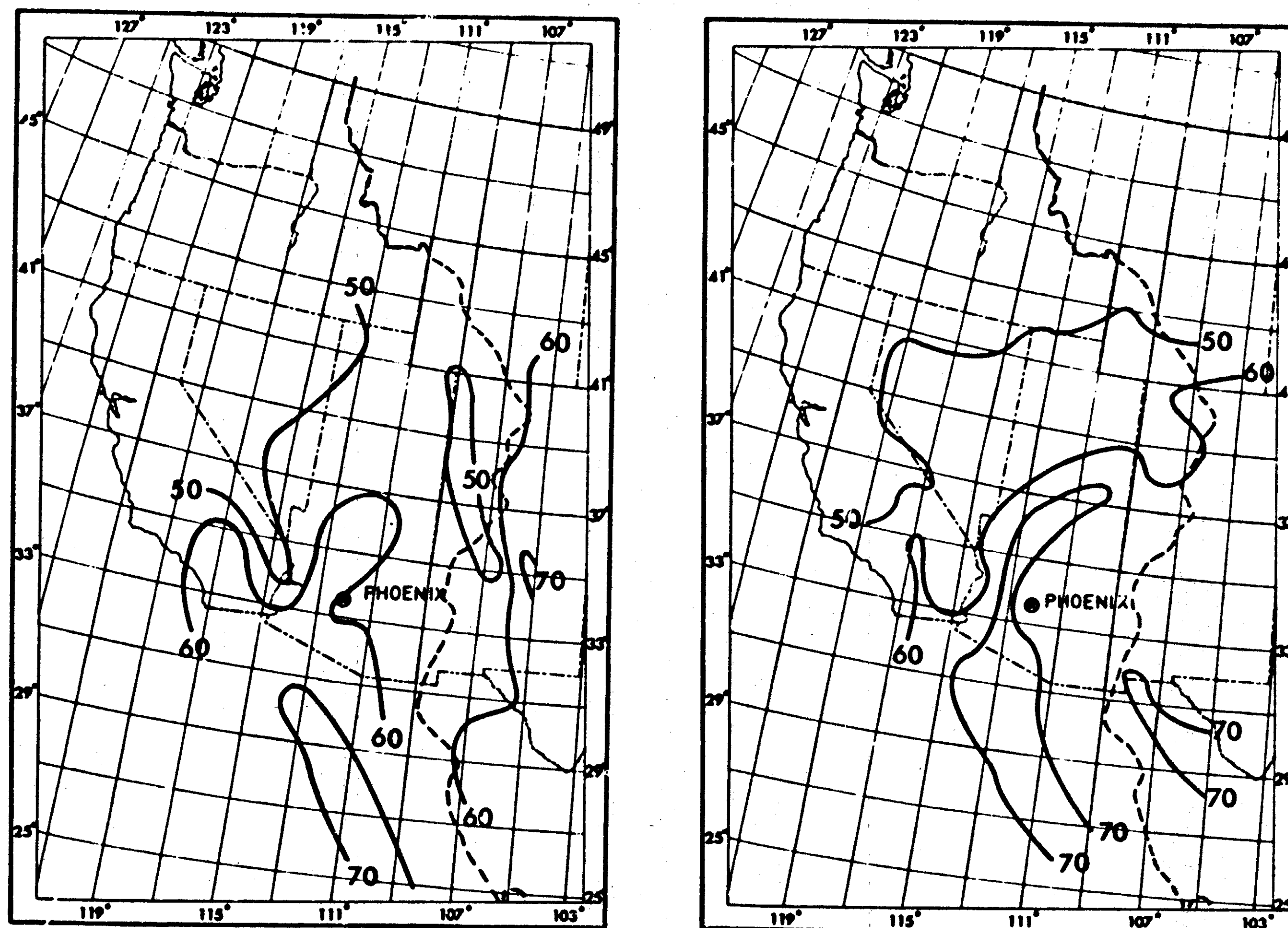
3.3.4 Campo, California 8/12/1891

On this date one of the most intense local storms ever reported in the United States occurred at Campo, Calif. Rain fell between 1140 and 1300 PST (1940 to 2100 GMT) with a minimum estimated catch of 11.5 in. [383%] from the observers unpublished record. The observer reported his gage overflowed at least once. The observer of this storm wrote that it was centered over "...the Campo store and station and south to the Mexican line into the Tecate Valley in Mexico a stretch of about 3 miles."

The town of Campo is located in the Campo Valley just to the north of the Mexican-United States border about 40 mi southeast of San Diego. Campo is at an elevation of 2,590 ft and the Valley extends about 10 mi to the east northeastward to the Tecate Divide, a ridge of about 3,500 to 4,000 ft elevation. Mountains to the northeast through northwest rise to about 4,000 ft. The Tecate Valley extends southwestward from Campo into Mexico. Because the terrain elevations are lower in the quadrant from southwest through southeast of Campo than from the remaining directions, inflow of moisture is more likely from this quadrant.

Surface pressure maps shown in figure 3.9 were developed from sparse data, but show a thermal low-pressure trough extending from the Gulf of California and Sonora, Mexico, northward into Nevada at 1700 PST (0100 GMT) August 13. Twelve hours later the surface pattern has changed to place the Low in northwestern Nevada. The 1000-mb dew point at Yuma, Ariz. (about 100 mi east of Campo) was 70°F at 1700 PST (0100 GMT), August 13, indicative of fairly high moisture at this location.

With the little information available, it is impossible to determine the actual source of moisture to the Campo storm, although the tropical Pacific Ocean appears most likely.



JUNE 21, 1972 (1200 GMT)

JUNE 22, 1972 (1200 GMT)

Figure 3.7.--Isodrosotherm analysis depicting moisture movement prior to storm of June 22, 1972.

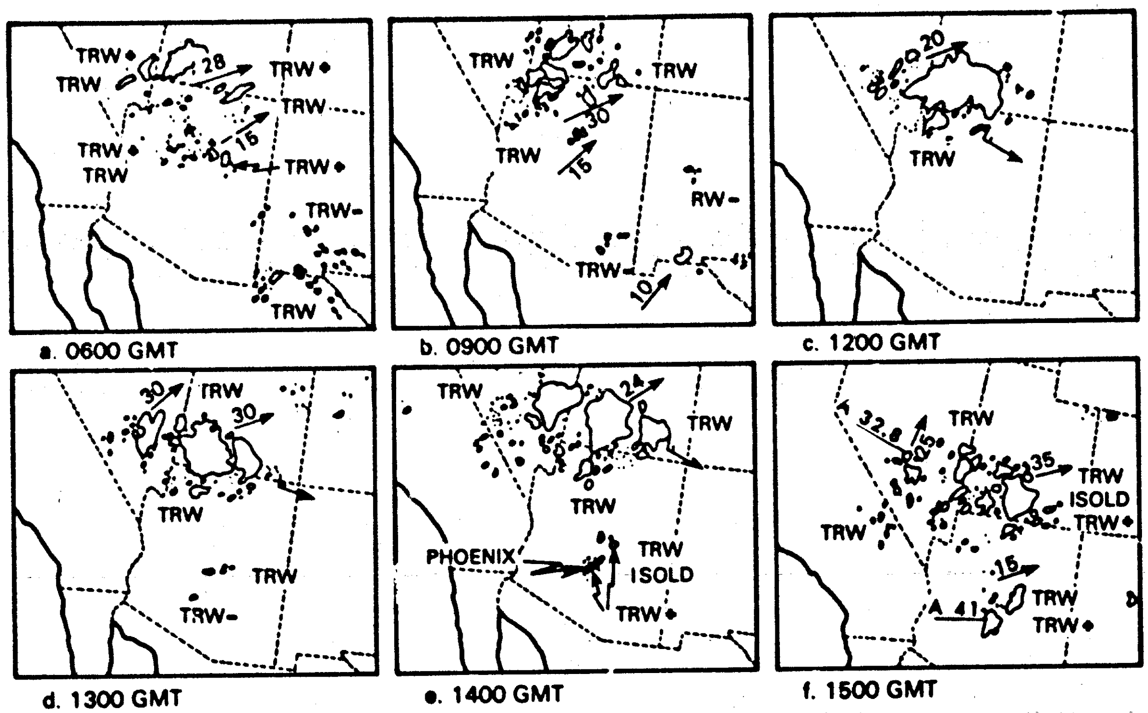


Figure 3.8.--Radar echo summary developed from ARTCC radar data for period 0600 to 1500 MST (1300 to 2200 GMT) for June 22, 1972.

Table 3.4.—Symbols used in figures 3.8 and 3.24

Symbol	Description
	Outline of radar echo.
	Direction and speed (kt) of echo movement.
	Direction and speed of mean wind (half barb = 5 kts, full barb = 10 kt).
TRW	Thunderstorm rainshower; intensity denoted as (-) light or (+) heavy.
RW	Rain showers.
A35.5	Cloud top height measurement reported by aircraft = 35,500 ft.
PTLY ALF	Partially aloft, means some of the precipitation not reaching the ground.
ISOLD	Isolated solid mass echo.
NEW	New echo mass since last report.

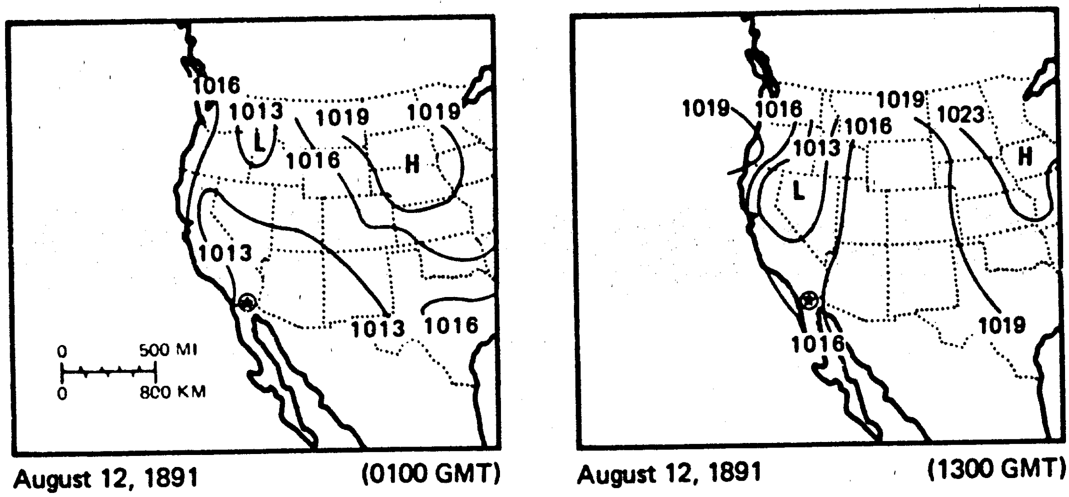


Figure 3.9.--Surface weather maps for August 11-12, 1891.

3.3.5 Campo, California 7/18/22

The Climatological Data summary for California (National Oceanic and Atmospheric Administration 1897-) reported that 7.10 in. [237%] of rain fell during one storm on July 18, 1922. A duration of 2 hr was attached to this storm by one of the observers in correspondence received about the 1891 Campo rainfall. No other information is available on the 1922 storm, except that on the same date 125 mi to the north of Campo at Squirrel Inn another local storm produced 5.01 in. [76%] in 90 min (storm number 20, table 3.1).

The surface pressure maps (fig. 3.10) show the thermal Low that had been in southern Arizona 24 hr earlier to have pushed northwestward into California and southwestern Nevada on the 18th. By the 19th, a cold front stretched northeastward from near Los Angeles, about 150 mi to the north of Campo. This front had moved southward during the previous 24 hr from northern California. The daily observations at Yuma during this period (16 to 19th) do not provide any support for high moisture at that location. Temperatures were very high, however, with daily maxima between 100° and 110°F. Winds were from the southeast to east as shown in figure 3.10. It is likely that Gulf of California moisture penetrated to the vicinity of Campo and the range of mountains northward towards Squirrel Inn, and that orographic lifting stimulated the extreme local storms.

The observer at Campo during this storm reported, "Campo has an attraction for these storms, I think, for we get more big ones there than any spot around." As one way to investigate the contention that Campo may be favored by larger rainfalls, we considered the 100-yr 6-hr analyses (Miller et al. 1973) under the assumption that these are a good index to exteme precipitation events. The Tecate Valley to the southwest of Campo shows values of about 3.0 in. for the 100-yr 6-hr rainfall (fig. 3.11). About 15 mi to the north of Campo in the vicinity of the higher terrain (elevations above 4,000 ft), the 100-yr 6-hr rainfall analysis shows a closed center of 5.0 in. From this comparison, it would not appear that Campo is frequented by unusual rainfalls. There does not appear to be any feature of the local terrain around Campo, that is much different from other locations along the coastal mountain ridges.

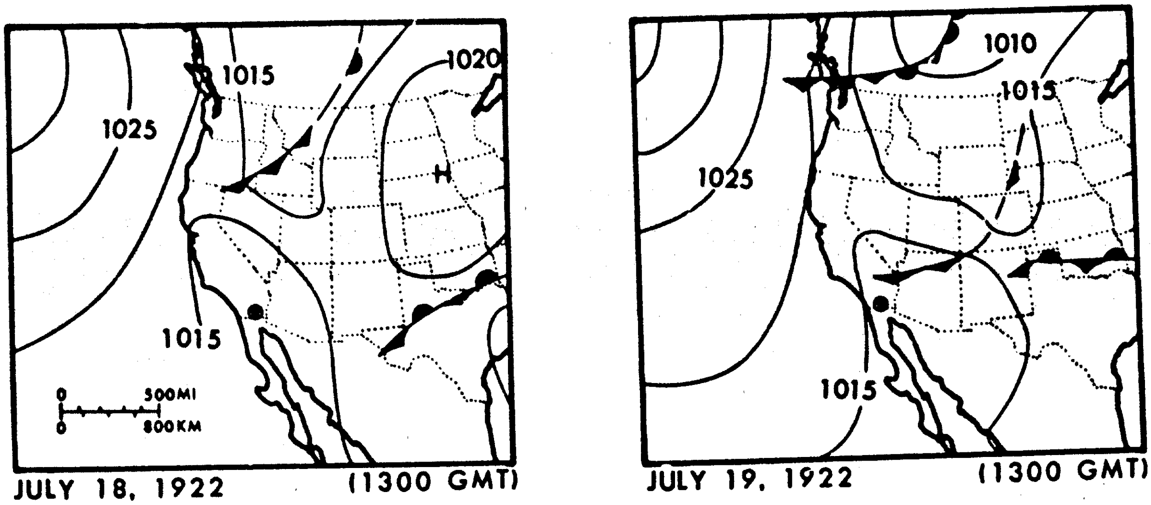


Figure 3.10.--Surface weather maps for July 18-19, 1922.

The likelihood that the entire ridge of coastal mountains is favored by heavy local storms over other parts of southern California is suggested by the 100-yr 6-hr rainfall analysis as the maxima of closed 5.0 in. isohyets formed along the ridgeline just north of Campo increase to the largest observed (>9.0 in.) along the San Gabriel Mountains (100 mi to the north of Campo).

3.3.6 Vallecito, California 7/18/55

A heavy local storm fell at Vallecito, less than 25 mi to the northeast of Campo in July 1955. A 6-in. glass tube gage at the stage station site at Vallecito overflowed according to the flood report (unpublished report, U.S. Corps of Engineers 1955, see table 3.1). The total amount of 7.1 in. [237%] was measured in a tub approximately 20 in. in diameter by the observer at this station. Rainfall began about 1440 PST (2240 GMT) and although most of the rain fell in 70 minutes, some light showers continued until 1730 MST (0130 GMT on the 19th). An isohyetal pattern (fig. 3.12), taken from the flood report, shows rainfall above 0.5 in. covered about 355 mi^2.

According to the California state climatologist (National Oceanic and Atmospheric Administration 1897-),"...there was considerable thunderstorm activity in the Southeast Desert Basins from the 18th through the 24th which spread northward into the Sierras on the 21st and 22nd (of July). Thunderstorms with attendant strong winds and heavy rains spread some damage in San Diego and Imperial Counties on the evening of July 18." The 2.34 in. [130%] (Twentynine Palms), 2.18 in. [73%] (Beaumont Pumping Plant), and 1.05 in. [38%] (Palm Springs) rains were measured on the 19th, but almost all occurred on the 18th. These heavy rains are more than 80 mi north of the Vallecito rain center. Not shown in figure 3.12 are the stations reporting no rainfall that show these surrounding rains to be spotty as is the case in general for outbreaks of air mass type local storms.

The center of the heavy precipitation occurred in the Vallecito Creek basin between the Vallecito Mountains, with elevations of 3,000 ft to the north and the

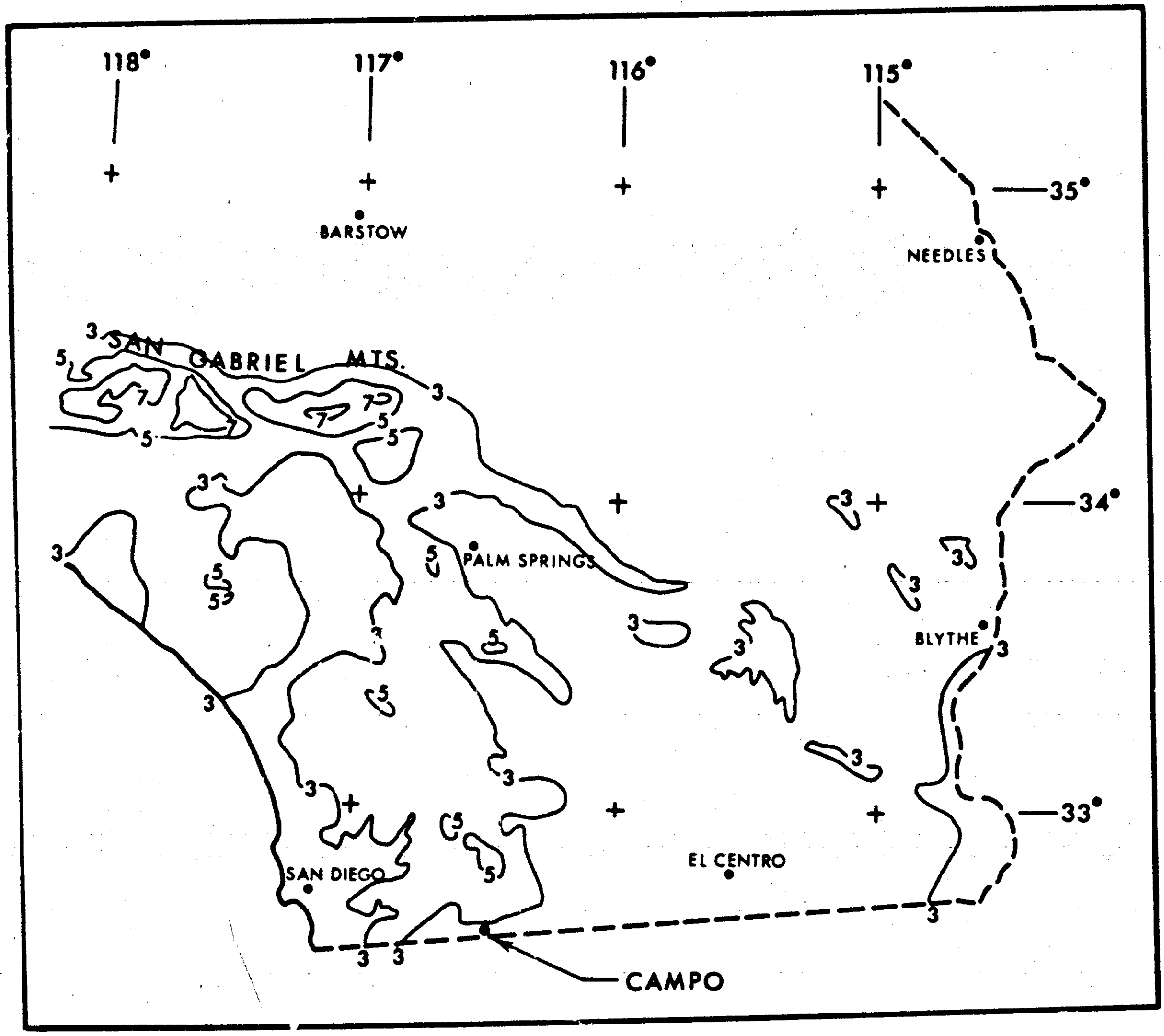


Figure 3.11.--100-yr 6-hr rainfall for southern portion of southern California.

Tierra Blanca Mountains, with elevations of 2-3,000 ft to the south. The western edge of the basin is formed by the Laguna Mountains, a segment of the southern California coastal range, with elevations of 5,000 ft. Vallecito Creek flows eastward through the valley toward the broader Imperial Valley.

On the surface weather map for 0430 PST (1230 GMT) of the 18th (fig. 3.13), a dissipating stationary front was positioned through southern Nevada and across California reaching the Pacific coast at San Diego. The thermal Low was not well established but was located in a near normal position. This weather pattern created a weak circulation where winds over southeastern California and southern Arizona were from the southeastern quadrant bringing moisture from the Gulf of California. Twenty-four hours later, the surface front could no longer be found

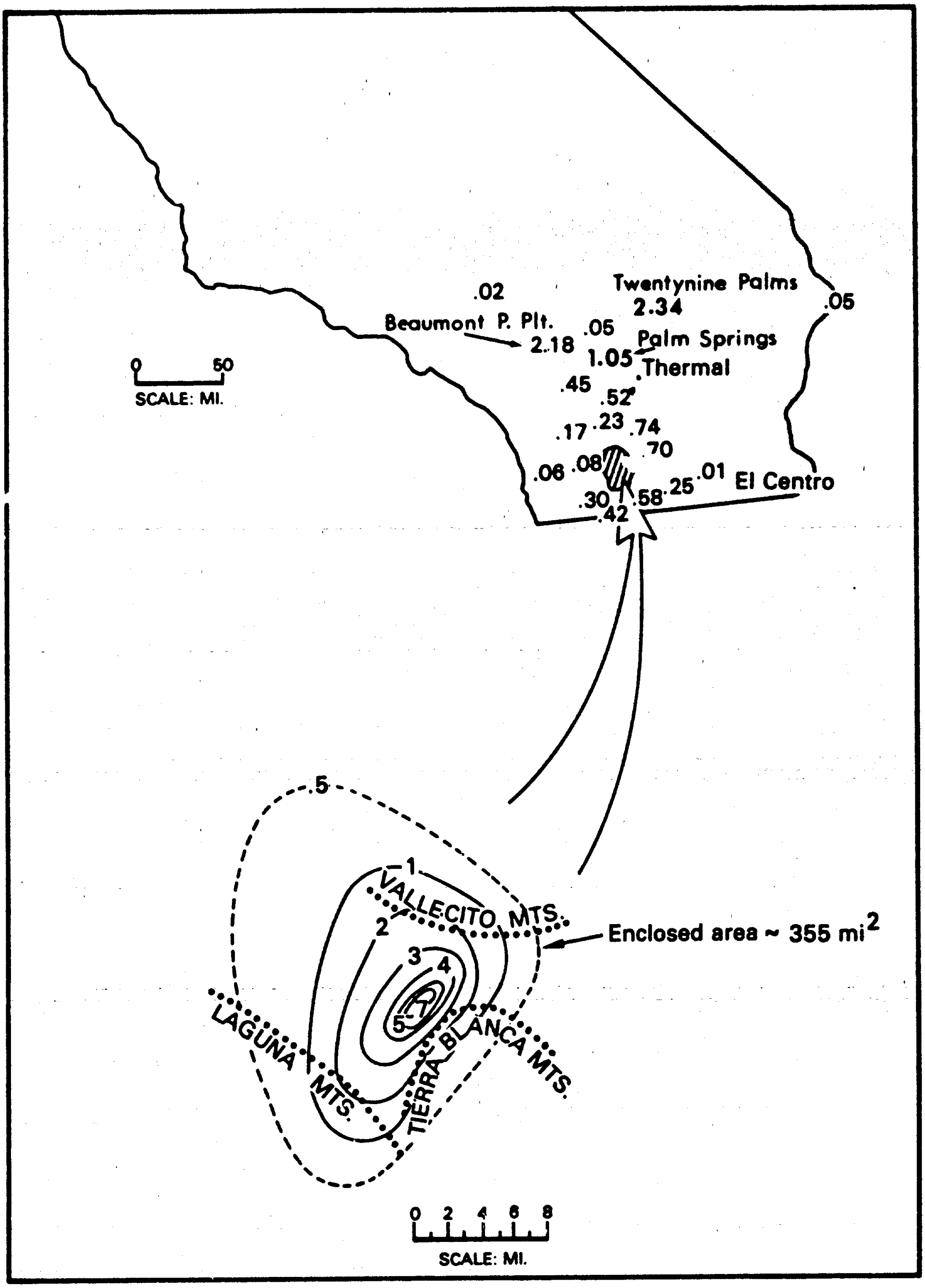


Figure 3.12.--Isohyetal map for storm at Vallecito, Calif. on July 18, 1955. Rainfall data are shown for other stations in southern California.

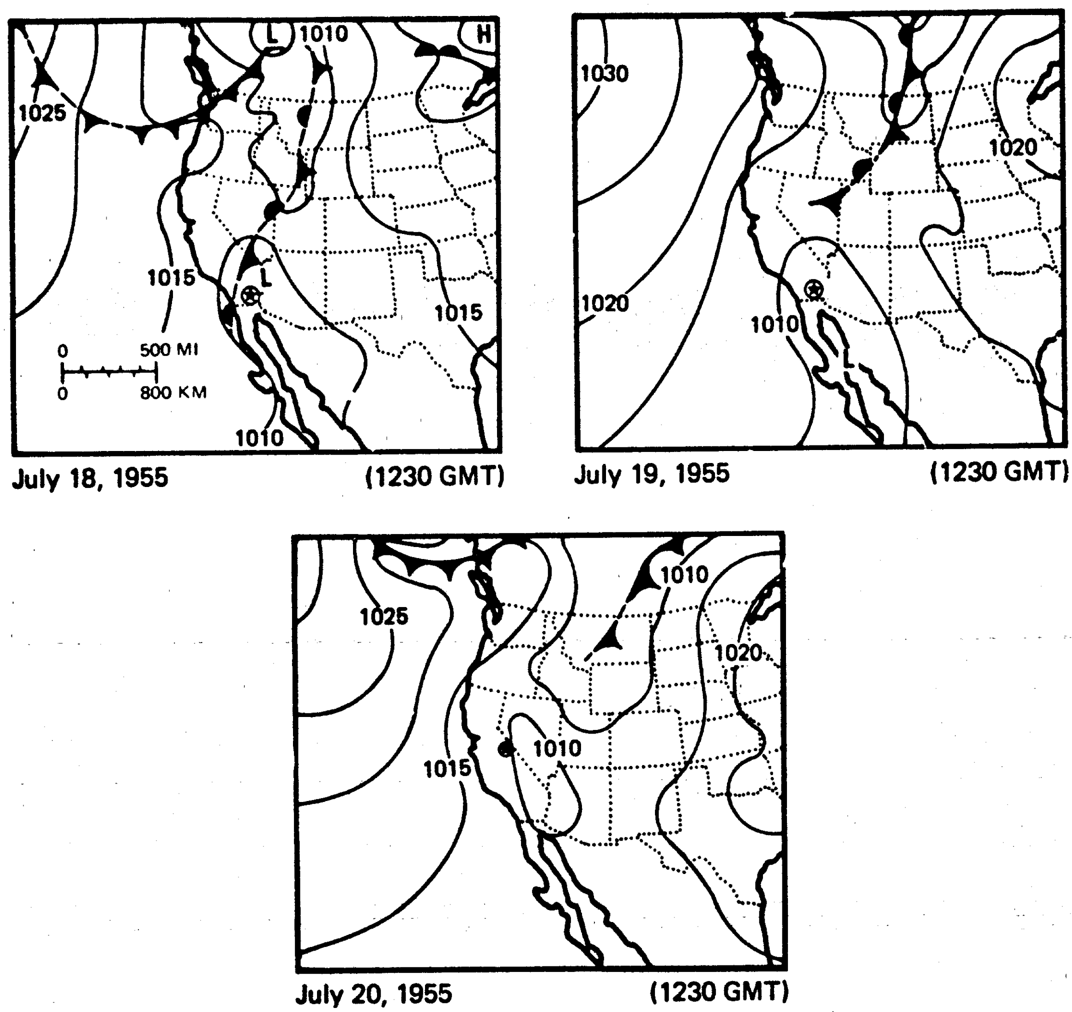


Figure 3.13.--Surface weather maps for July 18-20, 1955.

in California, but the moisture associated with this system was still present and may have combined with the moisture being advected toward the west by the circulation associated with the thermal Low, centered over the Gulf of California.

At the 500-mb level (maps not shown), a deep trough lay off the west coast, oriented north-south. Further east, a ridge of high pressure included a closed anticyclonic system centered over southern Montana. The axis of this ridge sloped southwestward toward southern California. Light easterly winds occurred throughout Arizona and southern California at 1030 PST (1830 GMT) of the 18th.

The heaviest rains occurred in this weather situation . Witnesses claimed that the storm moved into the valley from the north-northwest. This movement indicates the weak nature of the synoptic scale systems, and the intensity involved in the convective cell. The heaviest rain occurred at the narrowest point in the valley. This constriction may have contributed additional vertical motion to the local storm.

3.3.7 Chiatovich Flat, Calif. 7/19/55

On July 19, at Chiatovich Flat, near the crest of the White Mountains (fig. 3.14), another large isolated rainfall occurred in the same weak synoptic system as described for the Vallecito event that fell one day earlier. An observation of the extreme rainfall, amounting to 8.25 in. [330%] in approximately 2.5 hr, was fortuitous. A University of California graduate student hiking in this area carried a portable rain gage in which the measurement was made (Kesseli and Beaty 1959). This report indicated that "...the heaviest rain was concentrated on Chiatovich Flat in the south fork of Indian Creek; adjacent drainages showed no evidence of high water after the passage of this storm." Post-storm surveys reported debris deposits representing significant runoff at the base of Indian Creek.

Chiatovich Flat is located in a col along the north-south ridge line of the White Mountains at an elevation of 10,320 ft. About 2 mi north along the ridge there is a peak of 12,500 ft, while 6 mi to the south White Mountain Peak rises to 14,240 ft. Indian Creek flows down the east face of the White Mountains. The steepness of the slopes is demonstrated by the fact that the Owens Valley, at an elevation of roughly 4,000 to 5,000 ft is at the base of the western slopes at a horizontal distance of only 5-6 mi from the ridge. The base plain to the eastern slopes also are about 5,000 ft, but at 8-10 mi from the ridge.

No precipitation stations within 200 mi of Chiatovich Flat reported rain on the 19th. Therefore, it was impossible to find support for the timing of the rainfall, other than to say it was during the daylight hours.

Analysis of 3-hourly 1000-mb dew point observations showed moisture as far north as Blythe, Needles, and Daggett, Calif. prior to the 19th. These stations all had 1000-mb dew points of 70°F. North of these stations most dew points (reduced to 1000-mb) ranged in the mid 60's. A 1000-mb dew point of 74°F occurred at Bishop (in the Owens Valley, southwest of Chiatovich Flat) early on the 20th, that may be indicative of the continuation of moisture northward. A heavy cloudburst (2.5 in. in 2.5 hr) was reported at Mono Lake, Calif. (about 40 mi northwest of Chiatovich Flat, at the head of the Owens Valley) on the 21st. Insufficient stations are located near the eastern slopes of the White Mountains to establish whether similar moisture moved northward there, as well.

Figure 3.13 shows weather maps (July 19 and 20) surrounding the occurrence of the local storm at Chiatovich Flat. Little change occurred from conditions prevailing during the Vallecito storm. At 500 mb (maps not shown), the ridge of high pressure, that brought easterly winds to the vicinity of the Vallecito storm on the 18th, had retreated slightly to the northeast on the 19th. This movement brought about a southerly flow of wind over the Chiatovich Flat area through the period of the local storm.

We do not have the data needed to determine the trajectory of moisture flow into Chiatovich Flat or how the storm developed. We can speculate that strong heating of the east facing slopes brought about convective currents rising toward the ridgeline. Moist air approaching the base of the east slopes of the White Mountains from the south was lifted up the slopes as convection strengthened. The local storm cell that developed remained over the Chiatovich Flat site because of the weak upper-level circulation.

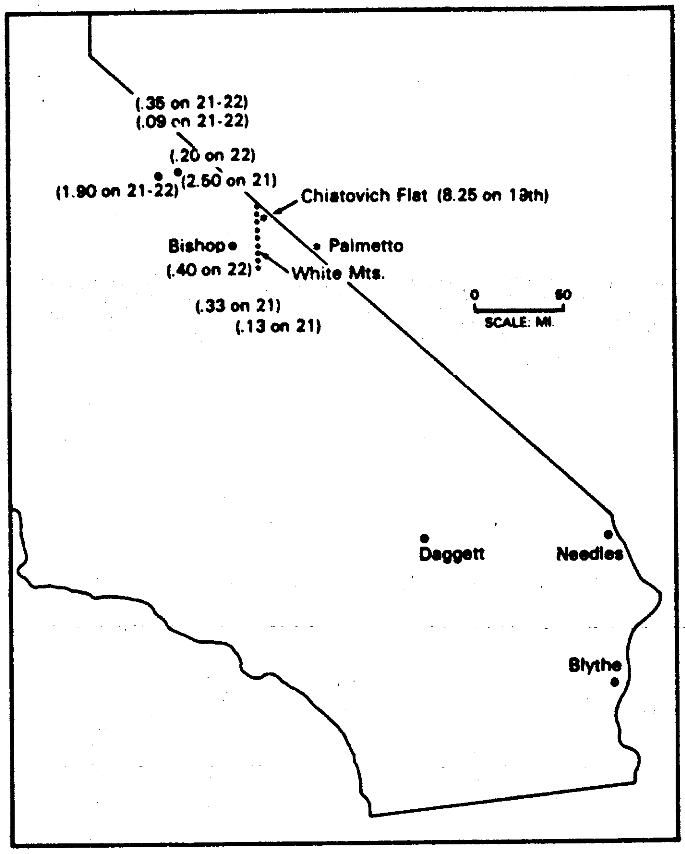


Figure 3.14.--Schematic diagram showing location of rainfall at Chiatovich Flat in relation to White Mountains. Data for other nearby stations are also shown.

3.3.8 Bakersfield, Calif. 6/7/72

This extreme local storm at Bakersfield was surveyed by the Corps of Engineers (Bryant 1972). The survey obtained a maximum point rainfall of 3.5 in. [206%] that fell between 1430 and 1545 PST (2230 and 2345 GMT) on June 7th. An isohyetal analysis prepared by the Corps of Engineers is shown in figure 3.15, and covers 85 mi^2 within the 0.5 in. isohyet.

Bakersfield lies in the southern portion of the San Joaquin Valley of California, about 10-15 mi west of foothills leading up to the southern end of the Sierra Nevada Range. The Tehachapi Mountains, rising 7,000 ft from the valley, are approximately 30 mi to the southeast. The western extension of the Tehachapi range curves around the valley to join with the coastal range that extends northwestward at a distance of about 50 mi west of Bakersfield. It is this semicircle of mountains that act to shelter the San Joaquin Valley from excessive low-level moisture from the south.

Surface pressure maps (fig. 3.16) for June 6-8, 1972 show a rather narrow thermal trough aligned northwest-southeast through southern California. Aloft, the 500-mb maps (fig. 3.17) show an upper-level trough along the Pacific Coast.

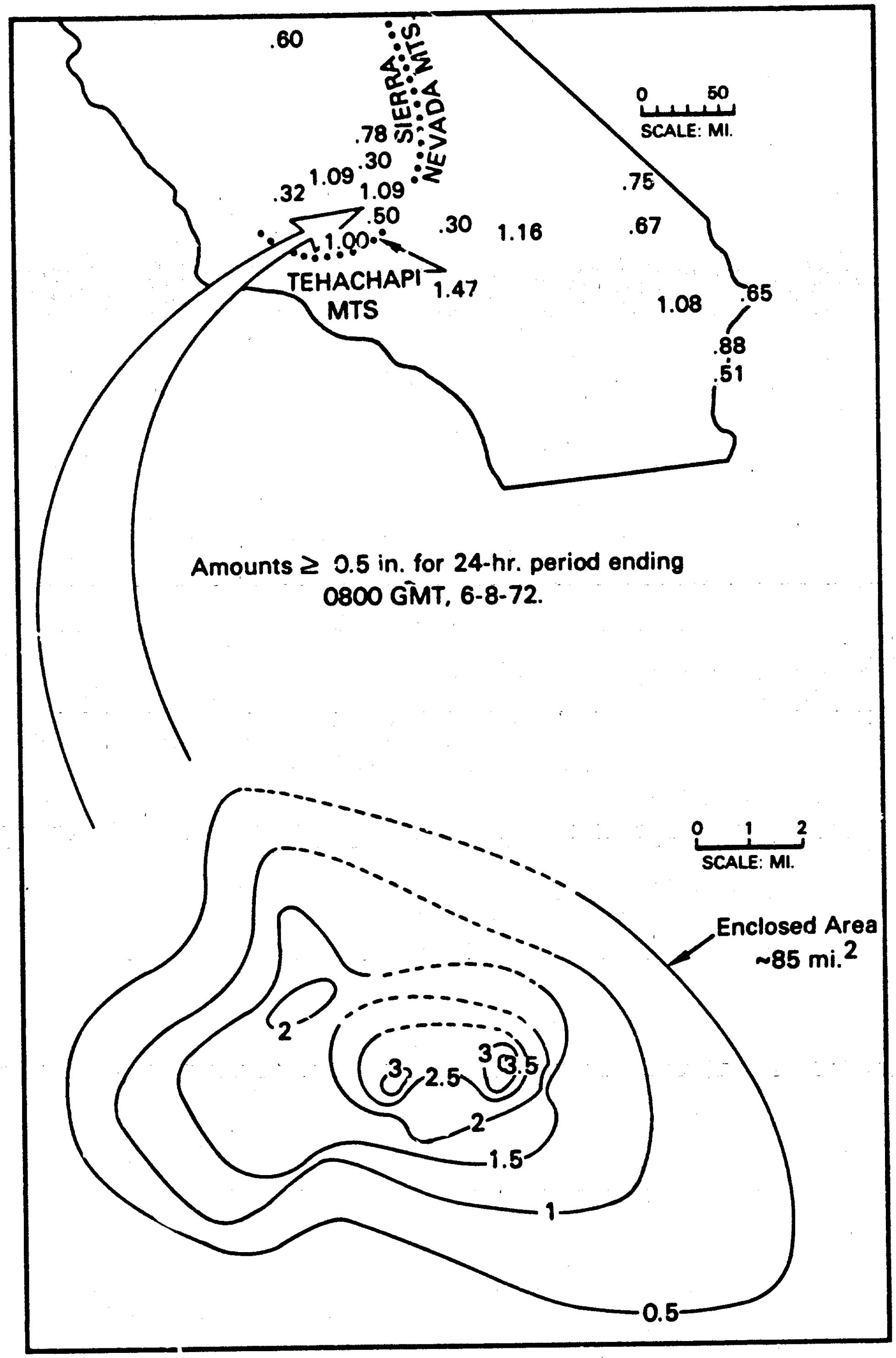


Figure 3.15.--Isohyetal analysis for storm of June 7, 1972.

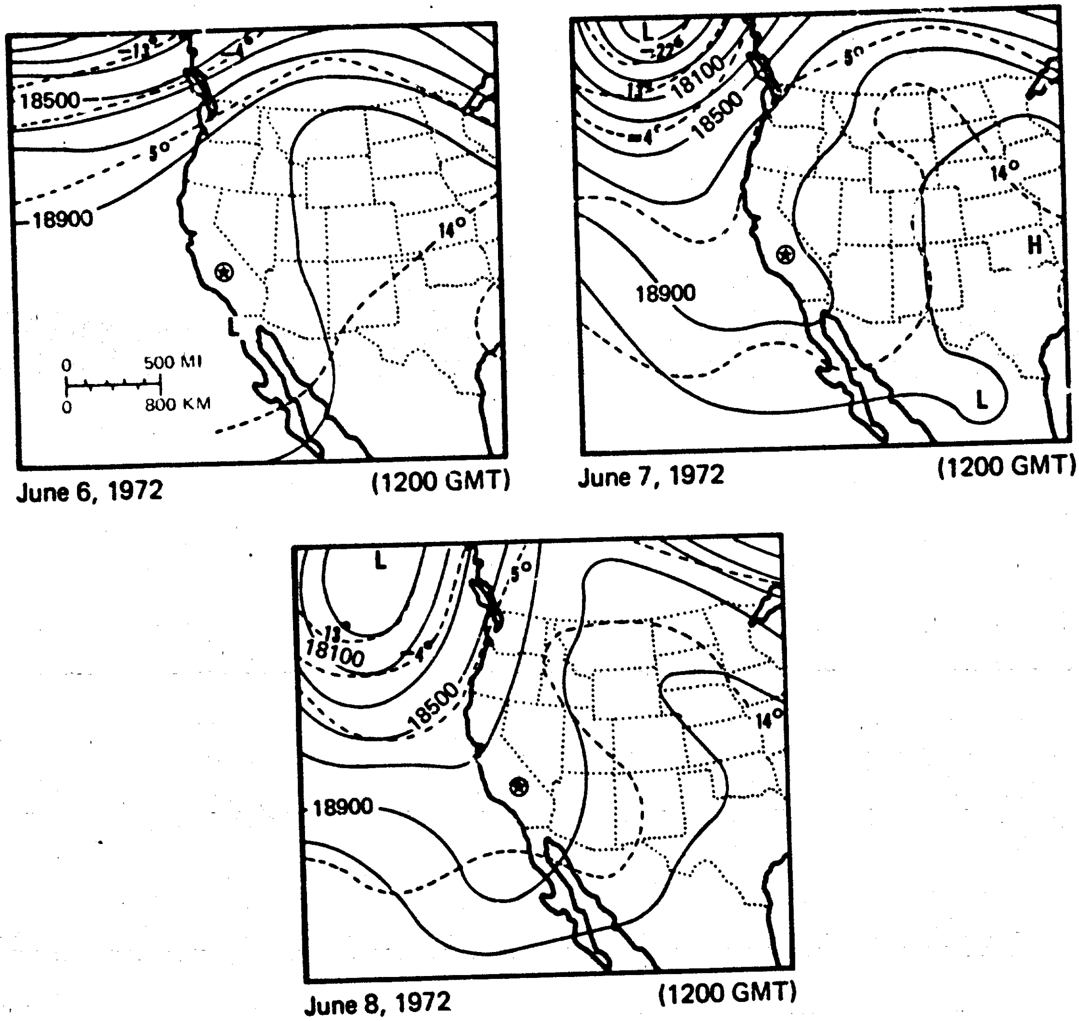


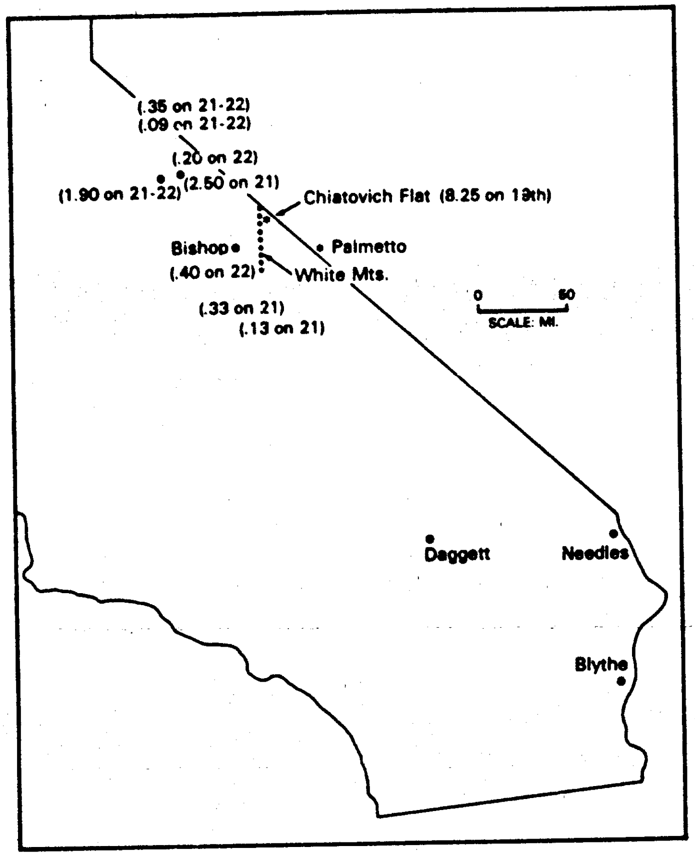
Figure 3.17.--500-mb charts for June 6-7, 1972.

Pyke says that thunderstorms developed along the Tehachapi range and spread northward across the San Joaquin Valley.

3.3.9 Mesa Verde Park, Colo. 8/3/24

The Climatological Data summary for Colorado (National Oceanic and Atmospheric Administration 1897-) reports a cloudburst that dumped 3.50 in. [152%] of rainfall at Mesa Verde Park on August 3, 1924. A personal communication from the Bureau of Reclamation offices in Denver indicated that most all of this rainfall occurred in about 45 min. We have no other information on the rainfall in this event, but have included the storm in this review because of its location, and because it exceeds our threshold of 150% for the percentage of 100-yr 6-hr rainfall.

Mesa Verde Park has a physical setting on the south-facing slopes of a small ridge oriented east-west to the west of Durango, Colo. (about 40 mi east of the Park headquarters offices). The rain gage at an elevation of 6,969 ft is located about 1.5 mi northeast of the Park post office. The Park slopes upward to the



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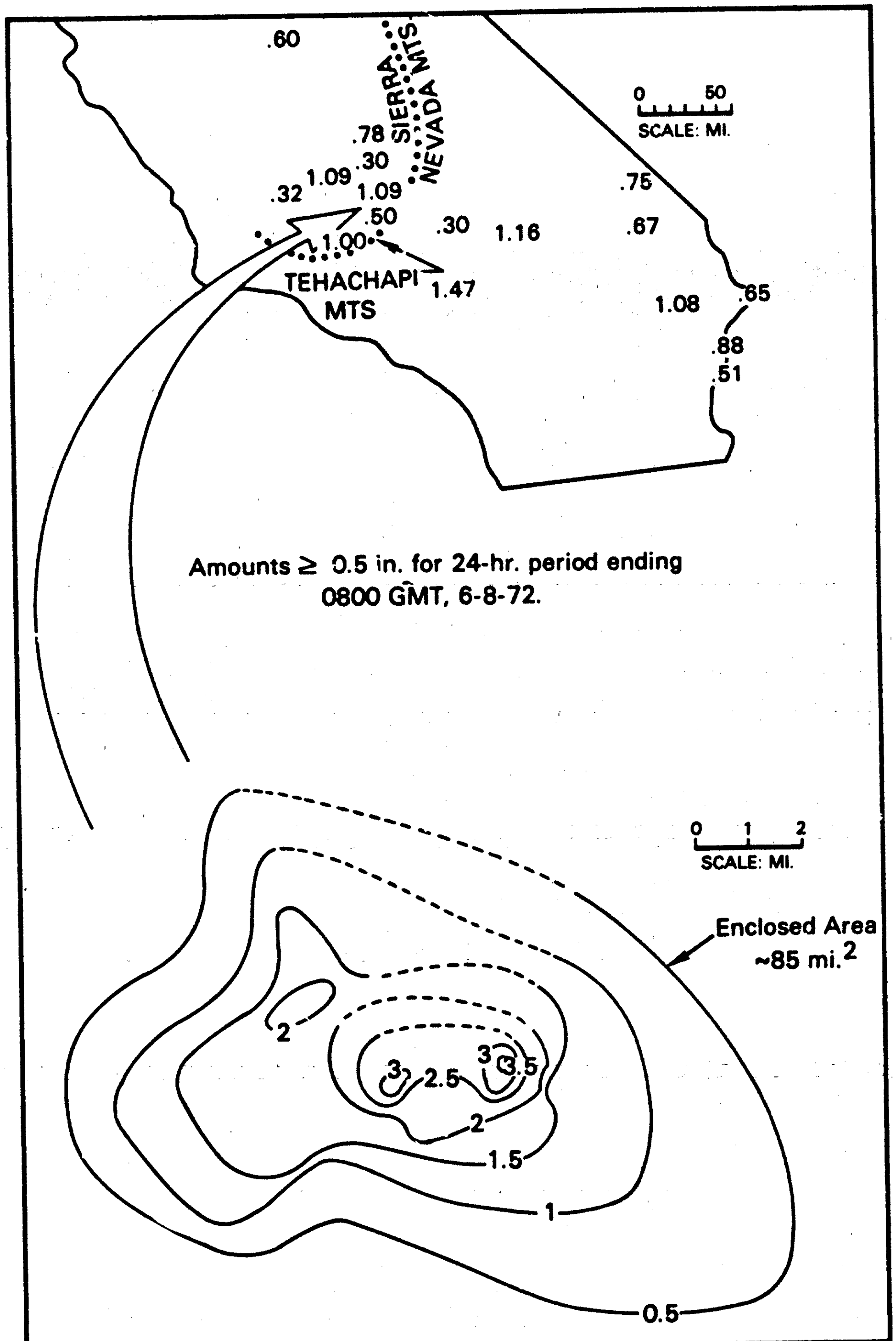

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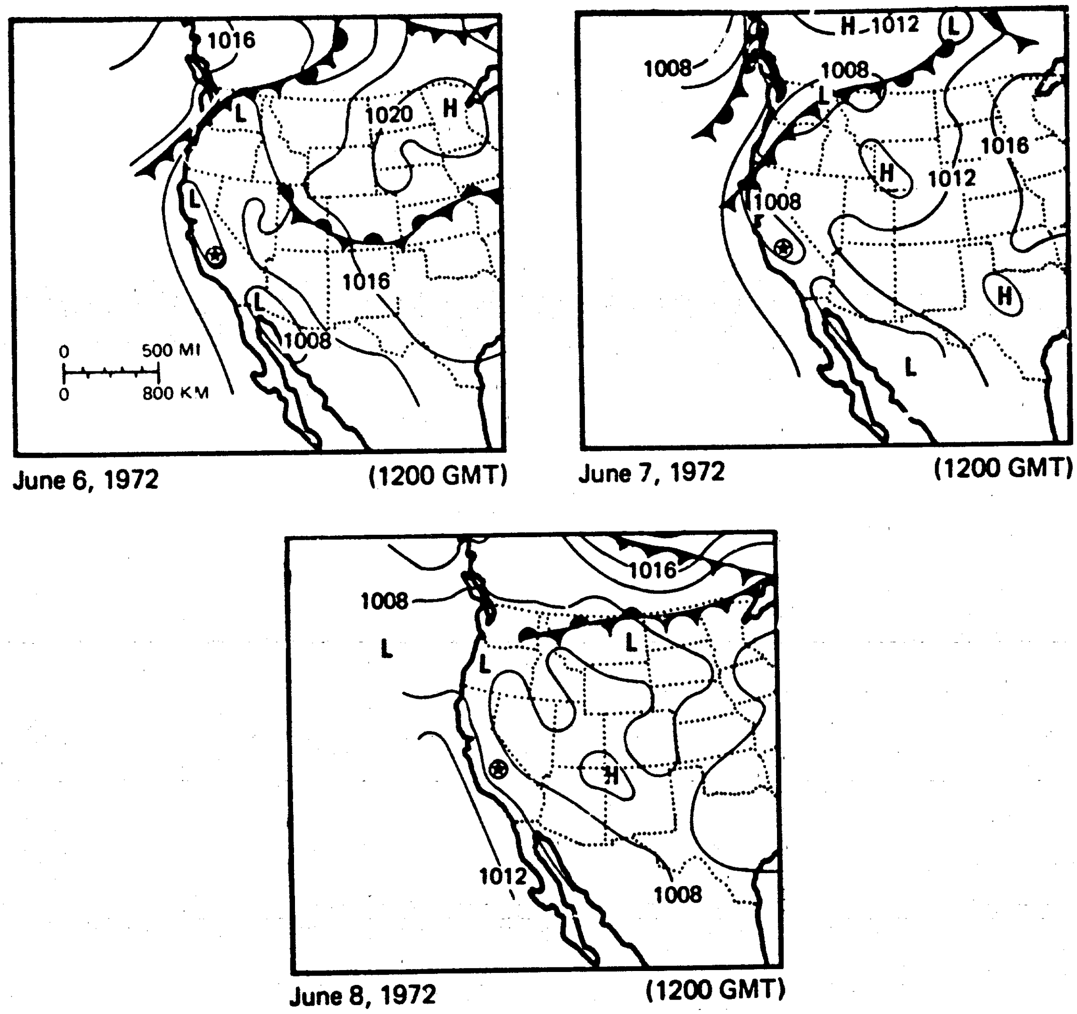


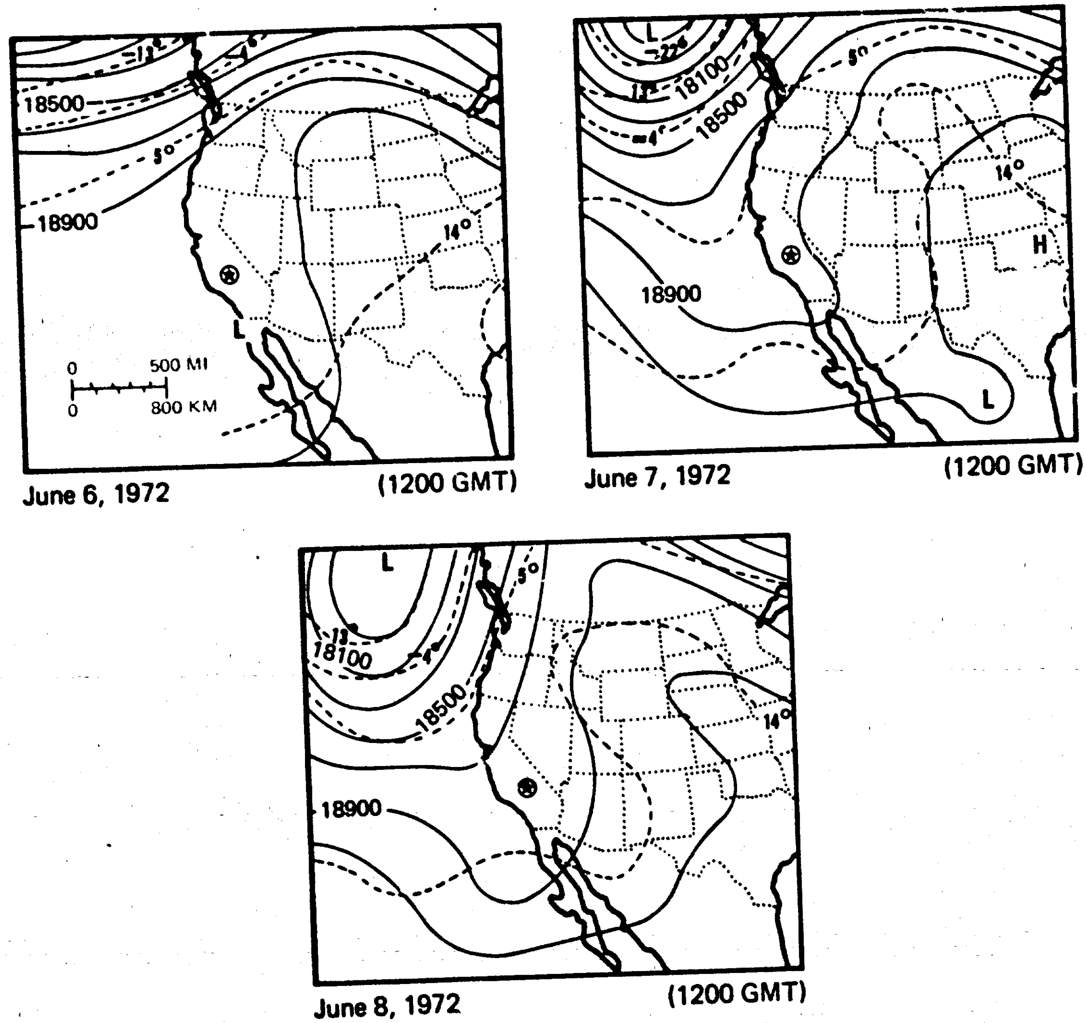
Figure 3.16.--Surface weather maps for June 6-8, 1972.

The axial orientation of this trough is unusual, being northwest-southeast (compared to the normal charts in appendix A).

Pyke states as (cited by Bryant 1972).

> "The conditions were caused by an unusually intense and unusually persistent upper level low pressure center which was located south and southwest of southern California. The circulation around this upper level low brought great quantities of tropical moisture into the southwestern United States from out of the Gulf of California and the warm Pacific Ocean southeast and southwest of Baja California."

He also suggests that moisture outflow from hurricane Annette located off the southern tip of Baja California could have contributed to the upper-level system.



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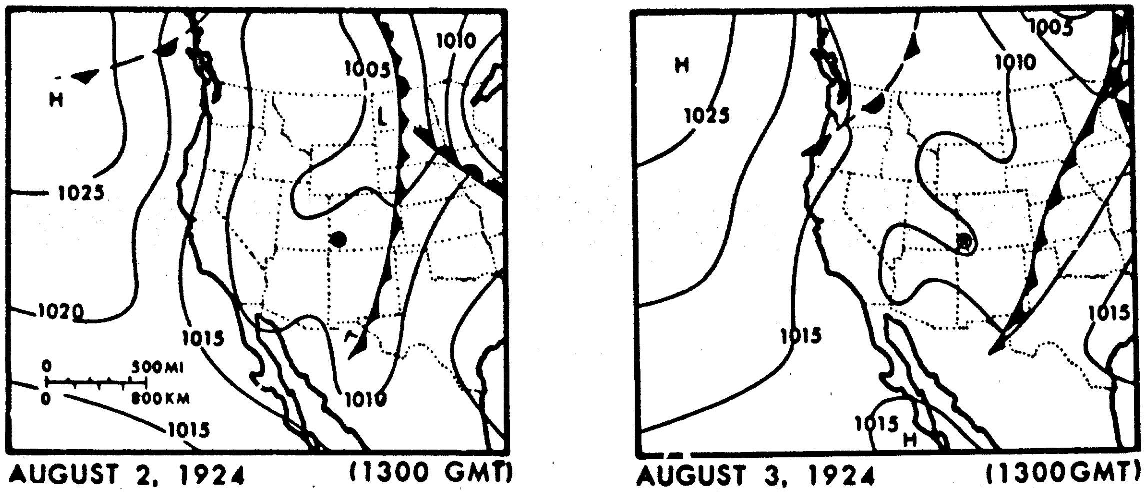


Figure 3.18.--Surface weather maps for August 2-3, 1924.

north to a peak of 8,574 ft, and is drained by the Mancos River (a tributary to the San Juan River) which flows southwestwards from the Park towards the Four Corners (Junction of Utah, Colorado, Arizona and New Mexico).

Surface weather maps (fig. 3.18) show a somewhat different picture than do those for other local storms in this report and are different as well from the normal charts (appendix A). A cold front lies along the Continental Divide of Colorado on the 2nd having moved through western Colorado during the previous 24 hr. The local storm at Mesa Verde Park thus occurred in a post frontal environment. However, the front did not bring rains to western Colorado. Figure 3.18 also does not show the thermal Low that is usually established in the lower Colorado River region.

We are unable to determine a source for the moisture inflow or a cause for the Mesa Verde Park local storm rainfall from within the scale of information available.

3.3.10 Palmetto, Nev. 8/11/1890

Reference to a reported extreme local storm rainfall of 8.80 in. [463%] occurring in 1 hr is made in a study of PMP for the western United States (U.S. Weather Bureau 1960). The same reference also indicates that this rainfall amount is of "doubtful reliability." It goes on to mention that, "Investigation of the original records and correspondence written by the observer shortly after the date of the observation indicate a possibility that the scale factor may not have been applied to the measurement of the precipitation." Although there is doubt about the magnitude of rainfall at Palmetto, we chose to accept that an extreme rainfall, probably satisfying our criteria, did occur, and therefore have included Palmetto in our discussion. One reason for accepting this occurrence is the similarity of the observer's descripition of the storm (see section 3.5.6.1) to features reported in other major local storms described in this chapter.

Palmetto (elev. 6,700 ft) at that time was a mining camp in the Palmetto Valley that drains northwestward from the Palmetto Mountains (peak heights of roughly 9,000 ft). The Sylvania Mountains rising to about 7,500 ft lie between Palmetto and Death Valley to the south. To the west of Palmetto (about 20 mi) is the southern end of the White Mountains (see discussion on Chiatovich Flat, section 3.3.7).

A crude surface weather analysis has been made based on the few available stations (fig. 3.19). Although no closed thermal Low is evident, a broad trough of low pressure prevailed through the Great Basin and into southern Arizona. There is too little information on which to analyze the meteorological conditions supporting this storm.

3.3.11 Las Vegas, Nev. 6/13/55

The Corps of Engineers made a survey (unpublished report, U. S. Corps of Engineers 1955, see table 3.1) of the heavy local storm at Las Vegas that occurred on June 13. This survey reports:

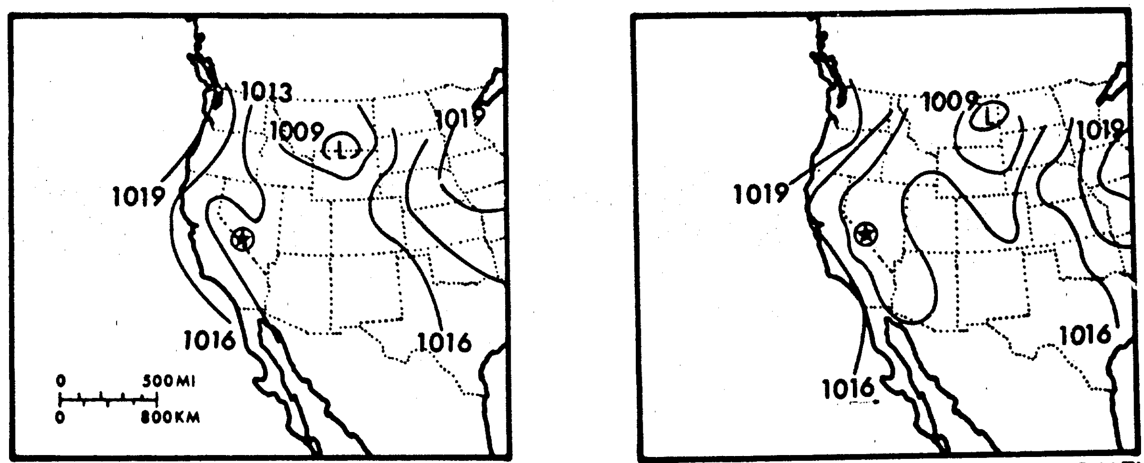
> "The greatest amount of rainfall recorded for the storm was at the residence of the Chief of the local Weather Bureau office. Several containers in his yard were measured immediately following the storm and a maximum of 3.4 in. of rainfall was recorded."

The heavy rainfall occurred in the 35-minute period between 1710 and 1745 PST (0110 and 0145 GMT on the 14th). From the various measurements, the Corps of Engineers drew the isohyetal analysis shown in figure 3.20. The 0.5 in. isohyet in this analysis encloses about 175 mi^2. The orientation of this pattern is northeast-southwest.

Las Vegas lies within the Las Vegas Valley with elevations of 2,000-3,000 ft, which is oriented northwest-southeast. The Spring Mountains are 25 mi to the west and rise to a peak height of nearly 12,000 ft. East of Las Vegas, rugged terrain encloses Lake Mead (about 20 mi distant). A number of north-south valleys extend to the south from Las Vegas, but the region is interrupted by numerous mountain ranges that rise 2,000-3,000 ft above the base elevation.

The surface pressure maps (fig. 3.21) show a high-pressure center over eastern Arizona and western New Mexico on the 13th, remaining through the 14th. Weak southeasterly winds associated with this system are found in Arizona. Moist unstable air covered the southwestern United States with numerous scattered air mass thundershowers throughout. The National Weather Service observer in Las Vegas reported that the extreme thunderstorm on the 13th moved from the southwest.

At 500 mb, a small closed Low in the vicinity of Los Angeles on the 12th moves slightly eastward on the 13th and weakens appreciably in passing to western Utah by the 14th (maps not shown). Although upper-level short-wave systems of this type are more commonly related to precipitation during the cold season, meteorologists do not generally believe they are a cause of extreme local storms. It is likely that the short-duration storm of the 13th was not related to any discernable synoptic scale feature.



AUGUST 11, 1890 (0100 GMT) AUGUST 11, 1890 (1300 GMT)

Figure 3.19.--Surface weather maps for August 11, 1890.

3.3.12 Elko, Nev. 8/27/70

The extreme local storm at Elko, Nevada was unusual relative to most recent local storm observations in that the only rain report was made at the official National Weather Service station (at the airport). The intense rainfall caused the pen to run off the chart scale of the recording gage, since the scale had been set to record amounts less than 1 in. that are more common to this region. The recording chart indicated heavy rains began about 1135 PST (1935 GMT) on the 27th. The observer noted the time of the end of heavy rainfall, and reported a total storm amount of 4.13 in. [258%] in 2 hr from a companion standard 8-in. gage. Witnesses said the storm was limited to a small area around the airport.

Elko, at about 5,000 ft, is located on the Humboldt River which flows between the Adobe Mountains about 7 mi to the northwest and the Elko Hills only 3 mi to the southeast. Peaks in these two ranges are 6,000 to 7,000 ft in elevation. Roughly 25 mi to the southeast of Elko are the more extensive Ruby Mountains with elevations up to 11,300 ft. Most of Nevada is covered with mountain ranges of varying lengths and heights separated by nearly flat valleys. These valleys are generally open to the south through southwest, providing natural channels for Nevada on the 25th through the 27th.northward penetrating moisture.

The surface pressure maps for August 27 and 28th are given in figure 3.22, and show a thermal low-pressure region extending northwest-southeast along the California-Nevada border. Small Highs occur in southwest Utah and northeast Nevada on these respective dates. Scattered showers occur throughout eastern Nevada on the 25th through the 27th.

At 500 mb, a large ridge of high pressure centered over New Mexico influences upper-level flows all the way to the Pacific coast. Winds at this level are generally southwesterly over Nevada.

Hansen (1975b), in an analysis of the 1000-mb dew points at 6-hr intervals, found how moisture inflow could have reached the vicinity of Elko. Figure 3.23,

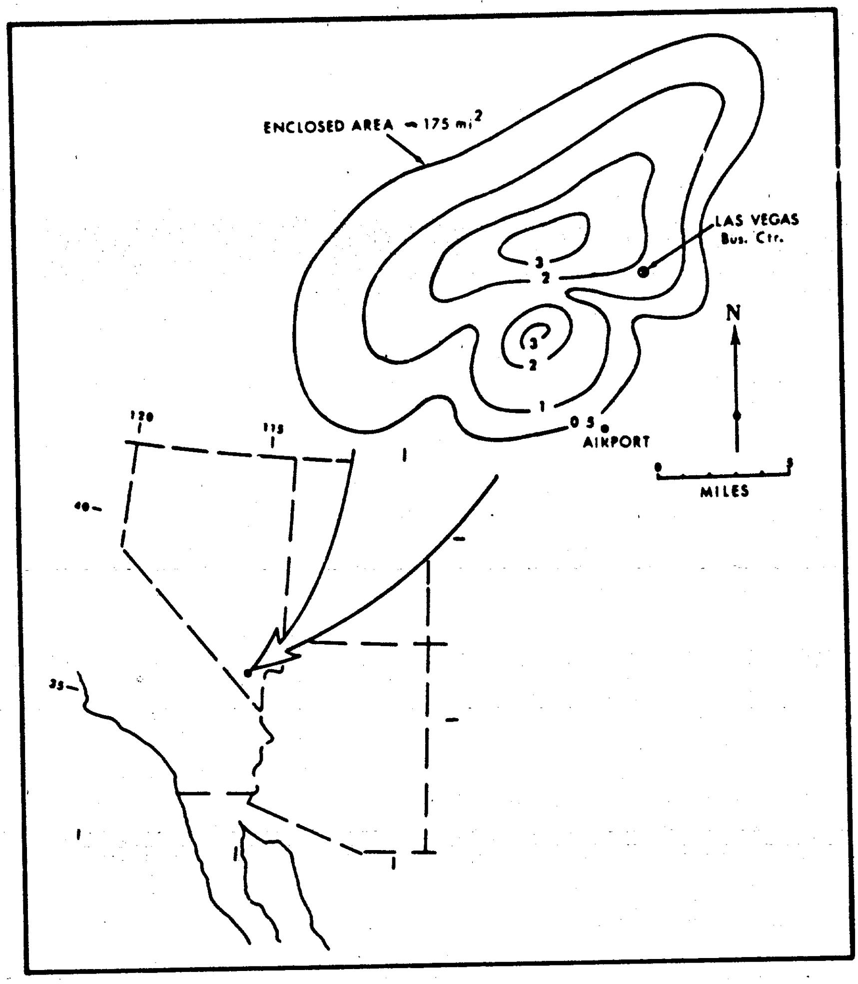


Figure 3.20.--Isohyetal analysis for storm of June 13,1955

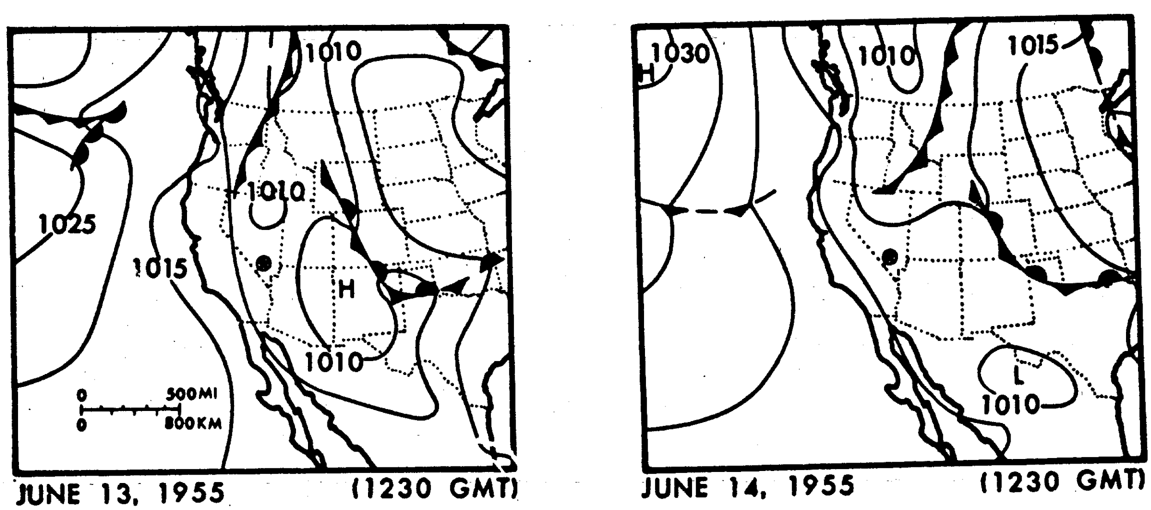
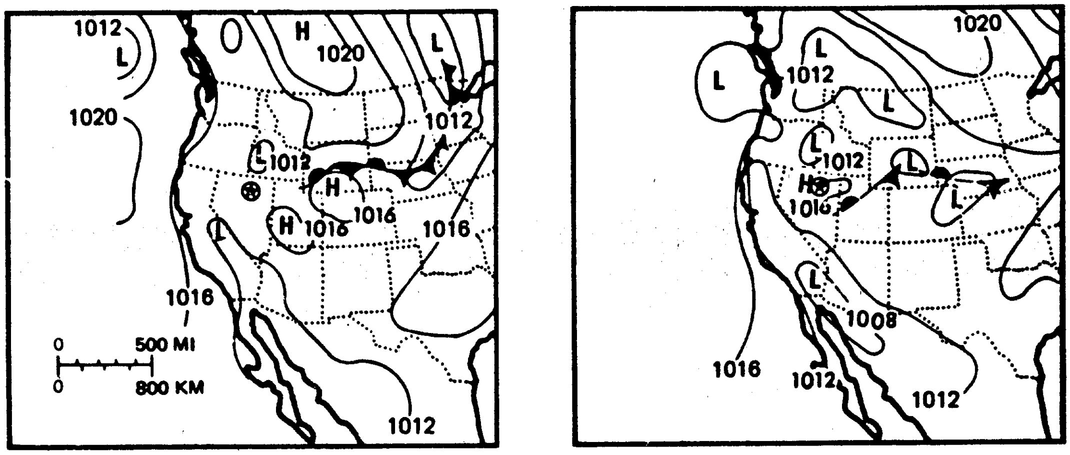
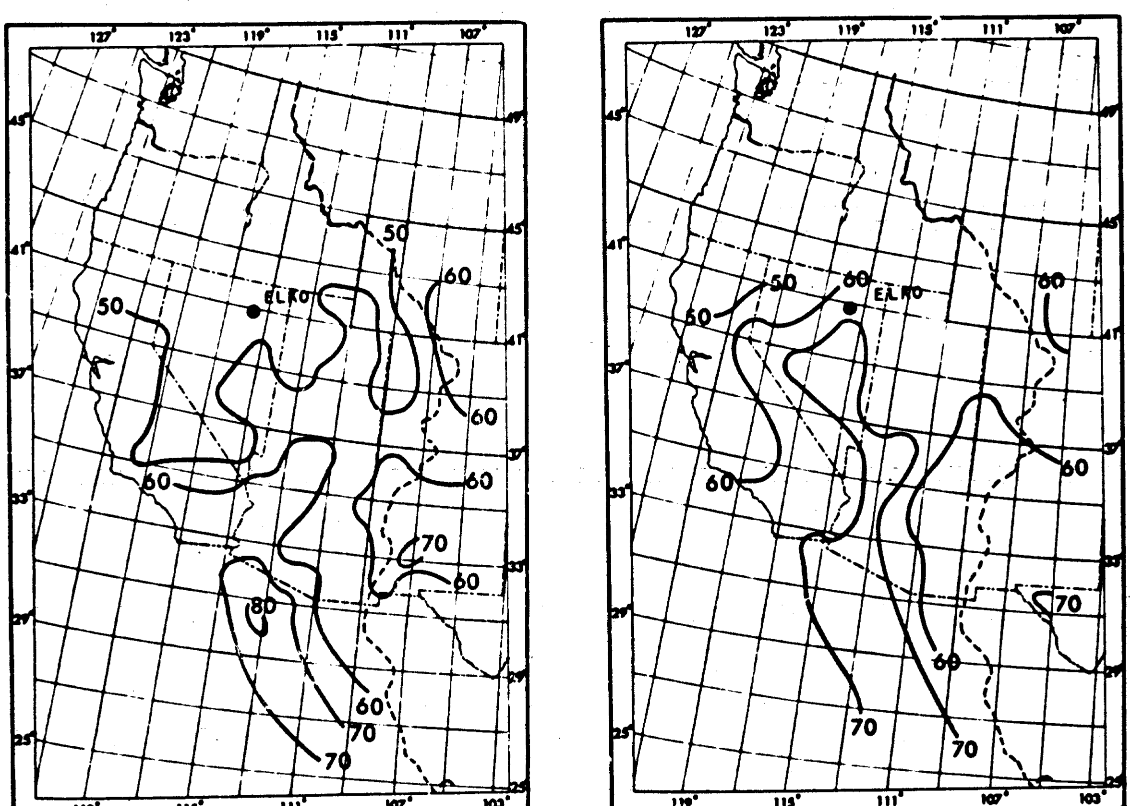


Figure 3.21. Surface weather maps for June 13-14, 1955.



August 27, 1970 (1200 GMT) August 28, 1970 (1200 GMT)

Figure 3.22.--Surface weather maps for August 27-28, 1970.



AUGUST 25, 1970 (0000 GMT) AUGUST 27, 1970 (2100 GMT)

Figure 3.23.--Isodrosotherm analysis depicting moisture inflow to storm of August 27, 1970 at Elko, Nev.

ternoon of the 26th) and 1.14 in. at Yuma between 1700 and 2000 PST on the 26th (0100-0400 GMT of the 27th).

ARTCC radar summaries of precipitation echoes for the period 1000-1300 PST (1800-2100 GMT) of the 27th are given in figure 3.24. (Refer to table 3.4 for a list of symbols for these diagrams). Widespread echo activity occurs throughout much of the Great Basin region and to the northwest. Envelopment of these echoes roughly conforms to the region enclosed by the 60°F dew point line in figure 3.23. In figure 3.24, a large echo develops in the vicinity of Elko between 1200 and 1300 PST (2000 and 2100 GMT), the time of the extreme local storm rainfall.

3.3.13 Las Vegas, Nev. 7/3/75

Between 1100 and 1420 PST (1900 and 2230 GMT) of July 3, heavy local storm rainfall on the order of 3.0 in. [158%] fell in western and northern Las Vegas. Randerson (1976) made an in-depth analysis of this extreme storm and an isohyetal analysis. The area of precipitation within the 0.5 in. isohyet in his analysis is approximately 215 mi^2. The total storm pattern has two centers oriented roughly north-south, in general agreement with the flow direction of the upper-level winds.

Randerson indicated that this thunderstorm formed over the Las Vegas Valley, not over the mountainous terrain. He was able to determine from his analysis of moisture that the intense convective activity formed near the leading edge of a strong moisture gradient with dry air to the west oN Las Vegas.

3.3.14 Morgan, Utah 8/16/58

A severe local storm dumped 6 to 7 in. [285 to 333%] of rain in about 1 hr between 1600 and 1700 MST (2300 to 2400 GMT) August 16, 1958 east of Morgan (elev. 5,150 ft). A survey team from the U.S. Geological Survey (Butler 1959) reported 6 separate measurements used to draw an isohyetal pattern, as shown in figure 3.25, covering an area of about 15 mi^2.

The Morgan storm occurred in Round Valley, a small basin surrounded by ridges some 2.5 mi east of Morgan, and some 25 mi north-northeast of Salt Lake City. The mountains are all part of the Wasatch range and reach ridge heights of 9,000 ft to the west of Morgan, and about 8,500 ft to the north and southeast of Morgan. Weber River drains Round Valley from the east and flows out to the northwest through an extremely narrow interruption in the front range of the Wasatch Mountains. The Wasatch are a major barrier extending north-south for almost the entire length of Utah. The Great Salt Lake Basin to the west of the Wasatch Mountains has a general elevation slightly less than 5,000 ft, while east of the Wasatch the terrain is considerably more rugged and contains numerous small ridges of 7,000 ft and higher elevations.

The synoptic weather conditions surrounding the Morgan event have been described in considerable detail by Hansen (1975b). Surface weather analyses (figure 3.26) show a thermal Low in near-normal position and intensity. Throughout the Great Basin a rather weak surface pressure pattern hardly supported large scale influx of moist air from the south. However, Hansen's study showed that a broad tongue of low-level moisture pushed northward to the vicinity of Salt Lake City by 0500 MST (1200 GMT) of the 15th, along a route of

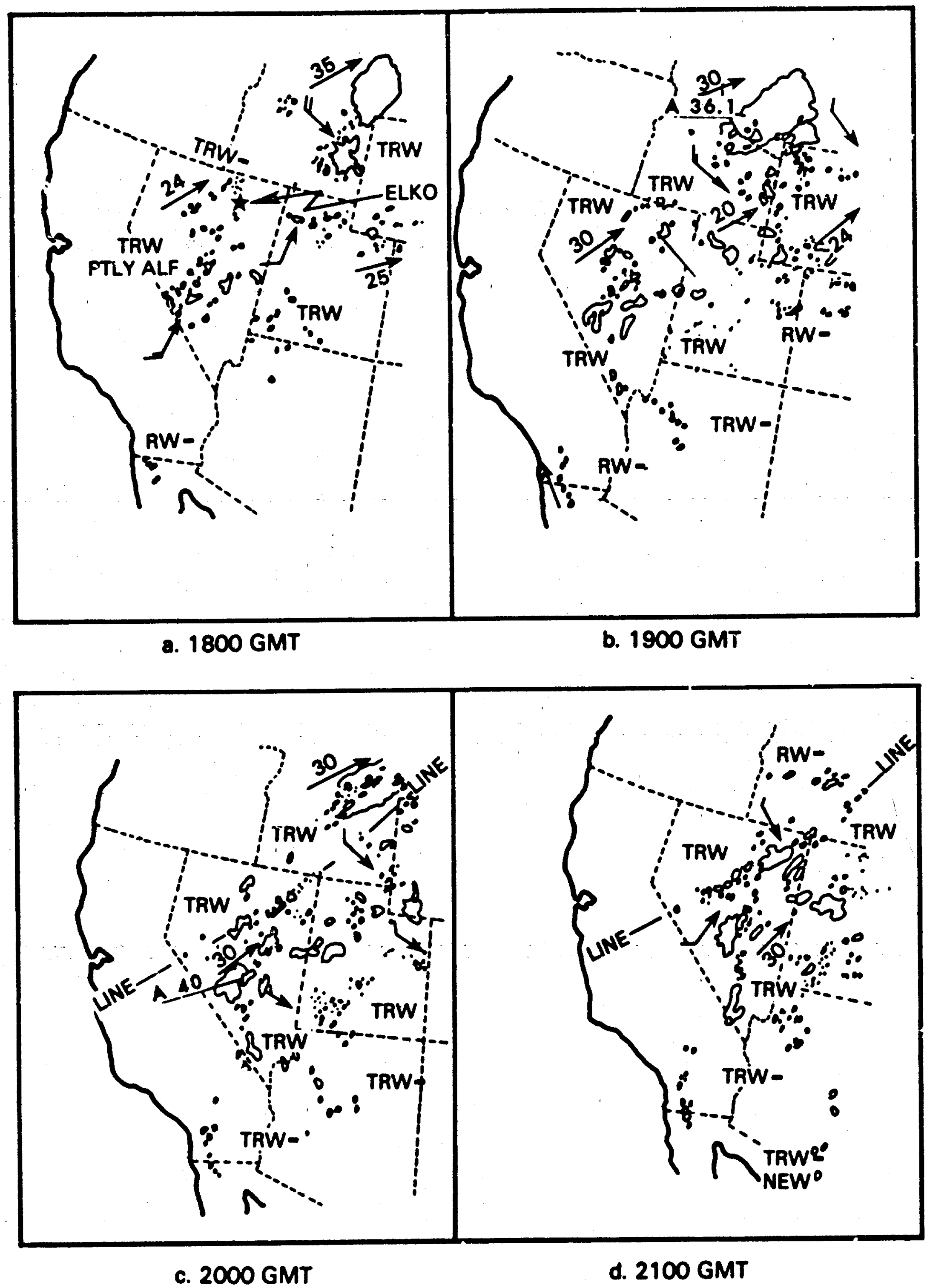


Figure 3.24.--Radar echo summary developed from ARTCC radar data for period 1000-1300 PST August 27, 1970. See pp. 83 for symbols.

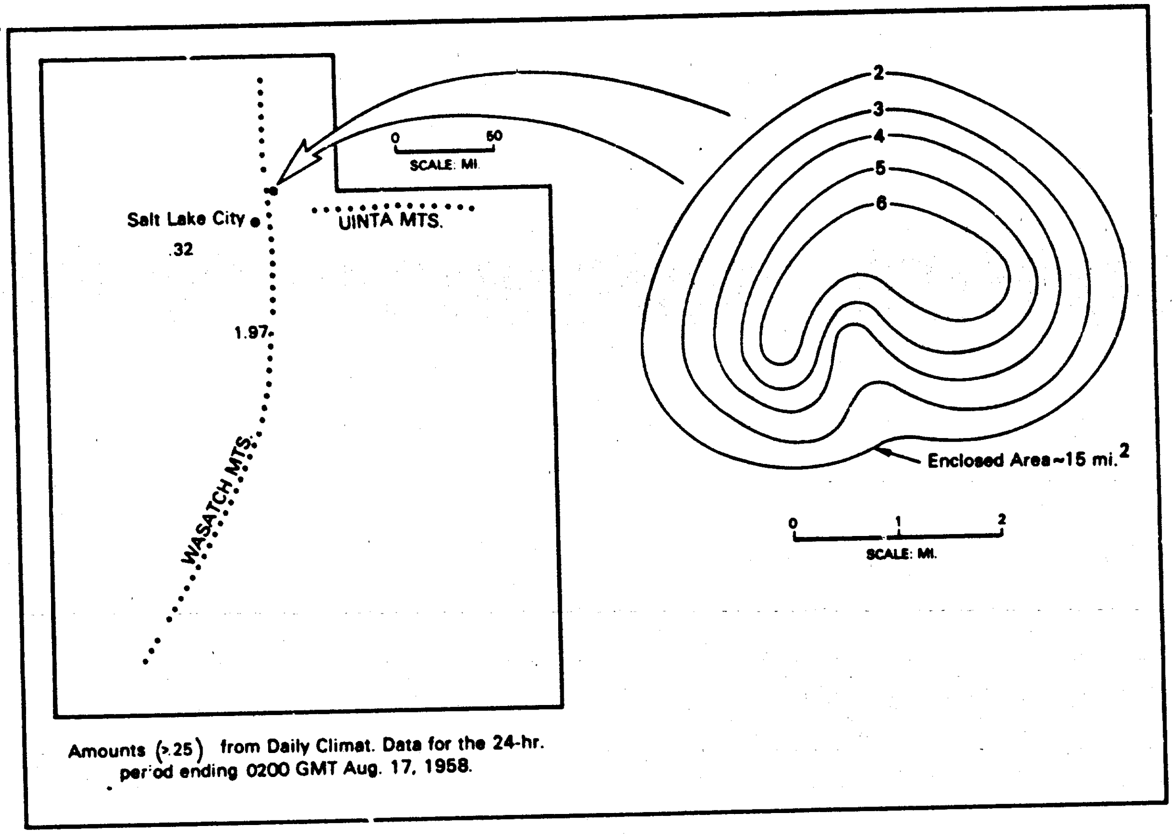
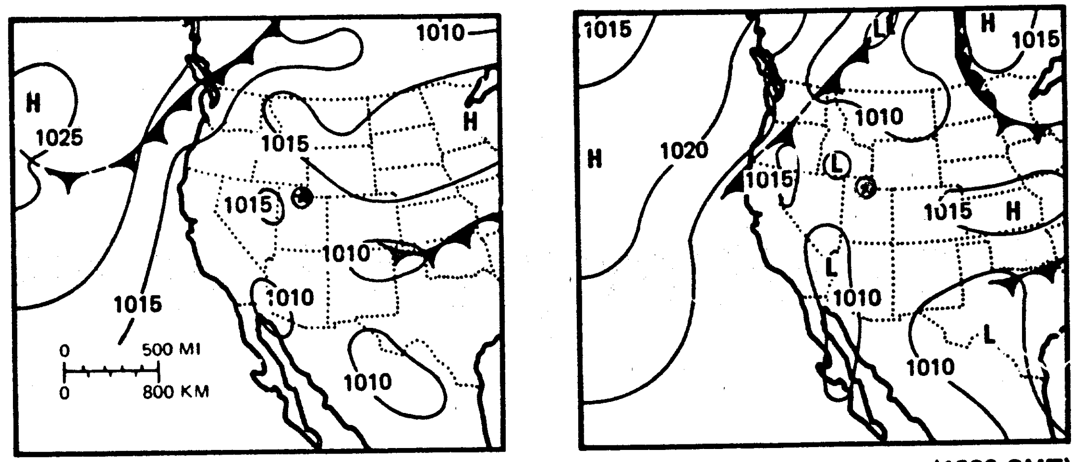


Figure 3.25.--General location map and isohyetal pattern for storm of August 16, 1958 at Morgan, Utah.

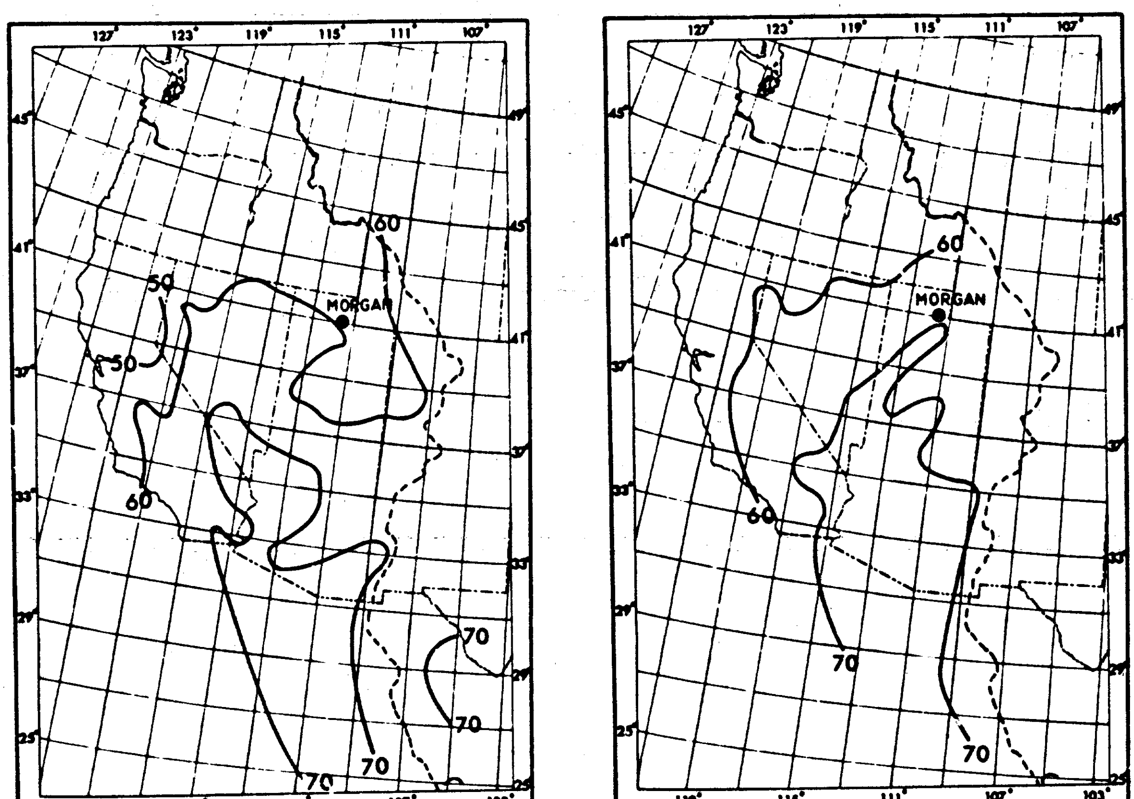
least terrain resistence (figure 3.27). The moist tongue then pushed against western slopes of the Wasatch Mountains and passed over them in the following 24 hr. Figure 3.28 shows a vertical cross section of moisture (analysis of surfaces of constant mixing ratio where the units are normally in g/kg) for 3 consecutive dates, and a profile of the surface terrain between San Diego, Calif. and Rapid City, S.D. The vertical scale on this figure has been exaggerated to emphasize the terrain and moisture features. The cross section between Las Vegas, Nev. and Lander Wy. is approximately aligned with the direction of flow of low-level moisture. By considering the variation with time of the mixing ratio surface for 8 g/kg (solid to dashed to dotted lines), one obtains a picture of the surge of moisture that passed across the Wasatch range on the 15th. In passing over the mountains, the moisture also contributed to other shower activity observed along and near the Wasatch range on the 16th (fig. 3.25).

Hansen's study (1975b) showed support for an independent source of low-level moisture, i.e., below 10,000 ft. A recognizable shear in the wind field in the vertical separated the low-level moisture from the drier air above. The implication of this finding is that moisture above 10,000 ft may have arrived from the Gulf of Mexico, while the surface layer of moisture was from the Gulf of



August 16, 1958 (12"0 GMT) August 17, 1958 (1230 GMT)

Figure 3.26.--Surface weather maps for August 16-17, 1958.



AUGUST 13, 1958 (1200 GMT) AUGUST 15, 1958 (1200 GMT)

Figure 3.27.--Isodrosotherm analysis depicting moisture inflow to storm of August 16, 1958.

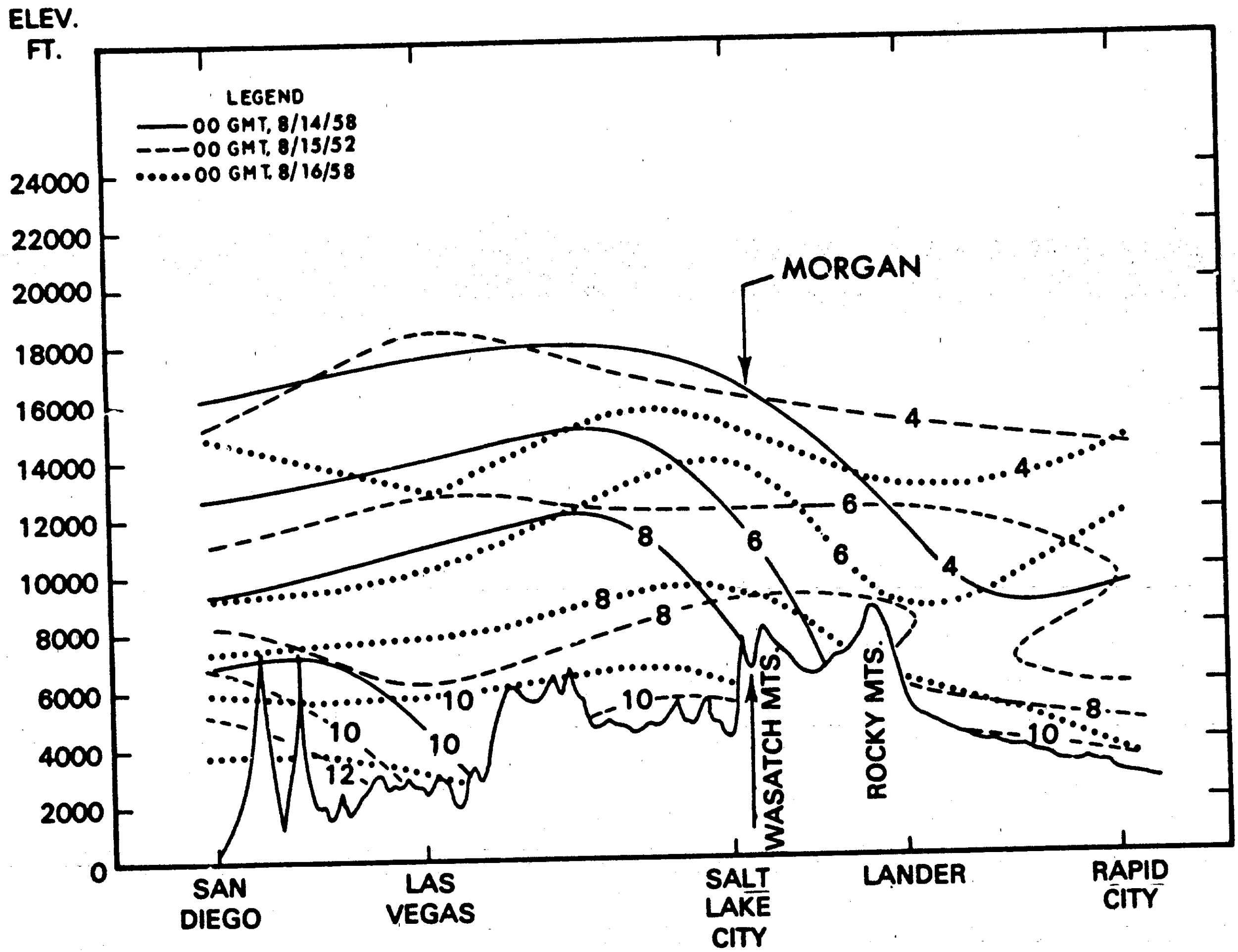


Figure 3.28.--Temporal variations of moisture (8 gm/kg) along vertical cross section along a line from San Diego, California to Rapid City, S.D.

California and eastern Pacific Ocean. Hansen concluded that the influx of low-level moist air was necessary for the heavy rain at Morgan.

3.4. Meteorology of Supplementary Extreme Storms in Western California

3.4.1 Red Bluff, Calif. 9/14/18

Weaver (1962) provided a brief description of the meteorological conditions surrounding the intense local storm at Red Bluff, California, September 14, 1918. Referring to a tropical cyclone, he states that, "This storm is the only one known to have moved northward offshore as far as Central California before veering inland" (fig. 2.2). Weaver noted that the surface circulation (low-pressure system) had dissipated prior to encountering land as shown in the figure 3.29. Even though there was no sequence of surface pressure maps in figure 3.29. Even though there was no organized pattern, an unusual concentration of moisture continued to push northward through the upper Sacramento Valley, reaching Red Bluff by the 14th.

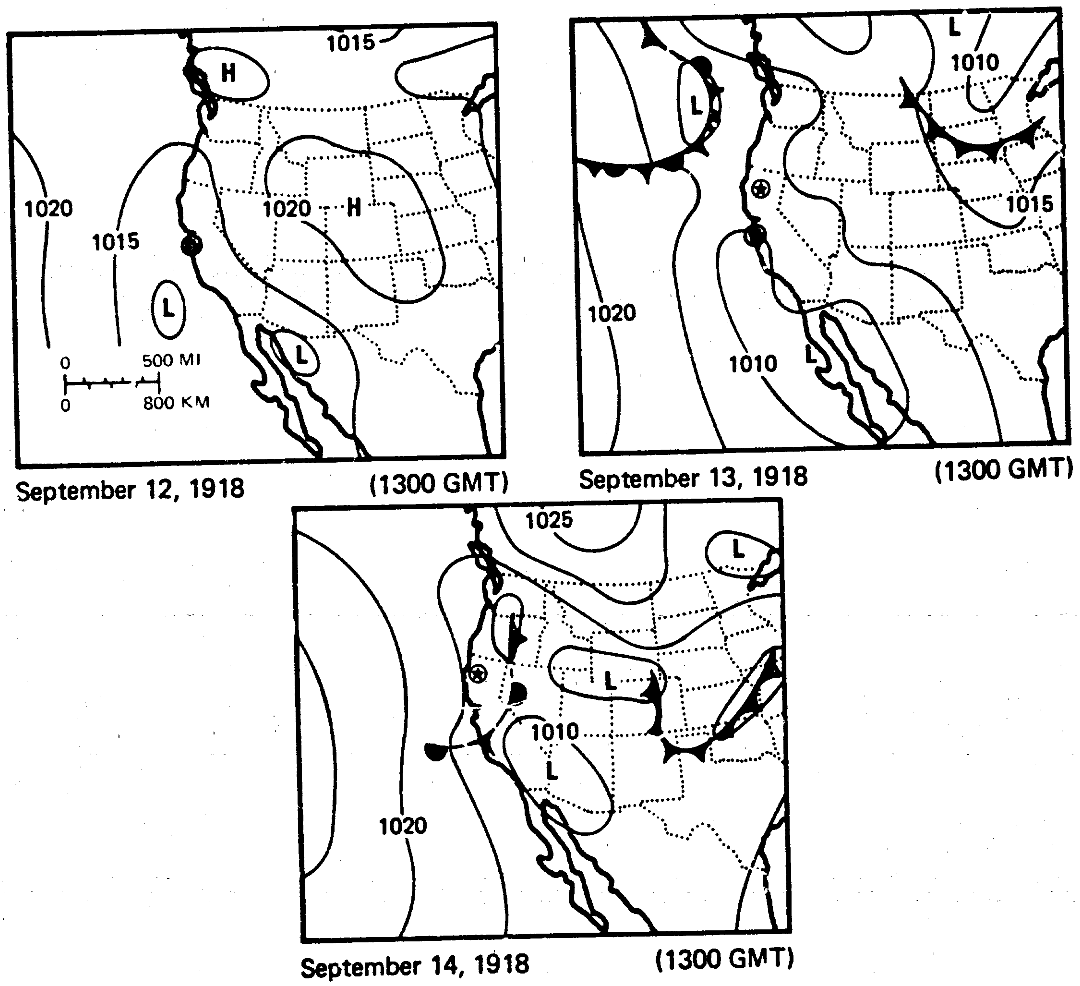


Figure 3.29.--Surface weather maps for September 12-14, 1918.

At Red Bluff, 4.7 in. [181%] of rainfall was reported in 3 hr (6.12 in. in 24 hr), caused by release of instability early on the morning of the 14th. Uplifting by terrain as well as by cool air approaching from the northwest triggered this release.

As this storm was crossing the coast on the 12th, a local storm occurred at Wrights, Calif. (amount judged doubtful, see section 3.1.2).

3.4.2 Encinitas, Calif. 10/12/1889

A severe heavy rainfall of 7.58 in. [303%] in 8 hr was reported at Encinitas from 2200 PST October 12 to 0600 PST of the 13th (0600 to 1400 GMT on the 13th), (U.S. Weather Bureau Monthly Weather Review 1889). Encinitas is located on the California coast about 25 mi north of San Diego. Some 30 mi to the east, the coast range of mountains rises to heights near 5,000 ft.

There is little synoptic weather information for this early storm. However, the Monthly Weather Review summary for this date included a chart on tracks of areas of low pressure for the month (fig. 3.30). One track, labeled VI on this figure, is especially interesting, and we believe it may offer a clue on the nature of the Encinitas storm. Track VI enters the coast near Monterey, Calif., near 1800 PST of the 12th (0200 GMT on the 13th). Although the track shown in figure 3.30 represents an extratropical storm system, it is unusual in its southerly landfall and direction of movement. The direction of the track at its coastal encounter suggests it may have come from a more southerly position, and we speculate that this storm may, in fact, have been a tropical cyclone that traveled northwards along the California coast and regenerated in mid-latitudes as an extratropical system. In this context the total storm track would not be too unlike that described for the decadent 1918 storm noted at Red Bluff (section 3.4.1). However, because of the timing of these events, the Encinitas rainfall would have occurred in the post storm moist environment, if indeed it was related to such an event.

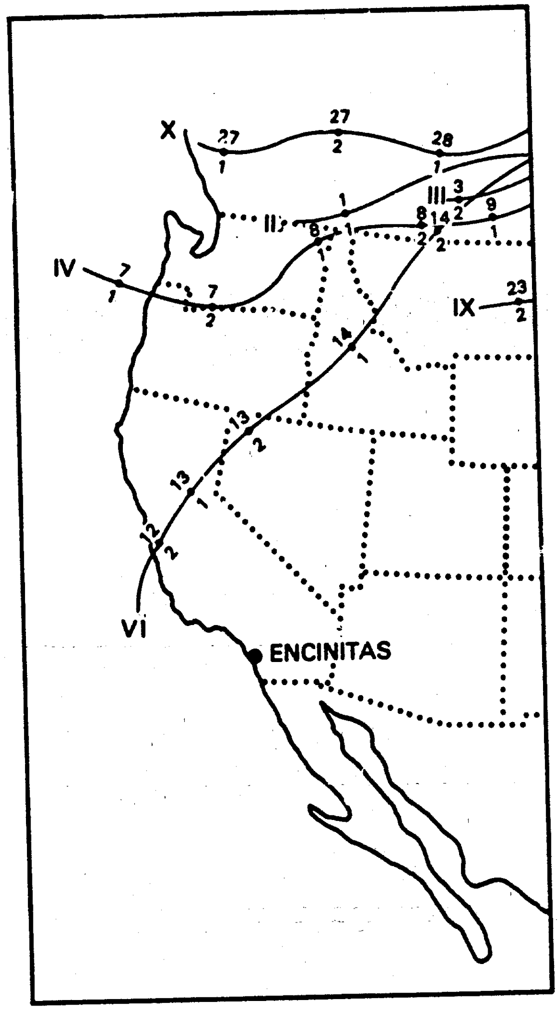


Figure 3.30.--Storm tracks for October 1889.

3.4.3 Kennett, Calif. 5/9/15

A brief description of the Kennett storm was given by Weaver (1962). Rain prior to a late cool season frontal passage accumulated 8.25 in. [156%] in 8 hr between 1200 and 2000 PST (2000 GMT of the 9th to 0400 GMT of the 10th). Over a 24-hr period Kennett had 9 in., while at Redding, Calif., (11 mi south of Kennett) only 1.3 in. was measured in the same period. Weaver stated that the relative positions of contrasting air flows aided development of the local storm. In this case, low-level moisture flowing northward through the Sacramento Valley clashed with cooler air arriving from the north (behind the front) and brought about lifting of the surface flow. In addition, the increasing terrain elevation and the constriction at the northern end of the Valley were favorable to the release of instability.

Figure 3.31 shows selected elevation contours that describe the terrain surrounding the Sacramento Valley. The gradual constriction of this Valley towards the north end is evident. A natural entrance to the Valley for low-level moist inflows from the south to southwest occurs in the vicinity of San Francisco where there is a break in the coastal mountains.

Surface pressure maps prior to and during the time of the Kennett storm are shown in figure 3.32. A review of the track of the storm centers shown in figure 3.33 indicates that the center off the coast of Washington on the 9th had tracked northeastward from a position near Hawaii on the 5th. Ship reports indicate

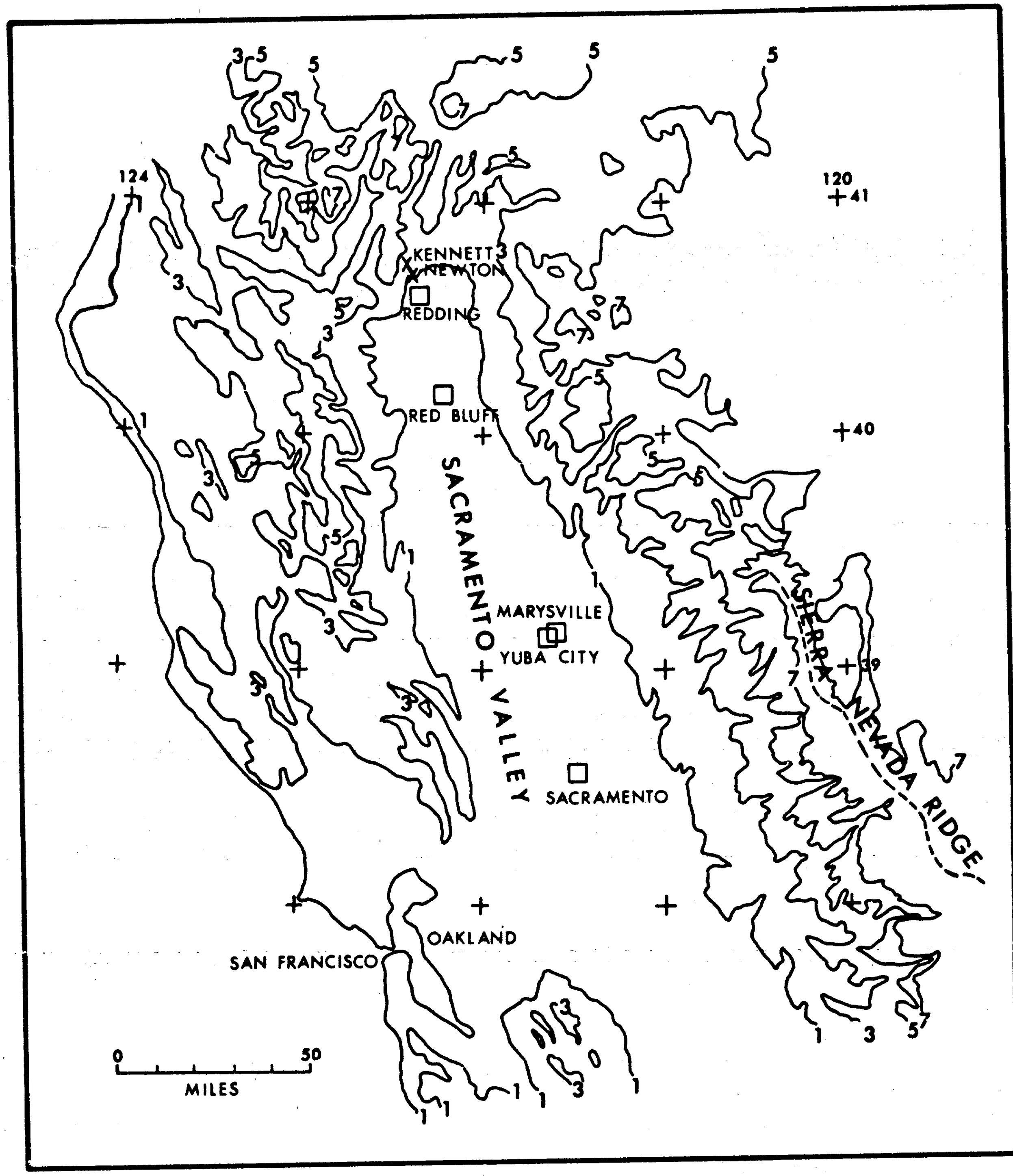


Figure 3.31.--Generalized contours for the Central Valley and surrounding mountains for north central California.

that this system was moist and unstable as rains are noted throughout this passage. Arriving on the coast between May 9 and 10, the system effectively carried its moist unstable air with it. This is in contrast to the situation in which moist air is advected (moved by pressure gradients) from tropical latitudes into a mid-latitude storm system.

3.4.4 Tehachapi, Calif. 9/30/32

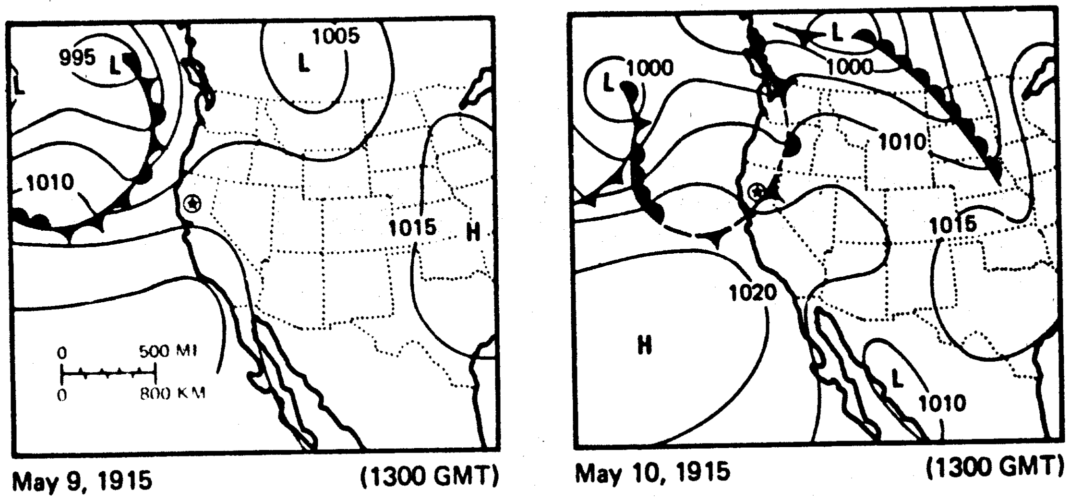
The Climatological Data summary for September 1932 (National Oceanic and Atmospheric Administration 1897 -) reported on heavy rains over the mountains of southern California. An observer at Tehachapi stated that, "Rain was nearly continuous from 1330 to 2300 PST (2130 the 30th to 0700 of October 1st)." A rainfall of 4.38 in. [248%] was observed in the 6.5 hr prior to 2000 PST (0400 GMT of October 1). A survey at the site of heavy rain located a second report of 4.34 in. that fell between 1500 and 2000 PST (2300 GMT on the 30th and 0400 GMT on the 1st).

An isohyetal map for this storm prepared by the Corps of Engineers (1961a) is reproduced in figure 3.34 and encloses approximately 325 mi^2 (within the 1.0 in. isohyet). The orientation of this pattern is northwest-southeast and is coincident with the axis of Tehachapi Creek which drains to the northwest from the crest of the Tehachapi Mountains.

Figure 3.35 shows surface pressure maps for September 29 and 30, 1932. What appears as a rather large thermal Low oriented along the southern California-Sonora coast line is in fact a low-pressure trough, in which the remnant moisture from a tropical cyclone reaches the site of the Tehachapi storm. The track for this storm is shown in figure 3.36. This track is unusual in that most tropical cyclones affecting the Southwest follow a path at some distance from the coast, and by doing so, the storm can maintain its intensity longer. When a track follows the coast, as in the September 1932 storm, much of the warm surface moisture is cut off, and the system is expected to dissipate sooner. Nevertheless, as this case shows, considerable moisture remained in the decadent system which continued to track northward in a favorable pressure regime. The California state climatologist provided an interesting commentary on this storm (National Oceanic and Atmospheric Administration 1897 -). He wrote;

> "This storm was the cloudburst type....Extremely heavy downpours are sometimes recorded, which in the course of a very short time tear up the ground and fill up gullies and watercourses; this may happen at any place, but it occurs frequently in hilly and mountainous districts, where it may sometimes be due to the sudden cessation of convectional movement, caused by the supply of warm air from the lower part of the atmosphere being cut off as the upward current, the rain drops and hailstones which it had been supporting must fall in a much shorter time than they would have done had the ascensional movement continued."

Although this explanation follows a reasonable logic, in reality other factors become involved in producing extreme local storms, as is evident in the Bakersfield storm (section 3.3.8) that occurred in the lee of these same mountains under somewhat similar meteorological conditions.



May 9, 1915 (1300 GMT) May 10, 1915 (1300 GMT)

Figure 3.32.--Surface weather maps for May 18-19, 1915.

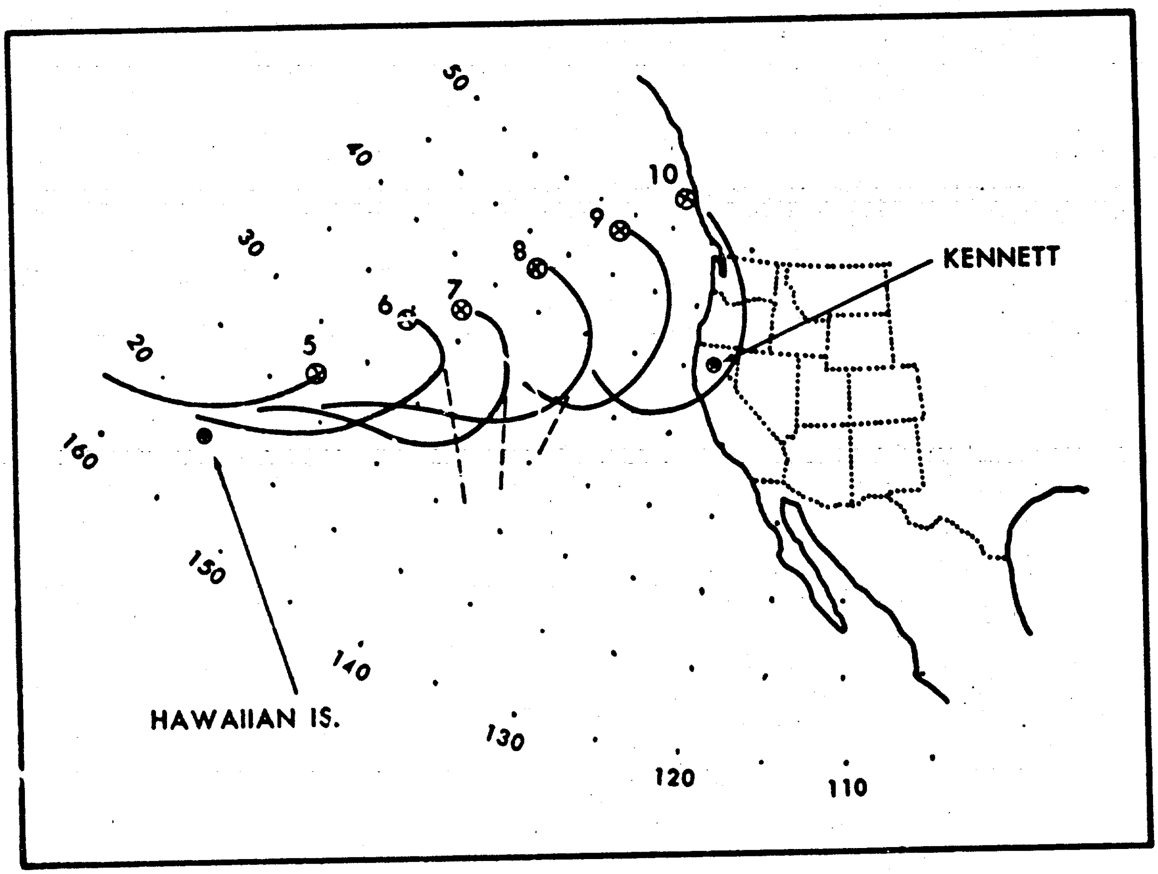


Figure 3.33.--Storm track for May 5-10, 1915.

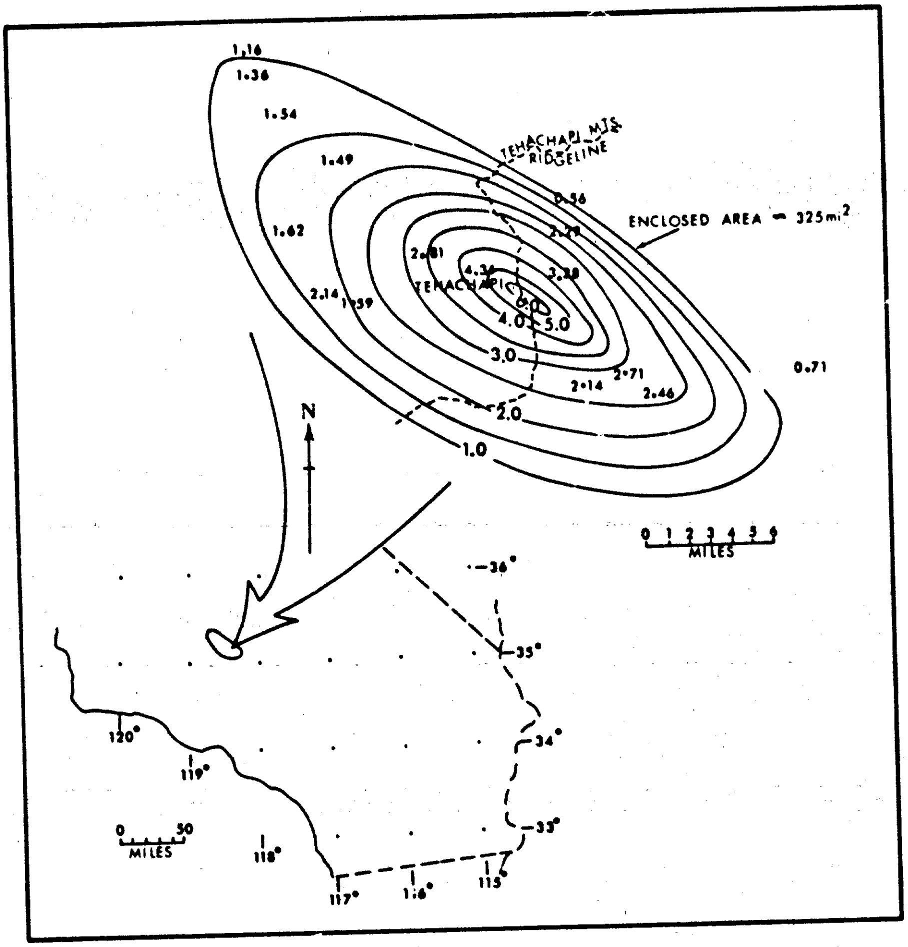


Figure 3.34.--Isohyetal map for storm of September 30, 1932.

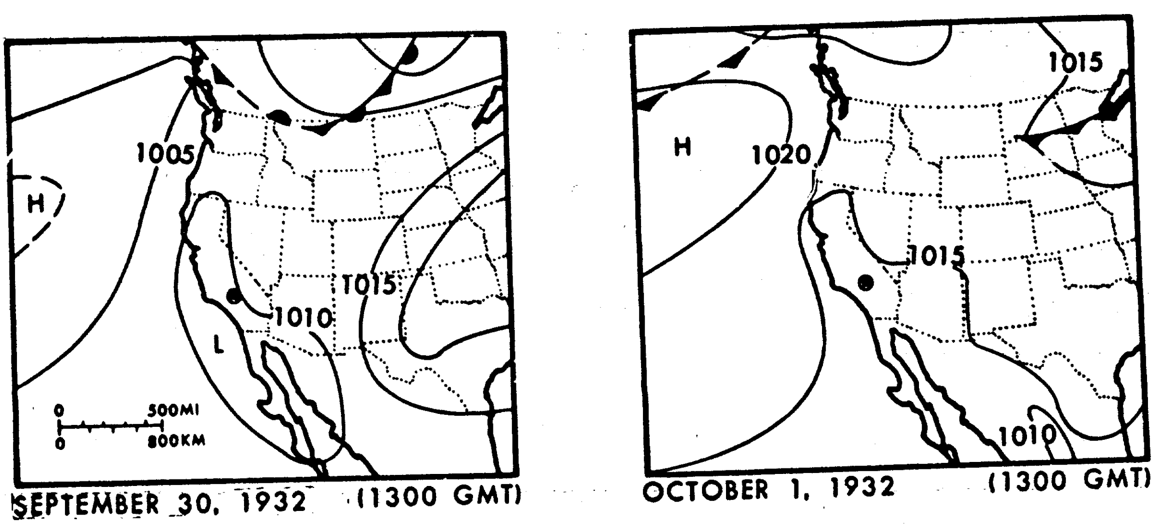


Figure 3.35.--Surface weather maps for September 29-30, 1932.

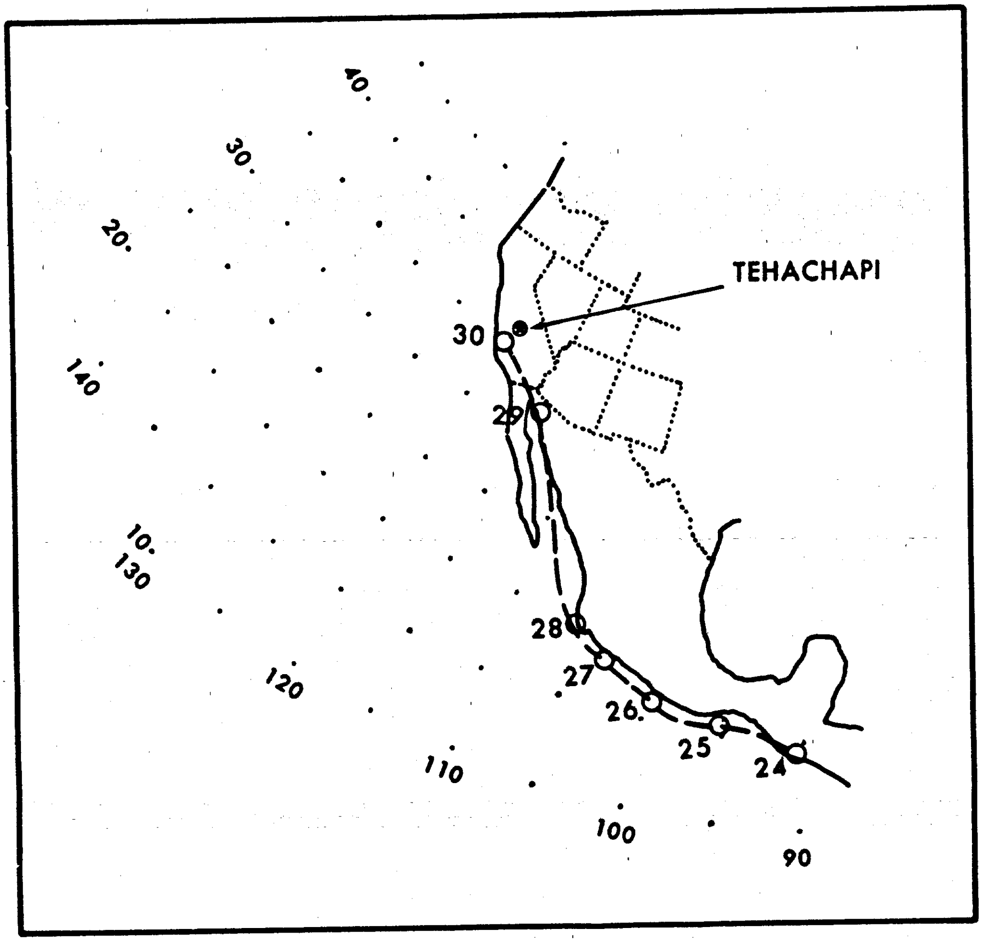


Figure 3.36.---Storm track for tropical cyclone that was important for the September 30, 1932 storm at Tehachapi, Calif.

3.4.5 Avalon, Calif. 10/21/41

An unusual storm on October 21, 1941 brought a 24-hr rain of 6.7 in. to Avalon on Santa Catalina Island off the coast of southern California. Within this storm was a local storm that contributed 5.53 in. in 3.5 hr between 0700 and 1030 PST (1500 to 1830 GMT), according to Weaver (1962).

Surface pressure maps for the dates surrounding this storm are shown in figure 3.37. Notable on these maps are the small Lows along the Pacific coast of California near 35°N. Weaver (1962) provided a track for the center of low pressure from the 19th (fig. 3.38) that is unusual in that it moved the Low off the coast, rather than the more commonly observed reverse. A cold front extends from the Low eastwards through southern California. A 3-4 day period of general showers preceded this frontal system over much of southern California.

Santa Catalina Island is but one of several small islands some 20 mi from the coast California west of Los Angeles. Santa Catalina is one of the larger of these islands, roughly 20 mi in length, 8 mi at its widest, and has peak heights of 2,100 ft. Its major axis is oriented northwest-southeast.

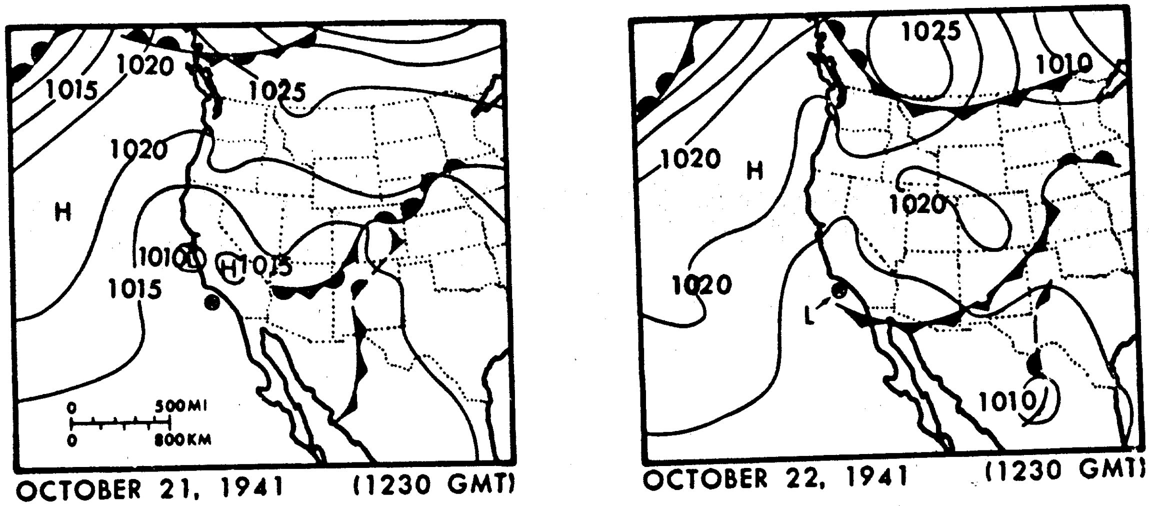


Figure 3.37.--Surface weather maps for October 20-23, 1941.

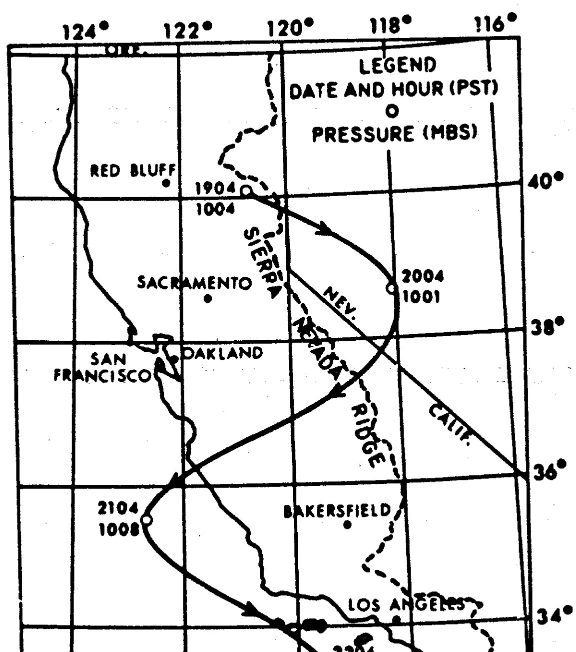


Figure 3.38.--Storm track for storm that produced heavy rain October 21, 1941 at Avalon, Calif.

It is difficult to determine the basis for this extreme local storm, since the time of occurrence rules out the most likely cause, that of surface heating. Ordinarily, such a small topographic feature is not regarded as a prime source of orographic lifting, since air tends to flow around singular peaks.

3.4.6 Los Angeles, Calif. 3/3/43

This storm occurred outside the time frame (May through October) of other storms described in this chapter, in which tropically moist air might be expected to contribute to major rains in the Southwest. Nearly 300 point rainfall amounts were obtained in the post-storm survey, and the information on timing made this storm useful in the development of depth-duration relations for local storm PMP in HMR No. 49.

Between 2100 and 2400 PST of March 3, 1943 (0500 to 0800 GMT of the 4th) an unusual local storm rainfall dumped a maximum 3.32 in. [60%] in 3 hr at Sierra Madre-Carter Dam, Calif. (10 mi northeast of Los Angeles at 1,110 ft elevation). The Corps of Engineers (1973) provided an isohyetal pattern for this storm (fig. 3.39) oriented southwest-northeast across the cities of Los Angeles and Pasadena, and the southwest facing slopes of the San Gabriel Mountains toward Mt. Wilson (5,750 ft). The 0.5 in. isohyet encloses 345 mi^2. The storm consisted of considerably more than the 3-hr local storm as the general storm surrounding this event lasted more than 48 hours and was spread over several thousand square miles.

Surface pressure maps for this storm are shown in figure 3.40. A surface Low and associated frontal systems approached the coast during the heavy rain event. The history of this storm system may provide some insight to the source of heavy rains observed. On February 26, the storm appeared as a minor wave along a cold front near the International Date Line at about 35°N. During the next few days, it tracked slightly to the south of east and overtook a second Low center on the 28th. This second Low was composed of warm tropical air, having moved northward from just east of the Hawaiian Islands (latitude 20°N). The combined storm intensified considerably, as is often noted in merged systems. By the 2nd of March, the storm had moved eastward to 130°W and by 0430 PST (1230 GMT) on the 3rd, it was at 35°N, 128° W, some 300 mi west of Los Angeles. In the following 24 hr, the Low moved somewhat northeastward to a position off the coast of San Francisco while the frontal pattern had begun to move out of the Low center, and in the process became occluded. On the 4th, the upper-level occlusion passed through California and extended northward from Las Vegas, while the surface occlusion remained along the coast. As is typical of such systems, the low-pressure center began to weaken, but somewhat atypically, it slowed down, and little movement occurred between 1600 PST of the 3rd (0000 GMT on the 4th) and 0400 PST of the 5th (1200 GMT).

Because of the infusion of tropical moist air into the combined storms, near Hawaii, this system brought unusual moisture to the California coast (in this aspect, the Los Angeles rainfall event was similar to the Kennett rainfall discussed in section 3.4.3). The moist unstable air was lifted orographically in confronting the San Gabriel Mountains. Figure 3.39 also shows lesser topographic features such as the Baldwin Hills (elevation of 500 ft) near Santa Monica Bay, and the Verdugo Mountains (3,000 ft elevations) and San Puente-San Jose Hills (1,500 ft elevations) that may have served to fix the location of heavy rainfall.

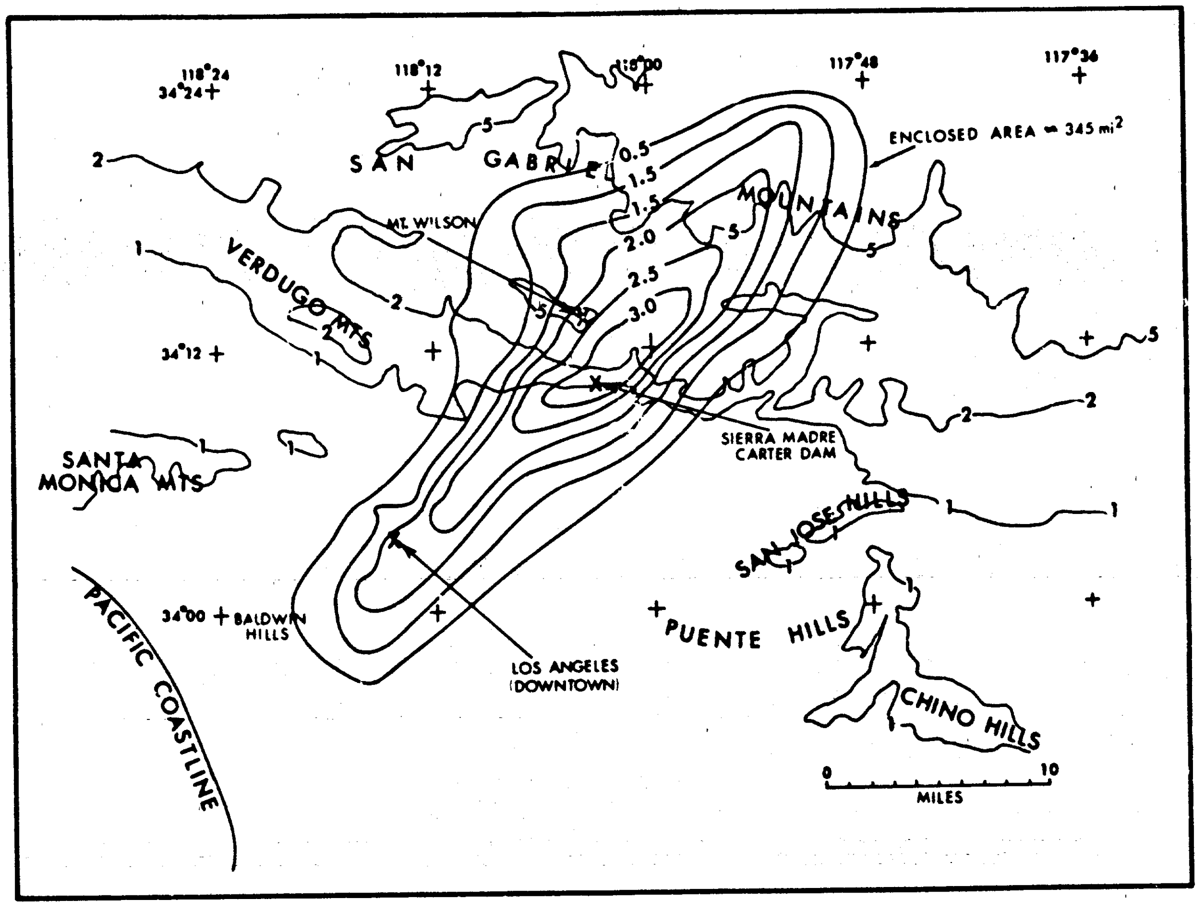


Figure 3.39.--Isohyetal map for storm of March 3, 1943.

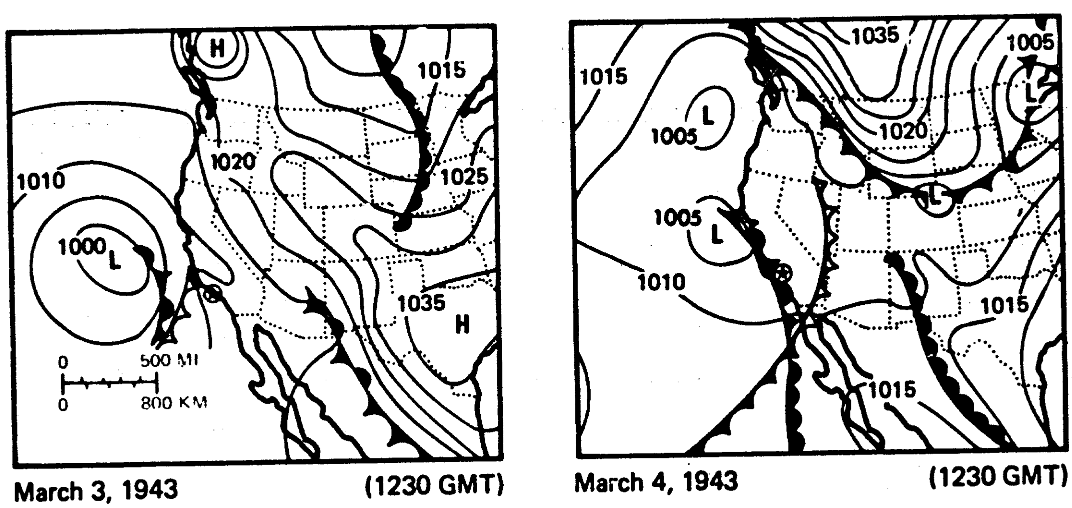


Figure 3.40.--Surface weather maps for March 3-4, 1934.

3.4.7 Newton, California 9/18/59

Newton is about 7 mi north of Redding, and only some 4 mi south of Kennett. About 10.6 in. [236%] of rain fell at Newton in 5 hr between 1700 and 2200 PST (0100 GMT and 0600 GMT on the 19th). The isohyetal pattern of this concentrated rain (taken from Weaver 1962) is shown in figure 3.41 together with the background rainfall (about 48 hr duration).

The surface weather pattern was similar to that of the Kennett storm. Figure 3.42 shows a strong cold front that approached northern California from the northwest and passed the vicinity of Newton about 0430 PST (1230 GMT) on the 18th. Unlike Kennett, however, the low-pressure system in the Newton storm did not track from tropical latitudes. The difference, in part, is the fact that the Newton storm occurred in September after a summer of increased thermal heating to the Sacramento Valley and warmer sea-surface temperatures offshore. Strong southerly winds ahead of the surface front brought Pacific moisture through the gap in the coastal mountains at San Francisco and into the Sacramento Valley. The moist unstable air was warmed additionally by surface heating as it moved northward through the Valley to be forced aloft by the mountains and horizontal convergence.

Aloft at 500 mb (maps not shown), an intense closed low-pressure system located off the coast of Washington resulted in strong southwesterly flow across northern California.

3.5 Summary of Meteorological and Physiographical Features of Extreme Local Storms

Sections 3.3 and 3.4 described physiographic and meteorologic conditions surrounding the occurrence of the more significant extreme local storms in the Southwest and the supplementary storms in Western California. Some similarities between these storms have been mentioned. This section will summarize our understanding about terrain, moisture, and general synoptic weather regime for these storms. Comments regarding instability, inflow direction, and storm movement are included.

3.5.1 Storm Occurrence vs. Terrain

Our survey of short-duration extreme rainfalls produced 35 events that met our definition of local storms (table 3.1). By considering the terrain over which the extreme rains fell, we find that 18 storms occurred over ridges and slopes that we classed as definitely orographic terrain conditions. The other 17 storms fell on essentially flat terrain, however, not all the rain could be considered nonorographic. In a good portion of the Southwest, the terrain is relatively flat, interspersed with prominent ridges or peaks. Convection can be triggered by the elevated heat source provided by these small-scale orographic features in the terrain, and then with time drift away from this source to dump heavy precipitation over some nearby flat region.

In section 3.3.13 we stated that Randerson (1976) found that the local storm at Las Vegas in July 1975 did not develop over the mountains. Such determination can only be made through eyewitness accounts. Using satellite photographs Pyke as cited by Bryant (1972) concluded that the local storm at Bakersfield (June 7, 1972) was triggered along the Tehachapi Mountains and moved northward over the site of heavy rainfall. One difficulty in satellite analysis arises in trying to distinguish a local storm cell in a mass of surrounding cells. Another problem

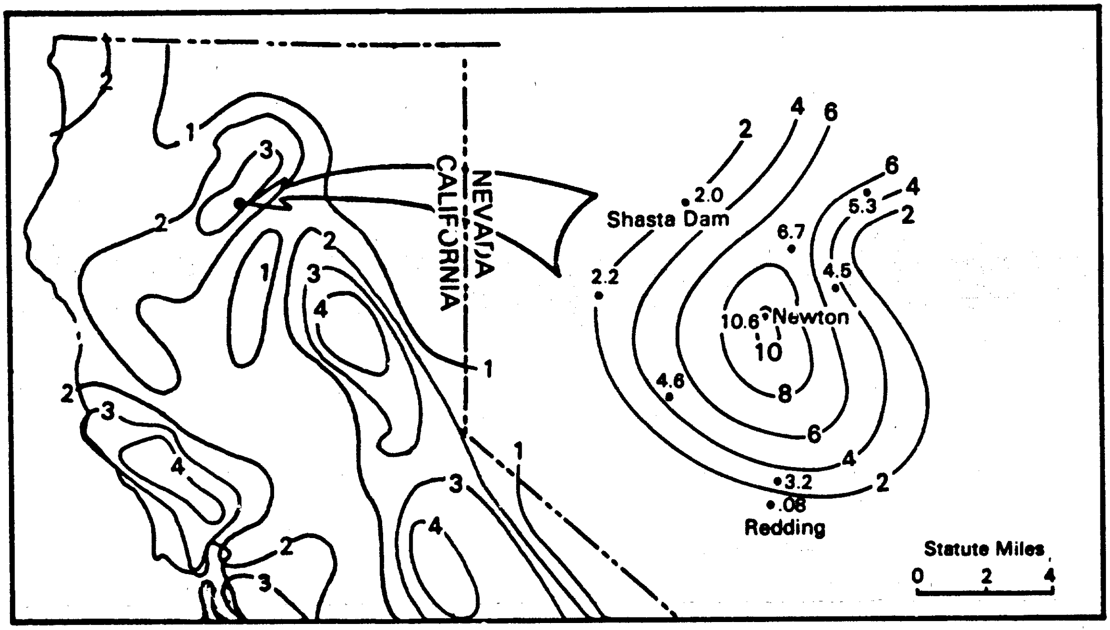


Figure 3.41.--Isohyetal pattern for storm of September 17-18, 1959.

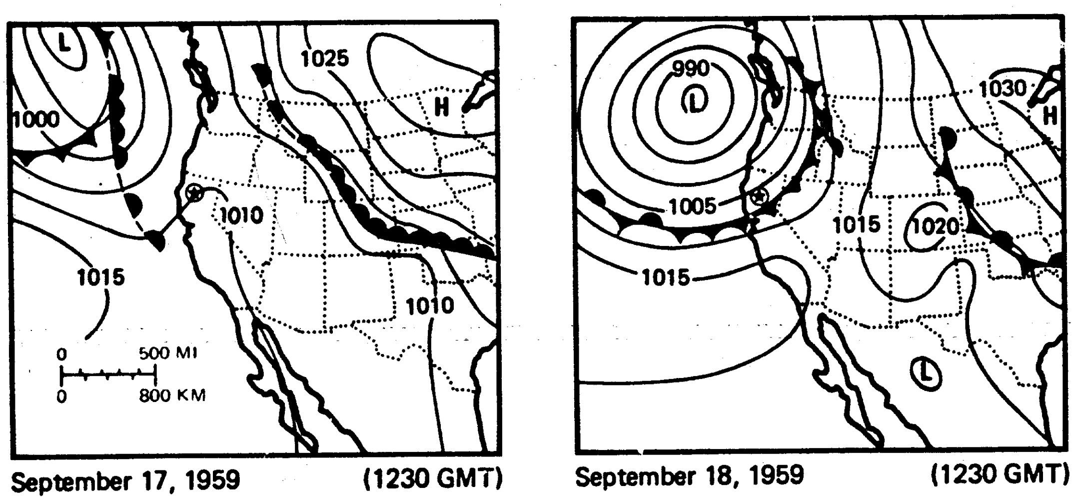


Figure 3.42.--Surface weather maps for September 17-18, 1959.

can be cloud identification between time frames. Geostationary satellites are therefore, preferred because they can take photos at short time intervals over a given location.

Still another aspect of terrain influence on local storm occurrence is that caused by channelling and barrier effect on moisture inflow. The terrain exerts considerable control on the movement of moist air flow through the region. Ridges channel moist flows or act as barriers depending on their orientation relative to low-level inflow. Our studies of moisture flow to Elko and Morgan, the two local storms most distant from the Gulf of California, showed that the low-level flow tended to take a path of least terrain resistance, that is, from the Gulf of California northwards along the lower Colorado River and continuing northward through the narrow valleys formed by the numerous north-south ridges into eastern Nevada and western Utah. The local storms at Wellton 15 WSW, Lake Havasu City, Nelson, Ft. Mohave, and Las Vegas lie along this route. Other low-level trajectories can be postulated that bring Gulf of California moisture to almost all the other local storm locations. An exception is the local storm at Mesa Verde Park, Colo. Numerous barriers lie between this site and any moisture source, and we cannot determine the source of moisture leading to this site.

With the exception of Morgan and Mesa Verde Park, no other major local storms have been reported northeast of the major barrier formed by the Mogollon Rim across northeastern Arizona and its extension into the north-south oriented Wasatch Mountains through Utah. A factor which may be partly responsible for this observation is that the population density for the region northeast of the Mogollon Rim is somewhat less than that along this barrier and to the south.

In Western California, the coastal range of mountains provides an effective barrier to moisture for heavy local rainfalls to the lee. The exception here is that low-level moisture flows through the break in this range near San Francisco and enters the Sacramento Valley. At Red Bluff, the gradual convergence in the Sacramento Valley may have forced initial convection, as mentioned for the events at Kennett (section 3.3.4) and Newton (section 3.4.7). Moisture may enter Western California from the south over the Tehachapi Mountains or over the coastal range at the southern border to the central Valley. Such moisture advection occurs at somewhat higher elevations due to passage over these mountains. An example of this condition is the extreme local rainfall at Bakersfield (section 3.3.8).

3.5.2 Moisture

The greatest potential rainfall will come from an atmosphere that is near saturation through the greatest depth. As with any extreme, the likelihood of total saturation is very rare. In the Southwest, for those few local storms for which we have sounding data, the atmosphere is far from saturated through any large depth. One difficulty with available sounding data is that rarely, if ever, do soundings give information from within the narrow tongue of moisture that feeds extreme local rains and even more rarely from within the cloud system that gives the heavy local rainfall.

Large moisture amounts in the lower portion of the atmosphere are noted in the vicinity of the few major storms studied in detail (Hansen 1975a, 1975b, and Randerson 1976). In these cases, low-level moisture moved to the site of heavy rainfall from the Gulf of California.

Since warmer air has a greater capacity for carrying moisture, air from tropical source regions is more likely to be involved with major local storms. In the Southwest, the Gulf of California is the nearest source of tropical moisture to the reported local storms. In some cases moisture may come from the tropical Pacific Ocean with the gulf acting as a channel. However, we cannot be certain that the Gulf of California was the only contributor to these storms. In section 3.2.2, we described how tropical moist air from the Gulf of Mexico also may reach the Southwest, but because of intervening barriers occurs at heights above 5,000 ft. In Western California, tropical Pacific air is brought to the region in association with tropical storms that move northward off the coast (see discussions for Red Bluff, Tehachapi and Encinitas), or with extratropical storms that reach the coast from a near tropical latitude (see discussion of Kennett and Los Angeles).

3.5.3 Synoptic Weather Pattern vs. Local Storms

In section 3.3, the location of selected major local storms was reviewed relative to the macroscale synoptic weather pattern. Of interest was to show that these extreme rainfalls were isolated from any apparent organized synoptic weather system that may have caused or contributed to their occurrence. Of 14 significant local storms described, only Mesa Verde Park occurred in a synoptic pattern that differed basically from general features found in the others. All the others showed a region of thermally induced low pressure in the vicinity of southeastern California, southwestern Arizona or northwestern Sonora, Mexico. In some instances, small anticyclonic centers occurred in addition to the thermal low-pressure centers, which may act to locally intensify the movement of low-level moist air to the site of heavy rainfall. However, the Mesa Verde Park storm, occurred in a post-frontal environment.

In Western California, few storms satisfied our criteria for a local storm. As a result we supplemented our sample in this region with other extreme rainfalls. For the most part, these supplementary storms had durations somewhat longer than those defined for local storms and occurred in association with more general storms. These general storms had remnant moisture from decadent tropical storms or frontal systems tied to low-pressure centers. Heavy local rainfall comparable to that in Western California, and associated with extratropical low pressure systems, was not reported in the Southwest. One reason for this result is sheltering by the Sierra Nevada. However, the Southwest is exposed to heavy showers associated with tropical storm systems, as has already been discussed for storms such as September 1939, August 1951 and September 1970 (chapter 2).

Aloft, data suggest that a well developed trough exists along or off the Pacific coast during major local storms. This was particularly the case for the Newton storm in Western California, the three storms (Phoenix, Elko and Morgan) studied by Hansen (1975b), and the Las Vegas storm studied by Randerson (1976). Since upper-air analyses are available only since December 1944 we cannot say with certainty that an upper-level trough is necessary to obtain extreme local rainfalls, or whether this feature is coincident with other conditions conducive to the isolated nature of these events. It is known from analysis of other tropical storm situations, that an upper-level trough is necessary to sustain their movement into the southwestern United States.

3.5.4. Instability

Instability is a measure of the degree to which vertical atmospheric motions are likely to develop once initiated. For the most part, the atmosphere of the

Southwest during the warm season is conditionally unstable; i.e., it is stable to vertical displacements if unstaturated, but becomes unstable once saturated. Thus, the importance of low-level moisture mentioned in section 3.5.2 is apparent, since release of this instability by convective and orographic lifting results in accelerated vertical motions. Once this vertical motion is established, the system becomes a machine for processing low-level moisture into water droplets. The result is that eventually the condensed water cannot be supported by the convective updrafts and it rains.

In the Chiatovich Flat storm, we believe moist air flow into this storm was lifted from low levels to heights exceeding 11,000 ft before saturation was reached. Such lifting is unusual and probably accounts for the rarity of extreme local storms at the higher elevations. Mesa Verde Park, Elko, and Morgan are other extamples of local storms where considerable lifting was needed before saturation was attained. By comparison, the heavy convective rainfalls at Lake Havasu City, Red Bluff and Newton occurred in air that was near saturation at low elevations, and little lifting was needed to trigger convection in these storms.

3.5.5 Storm Movement

In sections 3.3 and 3.4 we showed isohyetal patterns for the local storms for which numerous observations were obtained. Some of these patterns are elliptical, while a few are more concentrated (see patterns for Vallecito and Morgan). The implication of an elliptical pattern is that the total-storm rainfall occurred from convective cells that moved with time. The Phoenix, Bakersfield, and two Las Vegas storms are particularly elliptical and are also considered among the least orographic of those studied here. We expect that storms with the least movement are related to prominent terrain features (as well as synoptic conditions), and that the general case for the storms in the Southwest is for local storm patterns to show only limited movement.

One problem with the analysis of pattern shape in the mountains can be that the pattern is a function of the distribution of observing stations, and so often in mountainous regions, since the stations are situated along the valleys or highways, the results appear to be elliptical. This feature is undoubtedly the case for the Tehachapi isohyetal pattern (section 3.4.4).

The life cycle of a single convective cell is about 1/2 hr with possible upper limits of 1 to 2-hr. This fact must be remembered when one considers the isohyetal patterns composed from rains over a 6-hr duration, such as at Phoenix (section 3.3.3). This pattern was produced by a complex convective system involving multiple cells. The cells within such complex systems may regenerate, producing new cells to perpetuate the system, provided that the needed instability and moisture environment are available. At the shorter extreme are Ft. Mohave (section 3.3.1), and Las Vegas (section 3.3.11) lasting 45 and 35 min respectively, in which we concluded only one cell was involved. The effect of storm movement, is to reduce the rainfall observed at a point. That is, under similar conditions of moisture and instability, a storm that remains fixed in space should produce greater measured rainfalls. This line of reasoning may provide a basis for the larger observed maxima at Campo, Vallecito, Chiatovich Flat, Morgan, and Newton.

3.5.6 Cloud Mergers

The intensification observed in cloud dynamics that results when cloud systems merge may also contribute to increase some rainfalls over others. Eyewitness accounts of mergers of cells or group of cells accompany some of the major rainfall events on record. According to Simpson and Woodley (1971), the significance of cloud mergers comes from the synergistic effect that the resultant rainfall is "...often far greater than the sum of water production from the component clouds." We have reproduced here excerpts from the observational records of those extreme local storms for which cloud mergers were noted. They serve both to document this phenomenon and provide a basis for conjecture on a possible cause of rainfall intensification. These comments can also be appreciated for their candor.

3.5.6.1 Examples from the Southwest. Observers' accounts of cloud mergers occurring with storm events listed in table 3.1 are reproduced here.

> Campo, 1891: "...and then another cloud came up and the one that had first passed over drew back and the two came togather and it pourd down whole watter nearly." (From observer's unpublished monthly report).
>
> Palmetto, 1890: "On the 11th two intensely black thunder clouds appeared over the crests of the surrounding mountains. One approaching from the North the other from the East. At a short distance from the camp these clouds seemed to join and rush with extraordinary swiftness towards Palmetto....A steady column of water poured down, excavating a trench about 500 feet long and varying from zero to seven feet in depth and in places twenty feet in width.", (U.S. Weather Bureau 1960).
>
> Tucson, 1878: "The clouds began to gather at 3:00 p.m. and two were plainly visible, coming from opposite directions, which were heavily laden with water....At 5 p.m. the crash came....",(U.S. Weather Bureau Monthly Weather Review 1878).
>
> Morgan, 1958: "...heavy black clouds formed over Henefer about 7 miles to the southeast, and over Stoddard about 5 miles to the northwest. Each appeared to move toward the 'Round Valley' area.....The two clouds appeared to meet right over 'Round Valley'," (from unpublished report by U.S. Geological Survey 1959).
>
> Walnut Gulch, 1967: "The early cumulus appeared to dissipate, but by 14.00 hr two separate groups of heavy cumulous clouds were forming, one system just north and one just east of the upper end of the watershed....About 15.00, the 2 systems began to move toward each other, and by about 15.15 intense rain was falling on most of the upper end of the watershed. The two systems combined in the vicinity of Rain Gage 52, and intense rain was recorded there for about 45 min." (Osborn and Renard 1969).

Gage 52 was the site of the measured peak of 3.35 in. in this storm.

From a report of a lesser rainstorm of 2.25 in. in 90 min (not in table 3.1) at Jawbone Canyon near Mojave, California August 23, 1961, Mr. B. O'Brian of Sand Creek reported, "By 7 p.m. the storm was over. There appeared to be 3 parts to the storm, one from the southwest, one from the northeast, and one from the southeast, and they all met at Cache Peak." (from unpublished summary of bucket survey comments, U. S. Corps of Engineers 1961b).

3.5.6.2 Examples from Other Regions. Other incidents of cloud merging have been noted in the literature. HMR Report No. 45 (Schwarz and Helfert 1969) summarized major accounts from 11 extreme rainfall events in the Tennessee River Basin and mentioned an eyewitness report of the world-record rain of 30.8+ in. in 4.5 hr at Smethport, Pa. (7/17-18/42), in which it was stated that the storm approached the area from several directions.

The merger phenomenon has been witnessed on radar scopes in the form of echo mergers. Some examples are:

> "'Patch A' moves into the map at 1800 and 'Patch B' develops on the map at 1845, 75 nmi NE of Patch A. At...1950; ...A and B join aloft at 20,000 ft. An hour later..., Patch B intensifies and rapidly expands aloft and merges with Patch A down to 10,000 ft, at which time this combined patch contains its maximum total precipitation aloft....Such a large total precipitation aloft is never attained again." (Holtz and Marshall 1966).

> "The parent mesoscale system maintained itself by merging with or ingesting 11 separate convective entities of which several were intense multicellular storms." In another paragraph, they reported that, "...the first of these hailfalls... occurred only 15 minutes after a raincell merger and at the time that the mesosystem was producing its most intense rainfall." (Vogel and Huff (1975).

3.5.6.3 Cloud Merger Studies. It is apparent from these accounts that cloud mergers are a common, widespread phenomenon. It is likely that merging occurred in some of the other cases of extreme rainfalls noted in table 3.1 as well. Where the early observations of these phenomena were taken lightly, cloud mergers are now a topic of considerable importance relative to the enhancement of rainfall (Simpson and Woodley 1971, and their continuing studies). The dynamics of cloud merger enhancement of rainfall are still subject to discussion. Theories put forth by Pendleton (1969), and Agee and Schroder (1974), among others, essentially refer to the intensification of upward vertical motions between the approaching cloud cells. The vertical velocities increase directly as the distance between clouds narrows, and imply a maximum upon merger. Since merging is independent of the moisture supply, cloud mergers can occur anywhere, but in most cases soon exhaust the available moisture. However, in those cases where an unusually large low-level moisture supply prevails, mergers offer the potential for tremendous processing of this moisture into a Campo-like rainfall.

The sighting of cloud mergers in some of the most extreme rainfall cases indicates that this is an additional mechanism operating to cause unusual rainfalls. The significance of cloud mergers relative to local storms is not that of a triggering mechanism, but more as a reason for intensification of some storms over others with similar meteorological and topographical settings.

3.6 Application to Local Storm PMP

We have considered the meteorological and topographical settings in which some of the major local storms in the Southwest have occurred. From these considerations we have developed guidance for the local storm PMP analysis.

Probably the most important guidance has been the generalized effects of terrain. A maximum 1-mi^2 PMP was placed in the region of the Coastal Mountains in southern California and eastward to include much of the Imperial Valley, based on the maximum observed local storms. The Mogollon Rim of mountains across northeastern Arizona is an effective barrier to low-level moisture, and a tight gradient of 1-hr PMP was developed along this barrier. Minimum PMP occurs to the northeast of this barrier. The Sierra Nevada also inhibit the westward spread of tropical air into the Great Basin region, and the eastward spread of moist Pacific air from the west.

In Western California, maximum PMP occurs along the coastal mountains with a PMP maximum centered at the north end of the Sacramento Valley in response to the storms at Kennett and Newton. The Central Valley is sheltered from much low-level moisture inflow, and this feature is also reflected in the PMP analysis.

Considerations for moisture and also inflow direction to the major local storms were made in developing the local storm PMP. In anticipation of a local storm PMP event, tropical moisture will be necessary, and we have drawn our PMP analysis to take advantage of the most direct access to low-level tropical moisture, particularly as it is channelled into the Southwest through the Gulf of California.

Finally, our review of broadscale meteorological conditions surrounding major local storm occurrences has emphasized that these phenomena are brought about by factors of a much smaller scale than is found in synoptic weather charts. Nevertheless, it was believed that the mesoscale conditions leading to local storm PMP are likely to occur to some degree throughout the entire Southwest and Western California, and therefore, local storm PMP in HMR No. 49 was developed for the entire region.

4. ATMOSPHERIC MOISTURE

4.1 Introduction

Moisture availability and its geographic and seasonal distribution are key subjects for investigation in PMP studies. For this study we have revised previous estimates of maximum moisture. The most recent publication on available moisture for this region (Environmental Science Services Administration 1968) utilized data only through 1946. Three objectives of our investigation are:

a. To develop upper limits of moisture (availability) for storm maximization;

b. To use such regional and seasonal patterns of maximum moisture as guidance to PMP;

c. To determine moisture inflow directions as an aid in developing a generalized effective barrier map.

Atmospheric moisture distribution and amounts, from the surface to any upper level, can be obtained from radiosonde observations. Estimates of atmospheric moisture amounts can be made from surface dew points. Historically, surface dew points have been used because of the longer available record and the denser network of stations. Radiosonde observations are available only from 11 stations in the Southwest and another 11 stations adjacent to the region. Surface dew point data, however, are available for about 70 stations within the Southwest and nearly 100 in the area adjacent to the Southwest. This denser network of surface stations in some cases permitted the detection of the narrow tongues of moisture that play an important role in many storms.

The use of surface dew points as a measure of atmospheric moisture requires an assumption about the vertical distribution of temperature and relative humidity. The assumption commonly made for major storms, or extreme moisture cases representative of PMP, is that the atmosphere is saturated with a psuedo-adiabatic lapse rate. Tests in other regions (e.g., U.S. Weather Bureau 1960) have shown this to be a reasonable assumption in most major storms and high moisture cases. Some modifications to this assumption are required in this region as will be discussed in section 4.3.3.

Our approach has been to utilize the previously prepared charts of observed maximum persisting 12-hour 1000-mb dew points (Environmental Science Services Administration 1968) as a starting point. Dew point records were examined to see if these charts should be revised. Radiosonde observations were examined to determine, a) necessary modifications to the assumption of a saturated atmosphere with psuedo-adiabatic lapse rate, and b) seasonal and geographic variations.

4.2 Moisture Sources

Reitan (1960) used mean monthly values of temperature, relative humidity, and height to compute mean monthly values of precipitable water for radiosonde stations in the United States. His results were used to define a primary moisture source for the cool season. For the warm season, a primary source cannot be as clearly identified by use of mean monthly values.

4.2.1 Cool Season

Precipitation during the cool season results from general storms and generally covers areas of several thousand square miles. The moisture inflow to these storms occurs as a broad tongue, and can normally be detected by the upper-air network. Mean monthly values computed by Reitan (1960) were examined to find clues to the primary moisture source. Grand Junction, Colo. was selected as the key inland station for this analysis. For the months of December, January and February, years were selected when the monthly value exceeded the mean value for that month. At each other upper-air station in and near the Southwest, the percent of those months at the second station that also exceeded the mean for that station was also determined. For example, at Grand Junction, January 1953, 1954 and 1956, February 1944, 1948, 1950, 1951, and 1954, and December 1946, 1950, 1952, and 1955 all had larger values than their respective monthly means. At Phoenix, monthly precipitable water was above normal for 9 of the same 12 months. The analysis of these data is shown in figure 4.1. It shows that for a high percentage of the time when moisture is above normal at Grand Junction it is also above normal throughout much of the west. The axis of these frequencies of high precipitable water cases suggests that the moisture inflow is from the southwest, i.e., the Pacific Ocean.

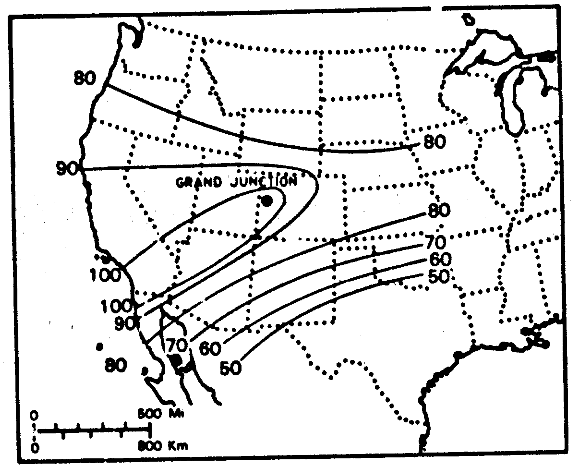


Figure 4.1.--Percentage of months at stations in Southwest with precipitable water values larger than monthly means concurrent with similar months at Grand Junction.

4.2.2 Warm Season

An analysis similar to that of figure 4.1, using warm season precipitable water (not shown) did not show a predominant moisture source. To define the primary moisture source, we examined the general features of the circulation and then considered specific cases of high surface dew points and high observations of precipitable water.

4.2.2.1 Monsoon-Like Feature. Mean warm season moisture in the Southwest States has a monsoon-like feature. This is shown by a plot (fig. 4.2) of mean monthly mixing ratio at various pressure levels for successive months at Phoenix, Ariz., developed from data in Ratner (1957) and covering the 10-yr period ending in 1955. There is an especially large increase in moisture between June and July. This increase is related to the increasing strength of southerly flow into the Southwest. Moisture from both the Pacific Ocean and Gulf of California play a major role, with moisture at the high levels coming from the Gulf of Mexico. Moisture for the summer storms, instead of originating in a broadscale southwesterly flow, has a more southerly trajectory and frequently will be channeled up the Gulf of California from tropical ocean latitudes. Occasionally, moisture will enter in narrow tongues rather than in a broadscale low. These narrow tongues are important in producing the small area intense showers discussed in chapter 3.

We want to evaluate the inflow of moisture at and near the surface, the moisture variability through depth, the greatest total precipitable water, and the influence of Gulf of Mexico moisture on total moisture availability. These factors were evaluated at many stations in and near the Southwestern States. To illustrate the first factor, we will discuss the high dew point situations at Phoenix, Ariz. To examine vertical moisture distribution and the total precipitable water, we considered as examples weather situations that produced high precipitable water amounts at both Tucson, Ariz., and Grand Junction, Colo. The influence of Gulf of Mexico moisture has been described in sections 2.3.8, 3.2.2 and 3.5.2. These factors are discussed in the following sections.

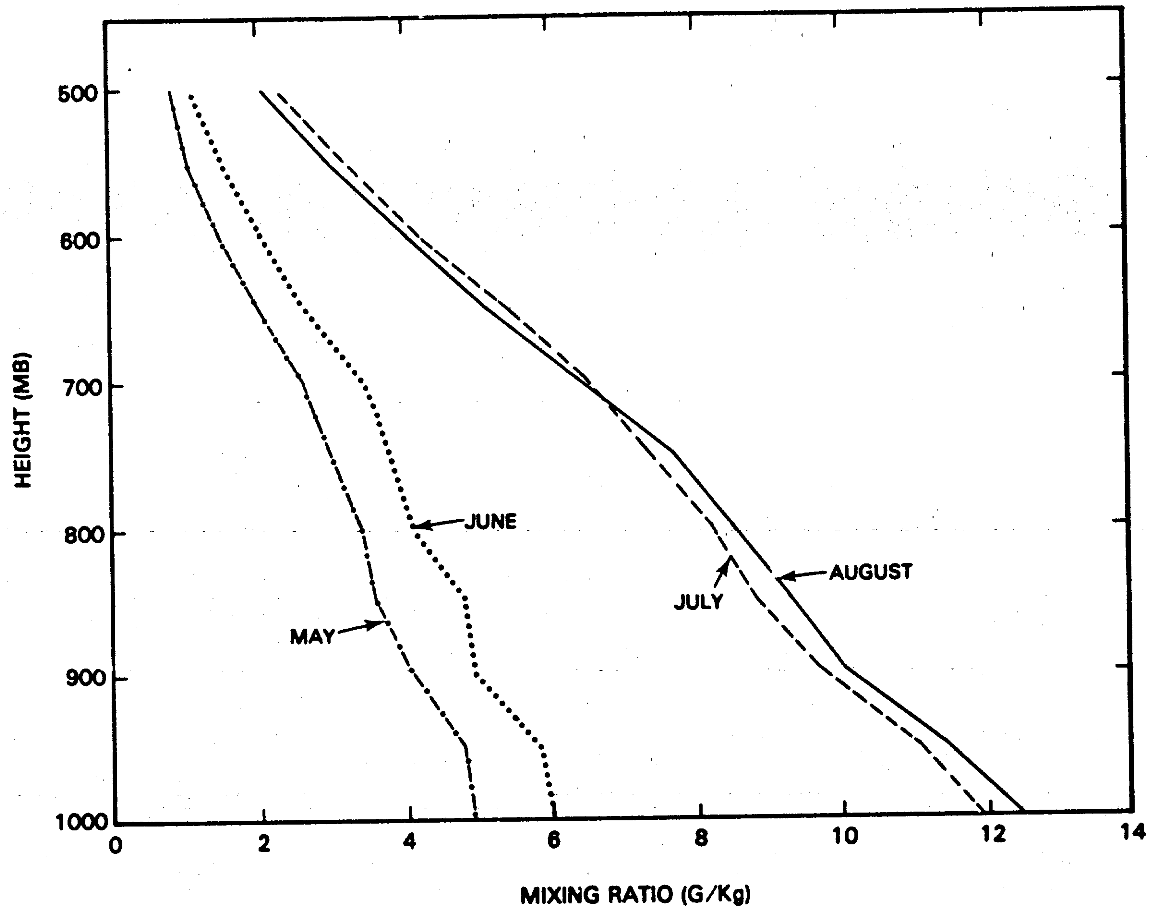


Figure 4.2.--Mean monthly mixing ratio for May, June, July and August at Phoenix, Ariz.

4.2.2.1.1 High Surface Dew Point Cases. Highest warm season persisting 12-hr 1000-mb dew point situations considered for this study are listed in table 4.1.

Table 4.1--Highest warm season persisting 12-hr 1000-mb dew point situations at Phoenix, Ariz.

Date	Dew point (°F)
8/03/51	73
8/04/54	72
8/13/55	73
8/01/80	73

During the first 4 days of August 1951 (fig. 4.3), the flow at the surface was light and the prevailing circulation was southerly through central and eastern Arizona. During much of this period, a consistent light, mainly southerly, flow of air prevailed on the surface, to well above the 500-mb level (fig. 4.4).

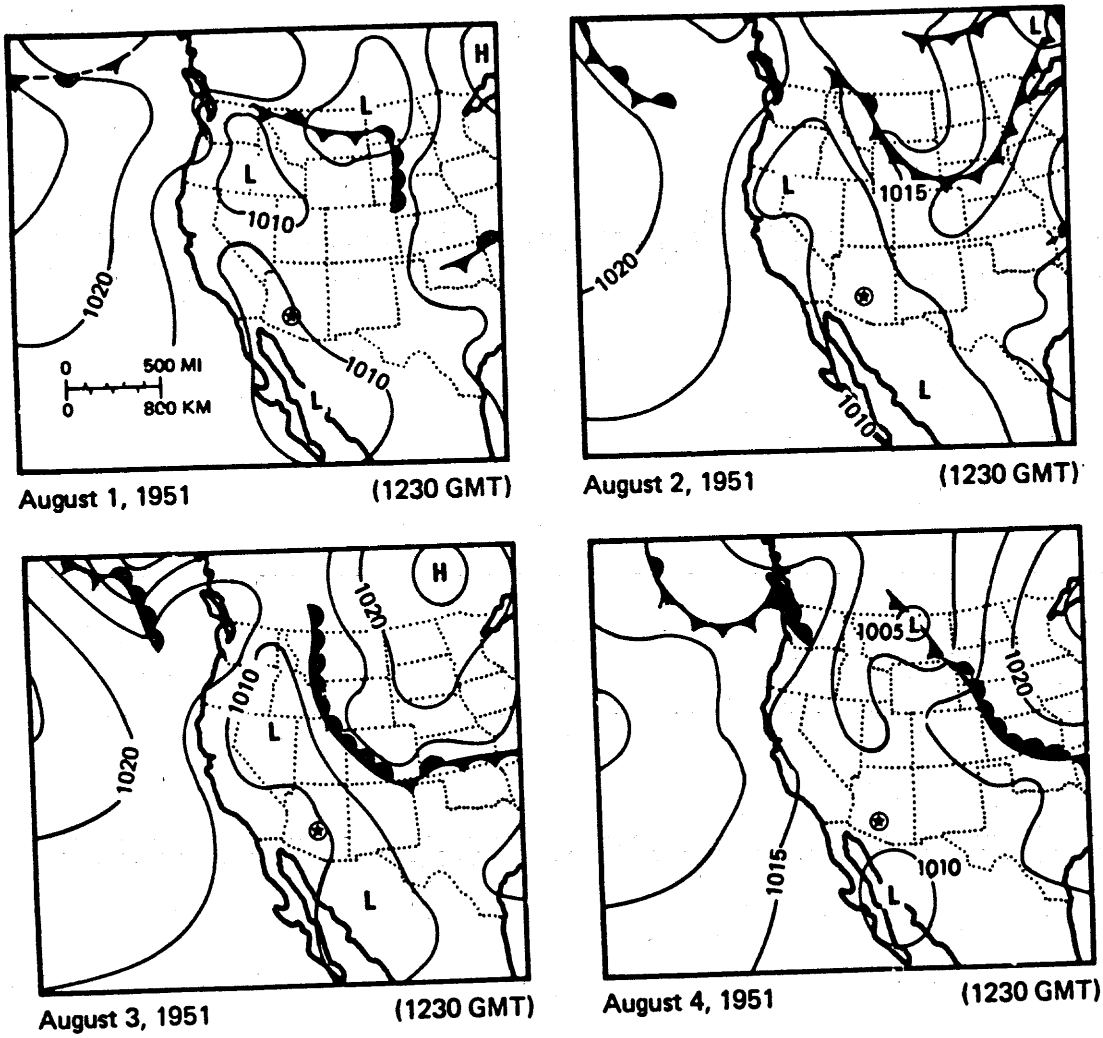


Figure 4.3.--Surface weather maps for August 1-4, 1951.

The analyses for August 2-5, 1954 (fig. 4.5) show a rather indistinct circulation through Arizona. A surface Low, associated with an upper trough (fig. 4.6), was over the Wyoming-Montana border on the morning of the 3rd hardly a position to bring surface moisture into Arizona. However, by the 4th the circulation from this system covered the entire West and could have influenced the increase in moisture to southern Arizona.

On a third occasion (August 13, 1955) of high surface-moisture at Phoenix (maps not shown), a weak surface-frontal system, again barely extended into Arizona.

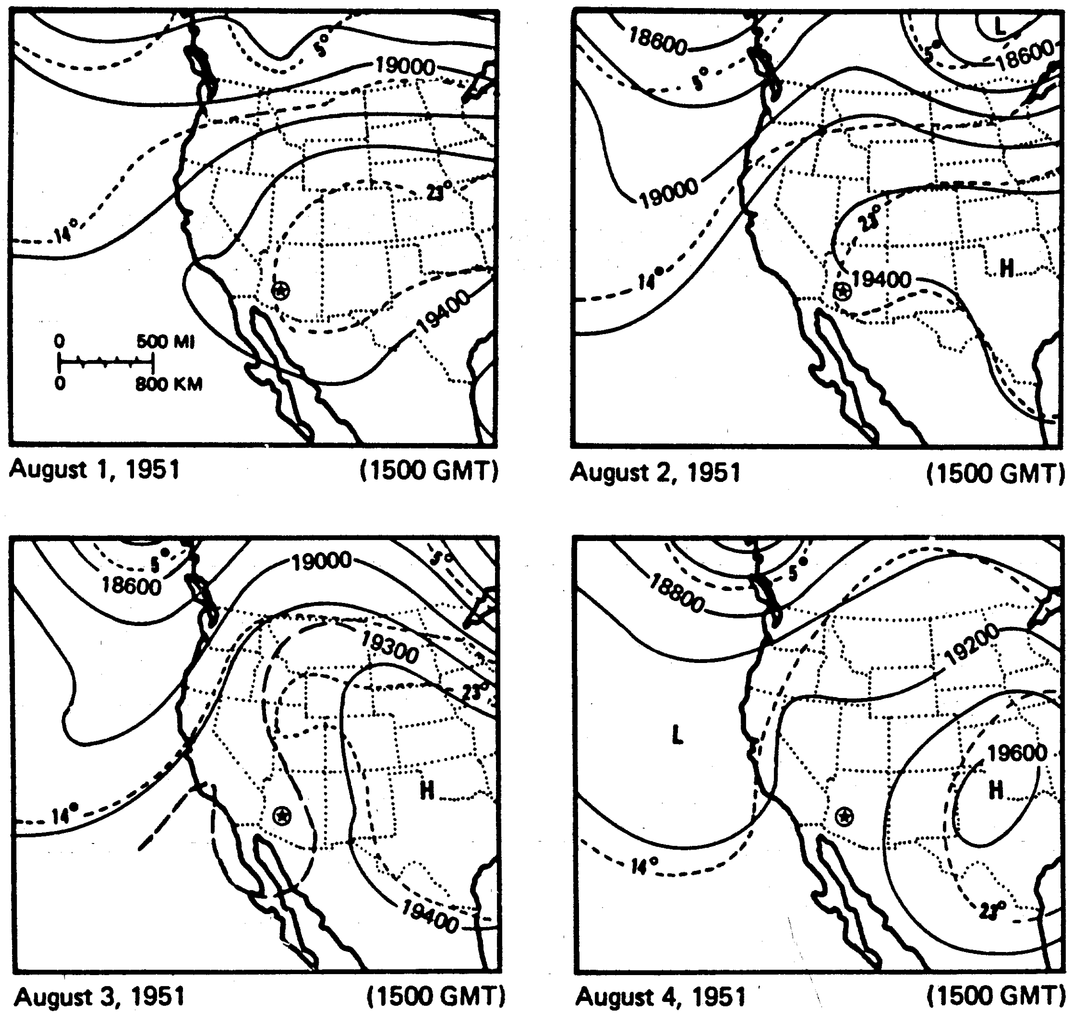


Figure 4.4.--500-mb charts for August 1-4, 1951.

The fourth case, for August 1964 (maps not shown), has high surface moisture ahead of a cold front that approaches Arizona from the west, but stagnates over southern California. A low-pressure trough aloft extends even farther south during this example than in the other cases studied.

From this investigation, the conclusion reached (from a synoptic scale viewpoint) was the same as from the investigation of most extreme local rain situations; i.e., moisture inflow of consequence was not discernable.

4.2.2.1.2 High Precipitable Water Cases. Selected cases of high precipitable water amounts at Tucson and Grand Junction are listed in table 4.2. The August 3, 1951, observation of precipitable water at Grand Junction (1.41 in.) given in the table was the same situation that gave the high persisting 12-hour 1000-mb dew point of 73°F at Phoenix (see table 4.1 and fig. 4.3 and 4.4).

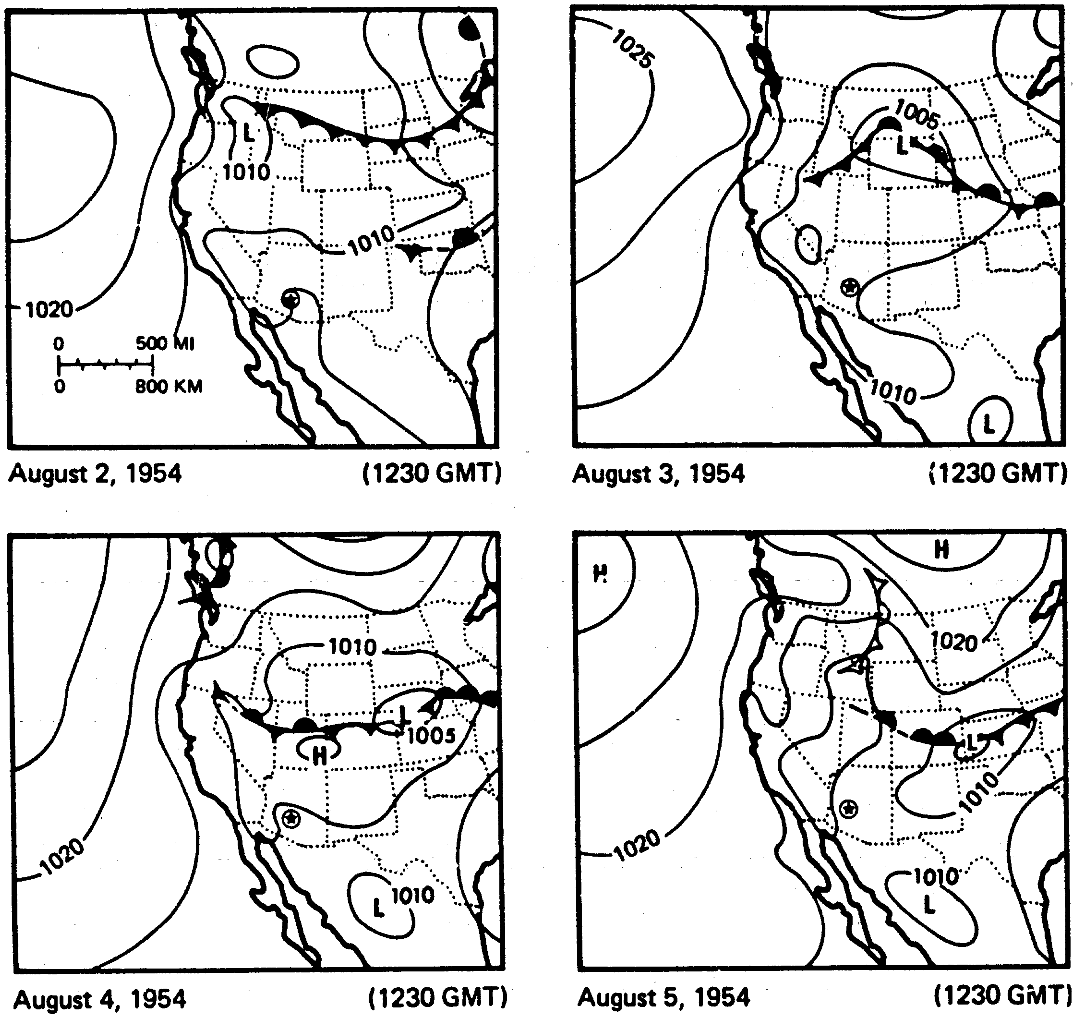


Figure 4.5.--Surface weather maps for August 2-5, 1954.

The highest precipitable water in September (for the period 1951-64) at Tucson of 1.77 in. was observed at 2300 MST September 11, 1958 (0600 GMT on September 12). Surface and 500-mb maps for September 10-13, 1958 are shown in figures 4.7 and 4.8, respectively. A vigorous trough aloft and associated surface Low

Table 4.2.--Some warm season high precipitable water at Tucson, Ariz. and Grand Junction, Colo.

Date	Station	Precipitable water (in.)
8/03/51	Grand Junction	1.41
8/01/52	Grand Junction	1.30
8/07/55	Tucson	1.86
8/26/55	Grand Junction	1.34
9/11/58	Tucson	1.77

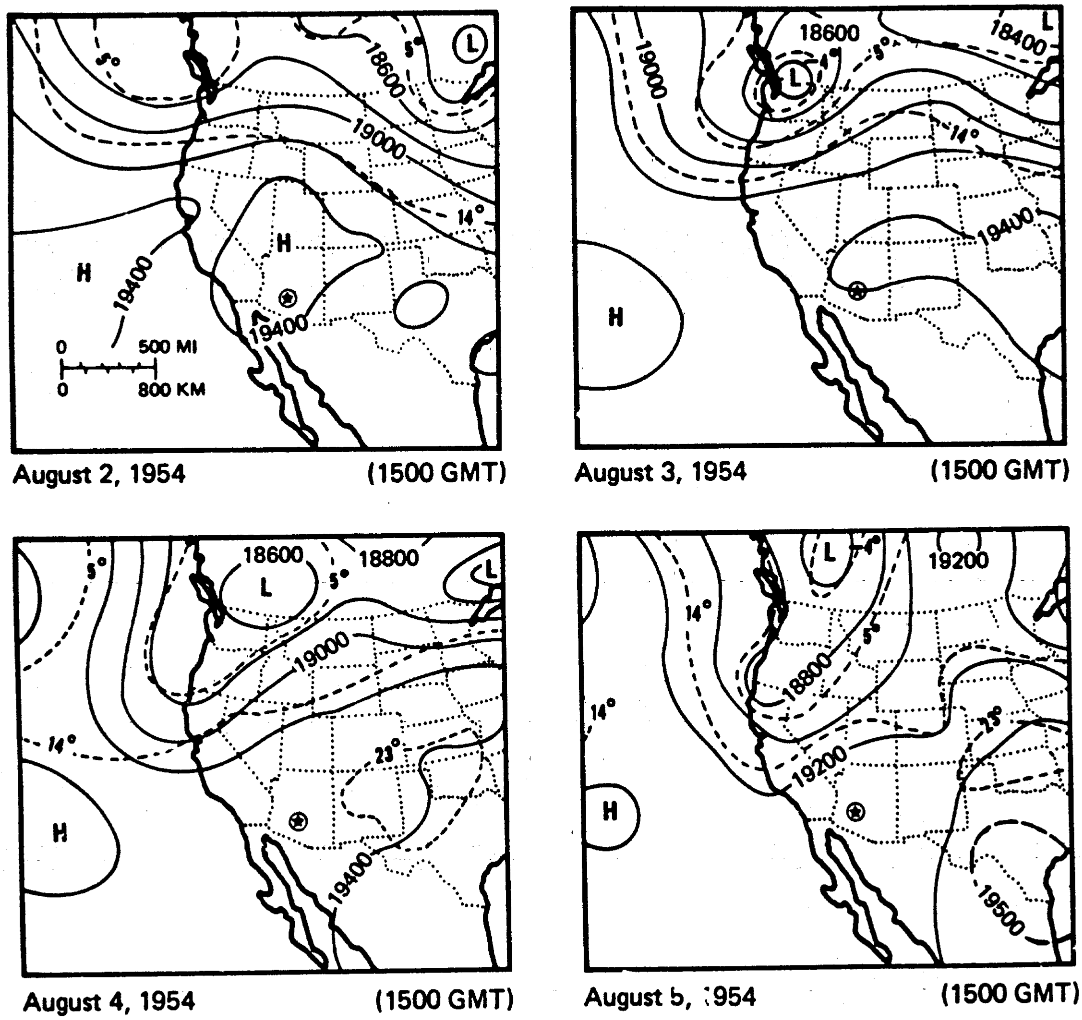


Figure 4.6.--500-mb charts for August 2-5, 1954.

approached the area from the west in this case. The precipitable water reached a maximum in the warm air ahead of the front. The investigation of high precipitable water cases from a synoptic weather scale point of view, produced essentially the same conclusions as the high surface dew point cases at Phoenix, that is, the absence of an appreciable broadscale inflow.

4.2.3 Summary of Information on Moisture Sources During Warm Season

In the warm season (depending upon the area size of concern) both local and general storms are of importance. Here, we shall concentrate on the elusive warm season conditions in developing conclusions on moisture climatology. These are necessarily based on a synoptic scale viewpoint.

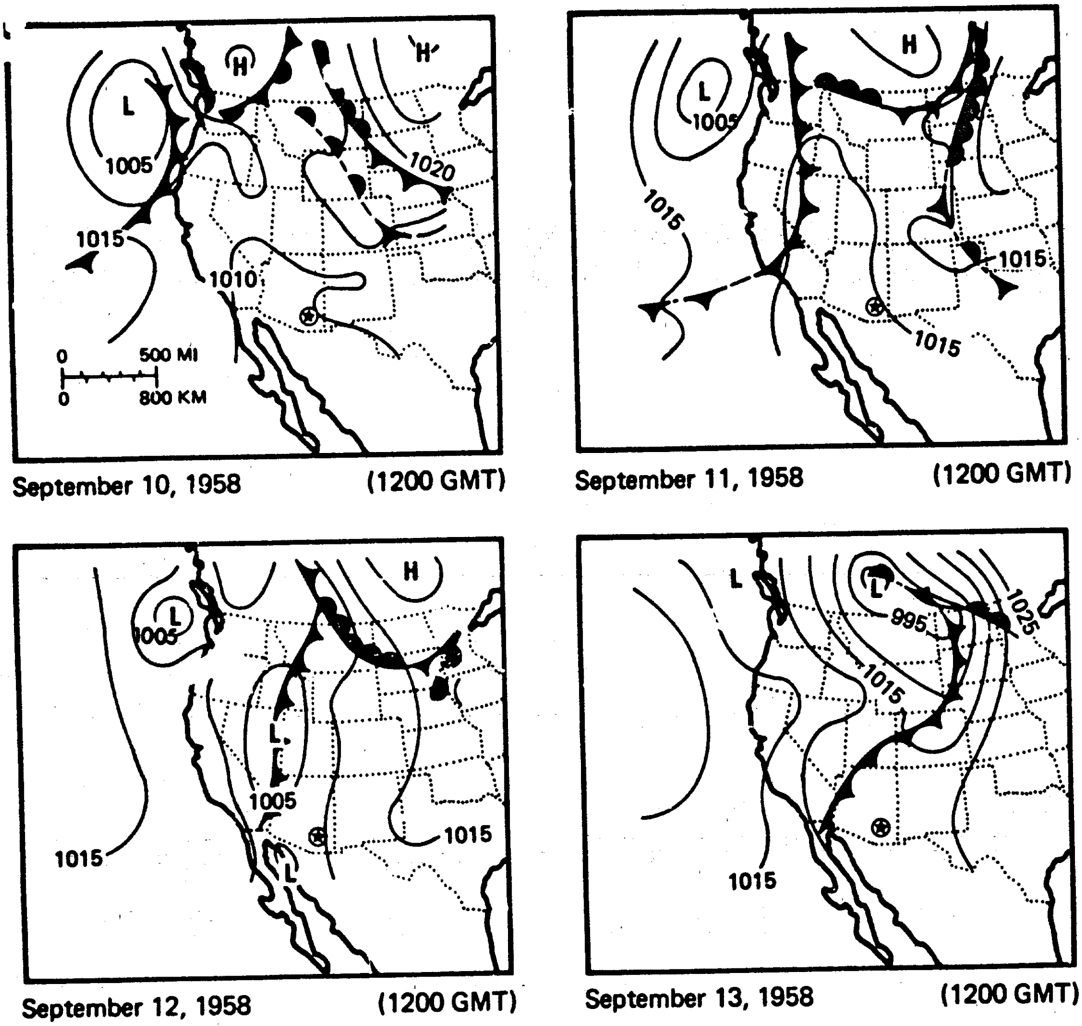


Figure 4.7.--Surface weather maps for September 10-13, 1958.

a. There is a summer monsoon-like effect. In the literature, this effect has been related to the slow influx of moisture from the Gulf of Mexico around the western edge of the Bermuda High and across the Southwest. This condition alone (without recharge by rain or other mechanism) does not provide sufficient moisture for extreme warm-season rainfall events, due to the interference of the intervening high terrain over which the slow seepage of inflowing moisture must pass. However, there is an influx of moisture at low levels from the tropical Pacific that is the more important ingredient to the total available moisture. The surges of Pacific moisture are distri-

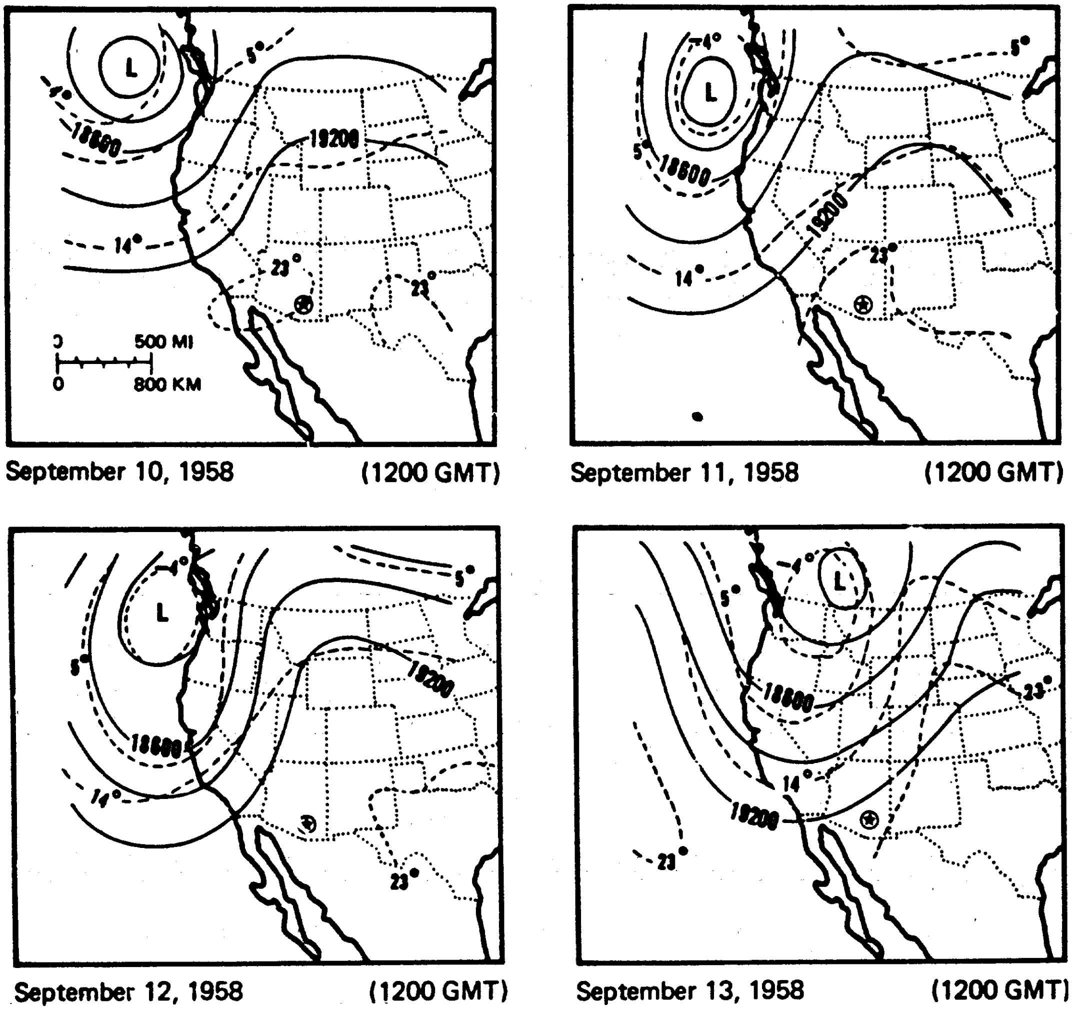


Figure 4.8.--500-mb charts for September 10-13, 1958.

buted through depth by the strong convection that occurs throughout the Southwest.

b. The important warm season general storm for much of the Southwest, primarily involves significant components of moist flow from the south. The tropical cyclone related event is responsible for general storm PMP. Both the Pacific Ocean off Baja California, and the Gulf of California contribute moisture to this event.

c. In a few regions of the Southwestern States, the warm season general storm occurs under special synoptic weather conditions (section 2.3.7). For example, the general storm PMP in southwestern Wyoming is likely to result from Gulf of Mexico moisture passing across the Continental Divide in central Wyoming, where the orographic barrier is somewhat lower.

d. The highest values of warm season moisture, both in the form of surface dew points and total precipitable water, in both general storm and local storm situations occur with light winds. (This includes many cases surveyed but not covered in the text.) Our conclusion is that various factors (e.g., prior showers, etc.) must increase moisture when synoptic scale indicators do not suggest a sustained broadscale inflow.

e. When the unusual tropical cyclone penetrates into the Southwestern States, the prevailing inflow moisture content is usually somewhat below maximum values, as, for example, in the August 1951 and September 1970 cases. The September 1970 storm played a key role in the development of the hypothetical tropical cyclone related PMP storm type discussed in section 2.4. Factors such as increased cloudiness and stronger orographically affected wind flow apparently served to diminish the moisture potential in September 1970 from the maximum values. The August 1951 storm provided evidence of sustaining conditions needed to extend the hypothetical storm to 3 days.

4.3 Development of Maximum Moisture Charts

4.3.1 Introduction

In light of the points listed under section 4.2.3 and consideration of moisture needs of the hypothetical tropical storm and the extreme local storm, it appeared that two sets of maximum moisture criteria would be necessary for the warm season. These were used in the analysis of local and general storm PMP in HMR No. 49.

In surveying both the dew point and precipitable water data for the Southwestern States and bordering regions to the north and east, we concluded that the general dew point level of the persisting 12-hour 1000-mb dew point charts (Environmental Science Services Administration 1968) was quite good. Adjustments consisted primarily of refinements to the warm season charts. These involved adopting local warm season values which slightly exceeded the existing values. The adopted general storm warm season values were somewhat lower than values on the existing charts (Environmental Science Services Administration 1968).

4.3.2 Procedure

Precipitable water and dew point data in and bordering the Southwestern States were used to develop maximum moisture charts for both the local and general storm situation. Reliance was primarily on analysis of surface dew point data. This was done for two reasons. First, the data are more plentiful, and thus we are able to define the narrow tongues of moisture that are important in local storm situations. Second, the longer record available for dew points as opposed to upper-air observations provides a more stable base for estimating extremes. This is true whether considering envelopes of maximum observed values or statistical analysis of a series of monthly or semi-monthly values.

A first step in the analysis was preparation of seasonal plots of maximum persisting 12-hour 1000-mb dew points for many stations in and near the Southwest. Figures 4.9 and 4.10 are examples of these analyses for Phoenix, Ariz. and Salt Lake City, Utah, respectively. These figures show four separate analyses: a) maximum observed persisting 12-hour 1000-mb dewpoints, b) statistical analyses of a series of monthly values of observed maximum persisting 12-hour 1000-mb dew points, c) a curve developed from the published charts (Environmental Science Services Administration 1968), and d) adopted curves for the local and general storm.

Phoenix was selected as representative of stations close to moisture and upwind of first upslope barriers, where many of the largest storms in the region occur. The statistical analyses were based upon the period 1940-44 and 1950-65, a 21-year period of record. The maximum observed values are based upon a more complete record which starts in 1905, a total of 56 years. The maximum observed values are plotted on the date of occurrence, and the statistical analyses on the middle of the period from which the data were selected, mid-month or mid-half-month interval. Statistical analysis of the dew point data applied the normal distribution to a series of monthly maxima for the summer and winter season and to half-monthly maxima during the spring and fall transition months, when moisture values are changing rapidly. A smooth curve was drawn by eye through the 50% probability level data. These curves, and data for the 1% probability level, were used as an aid in shaping the seasonal curves.

Figure 4.10 shows a similar analysis for Salt Lake City, Utah. A few maximum observed values were undercut in the analyses of these data, e.g., the value for the latter half of May. After study, the decision used in the original study (Environmental Science Service Administration 1968), that these values were unrepresentative of a moisture situation capable of producing moderate or more intense rainfall, was not changed. For this station, representing an inland station, we elected to show maximum dew points for only the period used in the statistical analysis 1938-44 and 1950-63. The data from this more restrictive 21-yr period are generally below the enveloping curves. Tests such as these indicate the need to rely heavily on the longer period dew point data and not to restrict our attention solely to the moisture measurements in the more recent period of upper-air observations.

Consideration of local and general storm situations as well as cases of high moisture through the atmosphere and high dew point situations suggested that a difference between the enveloping curves for these data should differ by about 2° or 3°. The curves for the local storm relation should be the higher because the total amount of moisture is smaller, and it can be supplied by a much narrower tongue of moisture. First approximation curves were drawn for each station studied and mid-month values picked off and plotted on a map. Smooth isodro-sotherms were then drawn over the Southwestern States for these values and for data from other sources. The regional analysis required some revision of the seasonal curves for some stations. An iterative process was carried out until realistic and compatible single station curves and regional analyses were completed. These final smooth curves are labeled as adopted local and general storm relations.

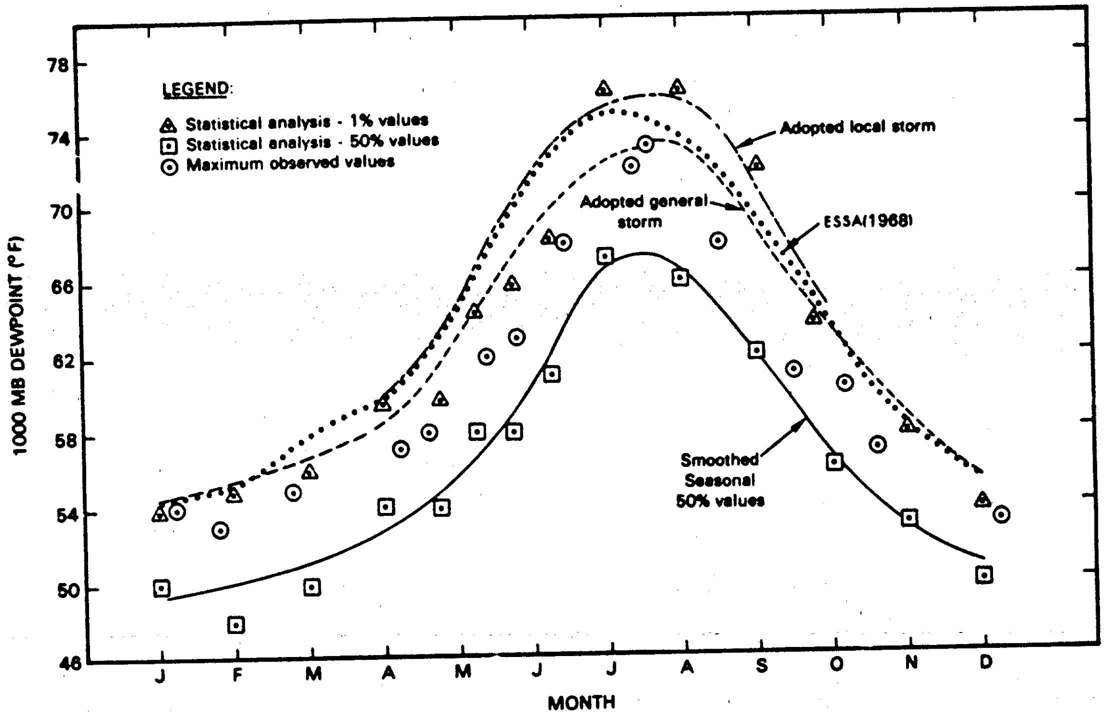


Figure 4.9.--Seasonal plot of dew point values for Phoenix, Ariz.

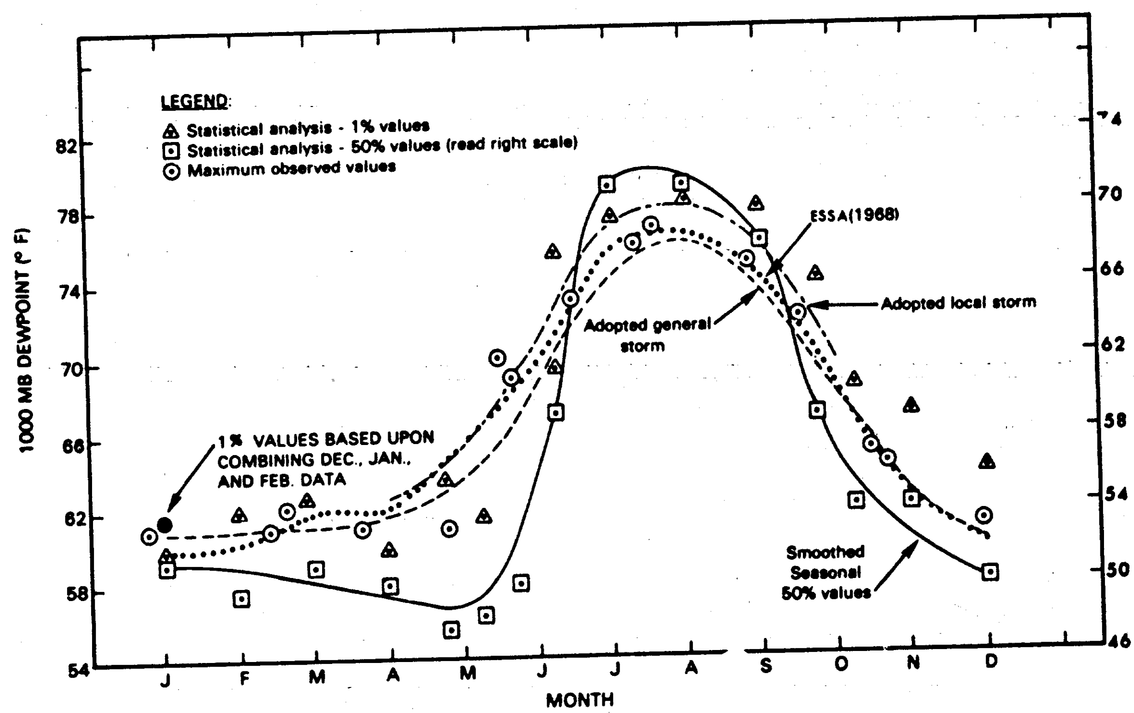


Figure 4.10.--Seasonal plot of dew point values for Salt Lake City, Utah.

4.3.3 Supporting Upper-Air Data

Reliable radiosonde observations have been available since about 1946 for stations in and near the Southwestern States. These data have been reviewed for selected stations to attempt to find support for analysis of extreme moisture determined from surface dew points. Except in high moisture cases where the radiosonde observation is located in the center of the moist air inflow or is the most extreme of record, precipitable water cases might be expected to measure lesser amounts of moisture than would be estimated assuming a saturated pseudo-adiabatic atmosphere. Because there are few radiosonde stations, this likelihood is small, and an adjustment of the moisture observed in the sounding was considered necessary for the study region to make the two analyses more comparable. For each month at the stations selected, the highest three or four precipitable water values for the period of record were compared with moisture determined from the surface dew point (corresponding in time to the sounding) under an assumption of a saturated atmosphere. This comparison led to a conclusion that an upward adjustment of the moisture observed in the sounding was required, varying beween zero and a little over 2F° (expressed in terms of equivalent 1000-mb dew points). An example of this adjustment is shown for the month of September in figure 4.11.

From the precipitable water measurements, a monthly series of data were obtained for a 15-yr period, centered on the late 1950s. These data were analyzed using the normal probability distribution. Smooth seasonal curves (not shown) were determined for each station for the maximum observed value, and for the 50% and 1% percent probability values. Regional charts were determined by plotting mid-month values at each station and drawing isodrosotherms of equivalent 1000-mb dew points. These data have been adjusted for the relation shown in figure 4.11. The portion of the published observed maximum persisting 12-hr 1000-mb dew point distribution and the revised general storm dew points are shown in figure 4.12 for Phoenix and Salt Lake City. Comparison of the isolines in these figures shows a general agreement on the orientation and gradient, but the magnitudes do not in general agree. This leads us to the conclusion that an observed maximum from the short period of upper-air moisture data (even after the adjustment is applied) tends to underestimate the extremes of moisture available in this region. Since the 1% chance value exceeds our adopted upper limit, our envelope of moisture has a greater frequency. We feel this is an optimum combination of precipitation-producing factors, and it is likely that an extreme occurrence of any one factor would not normally occur without affecting the other factors.

4.3.4 Dew Point Charts

Figures 4.13 to 4.31 show persisting 12-hour 1000-mb dew point charts for each month. Values shown are in °F applicable to mid-month. From April to October, each month has a local storm map and a general storm map. A single chart serves for each month between November and March. The charts applicable to local storm dew points have in general higher values than the comparable charts for the general storm. In addition to serving the purpose of providing a means for maximizing storms for moisture, the maximum moisture charts helped in establishing the seasonal variation of PMP in HMR No. 49. Since local warm season PMP criteria were derived for most of California in HMR No 49. these charts were extended to cover this additional coastal drainage area. In contrast, the general storm dew point charts are restricted to the basic interior drainage only.

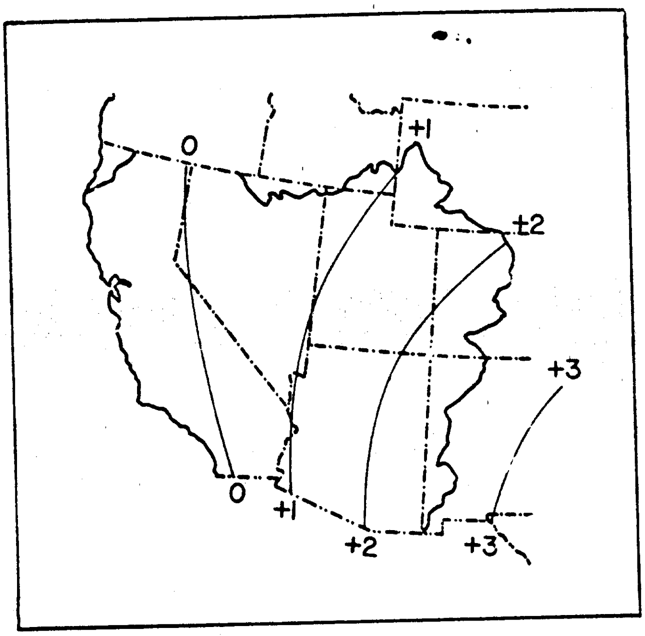
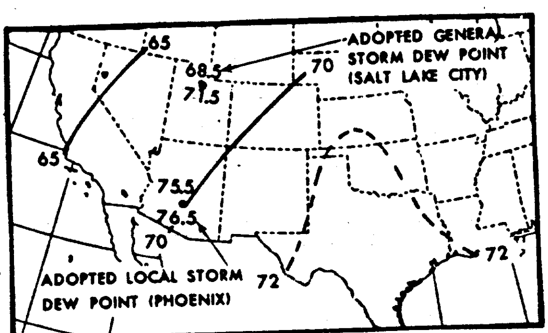
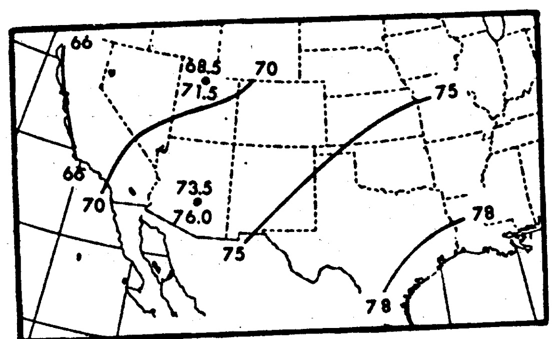


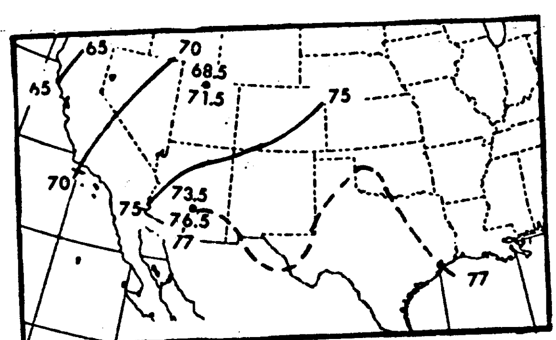
Figure 4.11.--Correction to maximum observed precipitable water to match values determined using 1000-mb 12-hr persisting dew point assuming saturated pseudo-adiabatic conditions.



A—ANALYSIS OF MAXIMUM OBSERVED PRECIPITABLE WATER EXPRESSED AS 1000-MB DEW POINTS (°F)



B—MAXIMUM PERSISTING 12-HR 1000-MB DEW POINTS (°F). AFTER ENVIRONMENTAL DATA SERVICE (1968)



C—ANALYSIS OF ONE PERCENT LEVEL OF PRECIPITABLE WATER EXPRESSED AS 1000-MB DEW POINTS (°F)

Figure 4.12.--Maximum observed, 50- and 1-percent probability precipitable water values (expressed as 1000-mb dew points) for mid-September.

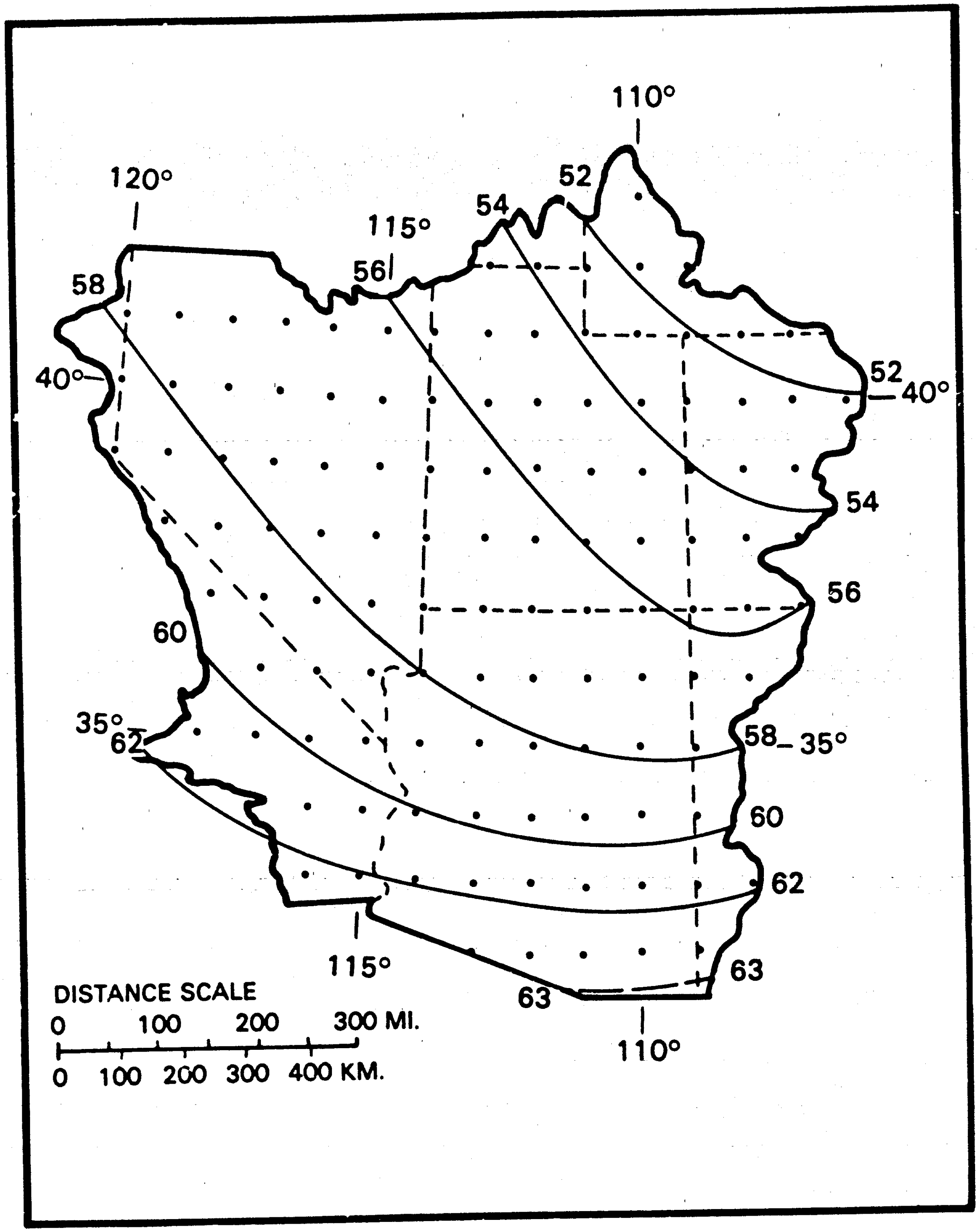


Figure 4.13.--1000-mb 12-hr persisting dew point for mid-January.

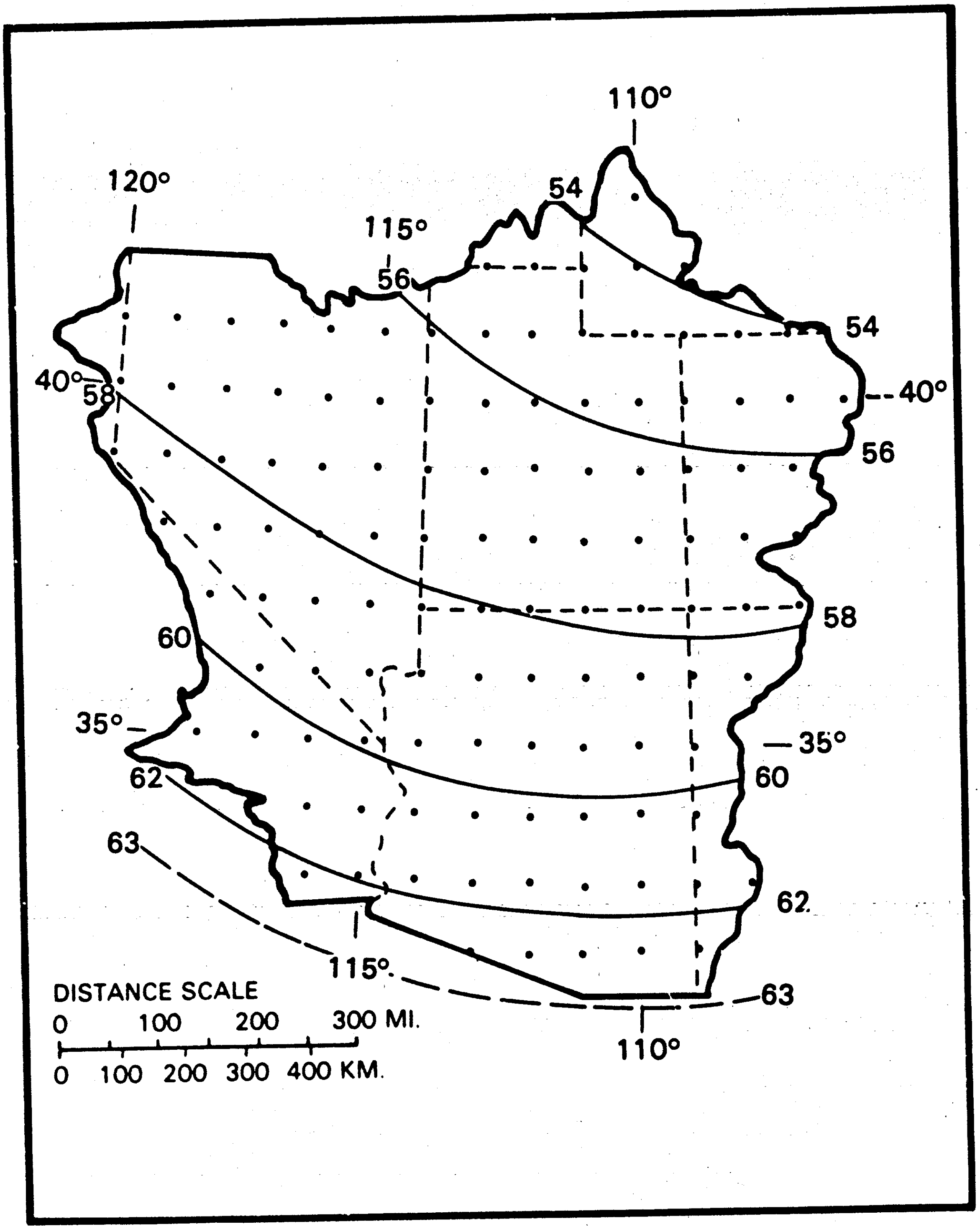


Figure 4.14.--1000-mb 12-hr persisting dew point for mid-February.

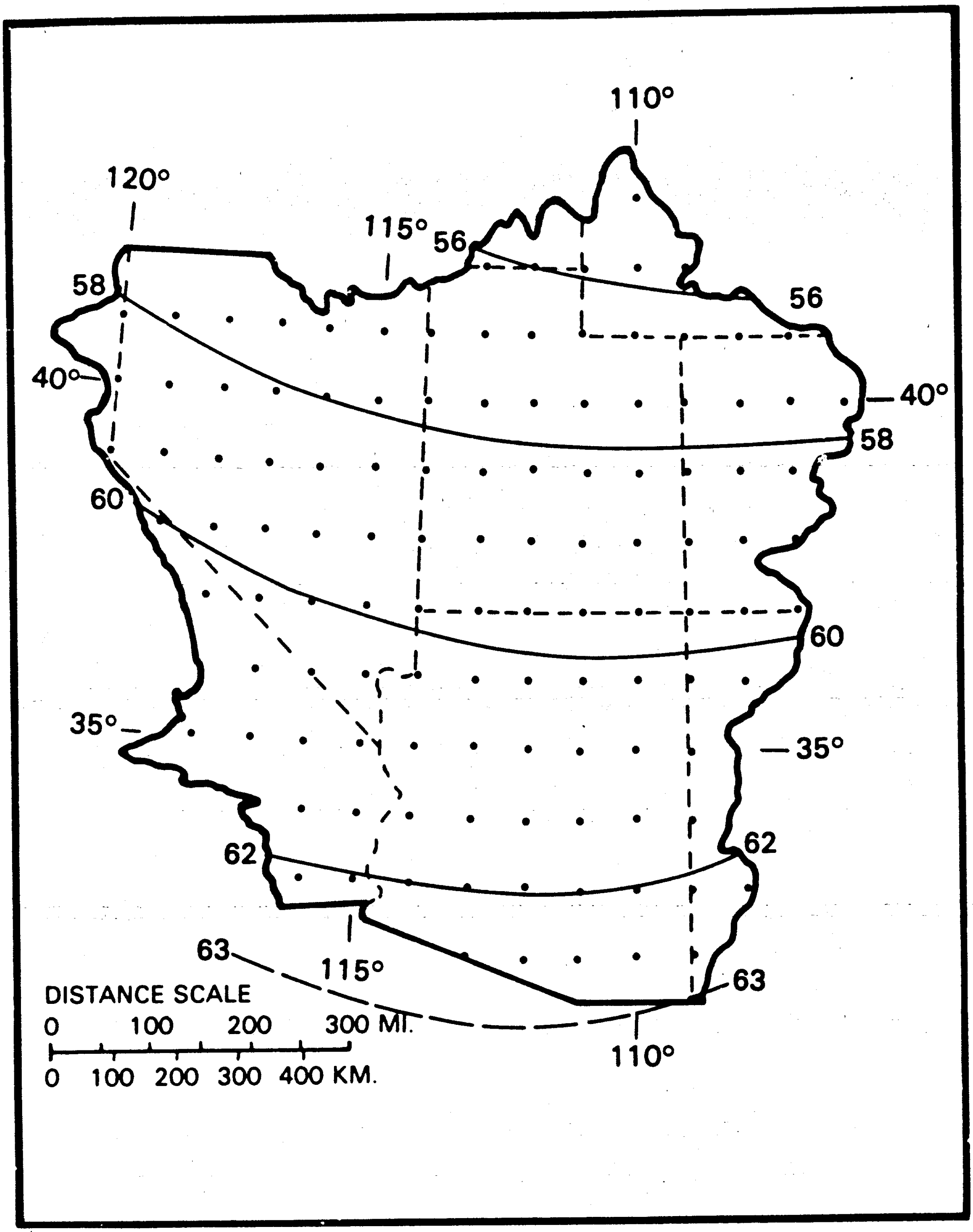


Figure 4.15.--1000-mb 12-hr persisting dew point for mid-March.

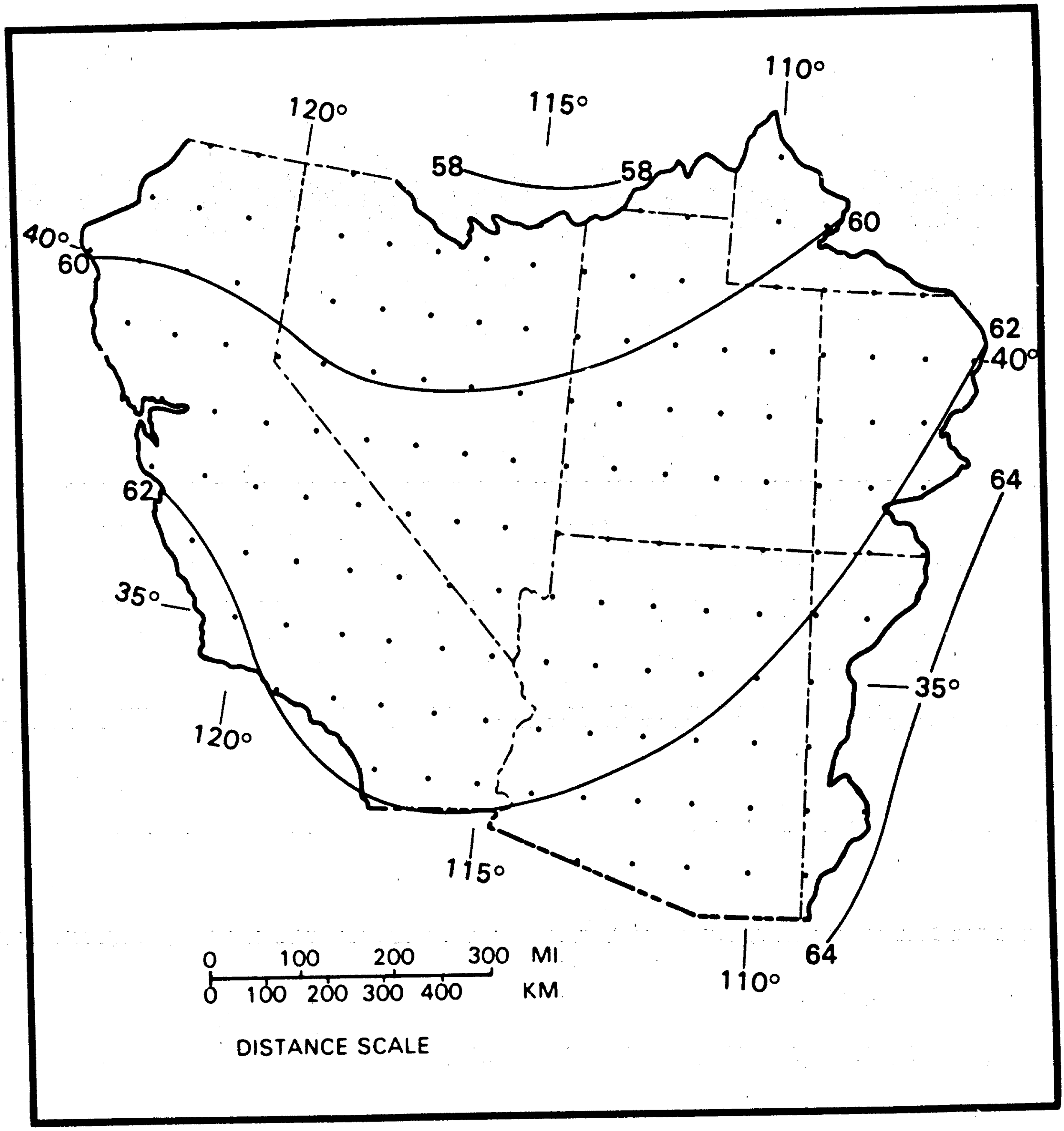


Figure 4-16.--1000-mb 12-hr persisting local storm dew point for mid April.

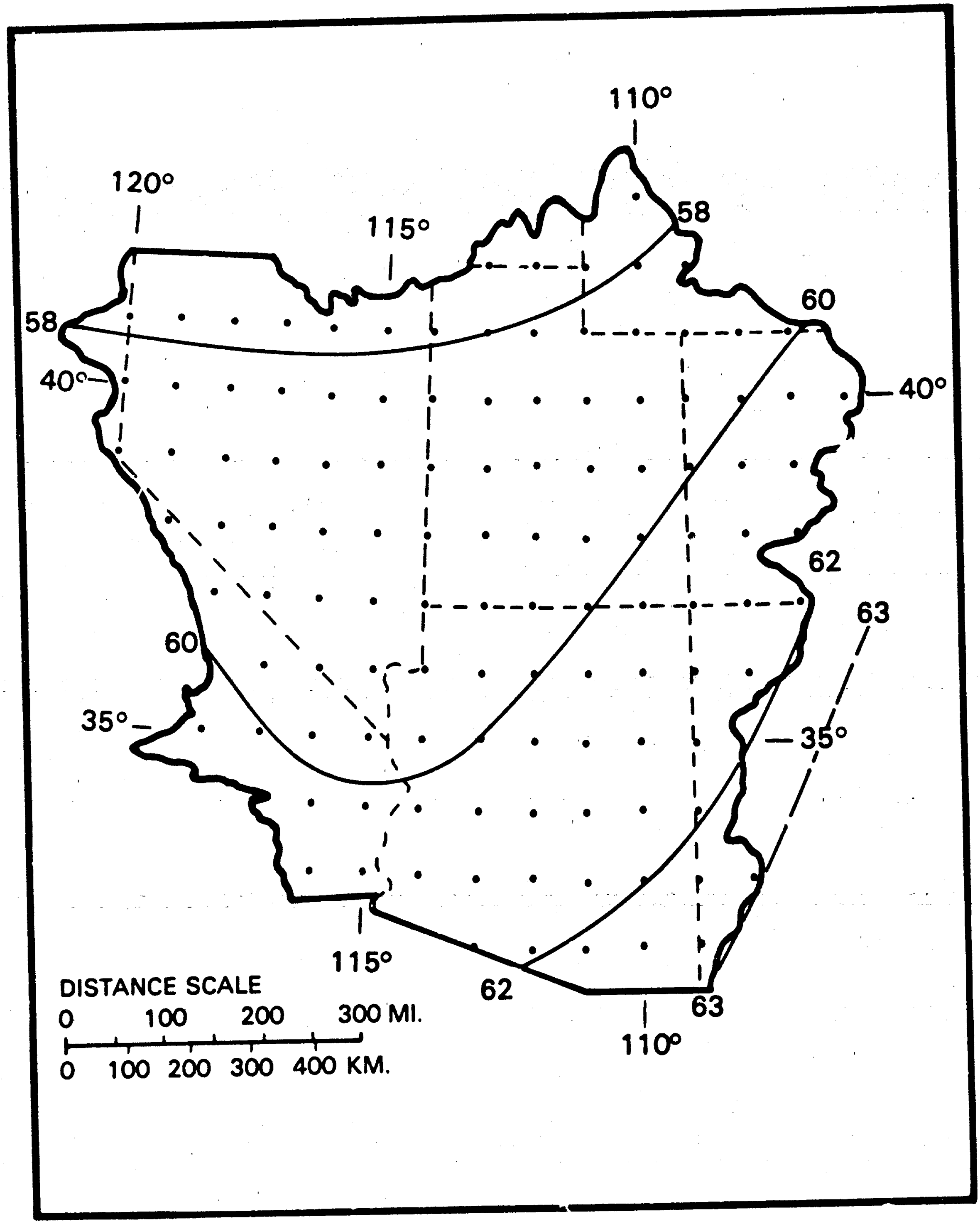


Figure 4.17.--1000-mb 12-hr persisting general storm dew point for mid-April.

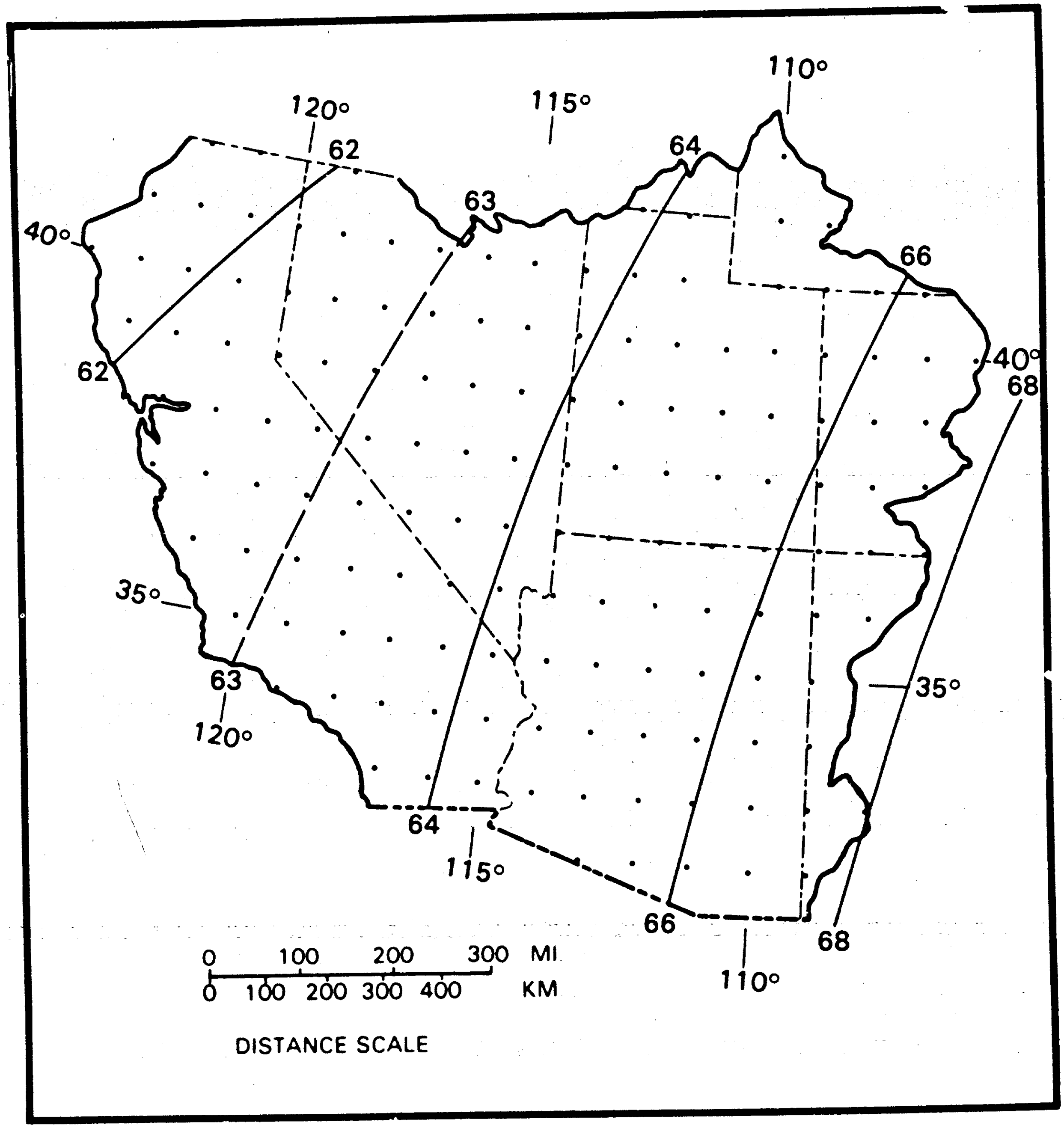


Figure 4.18.--1000-mb 12-hr persisting local storm dew point for mid-May.

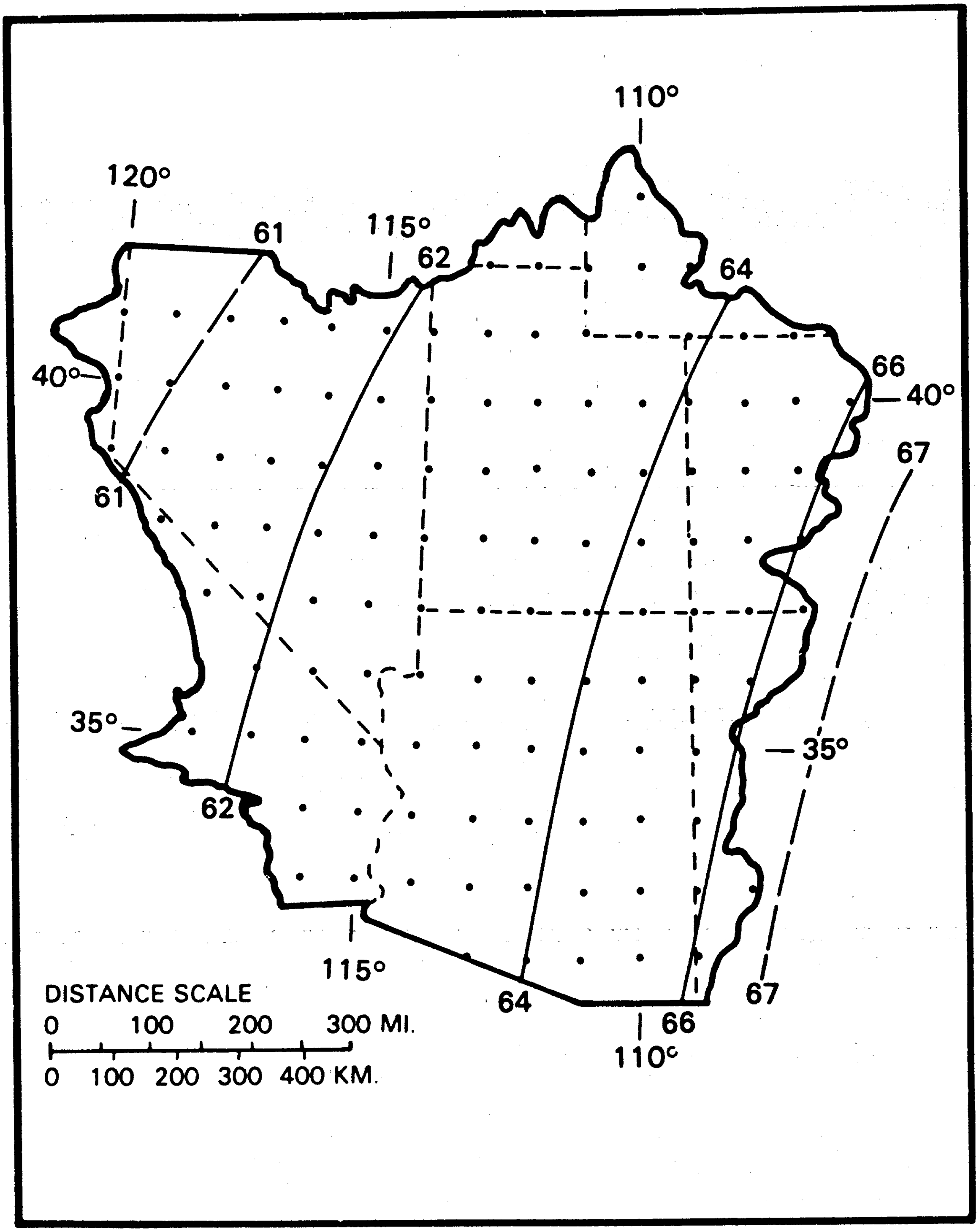


Figure 4.19.--1000-mb 12-hr persisting general storm dew point for mid-May.

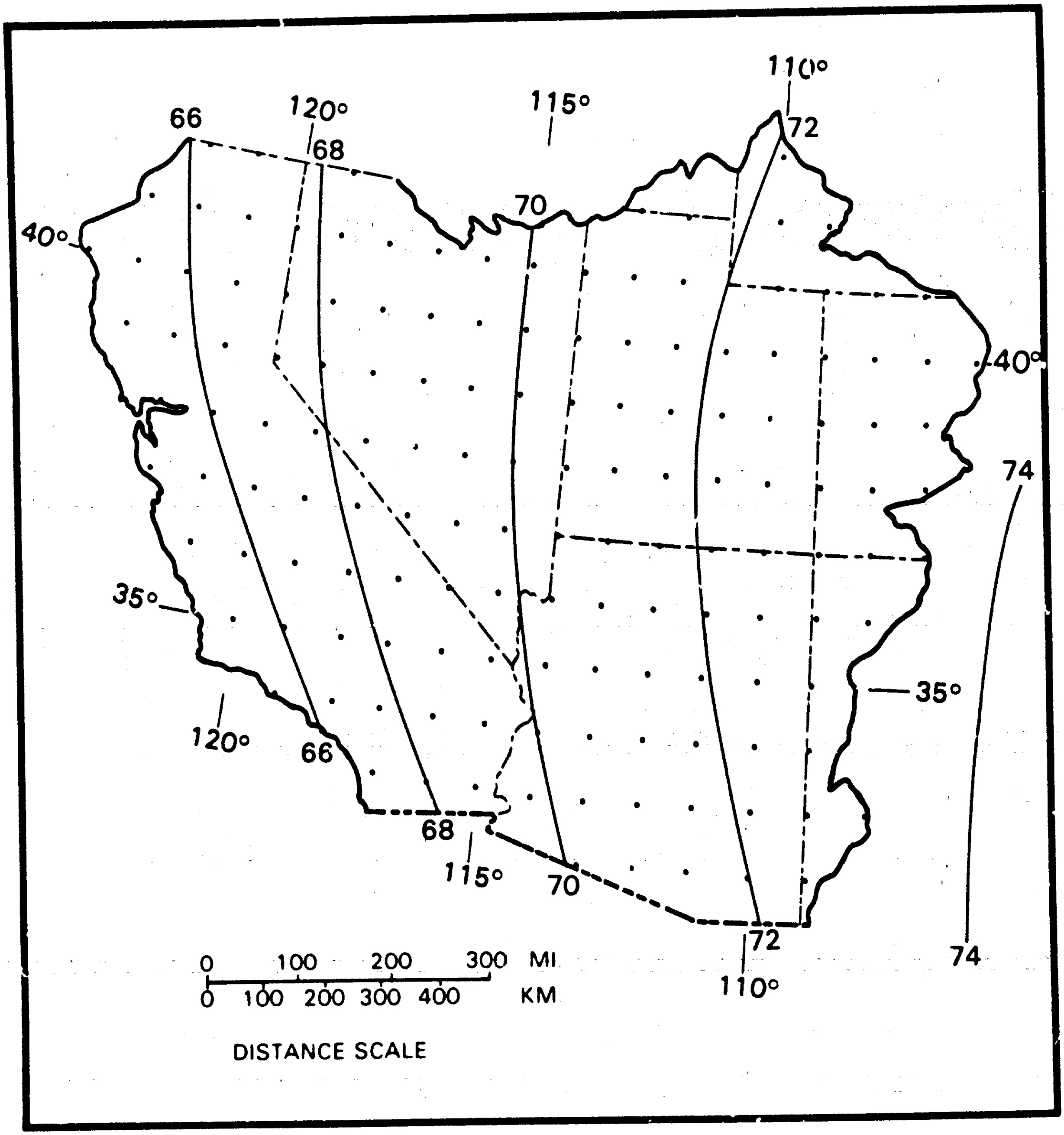


Figure 4.20.--1000-mb 12-hr persisting local storm dew point for mid-June.

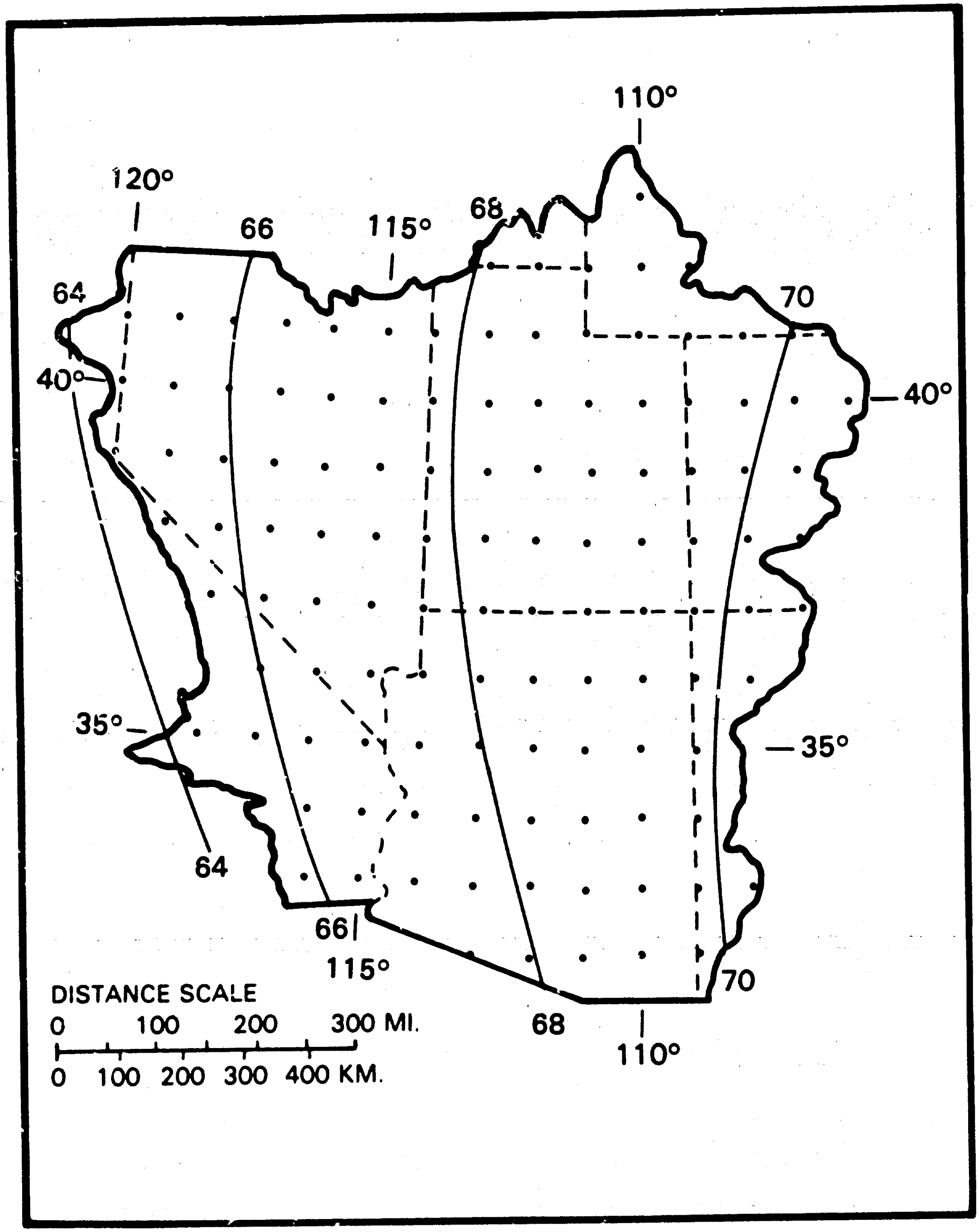


Figure 4.21.--1000-mb 12-hr persisting general storm dew point for mid-June.

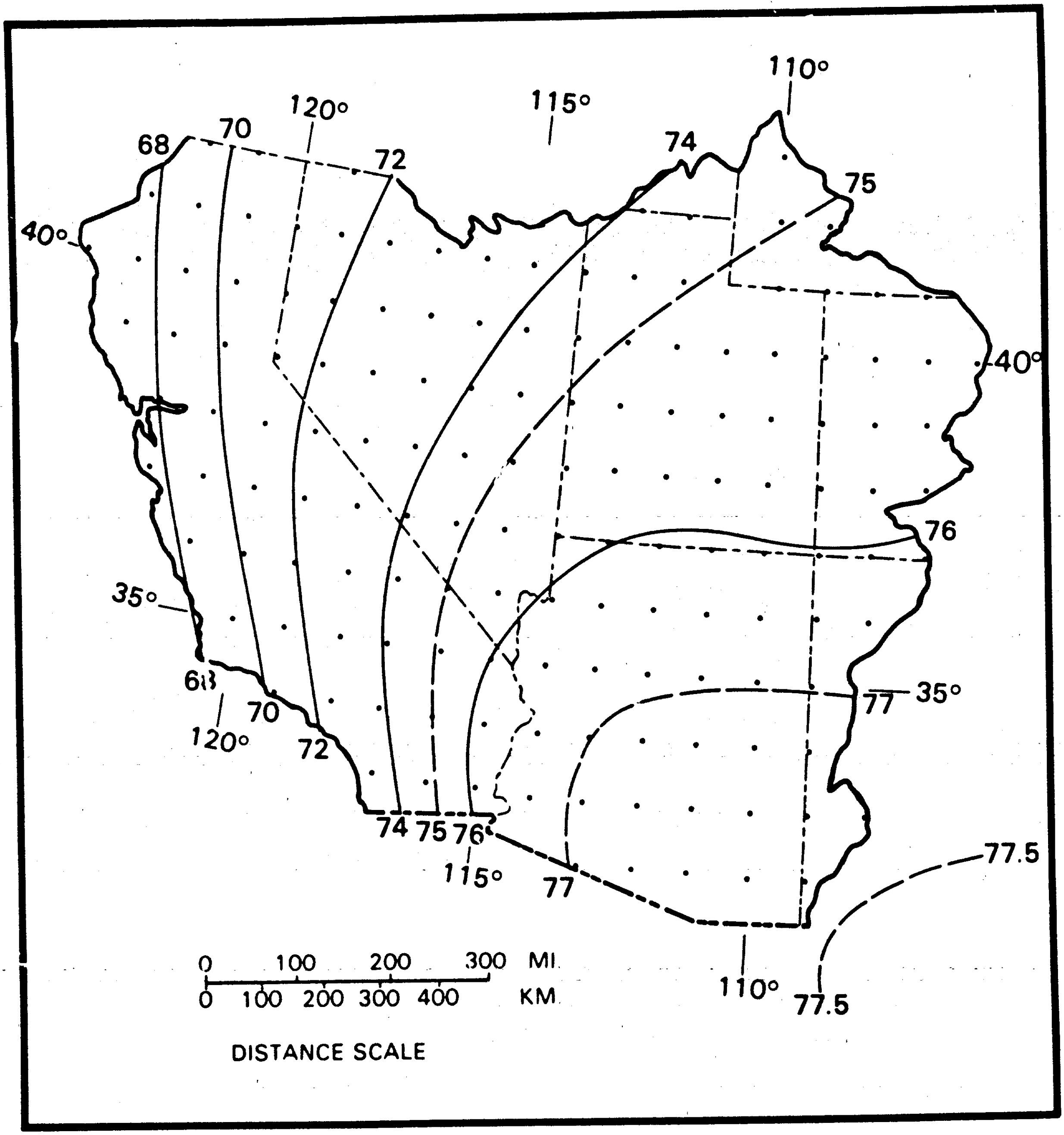


Figure 4.22.--1000-mb 12-hr persisting local storm dew point for mid-July.

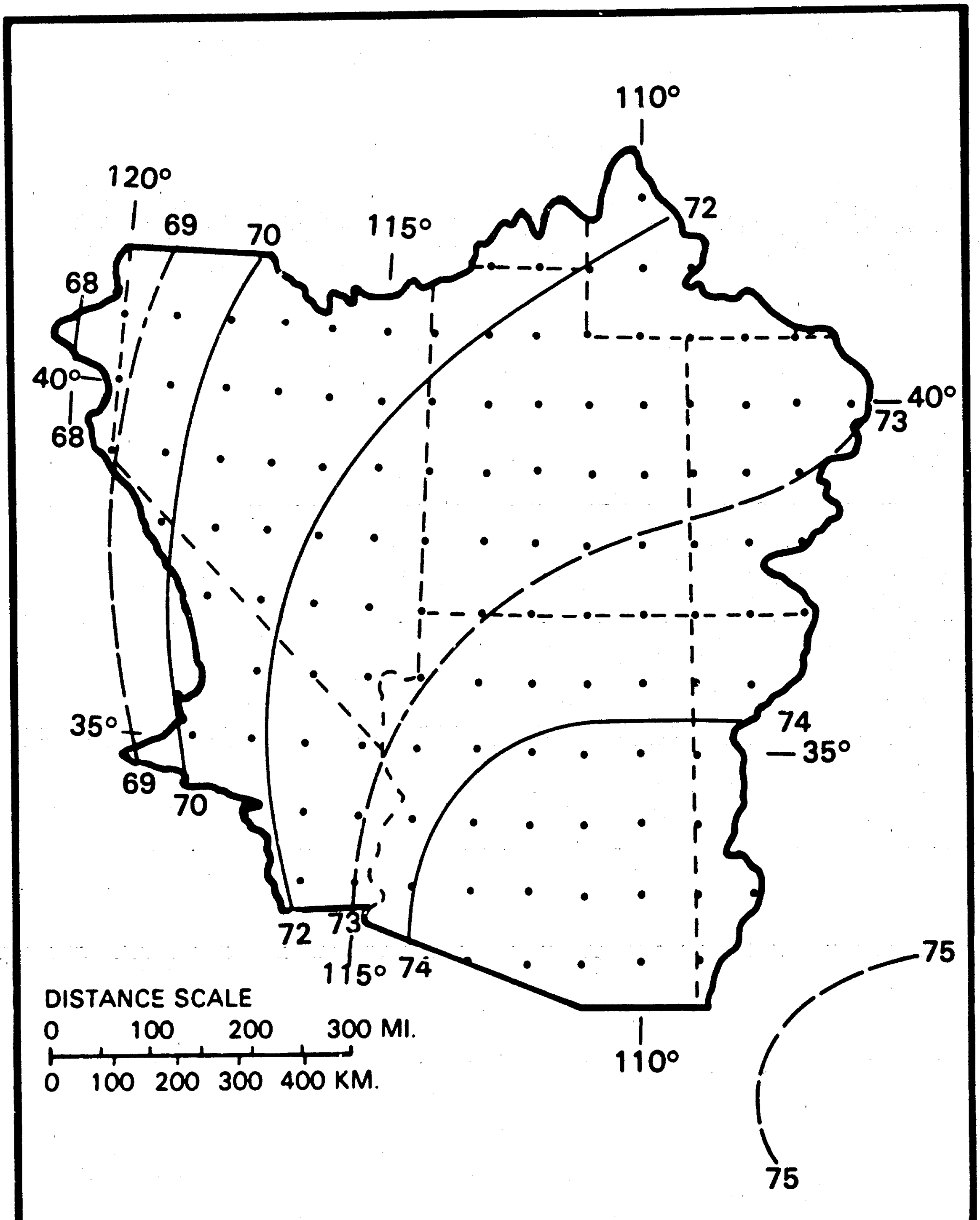


Figure 4.23.--1000-mb 12-hr persisting general storm dew point for mid-July.

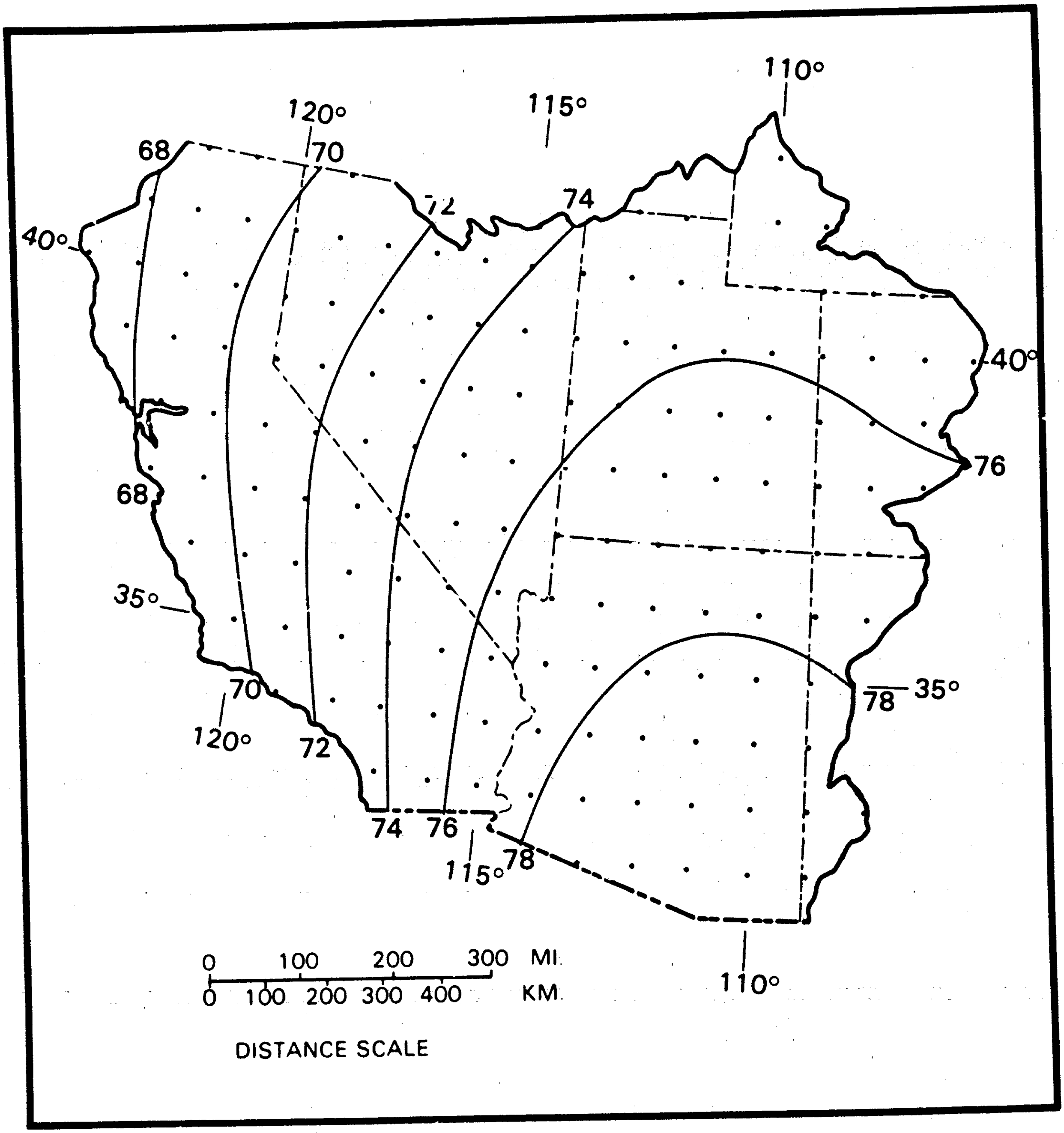


Figure 4.24.--1000-mb 12-hr persisting local storm dew point for mid-August.

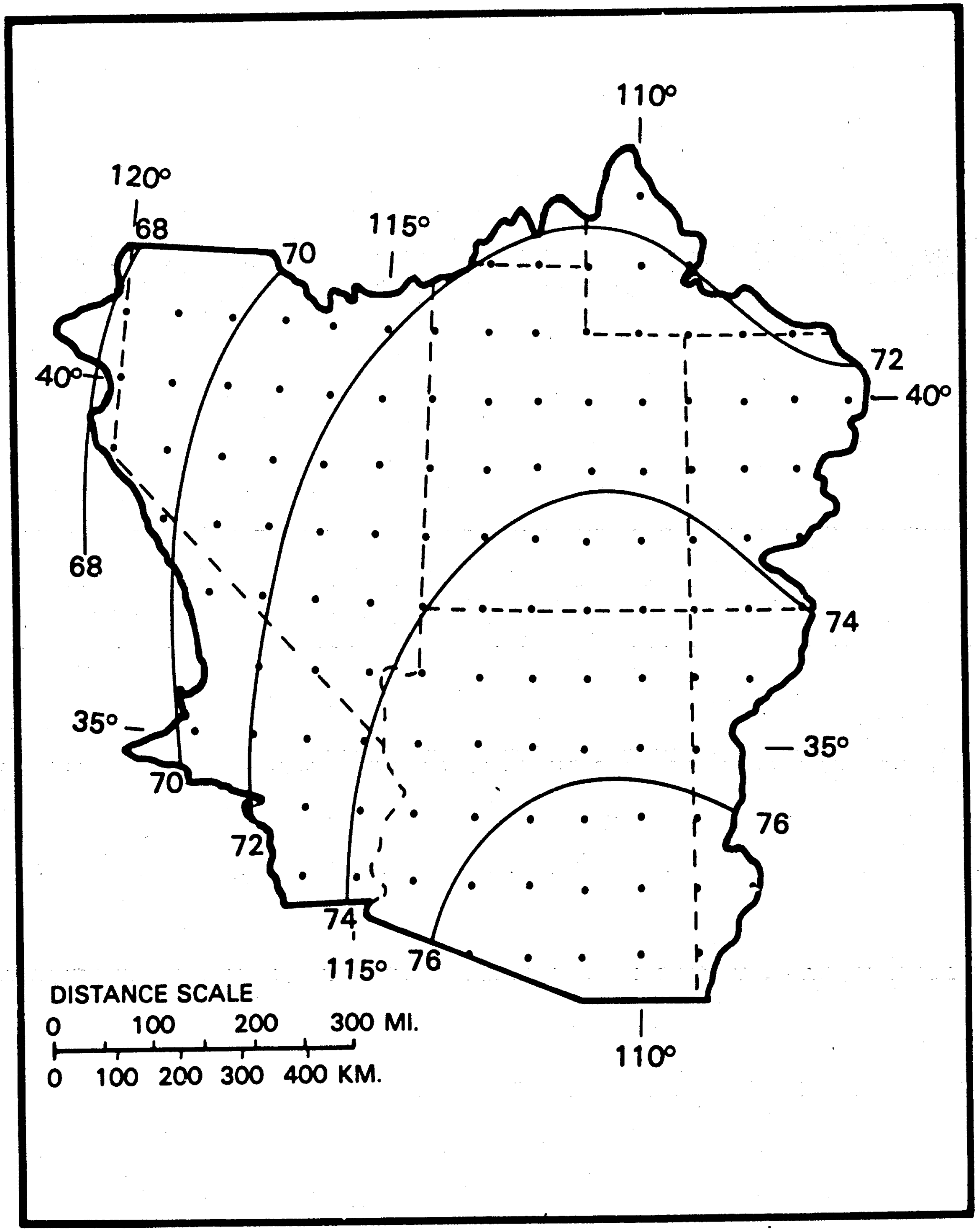


Figure 4.25.--1000-mb 12-hr persisting general storm dew point for mid-August.

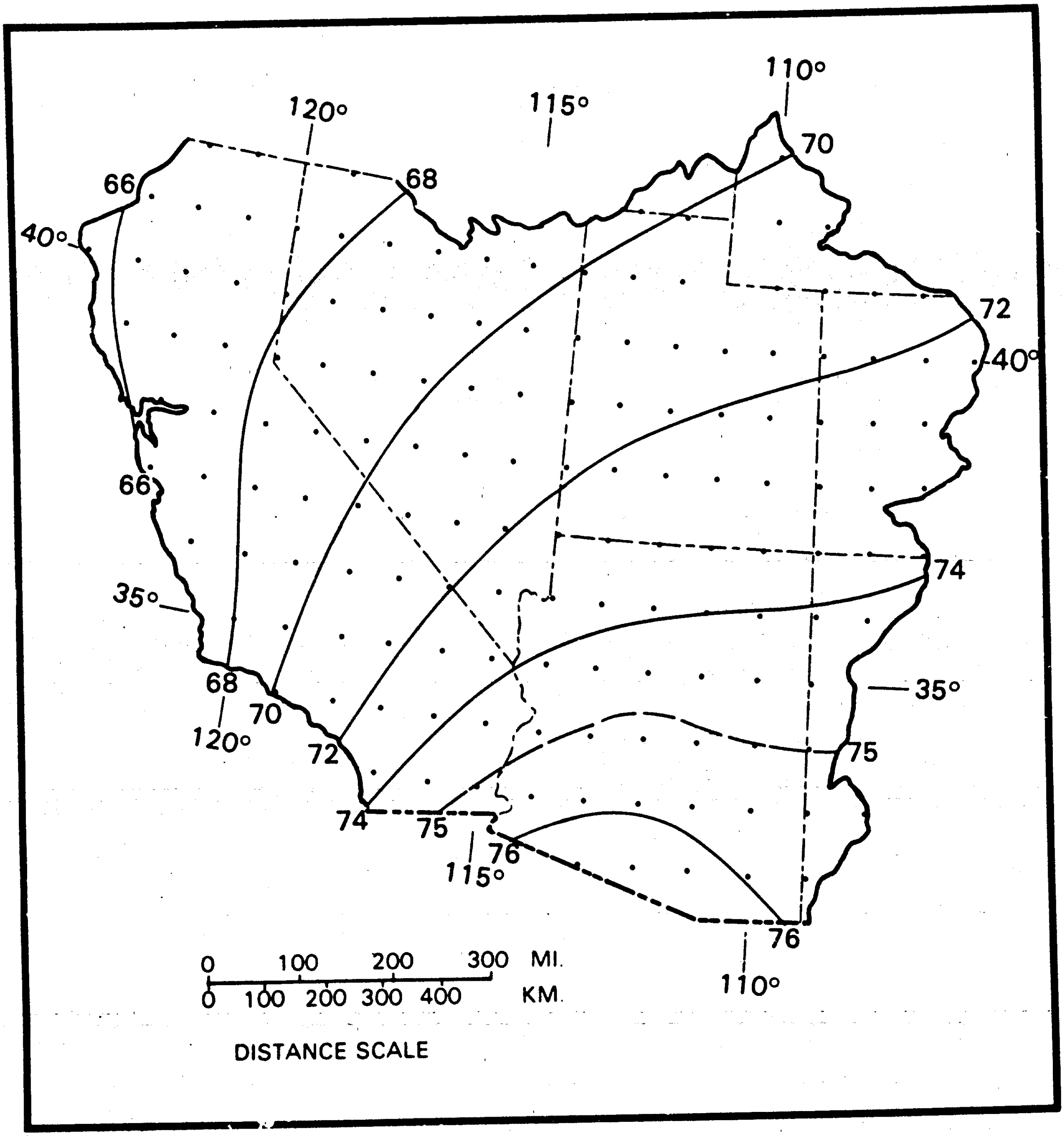


Figure 4.26.--1000-mb 12-hr persisting local-storm dew point for mid-September.

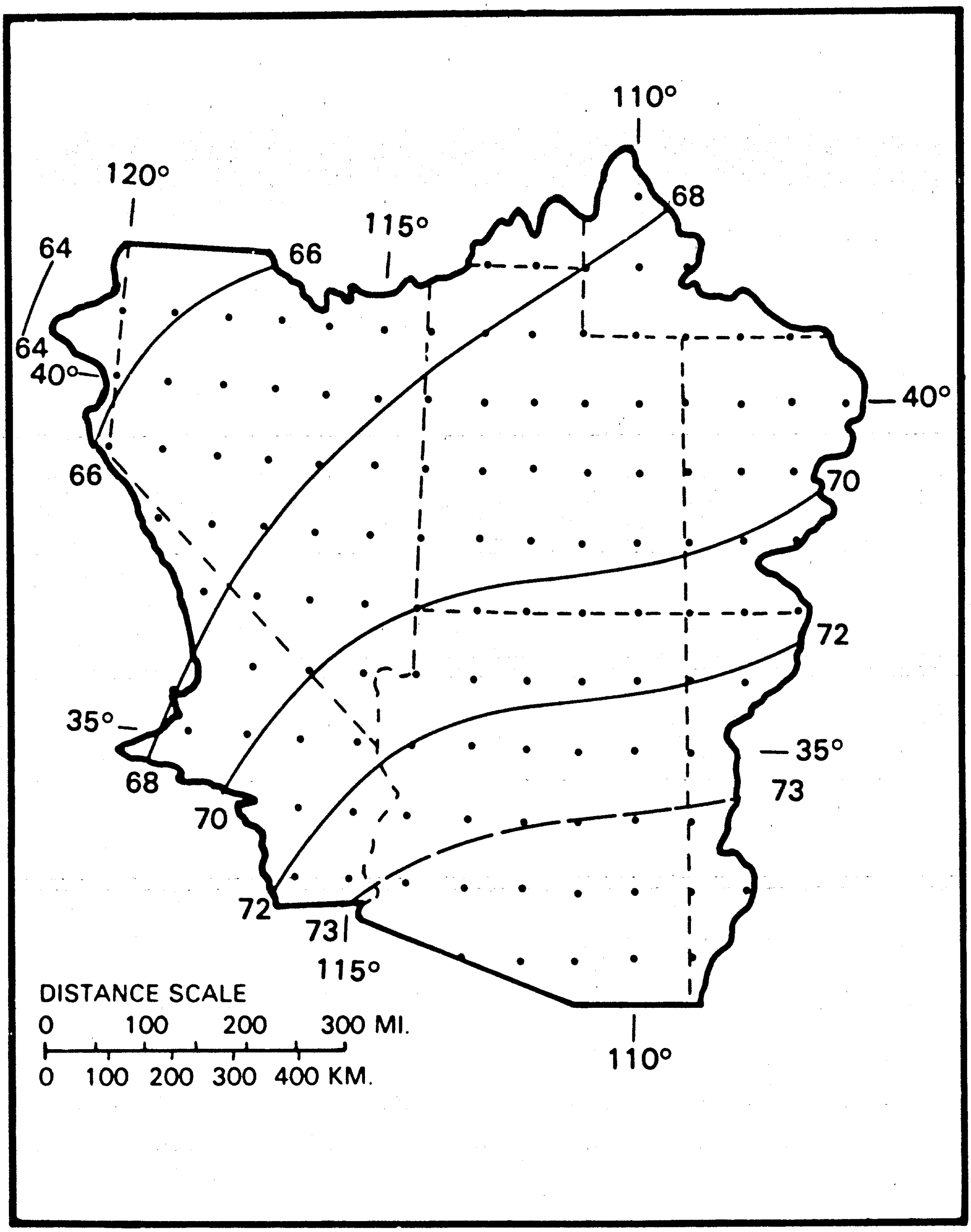


Figure 4.27.--1000-mb 12-hr persisting general storm dew point for mid-September.

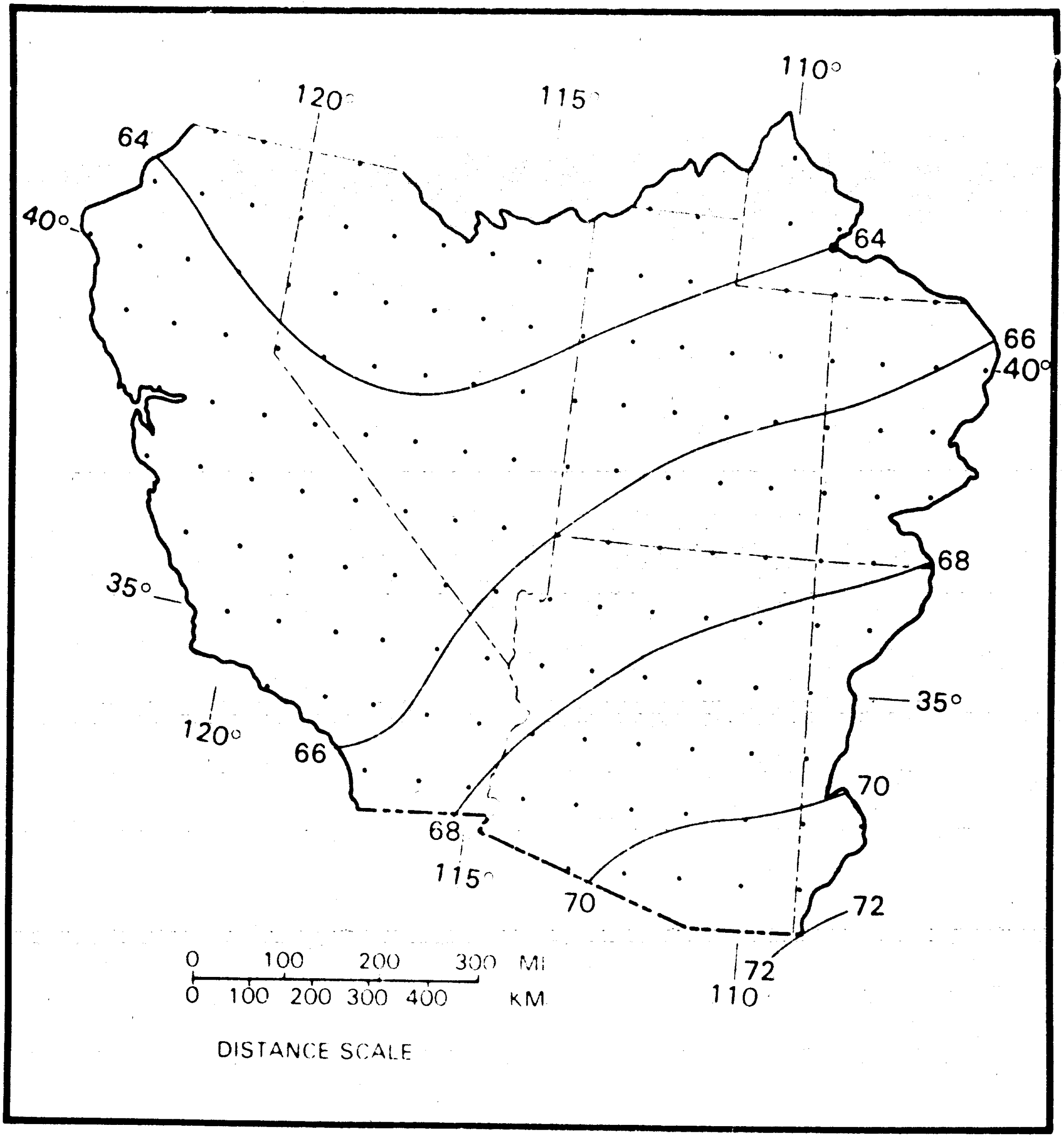


Figure 4.28.--1000-mb 12-hr persisting local-storm dew point for mid-October.

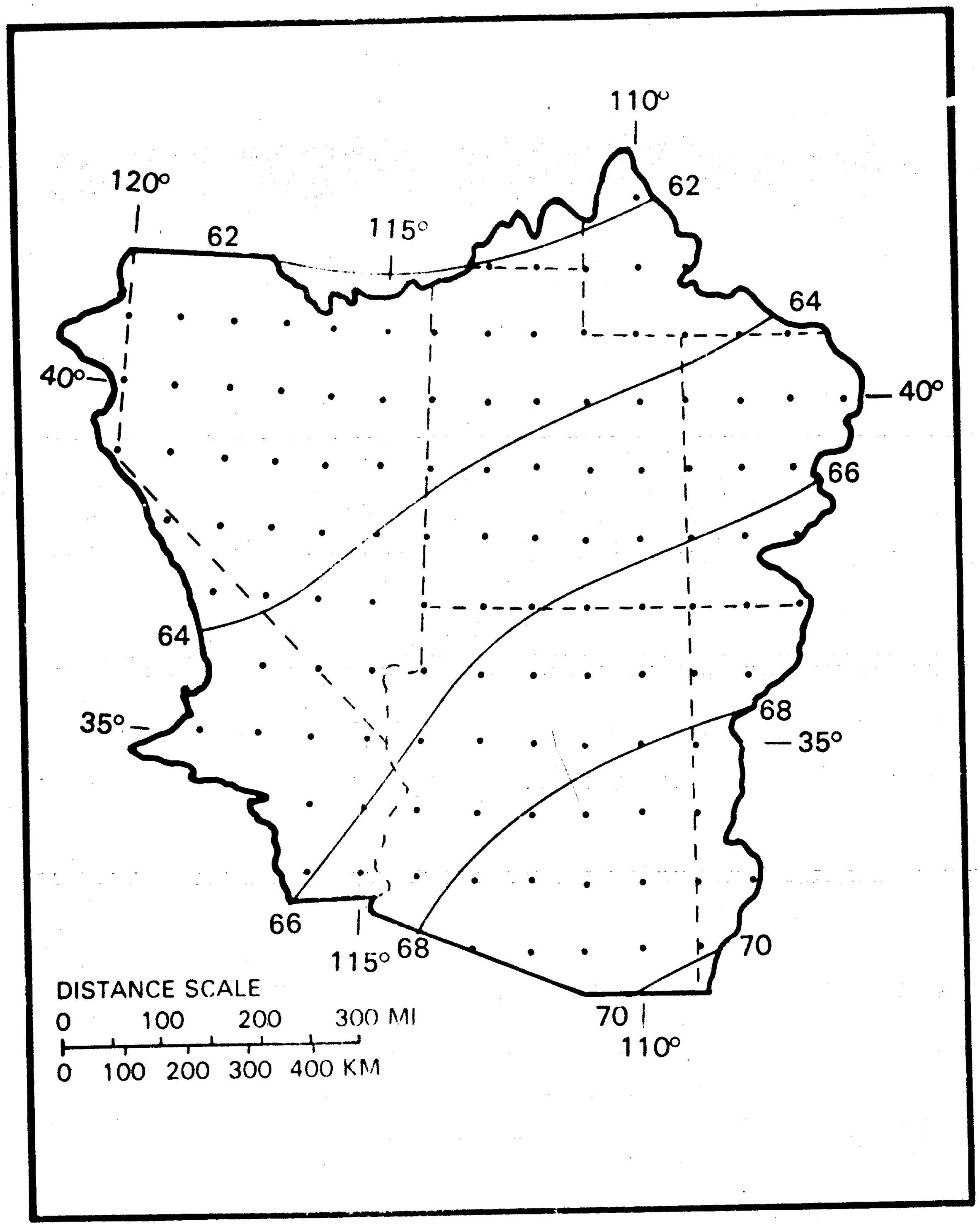


Figure 4.29.--1000-mb 12-hr persisting general storm dew point for mid-October.

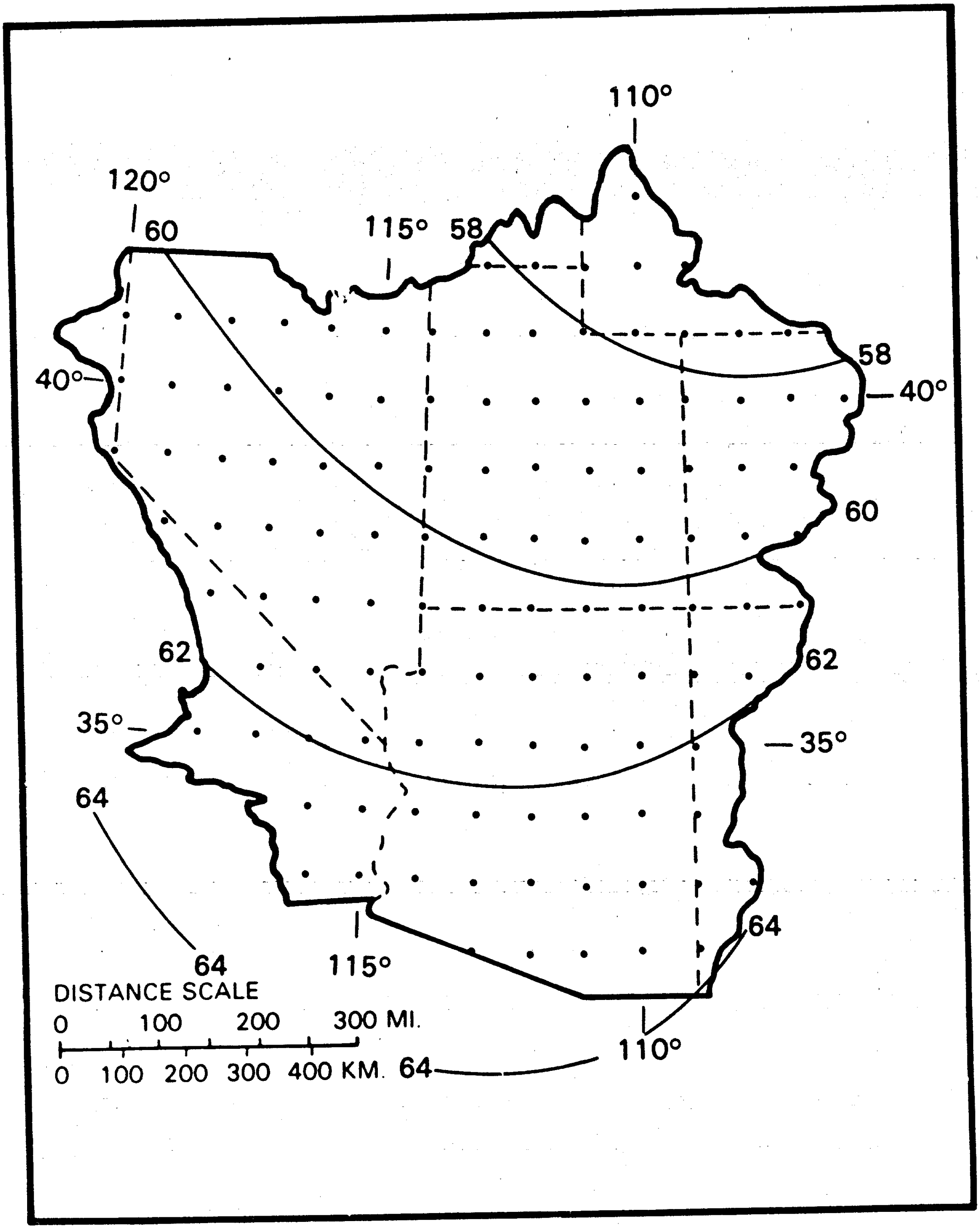


Figure 4.30.--1000-mb 12-hr persisting general dew point for mid-November.

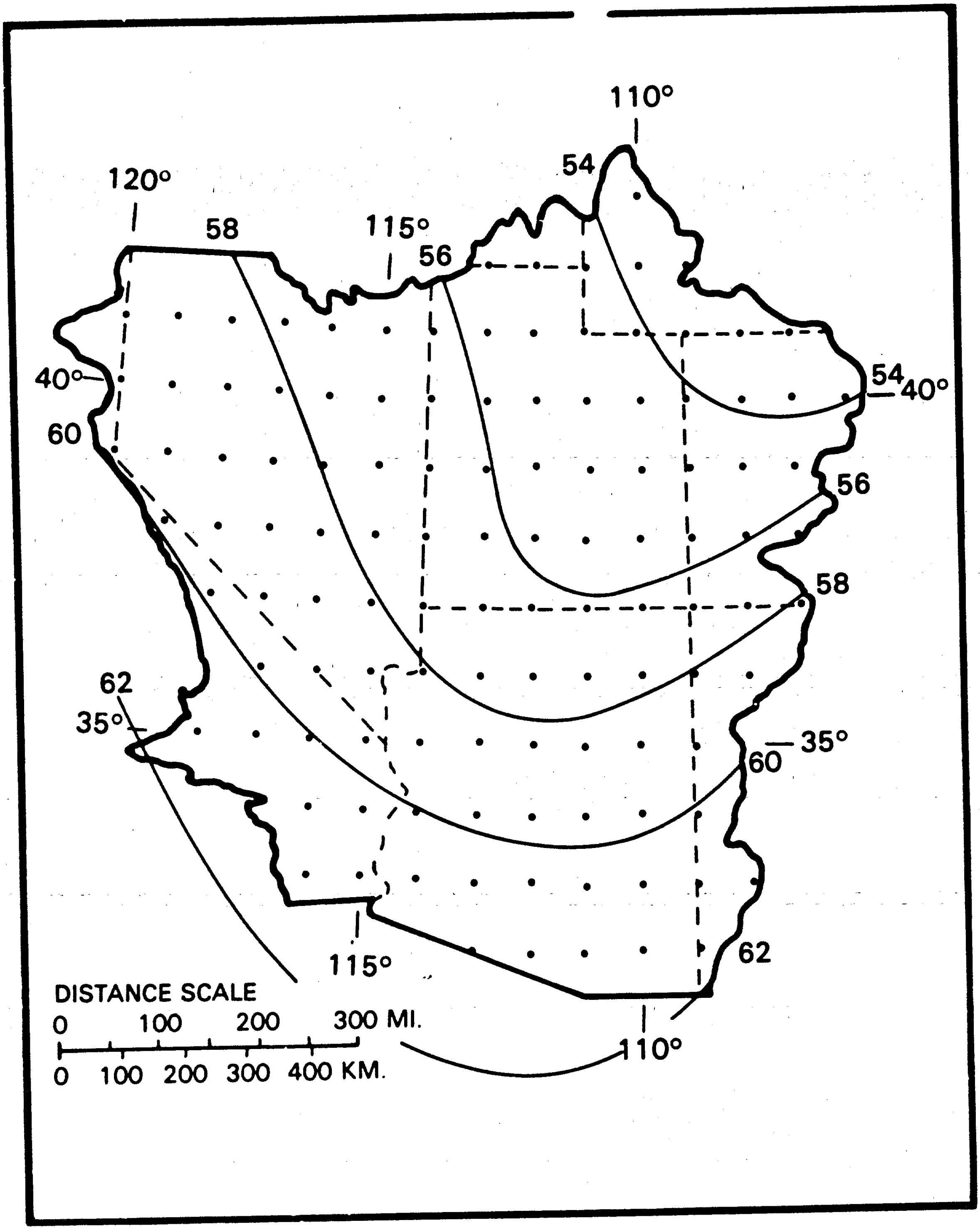


Figure 4.31.--1000-mb 12-hr persisting dew point for mid December.

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APPENDIX A - NORMAL SEA LEVEL AND 500-MB CHARTS

The two sets of monthly normal charts (U.S. Weather Bureau 1952) are reproduced covering the study area of this report. One set consists of sea level pressure charts (fig. A1 and A2). The lines of equal pressure on these are labeled in millibars. The other set consists of 500-mb contour charts of approximately 18,000 ft (fig. A3 and A4). The lines on these charts are labeled in tens of feet, and represent the intersection of the 500-mb surface with each 200 foot elevation.

Some of the charts are referred to in the text in relation to specific storm situations. Charts for all months are given so that the user may readily make reference to normal conditions relative to specific weather situations discussed in the text.

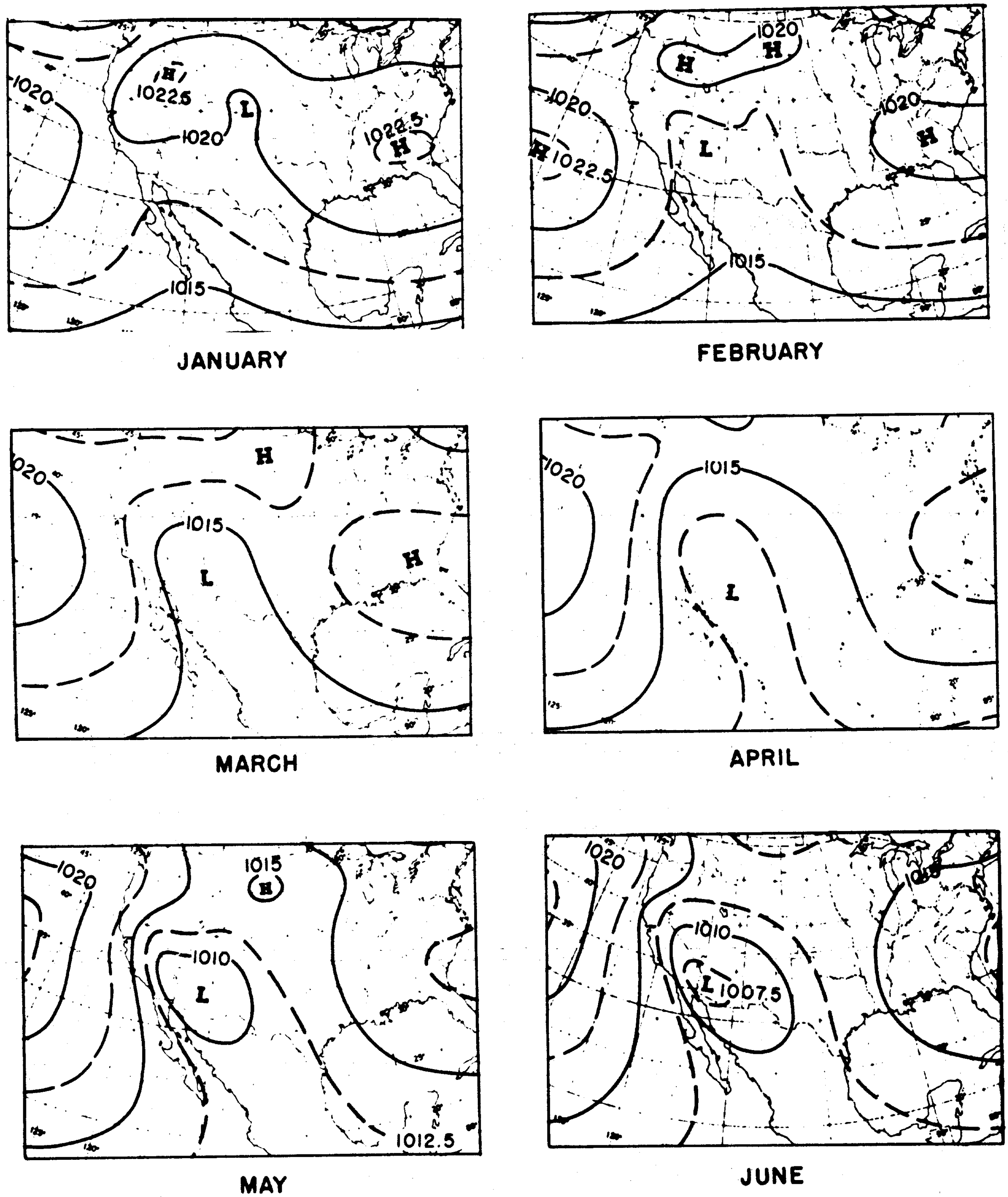

Figure A.1.--Normal sea level pressure charts for January through June.

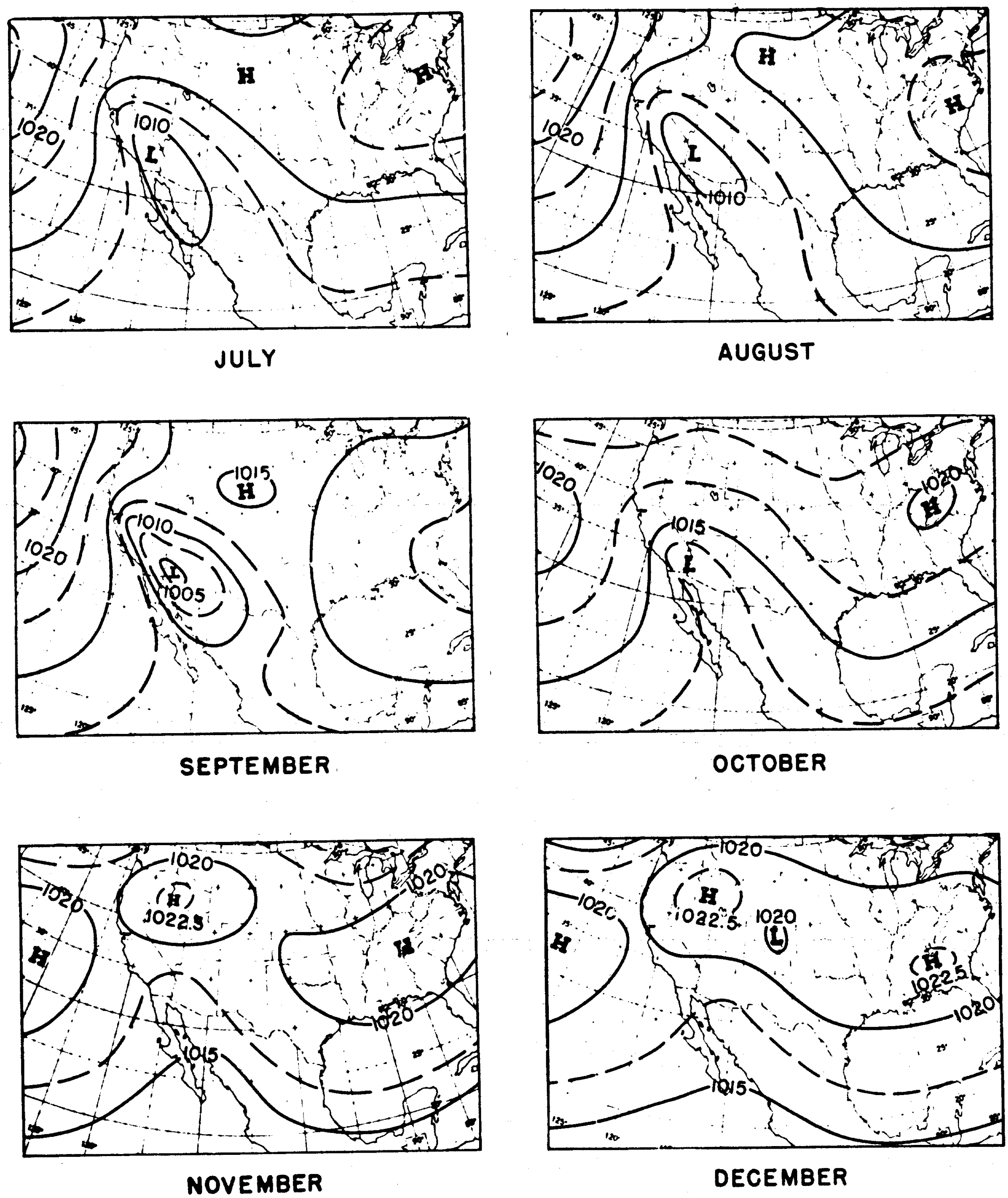

Figure A.2.--Normal sea level pressure charts for July through December.

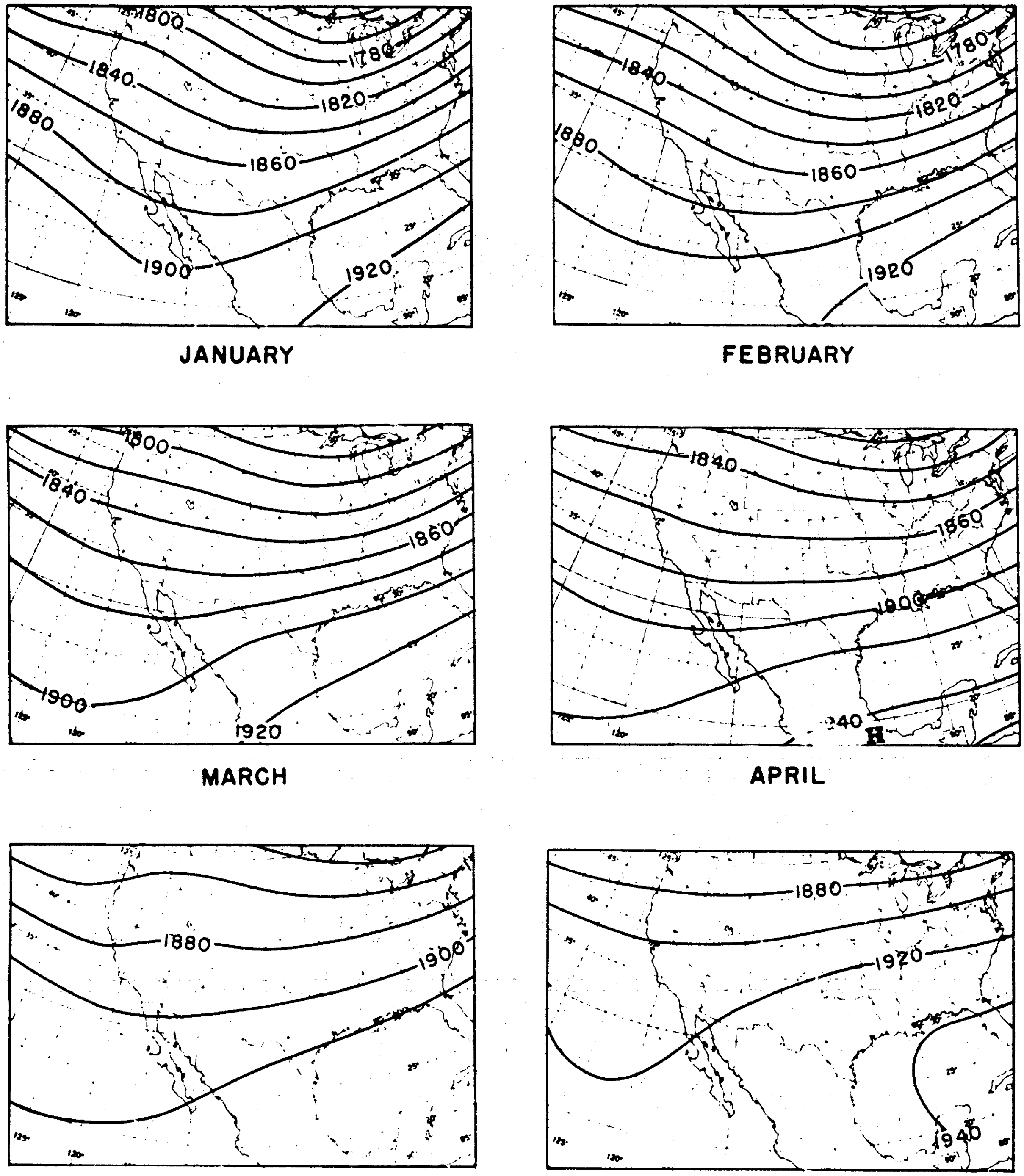

Figure A.3.--Normal 500-mb contour charts for January through June.

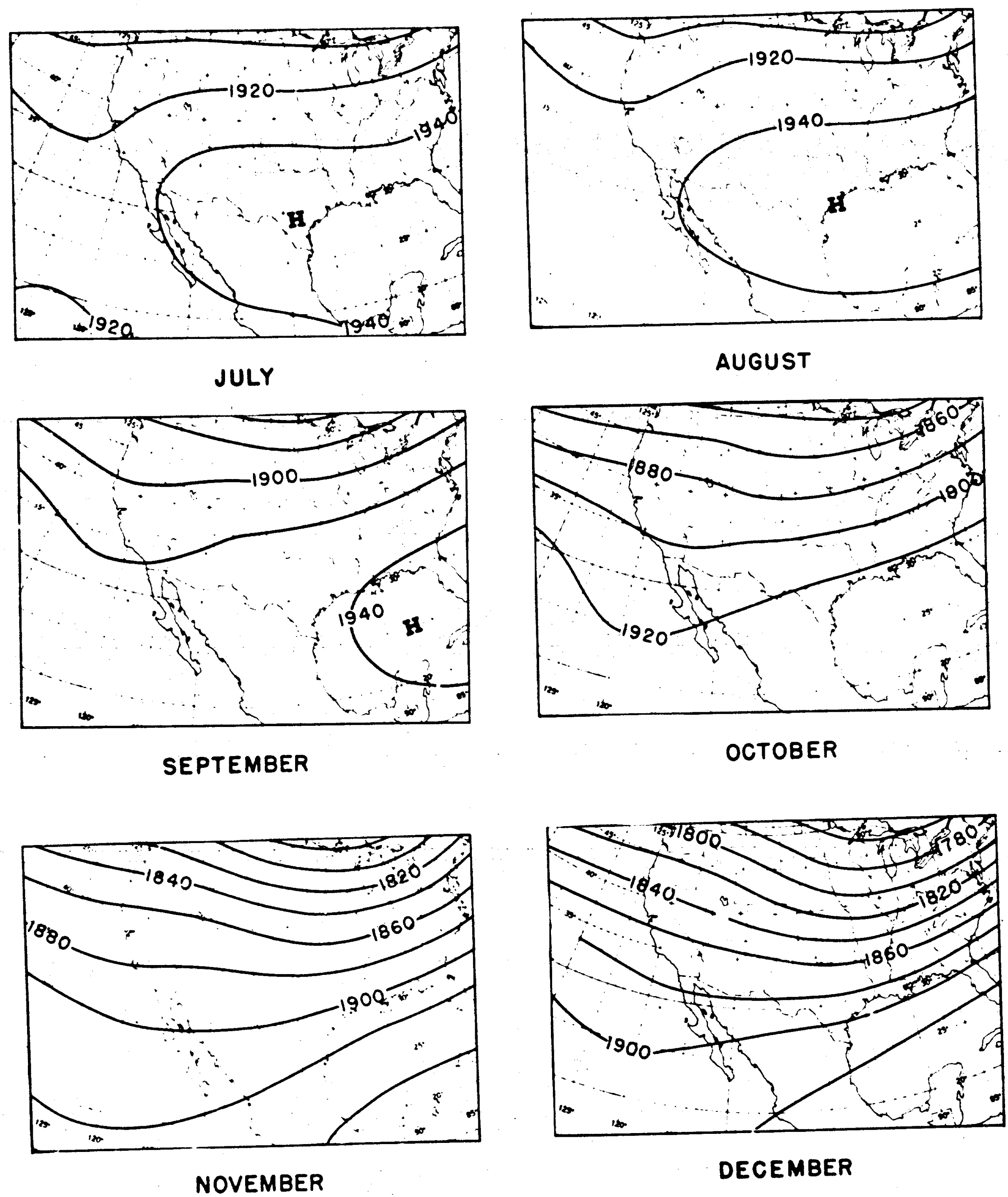

Figure A.4.--Normal 500-mb contour charts for July through December.

APPENDIX B

Glossary of Selected Geographical and Meteorological Terms as referred to in this report.

Geographical Terms

Baja California. The peninsula in Mexico extending southward from California and comprised of the two Mexican states of Baja California and Baja California Sur.

Eastern Pacific Ocean. Loosely defined as that portion of the Pacific Ocean adjacent to and to the west of the west coast of the United States.

Sonora, Mexico. The large State in the northwest portion of Mexico and immediately south of the Southwestern region.

Southwestern Region. (Also referred to as Southwest or Southwestern States). That portion of the Colorado River and Great Basin drainages for which PMP estimates are given in HMR No. 49. For general storm PMP, this region lies between the Sierra Nevada - Tehachapi - Coastal Range Divide on the west and the Continental Divide on the east, and between the southern boundary to the Northwestern States PMP (HMR No. 43) on the north and the United States - Mexico border on the south. For local storm PMP, this region also includes the remainder of California.

Tropical Pacific Ocean. The portion of the Pacific adjacent to and west of the west coast of Mexico, with the exception of the Gulf of California.

Western California. The portion of California that drains directly into the Pacific Ocean. This region is coincident with the portion of California that has only local storm PMP in HMR No. 49. It is in addition to the region covered by the general storm PMP in that report.

Meteorological Terms

Isentropic Surface. A surface of constant entropy, equivalent to surfaces of constant potential temperature in the atmosphere. Parcel movement on an isentropic surface is adiabatic; i.e., no gain or loss of heat. Isentropic charts are useful in following the motion of air particles.

Macroscale. Largest scale of atmospheric circulation system, considered larger than synoptic scale, with wavelengths greater than about 1,500 miles.

Mesoscale. Atmospheric systems smaller than synoptic scale but larger than microscale, covering phenomena usually smaller than those distinguishable from the normal observation network. Thunderstorms and underdeveloped tropical cyclones are examples of mesoscale systems.

Occluded Front. A composite of two fronts formed when a more rapidly moving cold front overtakes a warm or quasi-stationary front. Under certain conditions, the greatest frontal discontinuities in occluded fronts are observed above the surface.

Probable Maximum Precipitation (PMP). The theoretically greatest depth of precipitation for a given duration that is physically possible over a given size area at a particular geographic location at a given time of year. This definition revises that given in the Glossary of Meteorology (American Meteorological Society 1959), as a result of mutual understanding between the Corps of Engineers, Bureau of Reclamation, and National Weather Service.

Pseudo-Adiabatic Lapse rate. In meteorology this term is often taken as an approximation to the wet-bulb potential temperature or saturation adiabats. That is, the rate of decrease in temperature with height of a saturated parcel of air lifted adiabatically in hydrostatic equilibrium.

Quasi-Stationary Front. A front that remains stationary or nearly so between observations. Because of difficulty in determining exact frontal positions, this term is often applied loosely to any front that does not show rapid movement between observations.

Synoptic. Affording an overall view, based on simultaneously observed meteorological data. Synoptic scale approximates the dimensions of high- and low-pressure systems, having wave lengths roughly 600 to 1,500 miles.

APPENDIX C

Dimension Equivalents

Current policy is to provide metric equivalents for all dimensions given in English units. Although there are only a few types of units used in this report, the number of occurrences is considered excessive. We therefore decided to facilitate this requirement by listing the pertinent English to metric equivalents in the following table for reference.

English Unit	Equals	Metric Unit
1.0 inch (in.)		25.4 millimeters (mm)
1.0 foot (ft)		0.3048 meters (m)
1.0 mile (mi)		1.609 kilometers (km)
1.0 square mile (mi^2)		2.590 square kilometers (km^2)
1 foot/second (ft/sec)		30.48 centimeters/second (cm/sec) or 1.097 kilometer/hour (km/hr)
1.0 knot (kt)		51.48 centimeters/second (cm/sec) or 1.853 kilometers/hour (km/hr)
T° Fahrenheit [T = temperature]		5/9 (T - 32°) centigrade

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