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Meteorology of Major Storms in Western Colorado and Eastern Utah

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METEOROLOGY OF MAJOR STORMS IN WESTERN COLORADO AND EASTERN UTAH

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for

Bureau of Reclamation

Department of the Interior

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ABSTRACT

The 42 most intense general storms in eastern Utah and western Colorado since 1899 are studied in relation to the observed or estimated broadscale upper air circulation patterns and sources of moisture. The report summarizes individual analyses of the storms. Storms are typed by reference to the behavior of the 500-mb patterns. The role of upper Lows in transporting moisture is emphasized. Indices are developed which evaluate storm moisture, temperature and influence of topography. The relative importance to the precipitation sequence of peak moisture versus proximity of upper Lows or troughs is compared. Moisture source regions are related to storm type and season. Local topographic effects are summarized by upper wind direction. Other relationships between various factors are discussed.

METEOROLOGY OF MAJOR STORMS IN WESTERN COLORADO AND EASTERN UTAH

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CHAPTER 1. INTRODUCTION

1.1 Objective

1.1.1 The primary objective of the overall research program of which this investigation was a part is the greater understanding of the precipitation process. The study described in this report concerns storm precipitation over western Colorado and eastern Utah. To accomplish this objective the meteorological factors which led up to the major storms during the period 1899-1966 were investigated.

1.2 Approach

1.2.1 The three main approaches to this objective are stated as follows: (1) To develop a systematic classification of these storms in terms of their typical sequence of development at upper levels over a period of several days prior to and during the storm; (2) To determine the source of moisture and develop indices which permit comparison of moisture, temperature and orographic effects between storms; (3) To relate positions of observed or estimated centers of upper-level patterns of height and moisture during each storm to the location and timing of precipitation.

1.2.2 Basic to accomplishment of these objectives was a meteorological analysis of each of 42 storms. A series of daily sea-level maps and maps showing the essential features of the corresponding 500-mb maps (estimated for earlier years) were prepared. Also, moisture fields were drawn on 3-km, 10,000-ft. or 700-mb maps for storms since 1935. For each storm an isohyetal map was drawn of the study area. A series of mass curves, a schematic diagram of movement of upper Lows or troughs and, for storms since 1935, a time plot of Grand Junction moisture during the storm were completed. These charts are not shown in this report.

1.3 Scope

1.3.1 Period of study. The earliest date of Daily Northern Hemisphere Weather Maps [1] is 1899. This date limits the period of this historical storm review to 67 years. This date is also about the earliest date of a useful precipitation network in western Colorado and eastern Utah.

1.3.2 Study area. The rectangular study area of this report extends from 106° W. to 110° W. Longitude, as shown by the topographic map of figure 1-1. The area of this region is about 80,000 square miles and includes western Colorado, eastern Utah, a narrow strip east of the Continental Divide in Colorado and New Mexico and another along the San Juan River in extreme northern New Mexico.

1.3.3 Storm magnitude. To sample storms of large magnitude, 0.5 inch was set as the threshold value to be exceeded by the average 1-day precipitation at 16 key stations representing the study area. The 16 stations are underlined on the two station network maps, one for the period to 1932 (fig. 1-2) and the somewhat different network for the period 1933-1966 (fig. 1-3). Substitutions were made as necessary, especially in earlier years. The 0.5-inch average precipitation threshold over the study area limits the number of qualifying storms in the study period 1899-1966 to forty-two. Their average recurrence interval is 19 months.

1.4 Data sources

1.4.1 Precipitation data. Daily precipitation amounts for Colorado, New Mexico and Utah are from the Climatological Data [2] or in early years from the Monthly Weather Review [3] or the Climate and Crop Service Bulletin [4]. These data were used in assessing storm magnitude and plotting isohyetal charts. Hourly data come chiefly from the Hydrologic Bulletin [5] and the Hourly Precipitation Bulletin [6]. Daily, thrice-daily and hourly precipitation records as available (the latter primarily since 1940), data from the original station records giving information on precipitation timing, and unpublished storm studies were used to define the precipitation sequence and relate it to the weather maps.

1.4.2 Mean monthly precipitation. Station mean monthly precipitation amounts were taken from that Climatic Summary of the United States [7] which provides the greatest length of record for a station. Mean amounts for a few stations with less than 10 years of record were computed from amounts in Climatological Data [2].

1.4.3 Synoptic maps. The Daily Northern Hemisphere Weather Maps [1] provide surface maps for all but the most recent years, for which the printed Daily Weather Maps [8] are available. These sources provide 500-mb data since 1943. The 3-km, 10,000-ft. or 700-mb charts are available for years since 1932.

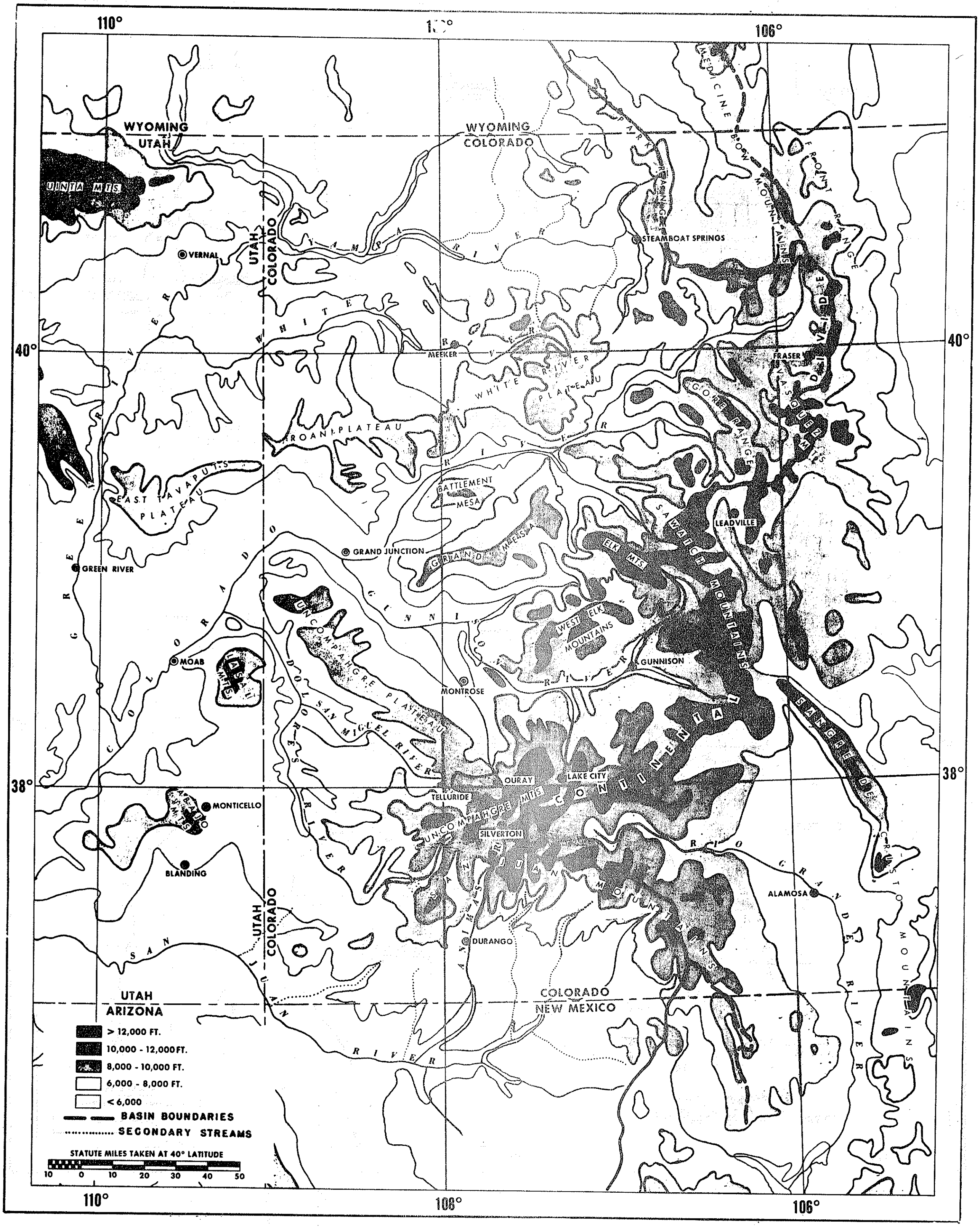


Figure 1-1. Topographic map of western Colorado and eastern Utah.

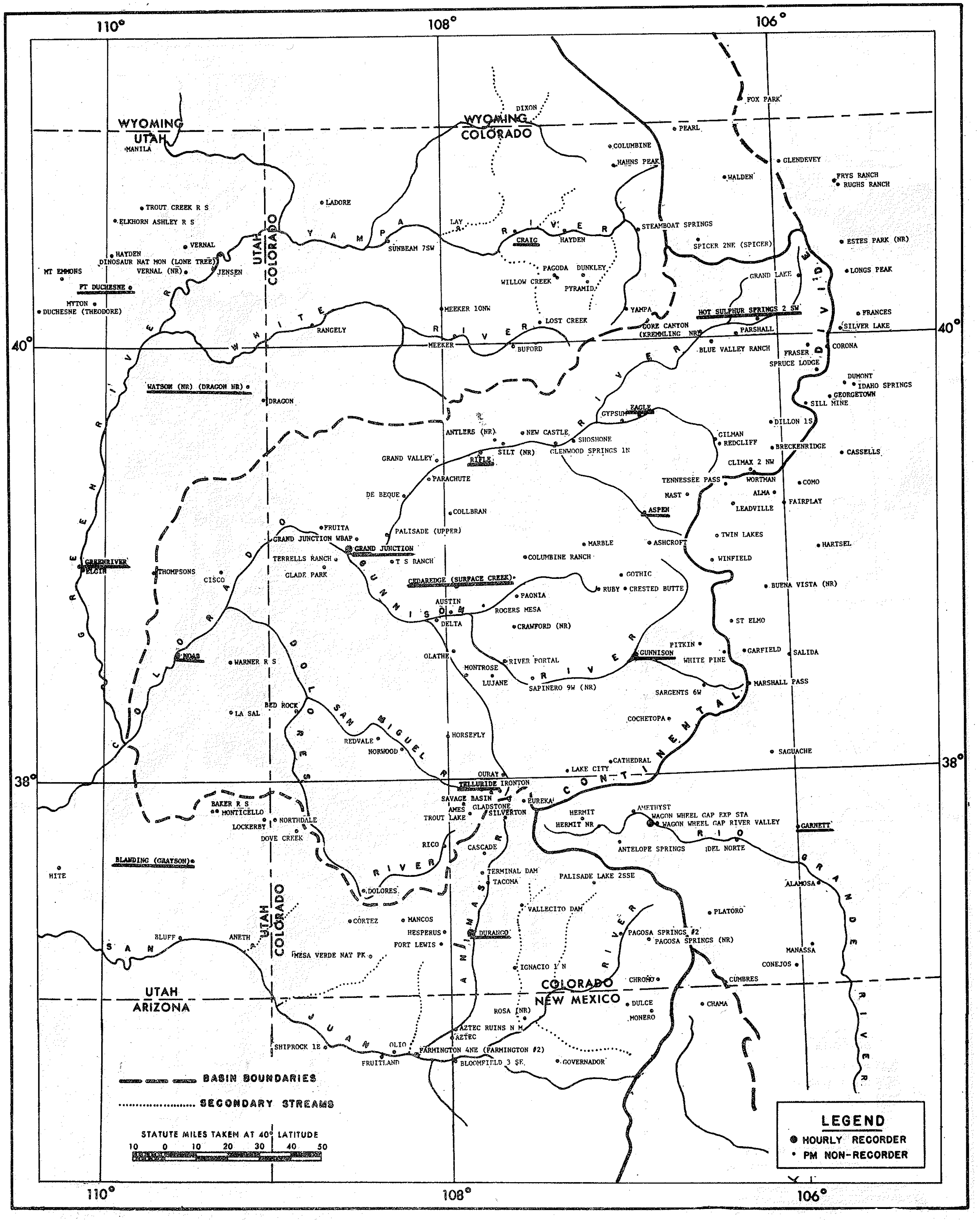


Figure 1-2. Map of precipitation stations in the study area for the period 1899 to 1932. (Key stations for selection of qualifying storms are underlined.)

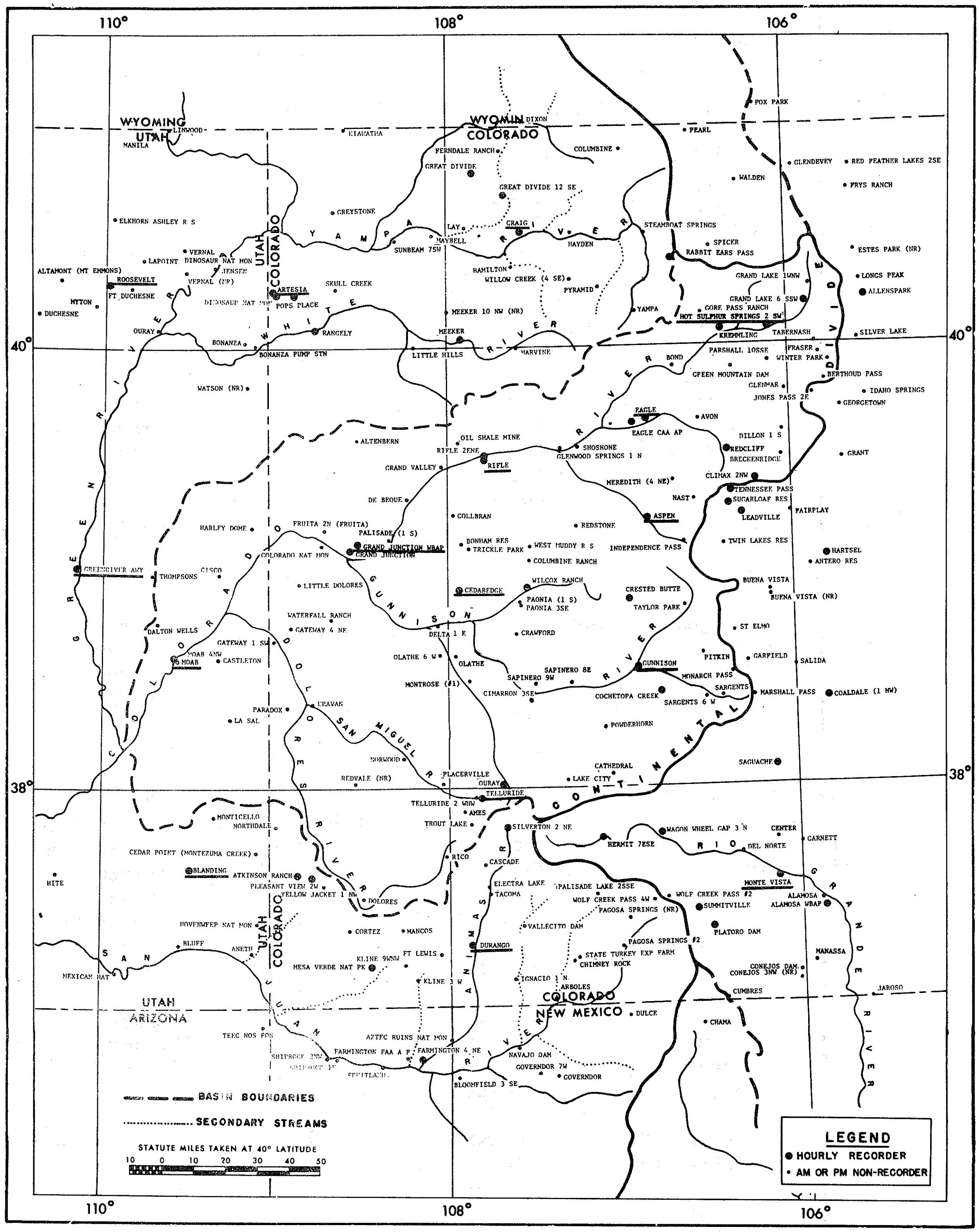


Figure 1-3. Map of precipitation stations in the study area for the period 1933 to 1966. (Key stations for selection of qualifying storms are underlined.)

CHAPTER 2. BASIC STORM TYPES

A. Development and Description

2.1 Development of types

2.1.1 Basis for use of 500-mb map. Upper-air charts are usually more relevant than sea-level charts in explaining the sequence of development of large storms over the study area. Lows on upper-air charts show more consistency of motion and more closely represent the free-air flow above high or sheltered terrain. But more important, storms with high precipitation potential for the study area require large amounts of moisture and horizontal convergence through a deep layer of the atmosphere. A Low or trough at the 500-mb level usually is indicative of the latter. The presence of large amounts of moisture depends on season and on track and speed of the approaching upper Low. When such Lows are cut off from the normal westerly flow, slow movement lengthens precipitation duration by sustaining high moisture inflow around the southeastern or eastern periphery of the Low. Storms of lesser magnitude than those studied here usually have less marked cyclonic patterns aloft or less favorable upper Low tracks and moisture inflow.

2.1.2 Typing of 500-mb circulation patterns. Ten storms exceeding the intensity threshold of an average of 0.5 inch per day (par. 1.3.3) and 12 storms exceeding 0.4 inch per day, all in the period of available 500-mb data (1943-1967), were used to establish the basic storm types presented in paragraph 2.2.2.

2.1.3 Storms above the threshold value for years prior to 500-mb data were typed under these same basic types. This typing first required sketching an estimated 500-mb height pattern on daily surface maps. Use of the surface to 500-mb relations observed in the later storms provided a valuable aid in estimating 500-mb patterns in earlier storms, as did also past experience in building analyses up to 500 mb lower level charts over the Pacific Ocean where upper data are sparse. A simplifying factor is that movements of upper troughs and Lows are mirrored in changes in the sea-level map. Whether as a wave developing along a front in a flat sea-level pressure field or as an area of falling sea-level pressure in advance of the upper Low or trough, the upper control on the sea-level map is usually sufficiently evident to permit a fair estimation of daily positions of 500-mb troughs and Lows and to detect formation of new Lows.

2.1.4 Upper-air patterns estimated from sea-level maps, however, lack detail. For example, it is sometimes doubtful at what point in the deepening of the trough at lower latitudes, a Low has formed in the trough and at what point it later fades out. Also, there may be doubt as to whether or not an upper Low has been completely cut off.

Here the strength of the sea-level High to north of the sea-level Low, the latitudinal temperature gradient and the speed and direction of the sea-level Low provide some clues. Relations between sea-level patterns and upper-air circulations are most definite in major storms. Thus the positioning of the 500-mb Low centers or troughs is relatively simpler in the storms which qualified for this study than for minor storms or even those of average intensity.

2.2 Storm classification by 500-mb circulation patterns

2.2.1 The latitude from which a 500-mb Low or trough moves toward the study area relative to the latitude of the study area is used as the primary typing index. Another index is whether the Low is "cut-off", i.e., it is no longer a part of the zonal westerlies and lies to the south of this current.

2.2.2 The basic storm types listed in table 2-1 classify general storms important to eastern Utah and western Colorado. The terms Low(L) and trough(T) refer to the observed or estimated 500-mb pattern. The letters H, M and L refer to High Latitude, Middle Latitude and Low Latitude, respectively, and indicate the direction of approach relative to the study area. The letter B (for Breakthrough) is used with H to indicate southeastward movement of a Trough or Low rather than formation of a Low to the southeast of an earlier position. Schematics of average tracks of Lows are shown in figures 2-1 and 2-2 and of average positions of troughs in figure 2-3. Explanation of the types is given in the next section.

Table 2-1. List of storm types

High Latitude Breakthrough Trough or Low (HBT or HBL)
High Latitude Breakthrough--Cut-off Low (HBT-C) or (HBL-C)
High Latitude--Cut-off Low (HL-C)
Cut-off Low (C)
Middle Latitude Trough (MT) or Middle Latitude Low (ML)
Low Latitude Trough (LT)
Tropical storm from off Baja California (Tropical)
Gulf of Mexico Inflow (Gulf Air)

2.3 Description of storm types

2.3.1 High Latitude Breakthrough Trough or Low (HBT or HBL) A lowering of the 500-mb height field near the British Columbia Coast allows a Low or trough to move southeastward toward the study area (fig. 2-1a). A strong ridge further offshore blocks approach from lower latitudes. Further deepening or accentuation usually occurs over the Great Basin. The term Breakthrough Trough (BT) is used in place of Breakthrough Low when at 500 mb a Low center is not well defined in the trough, or is of short duration, or is so far north that it is unimportant to the study area relative to the trough (fig. 2-3a). In the HBL storm the typical Low (fig. 2-1a) moves

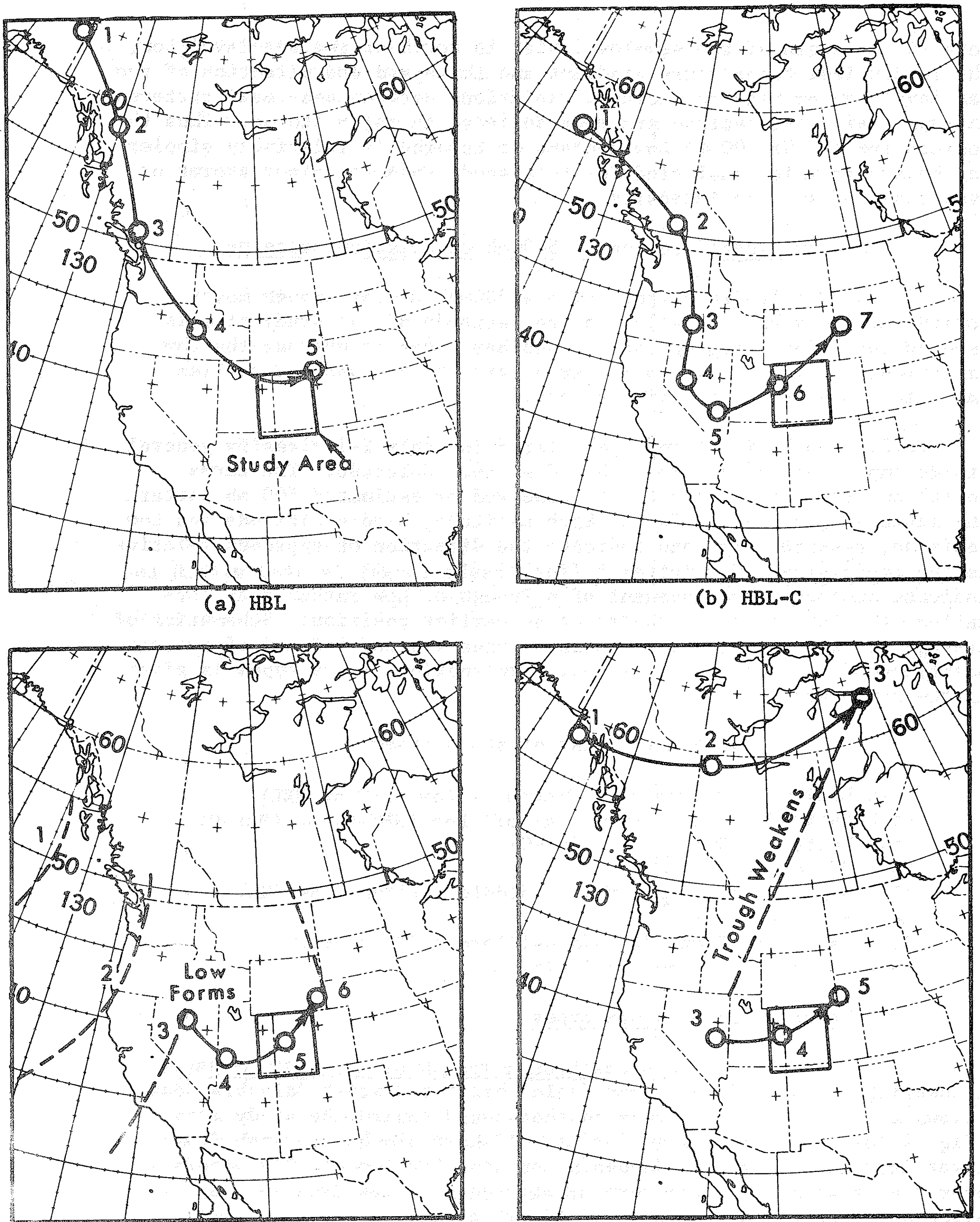


Figure 2-1. Average daily positions of 500-mb Low centers and troughs (---) by storms typed HBL, HBL-C, HBT-C, and HL-C. (Storm types are defined in section 2-3.)

southeastward from the interior of Alaska through British Columbia and Washington before accelerating and turning eastward across northern Utah. The typical HBT trough approaches the coast rapidly from far offshore to the northwest (fig. 2-3a), but on approaching the Great Basin it slows down and elongates southward; in so doing it allows moisture to move northeastward from a low latitude.

2.3.2 High Latitude Breakthrough-- Cut-off Low (HBT-C or HBL-C). This pattern is similar to the HB types (par. 2.3.1) before reaching the Great Basin. In this region there is a slowing down of the 500-mb Low or trough and a cutting off of a 500-mb Low from the westerlies. Typically the Low in the HBL-C storm moves southeastward from the Gulf of Alaska into southern British Columbia, then southward through Washington and Oregon into Nevada (fig. 2-1b) where it slows down as it is cut off. The Cut-off Low then turns northeastward and accelerates. There is more curvature in the track than in that of the HBL Low (fig. 2-1a).

2.3.3 A radical slowdown of the elongated north-south HBT-C trough, moving southeastward from the Gulf of Alaska, occurs in the Great Basin (fig. 2-1c) as an upper Low forms and is cut off over southern Nevada two days before crossing the study area. This Cut-off Low moves eastward into southern Utah, then northeastward across Colorado.

2.3.4 High Latitude--Cut-off Low (HL-C). In this type, a new 500-mb Low forms in Nevada in connection with an elongated trough extending southward from the main upper Low center, which has moved eastward across northern Canada (fig. 2-1d). The upper trough joining the two centers at time of formation of the new center in the southern portion is weak and soon fills, completing the cut-off process. Moving slowly into Utah the next day, this new Low then accelerates as it crosses northwestern Colorado. The difference in location of the trough on the date of formation of the Cut-off Low from that of the HBT-C type is noted by comparing figures 2-1c and 2-1d.

2.3.5 Cut-off Low (C). An upper Low which is no longer a part of the zonal westerlies to the north is referred to in paragraph 2.2.1 as a Cut-off Low. There is typically a sea-level High or ridge to the north of the 500-mb Cut-off Low. The motion of this Low is usually slower than that of a Breakthrough Low. The C type and the HC-C or HL-C type differ primarily as to when or where cut-off takes place. In the Cut-off Low type, the upper Low has become cut off so long before the main precipitation period in the study area begins and/or so far away from this region that the manner of formation of the Low is unimportant to development of the rain sequence. Hence the prefix is dropped from the title and this preliminary phase is not described. Often the upper Low is only faintly reflected at sea-level.

2.3.6 Cut-off Lows are classified into three groups delineating the general region of formation or stagnation; the C-West Low moves counterclockwise southeastward from off the northern California coast (fig. 2-2a), the C-Southwest Low moves clockwise northeastward from near or southwest of the southern California coast (fig. 2-2b), and the C-Great Basin Low moves eastward from near western Nevada (fig. 2-2c). The three tracks tend to merge over Utah. The motion of these three tracks can be characterized as follows: the C-West Low accelerates rapidly, the C-Southwest Low accelerates as it approaches the Coast, then slows down on moving inland, and the C-Great Basin Low accelerates slowly.

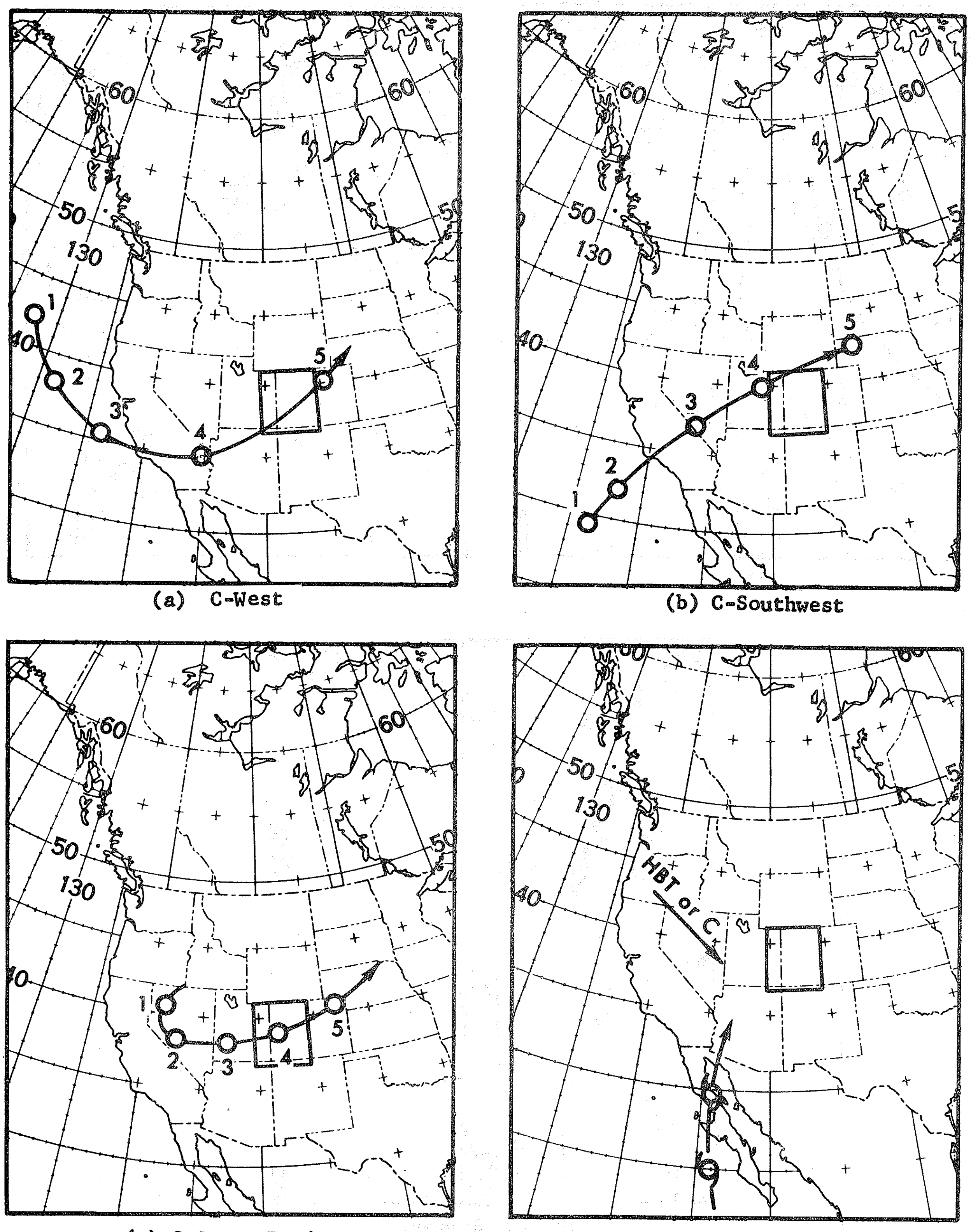
2.3.7 Mid-Latitude Trough (MT) or Mid-Latitude Low (ML). Qualifying storms of the M-type are rare. Approach of the trough or Low is from west or west-northwest. The one qualifying storm (an MT type) was slowed by a following HBT sequence. No average positions are shown.

2.3.8 Low-Latitude Trough (LT). In the cool season, upper troughs cross the eastern North Pacific Ocean from northwest to a low latitude, then move toward the study area from the southwest (fig. 2-3b). The associated sea-level waves or small Lows may be as important a feature of the storm as the broad flat trough at high levels. A typical orientation of the trough is north-northeast--south-southwest.

2.3.9 The summer and fall LT storm originates as a sharp upper trough, stationary off the California coast, which fades out at sea level, like a C-type Low. Average positions are shown on figure 2-3c. The trough is roughly parallel to the coast offshore, but it rotates clockwise as it moves inland slowly.

2.3.10 Tropical storms. The passage in September or October of a tropical storm, whose track from off Baja California is evident on surface maps as far north as southern Arizona, may be accompanied by widespread precipitation over the far Southwest. A Cut-off Low or HB type circulation usually moves into the Great Basin to help carry both the moisture and the rapidly diminishing tropical circulation northeastward toward the study area (fig. 2-2d). This sequence, descriptive of the three qualifying storms in table 2-2 in which the tropical storm was judged to play the primary role, is also somewhat descriptive of those storms in which the role of a tropical circulation appeared to be less important than that of the upper-air circulation over the Great Basin.

2.3.11 Inflow of Gulf of Mexico air. A southerly inflow during the warm half of the year may bring moist air into the study area from the Gulf of Mexico. This intrusion of Gulf of Mexico moisture was the predominating feature in three late August or early September storms (table 2-2). It was judged to be of secondary importance in most qualifying spring storms to an upper Low or trough to the west of the study area. Precipitation amounts may be rather spotty and greatly influenced by release of instability. Though inflow of Gulf air is frequent in mid-summer, precipitation is usually too scattered for the storm to qualify because of the absence of significant upper-level Lows to process the moisture.



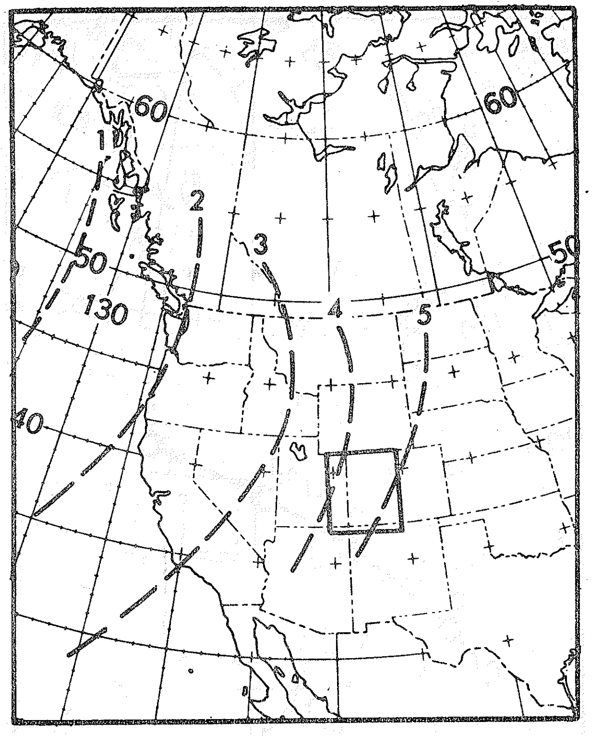
(a) C-West

(b) C-Southwest

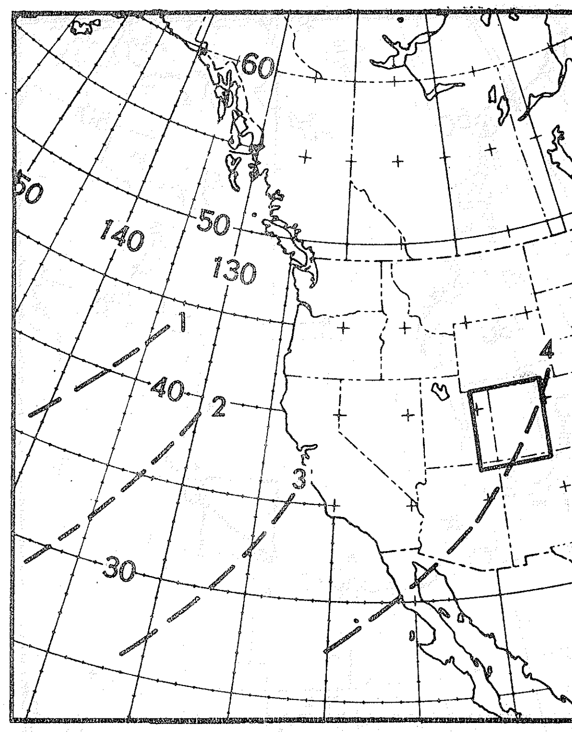
(c) C-Great Basin

(d) Tropical

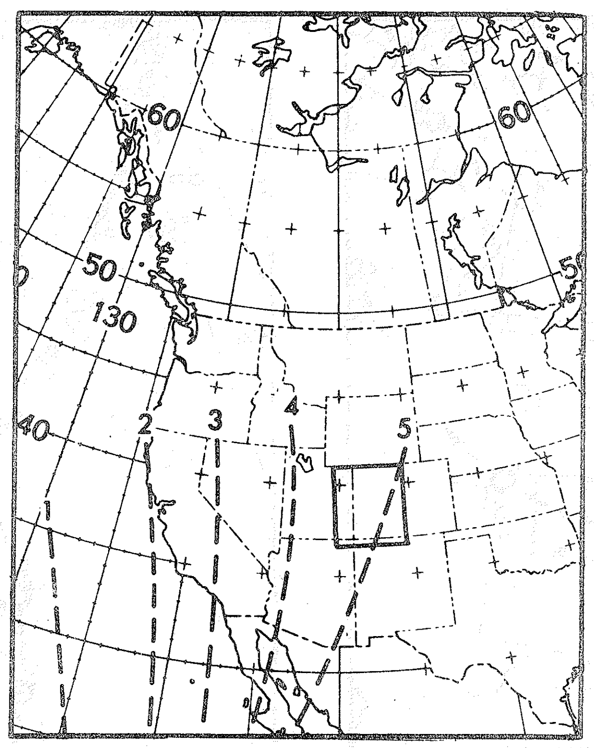
Figure 2-2. Average daily positions of C type 500-mb Low centers and of tropical storm centers (Storm types are defined in section 2-3.)



(a) HBT



(b) LT (Winter)



(c) LT (Summer)

Figure 2-3. Average daily positions of troughs in HBT and LT type storms. (Storm types are defined in section 2-3.)

2.3.12 Storms listed by type. Table 2-2 lists by storm type the dates of the 42 qualifying storms in the period 1899-1966. Also included in the table and indicated by an asterisk are the storms, used to help establish the types, which approach but do not meet the qualifying threshold of 0.5 inch average precipitation for one day.

2.3.13 Repetition or transformation of storm types. In several storms listed in table 2-2, a parenthesis encloses a second type designation, e.g., HBT (HBT) September 14-15, 1906. In this storm a second HBT sequence overtook the first one and dominated precipitation. Another example is the July 10-12, 1936 storm, typed LT (HBT), in which and HBT sequence followed the LT sequence. A transformation in type occurred in some initial HBT sequences by the development of a Cut-off Low over the Great Basin in the HBT trough. Likewise, the HBL Low may become cut off there. These storms are listed as HBT-C and HBL-C, respectively (par. 2.3.2).

2.3.14 Combination of storm types. Most storms designated Tropical or Gulf Air in table 2-2 also involved either an HBT or C type sequence which indicates the upper air pattern to the west of the study area prior to and during the period of precipitation. While this pattern plays a role in drawing moisture northward in these storms, the important feature was judged to be the influx of the tropical or Gulf moisture across the study area. In other storms of table 2-2, tropical or Gulf moisture was judged to have been a secondary feature and is not included in the type designation. In two HBL storms and one HBT storm, both titles are shown in table 2-2 (e.g., HBT-Tropical, September 12-13, 1927), since neither title alone adequately describes the storm. The presence of Gulf of Mexico air in storms is indicated in column 9 of table 2-5. Moisture from a tropical storm is designated by the word "Baja", indicating the approximate source region.

B. Factors Affecting Storm Types

2.4 Latitudinal controls on types

2.4.1 Controls on precipitation amount. Along the Pacific Coast, the effectiveness of approaching storms depends on meridional transport of air. The effectiveness of storms originating at a high latitude (the HB type of this report) increases at lower latitudes. For example, a cold outbreak southeastward from the Gulf of Alaska facilitates strong temperature gradients (and hence deepening) off the California coast at latitudes where highest moisture can be drawn into the storm. A steep temperature lapse rate and instability are also assured by the warmer ocean surface. Conversely, an unusually strong transport of heat and moisture northeastward in a Low Latitude type storm facilitates high temperature contrasts (but less instability) on the Washington or British Columbia Coast where peripheral low temperatures are normally present to produce deepening.

Table 2-2. Storm dates by type

HBT

HBT(HBT)Sept. 14-15, 1906
HBT Oct. 3-4, 1914
HBT May 20, 1916
HBT-Trop. Sept. 12-13, 1927
HBT Jan. 29-31, 1951*
HBT Sept. 21-24, 1961*

HBL

HBL-Trop. Sept. 20-21, 1902
HBL-Gulf April 14-15, 1921
HBL Oct. 31, 1928
HBL June 1-2, 1943
HBL June 11-12, 1947*
HBL April 6-7, 1957*
HBL June 15-16, 1957*

HBT-C

HBT-C Sept. 25, 1915
HBT-C Oct. 7-8, 1924
HBT-C May 26-28, 1926
HBT-C June 21, 1947
HBT-C Sept. 2-3, 1961*
HBT-C Aug. 31-Sept. 2, 1966*

HBL-C

HBL-C Nov. 26-28, 1919
HBL-C Sept. 22-23, 1941
HBL-C Oct. 8-9, 1961
HBL-C Sept. 17-20, 1965

HL-C

HL-C Oct. 16-19, 1908
HL-C Dec. 15-17, 1908
HL-C Oct. 30-31, 1920
HL-C Oct. 12-14, 1941

C

C(C) Oct. 12-15, 1899
C(HBL) Nov. 26-27, 1905
C April 6-7, 1906
C Oct. 14-17, 1910
C May 8, 1927
C Oct. 28-29, 1927
C Oct. 13-14, 1947
C(HBT) Dec. 22-23, 1948
C Oct. 23-24, 1953
C Oct. 11-13, 1957
C Oct. 19-20, 1963

MT or ML

MT(HBT) June 27-28, 1927
ML April 27-28, 1944*
MT Nov. 23-24, 1946*
MT Dec. 5, 1951*

LT

LT(HBT) July 10-12, 1936
LT(MT) Oct. 15, 1937
LT Feb. 7, 1937
LT(HBT) Dec. 29-31, 1951
LT Nov. 23, 1965*
LT(HBT) Nov. 25-26, 1965*

TROPICAL

Trop. (HBT-C) Oct. 4-5, 1911
Trop. (C) Oct. 4-6, 1925
Trop. (HBT) Sept. 6-7, 1939
Trop. Aug. 26-28, 1951*

GULF AIR

Gulf (C) Sept. 4-6, 1909
Gulf Aug. 27-28, 1932
Gulf Sept. 2-3, 1938

* Storms approach qualifying threshold

2.4.2 The extreme combination of storm parameters (high moisture and strong temperature gradients), produce the most intense storms at high and low latitudes. They operate in a more limited sense at intermediate latitudes. They operate inland from the Pacific Coast as much as terrain barriers will permit. It follows that Mid-Latitude type Lows, approaching the study area from the west, cause less intense and briefer precipitation over the study area than either (1) Low Latitude Lows approaching from southwest or (2) High Latitude Lows approaching from northwest, then turning east through Nevada or Utah, at a slow enough speed that will permit ingress of high moisture content from the southwest.

2.4.3 Role of meridional circulation. An important feature of upper Low movement toward low latitudes (and/or development there) is the breakdown of the normal zonal flow. There follows meridional transport of cold air through depth toward low latitudes and warm air to high latitudes to bring about the effects cited in par. 2.4.1. The HB type sequence is usually part of such a breakdown. While such transport is commonly observed in winter at low levels as a strong cold High, there is less extreme meridional exchange at upper levels, where the cold sea-level High is reflected as a flat ridge. Meridional exchanges are more evident on upper level charts in fall and spring than in winter.

2.4.4 Latitude and the time element. Qualifying storms usually last more than one day. They usually involve upper Lows or major troughs aloft that move slowly compared to short-wave troughs in a westerly flow whose effect on precipitation is briefer. A feature of the upper cut-off HB type Low is slow movement and prolonged precipitation, which begins with the Low far to the west of the study area. MT type storms are more dependent on the low-level circulation in the cool season. Their more rapid movement then tends to limit storm duration to less than one day and to the vicinity of the trough, a factor in the small number that qualify.

2.5 Modification for barriers

2.5.1 The generalizations of paragraph 2.4.1 applicable to the West Coast (moist inflow from lower latitudes meeting cold outbreaks from a higher latitude) are modified for the study area by the effect of upwind barriers. Much of the moisture reaching Colorado in a flow from west or west-southwest is removed as it crosses the Cascade, Sierra and Wasatch Ranges. But there is much less moisture depletion upwind in a flow over the southern and western portions of the study area from southwest and south-southwest. The San Juan mountains catch a good portion of the moisture in a southerly flow and shield the northeastern portion of the study area. Hence, most storms with large 1- and 2-day amounts over the entire study area have a moisture inflow from southwest to south-southwest. Upper Lows that develop, stagnate or intensify in the general vicinity of the Great Basin provide opportunity for moisture to be drawn over the study area from these directions with the least barrier depletion.

2.5.2 Evidence in storm dates. No major California storm in the period 1899-1966 produced a qualifying storm in the study area. (The ML December 23-24, 1964 major northern California-southern Oregon storm caused an average of 0.35 inch in slightly more than 24 hours over the study area. The lengthy but minor northern California storm of December 26-30, 1951 [9] later qualified as a LT(HBT) storm in the study area on the 29th to 31st.) This paucity of mutual storm dates between California and the study area arises both from the zonal movement required in storms that cross both areas (typically the Mid-Latitude type storm) and from the greater depletion of moisture before reaching the study area of storms with a westerly moisture inflow.

2.6 Seasonal variation of types

2.6.1 Table 2-3 shows the seasonal distribution by type of the 42 storms studied. Fall storms of the H and C types predominate.

Table 2-3. Seasonal frequency variation of storms in the study area by storm type.

	H	C	M	L	Tropical	Gulf	Totals
Fall(Sept-Nov)	14	8	0	1	3	2	28
Winter(Dec-Feb)	1	1	0	2	0	0	4
Spring(Apr-June)	5	2	1	0	0	0	8
Summer(July-Aug)	0	0	0	1	0	1	2

2.6.2 A brief explanation is given below for the seasonal distribution shown in table 2-3.

1. High Latitude type (H-type) storms occur mainly in fall when cold outbreaks can most often and most easily combine with high moisture from low latitudes to the southwest. They occur occasionally in spring when deepening in the general area of the Plateau is typical and when the Gulf of Mexico is the primary source of moisture.

2. Cut-off Low storms (usually a sequel to an H-type sequence) favor fall months for the same reason.

3. The tropical storm season is September-October. Storms primarily due to inflow of Gulf air occur in late summer or early fall.

2.7 Storm frequency distribution

2.7.1 By decades. Long-term variations appear in storm frequency. Long periods with no qualifying storms were found, as well as years with an abnormally large number of storms. For example, there were 10 qualifying storms in the decade 1920-1929 compared to only three in the decade 1950-1959. Of the ten, four occurred in the four months, May, June, September and October 1927. The distribution of qualifying storms with time is given in table 2-4.

Table 2-4. Distribution of qualifying storms

Period	Number of storms
1899-1909	8
1910-1919	6
1920-1929	10
1930-1939	6
1940-1949	6
1950-1959	3
1960-1966	3

2.7.2 By months. The monthly frequency distribution of qualifying storms, shown in the block diagram of figure 2-4, has a pronounced peak in October, seventeen of the 42 storms. The number of storms in each month drops sharply toward the cold season. For comparison, the frequency of daily precipitation over 0.49 inch at Grand Junction (1931-1960) peaks in August, as does mean monthly precipitation at Grand Junction (80 years) and Durango (68 years). These August peaks are due to frequent local thunderstorms.

2.7.3 Frequency versus magnitude. There is a high frequency of qualifying storms in September and early October in the study area (fig. 2-4). Moisture from a preceding tropical storm enabled eight of these storms to qualify (col. 9, table 2-5). The October 5, 1911 tropical storm was the most intense of the 42 storms, based on 1- and 2-day amounts (cols. 2 and 3, table 2-5). But early winter predominates in the dates of the three next most intense storms, one in late November and two in December. This suggests that, next to the tropical storm, the most effective combination of storm mechanism and moisture comes in early winter as the former increases in effectiveness and moisture decreases. Yet qualifying storms are infrequent in these two months.

2.8 Control of storm types on precipitation magnitude

2.8.1 The tropical storm has the highest moisture potential. A High Latitude Breakthrough Low or Trough is an efficient sequence to help carry this moisture to the study area and process it there. The tropical storm of October 4-5, 1911, the most intense 1-day storm over the study area and the one with record 1-day point precipitation in the study area (8.05 inches at Gladstone, Colo.) involved an HBT sequence which served to process the tropical moisture after it moved into the Southwestern States (fig. 4-8a). These data suggest that some form

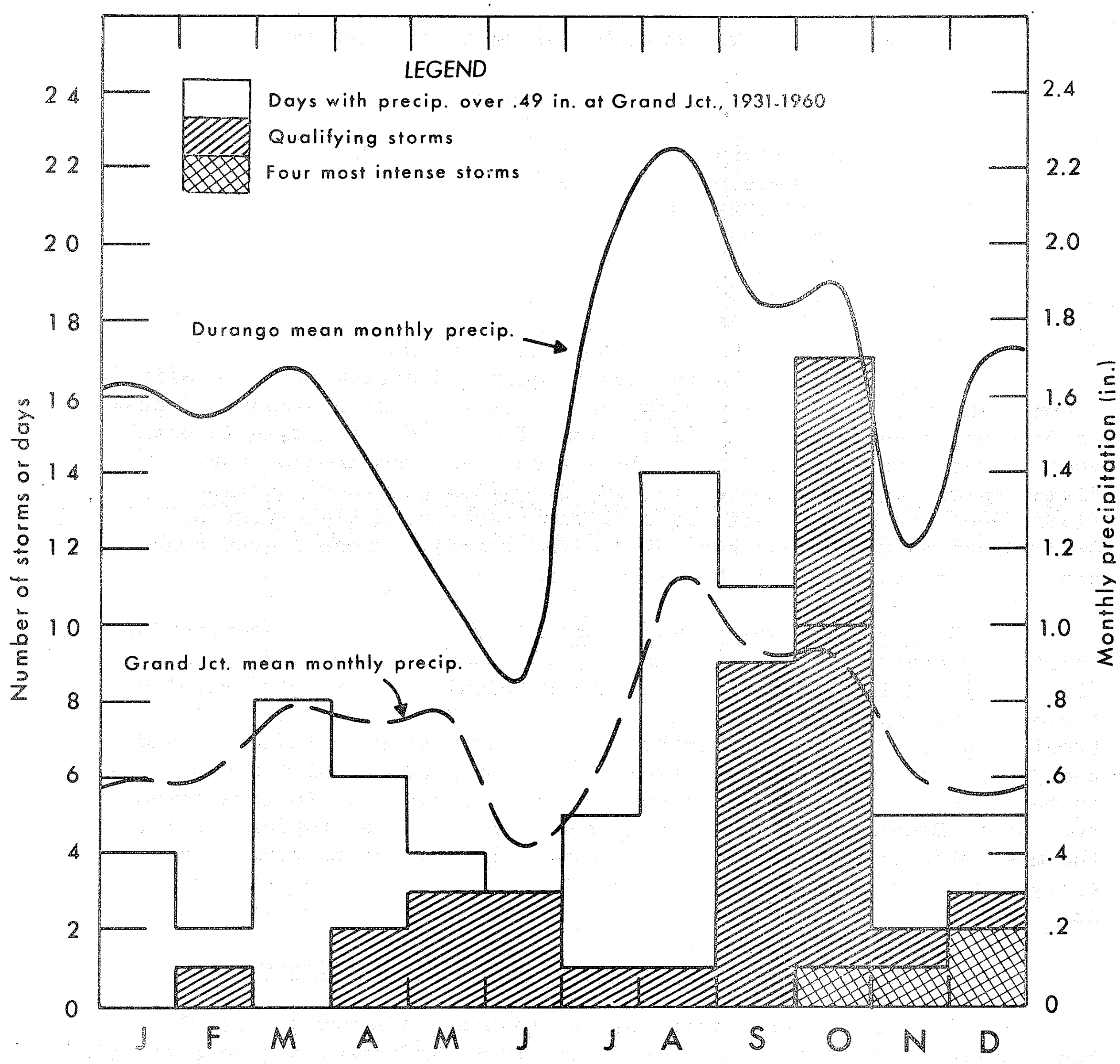


Figure 2-4. Monthly frequency variation of the four most intense storms, the 42 qualifying storms, days with over 0.49 inch at Grand Junction (block diagrams) and mean monthly precipitation at Grand Junction and Durango.

of a High Latitude type storm combined with tropical storm moisture represents the cause of the highest amounts of precipitation that could fall over a large portion of the study area for durations up to one day.

2.9 Tabulation of storm data by date

2.9.1 Table 2-5 presents in a condensed form much of the data on the qualifying storms on which the discussion in later chapters depends. The table is placed at the end of this chapter for convenient reference.

Table 2-5. Storm data.

Storm Dates (Heaviest date underlined)	Storm Type (1)	Ave. Precip. 1-day (in.) (2)	Ave. Precip. 2-day (in.) (3)	Moisture Index (%) (4)	Snow Level (1000 ft) (5)	Temp. Index (1000 ft) (6)	Orographic Index North (7)	Orographic Index South (8)	Moisture Source (9)	500-mb Wind Direction (10)
Oct 11,12,13,14,15, 1899	C(C)	.5	.9	50	9	2.7	0.2	1.5	SW	SW
Sep 20,21, 1902	HBL-Trop	.5	.9	71	10	3.4	1.6	2.0	Baja	SSW
Nov 26,27, 1905	C(HBL)	.6	.7	71	8	0.4	0.4	0.6	SW	SSW
Apr 6,7,1906	C	.5	.7	79	8	0.9	0.7	1.7	SW	SW
Sep 14,15,16, 1906	HBT(HBT)	.6	.9	46	9	5.7	0.7	2.3	W	SW
Oct 16,17,18,19, 1908	HL-C	.6	1.1	52	8	3.8	0.5	6.0	WSW	SSW
Dec 15,16,17, 1908	HL-C	.8	1.2	78	8	0.5	0.2	4.7	SW	SSW
Sep 4,5,6, 1909	Gulf(C)	.6	1.0	76	11	3.4	0.0	2.2	Gulf	S
Oct 14,15,16,17, 1910	C	.5	.7	65	10	1.6	0.8	1.9	SW	S
Oct 4,5, 1911	Trop(HBT-C)	1.4	1.5	78	10	2.7	1.0	1.6	Baja	SSW
Oct 3,4, 1914	HBT	.5	.8	65	12	0.7	2.9	3.3	SW	SSW
Sep 25, 1915	HBT-C	.7	.9	57	11	3.1	1.6	1.7	SW	SSE
May 20, 1916	HBT	.6	.7	57	8	4.3	.4	.2	Gulf	Variable
Nov 26,27,28, 1919	HBL-C	.8	1.4	62	8	0.8	1.0	4.0	SW	S
Oct 30,31, 1920	HL-C	.5	.6	63	9	2.3	1.3	1.7	SSW	SSW
Apr 14,15, 1921	HBL-Gulf	.5	.7	62	9	0.4	2.3	0.7	Gulf	SE
Oct 7,8, 1924	HBT-C	.5	.9	57	10	2.3	2.0	0.5	SW	SSW
Oct 4,5,6, 1925	Trop(C)	.5	.7	81	12	0.2	0.3	2.9	Baja	SSW
May 26,27,28, 1926	HBT-C	.5	.7	59	10	2.6	0.2	1.1	Gulf	SW
May 8, 1927	C	.5	.6	60	9	1.5	3.0	1.4	Gulf	WNW
Jun 27,28, 1927	MT(HBT)	.7	1.1	69	15	0.6	.7	1.2	Gulf	SW
Sep 12,13, 1927	HBT-Trop	.6	1.0	54	12	1.5	1.5	1.0	Baja	SSW
Oct 28,29, 1927	C	.5	.8	64	9	1.4	2.5	1.8	WSW	SW
Oct 31, 1928	HBL	.7	.8	71	8	2.2	.5	.7	SW	SSW
Aug 27,28, 1932	Gulf	.6	.9	69	14	1.0	.7	1.7	Gulf	SSW
Jul 10,11,12, 1936	LT(HBT)	.5	.7	72	14	1.5	.5	4.5	SSW	SSW
Feb 7, 1937	LT	.5	.6	77	7	1.1	3.2	1.5	SW	WSW
Oct 15, 1937	LT(MT)	.5	.6	70	11	1.2	1.9	0.4	SW	WSW
Sep 2,3, 1938	Gulf	.6	.9	70	14	0.6	1.0	0.0	Gulf	S
Sep 6,7, 1939	Trop-HBT	.5	.7	70	13	1.5	0.3	1.1	Baja	S
Sep 22,23, 1941	HBL-C	.6	.8	57	9	4.5	-0.2	2.2	Baja	SSE
Oct 12,13,14, 1941	HL-C	.6	.9	67	8	3.8	1.1	0.5	Baja	SW
Jun 1,2, 1943	HBL	.6	.7	49	12	3.6	1.3	4.2	W	WSW
Jun 21, 1947	HBT-C	.5	.7	58	12	2.8	1.9	3.0	Gulf	SW
Oct 13,14, 1947	C	.6	.8	70	10	1.9	-0.1	0.3	SSW	S
Dec 22,23, 1948	C(HBT)	.5	.6	70	7	0.5	0.7	0.5	SW	SW
Dec 29,30,31, 1951	LT(HBT)	.9	1.3	80	8	0.0	1.7	5.3	SW	WSW
Oct 23,24, 1953	C	.6	.6	63	9	2.0	0.9	2.7	SW	SSW
Oct 11,12,13, 1957	C	.7	.9	67	11	1.0	0.7	0.5	SW	Variable
Oct 8,9, 1961	HBL-C	.6	.9	61	9	4.2	0.6	1.7	SSW	S
Oct 19,20, 1963	C	.5	.7	90	11	1.0	0.5	0.2	Baja	Light
Sep 17,18,19,20, 1965	HBL-C	.5	.8	51	9	4.9	0.7	2.3	SSW	SSW

In Column (1), parentheses ( ) refer to type that follows.
In Column (9), Baja refers to Baja California and Gulf refers to Gulf of Mexico.

CHAPTER 3. STORM MOISTURE AND TEMPERATURE

A. Moisture Indices

3.1 Derivation of moisture index

3.1.1 Storm moisture. Values of highest average 12-hour storm precipitable water up to 400 mb at Grand Junction were obtained from raobs for the period 1949-1965. They were estimated from daily moisture maps at the 10,000-ft. level for storms in the period 1936-1949. For earlier storms they were estimated from surface dew points (assuming a moist adiabatic lapse rate), then adjusted (down for high dew points and up for low dew points) by the mean relation shown in figure 3-1. This figure compares precipitable water to 400 mb estimated from surface dew points by assuming a moist adiabatic lapse rate with precipitable water values to 400 mb simultaneously observed by the twice daily raob soundings at Grand Junction during the 13 largest storms since 1949. It includes the highest and second highest values of both surface dew point and precipitable water for each storm.

3.1.2 Record moisture. The basis for normalizing a representative value of 12-hour storm moisture is the maximum persisting 12-hour 1000-mb dew point of record for the storm date. Based on long-record surface dew-point data, areally and seasonally smoothed values of these dew points were read from recently updated monthly dew-point maps shown in the National Atlas of the United States [10]. Precipitable water for a column from the surface to 400 mb at Grand Junction was estimated from these maximum dew points for each month under the assumption of a moist adiabatic lapse rate. The results are presented in figure 3-2.

3.1.3 Storm moisture index. The 12-hour storm value of estimated or observed precipitable water at Grand Junction (par. 3.1.1) divided by the hypothetical maximum of record (par. 3.1.2) for the same date (fig. 3-2) gives the storm moisture index of column 4, table 2-5 as percent of maximum for that date. The distribution of these indices by 5 percent class intervals is shown in figure 3-3.

3.2 Discussion

3.2.1 Limitations on interpretation. The moisture index is a 12-hour point value which measures highest moisture near the center of the study area but not necessarily in the region of highest moisture. Variation of moisture with time and with distance from Grand Junction during a storm was not considered in the index. Usually highest moisture was south or east of the study area at the time the index was measured. Thus the moisture index serves only as a seasonally-adjusted approximation of storm moisture at a point for comparison among storms.

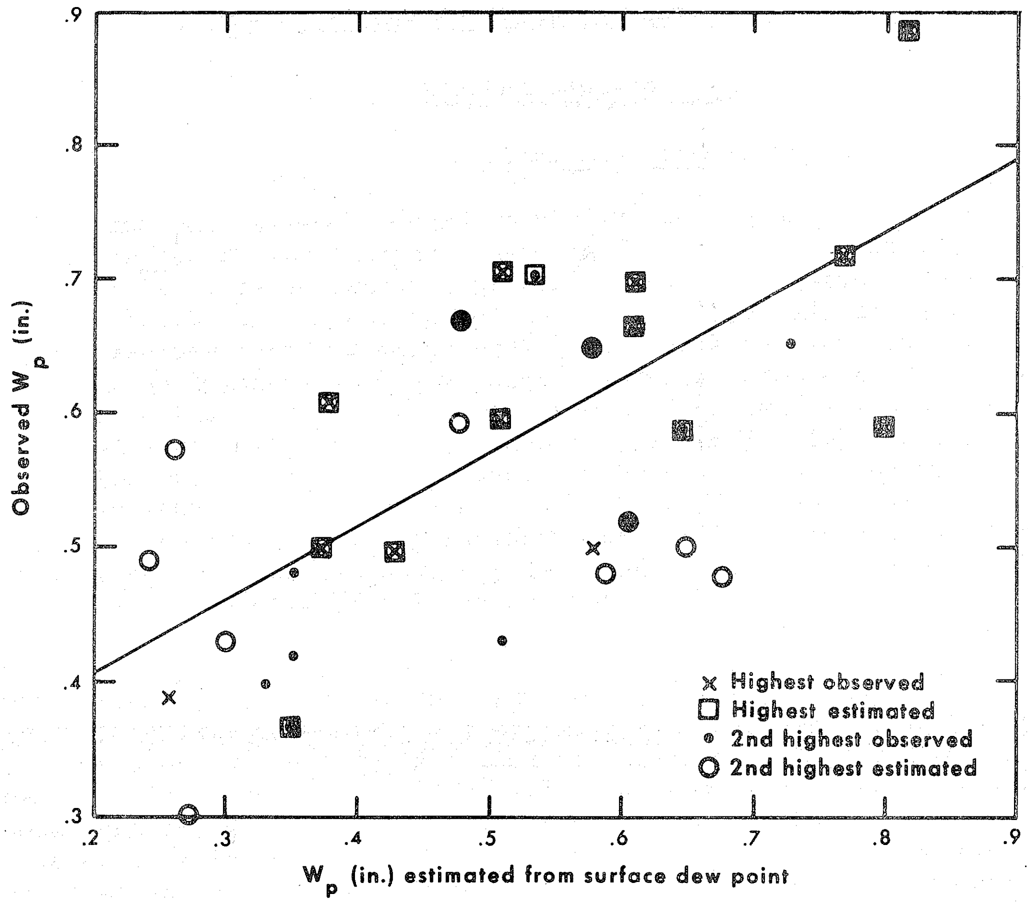


Figure 3-1. Relation between observed precipitable water, surface to 400-mb, at Grand Junction and that estimated from surface dew point, assuming a moist adiabatic lapse rate. Data are from 12 qualifying storms, 1949 to 1965.

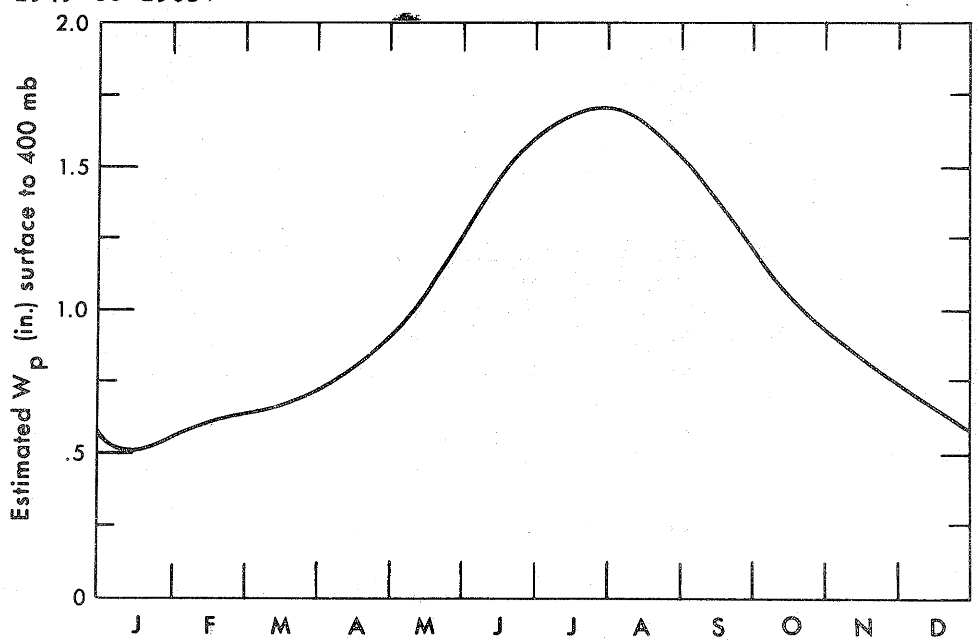


Figure 3-2. Seasonal variation of precipitable water (in.) at Grand Junction, surface to 400-mb, based on maximum persisting 12-hour 1000-mb dew points from reference 10.

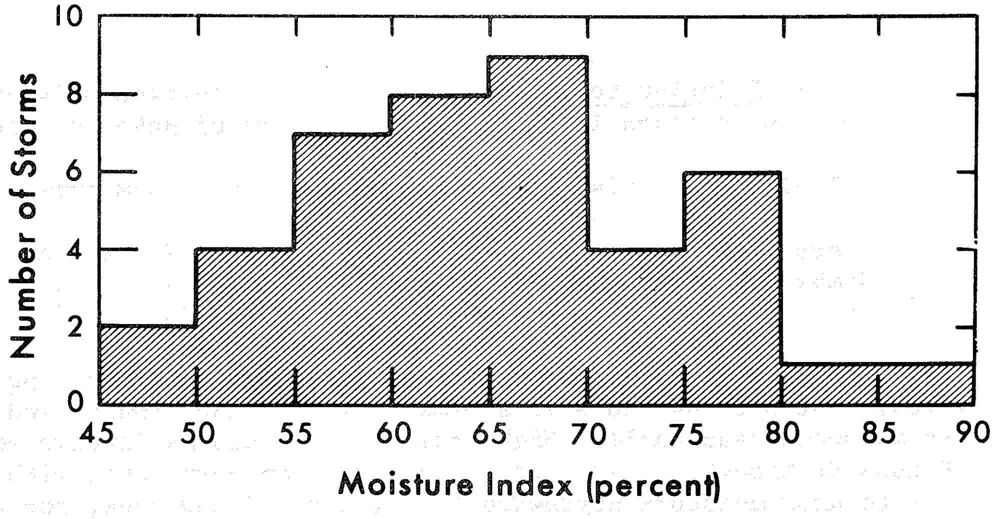


Figure 3-3. Frequency distribution of moisture indices in 42 qualifying storms.

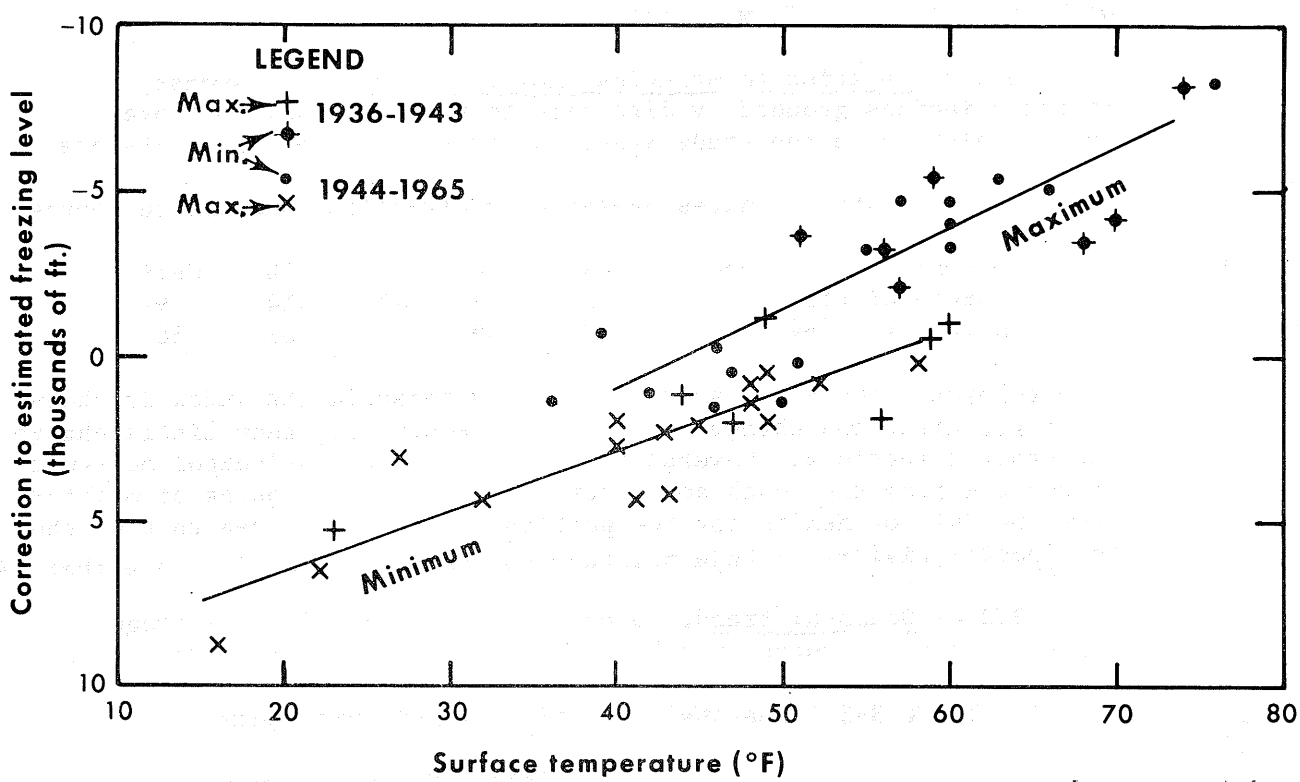


Figure 3-4. Correction to apply to storm freezing level estimated from Grand Junction maximum or minimum temperatures, assuming a moist adiabatic lapse rate. (Based on the freezing level at Grand Junction interpolated from 700-mb analysis in storms 1936-1943 and observed in storms 1944-1965. Storms used are listed in table 2-2.)

3.2.2 Relation to type. A breakdown of average moisture index by storm type is given in table 3-1, a summary of data in columns 1

Table 3-1. Moisture indices averaged by storm type

Storm type	HB,HB-C,HL-C	C	Gulf	LT	Tropical
Number of storms	20	11	3	4	3
Moisture index(%)	60	69	72	73	76

and 4 of table 2-5. The upward trend from High Latitude type storms through Cut-off Lows to Gulf storms, Low Latitude Troughs and Tropical storms seems reasonable. High Latitude type storms involve movement of Lows or troughs toward the study area from northwest, with less time to draw moisture northward than a Cut-off Low type, for example. Higher moisture in a Low Latitude type storm than in a High Latitude type results from the broad inflow from a low latitude in the former. High moisture in both the Gulf and Tropical type storms is to be expected; but the moisture track usually lies to the east of the study area, limiting the index values. Also the barrier influence varies with the moisture inflow direction.

3.2.3 Relation to principal moisture source. A summary of moisture indices grouped by direction to the principal moisture source relative to the study area, is given in table 3-2. Data are

Table 3-2. Moisture indices averaged by direction to moisture source

Direction to source	W	WSW	SW	SSW	Gulf
Number of storms	2	2	15	14	9
Moisture index	48	59	67	67	66

from columns 4 and 9 of table 2-5. An increase in the index is shown as source direction changes from west to southwest, then little change for other directions. Several of the storms whose principal moisture source was from the south-southwest had a secondary source of moisture from the Gulf of Mexico for the portion of the study area east of the Continental Divide. A Baja moisture source was classified as either SW or SSW.

3.2.4 Seasonal trend. Some seasonal variation of average moisture index is noted in table 3-3. The four winter storms had

Table 3-3. Seasonal variation of moisture index

	Fall	Winter	Spring	Summer
Number of storms	28	4	8	2
Moisture index(%)	65	76	62	70

high moisture indices because they depended on intense large-scale cyclonic patterns for transport of moisture from a source far to the southwest in the season of lowest record moisture (fig. 3-2). In spring and early summer, the most likely source of record moisture for this region is the Gulf of Mexico. The low moisture index for the six spring storms involving Gulf moisture appears to result from a more indirect track and subsequent moisture depletion in some of the storm cases than in situations providing maximum moisture.

B. Temperature Indices

3.3 Snow level as temperature index

3.3.1 The temperature index chosen in this study is the height of the Grand Junction snow level normalized for season. The snow level is taken at 1000 feet below the freezing level. The snow level (the level below which hydrometeors are assumed to fall as rain) serves a dual purpose.

(1) It is an index of upper-level storm temperature for comparison between storms, after normalization for season.

(2) It can be used to estimate the extension of spillover to the lee of a mountain crest as a result of downwind transport of snowflakes rather than raindrops. This extension is inversely proportional to the approximate 4 to 1 ratio of fall velocity of raindrops to that of snowflakes.

3.3.2 Evaluation in storms. The freezing level was obtained from the soundings at Grand Junction for the time nearest peak convergence precipitation intensity (Sec. 4.1) for storms since 1943. It was extrapolated from the 3-km or 10,000-ft. chart for the years 1936-1943.

3.3.3 For earlier storm dates, less accurate but reasonable estimates of freezing level were obtained from maximum and/or minimum temperatures by use of the two mean relations shown in figure 3-4. Data therein are differences between observed or areally interpolated freezing levels at Grand Junction and estimated values obtained by assuming a moist adiabatic lapse rate from the Grand Junction maximum temperature and minimum temperature on dates of heaviest rain in qualifying and near-qualifying storms since 1936 (table 2-2). These differences are plotted in figure 3-4 against the corresponding maximum and minimum temperatures on which they were based.

3.3.4 The relations of figure 3-4 were used to estimate freezing levels in storms prior to 1936 as follows:

(1) The minimum temperature curve was used when (a) maximum temperature was above 60°F and minimum between 40°F and 60°F, and (b) when both maximum and minimum were below 40°F.

(2) The maximum temperature curve was used when the maximum temperature was above 60°F and the minimum below 40°F or above 60°F.

(3) Both curves were used and the values averaged when the maximum and minimum temperatures were between 40°F and 60°F.

3.3.5 Normalization of snow level for season. The snow level of each storm, estimated to the nearest hundred feet as outlined above, is listed in column 5 of table 2-5 to the nearest thousand feet. A corresponding control snow level was obtained for the storm date by assuming a moist adiabatic lapse rate of temperature from a temperature representing record dew point at Grand Junction for that date (par. 3.1.3). The exceedance of the control snow level for a storm date over the snow level for the storm is the storm temperature index. This value for each storm is listed in column 6 of table 2-5 to the nearest hundred feet. A small index value indicates that the snow level over Grand Junction at the height of a storm was very high for that time of year.

3.4 Discussion of temperature index

3.4.1 The temperature index, as defined in paragraph 3.3.5 in terms of snow level normalized for season, appears to vary with storm type, moisture index, season and direction of moisture source.

3.4.2 Relation to storm type. Table 3-4 shows a trend of temperature index with storm type similar to that of moisture index with

Table 3-4. Temperature indices averaged by storm type.

Storm type	HB, HB-C, HL-C	C	Gulf	LT	Tropical
Temperature Index	2.8	1.7	1.0	1.0	1.0

type (table 3-1). The small temperature index numbers indicate high temperature for the season. Data are averaged from columns 1 and 6 of table 2-5. High snow levels (small index) are more typical of Gulf or Tropical storms and of Low Latitude type storms than of storms of the High Latitude type. In between is the average 1.7 index for the C type storm with a Cut-off Low similar in origin to the H type Low but with more opportunity for high temperature advection after movement from a high latitude.

3.4.3 Relation to moisture index. It is logical that index values of moisture and snow level show a relationship (fig. 3-5), Scatter in the data reflects inaccuracies in the method of approximation of the parameters, especially for storms prior to 1936, and variation among storms in degree of saturation.

3.4.4 Seasonal trends. Normalization of snow level described in paragraph 3.3.5 reduces but does not eliminate seasonal variation in temperature indices. The small winter average temperature index in table 3-5 implies that qualifying winter storms were warm for the

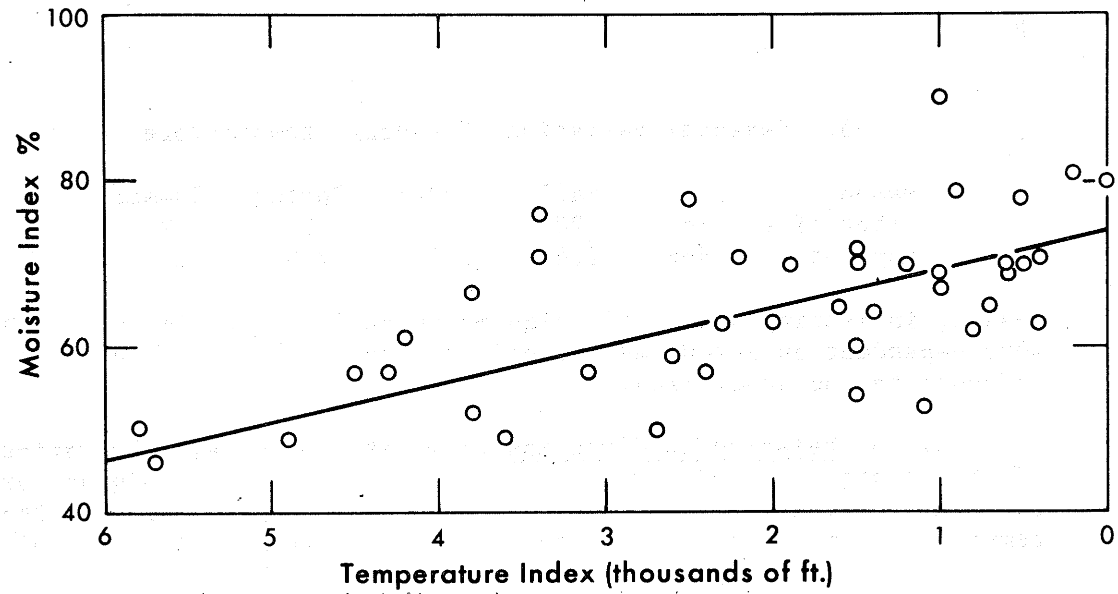


Figure 3-5. Relation of moisture index to temperature in the 42 qualifying storms. (Low temperature index is associated with high temperature and snow level.)

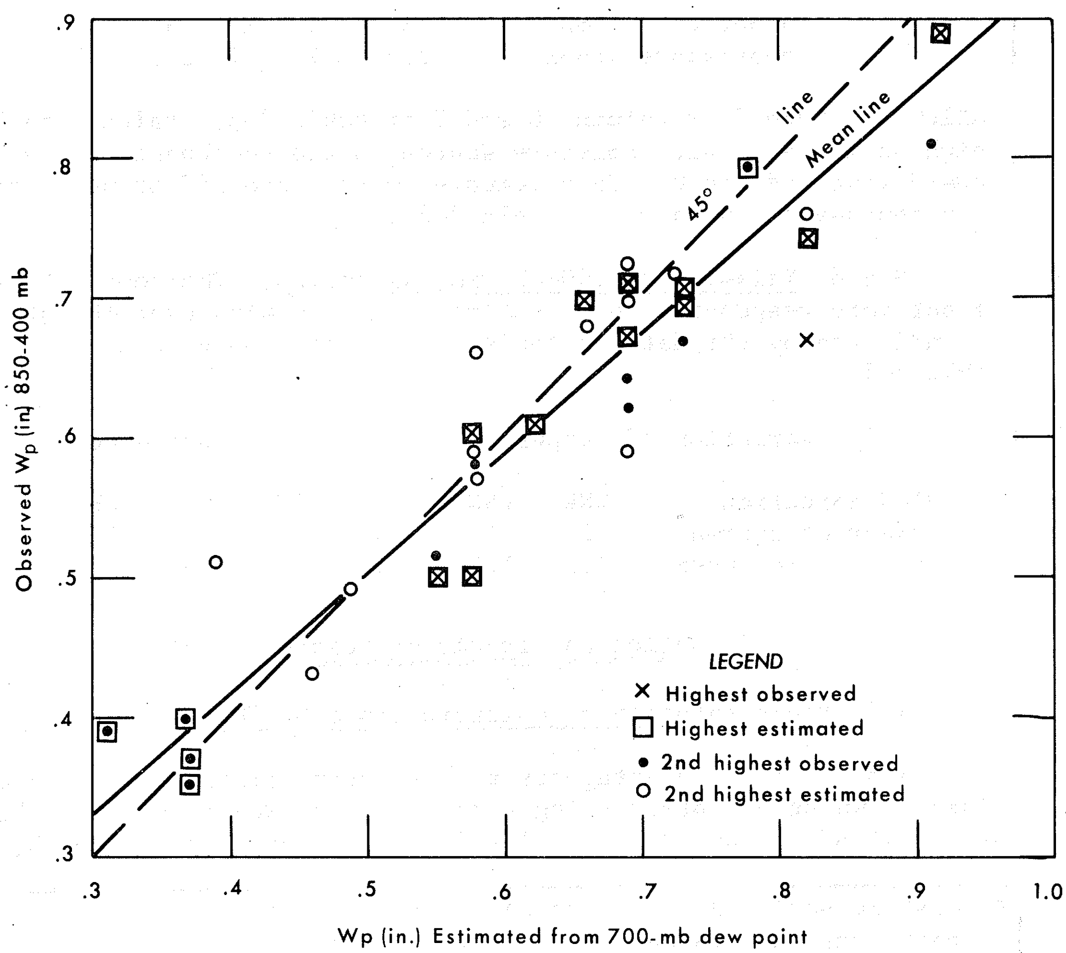


Figure 3-6. Relation between observed 850- to 400-mb precipitable water at Grand Junction and that estimated from 700-mb dew point assuming a moist adiabatic lapse rate. Data are from qualifying and near-qualifying storms 1949 to 1965.

Table 3-5. Seasonal variation of average temperature index.

Season	Fall	Winter	Spring	Summer
Number of storms	28	4	8	2
Temperature index	2.4	0.5	2.3	2.5

season, in keeping with their high moisture index (table 3-3). They were dependent on strong meridional transport from a low latitude offshore to the study area.

3.4.5 Relation to direction of moisture source. The variation of the temperature index with the direction from which moisture arrives over the study area is similar to that of the moisture index. Storm temperature index is shown in table 3-6, averaged by direction of

Table 3-6. Variation of temperature index with direction to moisture source.

Moisture source	W	WSW	SW	SSW	Gulf
Number of storms	2	2	15	14	9
Temperature index	4.6	2.6	1.2	2.4	2.1

inflow moisture from columns 6 and 9 of table 2-5. Values are low (high snow level) with moisture source to the southwest. They increase toward west and south. This compares with a dropoff of moisture index from southwest toward west (table 3-2).

3.4.6 Relation to 500-mb wind direction. The temperature index is not very responsive to direction of 500-mb wind over the study area, as indicated by the data in table 3-7, taken from columns 6 and 10 of table 2-5.

Table 3-7. Variation of temperature index with upper wind direction.

Wind direction	WNW	WSW	SW	SSW	S	SSE	SE
Number of storms	1	4	9	15	7	2	1
Temperature index	1.5	1.5	2.3	1.9	2.0	3.8	0.4

C. Formation and Tracks of Moisture Pools*

3.5 Representation of moisture pools by 700-mb moisture

3.5.1 It is advantageous to represent moisture pools by moisture lines drawn on an intersecting surface. The 700-mb level is the most useful standard raob data level to represent moisture in depth, since

* Moisture pool: a term used to identify large moisture amounts in depth over an area as an entity which can be represented by a pattern of isolines on a map.

the 850-mb level is below most of the terrain in the study area and the 500-mb level is above most of the moisture. (The 700-mb map approximates the 3-km and 10,000-ft. height charts drawn prior to 1945).

3.5.2 Justification. Justification for use of the 700-mb level moisture as an index of precipitable water above a fixed elevation was found in a comparison of data at Grand Junction. The parameters compared were: (1) observed precipitable water (W_p) from 850 to 400 mb and (2) the W_p estimated from the 700-mb dew point by assuming a moist adiabatic lapse rate for the layer. The comparison, made on qualifying and near-qualifying storms in the study area from 1949 to 1965, is shown in figure 3-6 for highest and second highest values of both parameters. A mean line indicates that the precipitable water amounts based on 700-mb dew points are on the average reliable estimates of moisture in the column during storms.

3.5.3 Justification on an areal basis was found by comparing, in five recent qualifying storms, daily areal patterns of W_p estimated from 700-mb dew point (par. 3.5.2) with those of observed W_p in the 850- to 400-mb layer. Sample charts for October 8, 1961 are shown for comparison in figure 3-7. On some days of the series of five storms, the forward edge of the W_p pattern estimated from 700-mb dew point was displaced somewhat downwind from the 850- to 400-mb moisture pattern, while the back edge sometimes lagged behind. During periods of highest moisture over the study area, values estimated from the 700-mb dew point are slightly higher than observed due to upwind barrier depletion of moisture in the lower layers of the 850-400 mb column. This depletion averaged 10 percent at Grand Junction and 7 percent at Denver in the five storms during the periods when precipitable water in the 850-400 mb column exceeded 0.4 inch.

3.6 Factors involved in formation of moisture pools

3.6.1 Moisture source. The main source of moisture reaching the study area in qualifying storms is the low latitudes of the eastern North Pacific Ocean, including tropical latitudes. A secondary source is the Gulf of Mexico.

3.6.2 Transfer processes. Two factors in the transfer of moisture from the water surface to the study area are (1) the mechanisms which accomplish its vertical transfer in depth at the source region and (2) the circulation pattern that determines the track the moisture will take from the source region to the study area. The first is discussed in this section. The second is discussed in chapters 2 and 4.

3.6.3 The process of charging upper levels with moisture from a warm water surface depends on sea-air temperature differences and air temperature lapse rates. The process is subject to wide variation in efficiency depending both on season and source region. The roles of the two source regions in supplying moisture to the study area are discussed below, with emphasis on seasonal effects.

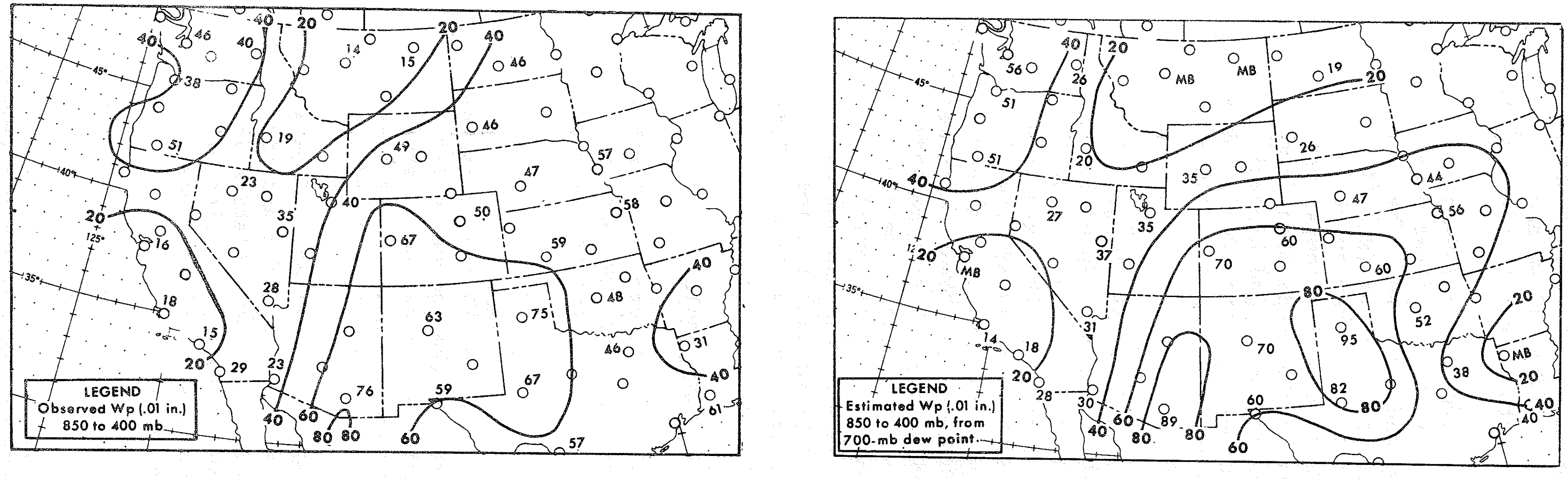


Figure 3-7. Comparison of precipitation water observed in the 850-to 400-mb layer, 1700MST October 8, 1961 with that estimated from 700-mb dew point, assuming saturation.

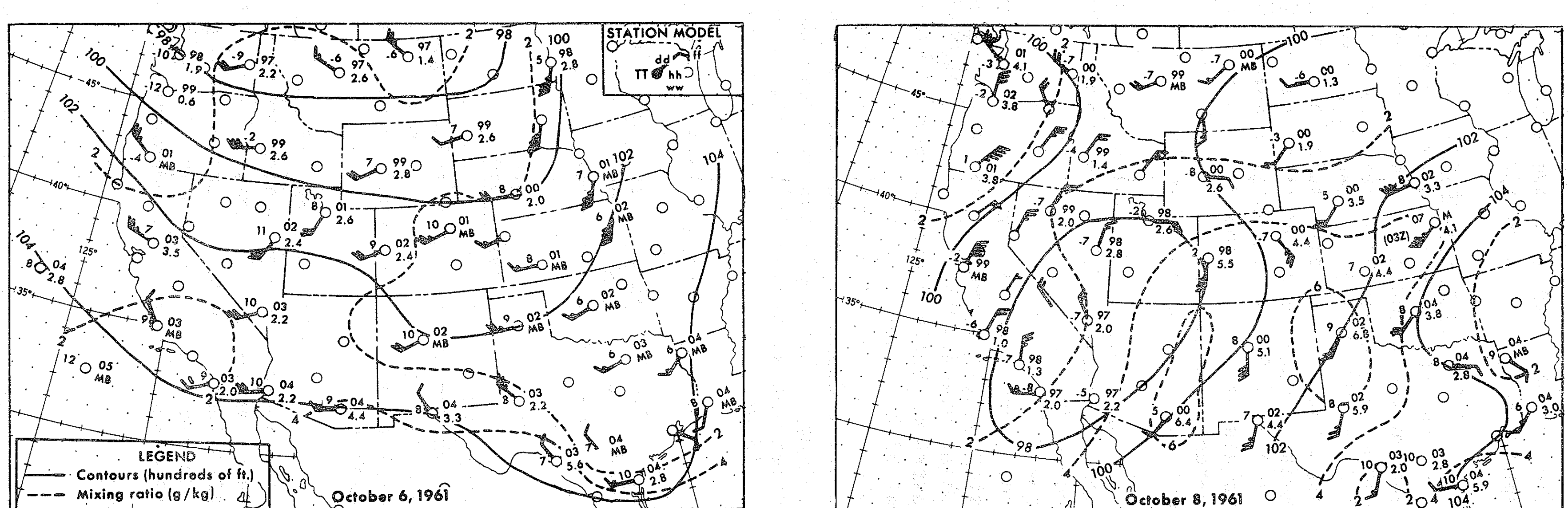


Figure 3-8. 700-mb charts 1700MST, October 6 and 8, 1961.

3.7 Low latitudes of the eastern North Pacific Ocean as a moisture source

3.7.1 The region off southern and Baja California is the main source of moisture reaching the study area. The four circulation patterns involved are discussed below.

3.7.2 The summer and early fall trough. Steep temperature lapse rates are rarely attained in spring or summer months. In spring the ocean surface is warming up more slowly than the air above, as cold air intrusion from northerly latitudes diminishes. In summer months the combined effect of upwelling of cold water near the coast and subsidence in the semi-permanent High over this area usually results in a stable lapse rate of temperature and the typical low-level inversion near the coast, whose height increases rather slowly westward and southward. But by late August or early September, and infrequently in July, there appears a stagnant upper trough just off the coast, oriented north-northwest to south-southeast. It is initially a col between a large upper High covering the eastern Pacific Ocean and a westward extension of the Bermuda High. Instability developing over a period of several days near the trough line permits vertical transfer of moisture to upper levels, particularly at latitudes south of San Diego.

3.7.3 The fall tropical storm. The coastal trough described above is usually a characteristic of the circulation when September and early October tropical storms move northward along the Baja California coast. The tropical moisture may be drawn northward on the east side of the trough far in advance of the tropical storm center, and then move toward the study area. While the low levels of the tropical storm are stabilized by a cooler ocean surface than that of its origin, the broad lateral extent of the storm's moisture pool at high levels provides unusual amounts of moisture to downwind areas determined by the peripheral upper-air circulation. The ideal circulation pattern for tropical moisture to reach the study area is for the tropical storm to move northward along the Baja California coast before an upper Cut-off Low near the California coast begins to move northeastward. However, if the tropical storm center remains as far south as the southern tip of Baja California, ingress of moisture from it is more likely to be northward through New Mexico and somewhat east of the study area.

3.7.4 Gulf of Mexico moisture may move northward through northern Mexico, Arizona and New Mexico on the east side of the offshore trough. Such a combination of moisture from different sources may be difficult to verify, especially in older storms, other than by the widespread rain pattern.

3.7.5 Breakthrough Trough or Low. As an upper Low or trough moves southeastward near the west coast, air at low latitudes offshore moves toward a lower latitude over a warmer ocean surface. This creates a lapse rate unstable enough in fall and winter that moisture is convected upward from lower levels. The height of penetration increases with the temperature lapse rate aloft, dependent on the presence of the upper trough or Low to the north. The moisture is then transported from these low latitudes on the southern periphery of the circulation inland toward the study area.

3.7.6 October is the month of most frequent occurrence of this moisture-producing sequence. The main source of moisture is the ocean area off northern Baja California. A northeastward motion of the moisture pool along a track that passes to the south or east of the study area is most frequent, although this track varies considerably in both position and orientation. The importance of slow motion of the Cut-off Low becomes obvious when one considers that several days are required to charge the air with moisture and transport it around the periphery of the Low to the study area. The HBL type Low (fig. 2-1) provides the least amount of time. Lows of the C type that stagnate far enough to the west (fig. 2-2) provide a period of two or three days longer and the possibility of a more direct moisture track over the study area. In a few storms, the moisture pool is formed by a previous cyclonic system which has filled.

3.7.7 The winter Low Latitude Trough. The paucity of qualifying mid-winter storms over the study area is in part due to the normally low moisture values available for storms at that time of year. Lower water temperature in winter than fall means less vertical transport of moisture from the offshore source region discussed in paragraph 3.7.5. Hence, a region further offshore becomes the predominant source of moisture in the few qualifying mid-winter storms. The ideal upper circulation pattern that provides this vertical transfer of moisture is a broad upper Low Latitude Trough (LT), with elongated axis oriented northeast-southwest. This trough moves slowly eastward from a far-distant offshore moisture source region toward the study area (fig. 2-3b). A series of waves in lower levels may help maintain a long fetch in the flow aloft. An accessory sequence such as the HBT may join the LT sequence to help provide the mechanism for release of the moisture over the study area.

3.8 Gulf of Mexico as a moisture source

3.8.1 Accessibility. In only nine of the 42 qualifying storms was the Gulf of Mexico the principal moisture source (col. 9, table 2-5) although it supplied moisture to eastern Colorado (and to a limited extent the eastern part of the study area) in others. This small number was largely due to the relative inaccessibility to the study area of Gulf moisture compared to Pacific moisture. There are two reasons for this inaccessibility. First, barrier restrictions to direct low-level inflow of Gulf moisture with a component from east of south are generally more formidable than those for Pacific air from west of south. Gulf moisture usually approached Colorado in a low-level southerly flow rather directly from the Gulf of Mexico. (In two storms it crossed lower barriers in Wyoming and became widespread over the northern Rockies before being drawn counterclockwise over the study area by an upper Low to the southwest.) Second, a circulation capable of both bringing sufficient moisture northwestward from the Gulf to the study area and later releasing it there is infrequent in months when Gulf moisture can move readily northward. The importance of this circulation is illustrated in the next three paragraphs.

3.8.2 Dependence on season and circulation patterns. An upper Low or trough to the west or southwest of the study area was present in eight of the nine storms indicated in column 9 of table 2-5 as dependent on the Gulf of Mexico for moisture. Three of these storms, typed in table 2-2 as "Gulf Air" storms as resulting primarily from inflow from the Gulf of Mexico, occurred in late summer (August 27, 1932, September 2, 1938 and September 5, 1909). Their average moisture index was a high 72 percent. A secondary feature was an LT(HBT) sequence in the August 1932 storm and a C sequence in the September 1909 storm. Even in the September 2-3, 1938 storm there was a weak 700-mb Low well to the south of the rain area.

3.8.3 Gulf of Mexico air provided the moisture as a secondary feature in the other six storms, all occurring in spring months. Four had a low moisture index, averaging only 59 percent. The April 1921 HBL storm depended on an upper Low over northern Arizona with a strong upslope easterly flow for heavy amounts east of the Continental Divide and lesser amounts to the west. In the May 1927 and June 1947 storms, Gulf moisture was already widespread to the north before a C type Low approached. Gulf moisture had reached eastern Utah and western Colorado from the south prior to approach of the upper troughs in the May 20, 1916 HBT storm and the June 1927 MT storm and ahead of the Low in the May 1926 HBT-C storm.

3.8.4 In mid-summer, Gulf moisture is frequently associated with local heavy showers over mountains of the study area. But there is lacking the necessary auxiliary cyclonic circulation to cause general precipitation heavy enough to qualify in this study. No storms qualified between July 11 and August 27.

3.9 Tracks of moisture centers

3.9.1 Charts of 700-mb moisture. Isolines of mixing ratio (g/kg) were drawn on daily 700-mb height charts (3-km and 10,000-ft. for early years) for each storm since 1936. Figure 3-8 shows examples of these charts for the storm of October 8-9, 1961.

3.9.2 Tracks defined. The positions of the moisture centers defined by these isolines were joined to represent the track of moisture pools from the source region toward the vicinity of the study area. Moisture tracks for individual storms, grouped by storm type, are shown in figures 4-1 through 4-8 for qualifying storms since 1936, along with Low tracks. Positions east of the Continental Divide tend to be affected by low-level inflow from the Gulf of Mexico, later convected to upper levels.

3.9.3 Relation to storm tracks. Because tracks of moisture pools can be documented only since 1936, there is a limited sample from which to determine a moisture track typical of storm types. Moisture tracks of a given storm type vary widely, depending on moisture source--tropical, Gulf or the general area southwest of southern California. Tracks of Gulf moisture differ with season.

3.9.4 Typical moisture tracks for each storm type are shown in figure 3-9, with seasonal differentiation as required to show difference. Moisture tracks from a given source region are largely controlled by movement of upper Lows or troughs. In general, Lows that stall or move slowly southward before moving eastward cause an initial counterclockwise moisture track which later straightens as the Low track becomes less cyclonic or anticyclonic.

3.9.5 A range of positions of moisture tracks from a tropical source is indicated on figure 3-9. The three qualifying storms designated in table 2-2 as tropical storms (because their circulation persisted nearly to the study area) had an average moisture track shown crossing Baja California farthest to the northwest and entering the southeastern quadrant of the study area. Tropical moisture in other storms passed northward farther east. The track of Gulf moisture in some spring storms (fig. 3-9) was increasingly cyclonic as it approached the study area; in others it approached anticyclonically from the south, as in late summer storms involving Gulf air, depending on the latitude of the Low or trough to the west.

3.9.6 Relation to moisture index. The typical moisture tracks shown on figure 3-9 tend to converge to the south of the study area. But there was considerable scatter in individual tracks from the typical track. This scatter accounted for part of the wide range of moisture index among storms of a given type. There were other causes for this variation of moisture index. For example, a pool of very high moisture along a nearby track may be so oriented or concentrated that only a modest moisture index prevails over the study area. This was the case in the September 22, 1941 storm (fig. 4-2) with index 57 percent. Involving moisture from a tropical storm, the moisture track for this storm was east of the Continental Divide in Colorado. On the other hand, a pool of high moisture with the center distant from the study area may result in a fairly high moisture index at Grand Junction

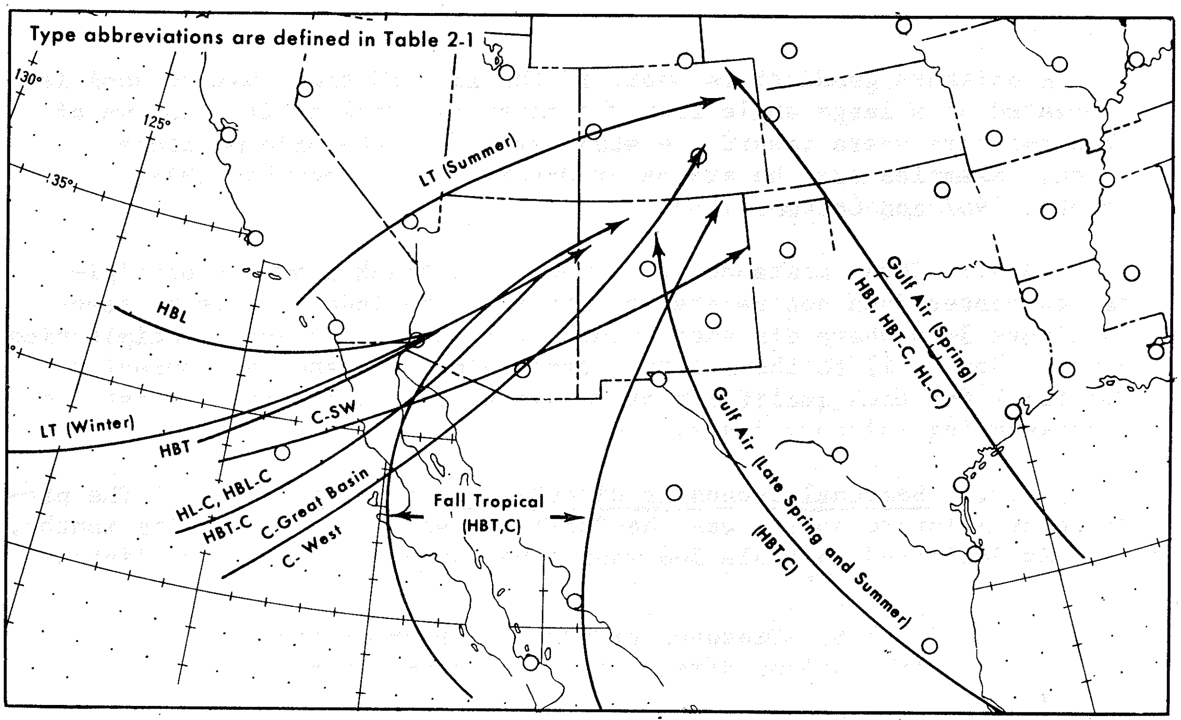


Figure 3-9. Composite of moisture tracks for all storm types.

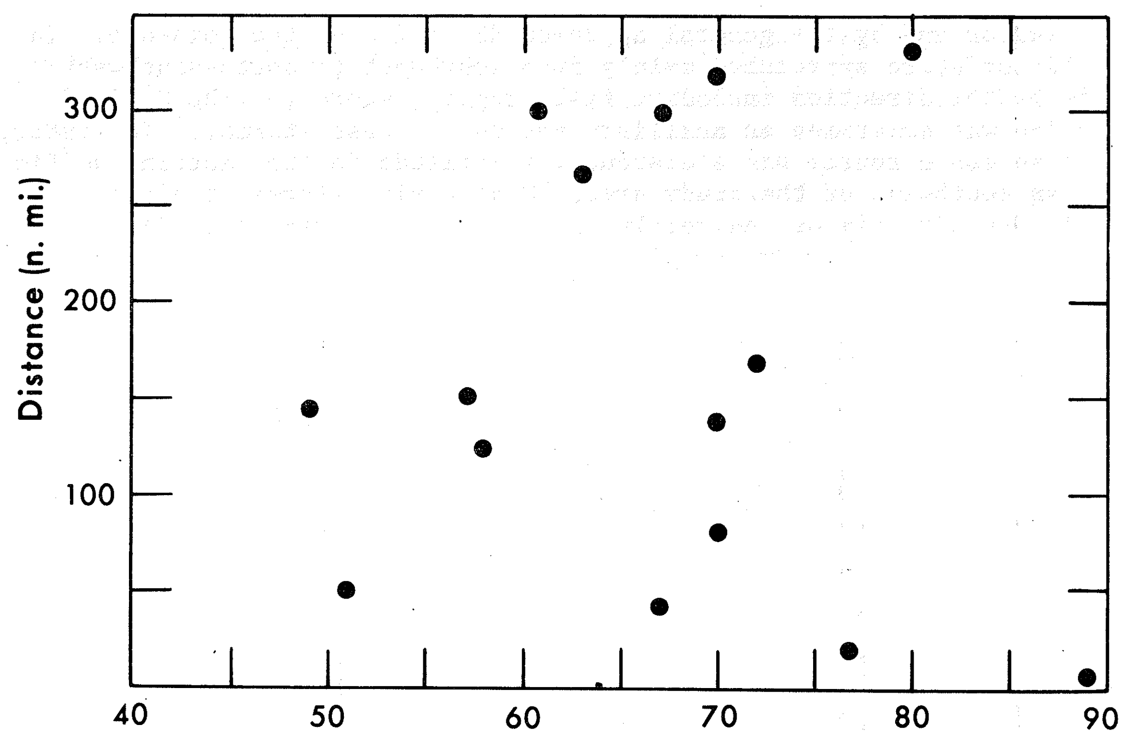


Figure 3-10. Comparison of storm moisture index with shortest distance (n.m.) from the precipitation center to the track of the moisture pool.

if the moisture gradient is weak, if the axis of the moisture pool is elongated at a large angle from the moisture track or if a tongue of high moisture veers toward the study area from the main moisture track. Examples are the storms of October 1941, December 1948, October 1957 and October 1963.

3.9.7 Thus, distance of the moisture track from the precipitation center does not relate well to moisture index. This is seen in figure 3-10 where distance (n.m.) from the convergence precipitation center (Sec. 4.1) to the moisture track along the shortest normal to the track for each qualifying storm since 1936 is plotted against the corresponding moisture index.

3.9.8 Seasonal trends in direction to moisture source. The predominant moisture source was the Pacific Ocean except in spring months. This is indicated in table 3-8 where the number of storms is listed

Table 3-8. Seasonal trends in number of storms with various directions to moisture source

	Fall	Winter	Spring	Summer	Annual
W to WSW	3	0	1	0	4
SW	10	4	1	0	15
SSW	13	0		1	14
SSE (Gulf)	2		6	1	9

by season and by the general approach direction of the moisture. In fall, moisture approached mainly from southwest to south-southwest, the latter direction including fall tropical storms. (The Gulf of Mexico was sometimes an auxiliary source in these storms.) In winter, the moisture source was a distant low latitude in the eastern Pacific Ocean southwest of the study area. Most spring storms obtained moisture directly or indirectly from the Gulf of Mexico (SSE).

CHAPTER 4. CONVERGENCE PRECIPITATION

A. Introduction

4.1 Definition

4.1.1 The isohyetal patterns in mountainous regions are distorted by topographic influences that increase or deplete the convergence precipitation--that due only to the storm mechanisms. In the following study of cause and effect, the estimated positive or negative orographic effect was deleted from observed storm precipitation before relating the residual convergence precipitation pattern to upper Low or trough positions and moisture. The orographic precipitation is the subject of Chapter 5.

4.2 Basis for location and timing

4.2.1 Location. Smooth convergence isohyets for each storm were sketched on an overlay of the total storm isohyets; the center of convergence precipitation was then located within this pattern and plotted as a solid circle in figures 4-1 through 4-8. The procedure used for drawing patterns of storm convergence precipitation was to draw for station values least affected by orography and to smooth out total storm isohyets by subjective discounting of lee and upslope effects at other stations. The subjectivity involved in discounting lee effects was greatest in the San Luis Valley and in the North and South Park areas, all east of the Continental Divide, where lee effects may be large.

4.2.2 Time of precipitation. Times of beginning (B), peak (P) and ending (E) of convergence precipitation at the convergence precipitation center were determined for each storm from mass curves of precipitation. Since 1941 these curves were based on hourly data from recording gage stations. In earlier years mass curves were based on daily station data, thrice daily amounts and some hourly data at Grand Junction and Durango, and on remarks concerning amounts and beginning and ending times obtained from original observational records at a few other stations. Stations near the convergence precipitation center with least orographic effect were favored in the determination of B, P and E. When precipitation showed no distinct peak intensity,(P) was taken midway in the precipitation period.

4.3 Factors influencing the timing

4.3.1 Upper versus sea-level Lows. In other chapters of this report, emphasis is placed on the 500-mb chart as a control on broad-scale storm tracks and on the development and transport of significant moisture pools. However, in storms with intense sea-level Lows, the convergence precipitation is more affected by horizontal convergence in lower layers, and its timing is advanced toward the time of passage of the sea-level Low center. An example is the November 1919 storm (fig. 4-2) where the sea-level Low was deep and initially displaced a considerable distance ahead of the upper Low.

4.3.2 Upper circulation versus moisture. The position (P) of the 500-mb Low center or trough at the time of peak convergence precipitation is indicated along the track of the 500-mb Low (or line normal to trough positions) in figures 4-1 through 4-8. For storms since 1936, time of peak 700-mb moisture (M) at Grand Junction is also plotted along the 500-mb Low track or along the line normal to the daily trough positions. Proximity of the position of (M) to (P), i.e., time of highest moisture near time of peak precipitation, would indicate that moisture is the important control on the timing of convergence precipitation, especially when (P) is distant from the precipitation center. It will be shown in later sections of this chapter that this was the situation in most qualifying storms since 1936. In most instances the primary role of the upper Low was to advect moisture over the study area from a low-latitude source. Release of this moisture depends on horizontal convergence which usually peaks before the Low passes, especially if the Low is filling as was typical of most qualifying storms.

4.3.3 Upper Lows and moisture advection. An efficient mechanism for generating and advecting high values of moisture over the study area is a deep slow-moving 500-mb Low centered just off the California coast or in the western part of the Great Basin. The moist tongue it advects may have ample time to extend northward through the study area if the Low stagnates. (In the October 1957 storm, a tongue of moisture invaded Utah with the Low centered over southern California.) But usually the moisture pool is forced by movement of the upper Low to move along a track passing south or east of the study area.

4.3.4 Instability as related to moisture and storm mechanism.

A factor to consider in the relation of moisture and upper Lows or sharp troughs to precipitation centers is the relative role of instability in enhancing the effects of horizontal convergence in storms. Instability increases the magnitude of vertical motions resulting from horizontal convergence. For this reason, instability plays a bigger role in May and June storms than in fall months as cold advection follows a period of southerly flow of moisture from the Gulf of Mexico in intermediate levels. The contrast in temperature between these air masses triggers instability. Hence, peak precipitation in spring storms is usually more dependent on instability near passage of the upper Low or trough and less on the early peak in moisture, compared to fall storms.

B. Presentation by Storm Type

4.4 Method of presentation

4.4.1 In this section, storm moisture tracks and tracks of 500-mb Lows and troughs are related to the corresponding sequence of convergence precipitation (par. 4.1.3). These tracks are shown in figures 4-1 through 4-8, grouped by storm type. The estimated moisture tracks shown for a few storms prior to 1936 are based on weather sequences. In this and the next section, mention of time and location of precipitation refers to convergence precipitation. The word "convergence" is omitted to avoid repetition.

4.4.2 Along the track shown for each 500-mb Low or trough in figures 4-1 through 4-8 the position of the Low at the average time of beginning (B) and ending (E) of precipitation is marked. Also plotted are Low positions at the time of peak precipitation (P) at the precipitation center located in the study area and at the time of peak moisture at Grand Junction (M) for storms since 1936. P_m indicates the major precipitation peak and P_s a minor peak when appropriate. These positions are marked also on the moisture tracks. Times (MST) represented by these positions are shown on either or both tracks.

4.5 Discussion

4.5.1 The relation of the positions of the parameters P and M on the 500-mb Low tracks and lines drawn normal to trough positions is discussed below for individual storms. This discussion is illustrated by figures 4-1 through 4-8.

4.5.2 HBL storms (fig. 4-1). The distance from the precipitation center to the 500-mb Low center at time of peak precipitation varied widely in the four HBL storms, both because of differences in the tracks of the rather fast-moving 500-mb Lows and because of wide variation of moisture source (fig. 4-1). At one extreme was the June 1943 storm, a winter-like storm, where both the 500-mb Low track and the moisture track were almost west-east. Peak precipitation near the center on the Wyoming border occurred with the upper Low still in southwestern Washington. It occurred as much as 15 hours later to the south as the Low entered Montana. A moisture pool which had stagnated over southern California on May 30-31 was already moving rapidly eastward toward the study area on June 1 as the deep upper Low in a very broad trough approached the coast. The rain sequence was associated with passage of this moisture although showers persisted until the Low reached southeastern Montana. This Low made up in intensity for its distance from the study area. The lateness of the season partly offset the limitation on high moisture imposed by the west-east track and high speed of the Low.

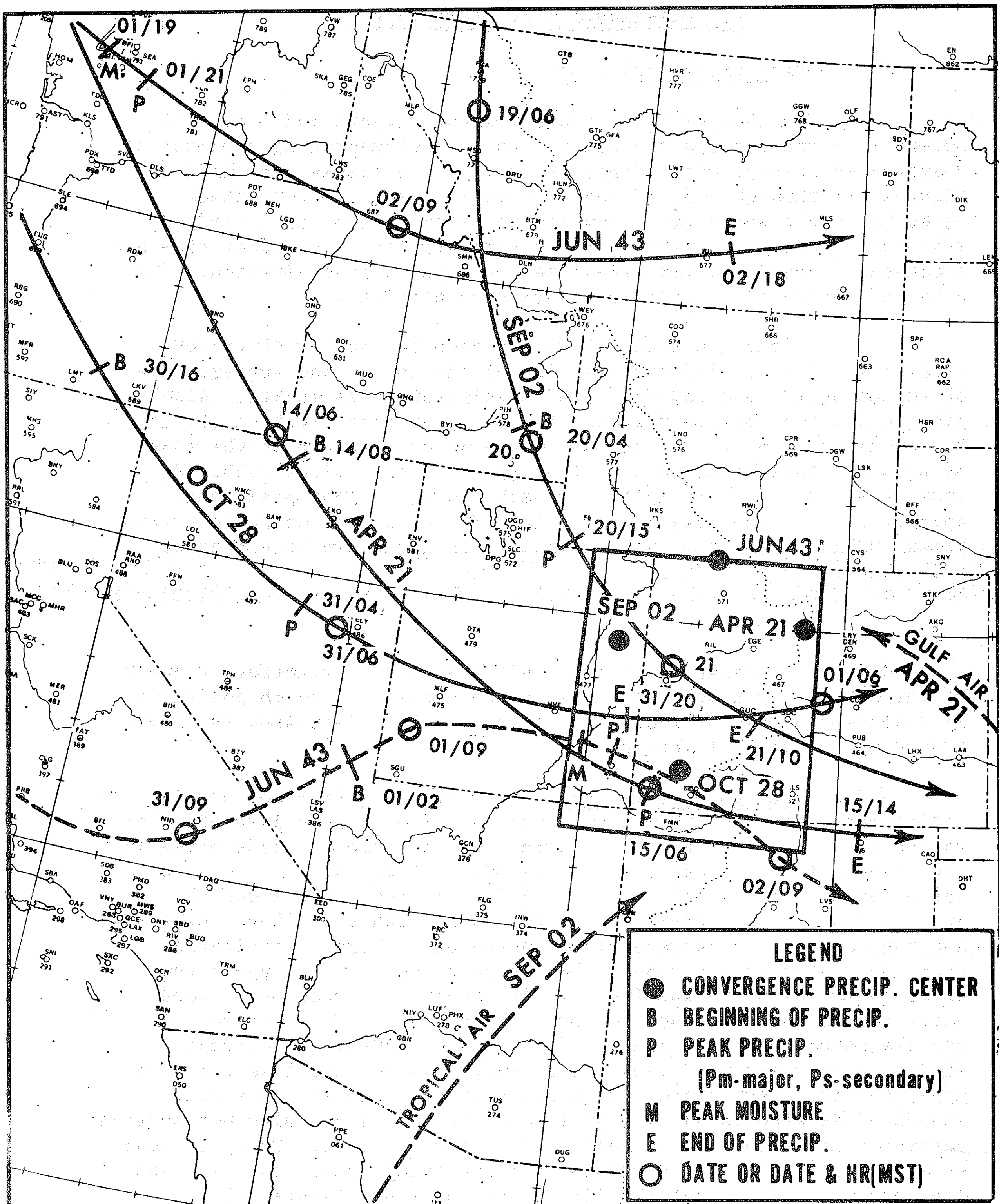


Figure 4-1. Tracks of 700-mb moisture (---) and 500-mb Lows (——) in HBL type storms. Month and year are shown for tracks and convergence precipitation centers.

4.5.3 In contrast was the southeastward track of the April 1921 Low which centered heavy orographic and some convergence precipitation on east-facing slopes of the northern Colorado Rockies in the northeastern portion of the study area. This track across southwestern Colorado allowed moist Gulf air to be drawn from eastern Colorado directly westward across the Continental Divide. The track of the Low from the northwest did not favor penetration of this moisture very far to the west of the Divide.

4.5.4 Precipitation began in the October 1928 storm with the deepening upper Low in southern Oregon, peaked with the center in eastern Nevada and ended as it entered the study area. In the September 1902 storm, precipitation centered in northeastern Utah and depended on a broad influx of moisture from a preceding tropical storm. It peaked as the upper Low entered northern Utah from the northwest.

4.5.5 HBL-C storms (fig. 4-2). Most of the variation in tracks of HBL-C Lows was in the early stages as the Lows moved southward across southwestern Canada and into the Pacific Northwest. Continuing southward into Nevada, they slowed down, were cut off and then changed direction toward northeast. Very little variation is noted in their tracks near the study area. The extreme change in direction and subsequent northward track through central Utah in the September 1941 and October 1961 storms kept upper winds in the south and the isohyetal axis north-south.

4.5.6 In the October 1961 storm the moisture track from a tropical storm was southwest-northeast across northern New Mexico. The moisture peak on the night of the 8th was nearer to the primary peak in precipitation on the morning of the 9th (with the Low in southwestern Utah) than it was to the earlier secondary peak. In the November 1919 storm a similar moisture sequence probably prevailed in the prolonged southwesterly inflow generated by the upper Low. Precipitation began in the northwest corner of the study area as the upper Low moved southward into western Nevada. The two peaks in precipitation (centered south of Grand Junction) came with the Low still moving southeastward near the California-Nevada border. Precipitation continued intermittently in western Colorado until the Low was passing out of the area.

4.5.7 Of special interest is the early peak of the main precipitation period in the September 1965 storm (fig. 4-2) as the upper Low moved southward in Idaho toward the northern Nevada border, over two days before it passed the study area. This Low was so sharply elongated north-northeast to south-southwest prior to this time that it was able to draw a pool of moisture, centered in northwestern Mexico on the 15th, northward directly across the study area by the 17th. The time of peak precipitation was coincident with that of highest moisture in the study area during the night of the 17th. The orientation of the

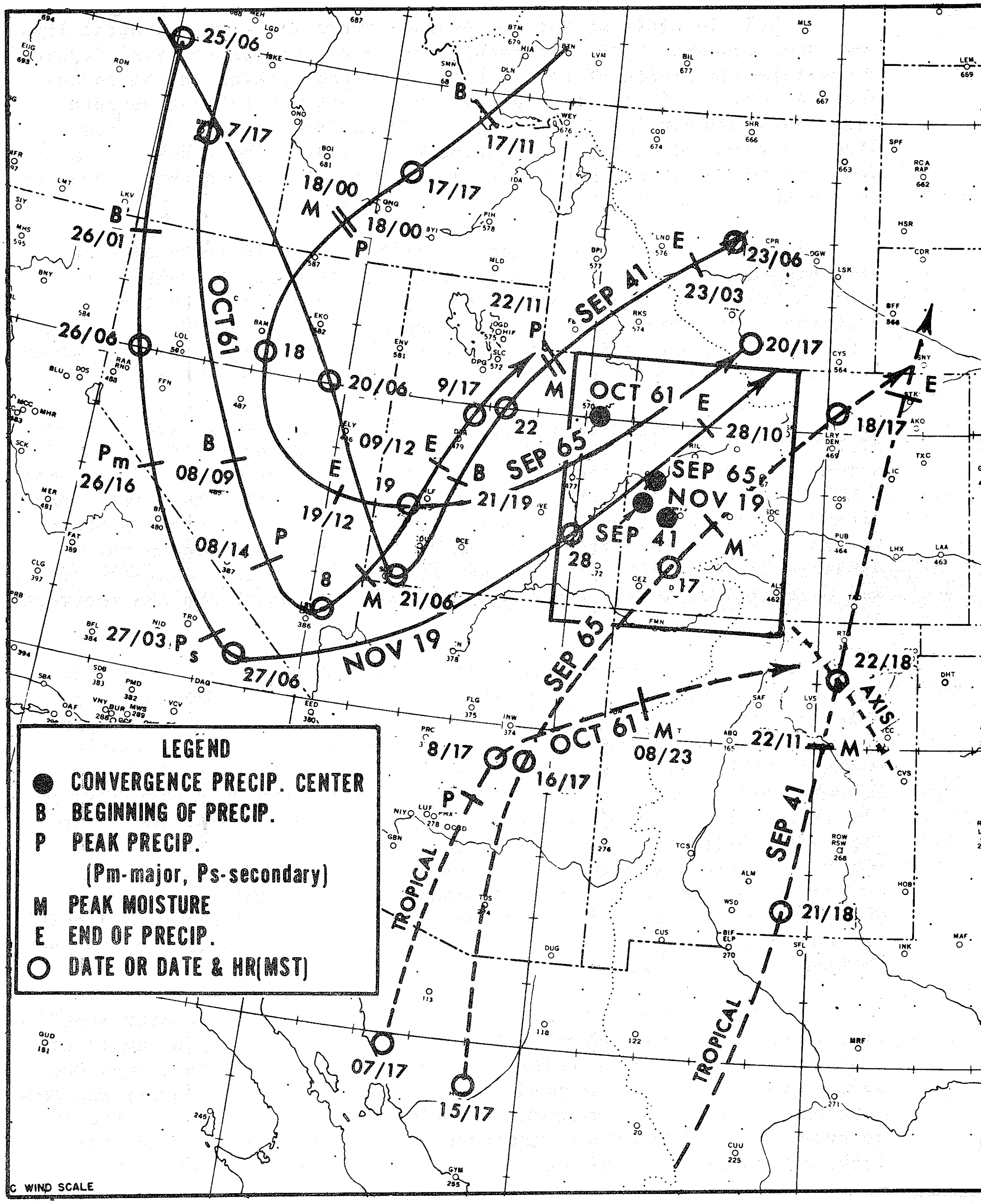


Figure 4-2. Tracks of 700-mb moisture (---) and 500-mb Lows (——) in HBL-C type storms. Month and year are shown for tracks and convergence precipitation centers.

2-inch convergence precipitation isohyet paralleled the moisture track. Although most of the rain was over by noon of the 12th with the Low still in southern Nevada, a brief period of light precipitation accompanied passage of the Low over the northwestern corner of the study area.

4.5.8 Only in the September 1941 storm did the Low center change direction toward northeast long before rain began. This Low approached the northwestern edge of the study area by the time of peak rain near Montrose, Colorado, about noon of the 22nd, when the moisture also peaked. This delay is explained by the late arrival of a moisture pool (from a tropical storm south of Baja California) which moved northward through eastern New Mexico with its axis then northwest-southeast. Note that the Low track was northward across Utah and parallel to the moisture track. The circulation about the Low following this track drew the moisture center northward to the northern Plains.

4.5.9 <u>HBT-C storms (fig. 4-3)</u>. The four HBT-C Low tracks are similar to the tracks of HBL-C Lows (fig. 4-2). Forming on an elongated trough in eastern Nevada, HBT-C Lows changed direction from southeast to northeast over southern Utah or northern Arizona. In the September 1915 storm, precipitation peaked west of Durango while the upper Low was still in southern Nevada and as a moist inflow from a combined tropical and Gulf of Mexico source apparently was drawn across the study area by the Low. Precipitation ended before the filling Low reached the study area by way of northern Arizona.

4.5.10 With a similar Low track skirting northern Arizona in the May 1926 storm, precipitation began much later and did not peak until the Low reached the 4-corners area in extreme southwestern Colorado. This storm was one of three qualifying storms with the precipitation peak occurring while the Low was to the south or southeast of the rain area. Precipitation reports indicate that moist air had moved northward from the Gulf of Mexico through New Mexico into southeastern Utah and southwestern Colorado for several days prior to the Low. It was later released as the Low center passed to the south.

4.5.11 The track of the 500-mb Low in the June 1947 storm (fig. 4-3) was similar to but a little north of that of the above two storms. Gulf air, which had invaded the Rocky Mountain area previously, reached a maximum near the rain center northeast of Grand Junction with the upper Low entering western Utah; precipitation peaked a few hours later with the Low center in south-central Utah. The upper Low in the October 1924 storm moved directly eastward across Utah, with precipitation centering in southeastern Utah and peaking on the afternoon of the 7th when the Low was rather close by to the northwest.

4.5.12 <u>HL-C storms (fig. 4-4)</u>. As the High Latitude Low centers of this storm type moved in a general easterly direction across northern Canada, the Cut-off Lows formed in eastern Nevada. The 500-mb Low centers in three of the HL-C storms were near Ely

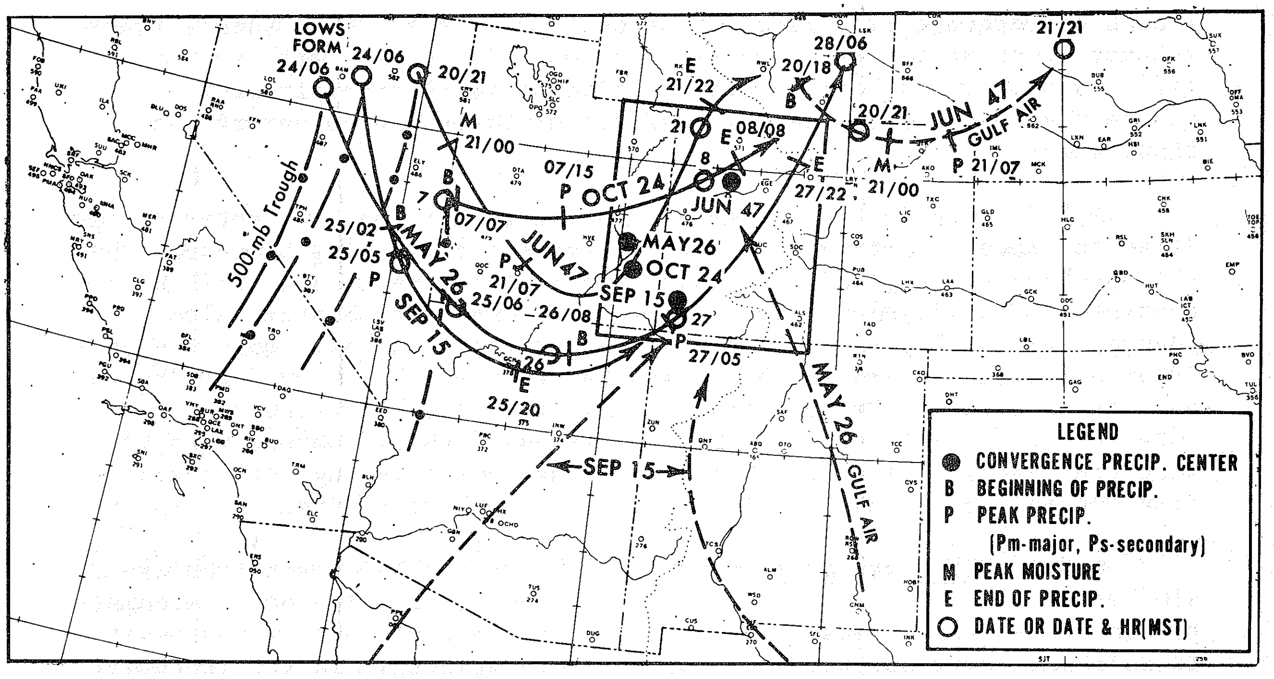


Figure 4-3. Tracks of 700-mb moisture (---) and 500-mb Lows (——) in HBT-C type storms. Troughs are shown by (—●—●) on date Low forms. Month and year are shown for tracks and convergence precipitation centers.

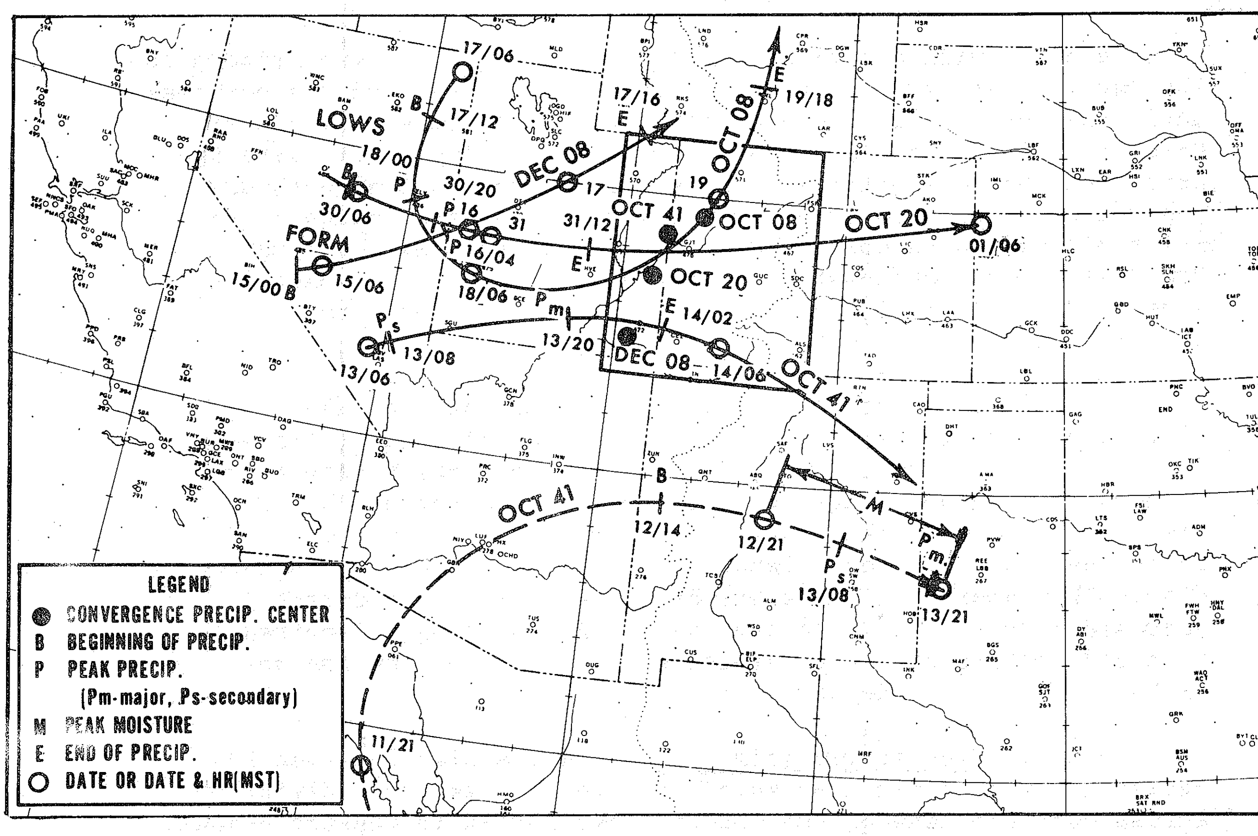


Figure 4-4 Tracks of 700-mb moisture (---) and 500-mb Lows (——) in HL-C type storms. Month and year are shown for tracks and convergence precipitation centers.

in eastern Nevada at time of peak precipitation centered near the Colorado-Utah border. Yet the three Low tracks varied considerably in location and direction: west-east through central Colorado (October 1920), southwest-northeast through northern Utah (December 1908), and a counter-clockwise circular path crossing eastern Nevada, southern Utah and north-central Colorado (October 1908). It is estimated in each case that moisture, drawn from low latitudes to the southwest by the trough in which the upper Lows formed and by the Lows themselves, was reaching the study area and peaked there soon after the Lows began an eastward motion, far to the west of the study area. Precipitation continued until the Lows moved into or beyond the study area in all but the 1920 storm.

4.5.13 An unusual clockwise circular Low path in the October 1941 storm forced a similar track on the immense moisture pool from a tropical storm (reinforced later with moisture drawn northeastward by the Nevada Low). Moisture was rather uniformly high however, from the 12th through the 13th; hence, no peak is shown. The first rain peak on the morning of the 13th related to passage over the study area of the frontal system which had caused the formation of the upper Low. The second one 12 hours later was induced by approach of the Low, eastward into southeastern Utah.

4.5.14 C-West storms (fig. 4-5a). Low centers moved counter-clockwise southeastward from off the Oregon or California coast before swinging onshore in the general area of southern California. In the October 1957 and October 1963 storms, the Low track was across Arizona, and northeastward through northern New Mexico. This Low track brought moisture over the study area from off northern Baja California in the October 1957 storm and tropical moisture from southern Baja California in the October 1963 storm (fig. 4-5a). Moisture remained high over the study area as the Lows skirted its southern and eastern edge. Precipitation in the October 1963 storm was heavy for several hours while the Low was moving rapidly northeastward in northwestern New Mexico; highest moisture at Grand Junction occurred at about the end of this time (in a branch of the main moisture pool) with the Low south of the precipitation center. A similar 500-mb Low track in the October 1957 storm led to a similar northward incursion of moisture into western Colorado, a branch of the main moisture pool which turned northeastward (not shown). Peak precipitation did not occur at the center in southwestern Colorado until early on the 13th, with the 500-mb Low in north-central New Mexico. This was about three hours before peak moisture at Grand Junction. Only in the storms of October 1957, October 1963 and May 1926 did the Low pass to the southeast at time of peak precipitation.

4.5.15 The October 1927 Low track passed northeastward through southern Utah and the northern half of the study area. The Low was in southeastern Utah at the time of the major precipitation peak in the

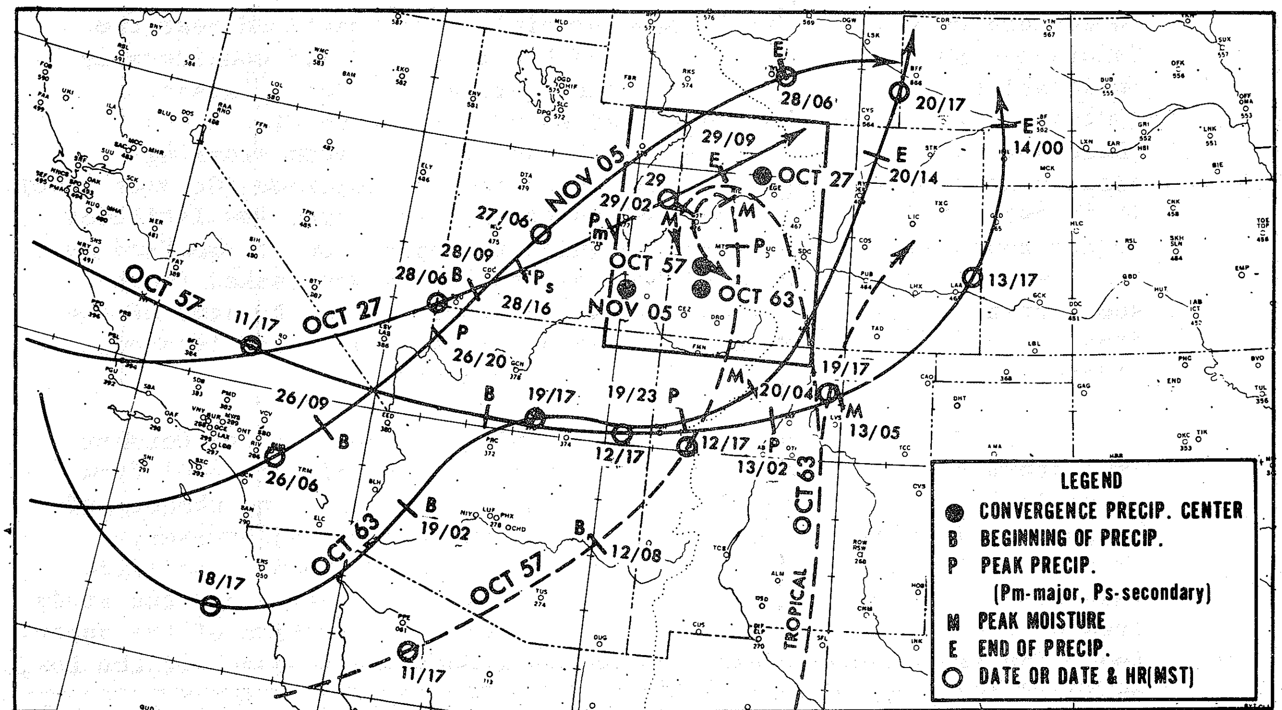


Figure 4-5a. Tracks of 700-mb moisture (---) and 500-mb Lows (——) in C-West type storms. Month and year are shown for tracks and convergence precipitation centers.

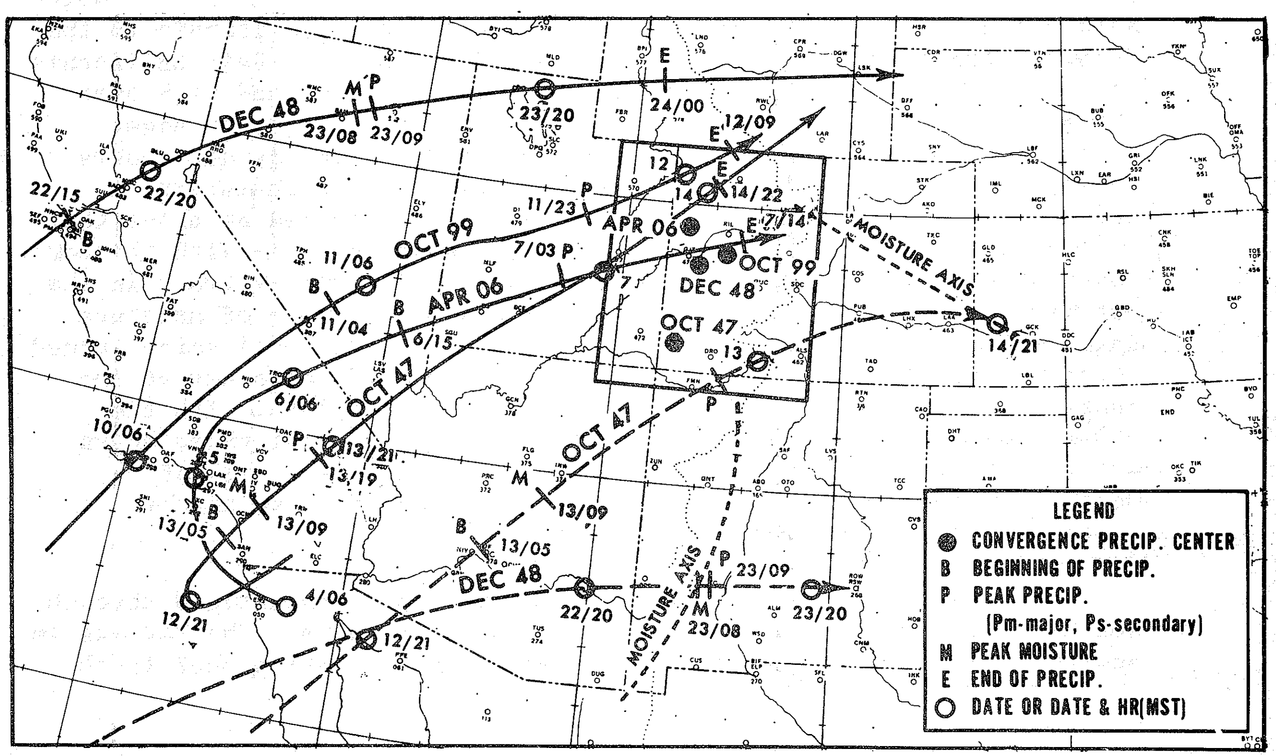


Figure 4-5b. Tracks of 700-mb moisture (---)and 500-mb Lows (——) in C-Southwest type storms. Month and year are shown for tracks and convergenee precipitation centers.

Colorado River headwaters. In the November 1905 storm, precipitation peaked in southeastern Utah with the Low east of Las Vegas, Nevada, on a northeastward track extending through extreme northwestern Colorado.

4.5.16 C-Southwest storms (fig. 4-5b). A clockwise motion characterizes the four storms in this group. The December 1948, 500-mb Low track passed northeastward from the central California coast and eastward to the north of the study area while the sea-level Low track (not shown) moved along the southern boundary. The upper Low tracks in the other three storms were northeastward from southern California through the study area. Low positions at time of peak precipitation were in southeastern Utah (April 1906), central Utah (October 1899), southeastern California (October 1947) and northwestern Nevada (December 1948). They were generally southeast of those in the HBL storms.

4.5.17 In the December 1948 storm, moisture peaked at Grand Junction shortly before time of peak precipitation. This moisture was drawn from far off the coast of northern Baja California. Highest moisture passed eastward across southern New Mexico. But the north-south elongation of the moisture axis permitted the moisture index to reach 70 percent. In the October 1947 storm, the moisture pool was drawn from near the northern Gulf of California on the 12th, northeastward through northwestern New Mexico and southern Colorado into Kansas, with a branch (not shown) moving cyclonically over northwestern Colorado on the 14th. Moisture peaked at Grand Junction prior to the main peak in precipitation which occurred on the evening of the 13th, with the 500-mb Low southwest of Las Vegas. Moisture continued fairly high into the 13th and precipitation continued intermittently until the evening of the 14th, when the Low had passed to the north of the study area.

4.5.18 C-Great Basin storms (fig. 4-5c). Upper Lows formed in the vicinity of western Nevada in the three C-Great Basin storms, then moved eastward across southern Nevada and Utah. The Low in the October 1910 storm filled as it entered the western part of the study area. The Low in the October 1953 storm filled in northwestern Colorado. The May 1927 Low turned northeastward from southeastern Utah to southeastern Wyoming. Lows at time of peak precipitation ranged from southwestern Nevada in the October 1953 storm to southwestern Utah in the October 1910 storm and to the western Colorado border in the May 1927 storm (fig. 4-5c). The position of the Low in the May 1927 storm was close to the convergence precipitation center at time of peak convergence precipitation, a characteristic of most spring storms, especially the few in which Gulf of Mexico moisture was carried around the Low, as in the May 1927 storm.

4.5.19 The track of the moisture pool in the October 1953 storm, northward from off central Baja California through central New Mexico, skirted the study area; but the north-south elongation

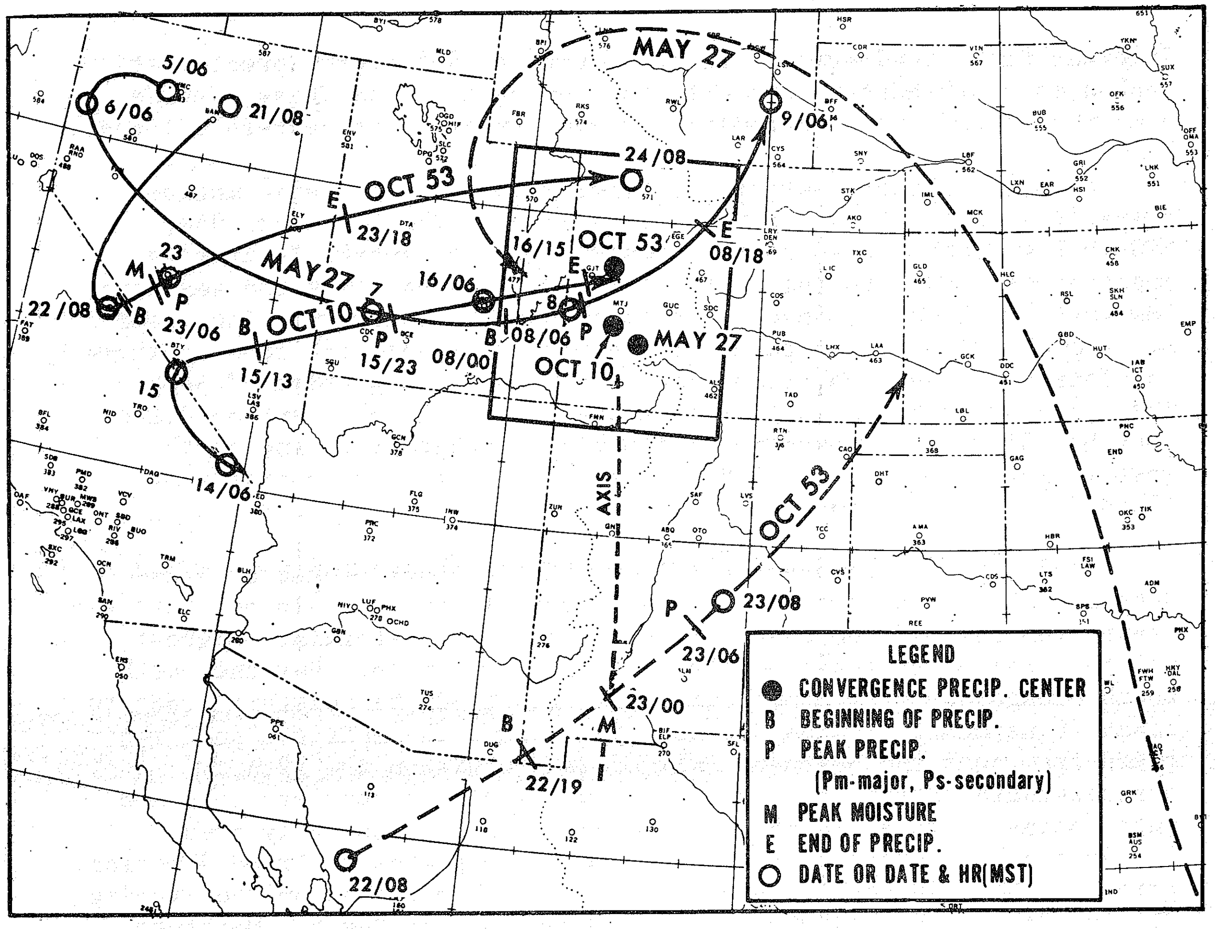


Figure 4-5c. Tracks of 700-mb moisture (— —) and 500-mb Lows (———) in C-Great Basin type storms. Month and year are shown for tracks and convergence precipitation centers.

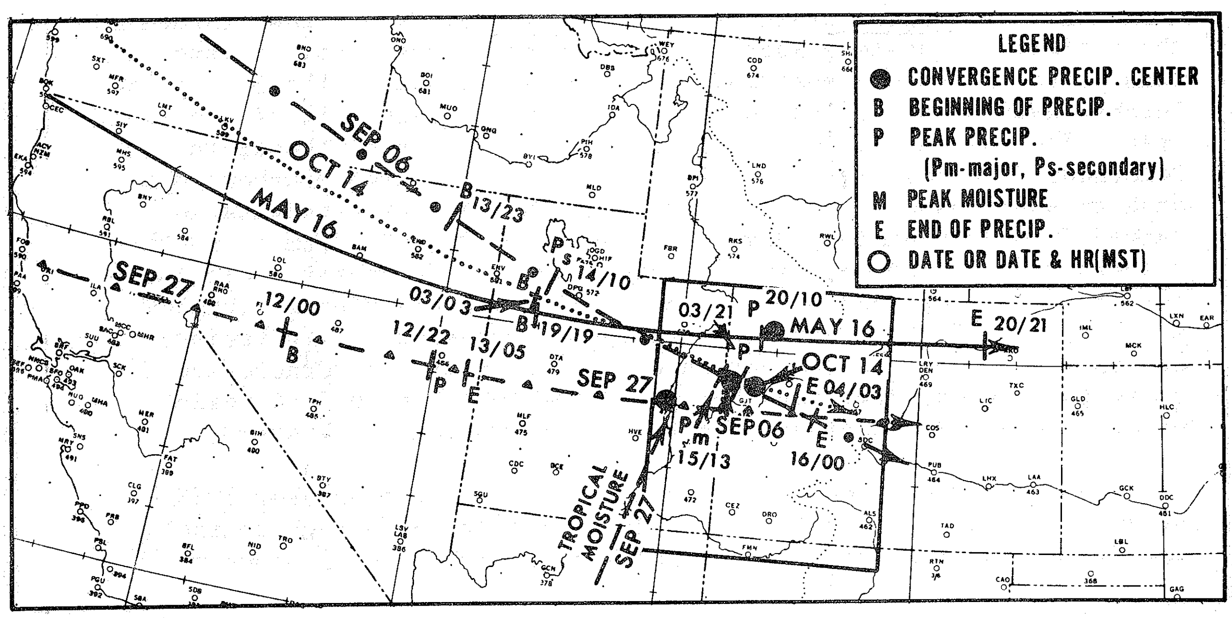


Figure 4-6. Lines drawn normal to daily position of 500-mb troughs through the convergence precipitation centers in HBT type storms. Month and year are shown for the line normal to the trough lines and convergence precipitation centers.

of the pool brought to the study area considerable moisture which reached a peak at Grand Junction a few hours prior to peak precipitation centered nearby. Its control on the precipitation sequence is obvious, with the upper Low still in southern Nevada at peak precipitation and in western Utah when precipitation ended.

4.5.20 HBT storms (fig. 4-6). The track of the 500-mb trough in each of four HBT storms is shown in figure 4-6 by a line drawn normal to the trough through daily trough positions and the circled precipitation center within the study area. The September 1927 storm precipitation sequence began and ended as the upper trough moved eastward across Nevada. The moisture pool, clearly identified with a tropical storm, evidently passed the study area more than a day ahead of the cold slow-moving upper trough and controlled the precipitation sequence.

4.5.21 Peak precipitation in the May 1916 and October 1914 storms is identified closely with trough passage, precipitation beginning while the troughs were in central Utah. In the September 1906 storm, the second and major precipitation sequence peaked with passage of the second and main HBT trough. A minor peak occurred the day before, probably with peak moisture, when the first trough was passing Salt Lake City; this trough faded out before reaching Colorado.

4.5.22 LT storms (figs. 4-7a and 4-7b). The troughs of the two LT winter storms extended to low latitudes. They were oriented such that the lines drawn normal to the troughs (fig. 4-7a) are at a higher latitude offshore than over the study area. In the December 1951 storm, precipitation peaked at the center in northwestern Colorado near time of peak moisture and while the associated broad HBT trough was passing through Oregon and northern California. It ended before the combined troughs reached the study area. In the February 1937 storm, the trough reached the coast at the beginning of precipitation, was crossing Nevada at time of peak moisture and was entering Utah by time of peak precipitation which was centered in extreme southern Colorado about nine hours after the flat peak in moisture.

4.5.23 The troughs of the two LT storms with summer characteristics (fig. 4-7b) were oriented so that the lines drawn normal to the troughs through the precipitation centers are at a lower latitude offshore than over the study area. The major precipitation peak in the October 1937 storm came with the trough in central Utah a few hours after peak moisture. A minor peak occurred with the trough passage. In the July 1936 storm, precipitation peaked shortly after time of peak moisture with the trough entering Utah. Except for the 1951 storm, precipitation ended as the troughs of the four LT storms moved out of the study area.

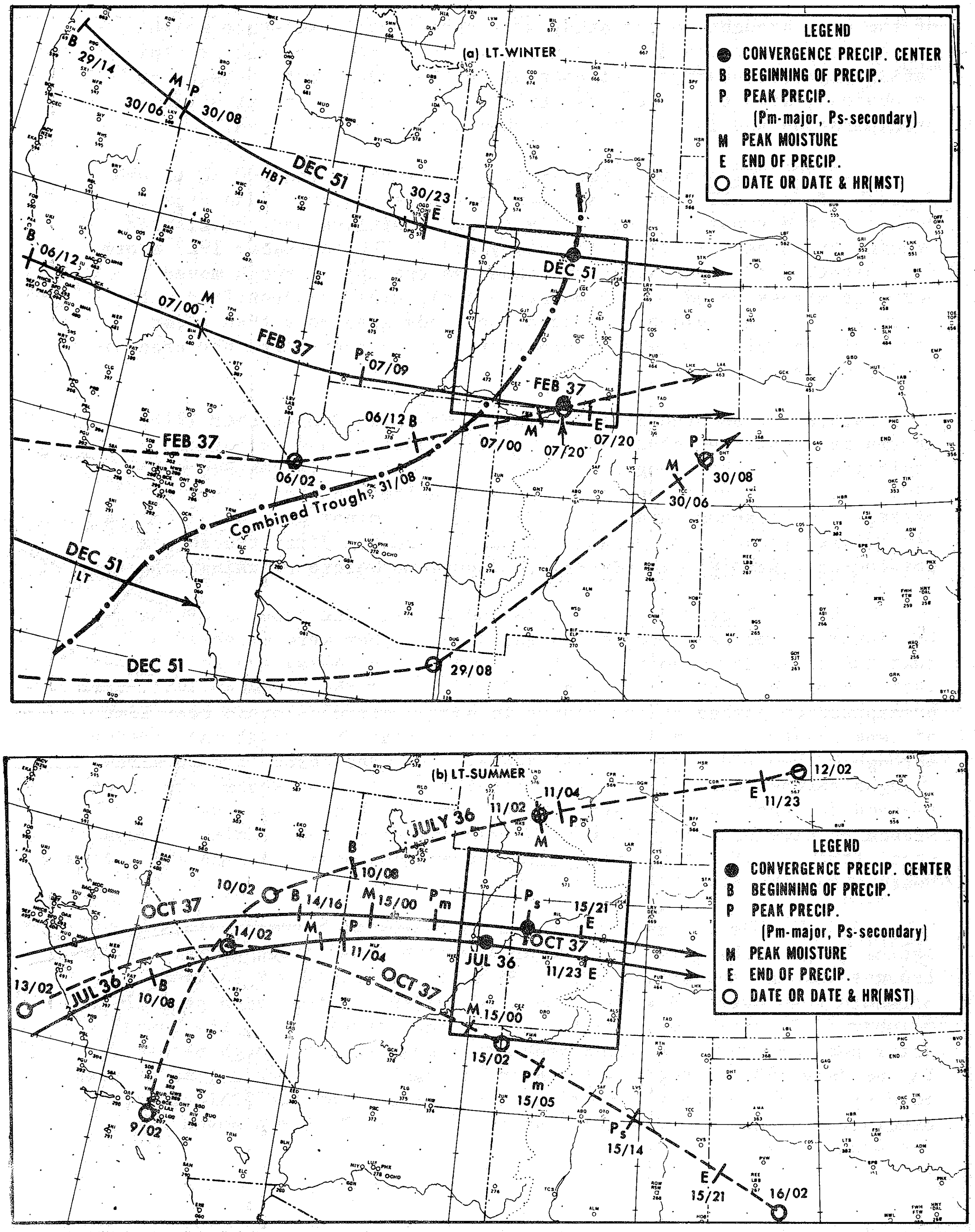


Figure 4-7. Tracks of 700-mb moisture (----) and lines drawn normal to daily positions of 500-mb troughs (——) through the convergence precipitation centers in LT type storms.

4.5.24 Tropical storms (fig. 4-8). The three tropical storm tracks varied considerably in longitude of northward movement, from 111° to 117°W. Longitude. The most intense storm in the study area (October 1911) entered farthest east through eastern Arizona (fig. 4-8a). There it filled on the morning of the 5th after an HBT-C Low had formed over southern Nevada and shortly before time of peak precipitation in southwestern Colorado. Moisture probably reached a peak in southwestern Colorado near time of peak precipitation intensity. This is based on the evidence which indicates that the center of moisture aloft usually precedes the surface center of the tropical circulation by a considerable distance, a feature also of many hurricanes moving northward from the Gulf of Mexico [11].

4.5.25 The tropical center in the 1939 storm (fig. 4-8b) moved northward across northern Baja California and filled on the morning of the 6th near the California-Arizona border. Meanwhile, an HBT trough was approaching the study area. The two peaks in precipitation are loosely associated with two peaks of moisture. The precipitation sequence on the afternoon of the 5th followed an initial influx of moisture far in advance of the tropical storm. The second precipitation period occurred the following afternoon with approach of the HBT trough and as the main moisture pool, oblong along a northeast-southwest axis, moved eastward across northern Arizona. There was not much difference in the intensity of the two precipitation periods.

4.5.26 A C-West Cut-off Low was the auxiliary circulation with which the October 1925 tropical storm combined after moving northward to near San Diego (fig. 4-8c). A minor peak in precipitation occurred on the night of the 4th but the brief intense major peak followed on the afternoon of the 6th as the combined upper Lows moved into southern Utah, and presumably with peak moisture.

C. Summary and Comparison

4.6 Summary

4.6.1 Positions of 500-mb Lows. In figure 4-9, the location of each 500-mb Low center (for those qualifying storms having 500-mb Low centers) is plotted on a latitude grid relative to the convergence precipitation centered at the time of peak precipitation at this center. In most storms the 500-mb Low was in the western semi-circle relative to the precipitation center. Their positions covered a wide range of distances. In only a minority of the storms were the Low centers close enough to the precipitation centers during the main precipitation sequence to determine the location of precipitation centers within the study area.

4.6.2 Positions of 500-mb troughs. The shortest distance from each precipitation center at time of peak precipitation to the approaching 500-mb trough (taken from the composite maps of troughs,

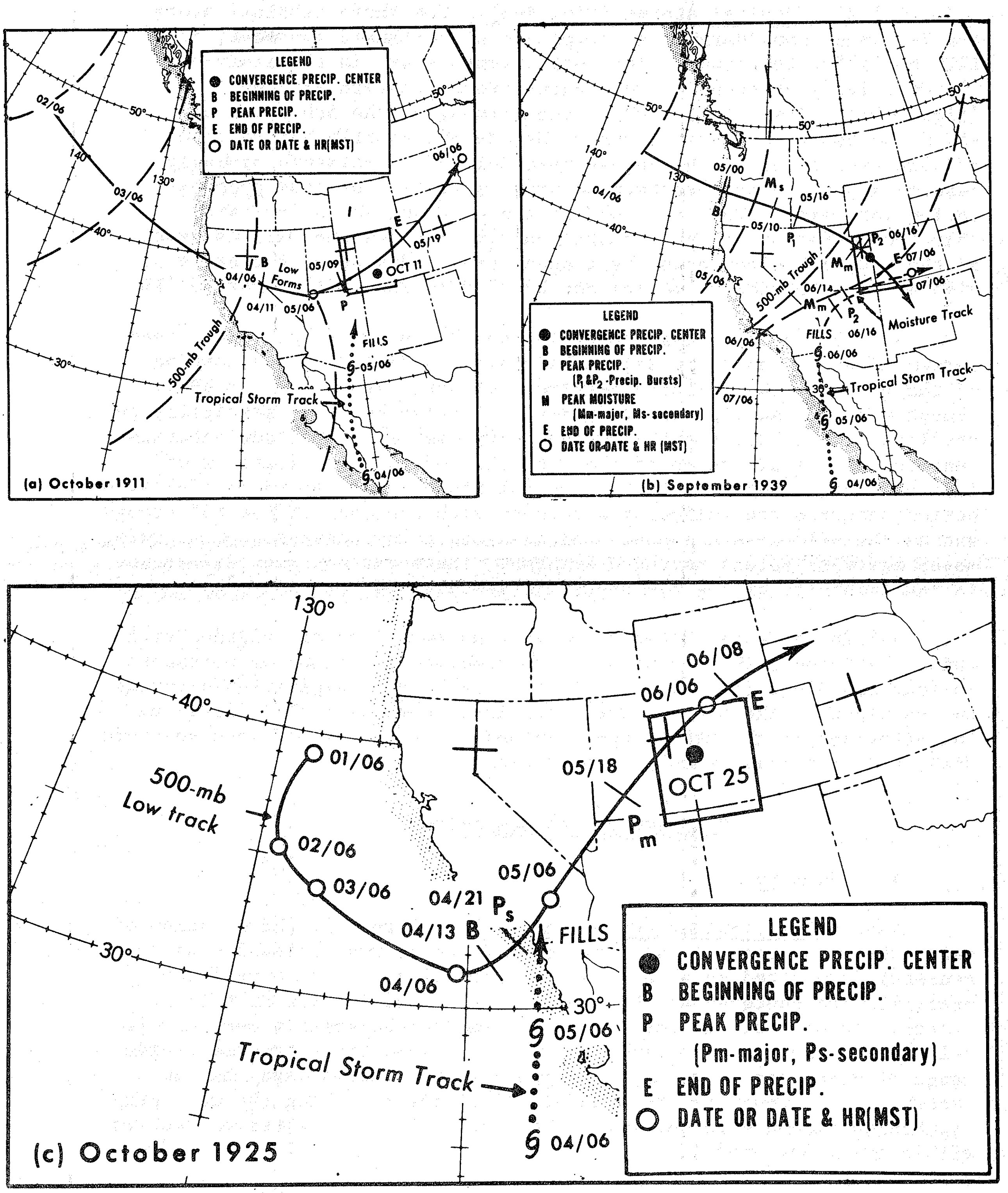


Figure 4-8. Tracks of tropical storms and positions of auxiliary troughs (— —) and/or Low tracks (——) at 500 mbs.

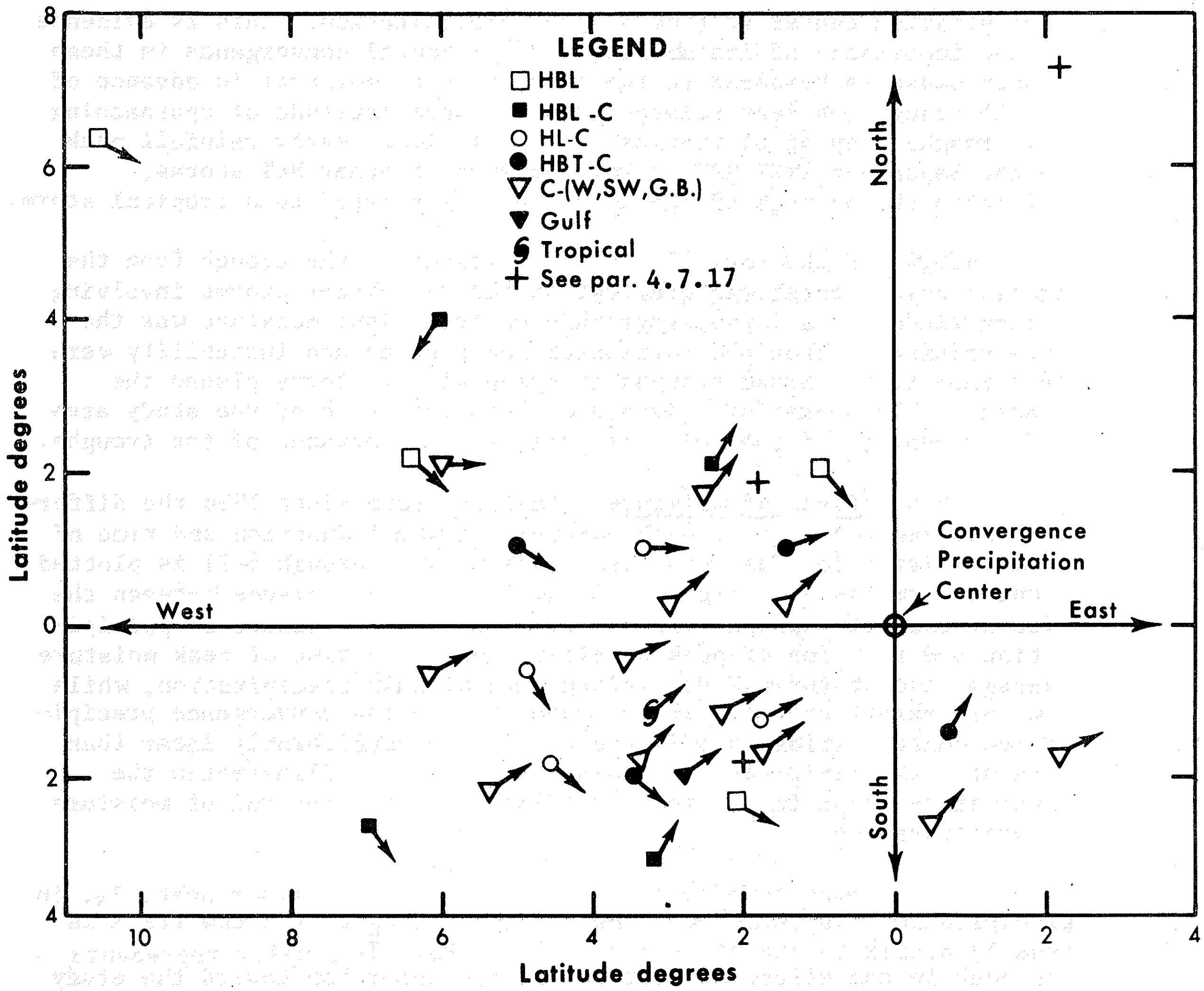


Figure 4-9. Positions of 500-mb Lows relative to convergence precipitation centers at time of peak precipitation. Arrows are parallel to tracks of Lows. (See Section 2.3 for explanation of storm-type abbreviations.)

figs. 4-6 and 4-7) is plotted on figure 4-10 in degrees of latitude to correspond with distances in figure 4-9.

4.6.3 The important distinction between the control on precipitation of the HBT trough and that of the LT trough is shown in figure 4-10. Three of the four HBT troughs were very close to the precipitation center at time of peak precipitation. This is evidence of the importance of instability and horizontal convergence in these trough passages compared to the importance of moisture in advance of the LT troughs, a fact related to the higher latitude of approaching HBT troughs than of LT troughs. The relatively early rainfall peak in the September 1927 HBT storm, compared to other HBT storms, reflected the passage of the moisture pool related to a tropical storm.

4.6.4 Of the four LT storms, distance of the trough from the precipitation center was greatest in the two winter storms involving strong winds and a large orographic contribution; moisture was the more critical factor and horizontal convergence and instability were less important. Broad troughs in these winter storms placed the tracks of the center of moisture well to the south of the study area and the centers of the moisture pools well in advance of the troughs.

4.6.5 Effect of moisture. In each storm since 1936 the difference between the time of peak moisture at Grand Junction and time of peak precipitation (as presented in figs. 4-1 through 4-7) is plotted along the abscissa in figure 4-11 against the difference between the time of closest approach of the 500-mb Low to the center of precipitation and the time of peak precipitation. The time of peak moisture averages two or three hours before time of peak precipitation, while time of nearest approach of the upper Low to the convergence precipitation center varies greatly and usually is considerably later than time of peak precipitation. This figure further illustrates the conclusions drawn in section 4-3 relative to the control of moisture on precipitation.

4.6.6 Combined effect. In several storms a minor peak, P_s, in precipitation was detected. The position of P_s on the Low track is usually closer to the study area than is P_m. It usually represents the peak in the effect of approach of the upper Low toward the study area, while the earlier main peak is more closely related to time of highest moisture over the precipitation center. Whether there was a secondary peak or not, the continuation of precipitation many hours beyond time of peak intensity usually is evidence that the moisture pool was well ahead of the Low, and as its effect waned, that of the upper Low increased. The net effect usually is an early peak in the precipitation sequence, as represented by points in the lower part of figure 4-11. Two of the points in the upper right quadrant involve continuation of high moisture beyond the time of its peak in C-West storms when the Low passed south and east of the precipitation center (fig. 4-5a).

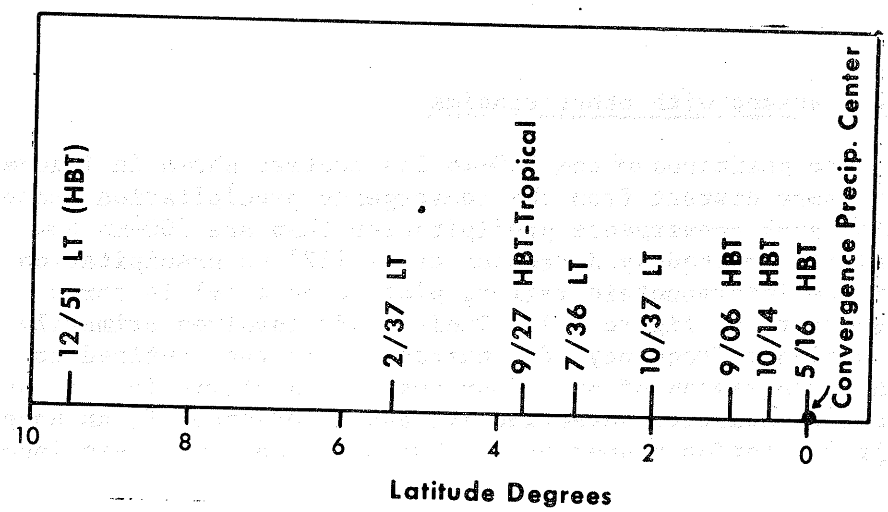


Figure 4-10. Shortest distance from convergence precipitation center to the 500-mb trough line at time of peak precipitation. Month, year and type of each storm is indicated. (See Section 2.3 for explanation of storm-type abbreviations.)

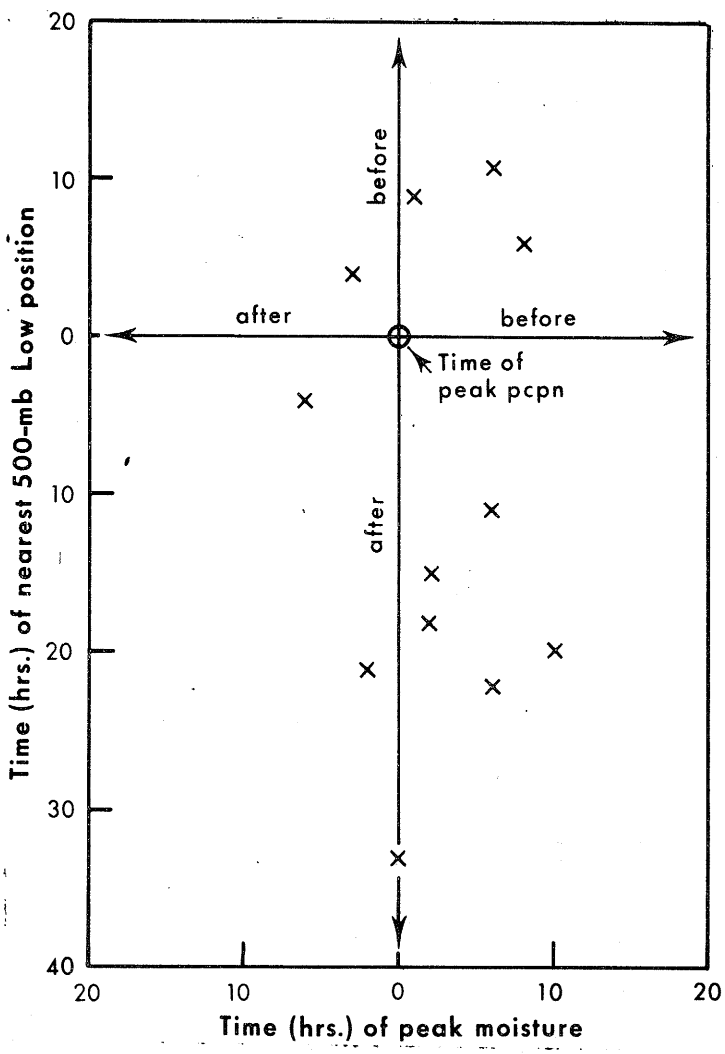


Figure 4-11. Difference in time (hours) between peak precipitation and (1) occurrence of peak moisture and (2) the nearest position of the 500-mb Low to the convergence precipitation center. Storms are from 1936 to 1965.

4.7 Comparison with other studies

4.7.1 The positions of the 500-mb Low centers shown in figure 4-9 are generally more distant from the convergence precipitation centers at the time of peak convergence precipitation than are 700-mb Low centers similarly related by Jorgenson et al [12] to precipitation centers over the intermountain region, plotted as a (+) in three different quadrants of figure 4-9. Their study involved primarily storms with a higher frequency of occurrence. It was confined to winter months, the season of only four qualifying storms in this study. Hence the role of moisture advection by, and in advance of, an upper Low in the precipitation sequences of that study was much less important.

CHAPTER 5. OROGRAPHIC PRECIPITATION

5.1 Definition

5.1.1 Orographic precipitation is that part of precipitation which falls as a result of the lifting of moist air over a barrier such as a mountain range. Orographic precipitation may begin some distance upwind of the base of steep slopes and continue for several miles to the lee of the barrier. Orographic precipitation on the windward side of the crest is termed "upslope" precipitation and that on the lee side "spillover" precipitation.

A. Factors in Orographic Precipitation

5.2 Upslope precipitation

5.2.1 Briefly stated, the amount of upslope precipitation falling on a slope increases with the height, breadth, and steepness of the slope, the wind component normal to the slope, the amount of moisture and the degree of saturation and instability of the air. If the air is unstable, lifting by the terrain stimulates showers on the windward slopes, part of which may be carried to the lee of the ridge.

5.2.2 Complications in the study area. The terrain in the study area is so complicated that only at higher elevations on the south side of the San Juan crest and near the crest of the Continental Divide are there broad slopes free of upwind barriers to moisture inflow. But few precipitation records at stations near these slopes indicate the orographic precipitation falling thereon. Most stations are in valleys protected from strong upslope effects by mountains immediately upwind.

5.3 Spillover precipitation

5.3.1 The distance to which spillover extends in a storm depends primarily on the fall rate of the hydrometeor, the horizontal wind velocity, proximity of downwind mountains, height of upwind barriers and the vertical fall distance. Average snow level in qualifying storms listed in column 5 of table 2-5 is about 10,000 feet above mean sea level. The high snow level served as one limitation on the horizontal extent of spillover precipitation because of the much faster fall rate of rain. While high winds are typical of most storms in free air above ridges they drop off and change direction in lee valleys, thus limiting horizontal displacement of hydrometeors as they descend into a valley. But counteracting this effect in narrow valleys is the effect of downwind ridges to limit this descent.

5.3.2 The variability of spillover precludes assigning limits to distances from a ridge beyond which spillover is ineffective and depletion begins in broad valleys. In narrow valleys it is often uncertain whether orographic precipitation reflects more or less spillover than upslope effect from nearby slopes downwind.

5.4 Precipitation depletion

5.4.1 The isohyetal maps of many of the qualifying storms show characteriestic minimum precipitation areas, for example, the San Juan and upper Gunnison River valleys. This depletion of precipitation by barriers upwind is especially noticeable in broad valleys to lee of considerably higher terrain either in the study area or farther upwind. The depletion increases with the drop-off in elevation to the lee of the ridge.

5.4.2 Peripheral barriers. The study area is surrounded by barriers, either close by or distant. The mountains comprising the Continental Divide reduce moisture entering the main portion of the study area from the northeast through east to southeast, but least from northeast. Hence, moisture may reach the study area by a circuitous route from the Gulf of Mexico across the rather low Continental Divide in Wyoming. The distant Sierra Nevadas, smaller ranges in Nevada and the nearby Wasatch Mountains of central Utah are barriers to moisture inflow from the west-northwest to west-southwest. Moisture from south-southwest and south is depleted in lower levels by higher upwind terrain in east-central Arizona and west-central New Mexico, respectively, before crossing the San Juan Valley. Inflow to the study area from southwest by way of the Colorado River Valley is less depleted by upwind terrain.

5.4.3 Local barriers. In addition to peripheral barriers to precipitation, the high ridges within the study area create precipitation shadows. For example, portions of the Gunnison River Valley and the lower Uncompahgre River Valley are strongly lee areas to the San Juan Mountains and Uncompahgre Plateau for south and southwest winds, respectively. The North Park area in north-central Colorado is sheltered from all directions but north. Many other locations within the study area could also be cited.

B. Orographic Precipitation Index

5.5 Purpose

5.5.1 The complications of terrain outlined in the previous section indicate the difficulty in evaluating orographic effects in a given storm. This section provides a broadscale index which represents the areally averaged role that terrain plays on a qualifying storm precipitation pattern (enhancing it on windward slopes and depleting it on lee slopes), compared to the role in the average storm.

5.6 Definition of index

5.6.1 The orographic index (I) is an indicator of the intensity of orographic effects observed in a storm compared to average effects. It is defined as:

$$I = R_s/R_n = \frac{(\Sigma o)_s}{(\Sigma c)_s} \div \frac{(\Sigma o)_n}{(\Sigma c)_n}, \text{ where}$$

o = orographic component at slope station (approximated by slope station precipitation minus valley station precipitation).

c = convergence component at slope station (approximated by the valley station precipitation).

R = sum of orographic precipitation at slope stations over sum of convergence precipitation at slope stations.

s & n are subscripts for storm and normal monthly, respectively.

Sample pairs of valley and upslope stations are joined on figure 5-1 for southwest inflow.

5.6.2 Explanation of parameters. The differences in storm precipitation amounts on slopes and at valley stations upwind comprise the basic data on which the orographic index is based. Most of the difference is the orographic precipitation at the upslope station, added to the convergence precipitation. In addition, if the valley station is a lee station to upwind barriers in a particular storm, a part of the difference is the depletion of convergence precipitation at the valley station. For our purposes, it suffices to assume that valley precipitation represents the convergence component of nearby upslope precipitation. The effect of upwind barrier depletion of the valley precipitation is later reduced by normalizing (i.e., storm/normal).

5.6.3 Use of means. Mean monthly precipitation amounts provide a base for normalizing R_s for season. For example, values of R_n obtained from mean October precipitation (fig. 5-1) adjust values of R_s in a particular October storm.

5.7 Application to the study area

5.7.1 An average orographic index is most meaningful if it represents an area in which values are comparable. A logical geographical boundary for averaging is the San Juan crest, with its general east-west orientation located so that about one-third of the study area is to the south and two-thirds to the north of the crest.

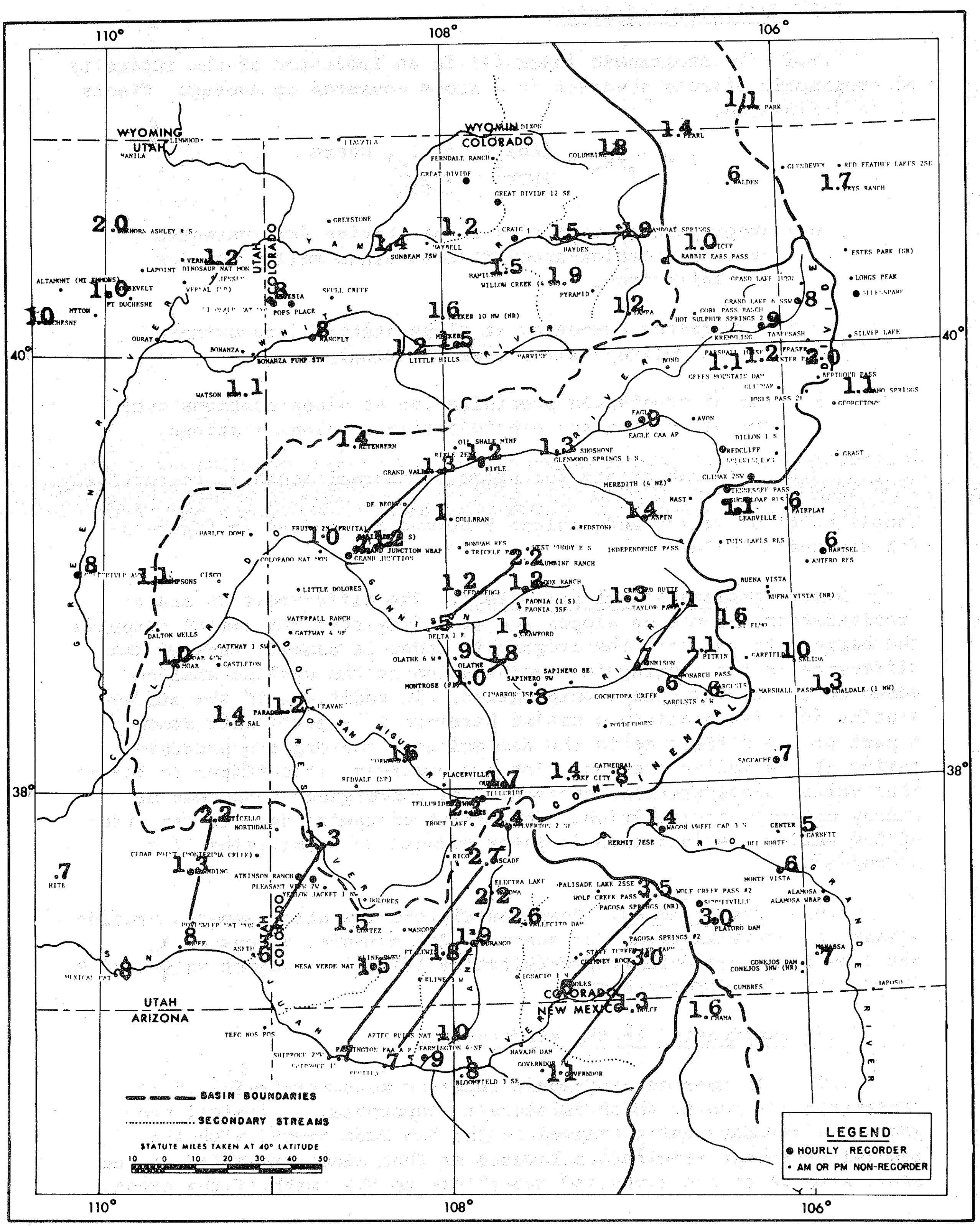


Figure 5-1 Mean October precipitation (in.). Lines connect preferred station pairs for determining orographic indices.

Major orographic effects to the south of this barrier often are associated with relatively minor effects at precipitation stations to the north.

5.7.2 For each storm an average index value (I) was based on data for several pairs of stations south of the San Juan crest. These pairs combine stations near the San Juan River Valley with those in higher terrain or near fairly steep slopes to the north. An example of height difference is Dulce (6950 ft.) and Palisade Lake (9230 ft.) in the San Juan headwaters, paired for south winds.

5.7.3 An average index value (I) for each storm was obtained also over the large area from north of the San Juan crest to the Wyoming border. Suitable pairs were selected depending on prevailing upper-wind direction and orientation of the convergence precipitation pattern. This area has few well-defined windward stations except for unusual wind directions. For example, most of the stations near but west of the Continental Divide are to lee of an upwind barrier for most wind directions. Station pairs represent the usually small contrast between precipitation at a valley station subject to lee depletion (e.g., Gunnison) and that at a foothill station with high nearby elevations that cause either upslope or spillover effects on the station precipitation (e.g., Crested Butte).

5.8 Comparison of indices

5.8.1 The orographic indices for each storm are shown in columns 7 and 8 of table 2-5 for the areas to the north and to the south of the San Juan crest, respectively. Figure 5-2 is a plot of the data from these columns. The index varies among qualifying storms from a high of 6 south of the San Juan crest to a slightly negative value to north of the San Juan (less precipitation at slope stations than at valley stations). South of the San Juan crest, where a high orographic index is typical of many qualifying storms, the average index for the 42 storms studied is 1.9. (The index that would be associated with a storm with average orographic effects is 1.0). North of the San Juan crest, the average index is 1.1.

5.8.2 North versus south. Figure 5-2 shows that there is poor correlation between index values on south-facing San Juan slopes and those for the portion of the study area north of the crest. Strong winds that result in large index values on south San Juan slopes may add little to orographic precipitation at stations rather poorly exposed to either upslope or spillover effects of southerly flow at stations north of the crest.

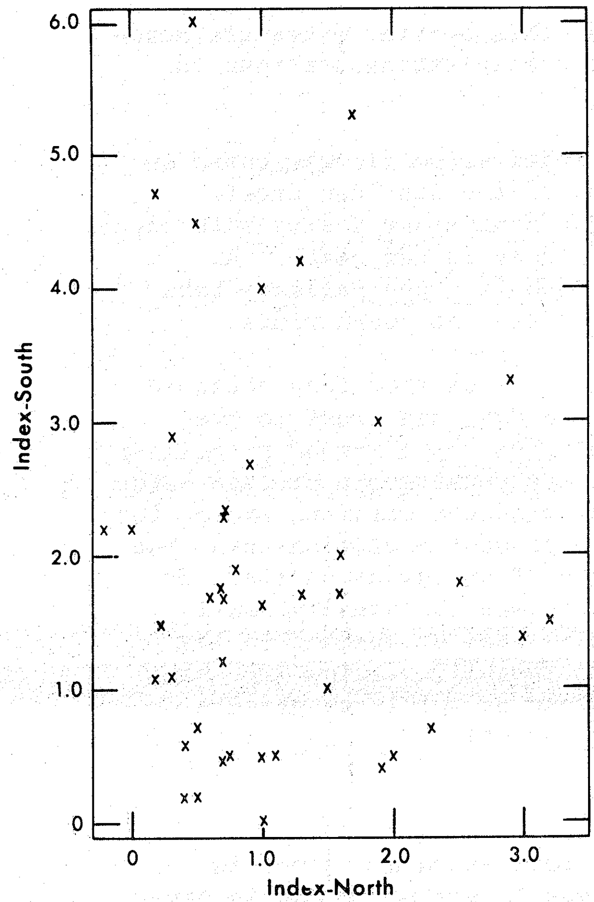


Figure 5-2. Orographic index south of San Juan crest versus index to the north.

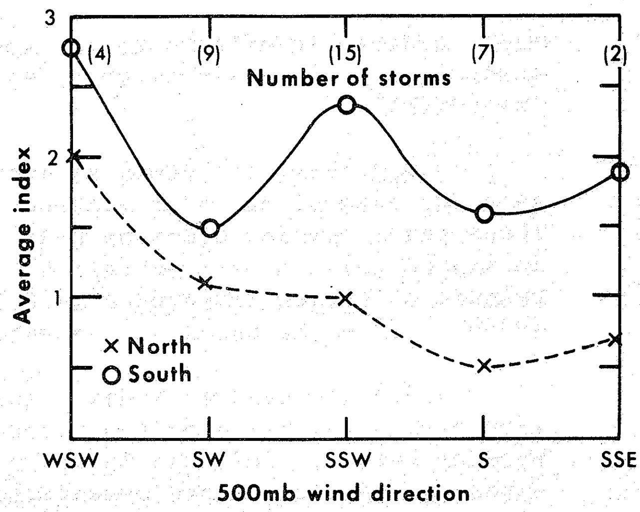


Figure 5-3. Orographic index to north and south of the San Juan crest stratified by 500-mb wind direction. (Not included are five storms with other directions or variable winds.)

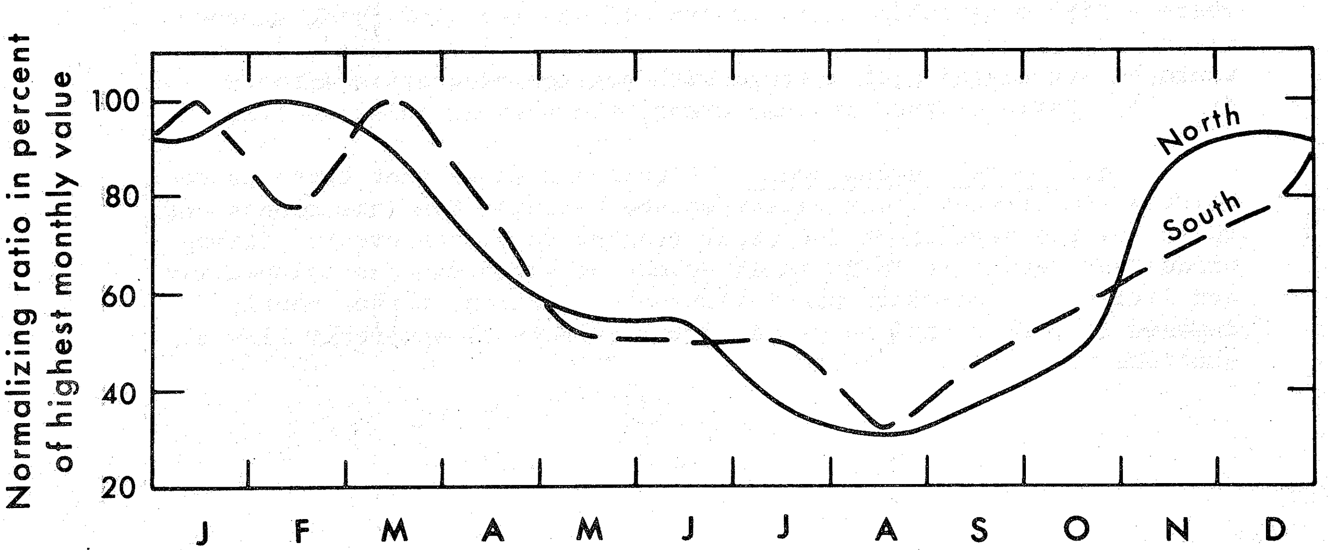


Figure 5-4. Monthly normalizing ratio(Rn) north (____) and south (---) of the San Juan crest, as percent of highest monthly value.

5.8.3 Independence of storm type. Table 5-1 shows orographic indices, averaged by storm type, both north and south of the San Juan crest. (The one MT storm is omitted.)

Table 5-1. Variation of orographic index by storm type

Storm Type		HBL HBT	HBL-C HBT-C HL-C	C	LT	Tropical	Gulf
Number of storms		8	12	11	4	3	3
Average 500-mb wind direction		SSW	SSW	SSW	SW	SSW	S
Orographic	North	1.5	0.8	1.1	1.8	0.8	0.8
Index	South	1.3	2.4	1.4	2.9	1.8	0.8

5.8.4 The exceedance of the index to the south over that to the north is greatest in the H-C types involving recently formed Cut-off Lows. Their strong winds, from a generally south-southwest direction over the study area are favorable for a high index to the south and relatively low index to the north. Indices averaged highest in LT storms, half of which were winter storms. Further explanation of these variations is not attempted.

5.8.5 Effect of mean storm wind direction. The mean upper-level wind direction during precipitation, estimated for each storm, is shown in column 10 of table 2-5. In storms of several days duration, a mean wind direction representing a range of directions may smooth out day-to-day effects of topography on precipitation. Index values to the north and to the south of the San Juan crest are averaged by 500-mb wind direction in figure 5-3. The relative orographic effects in the two areas are somewhat dependent on wind direction. Lower average index values to the north than to the south are apparent for all directions shown, with the least difference for southwest winds. The high average indices with west-southwest winds reflect strong persistent winds in two of the four cases (June 1943 and December 1951). Wind direction is only one of the variables determining the index. Others include wind speed and the convergence component of precipitation.

5.9 Seasonal variations

5.9.1 Seasonal variation of index. One purpose of adjusting storm orographic effects for season by use of the monthly ratio R_n of paragraph 5.6.1 is to reduce their seasonal variation so that values may be compared without regard to season. But there is still some seasonal variation remaining in storm orographic indices averaged north and south of the San Juan crest by season (table 5-2). For example, values to the south are high in qualifying winter and summer storms compared to spring and fall storms, and greater than in the average storm (i.e., 1.0) in all seasons.

Table 5-2. Seasonal variation of storm orographic indices.

		Fall	Winter	Spring	Summer	Total
Number of storms		28	4	8	2	42
Average orographic index	North	1.0	1.4	1.4	.6	1.1
	South	1.7	3.0	1.8	3.1	1.9

5.9.2 Effect of seasonal variation of R_n on I. The normalizing ratio R_n is the denominator of the index $I = R_s/R_n$(par. 5.6.1). The variation of R_n by months, averaged for each of the two areas (north and south of the San Juan crest) is shown in figure 5-4 in percent of the highest month. Eleven pairs of stations are involved in the average to the north and eight to the south. The ratio R_n is highest in the months January to March and lowest in August.

5.9.3 Table 5-2 indicates much higher orographic effects south of the San Juan crest in the four winter qualifying storms than in the average winter storm, in spite of a high R_n in this season. A lesser exceedance is typical of fall and spring storms.

5.9.4 Evidence of seasonal variation in January/October normal precipitation. The ratio of January/October normal precipitation serves to illustrate the seasonal variation of R_n. This ratio compares precipitation during typical winter and fall months (fig. 5-5). Two important factors influence the pattern of ratios of January/October mean precipitation. First, orographic effects (increase on windward slopes and depletion in lee areas) are greater in January than in October because of stronger winds in January. Hence, values on the ratio map of figure 5-5 are high on windward slopes and low in normally lee areas. Second, the "windward" and "lee" areas are shifted from October to January by a shifting mean storm wind direction, which has a a greater westerly component in January than in October.

5.9.5 On San Juan slopes and near the Continental Divide, ratios of figure 5-5 are highest where a westerly component is most nearly upslope. The low ratios east of the Continental Divide and near the Green River reflect greater depletion by a westerly wind component in January. In the Gunnison area (ratio greater than 1) there is less depletion from barriers to the west in January than to the south or southwest in October.

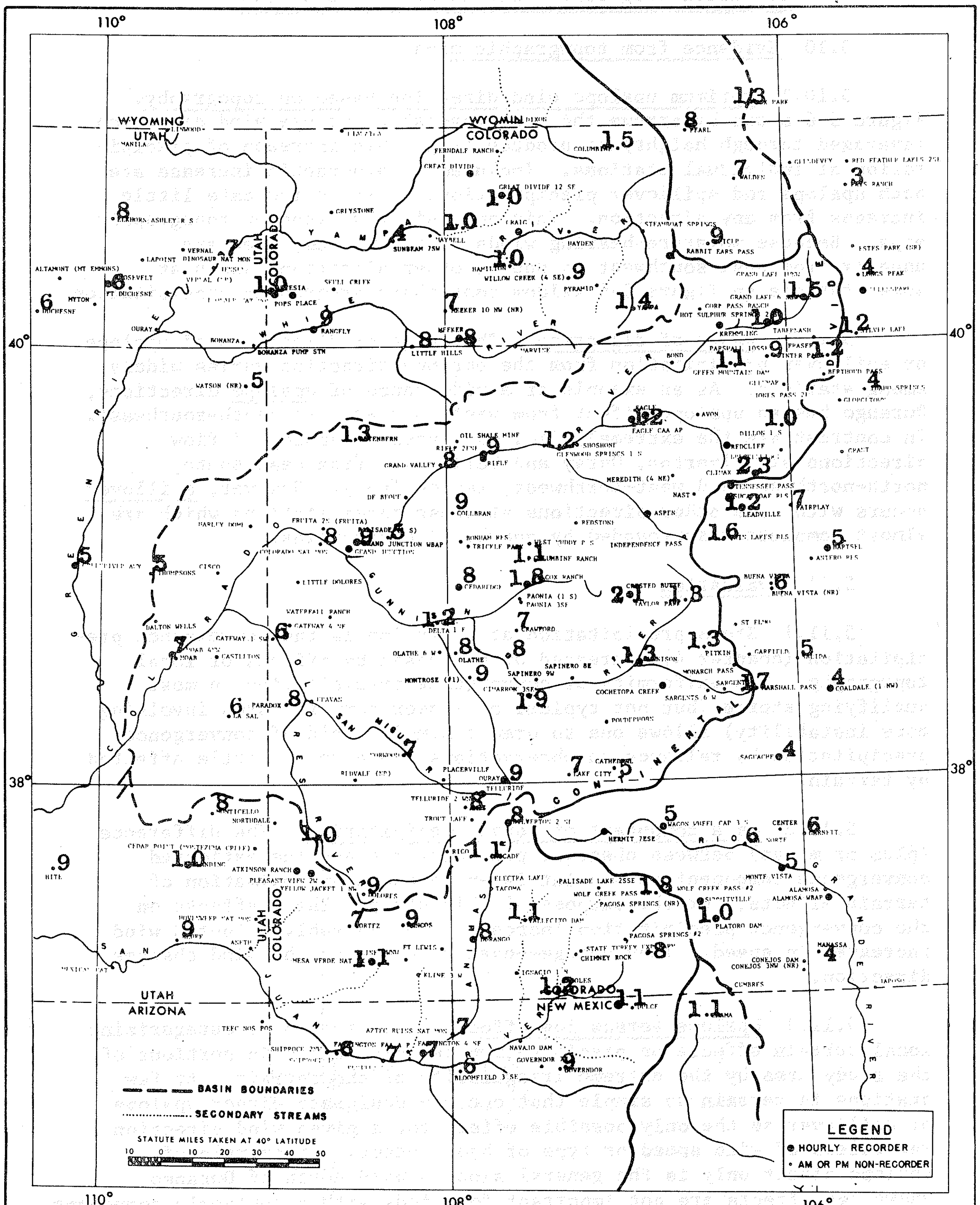


Figure 5-5. Ratios of mean monthly precipitation (Jan./Oct.).

C. Local Orographic Effects on Precipitation

5.10 Evidence from topographic maps

5.10.1 Optimum upslope wind direction based on topography. Figure 5-6 shows by arrows the most favorable upslope wind direction (averaged through height) to produce orographic increase of precipitation at individual stations. Included in orographic increase are both upslope and spillover precipitation. Circles indicate little increase from any direction. This analysis was based on topographic maps. Because moisture-bearing winds over the study area are usually from west-southwest to south, other directions shown at some stations on figure 5-6 seldom contribute orographic precipitation.

5.10.2 Range of direction. The range of directions of upslope or spillover precipitation from the optimum direction varies widely among stations. As an example of a wide range of upslope directions, Durango has an upslope effect from west-southwest to south-southeast. In contrast are the extremely limited ranges of upslope inflow directions at Silverton, Ouray and Telluride, from near south, north-northwest and west-northwest, respectively. However, spillover occurs with some other directions at these three stations which are almost completely surrounded by nearby high mountains.

5.11 Evaluation

5.11.1 Storm precipitation at a station is the convergence precipitation (chapter 4) increased or decreased by effects of local topography. The uniformity of convergence precipitation in most qualifying storms (but not typical of lesser summer storms involving more instability) allows one to draw a simple field of convergence precipitation by reliance on observations known to be little affected by terrain.

5.11.2 As a component of total precipitation. The difference (plus or minus) between observed precipitation and the estimated convergence component at a point is an adequate approximation of terrain effects, for the purpose of this study. These effects on the convergence precipitation increase as a favorably oriented wind increases in speed. They change--even reverse--as the wind changes direction.

5.11.3 Upslope versus lee effect. The problem of categorizing local terrain effects on precipitation is complicated in portions of the study area by the extreme irregularity of the terrain. At few stations is terrain so simple that one can designate either upslope or spillover as the only possible effect for a given wind direction regardless of wind speed or type of hydrometeor. An example of upslope effect only is the general slope upward north of Durango where lee effects are not important for winds with a southerly component.

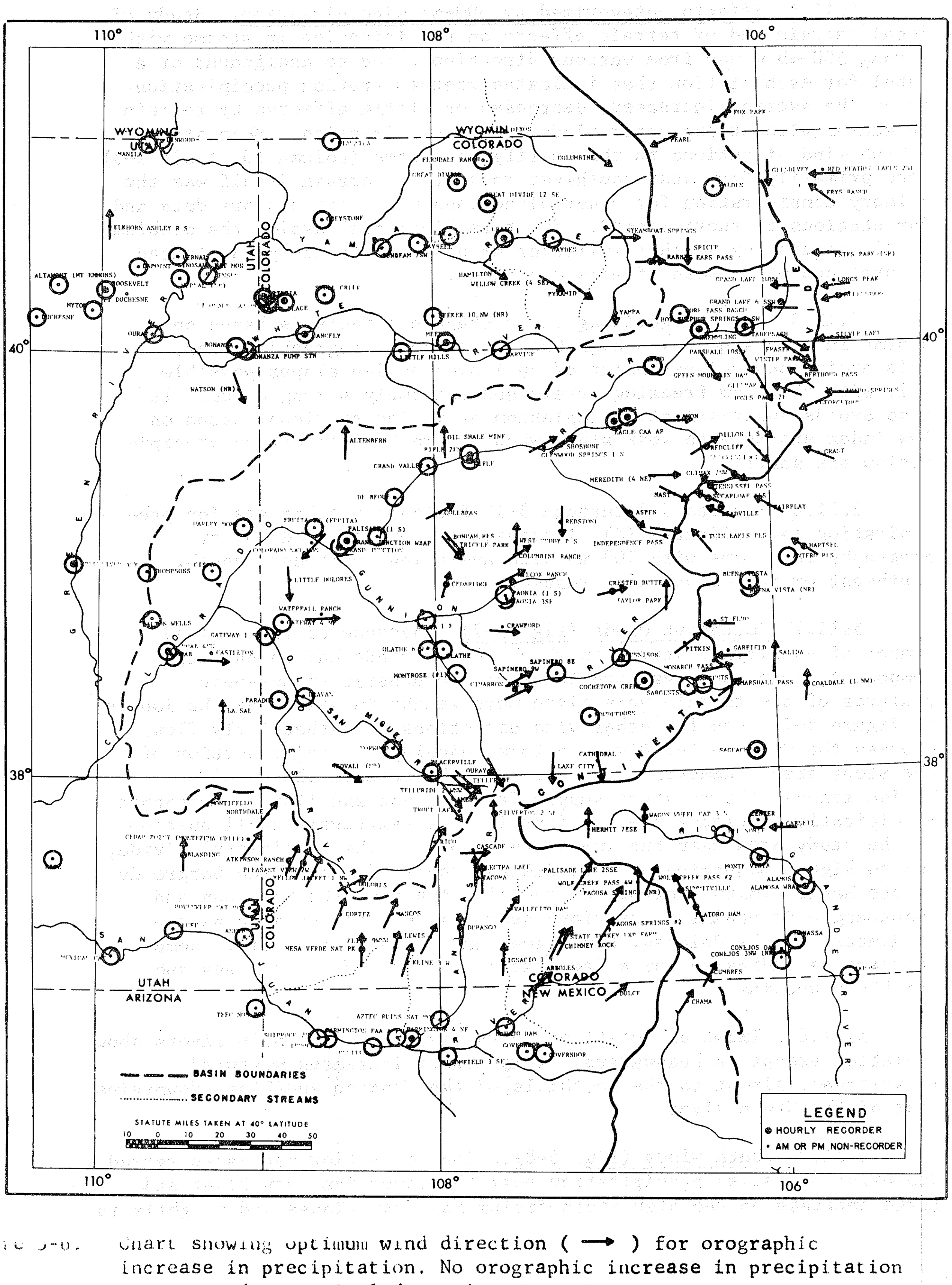


Figure 5-6. Chart showing optimum wind direction (⟶) for orographic increase in precipitation. No orographic increase in precipitation is expected at encircled stations.

5.11.4 Effects categorized by 500-mb wind direction. Study of local terrain and of terrain effects on precipitation in storms with strong 500-mb winds from various directions, led to assignment of a label for each station that indicates whether station precipitation is on the average increased, decreased or little affected by terrain in storms with strong upper winds from each direction. Mean storm 500-mb wind directions in the qualifying storms (column 10, table 2-5) were primarily from west-southwest to south. Terrain itself was the primary consideration for other directions with little storm data and for stations of short record. The term "increase" avoids the problem of distinguishing whether spillover or upslope effects predominated at stations where both effects can occur.

5.11.5 The categorizing of orographic effects is based on storms in this study with high but not extreme orographic index. This avoids unusual extension of spillover on lee slopes possible only with very low freezing levels and extremely strong winds. It also avoids underestimating depletion at valley stations, based on low index storms with weak winds when orographic effects on precipitation are small.

5.11.6 Figures 5-7 through 5-10 indicate whether station precipitation is unaffected (N), increased (I) or depleted (D) by orography in storms with 500-mb wind averaging southeast, south, southwest or west-southwest, respectively.

5.11.7 Southeast winds (fig. 5-7). Because of the limited number of qualifying storms in which 500-mb winds had an easterly component, (one southeast and two east-southeast), topographic features of the terrain were given more weight in assigning the labels of figure 5-7, than for other wind directions. Southeasterly flow crosses the Continental Divide before reaching the major portion of the study area. Removal of moisture on the eastern slopes of the Divide reduces the moisture supply farther west and limits orographic precipitation increase there primarily to a relatively small portion of the study area near the immediate slopes of the Continental Divide, and to higher mountains not far distant downwind. Also the Sangre de Cristo Range limits orographic precipitation over the San Juan and Uncompahgre Mountains to stations near high elevations such as the headwaters of the Dolores, San Miguel and Las Animas Rivers. Some increase is indicated for a few stations on or near Grand Mesa and the Elk Mountains.

5.11.8 Almost all stations in valleys along the main rivers show depletion except in headwaters. This effect increases westward (downstream) almost to the foothills of the Wasatch and Uinta Mountains west of the Green River.

5.11.9 South winds (fig. 5-8). Southerly flow can cause marked depletion of valley precipitation near the lower San Juan River and large increase on the high south-facing San Juan slopes and slightly to

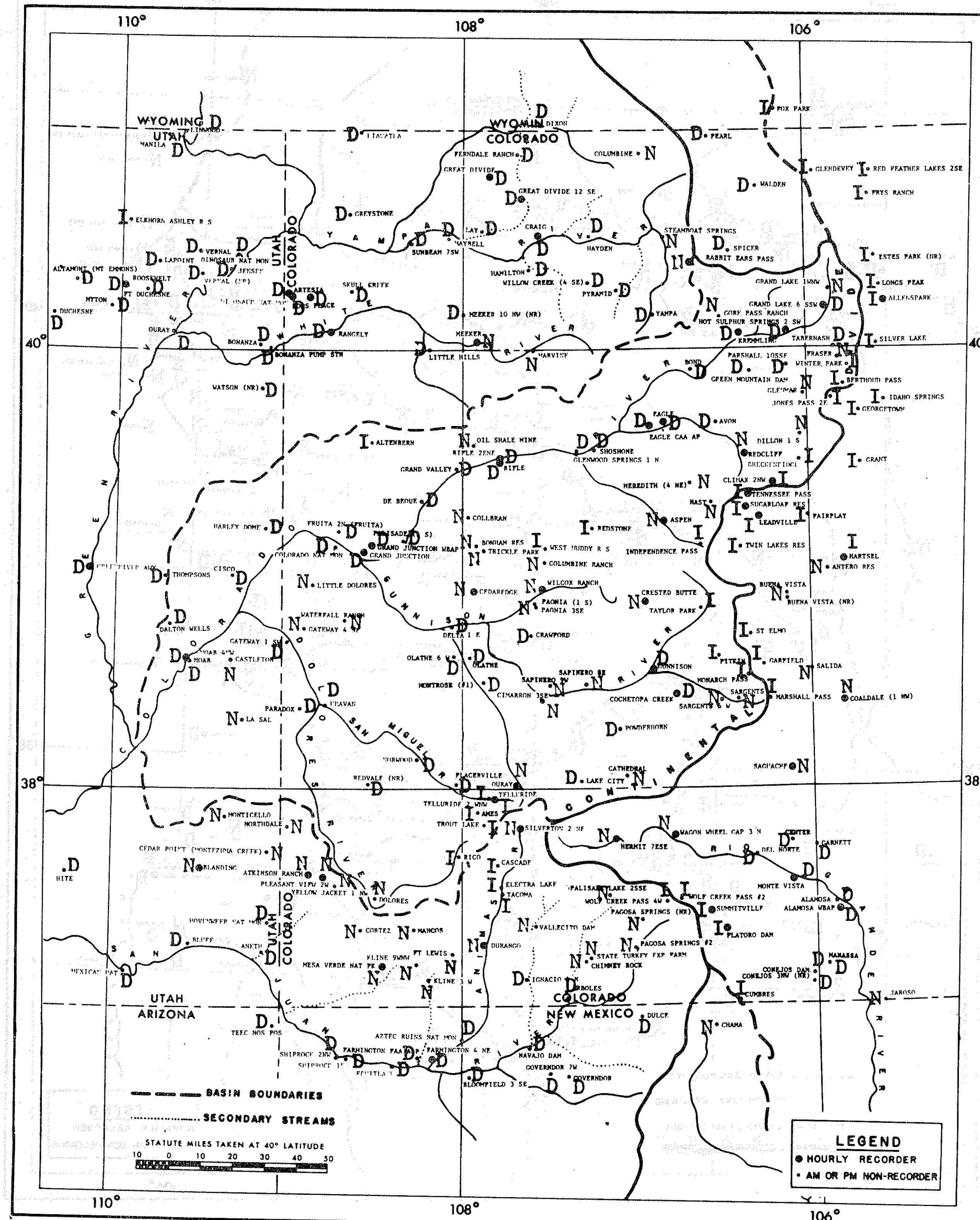


Figure 5-7. Local terrain effects on precipitation for southeasterly 500-mb winds. Letters indicate effects, observed in storms or estimated, to be depletion (D), no effect (N), or increase (I).

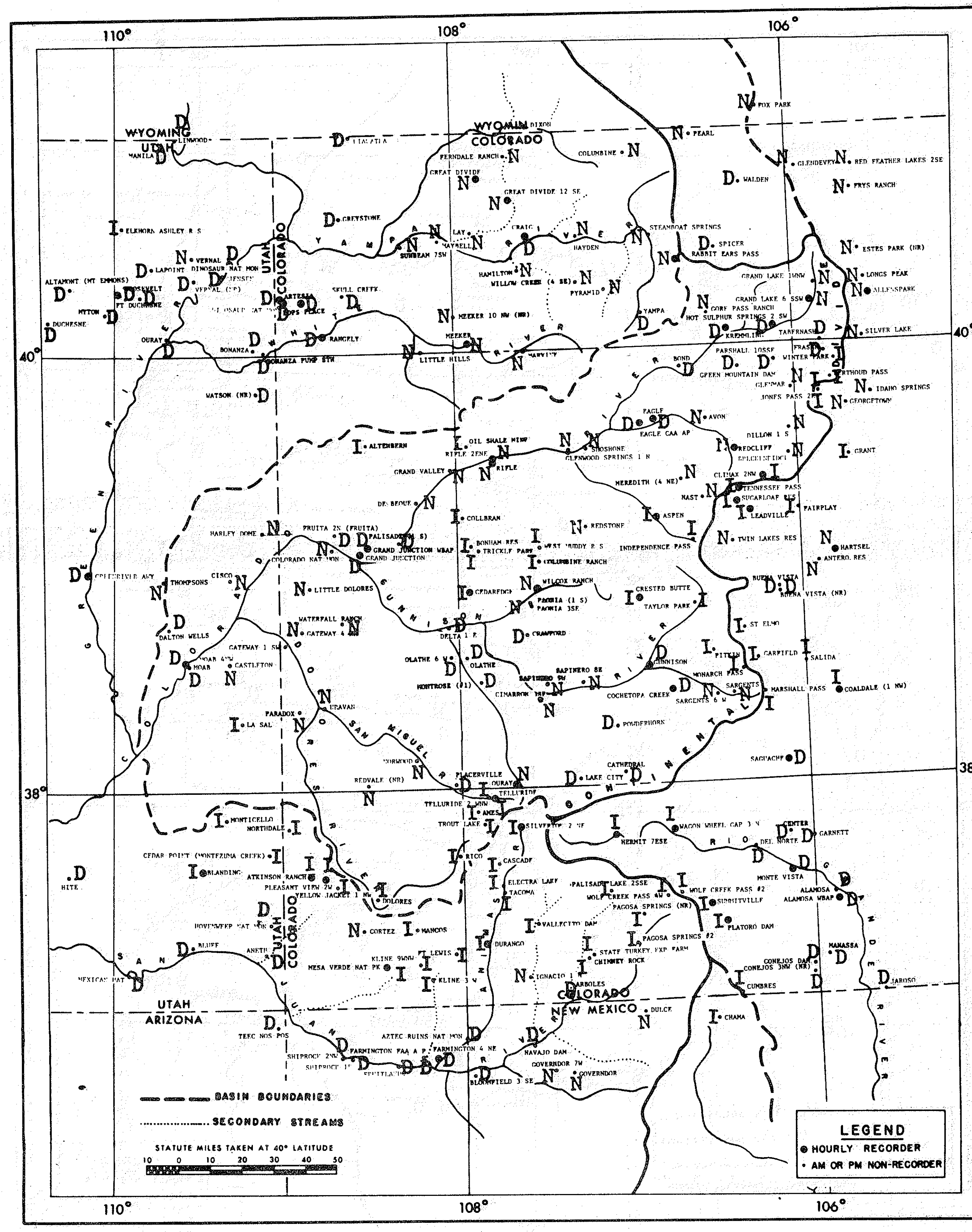


Figure 5-8. Local terrain effects on precipitation for southerly 500-mb winds. Letters indicate effects, observed in storms or estimated, to be depletion (D), no effect (N), or increase (I).

the lee. The loss of moisture in air crossing the San Juan Mountains limits increases northward to the Wyoming border to a few stations at high elevations or near high mountains. Examples of increase are stations near the Grand and Battlement Mesas, mountain valleys north of the Gunnison River and most stations near but not to the lee of the Continental Divide for southerly winds.

5.11.10 This loss of moisture causes depletion in the Uncompahgre River Valley, south slopes of the Upper Gunnison River Valley, the Grand Valley area around Grand Junction, the lower White River Valley and the Green River Valley, Utah. Depletion is shown also at most stations along the Upper Colorado River located in broad valleys (e.g., Eagle and Fraser).

5.11.11 Neutral areas include the upper portions of the White and Yampa River Valleys, the lower San Miguel and Dolores River Valleys, the Colorado River Valley between De Beque and Shoshone, and the east-facing slopes of the Divide.

5.11.12 Compared to southeasterly winds, southerly winds increase orographic precipitation on south San Juan slopes and, in general, decrease depletion north of the San Juan crest to the Wyoming border. Near the Continental Divide upslope effects either diminish or are reversed, especially those eastern slopes north of 40°N., which are well exposed to southeast flow.

5.11.13 Southwest winds (fig. 5-9). The terrain effects with southwest winds aloft become apparent by comparison with those for southerly winds (figs. 5-8 and 5-9). Depletion near the Green River is greater with southwest winds, as the role of the Roan and Tavaputs Plateaus is taken over by the Wasatch Range. Greatest orographic effects in the San Juan Valley shift to the east where exposure is better for southwest winds.

5.11.14 The labels at several stations in the area from 108°W. Longitude to the Continental Divide and from 38°N. Latitude to the Wyoming border change from (D) to (N) or from (N) to (I) with change in wind from south to southwest. At others there is a similar but smaller trend toward a positive orographic effect, even if not shown by change of label. Near the Divide this is because of a more favorable aspect; further west it is because of less depletion with southwest inflow from distant upwind barriers. The opposite is true at stations east of the Divide, where most labels change from (I) to (N) or from (N) to (D) with change in wind from south to southwest. Several change from (I) to (D), the dominant label for southwest wind.

5.11.15 West-southwest winds (fig. 5-10). Changes in terrain effects with west-southwest winds (fig. 5-10) from southwest winds aloft (fig. 5-9) are rather minor. Changes are mainly at stations

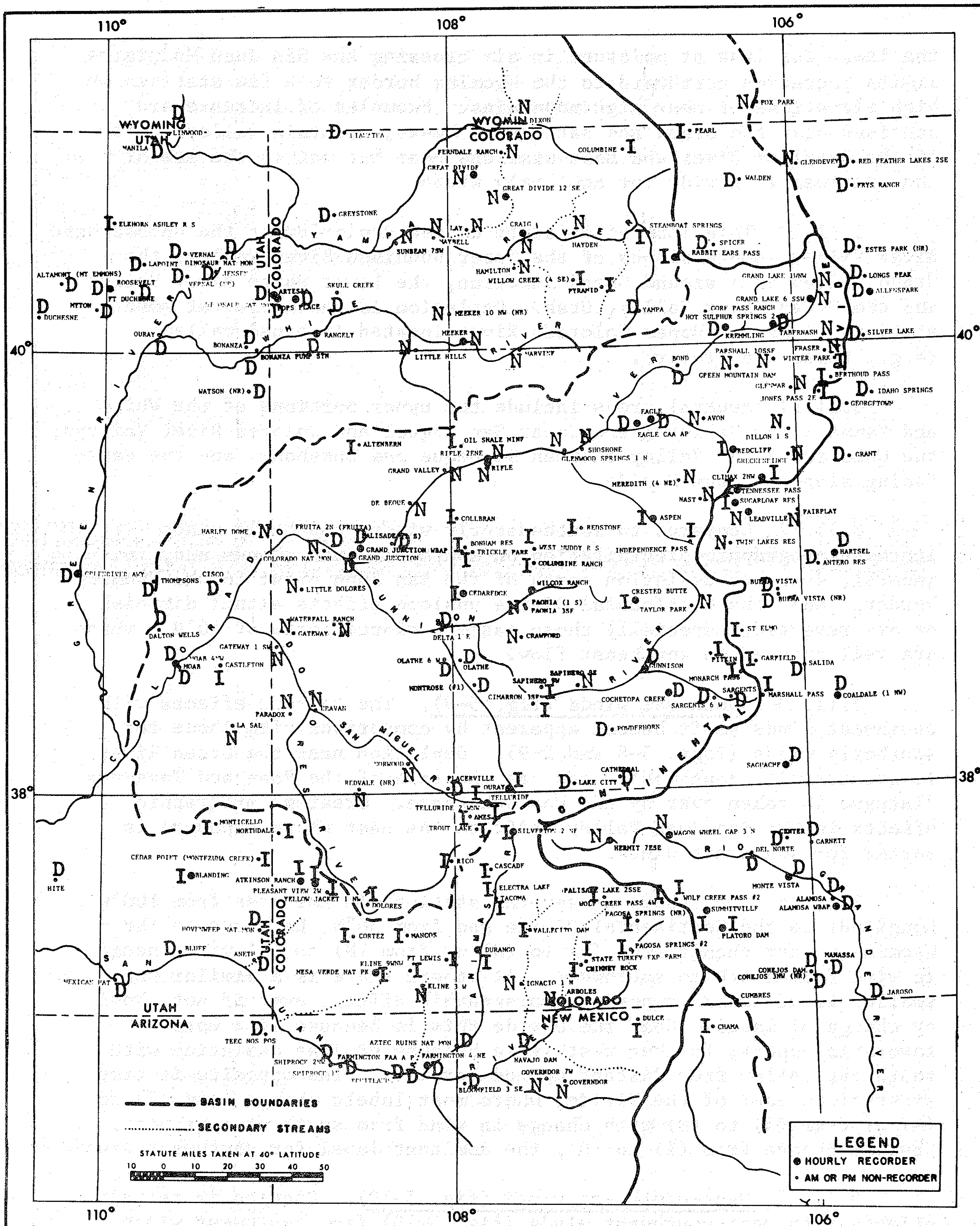


Figure 5-9. Local terrain effects on precipitation for southwesterly 500-mb winds Letters indicate effects, observed in storms or estimated, to be depletion (D), no effect (N), or increase (I).

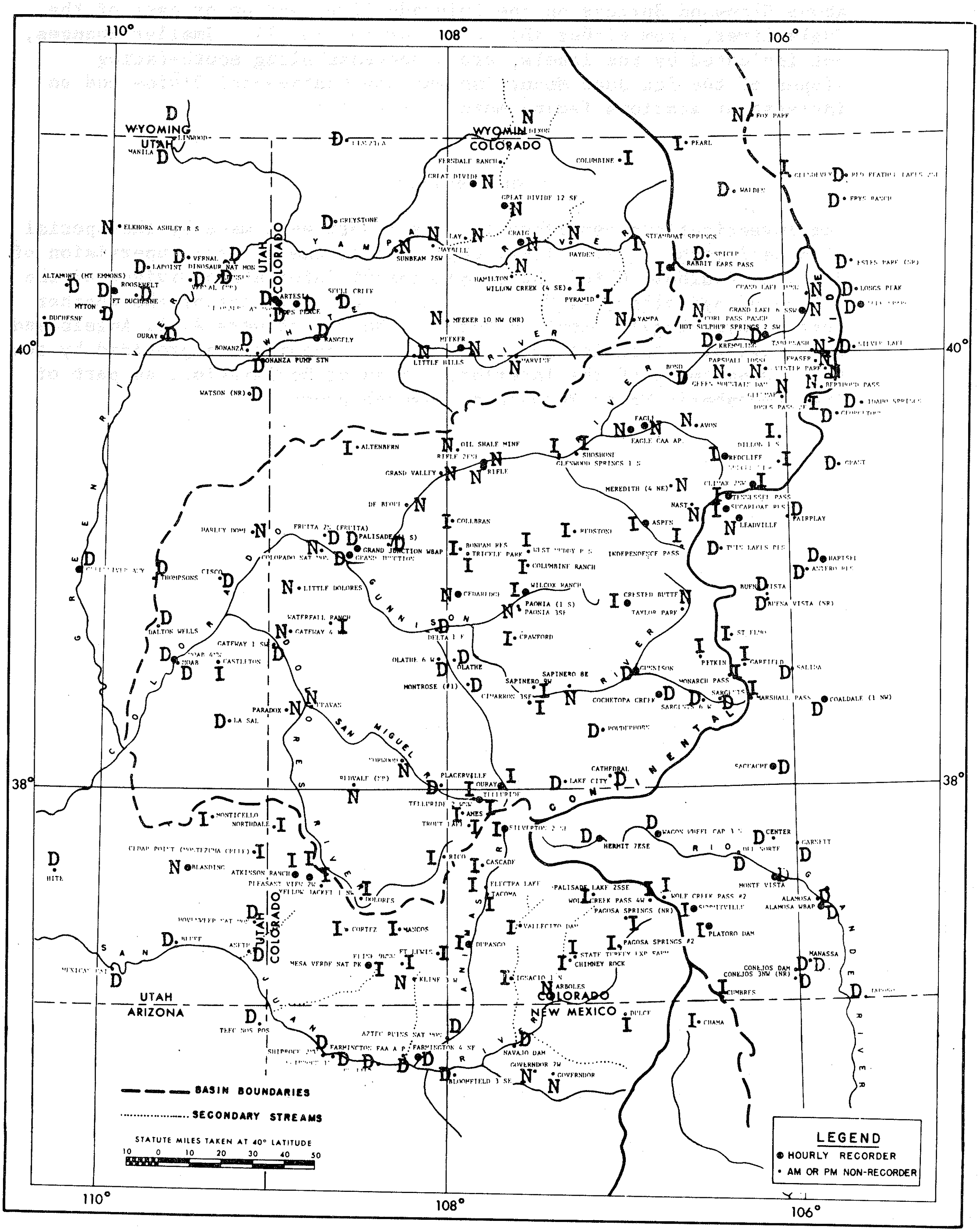


Figure 5-10. Local terrain effects on precipitation for west-southwesterly 500-mb winds. Letters indicate effects, observed in storms or estimated, to be depletion (D), no effect (N), or increase (I).

above Glenwood Springs on the Colorado River and on or east of the Eagle River, from either (D) to (N) or (N) to (I). Smaller changes, not indicated by the labels, are a decrease along south-facing slopes of the San Juan Mountains and the Continental Divide and an increase at stations facing more to the west.

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