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MOISTURE SOURCE FOR THREE EXTREME LOCAL RAINFALLS IN THE SOUTHERN INTERMOUNTAIN REGION

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MOISTURE SOURCE FOR THREE EXTREME LOCAL RAINFALLS IN THE SOUTHERN INTERMOUNTAIN REGION

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ABSTRACT. Three cases of extreme local precipitation within the Intermountain summer season were studied to determine the source of moisture for these events. The rains occurred at Phoenix, Ariz. on June 22, 1972 (133 mm in 2 hours), at Elko, Nev. on August 27, 1970 (105 mm in about 2 hours), and at Morgan, Utah on August 16, 1958 (about 150 mm in 1 hour). Synoptic data were used to analyze surface and upper level moisture changes in time and space.

In each case the study showed that a tongue of high moisture at low levels approached the vicinity of or encompassed the storm area prior to onset of the rain. The tongue of moisture was very narrow in reaching toward the Elko and Morgan storms and could be traced, through continuity of changes in pattern with time, back to the Gulf of California. The moisture is believed to be conveyed through the natural channel provided by the Gulf and the paralleling ridges. The low-level moisture followed a path controlled to some extent by major mountain barriers. A general conclusion is that greater emphasis should be given to tropical Pacific moisture in evaluating extreme summer precipitation values for the Intermountain region.

1. INTRODUCTION

1.1 Purpose of the Study

The summer precipitation regime of the southwestern United States has been analyzed and presented by Jurwitz (1953), Bryson (1957a, 1957b), Sellers (1964), and Houghton (1969), among others. They contend that the general circulation favors bringing moist air from over the Gulf of Mexico anticyclonically northwestward across the Intermountain region of the Southwest. Recent analyses, Hales (1972, 1974), Pyke (1972), and Brenner (1974), however, suggest that greater emphasis should be given to the tropical Pacific source regions. While Sellers and the more recent studies include above-average precipitation from intrusions of moisture associated with decadent tropical storms from the Pacific, none of these studies consider moisture supplied to local storms producing extreme rainfall. The purpose of the present study is to examine three such cases, to define the source of moisture for each, and to consider the impact of the results relative to the summer precipitation regime in the southern Intermountain region.

1.2 Season of Interest

The study is restricted to the summer precipitation season, June through September. During this season the southwestern United States is least effected by synoptic scale storm precipitation. At the same time many stations in the region record their maximum daily and monthly precipitation amounts.

1.3 Region of Interest

The present study is limited to precipitation extremes in the Intermountain Southwestern United States of Arizona, Utah, Nevada, portions of western New Mexico and Colorado, and southwestern California (fig. 1). This region of interest lies between the Continental Divide on the east, the Sierra-Nevada-Tehachapi-Transverse-Peninsular mountain complex on the west, the southern boundary of the Columbia drainage basin on the north, and the United States-Mexican border on the south. For the purposes of this paper, this region will be referred to as the southern Intermountain region or the Southwestern United States. This mostly **semiarid** region experiences some degree of summer precipitation maximum and, as described by Bryson (1957a, 1957b) and Pyke (1972), climatologically extends south of the border to include the Mexican Sonora. In order to fully study the airflow into the region of interest, it is necessary to extend consideration of moisture circulation patterns into northern Mexico.

The southern Intermountain region is composed of rugged terrain with elevations from below sea level in southeastern California to mountain peaks exceeding 4 km. Mountain barriers (average ridgelines) extend to heights of 2 to 3 km along the Continental Divide, 0.5 to 2 km along the western boundary, and up to 2 km within the region. It is for the most part the complicated system of mountain barriers that makes the precipitation regime so difficult to understand. Figure 1 shows 1.5- and 3.0-km contours and indicates barriers to moist air flow into the region and to some extent the channeling that takes place. From the contour pattern shown in figure 1, the most direct entrance of any Gulf of Mexico moisture at low levels to the southern Intermountain region appears to be between El Paso and Tucson. This low portion of the Continental Divide is the Sonoran gap.

1.4 Data

The three cases studied (Phoenix, Ariz., Elko, Nev., and Morgan, Utah) were restricted to recent events since these would have the most data for analysis. Occurrences near National Weather Service Offices (WSOs) were favored for the same reason.

Rawinsonde data were evaluated for stability, winds, and moisture variations aloft. These data were obtained for all U.S. stations within the southern Intermountain region, plus Albuquerque, N. Mex., Denver, Colo., El Paso, Midland, Fort Worth, and San Antonio, Tex., and Mazatlan, Mexico. Their locations are shown in figure 1.

Precipitation data have been taken from a number of NOAA publications: Climatological Data, Local Climatological Data, Hourly Precipitation Data, Storm Data, and Climatic Summaries of the United States.

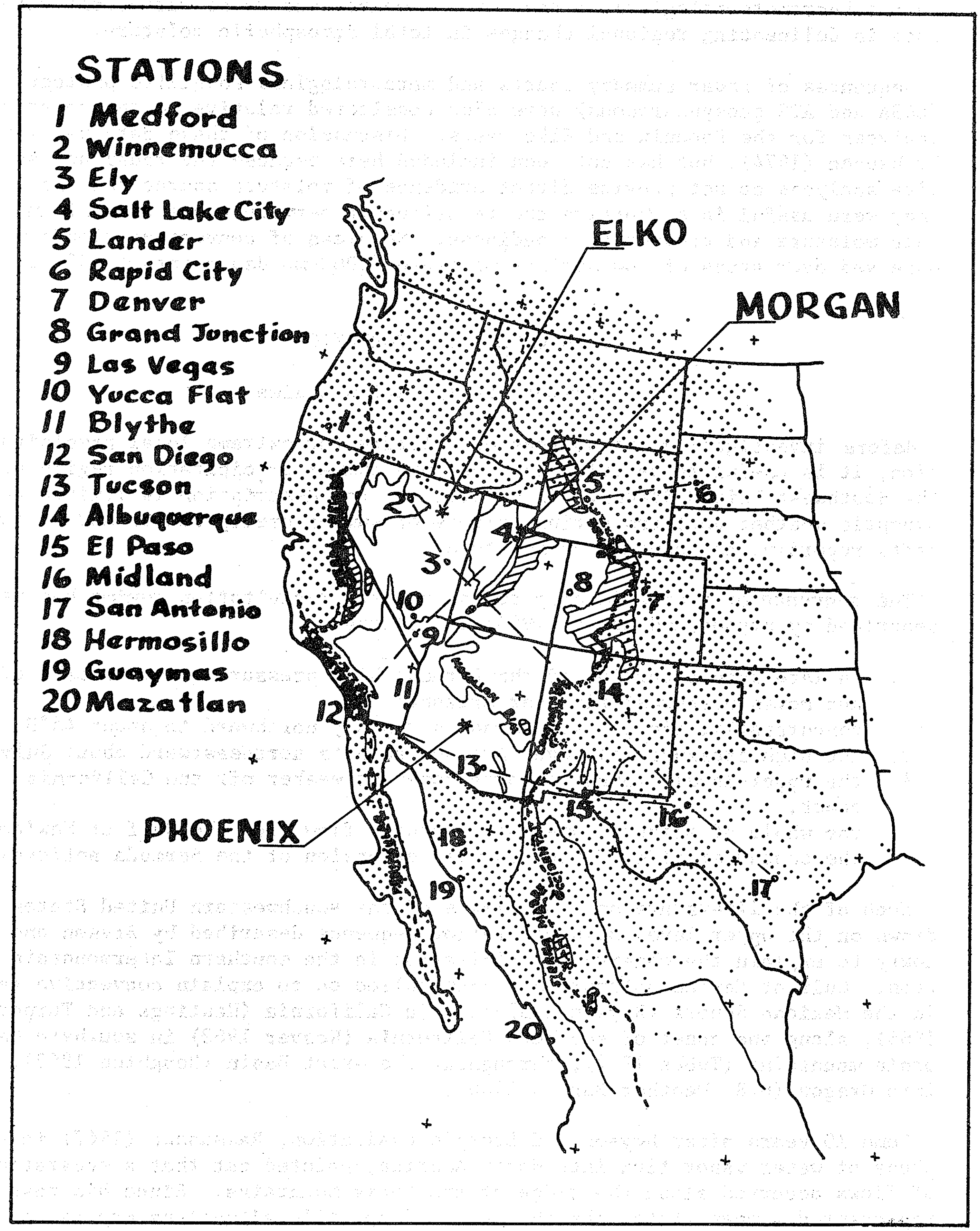


Figure 1.--Southern Intermountain region (within dotted line). Locations of stations, mountain barriers and cross sections (long dashes) mentioned in text. Elevations given for 1.5 km (solid lines) and 3.0 km (hatched areas).

Precipitable water tabulations were obtained from summaries available within the Hydrometeorological Branch, NWS. Twelve- and 24-hr variations were used in delineating regional changes in total atmospheric moisture.

Sequences of radar summary charts and meteorological satellite photographs (ESSA and ATS geosynchronous) were also considered relative to the moisture analyses for the Phoenix and Elko cases. Discussion of these data was given by Hansen (1974), but has not been included here because the radar and satellite analyses do not provide direct evidence of moisture source regions. They were useful in supporting the relationship between areas of maximum surface moisture and convective cloudiness. No areas of convective clouds were observed over areas of low surface moisture (1000-mb dew points $\leq$ 10°C).

2. BACKGROUND INFORMATION

2.1 Summer Precipitation Regime

Before investigating the sources of moisture for extreme local precipitation, it is useful to describe the observed summer precipitation regime of the Southwest United States. In particular, the description is limited to synoptic weather patterns during periods of summer precipitation and to comments regarding the sources of moisture.

The sequence of events leading to the summer precipitation regime has been described by Bryson and Lowry (1955) as follows:

1. in late June a portion of the Bermuda high pressure system breaks off and moves northwesterly over Arizona;
2. concurrently, the jet stream moves rapidly northward to about 45°N;
3. the high pressure cell over Arizona adjusts northeastward about July 1;
4. the upper-level trough re-forms somewhat weaker off the California coast;
5. the whole of Arizona comes under gentle flow from the Gulf of Mexico on the southwest side of the westward extension of the Bermuda anticyclone.

Much of the literature on the climate of the southwestern United States has drawn on the upper level moisture inflow sequence described by Bryson and Lowry to explain the observed precipitation in the southern Intermountain region. Gulf of Mexico moisture has been called on to explain convective rains in the Mexican Sonora (Bryson 1957a), Baja California (Hastings and Turner, 1965), along the coast of southern California (Weaver 1962) in southern California mountains (Tubbs 1972), throughout the Great Basin (Houghton 1969), and into Oregon (U.S. Weather Bureau 1966).

Some 10 years after Bryson and Lowry's evaluation, Rasmusson (1967) in a study of water vapor flux into North America, pointed out that a separation of flows occurred along the ridge of the Rocky Mountains. Since his results represented a mean state, the character of specific situations may be considerably different. Rasmusson stated that the northward flux maximum at the "northern end of the Gulf of California" extended to relatively high levels. Below 800 mb the inflow was from the southwest, while the flow was from the south-southeast from 750 to 500 mb. "Flux vectors at these levels showed a shift from the southwest and sharp increase in magnitude between June and July," according to Rasmusson.

A comprehensive dissertation on the winter precipitation of the western States and Baja California by Pyke (1972) included comments regarding the mid- to late summer precipitation maximum observed in southwest deserts. Pyke stated that summer precipitation "consists of convective air mass precipitation, ...almost exclusively in conjunction with an influx of tropical moisture from the warm waters of the Gulf of California, the Pacific Ocean south and west of Baja California, and to a certain extent the Gulf of Mexico." He goes on to discuss the seasonal changes in sea surface temperatures in relation to the movement of air masses, and presented the opinion that, "whereas the Gulf of Mexico might serve as the source region of many of the weak upper air disturbances (easterly waves and vorticity maxima) which could trigger thunderstorms..., it is likely that much of the moisture itself...would have to come from the Gulf of California or even the Pacific Ocean west of Baja California."

A similar viewpoint is held by Hales (1972, 1974) who analyzed summer monsoon moisture in southern Arizona and concluded that the greatest percentage of tropical moisture in southwestern United States and northwestern Mexico came from the Pacific Ocean by way of the Gulf of California rather than the Gulf of Mexico. Brenner (1974) and Hales (1972), presented arguments to show that the low-level pressure gradient established between the southern portions of the Gulf of California and southwestern Arizona can result in a surge of moisture northward within the natural channel provided by the Gulf of California. These papers described the circulation patterns below 850 mb as being almost independent of those above this level and, as such, should be considered separately. The depth of tropical air during the surge up the Gulf of California was between 2 and 3 km, and the air mass entered Arizona from a southeasterly direction as a result of deflection by the Sierra Madre orientation (fig. 1).

From a brief review of some of the many studies commenting on the source of moisture into the southwestern United States, it is apparent that at least two sources are possible; the Gulf of Mexico and the tropical Pacific Ocean via the Gulf of California. Nearly all the literature cited deals with the subject of day-to-day type summer precipitation throughout the region of interest, and one gathers from the many studies prior to 1970 that the opinion expressed by Sellers (1964) prevailed. That is, daily summer rains were the result of moisture from the Gulf of Mexico, while considerably heavier rains occurred occasionally from moisture associated with tropical storms off the west coast of Mexico. Studies after 1970 have appeared to stress moisture from the Gulf of California as being important to lesser rains.

2.2 Extreme Local Rainfalls

There is another category of summer rainfall that was not addressed by any of the studies cited in section 2.1. This category is extreme rainfalls from thunderstorms. These severe thunderstorm rains have overall durations up to about 3 hours and yield point rainfalls in excess of 75 mm. The purpose of this paper is to examine three cases of extreme local rainfall and in particular to trace the source of moisture **for these storms.**

Measured station rainfall occurrences that exceeded 75 mm for durations less than 3 hours have been extracted from climatological records and various references. These are considered extreme local rainfalls in the present study and are listed in table 1.

The list of rainfalls in table 1 represents measured extremes for the past 80 years, but it is unlikely that the 19 extreme events approximate the actual number of such events during the period. Precipitation gages are widely scattered through this rugged region and are concentrated primarily at lower elevations and in the more populated regions. Because of the lack of an adequate observational network and the fact that most of the intense local storms cover areas less than 100 mi^2, many events pass undetected. Knowledge of their occurrence sometimes comes from flash flooding or other evidence of unusual runoff. When news of such an event is passed on to hydrologic authorities, a survey can be conducted of the site for measurable rainfall quantities. The reliability of the amounts and durations listed in table 1 is less for some events (Palmetto and Chiatovich Flat, for example) than for others, but it can generally be supported that in each instance an unusually severe rainfall occurred at the site.

3. CASE STUDIES

The following section presents an analysis of three cases of extreme local rainfall. The cases were selected because they represented large recent rainfall amounts, occurred within the period of summer rainfall maximum, and were widely separated within the region of interest. The three cases do not all represent synoptic patterns characteristic of the Bermuda-high situation. I chose to examine moisture sources associated with large rainfall observations rather than choosing synoptic weather patterns and tracing moisture to see if significant rains occurred, since moisture is a necessary, but not sufficient, condition for extreme rain. Other interesting rainstorms could have been chosen, but their occurrence prior to the late 1950s limited too severely the amount of data available upon which to base conclusions.

3.1 Case 1; Phoenix, Ariz. Storm, June 22, 1972 (133 mm)

3.1.1 The Storm.

On the same day Hurricane Agnes brought record rains to most of the Atlantic Coast States, an isolated thunderstorm dumped more than 100 mm of rain in about 2 hours in the northeastern suburbs of Phoenix, Ariz. As described by Kangieser (1972), this event was part of a moisture inflow from the south that began on the 21st and set new high rainfall totals for the month of June at a number of long-record stations. Some stations set new observational-day records for any June since records began. The Phoenix storm and the high intensities associated with it were part of a series of unusual events that began on the evening of June 21st. A summary of reports compiled in Storm Data (National Climatic Center, Asheville, N.C., June 1972) is shown in figure 2.

Table 1.--Extreme thunderstorm rainfalls in the Southwest States

Location	Date	Depth (mm)	Duration (min.)	Reference*
Tucson, Ariz.	7-11-78	130	∿60	Monthly Weather Review, 1878
Palmetto, Nev.	8-11-90	224	60	a.
Campo, Calif.	8-12-91	292	80	b.
Farley's Camp, Ariz.	8-28-91	79	90	Monthly Weather Review, 1891
Fort Mohave, Ariz.	8-28-98	203	45	c.
Bisbee, Ariz.	7-22-10	108	70	Sellers (1964)
Campo, Calif.	7-18-22	180	120	CD,† Calif., 1922
Squirrel Inn, Calif.	7-18-22	127	90	CD, Calif., 1922
Mesa Verde N.P., Colo.	8- 3-24	89	45	CD, Colo., 1924
Crown King, Ariz.	8-11-27	124	170	Leopold (1943)
Sierra Ancha, Ariz.	9-10-33	113	105	d.
Pima, Ariz.	8- 2-39	79	60	Langbein (1941)
Sierra Ancha, Ariz.	8- 5-39	127	140	Langbein (1941)
Thatcher, Ariz.	9-16-39	104	90	e.
Globe, Ariz.	7-29-54	89	40	CD, Ariz., 1954
Vallecito, Calif.	7-18-55	180	70	f.
Chiatovich Flat, Calif.	7-19-55	209	150	g.
Morgan, Utah	8-16-58	150	60	h.
Santa Rita, Ariz.	6-29-59	114	60	i.
Walnut Gulch, Ariz.	9-10-67	85	45	Osborn and Renard (1969)
Tempe, Ariz.	9-14-69	89	60	Hales (1972)
Elko, Nev.	8-27-70	105	120	CD, Nev., 1970
Phoenix, Ariz.	6-22-72	133	120	CD, Ariz., 1972
Nelson, Nev.	9-14-74	82	45	j.

Table 1.--Continued

Legend

* a. Observers record, Medical Corps, U.S. Army, Nev., 1890.
b. Observeres record, Signal Service, U.S. Army, Calif., August 1891.
c. Climate and Crop Service Bulletin, Ariz. Section, August 1898.
d. Corps of Engineers Letter, Los Angeles District, April 27, 1964.
e. Corps of Engineers Report, Los Angeles District, December 15, 1961.
f. Corps of Engineers Report, Los Angeles District, August 5, 1955.
g. Hydrometeorological Report No. 37, Department of Commerce, Weather Bureau, December 1962.
h. Monthly Flood Report, Salt Lake City, Utah, September 15, 1958.
i. Corps of Engineers Letter, Los Angeles District, August 12, 1969.
j. National Weather Service Flood Summary, September 16, 1974.
† CD, Climatological Data Summary

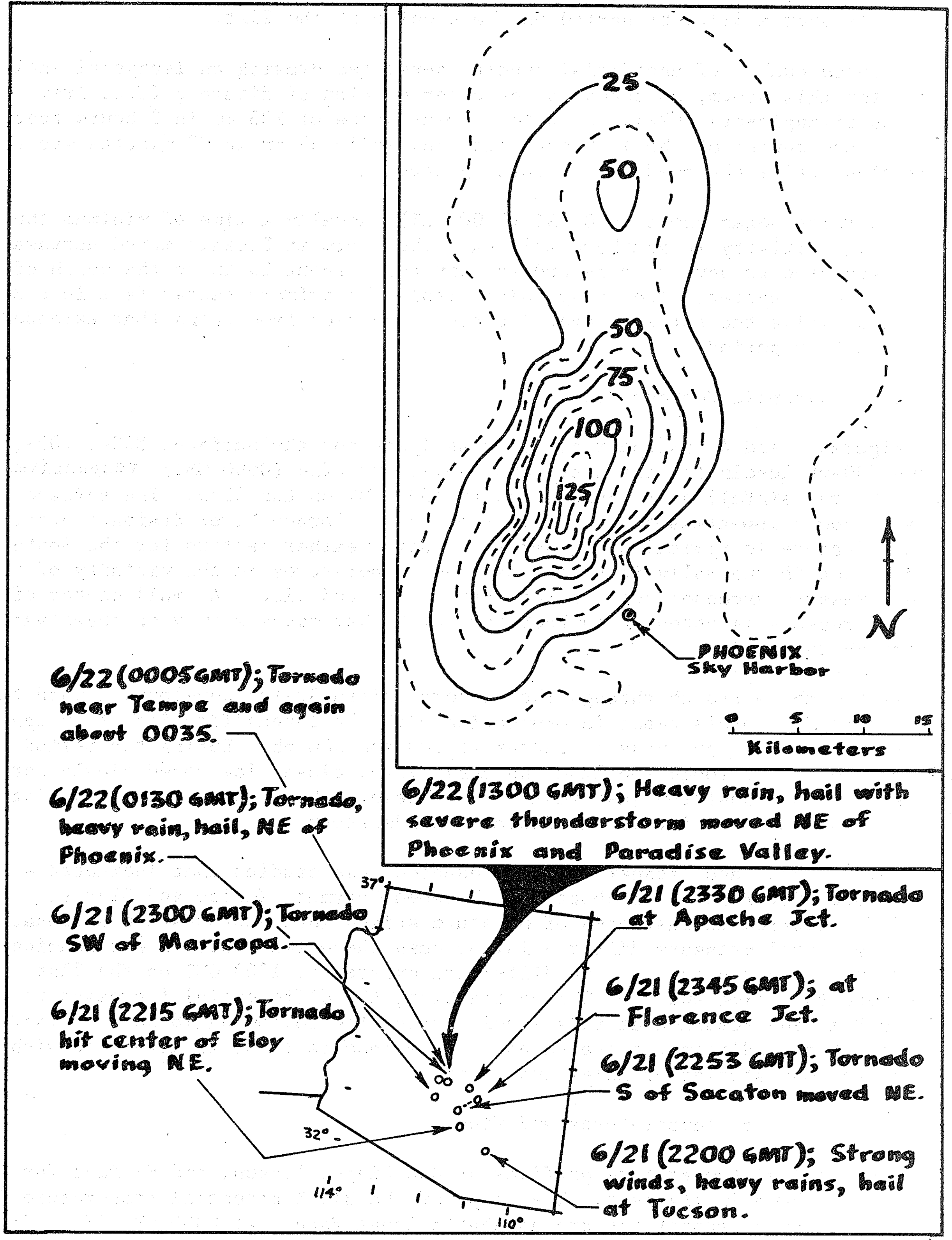


Figure 2.--Storm Data reports for June 21-22, 1972, Arizona. Isohyetal analysis (mm) of Phoenix storm (6-hr duration) prepared by Corps of Engineers (1972).

There were at least 6 separate tornado sightings in the region southeast of Phoenix over a 3-1/2-hr period on the evening of the 21st.

A large number of unofficial reports permitted drawing an isohyetal analysis for this storm, as shown in the upper portion of figure 2 (U.S. Army Corps of Engineers 1972). A maximum point value of 133 mm in 2 hours represents the center of the isohyetal pattern, while 65 mm in 80 minutes was the greatest value observed by a recording gage.

The rains began about 0600 MST (1300 GMT), usually a time of minimum thunderstorm activity in southern Arizona. The storm at Phoenix moved northward and appeared to develop a secondary rain burst about 25 km to the north of the primary center. The heavy rains within the primary center fell in a 2-hr period, while the total isohyetal pattern was made from rains that extended over a 6-hr period.

3.1.2 Synoptic Weather Maps.

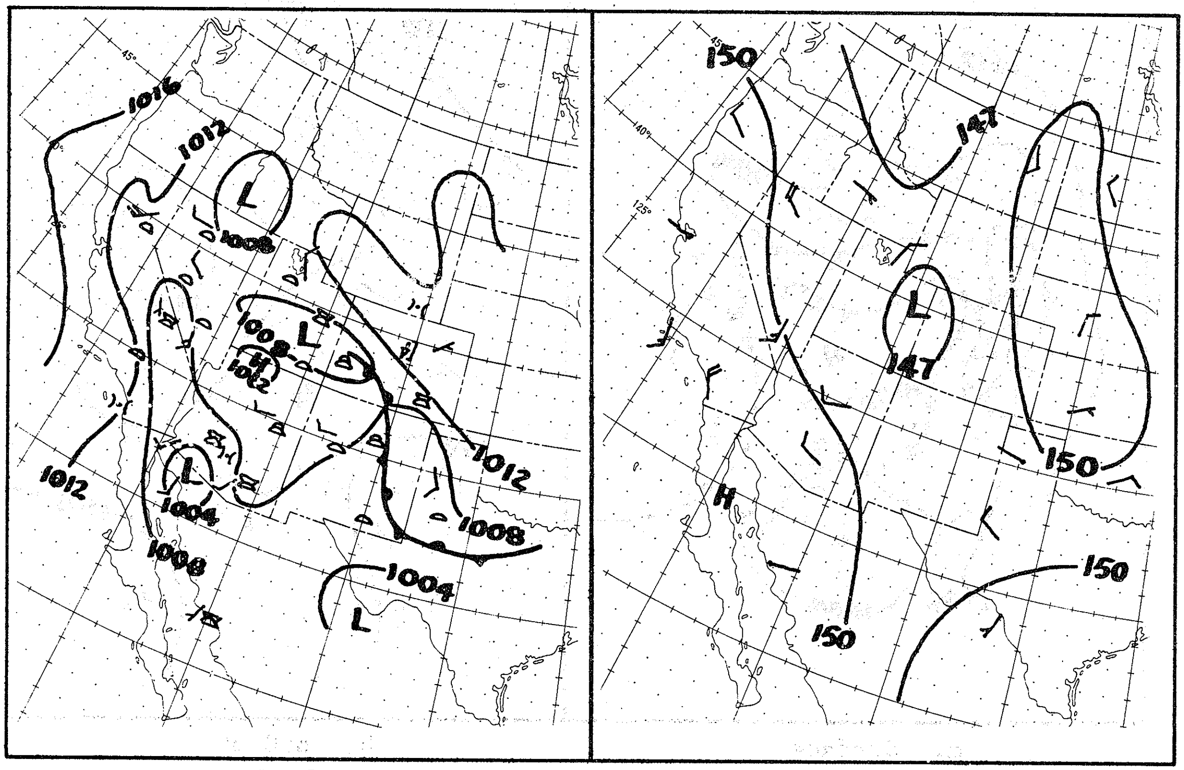
Figures 3 and 4 represent synoptic analyses for the surface, 850-, 700-, and 500-mb levels for the 21st (0000 GMT), and 22nd (0000 GMT), respectively. The heavy rainfall at Phoenix began at 1300 GMT on the 22nd. The surface maps show a low-pressure center in the lower Colorado River drainage area. This feature is typical of a summer synoptic weather pattern for the Southwest, and is thermally induced. Maximum temperatures in the vicinity of the low pressure exceeded 40°C on the 19th, 20th, and 21st. A small center of high pressure is noted in southeastern Utah that moves slowly southeastward through the period.

At 850 mb, a trough through the western United States developed toward the southern California coast in connection with the intensification of an upper level cold-core low pressure center at 700 and 500 mb. During the period from the 20th through the 22nd the upper level closed low moved slowly northeastward to a position just west of San Diego. The trough deepened during the 24-hr period prior to the Phoenix thunderstorm.

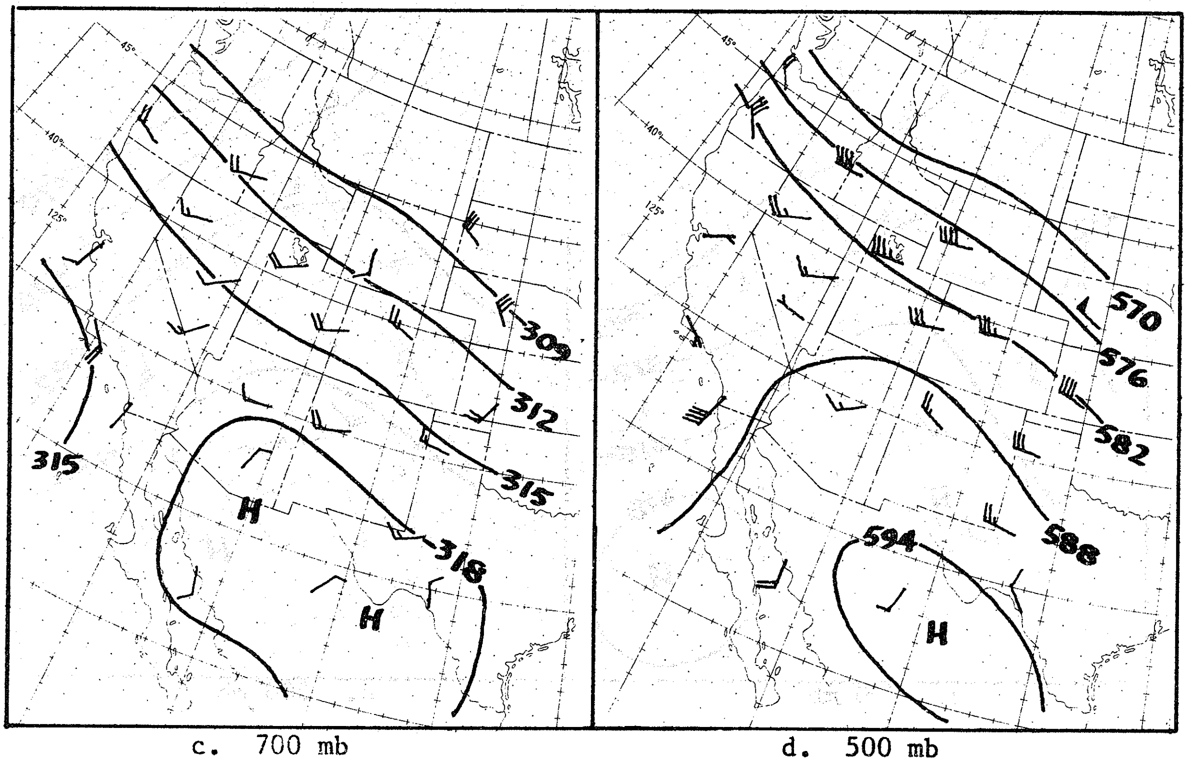
Hales (1972) and Brenner (1974) presented case studies that indicated a pressure differential of about 8 mb between Guaymes, Mexico and Blythe, Calif. occurred in instances of moisture surges into southwestern Arizona. The sea level pressure differential between these two stations was examined for the present case. A 5-mb difference existed at 1200 GMT on the 21st. Between this time and 2100 GMT on the 21st, the differential increased to 7 to 8 mb and remained at this level through the following 18 hours. Therefore, this condition for the Phoenix storm appears to be in agreement with the previous studies of Hales and Brenner.

3.1.3 Vertical Temperatures and Winds.

The vertical temperature profiles at San Diego, Tucson, and El Paso for the 22nd are shown in figure 5. The slope of the 313 K potential temperature is indicated to represent the dry adiabatic lapse rate. At 0000 GMT (fig. 5a), the Tucson sounding showed a 400-m surface inversion in a layer of otherwise conditionally unstable air that is nearly saturated above 3 km (700 mb). It

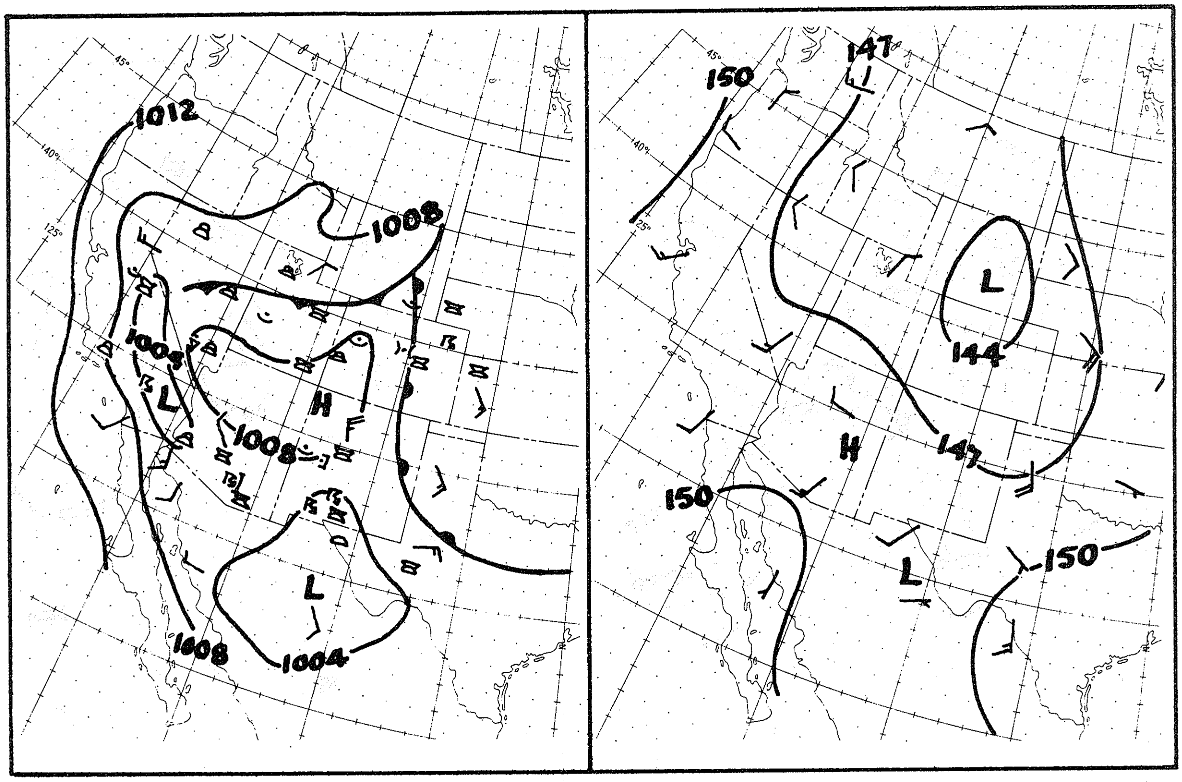


a. Surface b. 850 mb

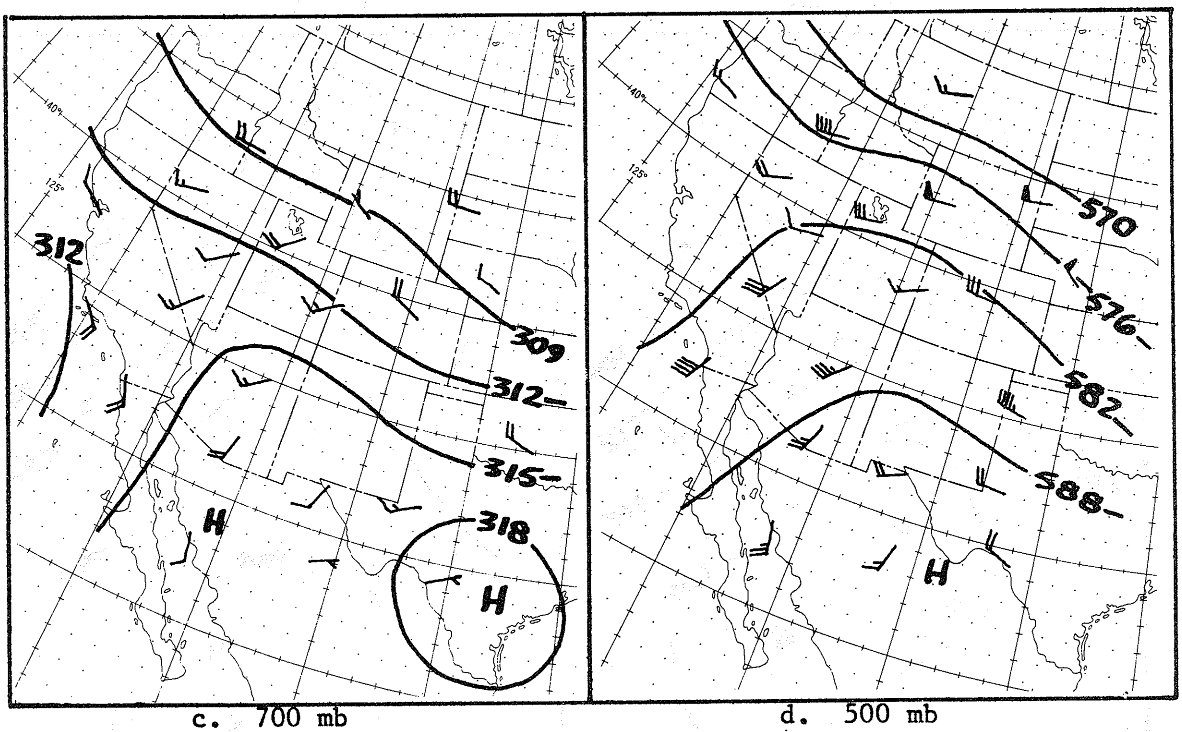


c. 700 mb d. 500 mb

Figure 3.--Standard pressure level charts for June 21, 1972, 0000 GMT. Pressure in millibars, heights in decameters, winds in knots.

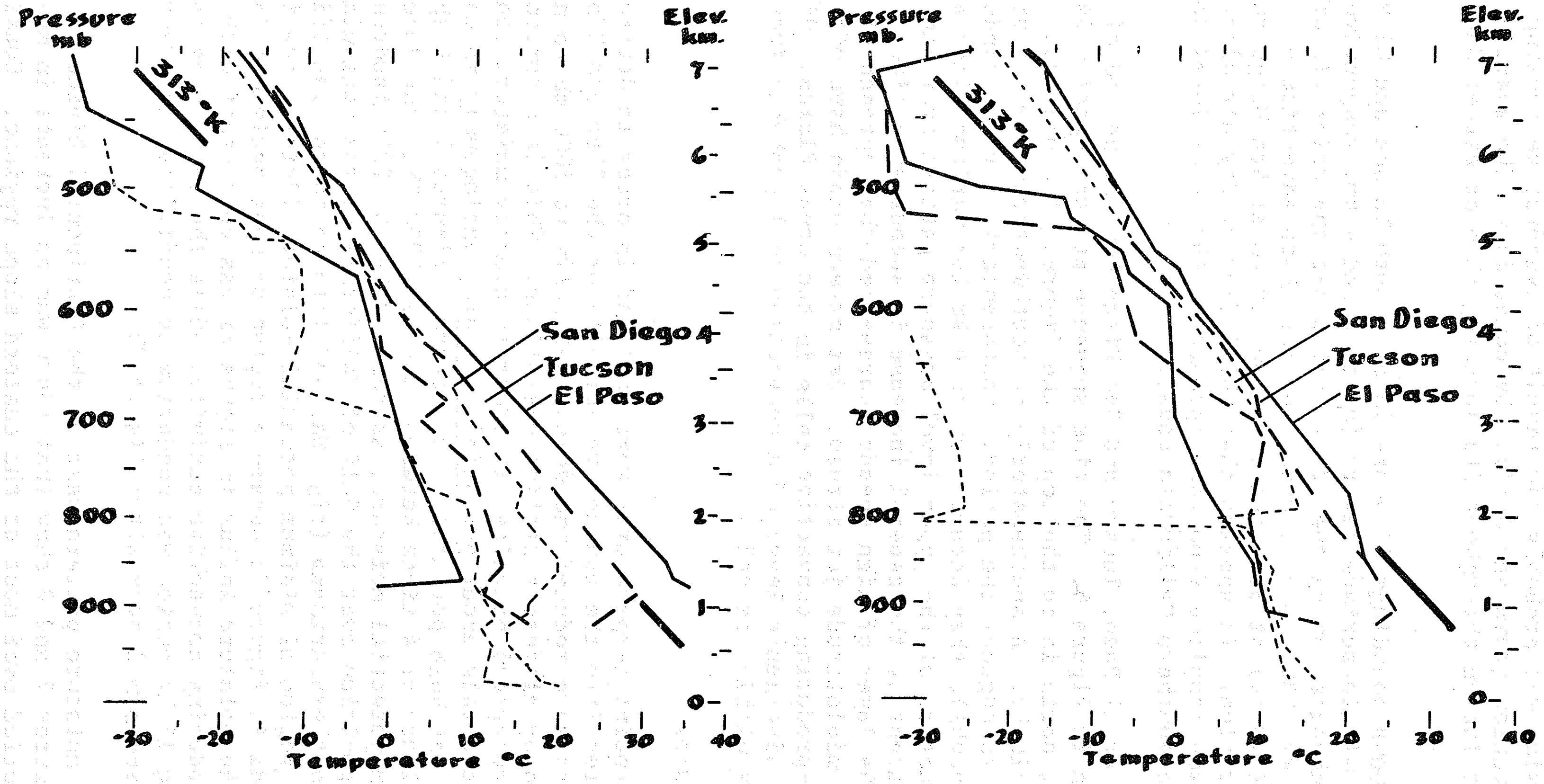


a. Surface b. 850 mb



c. 700 mb d. 500 mb

Figure 4.--Same as figure 3, for June 22, 1972, 0000 GMT.



(a.)

(b.)

Figure 5.--Temperature and dew-point soundings for June 22, 1972, 0000 GMT (a.) and 1200 GMT (b.). Slope of 313K isotherm represents dry adiabatic lapse rate.

appears that the Tucson sounding represented dynamically unstable air in the vicinity of the tornado-producing convective cells noted in figure 2. The surface inversion was probably the result of evaporative cooling from the heavy precipitation (rain and hail). By comparison, the available moisture was greater at Tucson throughout its sounding than at either San Diego or El Paso.

Figure 5b shows soundings 12 hours later. Both Tucson and El Paso indicated cooling within surface layers (up to 2 and 4 km, respectively). The most notable changes during the 12-hr period are the drier air at heights above about 5 km (530 mb) at Tucson, and the sharp advection of dry air above 1.8 km (810 mb) at San Diego. Below 1.8 km at San Diego the air approached saturation. It appears that the influx of dry air aloft at San Diego and Tucson resulted from the approach of the upper level low pressure system off the southern California coast.

Winds aloft at El Paso, Tucson and San Diego for the period of June 20-22, 1972 are given in figure 6. The time sequence at each station is read from right to left, north is to the top of the figure. A whole barb equals a wind speed of 10 kt. A southeasterly to southwesterly flow occurred at nearly all levels throughout the period. Southeasterly surface winds occurred only at Tucson, while they occurred up to 4 km for various times at San Diego. The intensification of the upper level pressure pattern over San Diego and Tucson is apparent by the general increase in speeds with time. The apparent lowering of the layer of high speeds represented the approach of the lower extent of the midlatitude jet stream. Jet stream winds have often been noted above tornado-producing convective cells in the Great Plains. High wind speeds at the divergence level of a convective cell probably induce greater updraft speeds within the cell.

3.1.4 Moisture.

Surface dew-point temperatures were analyzed in order to determine how the moisture entered into the convective activity of the 21st and 22nd. All surface dew points were reduced pseudo-adiabatically to 1000 mb to normalize the effects caused by different station elevations. This is a common procedure in hydrometeorological practices in order to clarify moisture tongues. By so doing, we can talk about potential moisture, analogously in concept to the definition of wet bulb potential temperature. Figures 7 and 8 show 1000-mb dew-point analyses at 4 times between June 21 (0000 GMT) and June 22 (1200 GMT). Maximum potential moisture, as denoted by the 20°C isodrosotherm, moved from a position over the Gulf of California at the beginning of the period into southern Arizona (fig. 8a) and into southern Utah (fig. 8b). Note that the region of minimum potential moisture (driest location) in southern Nevada in figure 7a became a region of near maximum moisture in figure 8b. The moisture influx in figure 8a was consistent with the outbreak of tornado-producing convective activity, while the continuing inflow over the succeeding 12-hr period was conducive to conditions that resulted in the Phoenix thunderstorm 1 hour after figure 8b.

Compare the moisture pattern west of the Continental Divide with that to the east. Figures 7 and 8 show that there was an increase in moisture through the period over most of the eastern slope regions. Considerable

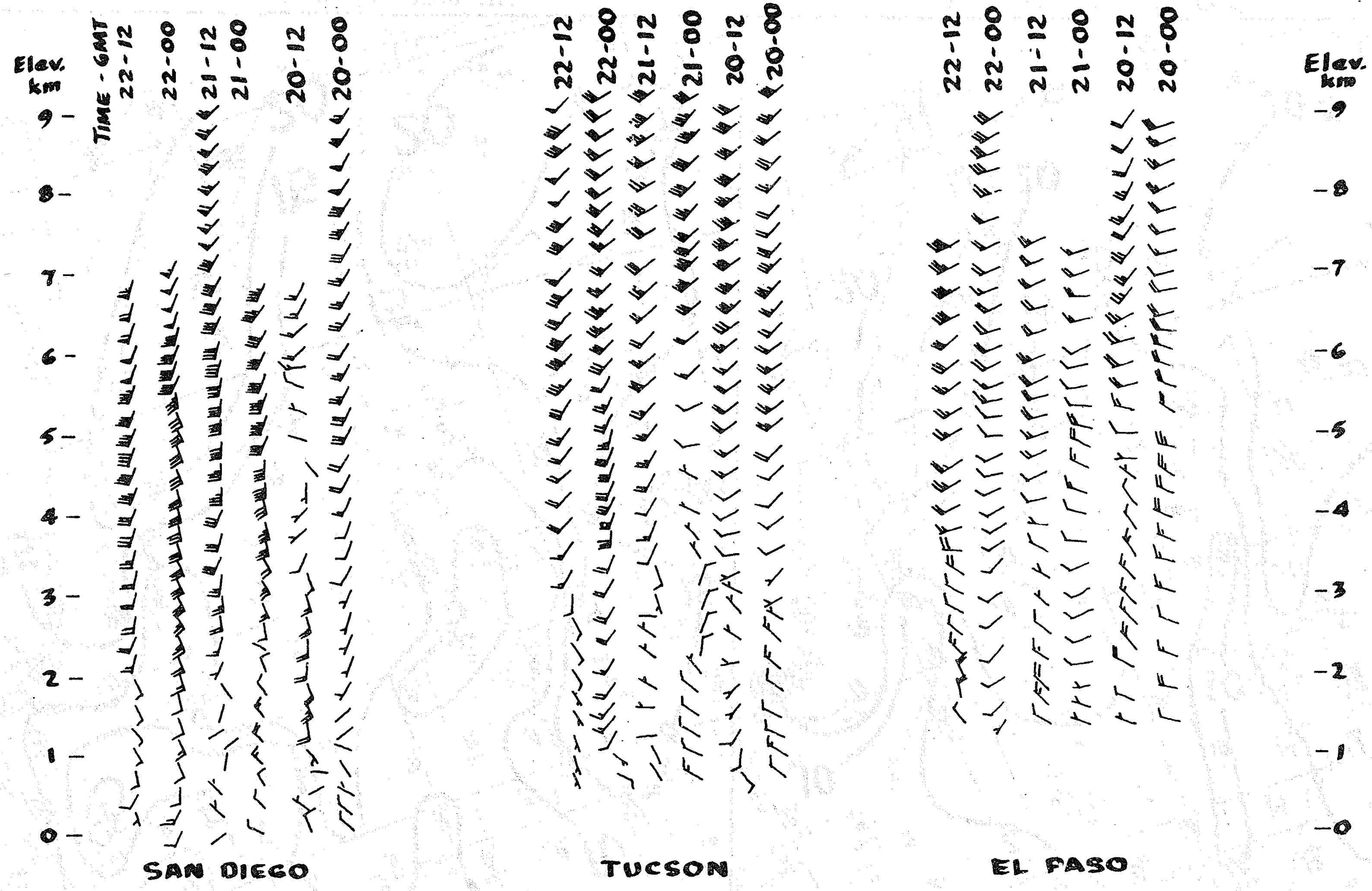
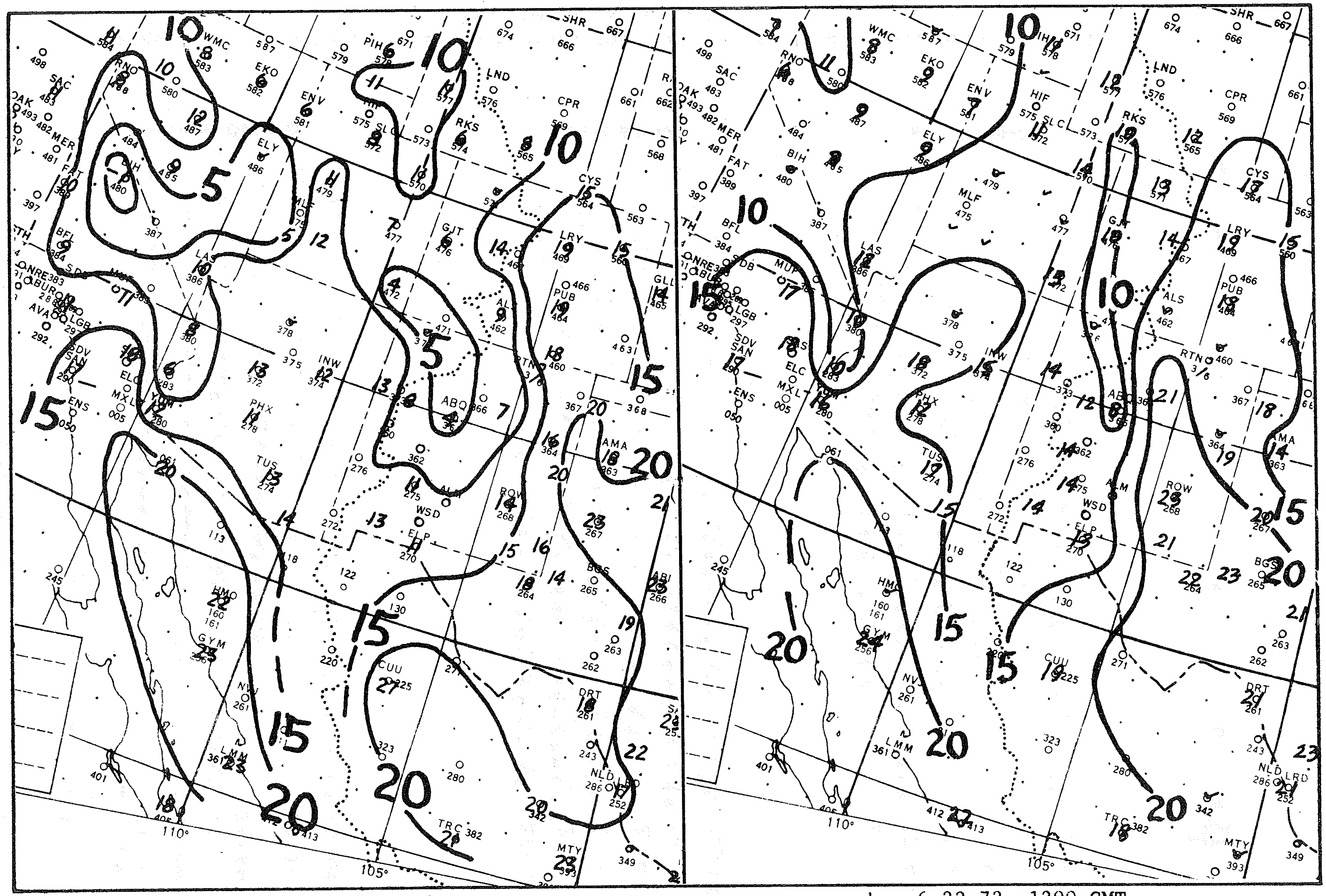


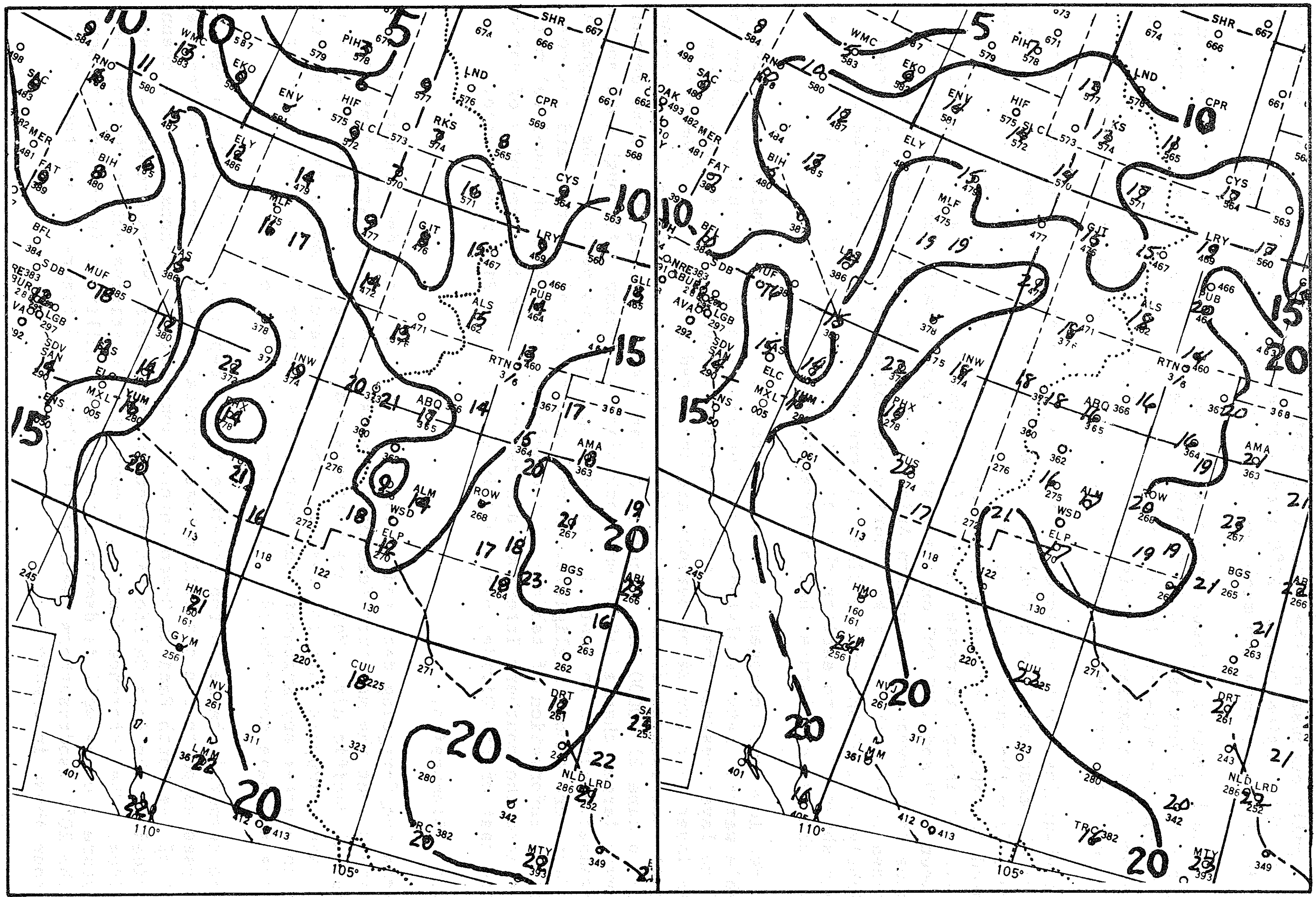
Figure 6.--Time section of upper winds for June 20-22, 1972. Full barb is 10 kt. Time reads right to left.



a. 6-22-72, 0000 GMT

b. 6-22-72, 1200 GMT

Figure 7.--1000-mb dew-point analysis (°C).



a. 6-22-72, 0000 GMT

b. 6-22-72, 1200 GMT

Figure 8.--1000-mb dew-point analysis (°C).

analytical bias may have gone into the analysis through northern Mexico, principally because of the paucity of stations. Although the few available data in this region support 20°C isodrosotherm centers on both sides of the Divide, I do not know how much less than 20°C lies between them.

For south-central Arizona, the maximum persisting 12-hr 1000-mb dew-point value for mid-June is 21°C (EDS 1968). From the latter reference a comparable value for mid-July in this region is 25°C. The moisture of June 21-22, 1972 provided a maximum persisting 12-hr 1000-mb value of 20°C at Phoenix, very near the extreme observed for this time of year in southern Arizona.

To visualize how the moisture inflow to the Phoenix storm changed in the vertical, mean specific humidities were computed for the three lowest 1-km layers from the rawinsondes at San Diego, Tucson, and El Paso. These are presented in table 2 for the period June 20 (0000 GMT) through June 22 (1200 GMT). The abrupt increase in specific humidity noted in all layers at Tucson between 0000 and 1200 GMT on the 21st was representative of the moist air tongue that moved into southern Arizona. Specific humidity over Tucson increased to more than 10 g kg^{-1} during the following 12 hours and lessened slightly by 1200 GMT on the 22nd. A more abrupt increase occurred at San Diego about 12 hours earlier than at Tucson. Of interest in table 2 is the small change in moisture that occurred over El Paso.

These low-level changes are also apparent in a brief examination of precipitable water. Data tabulated by station give the precipitable water for the 150-mb layer nearest the surface. Regional patterns of variations within this layer over two 24-hr periods are presented in figure 9. From this figure, the largest 24-hr change (+6.61 mm) during the period June 20 (0000 GMT) to June 21 (0000 GMT) occurred at San Diego. During the second period, an even larger change (+8.38 mm) took place at Tucson. Although some modest increases occurred in central Texas during these two periods, the changes at El Paso were almost negligible. From the analysis of figure 9 and the comparable information of table 2, I conclude that an influx of low-level moisture into the southern Intermountain region occurred independently of variations east of the Divide, particularly those in the Rio Grande basin.

3.1.5 Discussion.

From the foregoing data and analysis, it can be concluded without much question that the moisture feeding the unusual convective storm came from tropical Pacific air. Moisture patterns and strong S to SW flow patterns at all levels support this conclusion. The upper level flow pattern is of interest to counter any argument that moisture at higher levels from any other source may have contributed to the Phoenix thunderstorm.

The temporal change in the moisture tongue depicted by the 1000-mb dew-point analyses supports the contention that tropical moisture from the southeastern part of the North Pacific Ocean entered southeastern Arizona within a channel provided by the Baja California mountains and Sierra Madre Occidental mountain divides. The inference that major mountains in Arizona act to control the moisture flow as well is demonstrated by the similarity in the eastern bound of the 20°C isodrosotherm (west of the Divide) in figure 8b and the 1.5-km contour shown in figure 1.

Table 2.--Temporal variation of specific humidity (g kg^{-1}) for 1-km layer means

Layer above sfc. (km)	6/20 (00 GMT)			6/21 (00 GMT)			6/21 (12 GMT)			6/22 (00 GMT)			6/22 (12 GMT)		
	SAN	TUS	ELP	SAN	TUS	ELP	SAN	TUS	ELP	SAN	TUS	ELP	SAN	TUS	ELP
2-3	3.5	3.8	4.2	7.0	4.5	4.5	8.9	8.0	4.3	6.2	7.5	5.4	0.6	7.2	5.6
1-2	2.8	4.4	4.9	8.8	5.2	5.6	9.3	8.7	5.2	9.3	10.1	6.2	4.0	9.8	5.8
sfc-1	6.0	5.5	5.0	11.2	7.0	6.4	11.2	9.6	6.0	9.3	11.2	7.0	9.2	9.5	7.8

SAN = San Diego

TUS = Tucson

ELP = El Paso

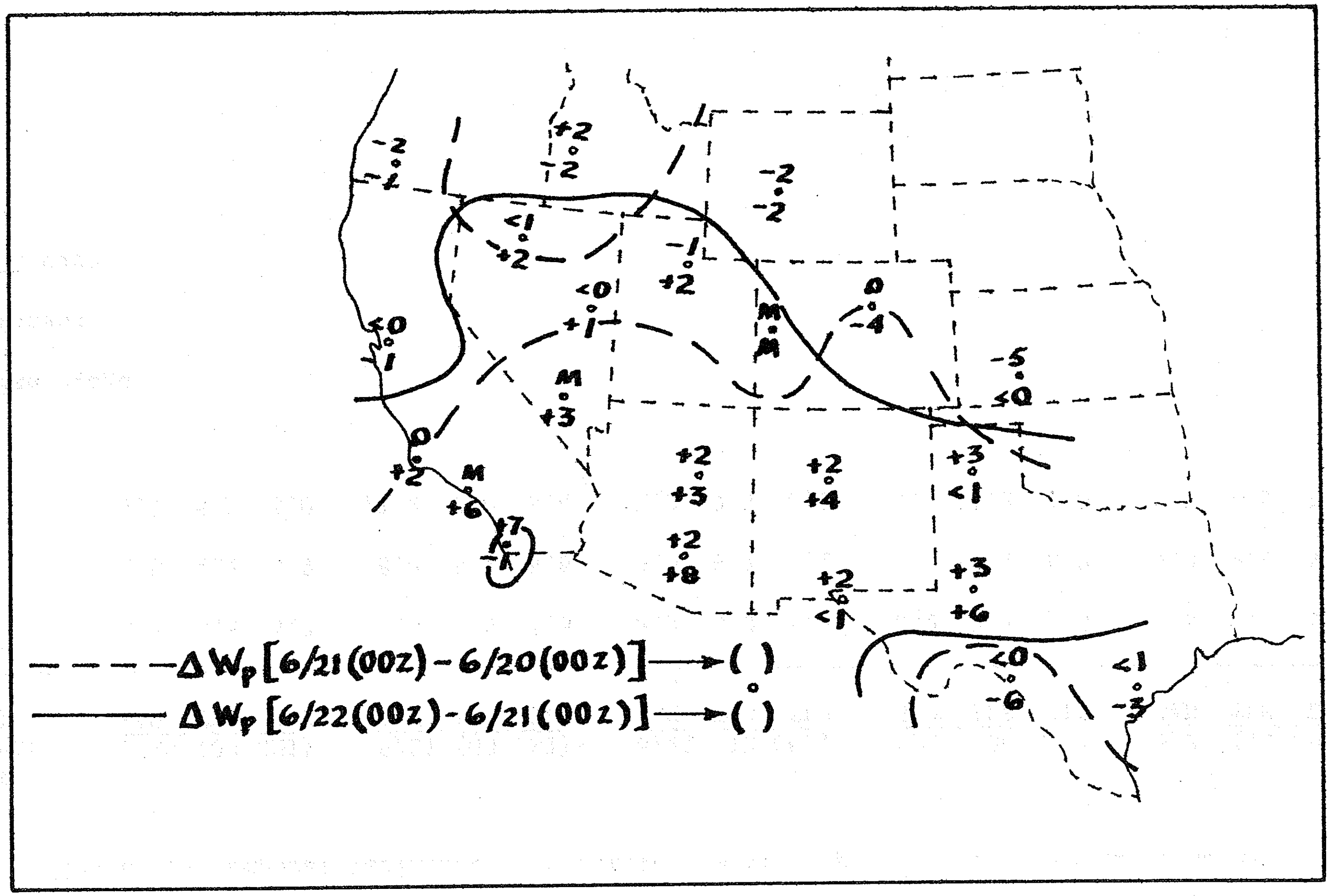


Figure 9.--24-hr change in precipitable water (mm) for 150-mb layer nearest the surface. Dashed lines separate +/- for June 20, 1972, solid lines for June 21, 1972.

That a pressure differential was responsible for the influx of moisture is not conclusive, there is evidence that conditions described by Hales (1972) were present during June 21-22, 1972.

3.2 Case 2; Elko, Nev. Storm, August 27, 1970 (105 mm)

3.2.1. The Storm.

The second case of extreme local thunderstorm rainfall occurred on August 27, 1970 at the Elko, Nev., Airport (Sakamoto 1970) far from any moisture source. Most of the 105-mm rainfall fell in 2 hours beginning about 1130 PST (1930 GMT). **The maximum 1-hr amount of 93 mm was the greatest in over 100** years of record. This event was unusual in that few 75-mm rains have been reported even in 24 hours in Nevada--with the exception of winter cases in the Sierra Nevada foothills near Reno. No isohyetal analysis is available; however, the storm was localized to a small area around the airport. From the same Storm Data Summary (NWS 1970) that included the Elko event, a report of flooding in parts of Las Vegas from some 2 in. (50 mm) of rain is given for the afternoon of the 26th, the day before the Elko event. The report states that hail fell at Las Vegas and that "four feet (120 cm) of water rushed down Mohave Avenue between Charleston and Bonanza roads." Taken together with the 29-mm rain that fell between 0000 and 0300 GMT on the 27th at Yuma, the Elko and Las Vegas events might be considered as further evidence that greater-than-normal moisture occurred along a north-south line through the Intermountain Southwest.

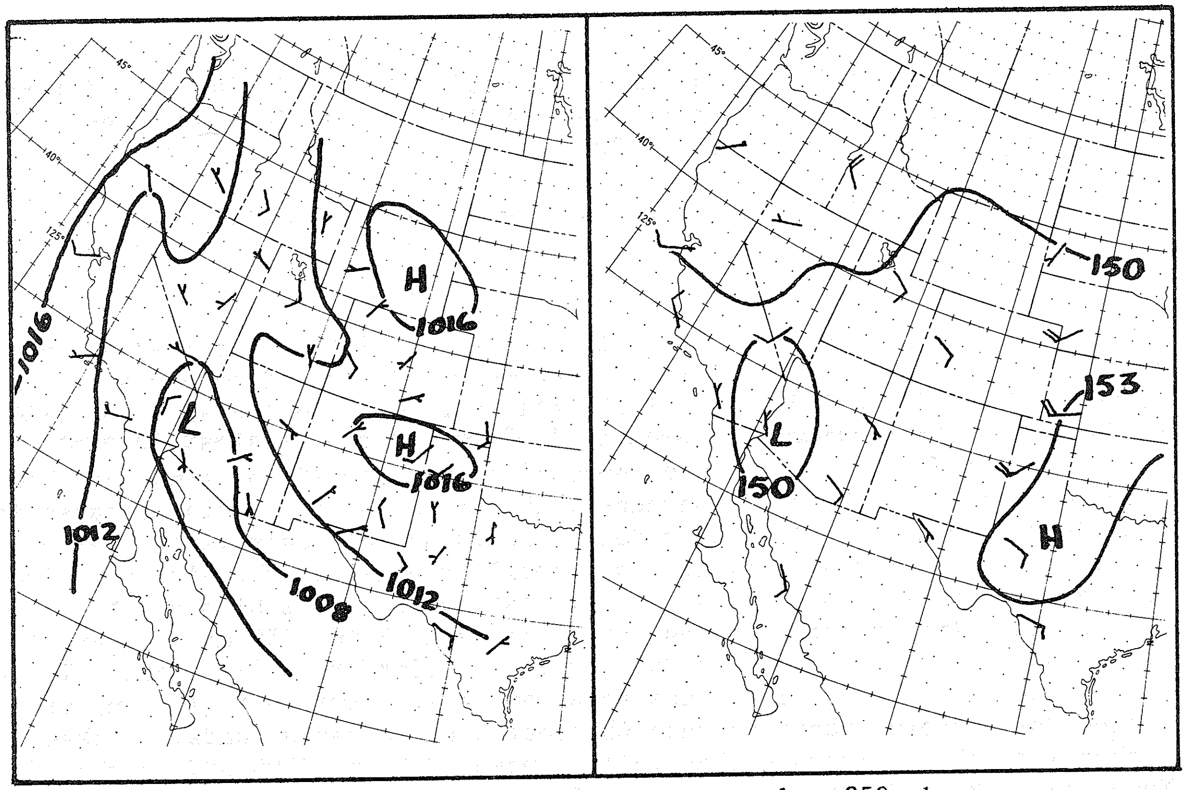
The Elko Airport is equipped with an official recording rain gage, from which the precipitation trace for the August 27, 1970 event was obtained. The recorder quickly exceeded the scale limits of the chart after only 33.5 mm had fallen. As a result, the observer noted that total storm precipitation was measured from a standard gage, and that precipitation began at 1004 PST (1804 GMT) and ended at 1345 PST (2145 GMT). No indication was given on how the maximum 1-hr reading was obtained.

3.2.2. Synoptic Weather Maps.

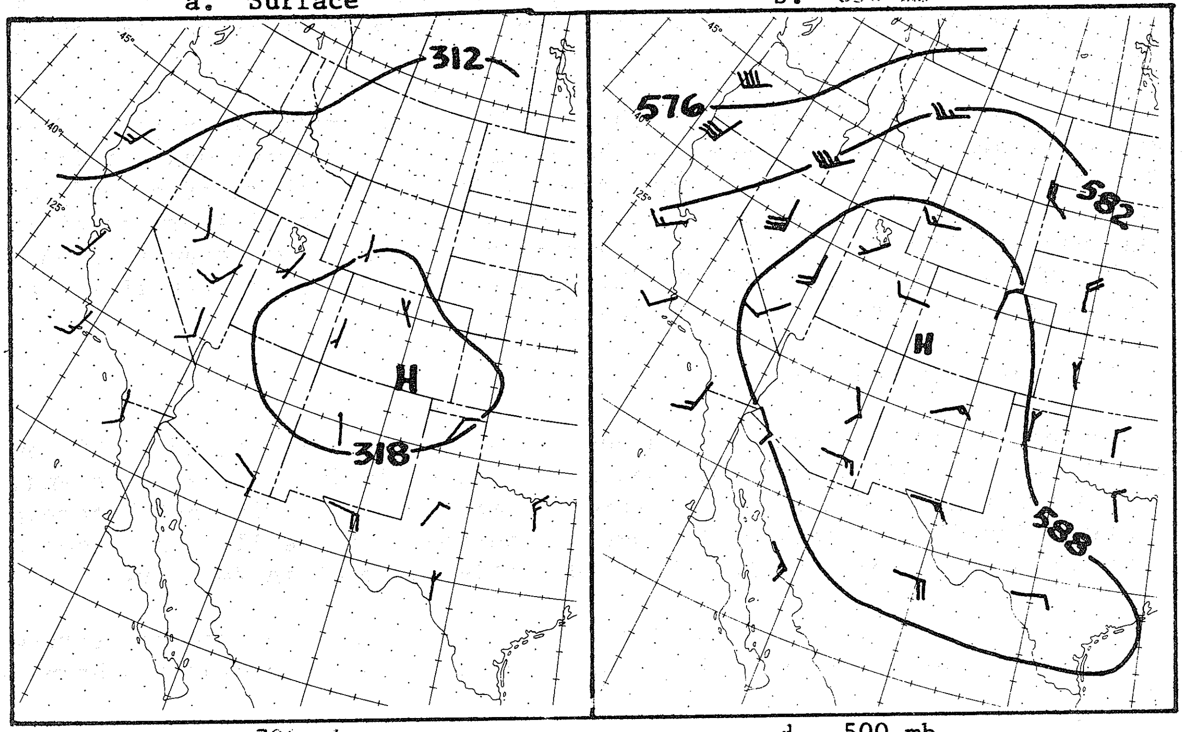
Figures 10 and 11 represent the conditions at the surface, 850, 700, and 500 mb for 1200 GMT on the 25th and 27th, respectively. The surface analyses show a thermally induced low-pressure center along the Arizona-California border which filled somewhat through the period. Figure 11a also shows a weak front across southern Wyoming that had little movement in 24 hours.

At 850 mb (figs. 10b and 11b) there was a flat pressure gradient throughout the Intermountain Southwest with minimum pressure-heights near southern California.

The analyses at 700 and 500 mb shown in figures 10 and 11 show anticyclonic circulation centered roughly in southern Colorado. This pattern is similar to those described for the summer Bermuda-high pressure situation by Bryson and Lowry (1955) and others. The circulation pattern extends toward the south through the period at both levels. This adjustment occurred at the same time

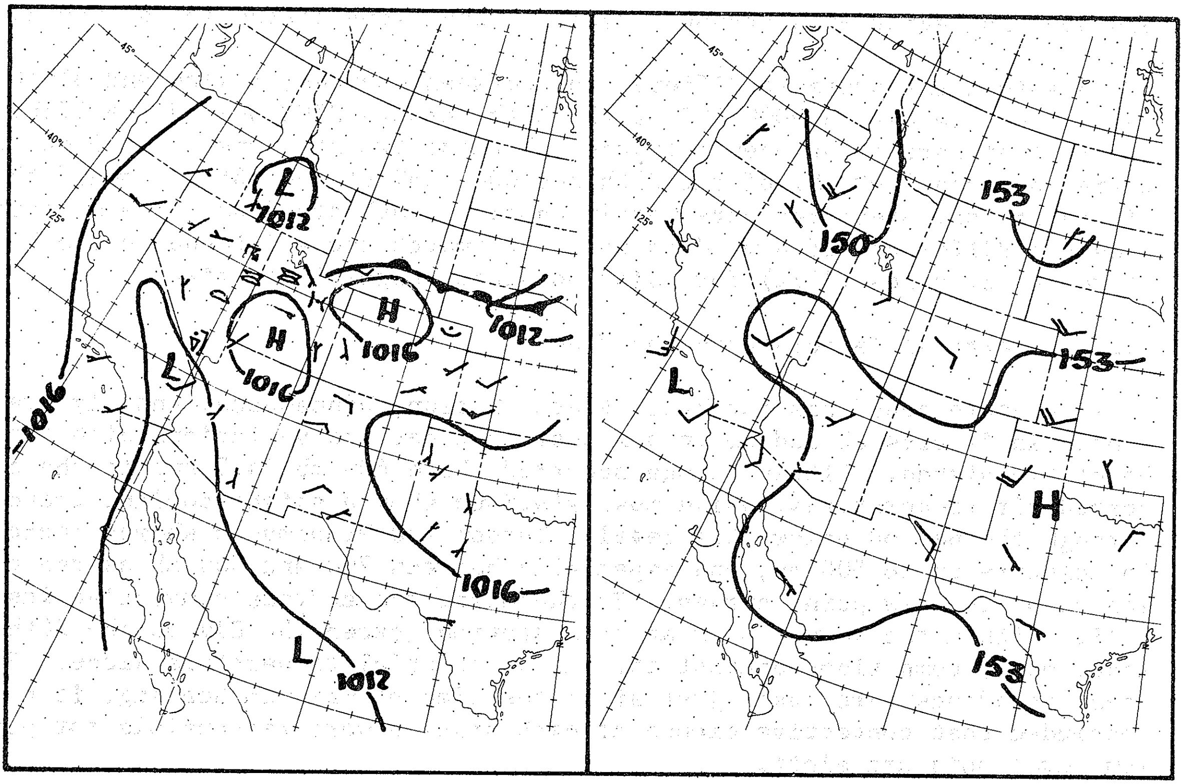


a. Surface b. 850 mb



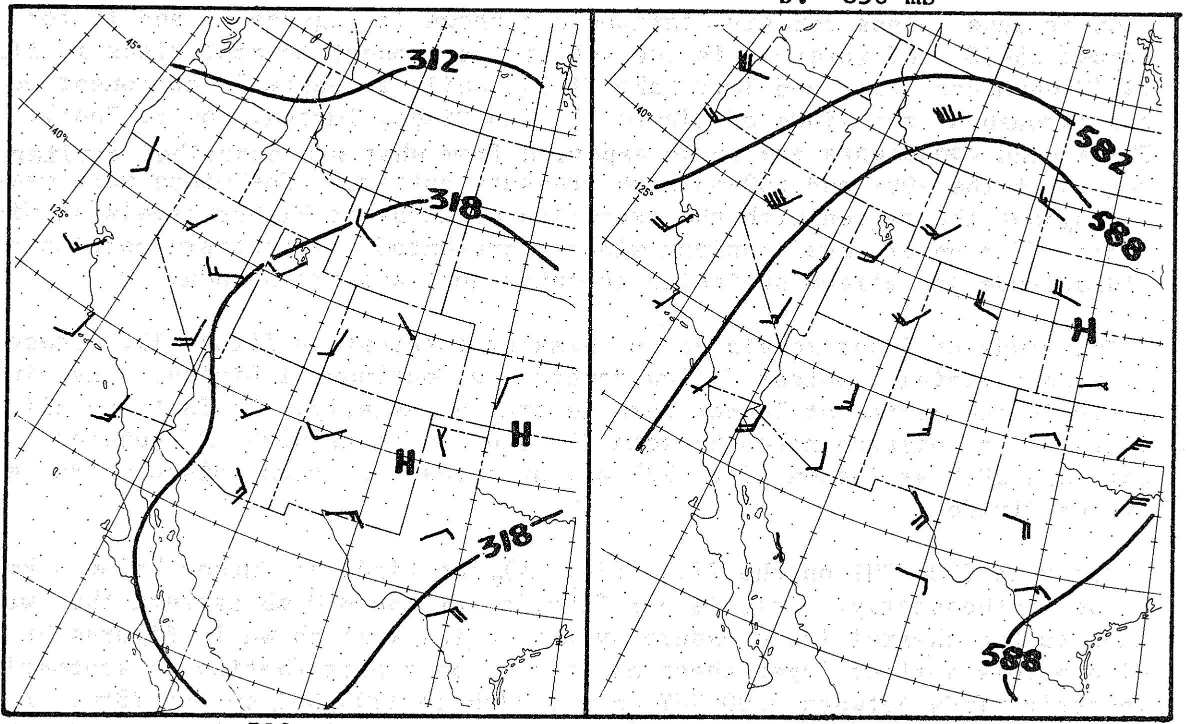
c. 700 mb d. 500 mb

Figure 10.--Standard pressure level charts for August 25, 1970, 1200 GMT. Pressure in millibars, heights in decameters, winds in knots.



a. Surface

b. 850 mb



c. 700 mb

d. 500 mb

Figure 11.--Same as figure 10, for August 27, 1970, 1200 GMT.

as a short-wave trough passed around the northern limits of the anticyclone, and does not agree with Bryson's typical conditions listed in section 2.1.

I examined the pressure differential between Guaymes, Mexico and Blythe, Calif. for the period 0000 GMT of the 25th through 2100 GMT of the 27th. The greatest difference between pressures at those two stations, 4 to 6 mb, occurred between 1200 GMT of the 25th and 0000 GMT of the 26th. Toward the end of the period, pressures were nearly equal at both stations. The maximum pressure difference of 6 mb does not quite match those I found in the Phoenix storm, or by Hales (1972) for major moisture surges into Arizona.

3.2.3 Vertical Temperatures and Winds.

Temperature soundings for Yucca Flats, Tucson, Winnemucca, and Ely are presented in figures 12 and 13 in a manner that permits variations with time to be distinguished. Little change occurred above 600 mb (4.5 km) in the observed air temperatures, while most stations show a slight cooling trend through the period below this level. Tucson and Winnemucca showed increases in moisture up to 500 mb, and especially between 700 and 500 mb as represented by the dew-point curves. Furthermore, the extreme convective instability within the lowest 3 km at each station (excepting Ely on the 28th) is apparent by comparison against the 315 K potential temperature slope. Since these soundings were taken just after the time of maximum heating, it can be concluded that convective clouds at each station were responsible for pumping low-level moisture aloft.

Upper level winds for six stations are shown in figures 14 and 15 for August 25-28. Of interest is the westerly component to most winds in figure 14 (Winnemucca, Ely, and Salt Lake City), while an easterly component occurred throughout the winds of figure 15 (San Diego, Tucson, and El Paso). These wind components are to be expected from what was described earlier with regard to the 700- and 500-mb high pressure pattern. The winds were weak throughout the region with the exception of those at higher levels at Winnemucca. The upper-level maximum winds represented the southern portion of the midlatitude jet stream beginning to enter northwestern Nevada.

The winds at lower levels are of greater interest in figure 15. These at El Paso certainly indicated flow toward the Continental Divide. The winds early in the period at Tucson were generally easterly. In fact the slight increase in moisture noted between 700 and 470 mb at 0000 GMT between the 26th and 28th at Tucson (fig. 12) may have resulted from moisture from east of the Divide.

Prior to 0000 GMT on the 27th (fig. 14), the winds at Tucson below 3 km tend to be southeasterly. This is a reflection of the 850-mb pattern that was tied to the thermal low pressure system to the west shown in figures 10 and 11. Within this surface layer there appears to be a perturbation of southerly to westerly winds between 0000 GMT on the 27th to 1200 GMT on the 28th. A somewhat comparable occurrence is also seen in the lowest levels above San Diego.

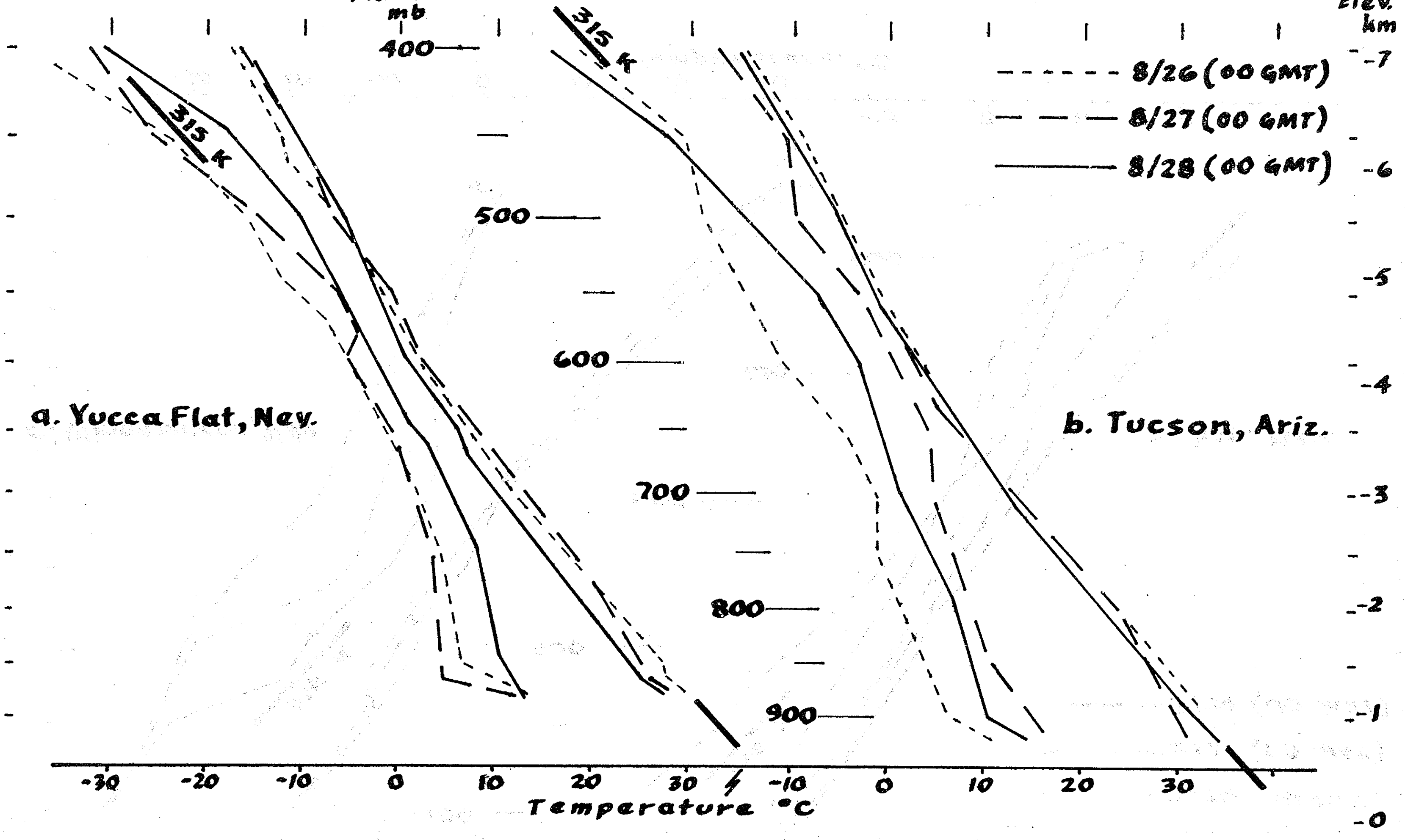


Figure 12.--Temperature and dew-point soundings for August 26-28, 1970. Slope of 315K isotherm represents dry adiabatic lapse rate.

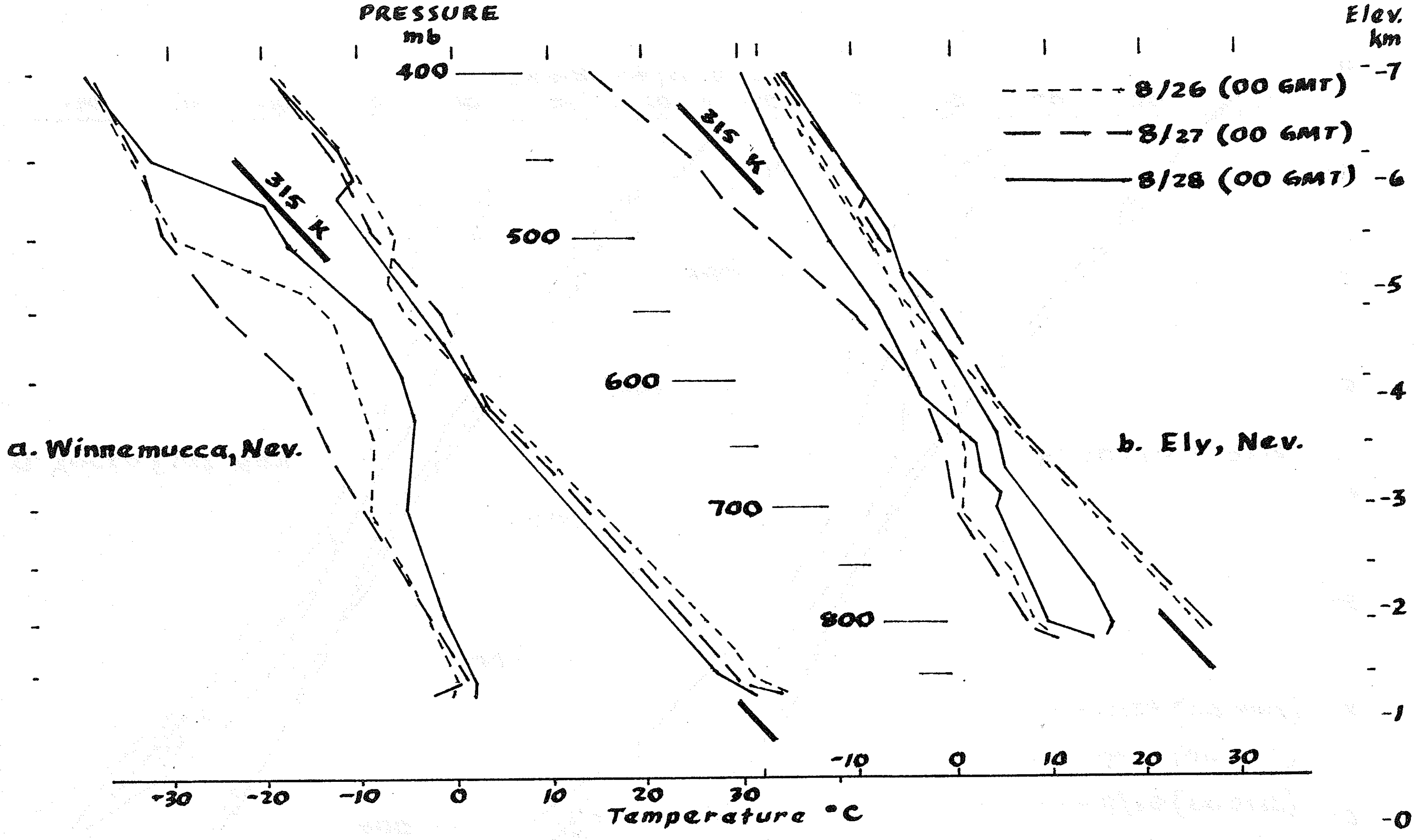


Figure 13.--Same as figure 12.

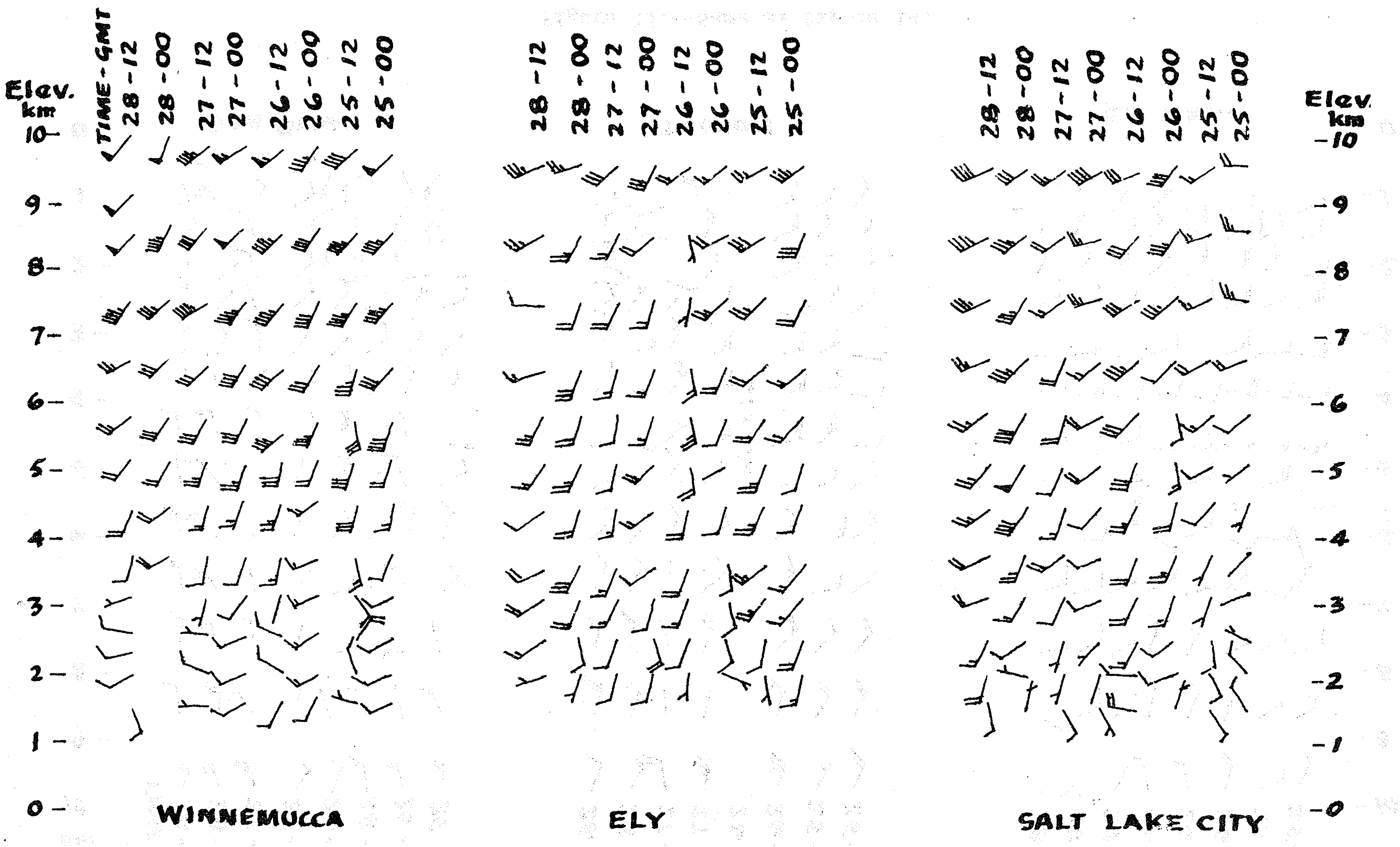


Figure 14.--Time section of upper winds for August 25-28, 1970. Full barb is 10 kt. Time reads right to left.

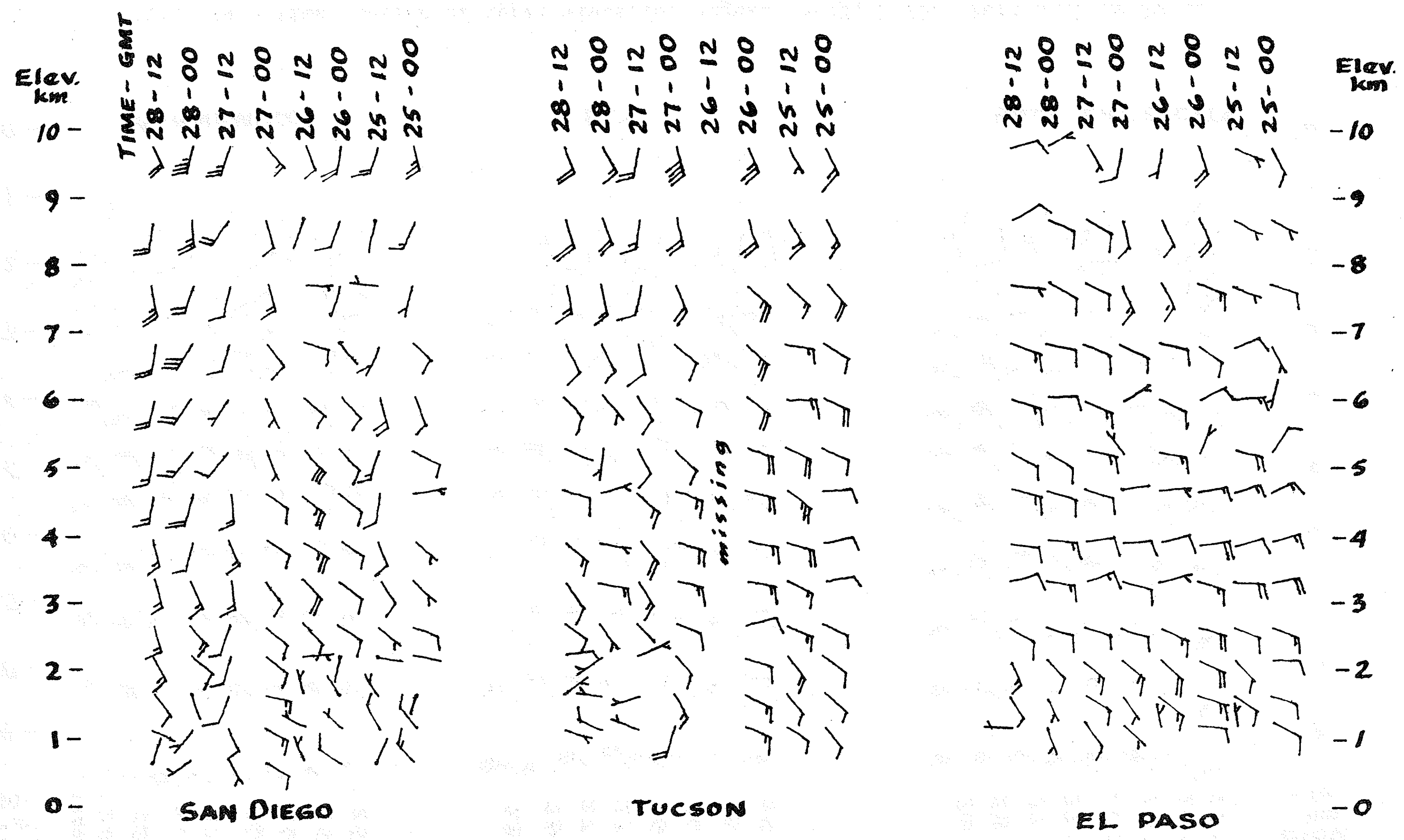


Figure 15.--Same as figure 14.

3.2.4 Moisture.

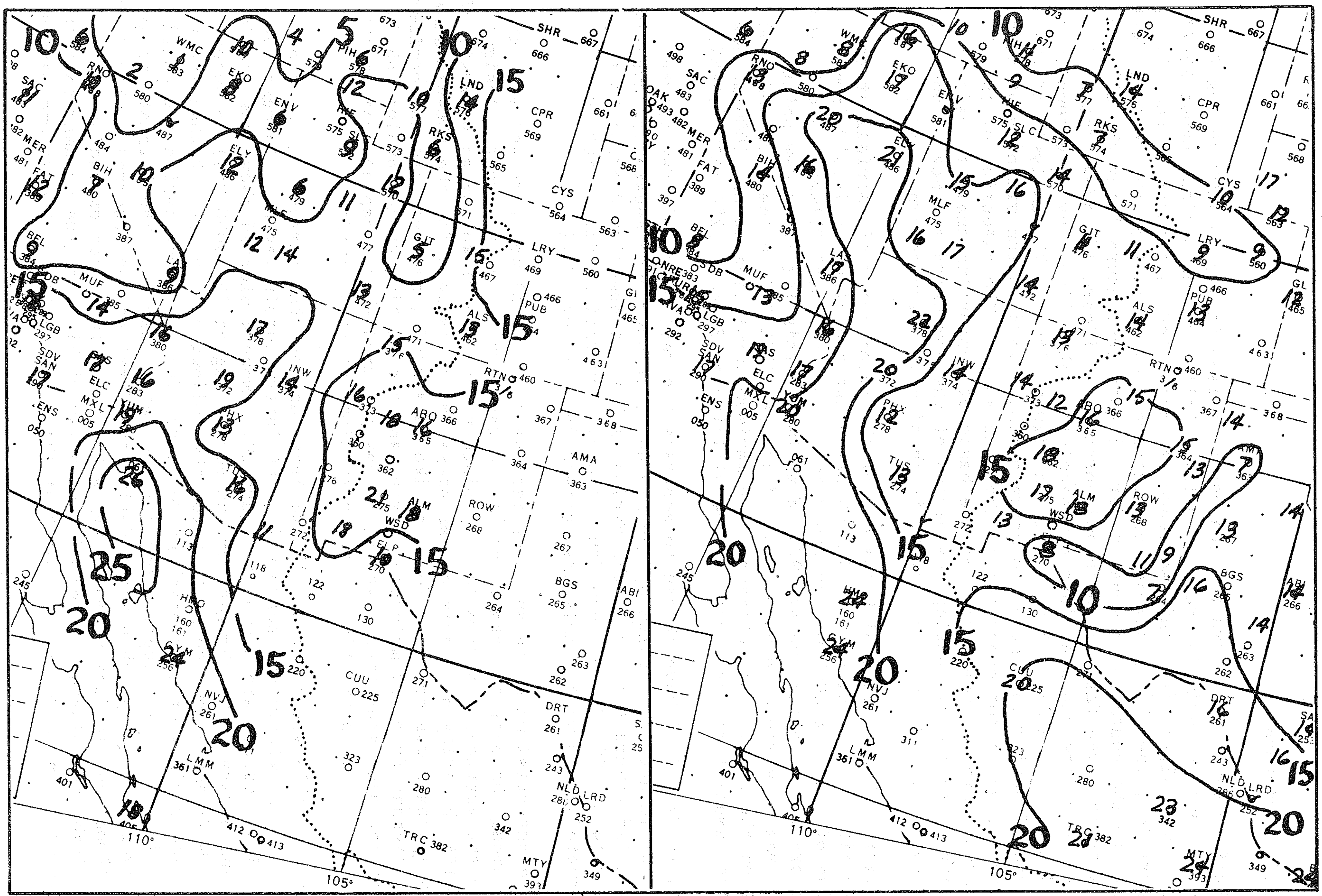
Surface dew points were reduced pseudo-adiabatically to 1000 mb, as for Case 1, and an analysis prepared 4 times daily for the period August 25-27. Selected analyses from this sequence are presented in figures 16 and 17. In figure 16a, the 20°C isodrosotherm extended northward from the Gulf of California to the southern Arizona border. Twenty-four hours later the 20°C isodrosotherm moved farther north and northwest. Figure 17a shows the 20°C isodrosotherm more expanded into southeastern Utah followed by an extension toward Elko on the 27th (fig. 17b). In figures 16b to 17b, analysis of the tongue of maximum potential moisture northwestward in the vicinity of southwestern Utah is not supported by the data shown. The extension of the 20°C isodrosotherm has been drawn on the basis of supporting analyses made at intermediate times. During the period of the northward advance of potential moisture, it is noted that drier air remains in northwestern Nevada.

Figure 17b coincides with the end of the major burst of rainfall at the Elko Airport. At Elko, the 1000-mb dew point had risen to 19.5°C from a value of 8.5°C at 0000 GMT on the 25th. From the Local Climatological Data Summary for Elko for August 1970, a maximum persisting 12-hr dew point of 19°C was determined to have occurred between 2000 GMT on the 27th and 0800 GMT on the 28th. For reference, the maximum persisting 12-hr 1000-mb dew point temperature for August in the vicinity of Elko is 22°C (EDS 1968).

As in Case 1, I have chosen to separate the region of 20°C dew points or greater in northern Mexico by the Divide. Although such separation appears justified toward the end of the period, it may be questioned prior to the analysis of 0000 GMT on the 27th. Again, insufficient data exist to adequately resolve the moisture pattern for northern Mexico.

The potential moisture analyses represent low-level moisture and as such are among the most important factors to thunderstorm development. Insight into the vertical distribution of moisture could be viewed by an analysis of specific humidity by layers as was presented in table 2 for the Phoenix storm. This approach was not used for the Elko case study, because Elko is considerably distant from any moisture source, and the listing would involve tabulations for many stations. Rather, it was presumed that a map analysis might provide better information on the directions of moist inflow.

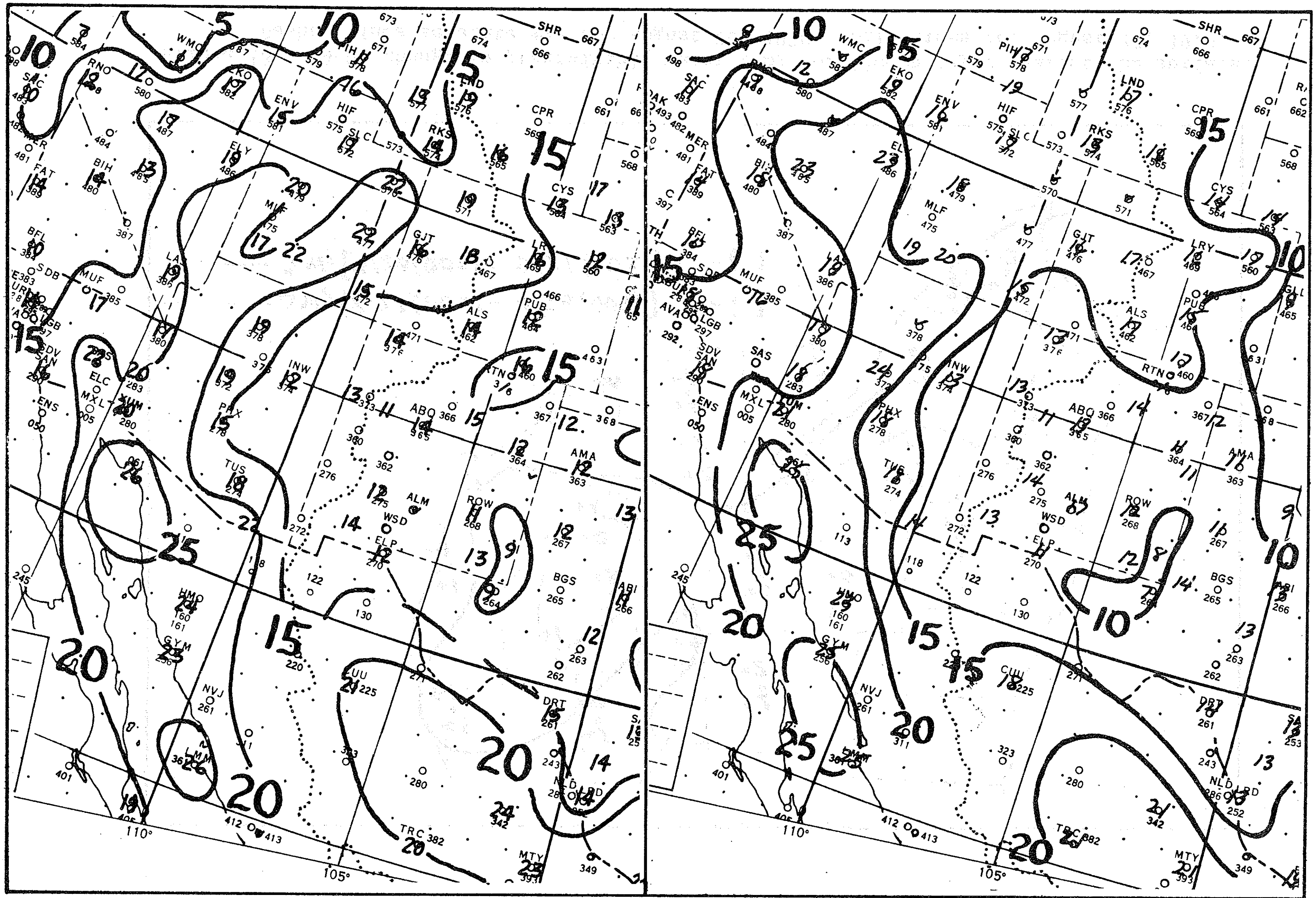
Precipitable water for the 150-mb layer nearest the surface was obtained for stations within and surrounding the Intermountain region. Changes over two 24-hr periods are shown in figure 18. Amounts plotted above the station designator are 24-hr changes for the period August 26 (0000 GMT) to August 27 (0000 GMT) and below the station for the following 24 hours. Dashed lines separate regions of increases and decreases for the first period and solid lines denote similar separations for the latter period. The largest change in low-level precipitable water during the first period occurred at San Diego (+7.87 mm) and at Tucson (+6.10 mm) with lesser increases extending northward into Utah and Colorado. Much of Nevada lay within a region of decreases that reversed to increases through most of the Great Basin for the second period.



a. 8-25-70, 0000 GMT

b. 8-26-70, 0000 GMT

Figure 16.--1000-mb dew-point analysis (°C).



a. 8-27-70, 0000 GMT

b. 8-27-70, 2100 GMT

Figure 17.--1000-mb dew-point analysis (°C).

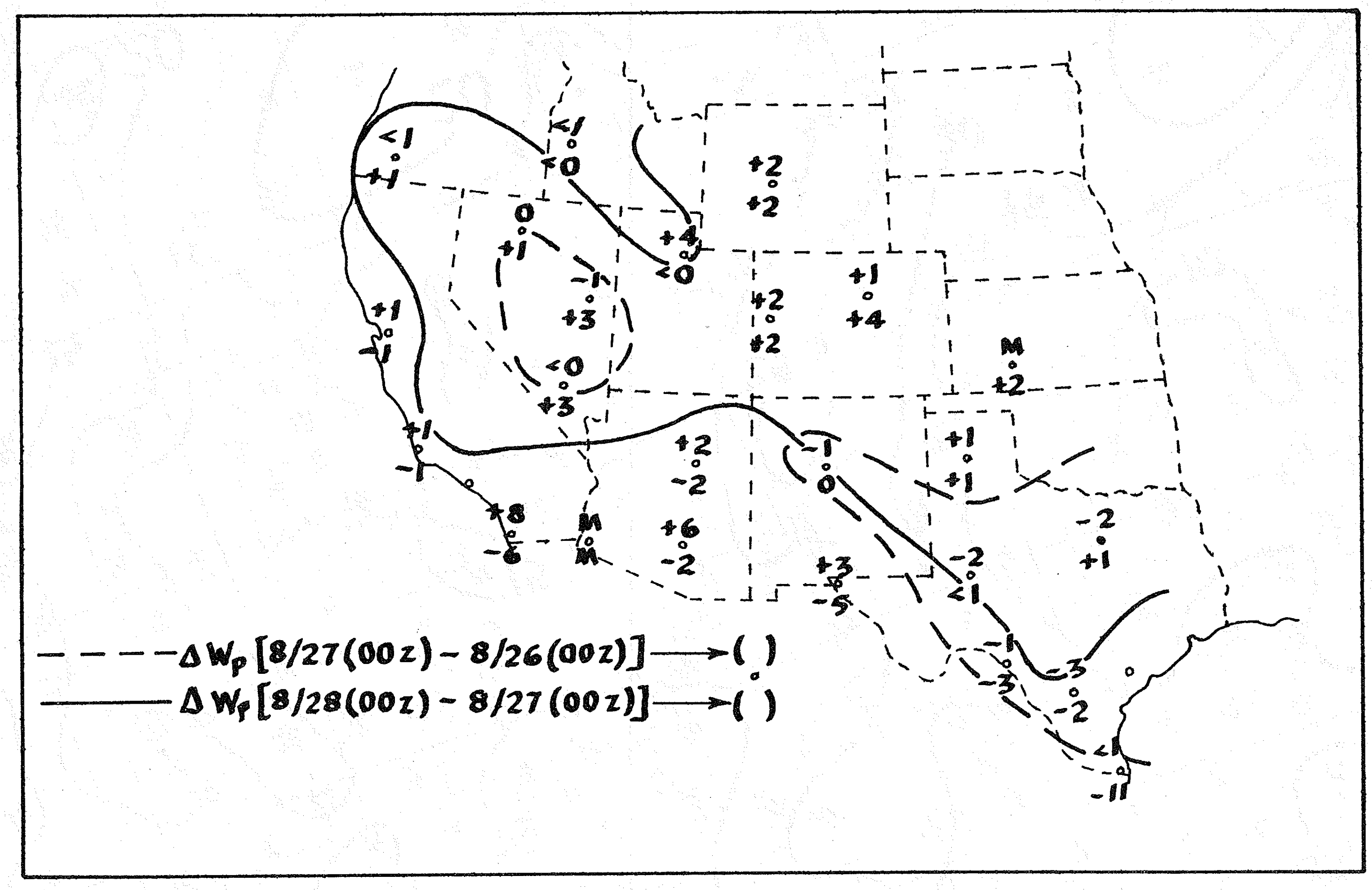


Figure 18.--24-hr change in precipitable water (mm) for 150-mb layer nearest the surface. Dashed lines separate +/- for August 26, 1970, solid lines for August 27, 1970.

The shift in location of low-level increases, although small in magnitude, suggests that the mass of moist air over the southern Intermountain region moved northward toward the Great Basin. This conclusion tends to support the previous analysis of potential moisture.

3.2.5 Discussion.

The preceding examination of the moisture inflow to the extreme local thunderstorm at Elko on August 27, 1970, as in the first case study, appears to point to the Gulf of California and the tropical Pacific Ocean as the moisture source. Since the distance between the Gulf of California and the extreme rain event was much greater in this case than in the first case, the conclusion is based primarily on the evidence of the continuity of maximum potential moisture as shown by the 1000-mb dew-point analyses. Abnormally heavy local rains at Yuma, Las Vegas, and Elko within a span of 24 hours apparently occurred because the 3 stations lie on a line whose axis conforms generally with the maximum moisture shown by the dew-point analysis. This line of exceptional storms is evidence of the low-level moisture surging northward from the head of the Gulf of California. Some support for the northward movement of low-level moisture in this case study is also evident in the temporal changes in precipitable water.

The dew-point analyses show a tendency for maximum moisture to follow a path of least resistance with regard to terrain. The flow of moisture was diverted by the Mogollon Rim in south-central Arizona.

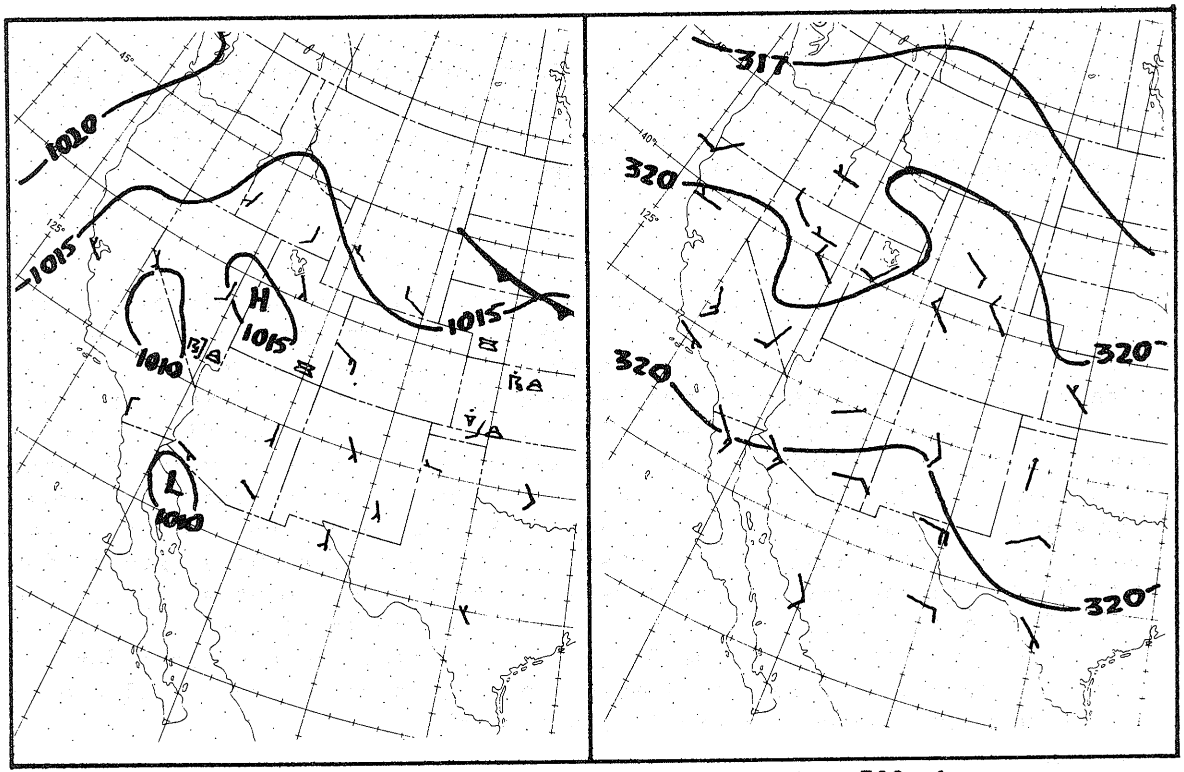
3.3 Case 3; Morgan, Utah Storm, August 16, 1958 (150 mm)

3.3.1 The Storm.

As a result of localized but intense flooding at Morgan, Utah (about 40 km northeast of Salt Lake City) on the evening of August 16, 1958, a survey was conducted of the Round Valley basin (about 4 km east of Morgan) for evidence of rainfall amounts. The report of the U.S. Geological Survey team describes the finding of four separate values that were used to prepare a tentative isohyetal pattern. Witnesses to the heavy precipitation said the storm lasted approximately 1 hour, 1600-1700 MST (2300-2400 GMT), and appeared to intensify after the merger of two storm clouds. The reliability of the maximum amount of 175 mm determined from the bucket survey is doubtful; however, most of the hydrologists who reviewed the Morgan event accepted a value of 150 mm (summary report by Salt Lake City District Hydrologist, May 19, 1964).

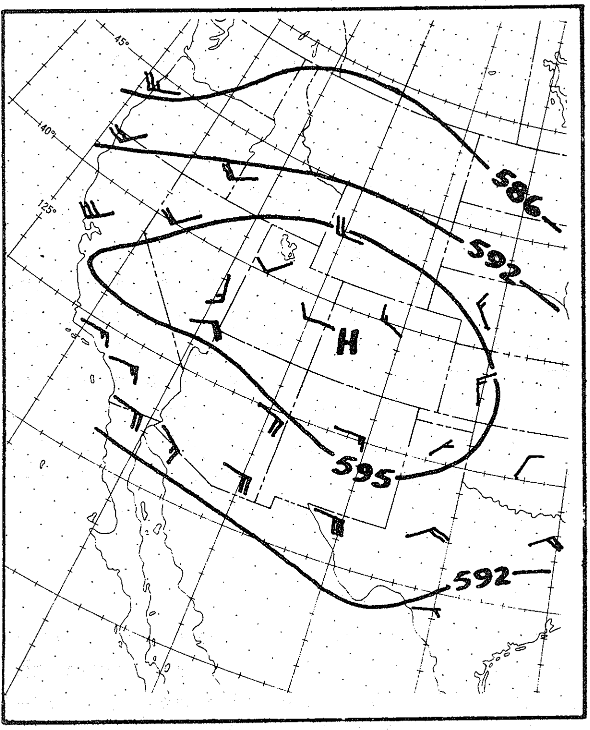
3.3.2 Synoptic Weather Maps.

Little day-to-day variation was evident in the surface analyses between the 12th and the 17th for the Intermountain Southwest. Figure 19a shows the surface pressure pattern for August 15th at 1200 GMT. The thermal low pressure system was split into twin cells; one in central California and the other at the mouth of the Colorado River. Surface winds were generally light and variable, although most stations in the Southwest showed a southerly component.



a. Surface*

b. 700 mb



c. 500 mb

* Surface analyses for August 15, 1958 were not available; IGY World Weather Map for 1200 GMT August 15, 1958 shown here.

Figure 19.--Standard pressure level charts for August 15, 1958, 0000 GMT. Pressure in millibars, heights in decameters, winds in knots.

During the succeeding 36 hours, the size of the thermal low-pressure trough fluctuated considerably. Figure 20a shows the surface pattern at the time of the Morgan storm (0000 GMT, August 17, 1970). Surface winds were light and variable and convective activity was extensive throughout the region.

Figure 19b shows that the 700-mb pattern was unorganized on August 15, but developed into an anticyclone on the 16th that became more organized by the 17th (fig. 20b). The 700-mb pattern resembles the break-off anticyclone described by Bryson and Lowry (1955). The winds were generally less than 10 kt throughout the Intermountain region. At the time of the Morgan storm, shown in figure 20b, the center of the anticyclone had moved northward to a position over southern Wyoming. These changes result in a rapidly varying flow pattern bringing southerly winds over northern Utah once again.

The 500-mb patterns shown in figures 19c and 20c reflected the changes described for the 700-mb level. The winds conformed in general to the anticyclonic pattern centered over southwestern Colorado.

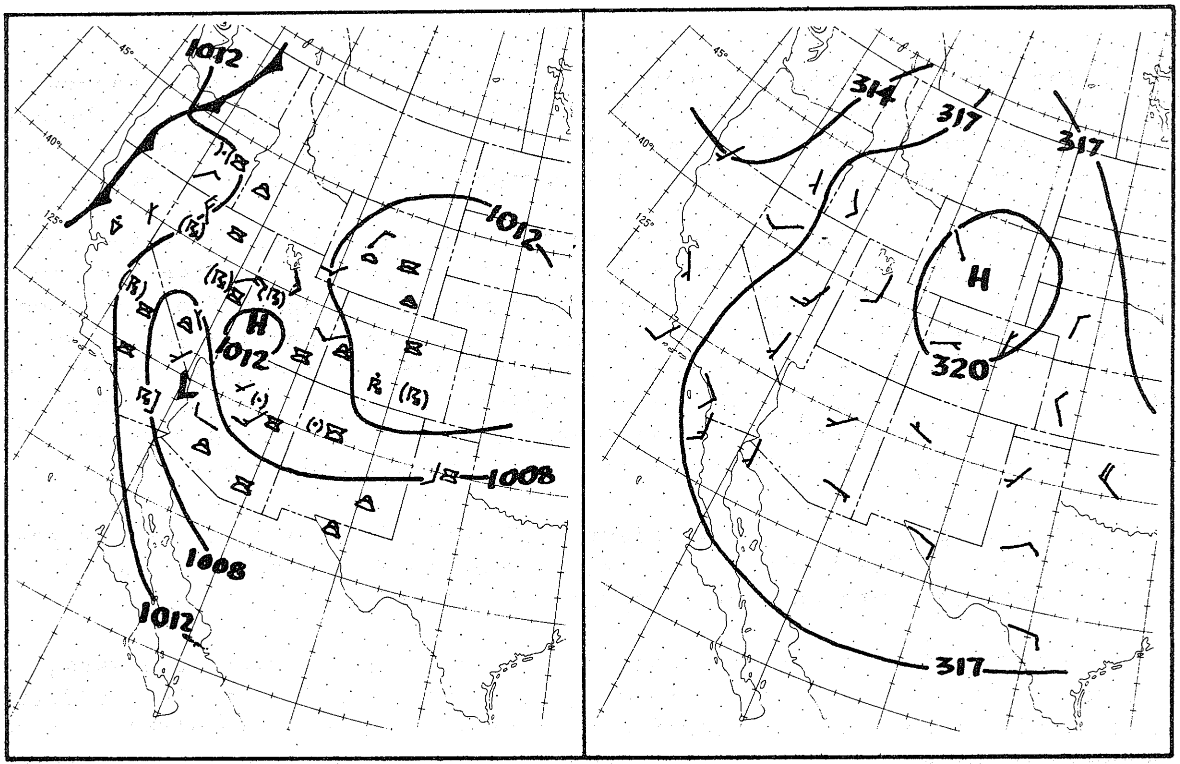
Some indication of surface weather is shown on the surface analyses, but a closer inspection of Local Climatological Data summaries provided additional information about the distribution of rainfall. Only a few widely scattered showers occurred in Utah prior to the 16th. Recorder stations are shown in figure 21 with their respective amounts for August 16th. Most of the showers at stations along the Wasatch Mountains occurred during the afternoon while those at stations in eastern Utah occurred near midnight. The Morgan value fits into the time pattern of other showers reported along the Wasatch Mountains, but it was much larger than any other observed amount. The nonrecorder station at Elberta, Utah, 130 km south of Morgan, reported 50 mm, and the one at Wanship Dam, Utah, 48 km east-southeast of Morgan, reported 29 mm on the 16th.

3.3.3 Vertical Temperatures and Winds.

Soundings were plotted for all stations in the Intermountain region as well as those immediately east of the Divide for the period of August 15-17, 1958. The rawinsonde nearest to Morgan was Salt Lake City. Figure 22 shows that moisture generally increased between the 15th (dotted line) and the 17th (solid line). The large change to drier air above 4 km on the 16th reflected the movement of the 500-mb center.

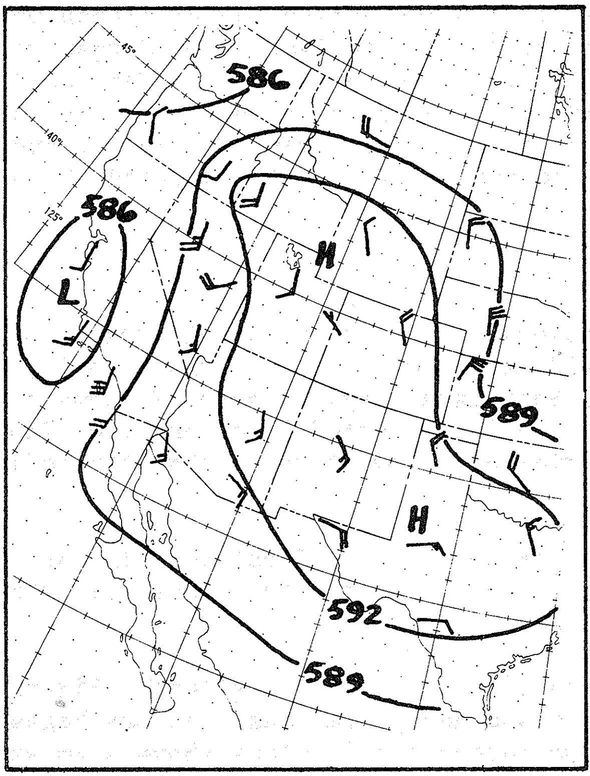
Winnemucca, Grand Junction, and Denver soundings indicated a similar change of moisture at levels to 6 km, while at Las Vegas moisture increased through the period only in a layer near 700 mb.

The winds aloft are shown in figures 23 and 24 for 6 stations. Figure 23 shows some interesting features of the southerly stations. At Las Vegas, the sequence shows the gradual change from southeasterly winds above 4 km at the beginning of the period to southerly winds above 2 km at the end of the period. Albuquerque winds changed from easterly to southwesterly above 3 to 4 km. At Amarillo, easterly winds above 4 km shifted abruptly to westerly or northwesterly winds above 3 km at 1200 GMT on the 16th.



a. Surface

b. 700 mb



c. 500 mb

Figure 20.--Same as figure 19, for August 17, 1958, 0000 GMT.

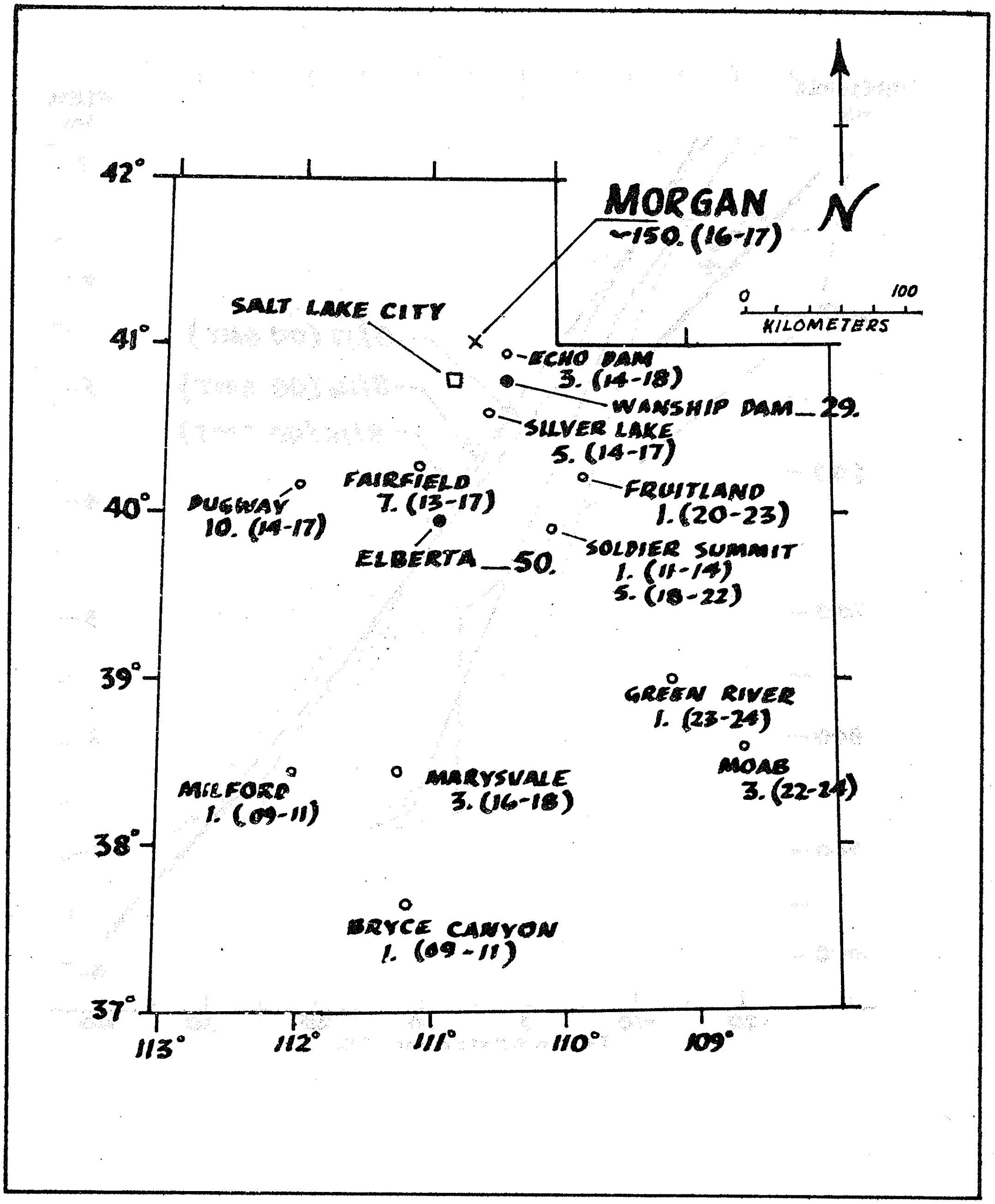


Figure 21.--Precipitation for August 16, 1958 at Utah recorder stations (open circles). Selected nonrecorder amounts shown by solid circles. Amounts in millimeters with time (MST) period of accumulation in parentheses. Morgan storm included for comparison.

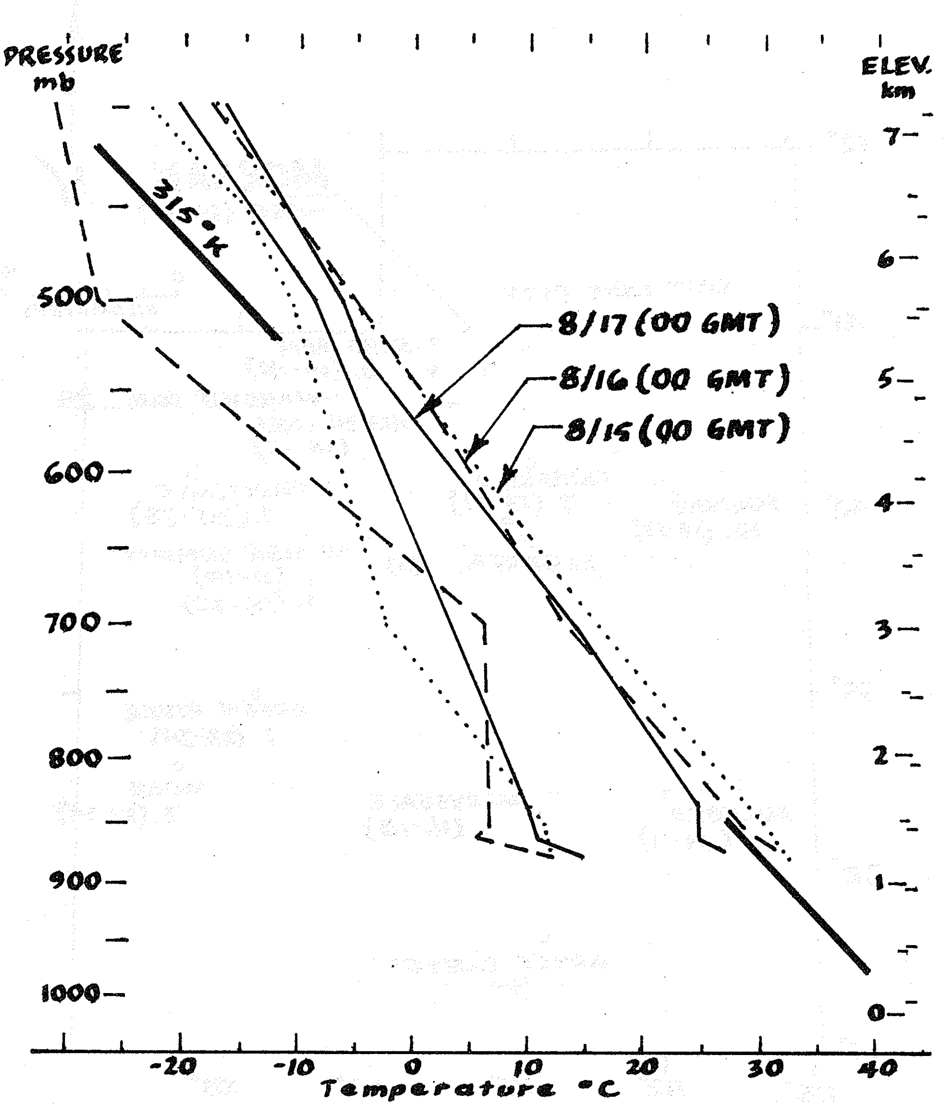


Figure 22.--Temperature and dew-point soundings for Salt Lake City. Slope of 315 K isotherm represents dry adiabatic lapse rate.

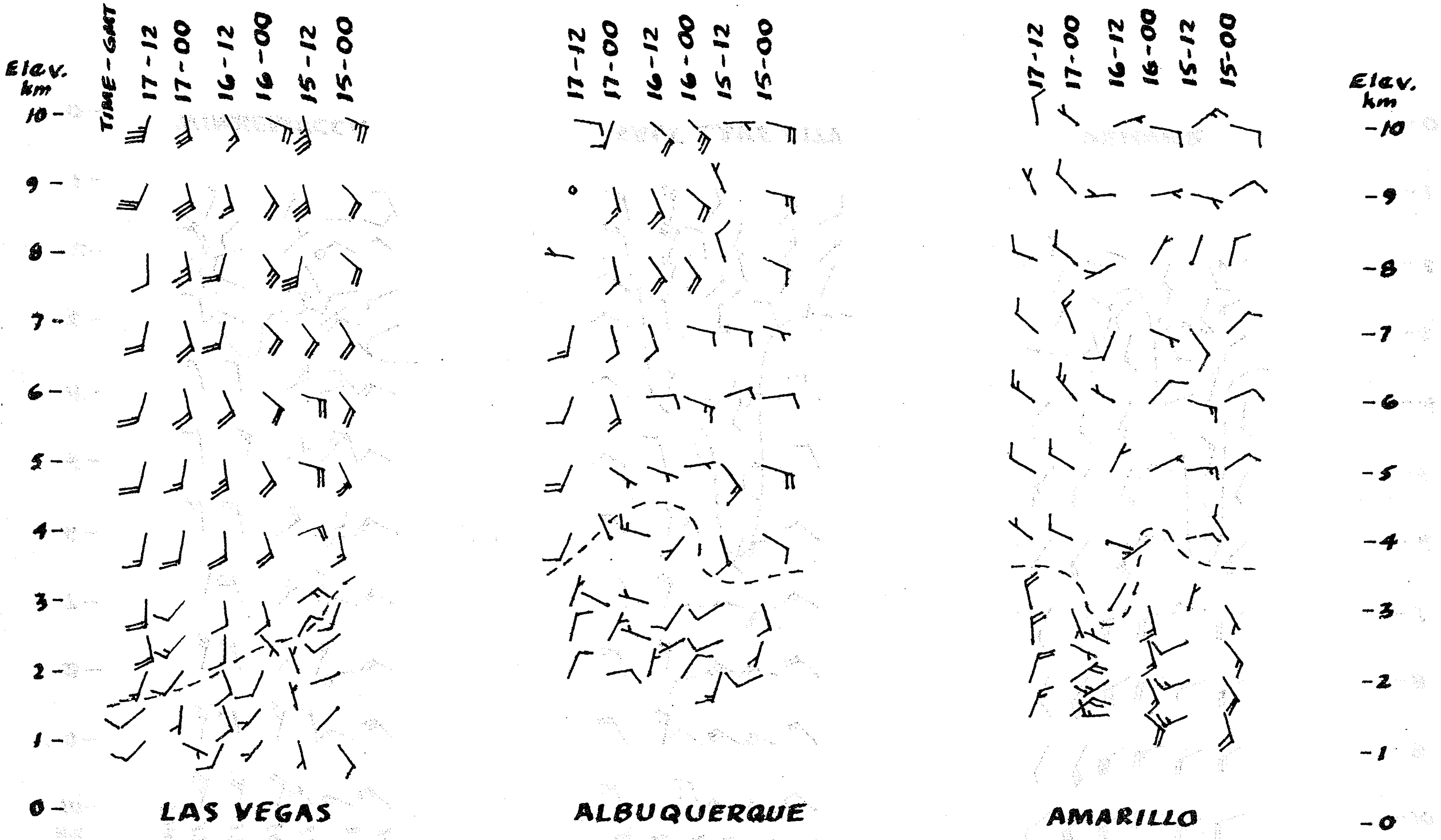


Figure 23.--Time section of upper winds for August 15-17, 1958. Full barb is 10 kt. Time reads right to left. Dashed lines indicate level of shear discussed in text.

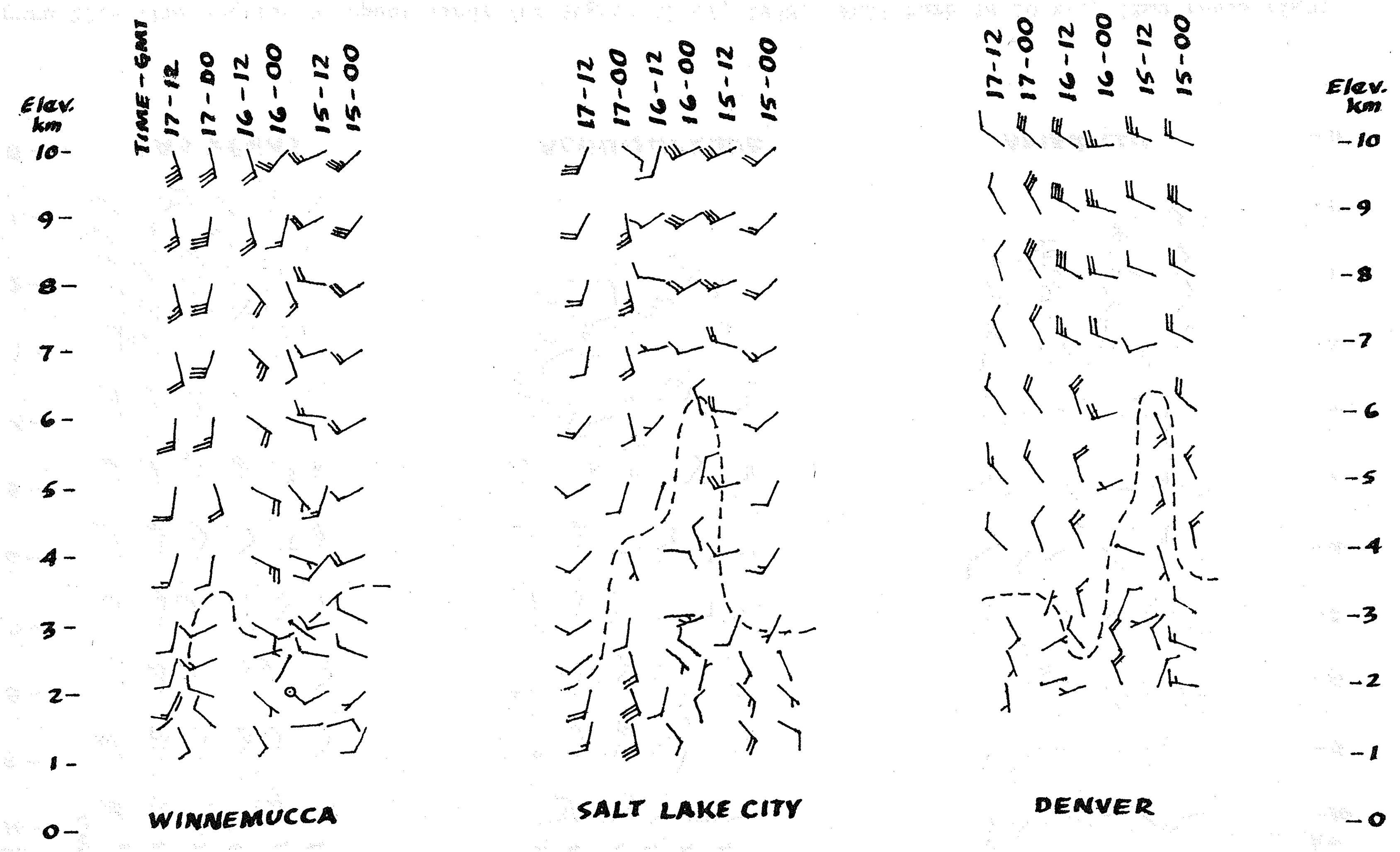


Figure 24.--Same as figure 23.

Figure 24 presents wind profiles for stations along the northern border of the study region. These also show considerable change in direction through the period. Winnemucca winds backed from southwesterly above 3 km to southerly above 2 km. Winds at Salt Lake City and Denver showed changes that differed from those at the other stations. Significant directional fluctuations occurred to heights of 7 km over a 36-hr period within otherwise consistent flow. Separation of these consistent winds from the more variable winds at lower levels is indicated by dashed lines. It should be noted that the upper level winds for all 6 stations were consistent with the general movement of 700- and 500-mb anticyclonic pressure centers shown in figures 19 and 20.

It is apparent that winds at the lowest levels were light and variable as is generally the case in mountainous regions during weak pressure gradients. An exception was noted in the strong winds below 2.5 km at Salt Lake City at 0000 GMT on the 17th, the time of the Morgan thunderstorm. These strong surface winds probably were due to convective activity, although the airport station reported only a trace of precipitation on the 16th.

3.3.4 Moisture.

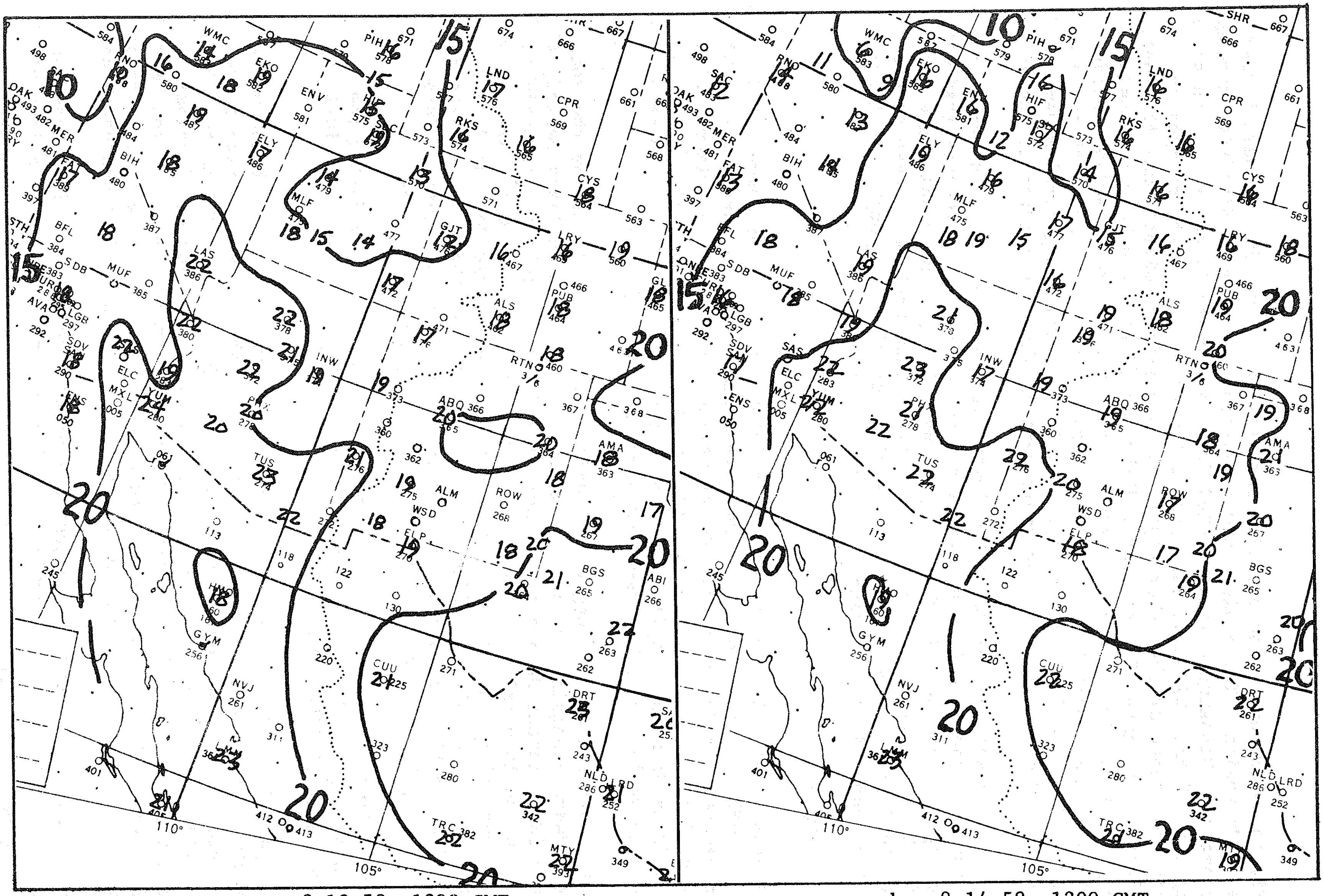
Figures 25 and 26 show the surface moisture analyses for August 13-16, 1958 at 1200 GMT. A broad tongue of low-level moisture represented by the 20°C isodrosotherm (reduced to 1000 mb) penetrated from southern Arizona (fig. 25a) to the vicinity of Salt Lake City on the 15th (fig. 26a). Figure 26b shows the 20°C isodrosotherm split into two tongues on the 16th, one pointing toward Reno while the second remained over southeastern Utah.

The separation of the tongues of maximum potential moisture by the Rocky-Sierra Madre Mountains has been maintained through the analysis period, although insufficient data exist in northern Mexico to confirm the analysis for the 13th and 14th (figs. 25a and b). Since the tongue of moist air at low levels west of the Divide was consistent with the little Mexican data reported along the Gulf of California, it appears that there was an extention of Gulf of California moisture at lowest levels into the southern Intermountain region, in a manner similar to the Phoenix and Elko cases.

The maximum persisting 12-hr dew point at Salt Lake City during the period of August 14-17, 1958 was 19°C--about 3°C lower than the mid-August record value of 22°C (EDS 1968).

Two periods of 24-hr changes in precipitable water within the 150-mb layer nearest the surface are shown in figure 27. Dashed lines separate increases and decreases for the period 0000 GMT on the 15th to 0000 GMT on the 16th, and solid lines provide similar separation for the following 24-hr period. During the first period, the largest increases occurred near the southern California coast, western Kansas, and central Texas. The largest increases in the second period occurred at Oakland, Winnemucca, and in western Texas.

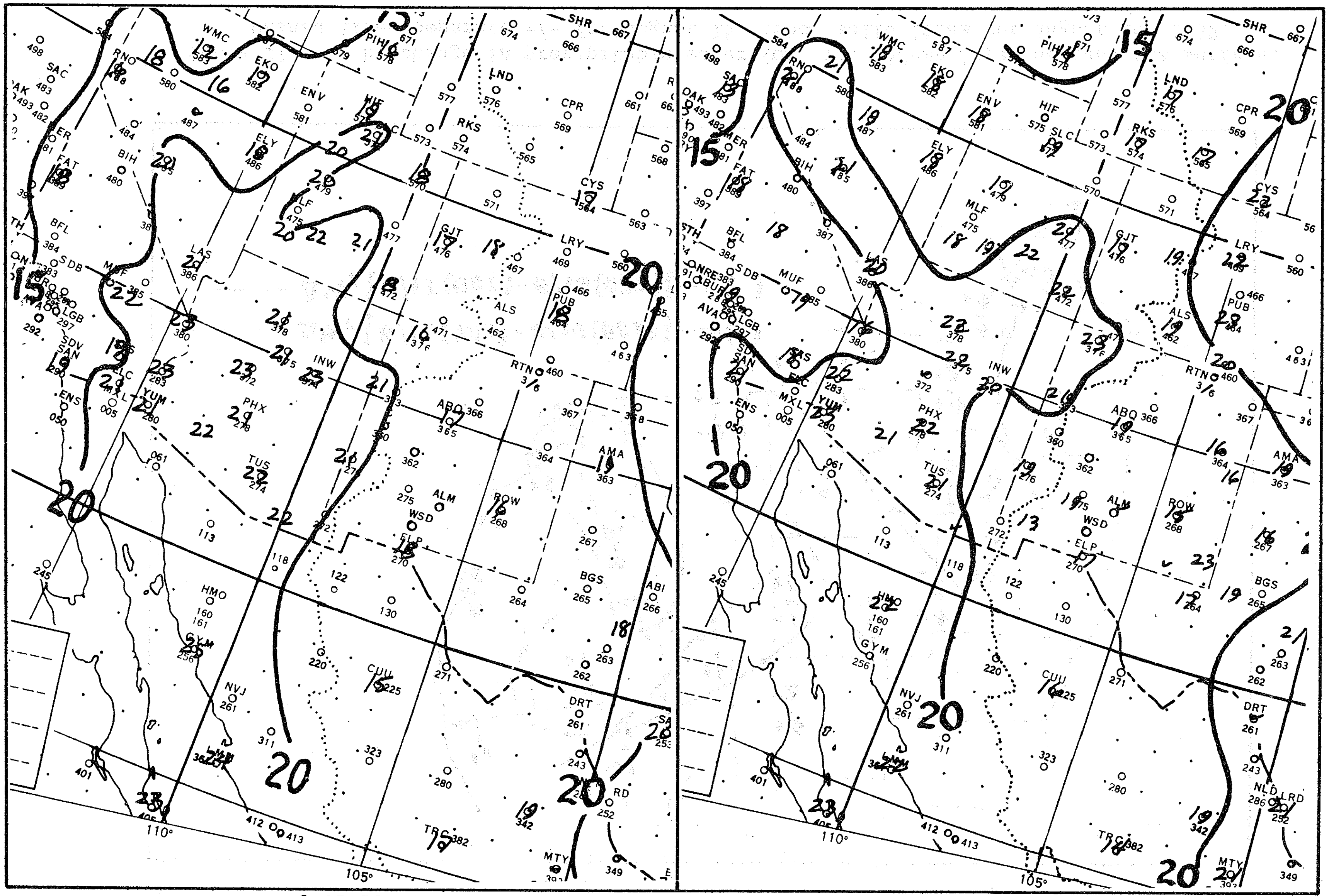
The Morgan study does not suggest any orderly movement of increases into Utah. The results of the examination of precipitable water were inconclusive.



a. 8-13-58, 1200 GMT

b. 8-14-58, 1200 GMT

Figure 25.--1000-mb dew-point analysis (°C).



a. 8-15-58, 1200 GMT

b. 8-16-58, 1200 GMT

Figure 26.--1000-mb dew-point analysis (°C).

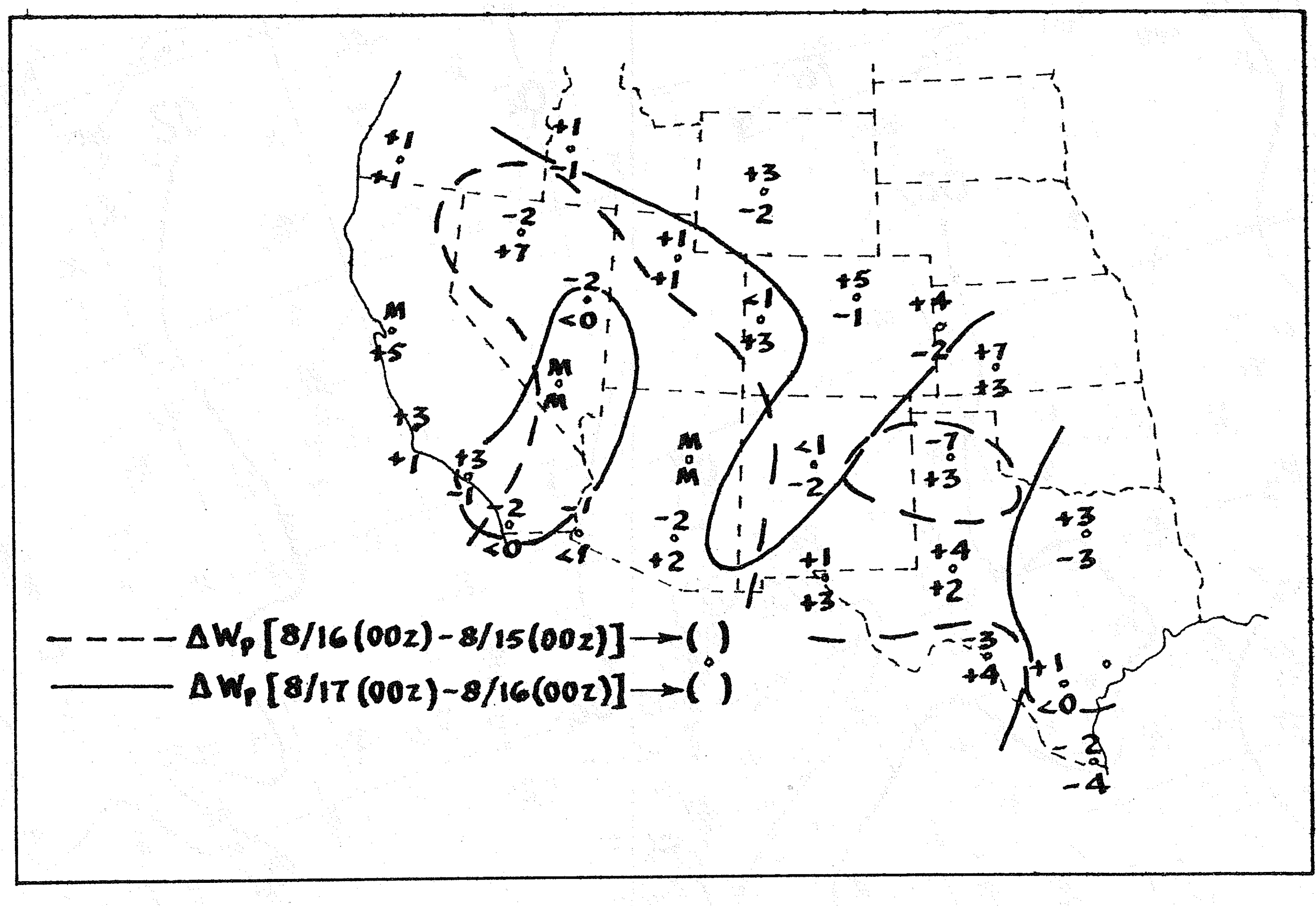


Figure 27.--24-hr change in precipitable water (mm) for 150-mb layer nearest the surface. Dashed lines separate +/- for August 15, 1958, solid lines for August 16, 1958.

Another view of the vertical distribution of moisture can be obtained from vertical cross sections depicting specific humidity. Two such cross sectional profiles were chosen for this study (see locations indicated in fig. 1). One profile between San Antonio and Medford was chosen to detect moisture fed into the Intermountain region anticyclonically from the Gulf of Mexico. A second profile from San Diego through Salt Lake City to Rapid City provided similar information relative to Pacific Ocean moisture.

Two sets of cross sections, 24 hours apart, are shown in figures 28 to 31. An approximate profile of intercepted terrain appears along the bottom of each diagram. On these figures, the solid lines represent moisture in terms of specific humidity (g kg^{-1}).

Figure 28 shows moisture of more than 9 g kg^{-1} from over San Diego dipping into the mountains near Las Vegas. Of interest is the wave effect of higher moisture which appears to spill over the mountains near Lander. A comparable effect at higher levels is noted over Winnemucca in figure 29. Also shown in figure 29 is the tongue of high moisture (>10 g kg^{-1}) that pushes against the Rocky Mountain foothills near Albuquerque from the east. Near the intersection of both cross sections (I on figs. 28 and 29) a shallow surface layer of moisture greater than 10 g kg^{-1} occurs.

Some interesting changes occurred between the cross sections of the 15th and 16th. Figure 28 shows considerable high-level (above 6 km) moisture that does not appear in figure 30. A wave of high-level moisture is also seen near the intersection in figure 29; this wave appeared to move northwestward to a position over Ely and Winnemucca in figure 31. The change in high-level moisture between figures 28 and 30 seems to be a reflection of this northwestward movement of moisture at elevations above 6 km. Nearer the surface (below 4 km), the wave-like crests that appear between Lander and Rapid City in figure 28 and over Winnemucca in figure 29 have progressed northeastward in figure 30 and northwestward in figure 31.

In all the cross sections there appeared to be a degree of independence between the observed moisture below about 3 km and that above. There was some variation in the low-level moisture observed over the 24-hour period, but primarily it was the manner in which the height of moisture surfaces varied with time that was of interest. Moisture below 3 km appeared to be controlled by terrain features, as evidenced in the pockets of higher specific humidity (>10 g kg^{-1}) shown in figures 28 to 31. To understand the temporal variations of lower level moisture in the vicinity of Morgan, Utah, an additional San Diego-to-Rapid City cross section was prepared for the 14th at 1200 GMT (not shown). Using this analysis, a composite vertical section shown in figure 32 indicates the relative progress of the lower level moisture across the mountains northeast of Salt Lake City. The motion of the surfaces of specific humidity with time was not uniform. There appeared to be a low-level pulse or surge of moisture that moved across the Rocky Mountains during the 15th as represented by the movement of the 6 g kg^{-1} surface.

Calling attention to the 10 g kg^{-1} moisture in figure 32, there is apparent advection from Las Vegas to the vicinity of Salt Lake City as one follows the sequence of the 14th (solid line) to 15th (dashed line) to 16th (dotted line.) Since the 10 g kg^{-1} surface lowers over Las Vegas during the middle of the period, it appeared that a surge of moisture passed this location at low levels.

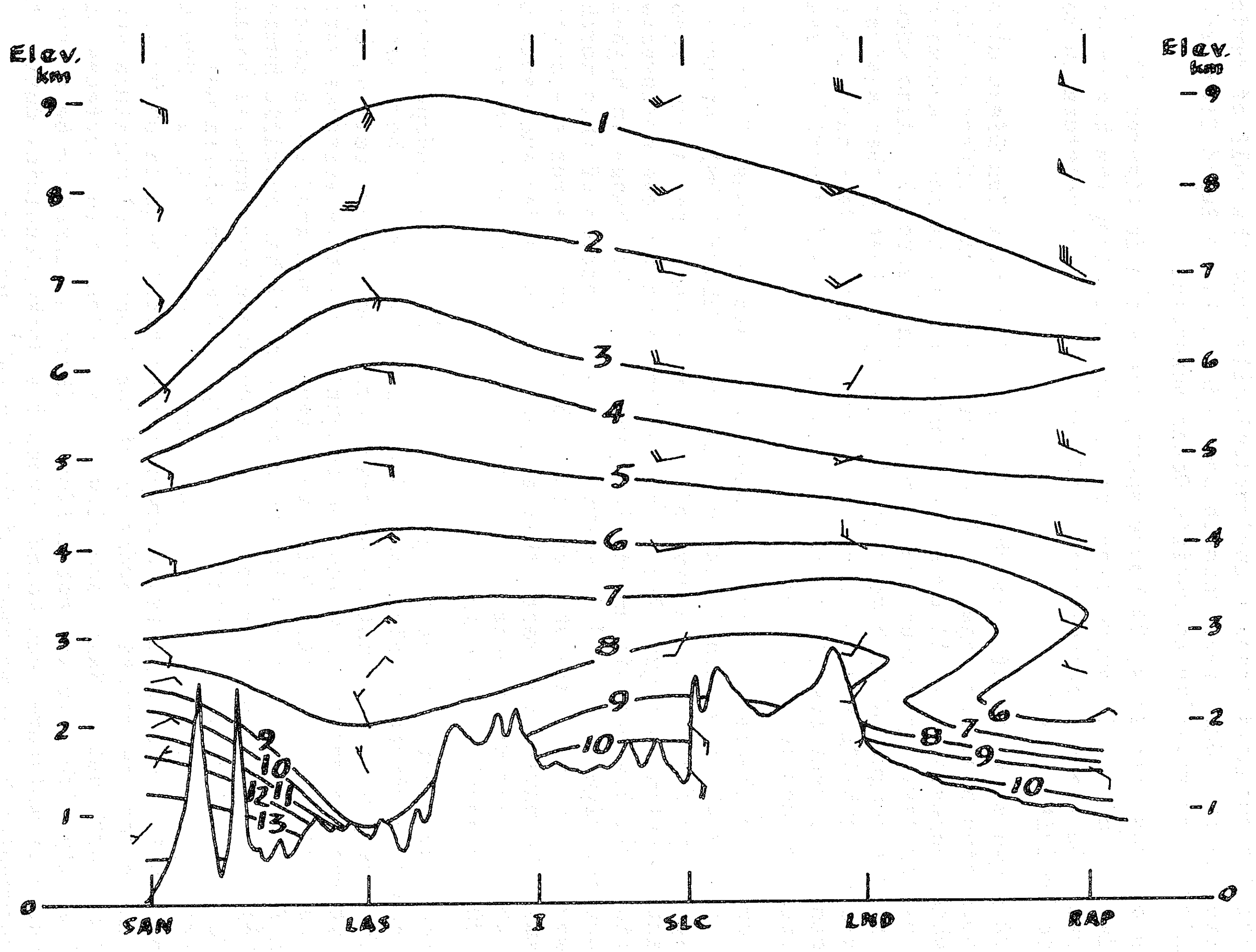


Figure 28.--Vertical cross section for August 15, 1958, 1200 GMT from San Diego (SAN), Las Vegas (LAS), Salt Lake City (SLC), Lander (LND), and Rapid City (RAP). Intersection of cross sections at I. Solid lines are intersection of surfaces of specific humidity (g kg^{-1}). Winds in knots.

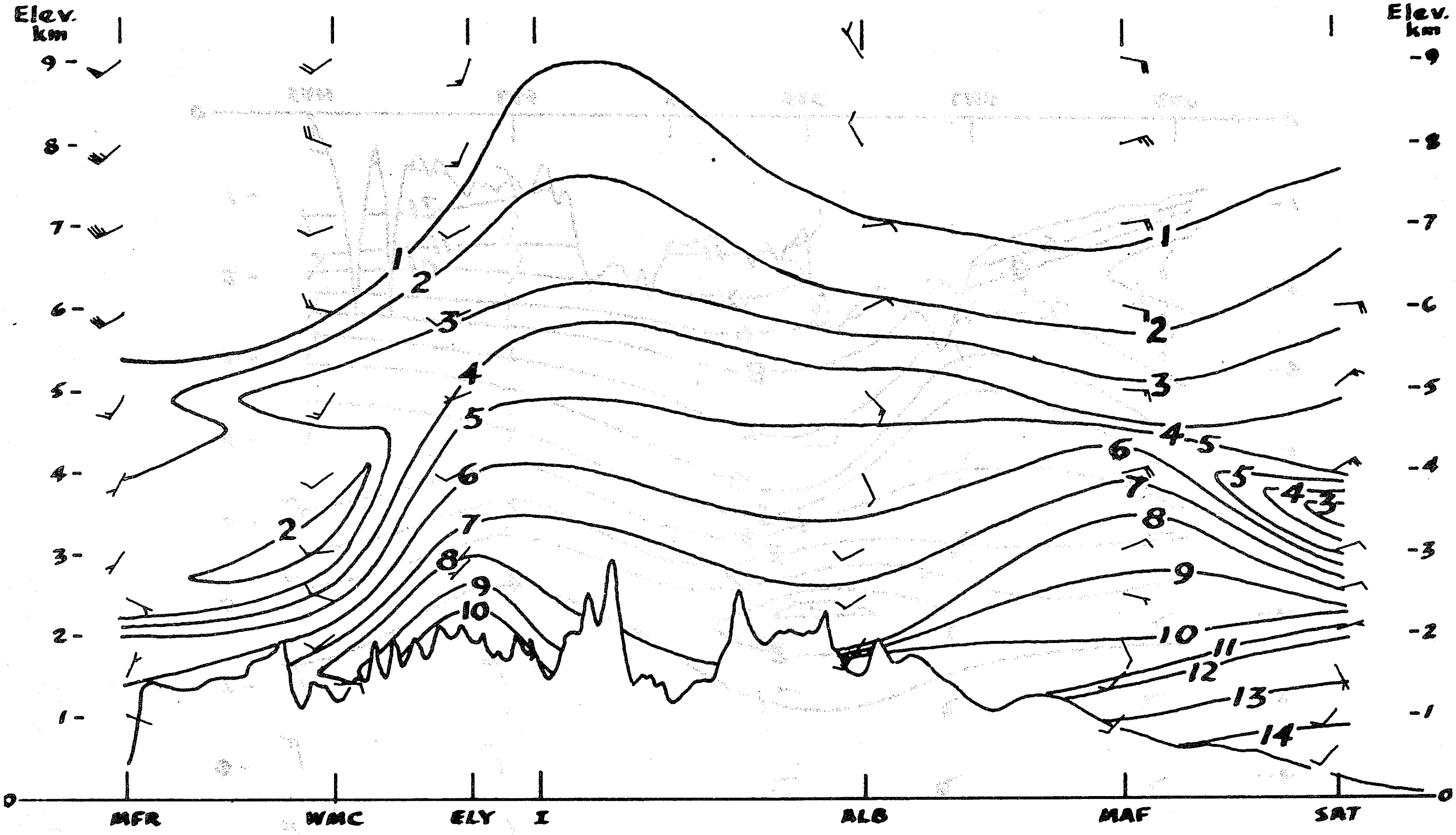


Figure 29.--Same as figure 28 for Medford (MFR), Winnemucca (WMC), Ely (ELY), Albuquerque (ALB), Midland (MAF) and San Antonio (SAT). Intersection of cross sections at I.

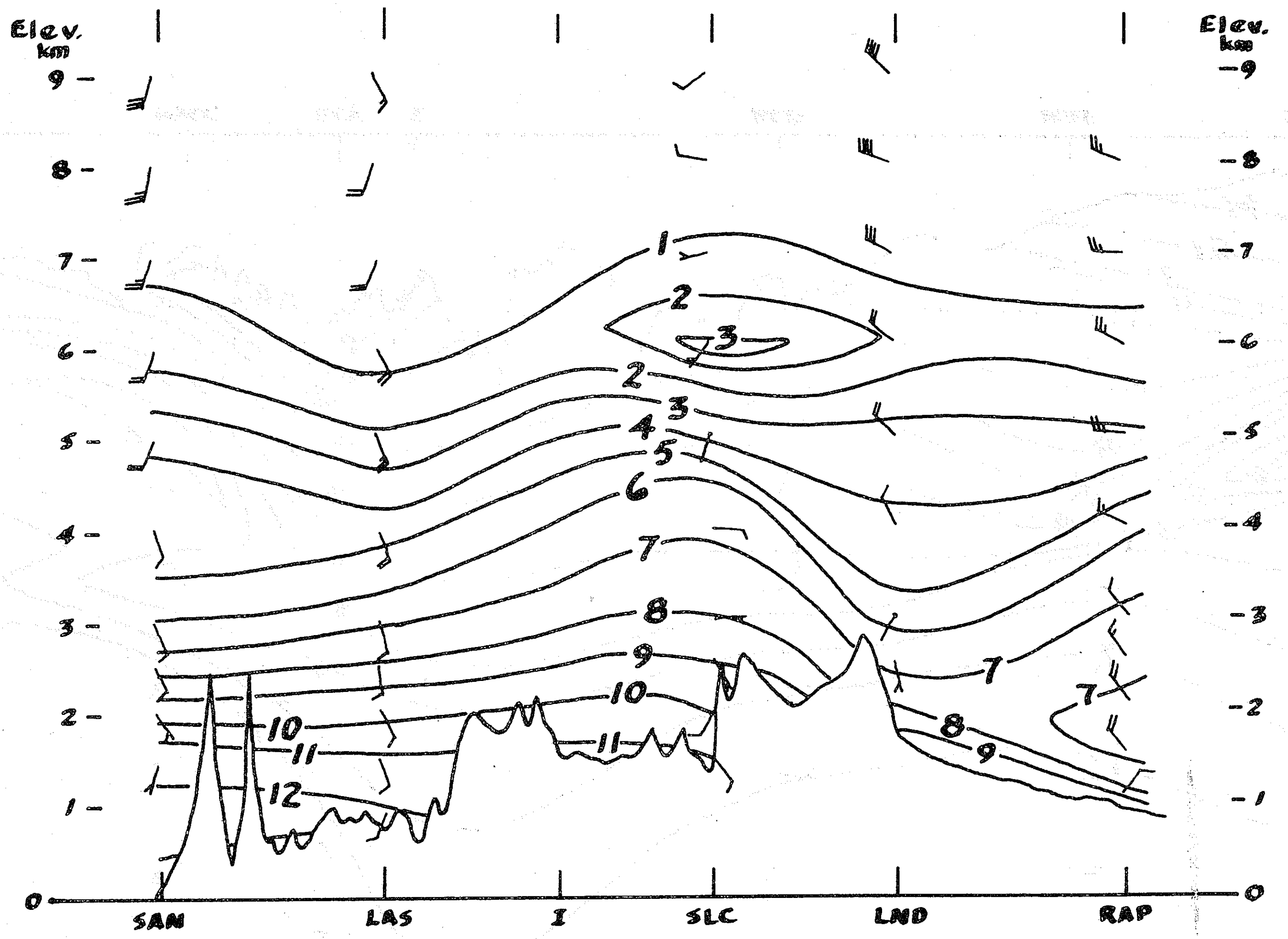


Figure 30.--Same as figure 28 for August 16, 1958, 1200 GMT.

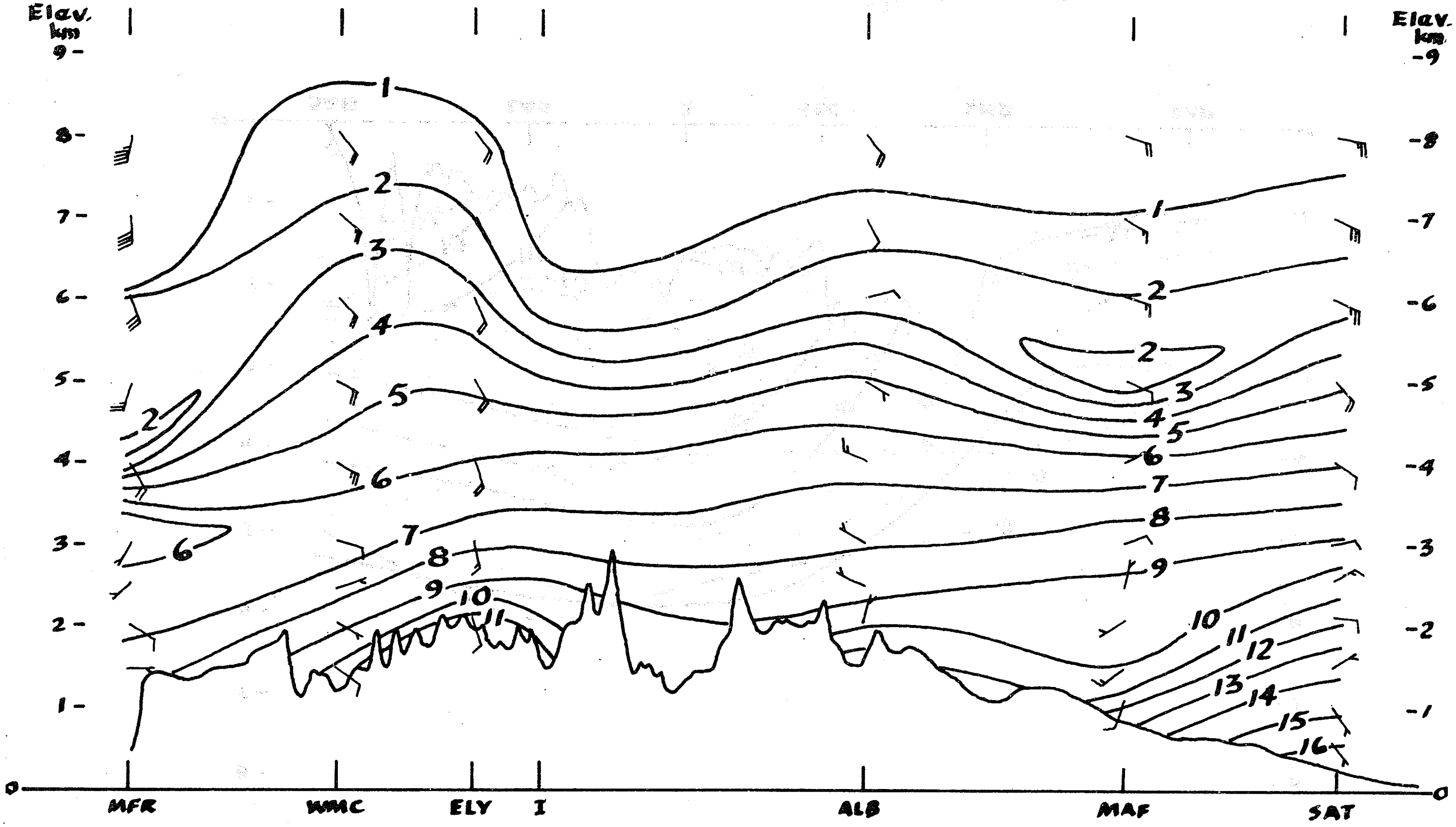


Figure 31.--Same as figure 29 for August 16, 1958, 1200 GMT.

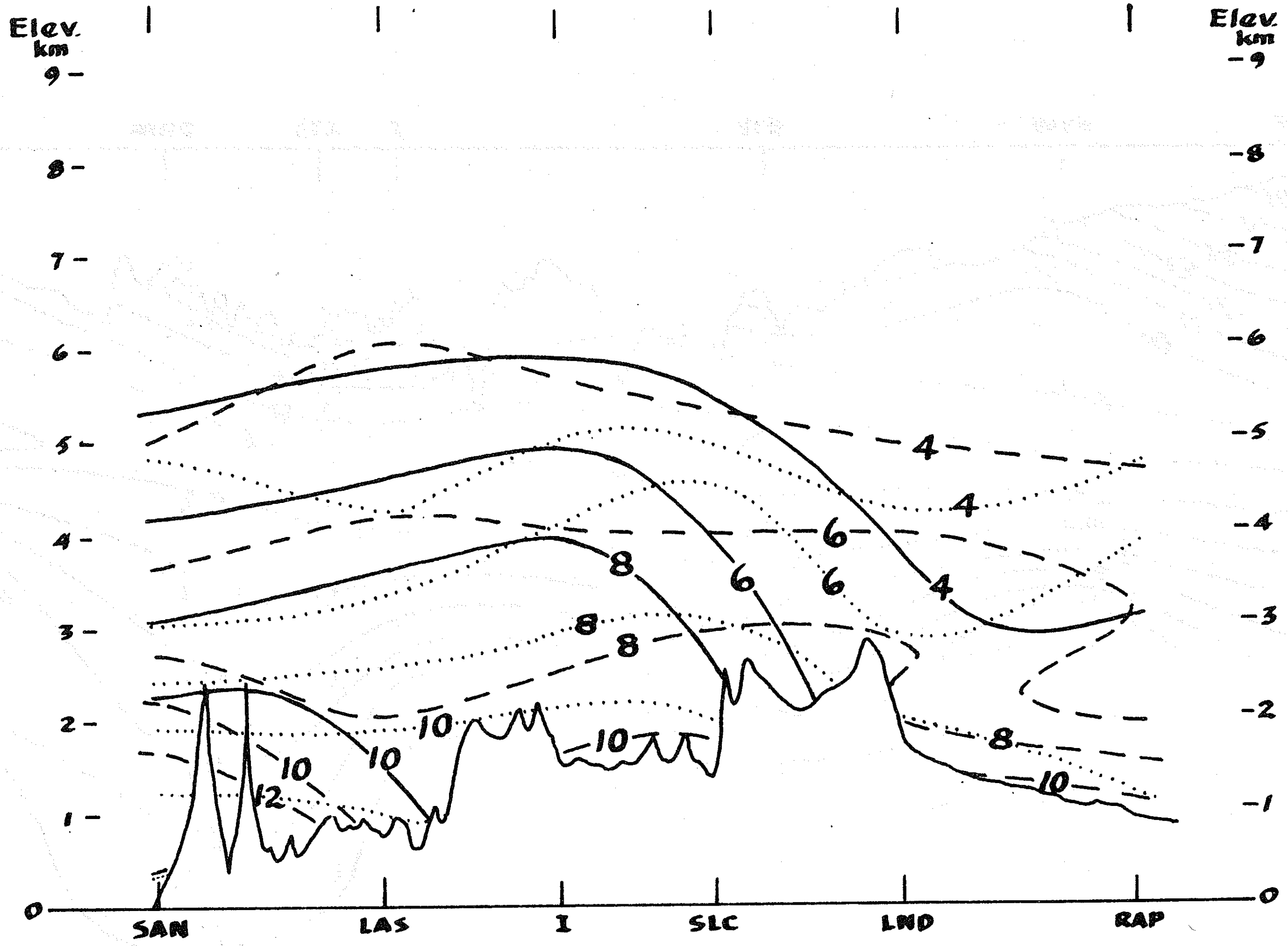


Figure 32.--Temporal variations of moisture (g kg^{-1}) along vertical cross section. August 14, 1958, 1200 GMT (solid lines), August 15, 1958, 1200 GMT (dashed lines), and August 16, 1958, 1200 GMT (dotted lines).

Some evidence of wave-like motion is seen in the moisture surfaces at higher elevations (8 g kg^{-1} for example). Since the air with moisture of >10 g kg^{-1} near Salt Lake City appears to extend continuously from the lower levels of the San Diego sounding on the 16th, I concluded that the low-level moisture was of the same origin. Following the same argument, I suggest that the moisture over Morgan (just to the northeast of Salt Lake City) was also derived from air extending to the southwest.

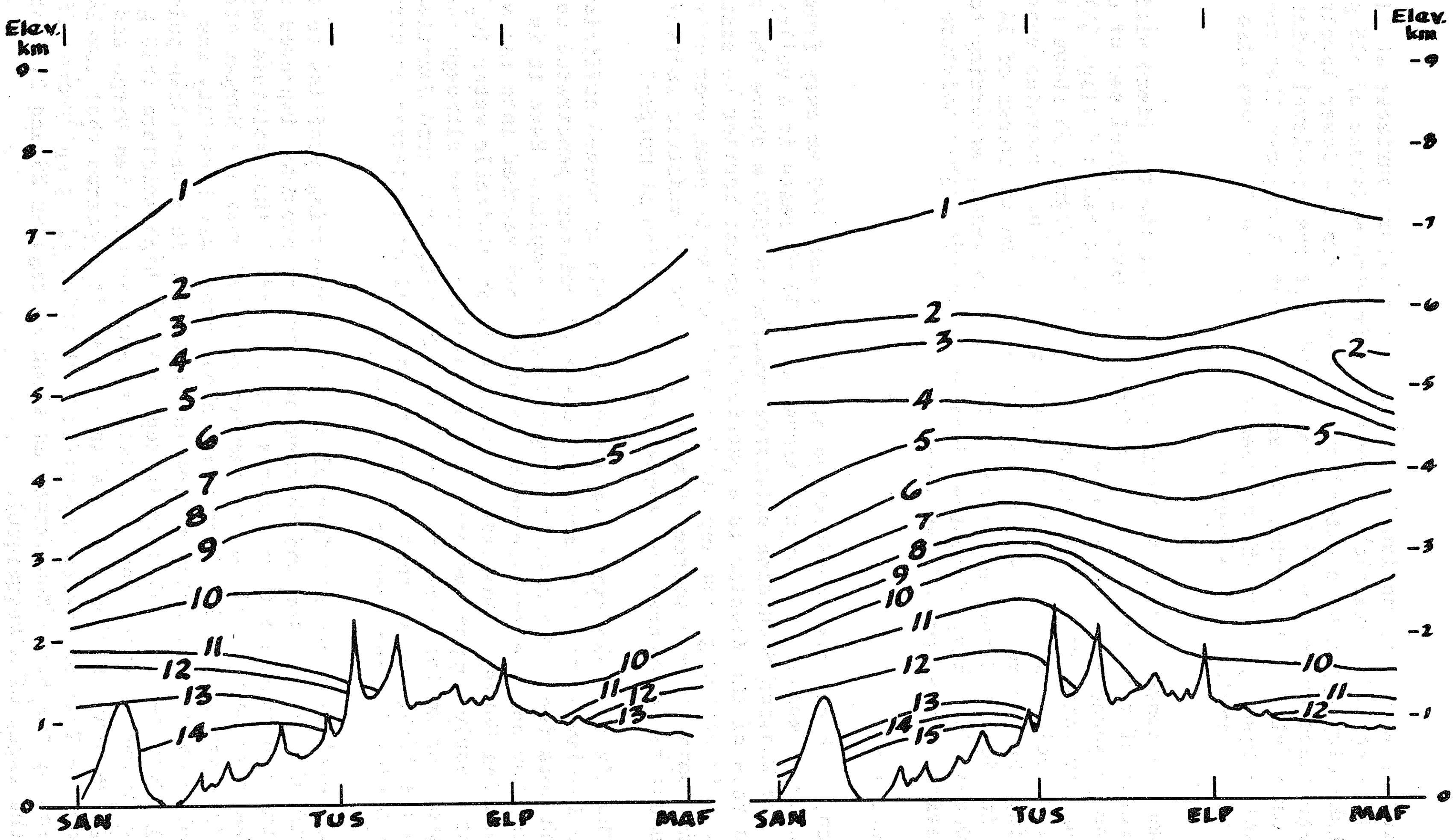
To examine the concept that low-level moisture from the San Diego vicinity was independent of that east of the Continental Divide, a final set of cross sections was prepared for a line between San Diego and Midland (fig. 33). Again noting the moisture at low levels (>10 g kg^{-1}), figure 33 shows clearly that a mass of moist air occurs between San Diego and the mountains east of Tucson during the period. Note that low-level moisture in excess of 14 g kg^{-1} shown in figure 32 does not reach inland to Las Vegas, according to figures 28, 30, and 32. This, of course, does not rule out higher moisture amounts passing to the east of Las Vegas.

3.3.5 Discussion.

The Morgan, Utah extreme thunderstorm occurred about 1000 km away from the nearest source of moisture. Morgan (elevation 1500 m) rests in a valley surrounded by the Wasatch Mountains extending upwards to 1000 m above the valley. The western face of the Wasatch is a particularly abrupt barrier to easterly moving air. Air arriving from any other direction had to pass over other mountains in coming from a source of moisture. How did moisture sufficient for the unusual rains observed on August 16, 1958 arrive at Morgan?

For the Phoenix and Elko cases discussed previously it seemed sufficient to show that a low-level tongue of maximum potential moisture penetrated to or through each location. The case at Morgan is more complex. Here it is also necessary to show how the surface moisture might have reached into the mountains surrounding Morgan. Analysis of changes in precipitable water (w_p) with time did not clearly support advection from moisture sources although there was a tendency for an increase in w_p at Salt Lake City and Grand Junction from the 15th to the 17th, in contrast to decreases or minor increases at stations east of the Divide (Lander, Denver, Albuquerque).

The use of vertical cross sections along two intersecting profiles to clarify the vertical distribution and changes of moisture provided improved understanding. One can conclude from figures 28, 30, and 32 that moisture below 3 to 4 km was most meaningful to the changes observed over the Morgan storm site. The increase in low-level moisture shown near Salt Lake City was due to moisture pushed over the mountains from the southwest in a wave-like pulse. The vertical cross sections also indicated that the high moisture (>10 g kg^{-1}) below 3 to 4 km was an extention of moisture observed over San Diego and Las Vegas during the study period. At the same time, it appeared that low-level moisture from the Gulf of Mexico (specific humidities $\geq$10 g kg^{-1})were effectively blocked by the Rocky Mountains, as shown in figures 29 and 31 (note section to the right of Albuquerque).



(a.)

(b.)

Figure 33.--Vertical cross section for August 15, 1958, 1200 GMT (a.) and August 16, 1958, 1200 GMT (b.) for San Diego (SAN), Tucson (TUS), El Paso (ELP) and Midland (MAF). Solid lines are intersection of surfaces of specific humidity (g kg^{-1}).

Because of the results of the moisture analysis, consideration was once again directed to the wind profiles. If the synoptic weather patterns indicated circulation around the anticyclonic centers above 700 mb, how did the low-level moisture pattern develop? I examined the station wind profiles in detail at lower levels and noted that a level of directional shear could be found in every case for the more southerly stations. The height of the shear level showed large fluctuations at some stations (3 to 4 km differences in 12 hours) which were difficult to understand. I was willing to accept that fluctuations in height could have been misinterpreted or confused with mesoscale synoptic changes. Nevertheless, a sloping shear line appeared between 3 and 4 km over El Paso and Albuquerque to 3 km over Tucson and 1 to 1.5 km over San Diego (not shown). To the north the shear level appeared at 2 to 2.5 km over Las Vegas and Winnemucca, and at about 3 km at Ely. At Salt Lake City, the shear layer was quite variable but lowered from about 6 km at 0000 GMT on the 16th to 4 km 12 hours later, and to 2 km by 1200 GMT on the 17th.

The significance of the analysis is that the conditions below the shear level, where most of the moisture was concentrated, were independent of those above this level in support of a similar conclusion by Hales (1972). Since the shear level was near the height of the Continental Divide, it was concluded that low-level moisture was effectively separated by the Rocky Mountain complex. The wind speeds within the surface-to-3 km layer were generally less than 10 kt and had variable directions that were complicated by convective activity and terrain influences. At a mean speed of 10 kt, it would take moisture more than 2 days to pass from the Gulf of California to the vicinity of Morgan. However, the low-level moisture surge may be partially independent of mean flow conditions. That is to say, small masses of air containing high moisture may travel at higher local speeds as a result of low-level convective winds, localized thermal gradients, or possibly a low-level jet wind (Fujita, et al. 1962).

Thus, the picture that appears from study of moisture for the Morgan case is that moisture traveled northward from the tropical Pacific at heights below 2.5 to 3 km through the Gulf of California, and that apparently the moisture above the 700-mb level contributed little to the heavy rains.

4. SUMMARY AND CONCLUSIONS

Three cases of extreme local thunderstorm rainfalls were studied to determine the source of moisture for each event. These cases were chosen on the assumption that unusually high moisture was necessary for the extreme events. Only if high moisture amounts were unusually extensive did I consider it possible that synoptic scale analysis could yield any information concerning a mesoscale phenomenon.

Each of the three cases presented different meteorological and topographical conditions. The study was aimed at determining whether storm moisture came from the Gulf of Mexico, as suggested by much of the literature, or from the Gulf of California. Analyses were made of a number of meteorological features that described changes in moisture with time and space.

Conclusions:

1. Each case yielded evidence that storm moisture probably penetrated northward from the Gulf of California. Although not specifically traced to the Pacific Ocean, it is the inferred source since the area of the Gulf of California is small.

2. There was evidence, particularly in the Elko and Morgan cases, that moisture entered the Intermountain region in the form of low-level surges or waves, possibly in the boundary layer. The surges of high moisture at low levels penetrated much farther into the region than other investigators had supposed.

3. The low-level moisture surges appear to follow a course of least resistance under light wind conditions. Major barriers to low-level moisture flow in this region are the Sierra Nevada-Baja California mountain complex, the Rocky-Sierra Madre mountain complex, the Mogollon Rim in Arizona, and the Wasatch-Uinta mountain complex in Utah. The effectiveness of these and lesser barriers is a function of depth of moisture and speed of movement.

Table 3 summarizes the results of this study for the three cases. The meteorological features analyzed were low-level potential moisture and precipitable water, 700- to 500-mb flow pattern (possible advection of upper level moisture), and vertical cross sections of specific humidity. The origin of moisture near each storm is given in the table as determined from the analyses. Reference is also made to applicable figures in the body of the study pertinent to the interpretation given.

As a result of the present study, I have concluded that tropical Pacific moisture moving via the Gulf of California was the most likely source of moisture for the three extreme local rainfall cases examined. Since a number of other extreme local rainfalls have occurred within the Intermountain region during the summer (table 2), I propose that they too could have resulted primarily from tropical Pacific moisture.

Table 3.--Summary of conclusions on moisture sources for three cases (References given to figures in text supporting conclusions)

Meteorological Feature Analyzed / Storm	Low-level moisture: Potential Moisture* Analysis	Low-level moisture: Precip. Water** Analysis	Upper-level moisture 700-500 mb Flow Pattern	Vertical Anal. of Specific Humidity
Phoenix, Ariz. 6-22-72 (133 mm/2 hr)	Tropical Pacific (figs. 7-8)	Tropical Pacific (fig. 9)	Tropical Pacific (figs. 3-4)	Tropical Pacific (table 2)
Elko, Nev. 8-27-70 (105 mm/2 hr)	Tropical Pacific (figs. 16-17)	Tropical Pacific (fig. 18)	Gulf of Mexico (figs. 10-11)	Not Analyzed
Morgan, Utah 8-16-58 (∿150 mm/1 hr)	Tropical Pacific (figs. 25-26)	Inconclusive (fig. 27)	Gulf of Mexico (figs. 19-20)	Tropical Pacific (figs. 28-33)

* Surface dew points reduced pseudo-adiabatically to 1000-mb
** 150-mb layer nearest the surface

Combining the results of this study with the recent investigations by Hales (1972, 1974), Tubbs (1972), Pyke (1972) and Brenner (1974), I conclude that tropical Pacific moisture is more important to the Intermountain summer precipitation regime than previous literature suggests.

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