U. S. DEPARTMENT OF COMMERCE
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

NOAA Technical Memorandum NWS TM SR-60

SOME MERIDIONAL MOISTURE EXCHANGE FEATURES OF THE EARLY SEPTEMBER 1970 HEAVY RAIN EPISODE, SOUTHWESTERN UNITED STATES

SOUTHERN REGION HEADQUARTERS
SCIENTIFIC SERVICES DIVISION
FORT WORTH, TEXAS
November 1971

SOME MERIDIONAL MOISTURE EXCHANGE FEATURES OF THE EARLY SEPTEMBER 1970 HEAVY RAIN EPISODE, SOUTHWESTERN UNITED STATES

H. T. May, WSFO, Albuquerque, New Mexico

INTRODUCTION

The purpose of this study is to present data related to the unprecedented rainfall over the Southwestern United States during early September, 1970. Events of this period illustrate the effects of tropical and subtropical atmospheric developments on meteorological events over the Southwest. Certain aspects of the situation are compared with models suggested by other investigators. It is hoped that the analysis will aid in the recognition of meteorological developments which may result in the transport of large amounts of moisture from low latitudes to the mid-latitude westerlies.

Unprecedented rainfall amounts over the Southwest during the period 4-6 September 1970 (Fig.1), appear to have resulted from the meriodional transport of moisture from the low-latitude marine environment to the mid-latitude westerlies in a manner similar to the slope convective model discussed by Green, et al (1966). In their model, boundary-layer air from low latitudes is isentropically lifted in a region of confluence into the mid- and upper troposphere where it becomes available for large-scale meridional exchange. This type of exchange is not limited to summer or fall, but, as in the cases presented by Hill (1964), can be an important mechanism for supplying moisture ahead of cyclonic disturbances in the westerlies, resulting in widespread cloudiness and precipitation during winter. A condition especially favorable for this type of meridional exchange is the development of a split flow around a mid-latitude block which results in a jet stream far south, near a region of subtropical convective activity. Although unprecedented precipitation amounts were recorded at some stations during this period, and a new 24-hour precipitation record of 11.40 inches was established for Arizona, stream flow records suggest that episodes of unusually heavy rain occur during the late summer and early fall with a frequency of about once in fifteen years.

The probability of a vigorous tropical storm of eastern Pacific origin passing over the southwestern United States is small, but these storms do occasionally provide a means for the transport of subtropical moisture into the middle latitudes. Moisture from the eastern Pacific may also be transported over the Southwest by the circulation of the North Atlantic anticyclone. Likewise, the strong southerly flow ahead of cyclonic disturbances in the westerlies is an effective means of meridional moisture exchange. In the September, 1970 case, all of these atmospheric mechanisms appear to have been operating and the orographic features of the area further enhanced the resulting precipitation.

The summer precipitation regime over the Southwest is one of frequent mainly orographic showers associated with moisture advected from the Gulf of Mexico. More general and heavier precipitation patterns are usually the result of easterly waves passing over the area. As summer progresses moisture from the eastern Pacific is sometimes brought northward over the interior western states.

DATA

The data for this investigation comprise real-time teletype transmissions, although those for Mazatlan, Mexico (MZT), were obtained from the National Climatic Center. These were available only for 0000GMT and were used without corrections for diurnal variation. At those stations which did not encode maximum wind data, the fastest wind reported between 500mb and 100mb was selected as the maximum. Fig. 2 illustrates the cross sections used in this study. No upper-air data were available for Yuma, (YUM), on September 5 and 6. Satellite data, including film loops from the ATS I and III geosynchronous satellites, were reviewed to further evaluate the moisture distribution during the study period.

EVOLUTION OF THE CIRCULATION PATTERN

A dual-cell circulation began to develop in the North Atlantic anticyclone on August 28. As the western cell spread westward over the Caribbean and Gulf of Mexico, it suppressed most widespread convective development in the area. (The suppression continued into September and is evidenced in Fig. 10 as a lack of activity over the Gulf.) The circulation of tropical storm Norma became evident on August 30 over the eastern Pacific near 15N-105W and the storm subsequently moved northwestward. During the first days of September the westward extension of the Atlantic high became effective in controlling the circulation over the extreme eastern Pacific and this acted in conjunction with the peripheral flow around tropical storm Norma to displace the intertropical convergence zone in the eastern Pacific northward to a position near the coast of Mexico (Fig. 3). Through a series of convective and isentropic liftings the resulting stream of north-bound, moisture-rich air became the source of precipitation over the southwestern United States. Fig. 4 illustrates the change in moisture distribution over the area during the period 2-7 September. A daily set of four west-east cross sections was taken from the surface to 250mb through GYM-CUU-DRT, YUM-TUS-ELP-MAF, LAS-INW-ABQ-AMA, ELY-GJT-DEN-LBF (see Fig. 2). The figure depicts those areas in the vertical plane where the dew point depression is 5C or less, or where the air is about 60-70 percent saturated with respect to water over the observed temperature range. Observed winds at the 700-, 500-, and 300mb levels are plotted in the conventional manner. The rapid northward advance of moisture is seen in the successive increases of moist areas, particularly in the upper troposphere, in the GYM-DRT section (2nd-3rd), YUM-MAF section (3rd-4th), and LAS-AMA section (4th-5th). (Note also Figs. 5a and 5b.)

COMPARISON WITH EARLIER MODELS

Hill (1964) proposed a model for meridional exchange over the southwest Pacific based on a study of winter cases. In his model the mechanism

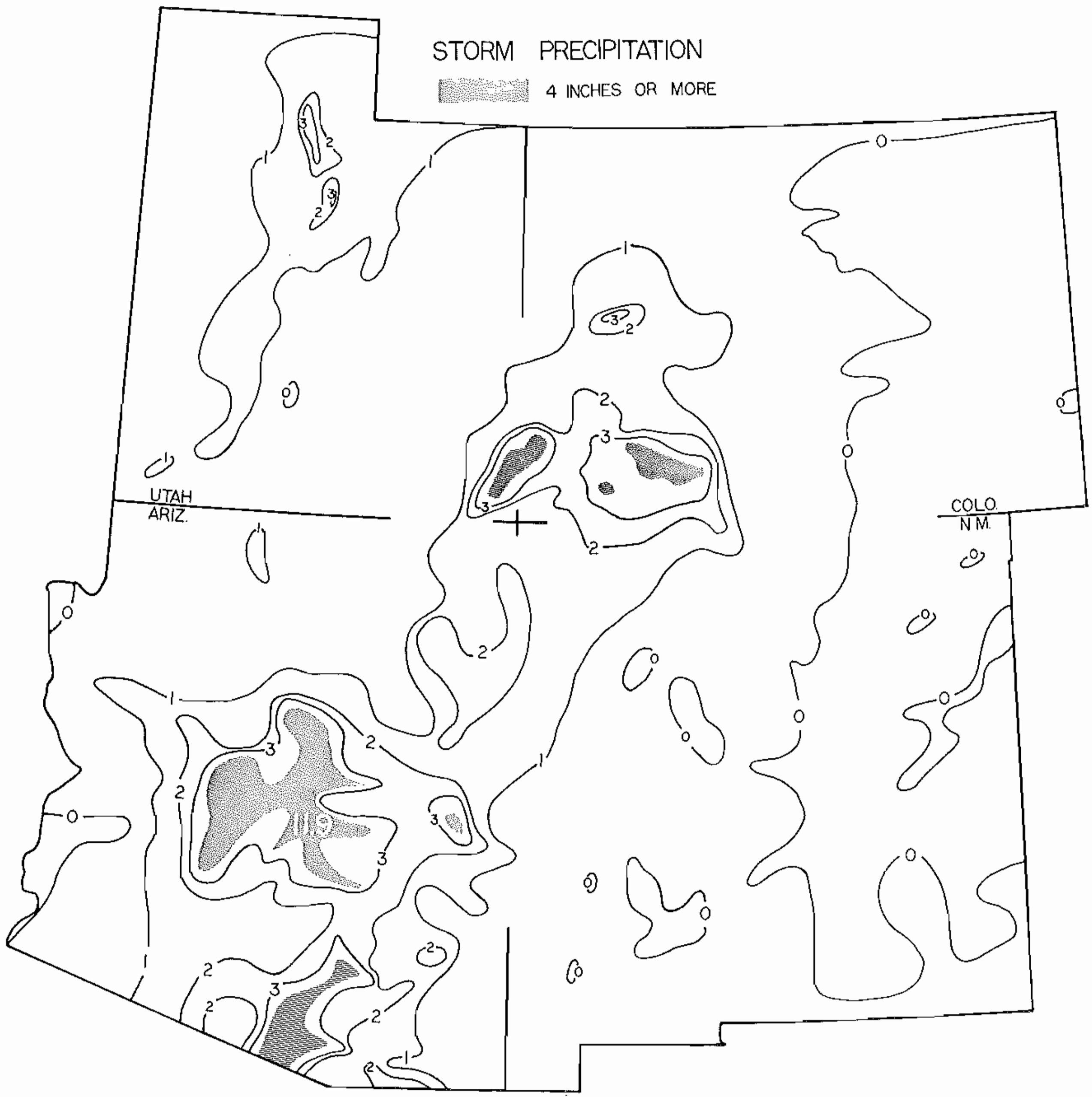


Figure 1. Total storm rainfall for the period 4-6 September, 1970. (Data for the 3rd included for Arizona.) Data were taken from Monthly Summarized Station and Divisional Data. Some bucket survey data were used to augment conventional observations in data-sparse regions.

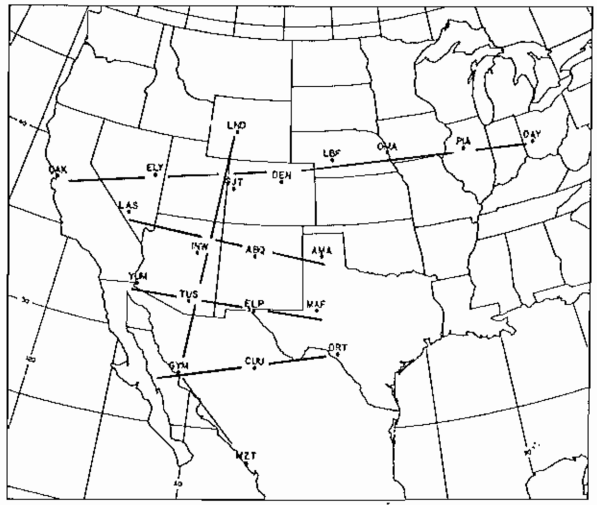


Figure 2. Stations used in the construction of vertical sections.

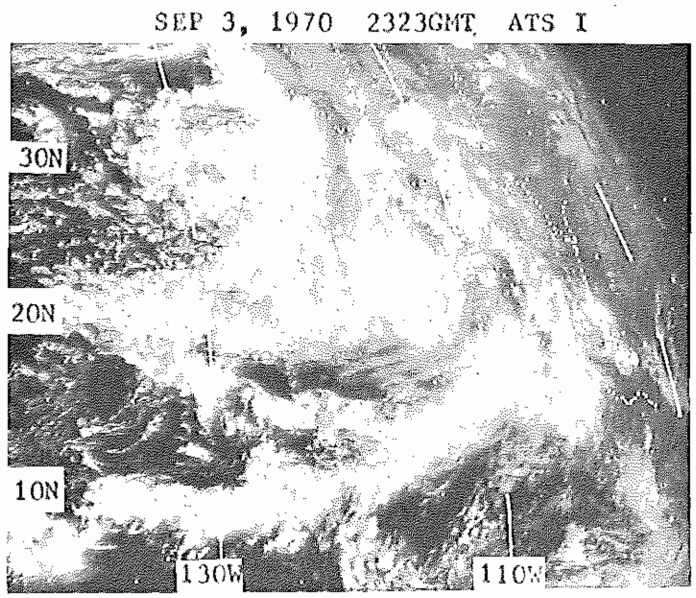


Figure 3. Geosynchronous satellite view of the eastern Pacific. Note the northward displacement of the ITC along 110W.

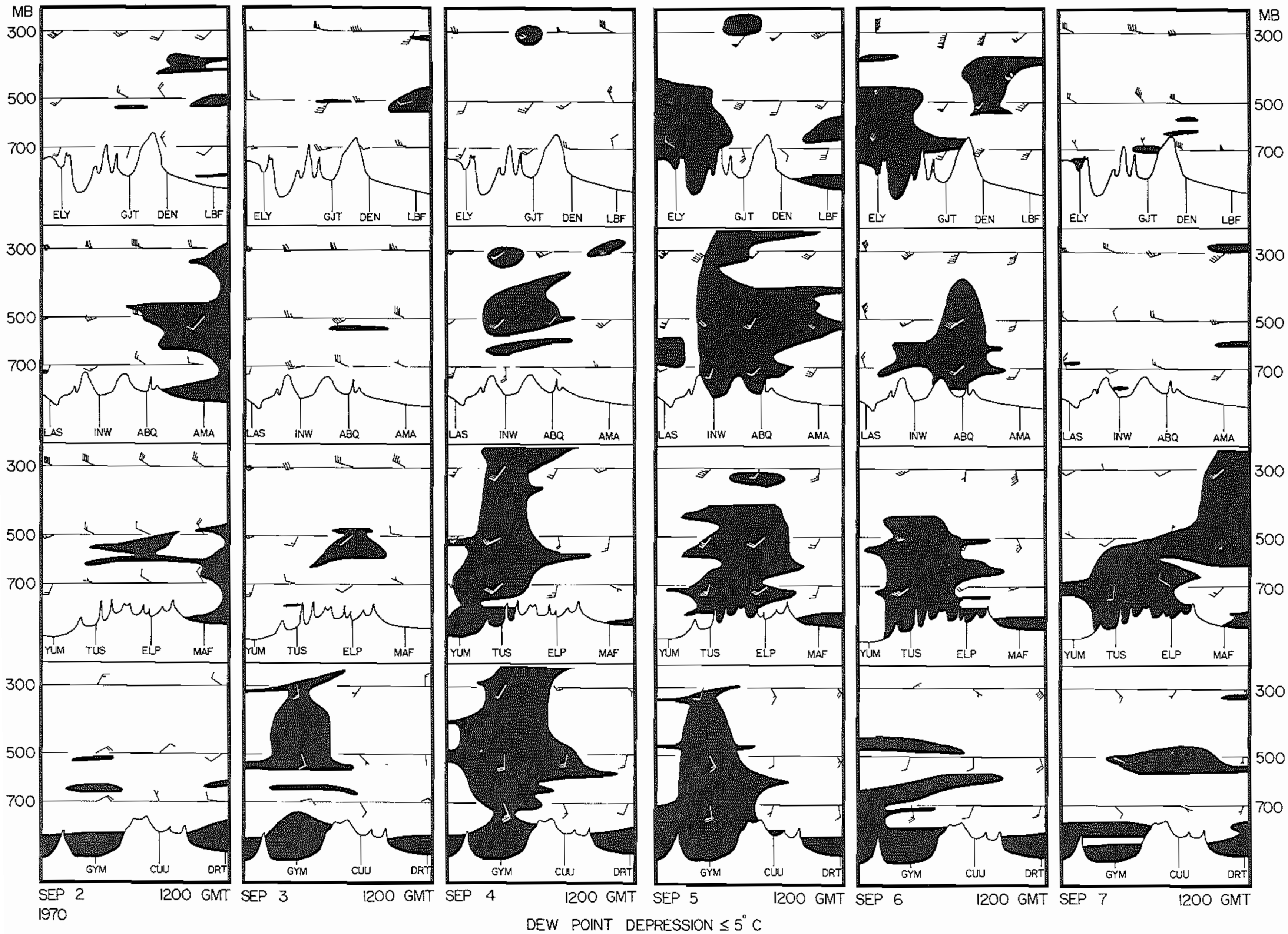
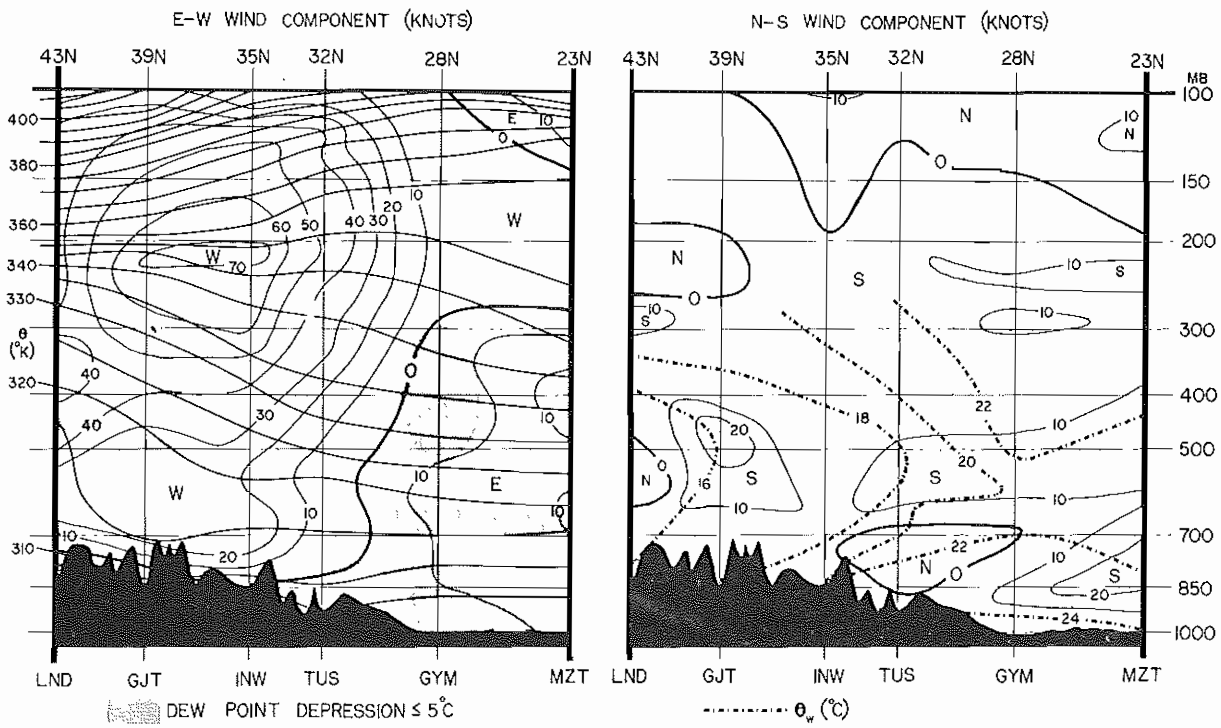
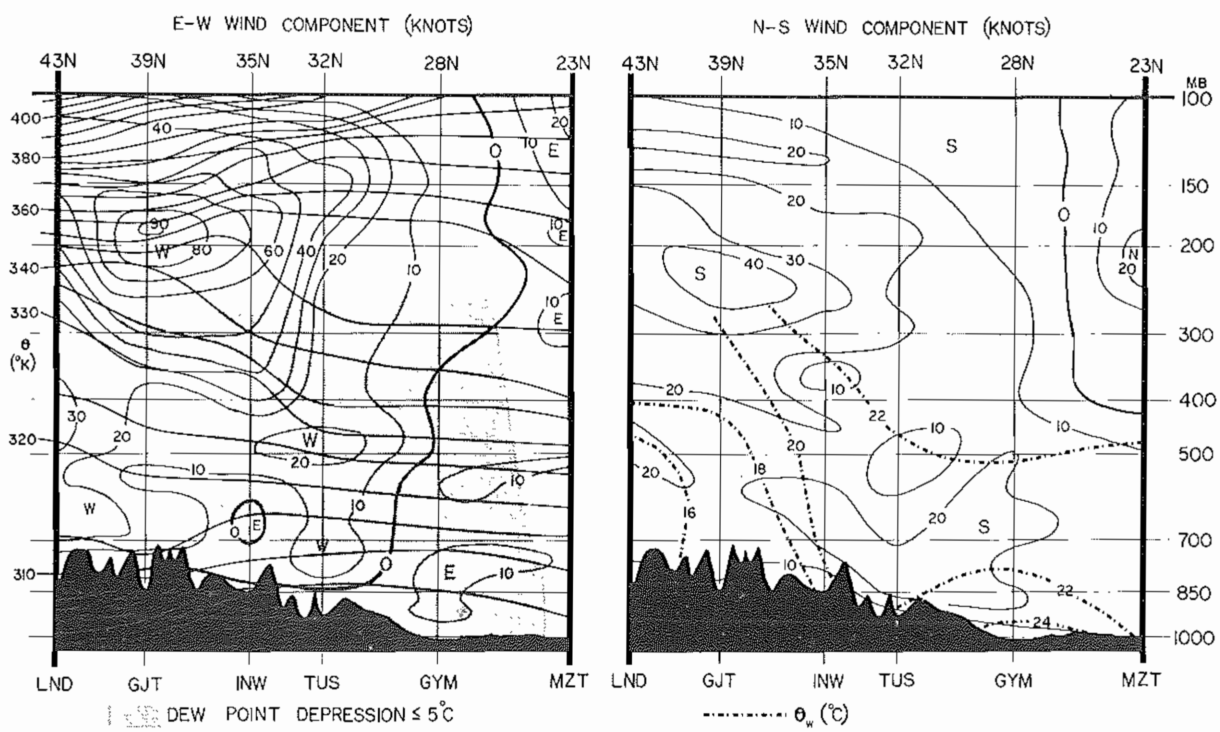


Figure 4. Vertical distribution of moisture over the Southwest during the period 2-7 September, 1970. Shading indicates areas where dew point depression is ≤ 5C.

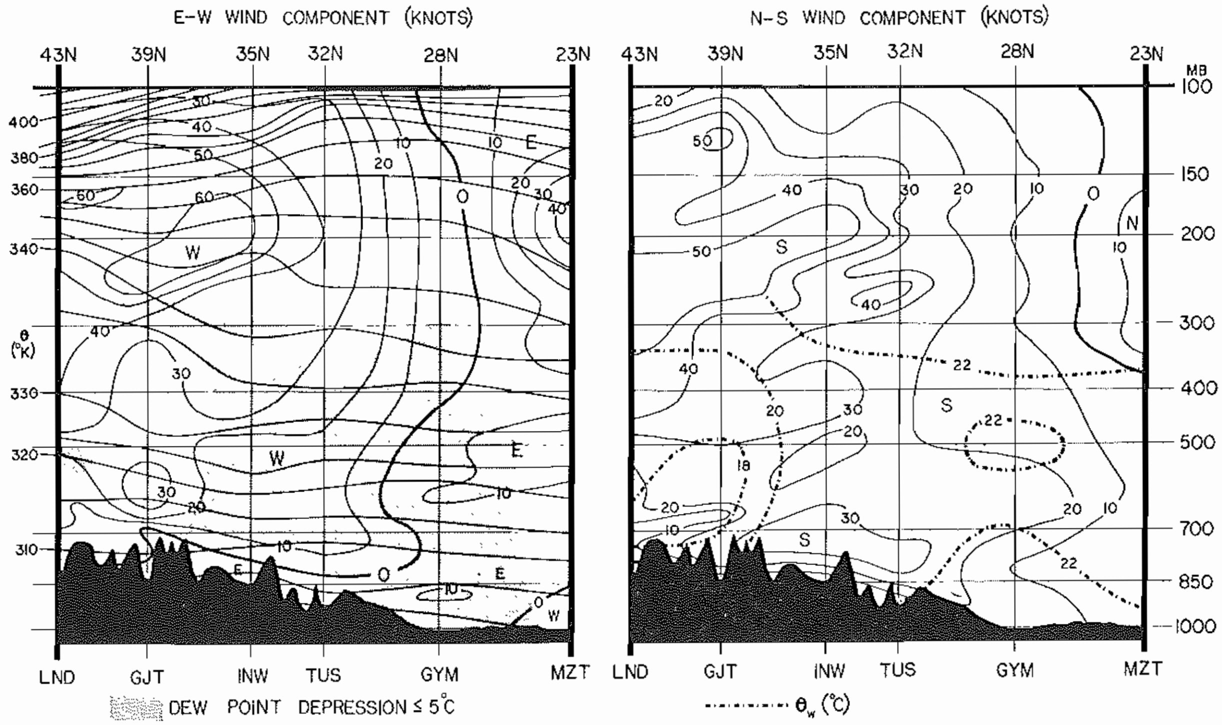


a. 1200 GMT 3 SEPTEMBER 1970

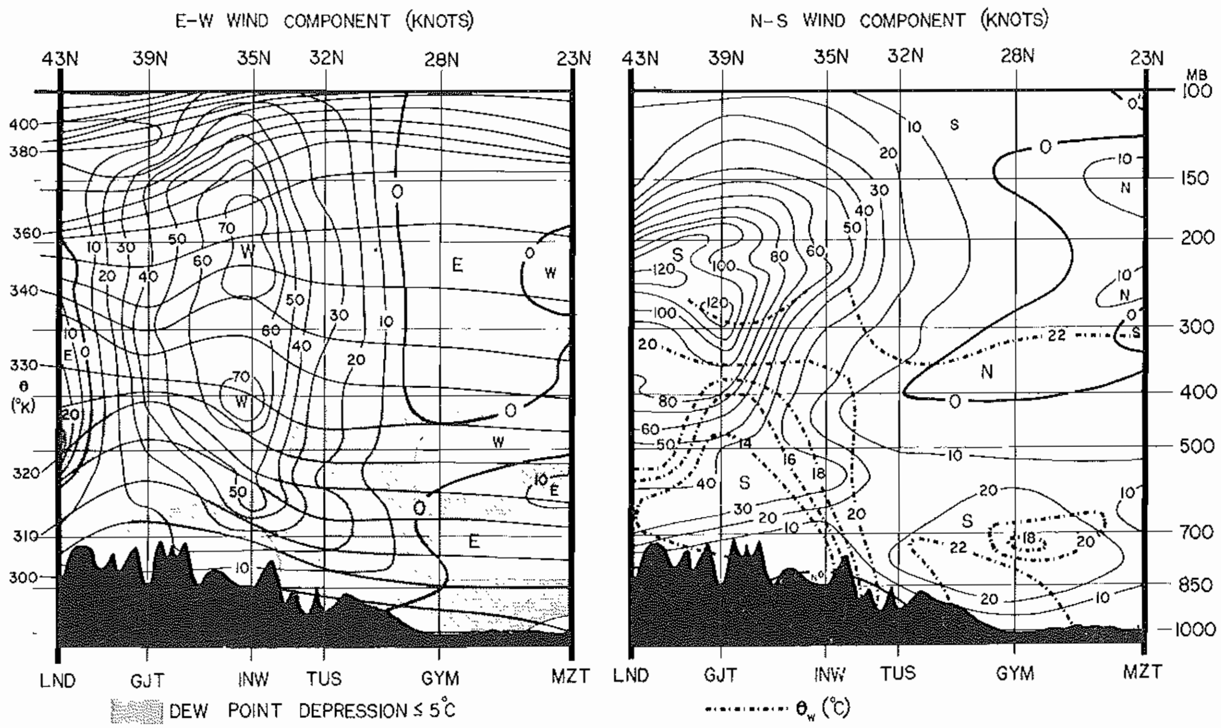


b. 1200 GMT 4 SEPTEMBER 1970

Figure 5. North-south cross sections near 110W during the period 3-6 September, 1970. Left panels show east-west wind component, potential temperature, and areas of dew point depression ≤ 5C. Right panels show north-south wind component and wet-bulb potential temperature.



c. 1200 GMT 5 SEPTEMBER 1970



d. 1200 GMT 6 SEPTEMBER 1970

Figure 5. (Continued)

for the poleward moisture transport is an unusually large horizontal wind shear associated with a jet stream in a large-amplitude, mid-latitude flow. The isentropic entrainment of low-level tropical moisture results in extensive areas of middle cloud and rain which is not directly associated with a cold front. In general, the features of Hill's model were present in the September event over the Southwest.

Although not as extensive as that described by Hill, a steep isentropic slope existed north of Tucson during the episode. This is reflected in the 330K isentrope in the left panels of Figs. 5a and 5b. The east-west wind component, also shown in Fig. 5, reveals the existence of a weak isotach maximum, far south for the season, over northern Arizona. The jet stream is also depicted in Fig. 6. The rapid northward advance of moisture over the Southwest was coincident with an increase in the southerly wind component--particularly between the 3rd and 4th, as seen in the right panels of Fig. 5. At the onset of the moisture exchange a cold front (seen in Fig. 7) was far north of the transport region. Its subsequent effects on precipitation during the study period will be discussed below.

Drying was noted in the lower atmosphere over the western United States and adjacent Pacific following the passage of a trough aloft, but it did not extend into low latitudes as in the cases presented by Hill. The most significant difference from Hill's model was the lack of a mechanism for isentropic conveyance of low-level subtropical air directly into the jet stream. Rather, the transport of such air to the mid-and upper troposphere of higher latitudes was accomplished in a manner more similar to the slope convection model suggested by Green, et al (1966). In their model mass is conserved from the lifting condensation level to the outflow level of the convective system--it may then be distributed over great distances by mid-latitude jet streams.

Widespread convective activity over the southern Gulf of California vented large amounts of moisture into the mid-and upper troposphere during the early part of the September period. This created a source region for additional moisture, eventually affecting the rainfall over the Southwest. Isentropic surfaces were nearly horizontal over the southern Gulf region (Fig. 5), thus convective activity over Mexico was in large part the result of orographic lifting. Over Arizona the southerly flow encountered a formidable orographic barrier and was lifted to at least 7,000 feet (MSL). This, in conjunction with the steep isentropic slopes in the mid- and upper troposphere, resulted in extensive convective activity with the resulting outflow spread over a large area by the jet stream. Fig. 7 illustrates the rapid cloud development which occurred between September 3rd and 4th over the Southern Rockies. The horizontal spreading of moisture aloft is also reflected in the 500mb analyses of wet bulb potential temperature (Θ_W) in Fig. 6. Green, et al, showed that a Θ_W of 20C or more above 850mb is characteristic of trade wind air. Note in Fig. 6 the progressively larger area (shaded) enclosed by the 20C Θ_W isotherm between September 3rd and 5th. The west-east cross

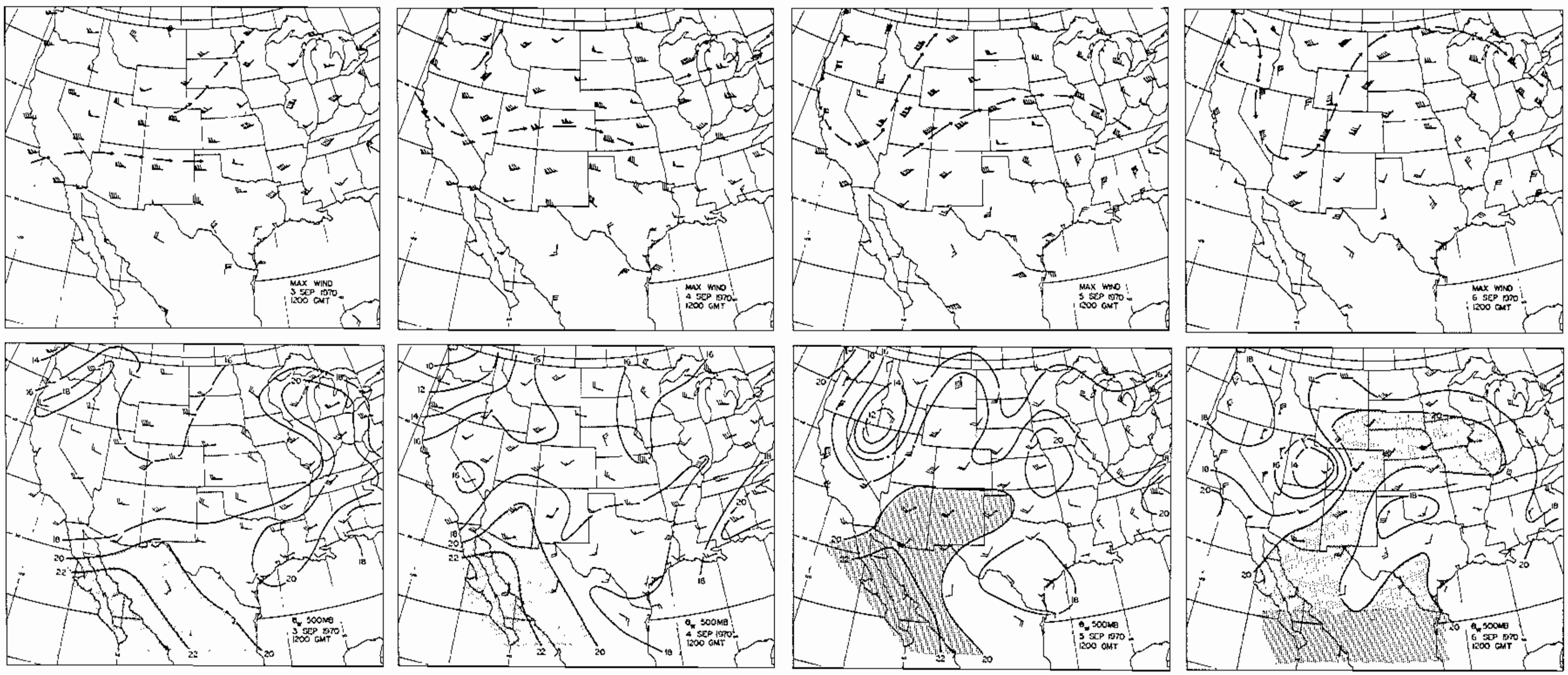


Figure 6. Observed maximum wind and 500mb wet-bulb potential temperature analyses for the period 3-6 September, 1970. Trade wind air (shaded) is characterized by $\theta_w \geqslant$ 20C.

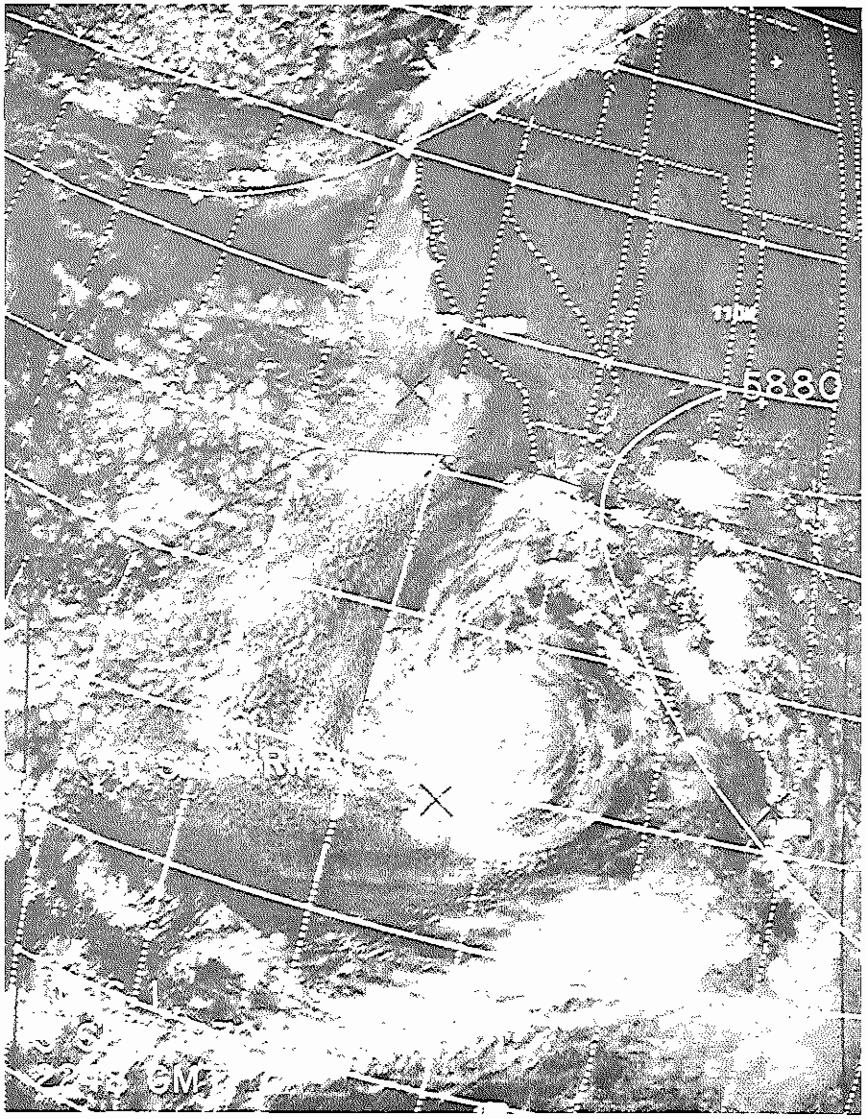
sections in Fig. 8 illustrate the atmospheric adjustments which took place hundreds of miles from the convection and precipitation region over the Southwest. Moisture brought northward from the Gulf of Mexico ahead of the upper level trough was isentropically entrained by the jet stream in a region of moderate convective development through a lowering of isentropic surfaces over the Great Plains. Note, for example, the 330K isentrope over North Platte (LBF) which lowers from near 350mb on the 4th to near 500mb on the 6th. Also evident in Fig. 8, as the period progresses, is the increasingly larger area (shaded) over which θ_W 20C.

In a study of the energetics of the tropical atmosphere, Sikdar and Suomi (1971) state in regard to deep convective activity in cloud clusters, that, "the water vapor...flowing into these storms...is almost completely converted to liquid or frozen water...(of which) only a fraction falls out as rain (Braham 1952) with as much as 90 percent remaining behind as cloud. Cirrus shield air carrying these hydrometors penetrates deeply into the upper troposphere...(and) the magnitude of the average heat transport is directly proportional to the rate of expansion of cirrus shields at the top of cloud clusters...". While these observations relate to cloud clusters over the tropics, a similar sequence of events may have occurred in the September episode. The visual evidence in Fig. 7 of rapid and extensive increases in cloud amount suggests a large heat transport, perhaps sufficient to account for the strengthening and reorientation of the jet stream in the area of moisture advection (Fig. 6), and the marked warming of the mid-troposphere over the Great Plains (Fig. 8).

PRECIPITATION FEATURES

An examination of hourly radar data for the Arizona-New Mexico area reveals two precipitation periods in this episode. During the first period, from the late afternoon of the 3rd until the evening of the 4th, the heaviest precipitation was over the southwestern half of Arizona. Most totals for this period were less than one inch but two stations reported totals near two inches. Tucson received 1.99 inches, with precipitation first reported during the hour ending at 10 p.m. on the 3rd. Precipitation began at Grand Junction, Colorado, 420 miles north of Tucson, twelve hours later. The relatively light rain and extensive cloud cover over the area suggest that convective activity during this period had the characteristics noted over the tropics in which much of the moisture was converted into cloud particles.

The second precipitation period, from late on the 4th through the 6th, was the result of the interaction of the cyclonic disturbance in the westerlies with the residual moisture from the first period and the abundant moisture transported northward by the strong low-level southerly flow ahead of the trough. The radar composites in Fig. 9 indicate that although the front apparently enhanced the precipitation in the area of strong moisture advection, it did not advect the precipitation pattern eastward. This suggests that the controlling factors were at mid- and upper levels.



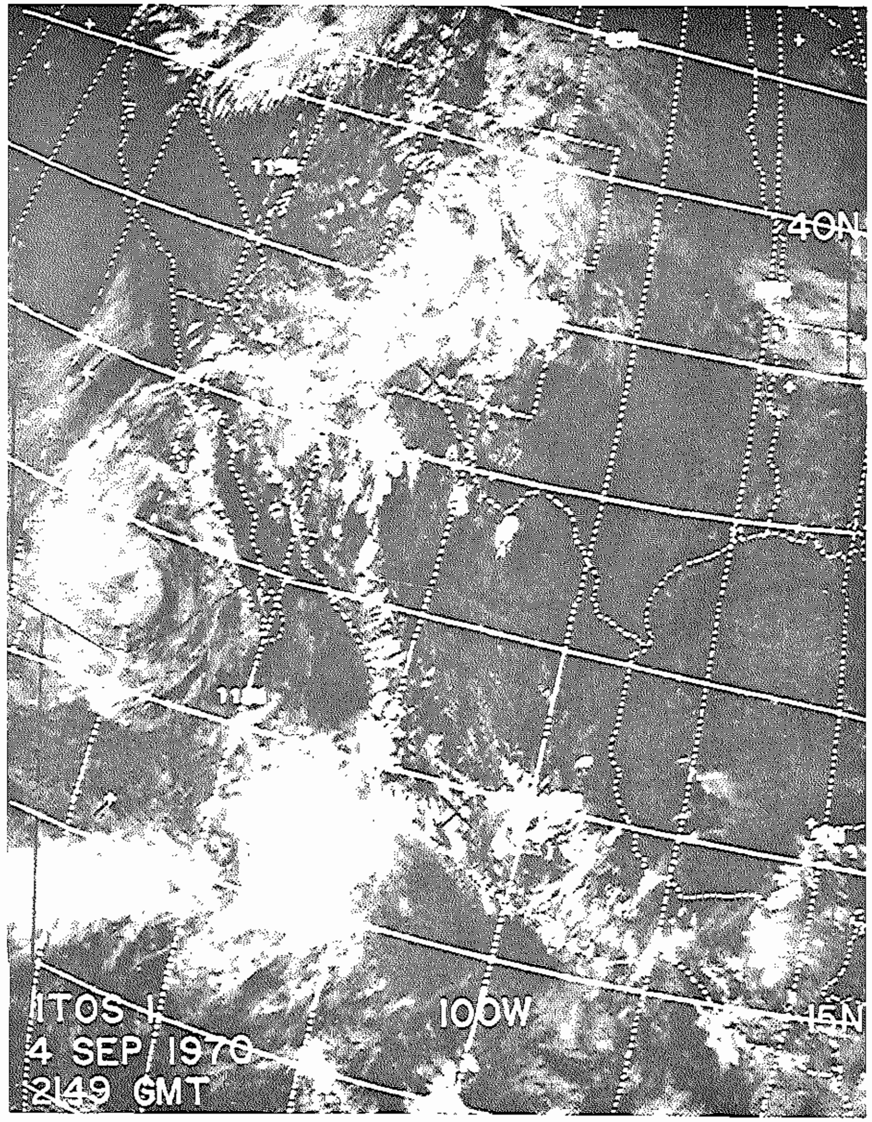


Figure 7. Left photo indicates positions of surface cold front and 5880m contour at 500mb. Note the "explosive" cloud increase over the Southern Rockies between 3 and 4 September.

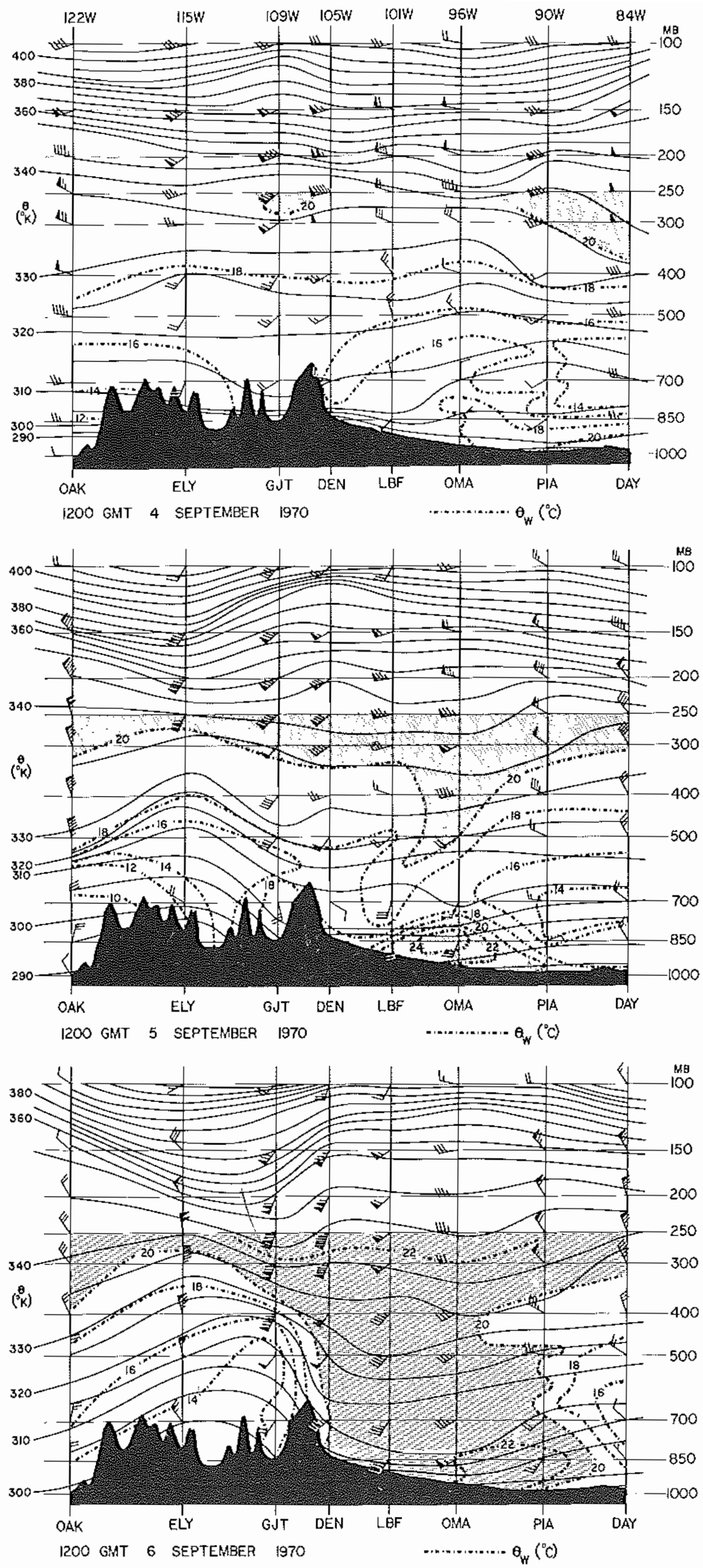


Figure 8. West-east cross sections during the period 4-6 September, 1970. Note the change in elevation of isentropic surfaces over the Great Plains, development of moist tongue ahead of the trough, and increase in area of the region over which $\theta_w \geqslant 20C$ (shaded below 250mb).

Precipitable water values were in excess of one inch early on the 3rd over southern Arizona and the area was characterized by negative Showalter stability indices. The precipitable water value over Yuma reached 1.91 inches at 1200 GMT of the 4th, a very unusual amount for the area, and the maximum over Tucson was 1.63 inches on the afternoon of the 4th. Following the dissipation of tropical storm Norma and the rapid clearing of the convective area southwest of Mexico, precipitable water values over Tucson continued to exceed one inch through the 11th.

The passage of the upper trough was accompanied by an influx of drier air over most of the Southwest. The strong westerly flow weakened and retreated northward and with this, normal convective activity resumed over the area. It is interesting to note the rapid clearing which occurred southwest of Mexico between the 5th and 6th (Fig. 10). This may be the result of mesoscale downdrafts of dry mid-tropospheric air in areas of convective disturbances. According to Zipser (1969), such a mechanism can produce downdrafts sufficient to clear an ocean area equivalent to the combined area of the states of Arizona and New Mexico in a 24-hour period.

SUMMARY

In summary, it is evident that in early September large amounts of low-level moisture were vented into the upper troposphere where isentropic surfaces were nearly horizontal, near the west coast of Mexico. This moist air of tropical origin was spread northward by the southerly flow and increased moisture and condensation nuclei over the Southwest, thus raising the potential for cloud development. When orographically induced convective activity developed in the moist southerly flow at lower levels over northern Mexico and southern Arizona, the outflow resulted in widespread cloudiness over the Southern Rockies. Thus, the heavy rains over the Southwest during this period resulted from moisture of tropical origin. The influence of high-level moisture of such origin on precipitation amounts over the arid Southwest merits additional investigation.

A significant number of convective developments which enter the eastern Pacific from the Caribbean or Orinoco and Upper Amazon Basins of South America ultimately affect the circulation and weather of the Southwest. The paucity of data over the eastern Pacific, however, inhibits our understanding of the true role of such systems. Geosynchronous satellites such as ATS III have demonstrated the potential for solving some problems associated with data-sparse regions. Hopefully, the orbiting of improved satellites, such as GOES, in the near future, will furnish data to aid in furthering our understanding of such systems.

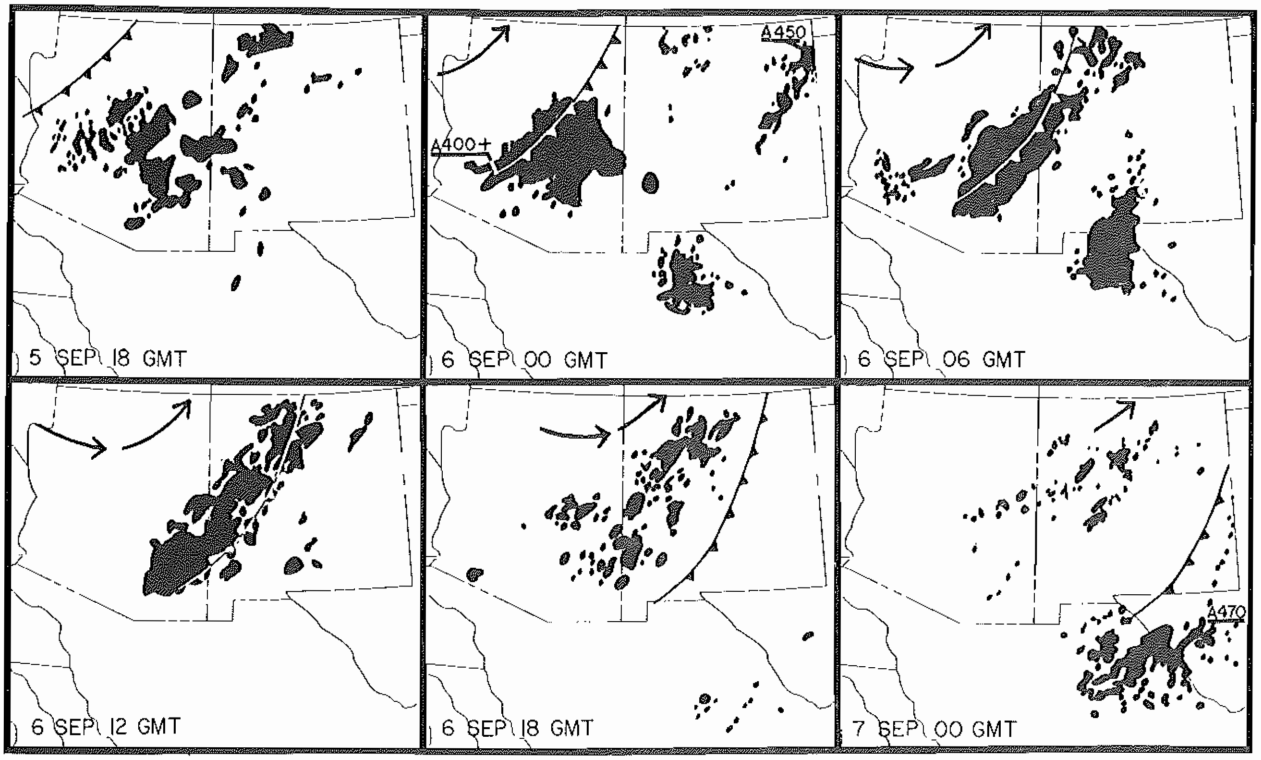


Figure 9. Six-hour radar composites, centered on time indicated, for second period of rainfall. Note the effect of the front and jet maximum (arrows) on precipitation pattern.

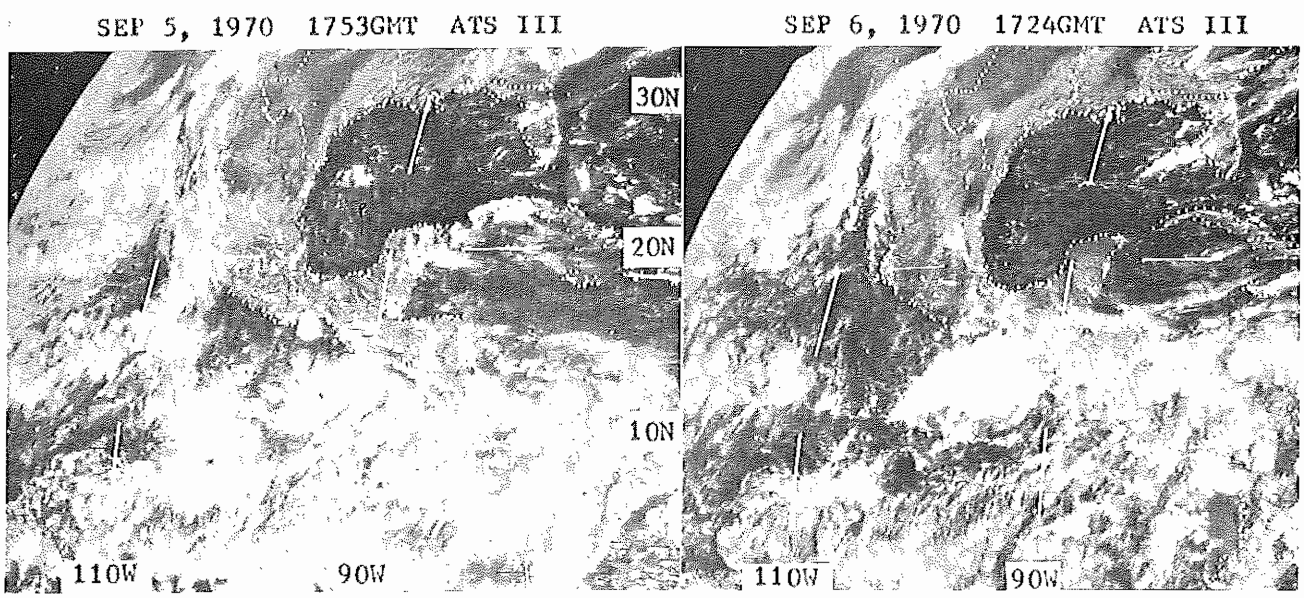


Figure 10. Geosynchronous satellite views of the eastern Pacific and Gulf of Mexico. Note the rapid clearing west of Mexico between 5 and 6 September.

REFERENCES

Green, J.S.A., F.H. Ludlum and J.F.R. McIlveen, 1966: Isentropic relative flow analysis and the extended parcel theory. Quart. J. Roy. Meteor. Soc., Vol. 92, 210-219.

Hill, H. W., 1964: The weather in lower latitudes of SW Pacific associated with the passage of disturbances in the middle latitude westerlies. Proc. Symp. Tropical Meteorology, 1963, New Zealand Meteorological Service, Wellington. 352-365.

Sikdar, D.N., and V. E. Suomi, 1971: Time variation of tropical energetics as viewed from a geostationary altitude. J. Atmos. Sci., Vol. 8, 170-180.

Zipser, E.J., 1969: The role of organized unsaturated convective downdrafts in the structure and rapid decay of an equatorial disturbance. J. Appl. Meteor., Vol. 8, 799-814.