IMPACT OF THE SOUTHERN OSCILLATION ON THE NORTH AMERICAN SOUTHWEST MONSOON

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Abstract: The intensity and spatial variations in the North American Southwest Monsoon are examined to determine the influence of the Southern Oscillation. Sixty-five years (1920–1984) of July and August monthly precipitation data from Arizona and New Mexico are normalized using a square root transformation, converted into z-scores, and stratified according to onset and following years for Warm Events and Cold Events of the Southern Oscillation. The results for July reveal different spatial patterns in the monsoonal precipitation for the extremes of the Southern Oscillation. Warm-Event onset years are associated with positive precipitation anomalies that decline along a northeast-to-southwest gradient across the study area whereas the Cold-Event onset years produce highest positive values in west-central Arizona and negative values throughout the eastern two-thirds of the study area. Spatial patterns for the August precipitation data do not appear to be influenced by the extremes of the Southern Oscillation. [Key words: Southwest Monsoon, Southern Oscillation, Arizona, New Mexico.]

INTRODUCTION

In recent years, the impact of climatic variations on local and regional precipitation patterns has received increased public and scientific attention. Much of this interest is fostered by the widely recognized social and economic impacts associated with changes in precipitation regimes (e.g., Brown et al., 1986). The scientific community has addressed this growing concern through an increasing number of studies dealing with connections between global-scale circulation changes and regional precipitation variations (e.g., Douglas and Englehart, 1981; Ropelewski and Halpert, 1986, 1987; Aceituno, 1987). Results from these and other investigations show that observed precipitation changes in many parts of the globe are linked to variations in the set of large-scale climatic phenomena referred to as the Southern Oscillation (SO) (Aceituno, 1992).

The sub-continental scale warm-season precipitation pattern in the southwestern United States also may be impacted by the phenomena. This precipitation

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singularity, popularly called the "Southwest Monsoon," is a summertime event that generally occurs between early July and mid-September (Carleton, 1985; TenHarkel, 1980). Tang and Reiter (1984) demonstrated that a monsoon circulation exists in western North America in a semicircular region which includes the Pacific coast, the Southwest, and the western Great Plains. High surface temperatures coupled with an influx of moisture from the Pacific Ocean and the Gulfs of Mexico and California create frequent thunderstorms in Arizona and New Mexico throughout this mid- to late-summer period (Jurwitz, 1953; Hales, 1974; Schmidt, 1983; Carleton, 1986; Moore et al., 1989). These thunderstorms supply a significant portion of the region's total annual precipitation and, at times, can cause local severe flooding with resultant property damage and loss of life (Maddox et al., 1979).

Other investigators (e.g., Douglas, 1981, 1982; Douglas and Englehart, 1981; Sheaffer and Reiter, 1985; Ropelewski and Halpert, 1986, 1987; Aceituno, 1987; Nicholls, 1988; Wang and Li, 1990) have shown relationships between the Southern Oscillation and temporal and spatial variations in precipitation patterns for many regions of the globe. Previous studies dealing with the southwestern United States document a relationship between the amount of precipitation in spring and autumn for Arizona and the occurrence of El Niño years (Andrade and Sellers, 1988), between extremes of the Southern Oscillation and forest fire dynamics (Swetnam and Betancourt, 1990), and present evidence for above-normal precipitation in the Great Basin area of the western United States from April to October during the onset of a warm event (Ropelewski and Halpert, 1986). However, these studies have concentrated generally on the magnitude differences in precipitation and have not addressed geographic patterns in precipitation anomalies.

Accordingly, the objective of this study is to examine the relationship between fluctuations in the Southern Oscillation and the pattern and intensity of precipitation anomalies associated with the Southwest Monsoon. The results should prove useful in: (a) long-range forecasting of convective precipitation events in the region, (b) refinement and verification of numerical models, (c) supplementing the global inventory of the teleconnections associated with the Southern Oscillation, (d) furthering understanding of the synoptics and dynamics of this important subcontinental scale precipitation pattern, and (e) promoting interest in Southern Oscillation teleconnections with the geographic distributions of other convective precipitation regimes.

BACKGROUND

The Southwest Monsoon is a precipitation singularity (Bryson and Lowry, 1955) defined by a recurrent departure in rainfall from the normal seasonal value centered around a specified calendar date (Lanzante, 1983). The singularity is marked by the arrival of moisture and a resultant increase in thunderstorm frequency and rainfall (Moore et al., 1989). The strength of this singularity is evident when one compares the aridity of a normal June in the region with the numerous thunderstorms and resultant precipitation of a normal July (Table 1). Locations to

Table 1. Selected Monthly Precipitation and Thunderstorm Day Percentage Statistics for First-Order Weather Stations in the Study Area[a]

Station	Precipitation June	Precipitation July	Precipitation August	Thunderstorm Days June	Thunderstorm Days July	Thunderstorm Days August
Clayton, NM	12.4	18.8	16.8	19.5	24.9	21.1
Roswell, NM	11.6	15.4	14.9	18.7	19.8	21.2
Albuquerque, NM	7.1	16.4	16.3	11.9	26.7	26.2
El Paso, TX	7.3	19.2	17.2	13.1	28.3	27.8
Winslow, AZ	3.7	14.3	18.3	8.5	31.4	29.5
Tucson, AZ	2.3	19.7	18.8	6.3	33.9	32.7
Flagstaff, AZ	2.4	13.3	13.6	7.3	32.9	31.1
Phoenix, AZ	1.3	12.4	13.3	4.2	26.3	30.4
Yuma, AZ	0.3	6.2	16.9	4.2	22.2	30.5

[a] Data are expressed as monthly percentages of the annual total in order to standardize for pronounced differences in monthly and annual totals that are a result of elevation differences. Note that a value of 8.33% corresponds with 1/12.

the east of the Rocky Mountains (e.g., Clayton and Roswell, New Mexico) are influenced by mid-continent warm-season precipitation generation mechanisms in June (Harrington and Brown, 1985). By July, the majority of locations in New Mexico and eastern and central Arizona are receiving relatively frequent thunderstorms which account for a significant percentage of the annual precipitation total. The onset in early July of the Southwest Monsoon is accompanied by a tendency for a decline in precipitation for sites east of the Rocky Mountains (Trewartha, 1981; Harrington and Brown, 1985). Precipitation associated with the Southwest Monsoon is usually delayed until August for locations in southwest Arizona.

Mitchell (1976) documented the westward migration of a pronounced gradient in equivalent potential temperature across the Southwest during the warm season. He called this gradient the "monsoon boundary" and related it to changes in flow around the Bermuda high-pressure cell and westward penetration of a warm, moist tongue of air. This gradient undergoes a strong westward displacement from east central New Mexico in June, into central Arizona by July, and to western Arizona by August (Bryson and Lowry, 1955; Mitchell, 1976). Monthly maps of isodrosotherms and the standard deviation in dew point temperatures (Dodd, 1965) corroborate this westward migration of moisture into the study region. In addition to higher dew point temperatures in July, the area of maximum standard deviation, which is centered over New Mexico and Arizona in June, shifts westward to a position on the California-Arizona border by July.

Recent studies into the characteristics of this precipitation singularity have concentrated on the temporal consistency of the Southwest Monsoon through studies of its "bursts" and "breaks" (Carleton, 1985, 1986, 1987). These studies suggest that "bursts," or periods of heavy thunderstorm activity, are related to the

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development of an upper air trough over the area, whereas the southward displacement of the subtropical ridge that is prevalent over the region is linked to "breaks." The source of moisture for the Southwest Monsoon "bursts" has been a topic of considerable interest and it is now recognized that there are two distinct source regions (Mitchell, 1976; Schmidt, 1983; Carleton, 1986). One moisture source is water vapor advected from the Gulf of Mexico via light southeasterly flow. The second source is a rapid lower-level influx of moisture from the Gulf of California and the Pacific Ocean (Brenner, 1974; Hales, 1974).

Whereas these studies have addressed temporal aspects and moisture source regions of the Southwest Monsoon, they have not examined in detail the year-to-year changes inherent in the pattern of precipitation. The purpose of this study is to determine if significant variations in the position of Southwest Monsoon precipitation anomalies occur with the two extreme phases of the Southern Oscillation. A link between the Southern Oscillation and monsoonal activity may be anticipated given (a) the baroclinic response of the Hadley circulation to a low-level heat source (Yarnal and Kiladis, 1985) and possible teleconnections to the westerlies and (b) the observed teleconnections between the Southern Oscillation and major circulation features over North America (Yarnal and Diaz, 1986; Granger, 1988).

DATA AND METHODS

The precipitation data used in this investigation were obtained from the United States Historical Climatology Network (Quinlan et al., 1987) comprising 52 stations in New Mexico and Arizona (Fig. 1). The stations have relatively long-term records, experienced few instrument and/or site changes over the data collection period, and are located primarily in relatively small towns. An exhaustive set of quality control measures has adjusted the data for time of observation biases, station and instrument changes, and relative inhomogeneities (Karl and Williams, 1987; Quinlan et al., 1987).

The 52 stations in New Mexico and Arizona all have monthly precipitation data extending from 1920 through 1984; the selection of an earlier starting date for the analyses would substantially reduce the size of the available station network. To assess the representativeness of the spatial distribution of the network, a nearest-neighbor statistic was calculated as the ratio between the observed mean distance among the stations, D_o, and the expected distance, D_e, given a random distribution. These distances are computed as:

$$D_o = \frac{\sum_{i=1}^{N} d_i}{N} \quad \text{and} \quad D_e = \frac{\sqrt{A/N}}{2}, \tag{1}$$

where d_i is the distance for any station to its nearest neighbor, A is the area of New Mexico and Arizona, and N is the number of stations in the network. The nearest-neighbor statistic for the station network equals 1.30 and falls between the threshold values of 1.0 for a random distribution and 2.0 for a square lattice (Clark

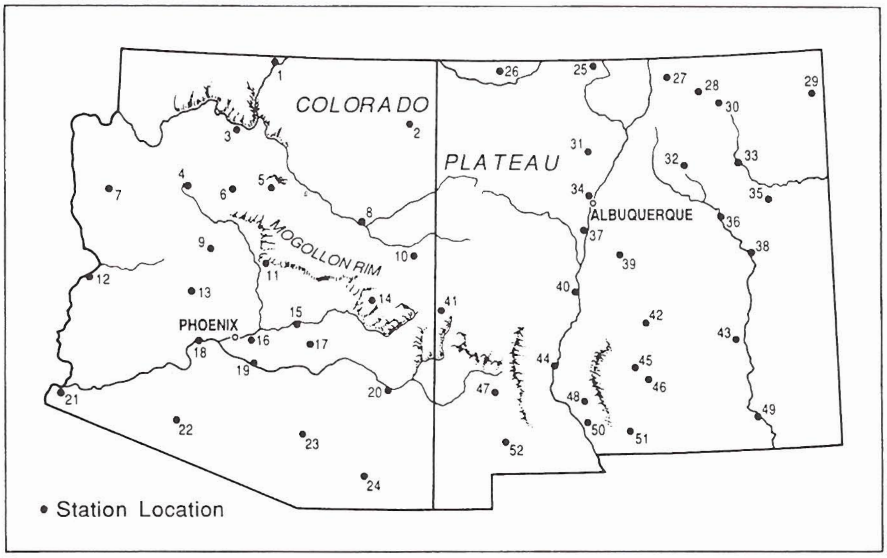

Fig. 1. Weather station locations and topography in Arizona and New Mexico.

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16 MESA EXPERIMENT FARM
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45 TULAROSA
46 MOUNTAIN PARK
47 FORT BAYARD
48 JORNADA EXPERIMENTAL RANGE
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50 STATE UNIVERSITY
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and Evans, 1954). The result of this test indicates that the stations are well distributed across the two states with no significant clustering or areal bias.

At each of the 52 stations, the July and August precipitation totals for the 65-year study period were checked for normality (using a Gaussian distribution) before being transformed into standardized, z-score values. The test for normality included the determination of the standardized coefficients of skewness and kurtosis (Siegel, 1956; Keeping, 1962). At each station, a square-root transformation was used to produce a precipitation array with a normal distribution. The matrices of transformed July and August rainfall levels were standardized through time to produce two 65-by-52 matrices of z-scores depicting precipitation patterns through the study period.

Geographic patterns of the Southwest Monsoon were obtained for the 52-station network through stratification of the rainfall z-scores corresponding to the

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Table 2. Warm- and Cold-Event Years for the Southern Oscillation

Warm-Event years		Cold-Event years	
1923	1957	1920	1954
1925	1963	1924	1964
1930	1965	1931	1966
1932	1969	1938	1970
1939	1972	1942	1973
1951	1976	1949	1978
1953	1982		

Source: van Loon and Shea, 1985.

phase of the Southern Oscillation (van Loon and Shea, 1985). The matrices of z-scores of July and August precipitation were stratified according to Warm-Event years and Cold-Event years (van Loon and Shea, 1985), over the period from 1920–1984; 12 years were classified as Cold-Event years and 14 years were classified as Warm Events (Table 2). In a typical SO event, eastern Pacific warm temperature anomalies peak in the late fall/winter (Ropelewski and Halpert, 1986). Thus, by using the Warm- and Cold-Event years identified by van Loon and Shea (1985), this study first analyzes and compares (warm vs. cold) the summer months during the onset of peaks in the Southern Oscillation. Since Carleton et al. (1990) demonstrated a tendency for the subtropical ridge to be farther northward (southward) with wetter (drier) summers in Arizona during summers following Warm (Cold) Events. analyses were also performed comparing the Warm- and Cold-Event precipitation amounts and patterns for summer months following the peaks in the Southern Oscillation.

RESULTS

The maps of the July precipitation anomalies for the extremes of the Southern Oscillation reveal differences in precipitation magnitude and pattern. In Warm-Event onset years (Fig. 2A) a general northeast-to-southwest gradient exists with highest positive anomalies located in northern New Mexico. The anomalies are positively related to latitude and negatively related to longitude; both correlations are statistically significant at the 0.95 confidence level (Table 3). Elevation in the study area also has a strong northeast-to-southwest gradient and, therefore, elevation and the Warm-Event onset precipitation anomalies are positively related. The map pattern suggests a greater effectiveness of the Bermuda High moisture advection mechanism with increased moisture moving into the area via light southeasterly winds (Jurwitz, 1953; Bryson and Lowry, 1955).

The map for the July Cold-Event onset years (Fig. 2B) shows the highest precipitation anomalies to be located in west-central Arizona while negative values are found throughout the eastern two-thirds of the study area. The Cold-

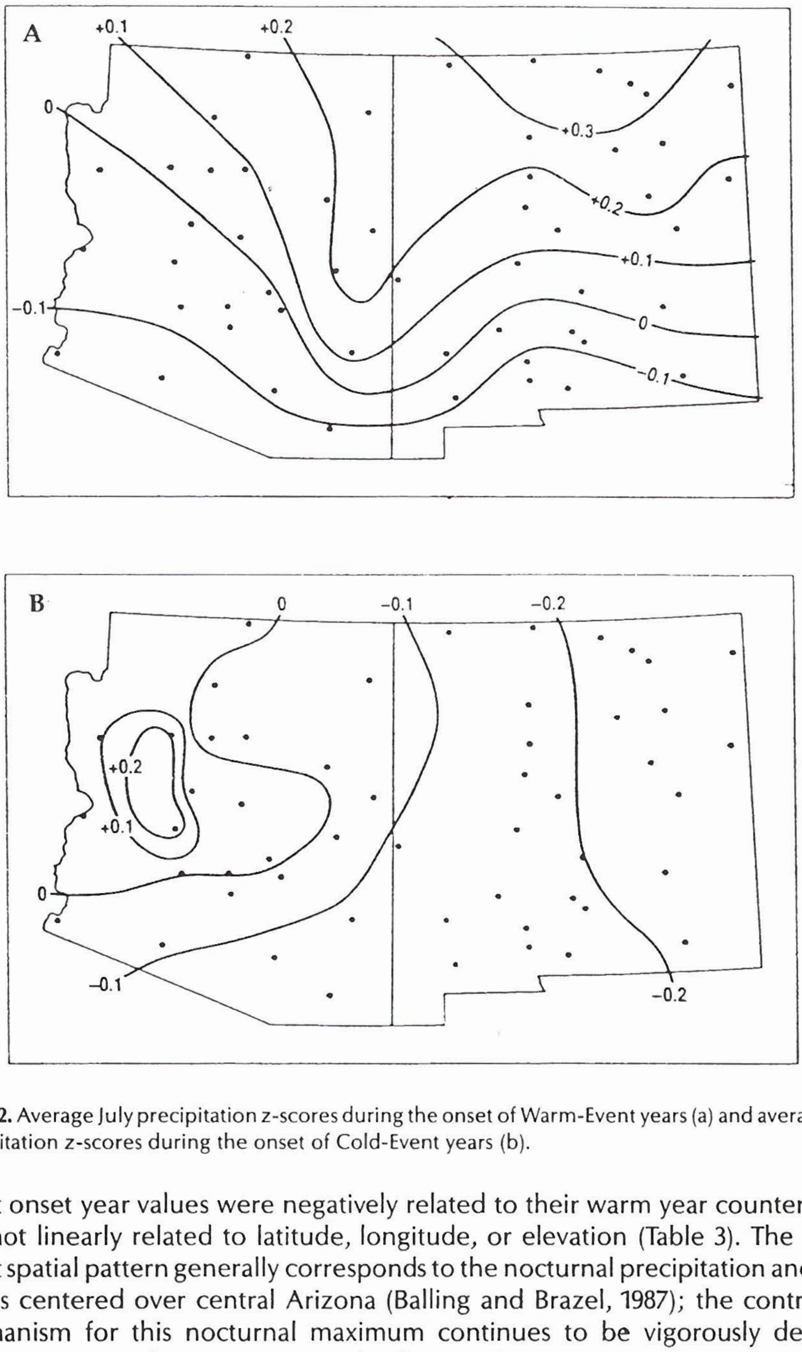

Fig. 2. Average July precipitation z-scores during the onset of Warm-Event years (a) and average July precipitation z-scores during the onset of Cold-Event years (b).

Event onset year values were negatively related to their warm year counterparts, but not linearly related to latitude, longitude, or elevation (Table 3). The Cold-Event spatial pattern generally corresponds to the nocturnal precipitation anomaly that is centered over central Arizona (Balling and Brazel, 1987); the controlling mechanism for this nocturnal maximum continues to be vigorously debated (Wallace, 1975; Hales, 1977; Tang and Reiter, 1984).

To compare the magnitudes of the anomalies across the study area between the onset of the two extremes of the Southern Oscillation, the Student's *t*-statistic was computed.

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Table 3. Intercorrelations Among Selected Variables Over the 52 Stations for July SO Onset Years[a]

	z_{warm}	z_{cold}	Latitude	Longitude	Elevation
z_{warm}	1.00	−0.35	0.39	−0.32	0.41
z_{cold}		1.00	−0.05	0.24	−0.11
Latitude			1.00	−0.17	0.50
Longitude				1.00	−0.45
Elevation					1.00

[a] Absolute values ≥ 0.27 are significant at the 0.95 confidence level.

The one-tailed Student's *t* was found to be 2.04; this value is statistically significant at the 0.95 level indicating higher precipitation for the study area during the Warm-Event years. While the difference in July rainfall was not significant at all individual stations, the Student's *t*-test for the entire network revealed a tendency for Warm-Event years to produce more rainfall across the study area than the Cold-Event years.

The analyses described above were also conducted on the August precipitation data. Unlike the results for July, the Warm- and Cold-Event onset August subperiods did not produce coherent spatial patterns in the precipitation anomalies, nor did the Student's *t*-test identify any significant differences between the two extremes of the Southern Oscillation.

The same analyses used for the onset years of extremes in the Southern Oscillation were performed for years following the extremes. Thus, the years used in these analyses can be determined by adding one to the years identified in Table 2. Owing to the timing of some SO events, this second set of analyses involves several years that have switched classes. For example, 1924, 1931, 1954, 1964, 1966, 1970, and 1973 are Cold-Event onset years that are also Warm-Event following years.

For all 52 stations combined, a comparison of Warm-Event following years versus Cold-Event following years for the month of July using the Student's *t* test produces a statistically significant *t* value of −2.01. This suggests that years following Warm Events are generally drier than years following Cold Events. In addition, the Cold-Event following year values were negatively related to longitude (Table 4); this would suggest a tendency for higher July precipitation amounts in New Mexico. As was the case with the comparison of onset years using July data, not all individual stations exhibit this characteristic. A total of 21 stations had a statistically significant *t* value that was negative whereas only 2 stations had a positive and significant value.

As was the case with the comparison of onset years for August, analyses comparing the August Warm-Event and Cold-Event following years did not produce coherent spatial patterns in the precipitation anomalies. In addition, the Student's *t*-test did not identify any significant differences for Augusts following the two extremes of the Southern Oscillation.

Table 4. Intercorrelations Among Selected Variables Over the 52 Stations for July SO Following Years[a]

	z_{warm}	z_{cold}	Latitude	Longitude	Elevation
z_{warm}	1.00	0.10	0.25	0.19	0.32
z_{cold}		1.00	−0.20	−0.47	0.35
Latitude			1.00	−0.17	0.50
Longitude				1.00	−0.45
Elevation					1.00

[a] Absolute values ≥ 0.27 are significant at the 0.95 confidence level.

DISCUSSION AND CONCLUSIONS

Few studies have examined the changing geographic patterns of precipitation in relation to the SO phenomena; past research has concentrated on the temporal or magnitude aspects of precipitation variations associated with the SO. In addition, many studies have limited their analyses to winter and spring precipitation events. Circulation studies (e.g., Yarnal and Diaz, 1986) suggest that existence of a strong meridional circulation pattern over North America and the eastern Pacific should influence winter precipitation patterns during El Niño events. However, direct linkage between SO-driven circulation and warm-season precipitation associated with the Southwest Monsoon has not been made previously.

The major result of this investigation is the identification of contrasting geographic patterns of precipitation for July SO event extremes. While the July patterns may simply be the result of chance, several factors support the contention that the identified patterns are significant. First, Conrad (1941, p. 7) stated that "the distribution of positive and negative anomalies is therefore not ascribed to chance or accidental local conditions, but represents a significant climatological element." Secondly, more convincing process-oriented evidence is provided by numerous authors (e.g., Bryson and Lowery, 1955; Mitchell, 1976; Tang and Reiter, 1984; Dodd, 1965; Sellers, 1968) whose research has helped unravel the temporal evolution of the summertime influx of moisture into the Southwest. These studies indicate a westward migration of increased moisture across the study area during the period from late June through July. The fact that we did not find geographic differences in August in our comparison of Warm-Event and Cold-Event years does not lessen the significance of the July geographic patterns. Rather, it suggests that the onset of the Southwest Monsoon in July may be differentially impacted by the onset or decline of SO extremes, and that the strength of the plateau monsoon effect (Tang and Reiter, 1984) may have an overriding influence in August. Thirdly, the separate analyses of SO extreme onset and following years are supportive; that is, an analysis using a one-year lag in the data provides the opposite pattern.

The majority of studies on SO and Southwest Monsoon relationships have been concerned only with Arizona data. Carleton et al. (1990) have recently found

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stronger synoptic controls on Arizona summer precipitation during August and a tendency for wetter months to follow a Southern Oscillation Warm Event. Thus, additional research investigations incorporating New Mexico into the study area and perhaps several decades of additional data collection are necessary to further understanding of atmospheric circulation processes related to these spatial problems.

Our work follows studies for Florida and the southeastern United States (Douglas and Englehart, 1981; Douglas, 1981, 1982) that have suggested that increased precipitation in the southeastern United States during a Warm Event is associated with an accelerated jet found in the eastern North Pacific and southwestern North America. An eastward movement of the subtropical jet may occur during the early stages (July) of the Southwest Monsoon in Warm-Event years. This movement may lead to increased warm advection at the New Mexico stations and therefore an increased potential for convective activity (Maddox and Doswell, 1982). However, Arkin's (1982) study indicated that anomalies in the subtropical jet stream during summers following an east Pacific warm SST anomaly resulted in accelerated flow and enhanced warm advection into the southwestern United States, particularly the eastern portion of the region, New Mexico. More research on the role of the subtropical jet and its relationship to variation in moisture advection into the southwestern United States is needed. One hypothesis that should be tested is that enhanced advection arising from the accelerated flow apparently expands throughout the region during the course of the Southwest Monsoon and that, by August, widespread moisture advection throughout the region apparently obscures any underlying regional patterns associated with the Southern Oscillation.

Our analyses lead us to conclude that, on average, for an onset Warm-Event year (a) greater July precipitation falls over much of the southwestern United States and (b) the largest positive precipitation anomalies in July for the two-state study region are located in northeastern New Mexico. A Cold-Event onset year generally results in (a) lesser amounts of July rainfall over most of the study area and (b) a relocation of the largest positive precipitation anomalies into west-central Arizona. An opposite pattern in precipitation anomalies is found in analyses of July years that follow SO extremes. Comparison of these results with studies of convective, summer rainfall patterns in other parts of the globe may aid in our understanding of teleconnections associated with the Southern Oscillation.

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