Interannual Rainfall Variations in the North American Summer Monsoon Region: 1900–98*

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ABSTRACT

The following questions are addressed in this study using an array of data and statistical methods: 1) does the North American monsoon region have a single dominant monsoon system; 2) if it has more than one, what are they; and 3) what are major causes of interannual monsoon rainfall variations in these systems? Results showed two dominant summer monsoon systems in the region: one in south-central Mexico, south of the 26°N, and the other in the southwestern United States and northwestern Mexico. Monsoon rainfall variations in these regions are usually opposite to each other and have different causes. The interannual variations in monsoon rainfall in south-central Mexico were highly affected by interannual variations in the intertropical convergence zone (ITCZ) in the eastern tropical Pacific. A northern (southern) position of the ITCZ, often related to cooler (warmer) than normal sea surface temperatures in the eastern tropical Pacific Ocean, corresponded to strong (weak) monsoon.

The ‘‘land memory effect’’ was evident in interannual variations of monsoon rainfall in the southwestern United States, shown by strong correlations of the summer rainfall variation versus antecedent winter precipitation anomalies in the western United States. However, the effect was not robust but varied fairly regularly. It was strong from approximately 1920 to 1930 and disappeared from 1931 to 1960. It regained its strength from 1961 to 1990 but has weakened again since 1990. The forcing of this variation was identified as a multidecadal variation in atmosphere circulations in the North Pacific–North American sector and the land memory effect was part of this variation. This multidecadal variation has to be included in prediction methods in order for them to correctly describe seasonal and interannual variations in summer rainfall in the North American monsoon region.

1. Introduction

Annual rainfall variations in the southwestern United States and Mexico, west of the Sierra Madre Occidental Mountains, show an outstanding warm season monsoon rainfall feature: most of the annual rainfall occurs in a few warm season months (Fig. 1). Monsoon rainfall starts in the first few days in July (onset date) and lasts for nearly three months. This 3-month rainfall makes up 50%–70% of the annual precipitation in that semiarid region (Carleton et al. 1990; Douglas et al. 1993; Higgins et al. 1997). The nearly regular annual recurrence of the monsoon is an attractive feature for prediction of the region's summer rainfall. However, because both the onset date and intensity of the monsoon can be substantially different from one year to another, the recurrence feature only becomes useful when the interannual variations in monsoon rainfall are understood.

Interannual monsoon rainfall variations have been examined in several studies. Most focused attention is on the monsoon rainfall variation in the southwestern United States and northwestern Mexico. Carleton et al. (1990) showed that the interannual variation in monsoon rainfall intensity in this region was associated with interannual variation in the region's summer circulation, particularly the location of a seasonal pressure ridge in the mid- and lower troposphere. When the ridge location was north of the area of Arizona and New Mexico, the monsoon rainfall was often intense; when it was south of the area, the monsoon rainfall was weak. They further showed that the interannual circulation change was affected by sea surface temperature anomalies (SSTAs) in the eastern North Pacific Ocean and in the Gulf of California. A particularly interesting finding was that the SSTAs in the eastern Pacific Ocean in the antecedent winter season were often linked to summer monsoon rainfall anomalies in the southwestern United States and northwestern Mexico (see Fig. 10 in Carleton et al. 1990).

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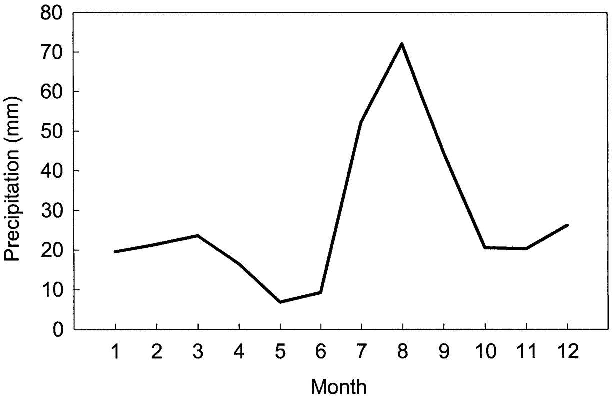

FIG. 1. Average (1900–98) annual precipitation variation in the southwestern United States (32.0°–35.0°N, 108.75°–112.50°W).

This link was carefully examined in a few recent studies. Higgins et al. (1998) suggested that the link was achieved through the North Pacific SSTA effect on winter precipitation anomalies in the southwestern United States. The winter precipitation anomalies further affected the following summer monsoon rainfall through the regional hydrological cycle. Gutzler and Preston (1997) showed a strong negative correlation of the antecedent winter snowfall amount in the northwestern United States and the U.S. Rocky Mountain plateau versus the summer monsoon rainfall in the southwestern United States in 1960–90. Using their evidence, Higgins et al. concluded that there was often a dipolar distribution of winter precipitation anomalies in the western United States corresponding to North Pacific SSTA. A higher (lower) than normal snowfall in the northwestern United States coexisted with a lower (higher) than normal winter precipitation in the southwestern United States. This winter precipitation anomaly pattern preceded and may have contributed to summer monsoon rainfall anomalies in the southwestern United States through a yet to be understood ''land memory'' that somehow stored the winter precipitation anomalies in the region and released the effect of the anomalies in following summer to influence the monsoon rainfall. These results brought us one step closer to using the winter precipitation and snow anomalies to predict interannual summer rainfall variations in the monsoon region.

Besides the North Pacific SSTA, the tropical SSTA associated with the El Niño–Southern Oscillation (ENSO) cycle also was suggested to influence summer monsoon rainfall variations in the southwestern United States (Harrington et al. 1992; Hereford and Webb 1992). Castro et al. (2000) further showed that the North Pacific and tropical SSTA contributed differently to the large-scale circulation changes in the western Northern Hemisphere (NH). These changes affected the monsoon ridge position Carleton et al. (1990) defined, the low-level moisture transport, and the summer monsoon intensity.

The usefulness of these links for prediction of interannual variations in the summer monsoon rainfall lies in their robustness. As summarized in Higgins and Shi (2000), ''at the present time it is unclear whether any of the links between the monsoon in the southwestern United States and antecedent conditions are robust enough to have a positive impact on the predictability of warm season precipitation.'' Citing the findings reported in Namias et al. (1988), Higgins and Shi cautioned that decadal-scale variations in SST in the North Pacific might weaken such links.

Fewer studies have examined the summer rainfall variations in the south-central Mexican monsoon region, especially the differences between it and the monsoon rainfall in the southwestern United States and northwestern Mexico. In fact, the Mexican monsoon rainfall has often been considered and discussed in the same context with the southwestern U.S. monsoon rainfall as though they were in the same regime. However, evidence has shown that the southern and south-central Mexican monsoon rainfall system is different from the southwestern U.S. monsoon rainfall and suggests its variations are due to different causes (Douglas and Englehart 1996; Tucker 1999; Magana 2000).

In this study, we will first examine the monsoon rainfall variations in the North American monsoon (NAM) region and develop a proper context for analysis of monsoon rainfall variations in the NAM region. We will show in section 3 that the NAM region has two distinctly different monsoon rainfall regimes: one in the southwestern United States and northwestern Mexico and the other in south-central Mexico. Within this context, we will examine in section 4 the development and variation of the monsoon rainfall in south-central Mexico. In section 5, we will examine the robustness of the identified links between the antecedent winter precipitation anomaly in the western United States and summer monsoon rainfall in the southwestern United States, and explain the interannual variations in the monsoon rainfall. Our results will reveal nonrandom changes in these links/relationships, and show that the ''land memory effect'' on the summer monsoon rainfall variations was a feature of the dominant atmospheric circulations. In other words, the storing and releasing of the antecedent winter precipitation and snow anomalies in the western United States worked only in a certain circulation environment. The significance of this study in improving seasonal and interannual monsoon rainfall predictions is discussed in section 6.

2. Data

The monthly precipitation data were from Hulme (1992) and Hulme et al. (1998) and covered the North America from 15° to 60°N for 1900–98. The data spatial resolution was 2.5° lat × 3.75° lon. A relevant feature of this dataset for this study was that it covered Mexico with few missing values and had no missing data in the United States and western Canada. In this dataset, precipitation values at grid points were calculated using a method that interpolated precipitation anomalies, instead of precipitation themselves, from stations in a defined neighborhood of the grid points, and then added the anomalies to a reference area mean (Hulme 1992). As shown in Jones and Hulme (1996), the resulting grid precipitation from this method could have nontrivial errors particularly in precipitation trend in regions of great spatial variability in rainfall variance, such as the North American monsoon region. However, because our study focused on the interannual and decadal variations in summer rainfall, this interpolation effect on trend should have only limited influence on the results. Nonetheless, those data limitations should be kept in mind when we interpret the results of the rainfall analysis. Additional details of quality and limitations of the precipitation data were discussed online at http://www.cru.uea.ac.uk/~mikeh/datasets.

The dataset had 48 grid points in the NAM region, defined here as 15.0°–37.5°N, 98.0°–116.0°W. Among them, 27 had no missing data [for July–September (JAS)], 4 had 1 missing monthly value, 2 had missing data for about 20 yr, and each of the rest had a total of 2 to 23 missing monthly values. Those missing data were estimated by averaging the values at the neighboring grids.

Monthly SST data were from the Global sea-Ice SST (GISST) dataset version 2.3b from the Met Office (Parker et al. 1995). They covered the period 1871–1998 and had a 1.0° × 1.0° resolution. In our analysis, we used a 3-month running average of the SST data to avoid the potential biases in the data noticed in Hurrel and Trenberth (1999).

The sea level pressure (SLP) data were from the National Center for Atmospheric Research (NCAR dataset ds010.1; Trenberth and Paolino 1980). The data resolution was 5.0° × 5.0° over the NH from 15° to 90°N, and the time period was from 1899 to 1997. The SLP data from Kaplan et al. (2000) with a 4.0° × 4.0° resolution were used to analyze the tropical SLP variation. This dataset was derived using marine SLP from the Comprehensive Ocean–Atmosphere Data Set (COADS) from 1854 to 1992 and the reduced space optimal interpolation method (Kaplan et al. 2000). It showed consistent features with the other SLP datasets, including the NCAR SLP data in the shared latitudes in NH.

We used the National Centers for Environmental Prediction (NCEP)–NCAR reanalysis data to analyze the lower-tropospheric circulation and to identify characteristic flow features in different monsoon years and the influence of the flows from the Gulf of Mexico and the Gulf of California on monsoon rainfall variations. Statistical methods used in the analyses are described when introduced in the discussion.

3. North American summer monsoon rainfall feature—Two regimes

There are a few fundamental differences between the North American summer monsoon and the well-known Indian summer monsoon. In the NAM region, the change of low-level wind direction between winter and summer is barely 120° (Tang and Reiter 1984), not as significant as the near 180° direction reversal in the Indian monsoon winds (Ramage 1971). Winds shift from southwesterly to southeasterly in the NAM region as the monsoon starts and the monsoon anticyclone shifts northward (Carleton et al. 1990), whereas low-level wind shifts from easterly to westerly following the onset of the Indian monsoon when the monsoon trough imbedded in the ITCZ migrates over the Indian peninsula. Monsoon rainfall in the NAM region relies on moisture from primarily the south, the Gulf of California, and the southeast in the Gulf of Mexico where water temperatures are high; whereas in the Indian monsoon, heavy rainfall develops from the unique configuration of orographic and warm water surrounding the Indian Peninsula. These differences attribute to many unique monsoon features in the NAM region.

Spatial monsoon rainfall features in the NAM region can be displayed by the leading modes of empirical orthogonal expansion of the region's rainfall variation. Figure 2 shows the first three empirical orthogonal functions (EOFs) of total JAS rainfall. They explain 50.2% of the JAS rainfall variance. EOF-1 shows a tendency of large variations in summer rainfall in south-central Mexico. EOF-2 reveals that rainfall variation in Texas and northeastern Mexico is out of phase with that in the western United States and the west coastal regions of Mexico. This out-of-phase rainfall variation also was shown in several previous studies (Higgins et al. 1997; Barlow et al. 1998; Arritt et al. 2000). It suggests the terrain effects of the Sierra Madre Mountains and the Rocky Mountain plateau on dividing moisture sources and rainfall anomalies in the two regions. EOF-3, which explains 13.1% of the JAS rainfall variance, describes a seesaw variation in rainfall between the north and south regions divided approximately by the 26°N parallel. This feature is similar, to some degree, to the observation in Douglas and Englehart (1996), who showed an out-of-phase relationship of temporal variations in monsoon rainfall between southern Mexico and the southwestern United States. It indicates that the JAS rainfall variation in south-central Mexico has a component opposite to that in the southwestern United States and northwestern Mexico, a notion also supported by the recent findings in Metcalfe et al. (2000), who examined various paleoclimatic records in Mexico and found that summer rainfall anomalies in south-central and southern Mexico often were opposite to that in northern Mexico.

Summarizing these leading EOFs, we could define two rainfall regimes in the NAM region: one in the southwestern United States and northwestern Mexico[1]

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[1] The dataset has 10 grid points in the portion of Mexico north of 26°N and west of 99°W. They are adequate for the analysis to distinguish the rainfall variations in northwestern Mexico from that in south-central Mexico.

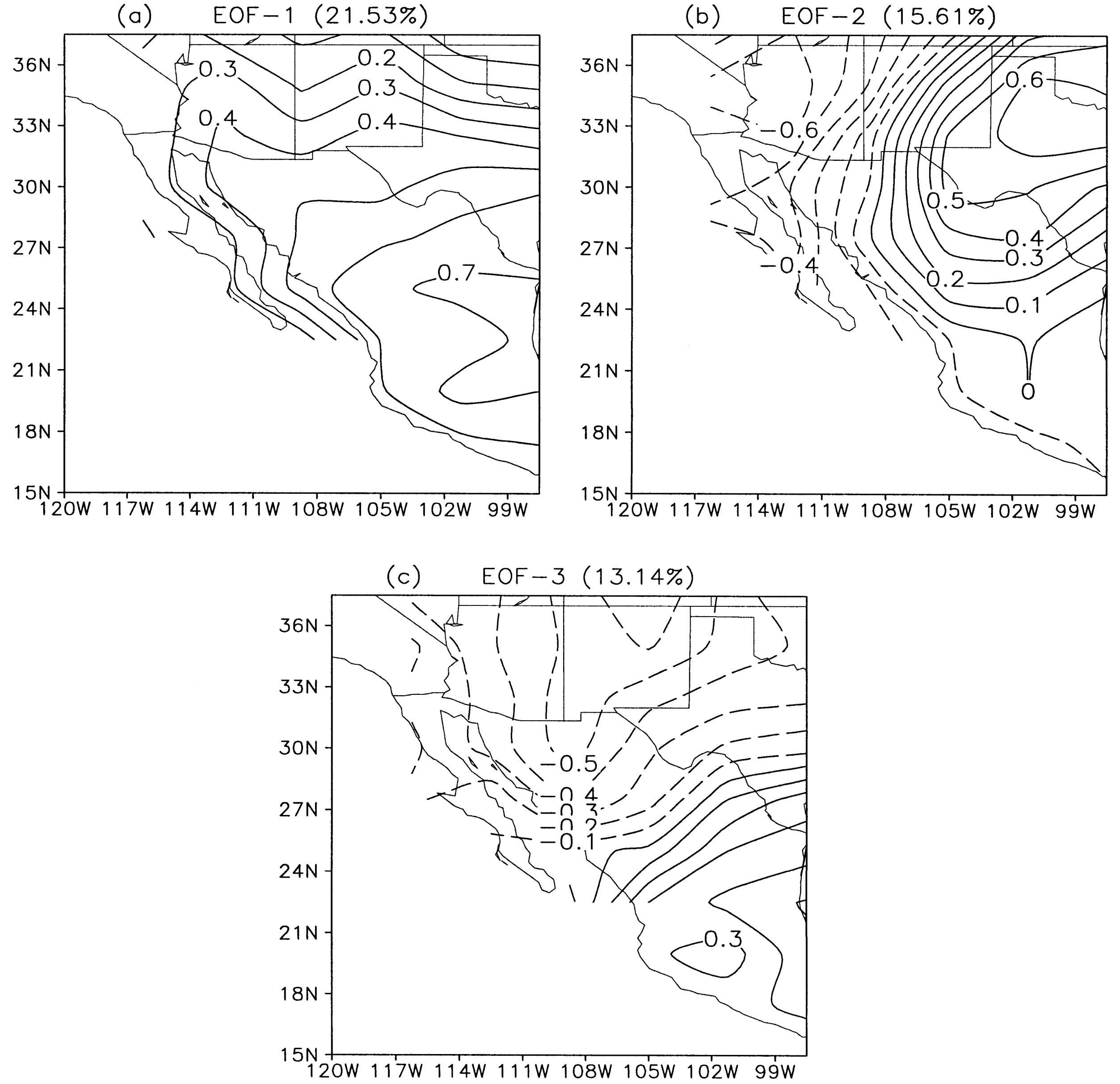


FIG. 2. Leading EOF of the JAS rainfall variation based on data 1900–98. (a) A sole variation center is in south-central Mexico; (b) there are two variation centers: a positive one in northern TX and a negative one in western AZ and southern CA; (c) there also are two variation centers: a positive one in south-central Mexico and a negative one in the eastern AZ and NM.

and the other in south-central Mexico. Monsoon rainfall variation in the two regions has a significant out-of-phase variation component. In the following section, we will articulate the details of these monsoon rainfall systems and show the processes contributing to their seasonal and interannual variations.

4. Monsoon rainfall variations in south-central Mexico

Riehl (1979) suggested that the monsoon rainfall in southern and south-central Mexico is affected by the seasonal north–south shift of the ITCZ in the eastern tropical Pacific region. Monsoon rainfall anomalies may result from anomalies associated with changes in the geographic location and intensity of the ITCZ. Interannual variations in the ITCZ can thus cause similar timescale variations in monsoon rainfall in southern and south-central Mexico. We examined the ITCZ variation in the eastern equatorial Pacific region and provided additional evidence and warrants to support these variation relationships.

The location and intensity of the ITCZ may be determined by monthly mean precipitation, wind conver-

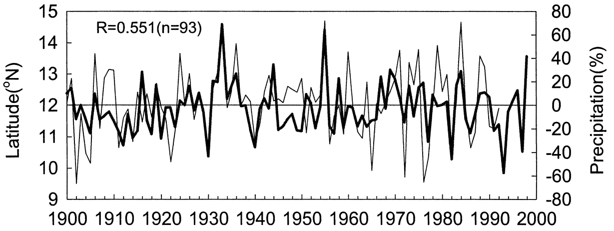


FIG. 3. Time series of JAS ITCZ location, averaged in lon band 82.0°–122.0°W (thin line), and rainfall in south-central Mexico (thick line, unit is in percentage of mean value). The ITCZ location is positive (negative) if the ITCZ is north (south) of its average location, 12°N. The correlation coefficient (*R*) of the two time series is printed.

gence, and SLP. Because the satellite-based precipitation observation in ocean areas is still too short to reveal long-term variability of the ITCZ, low-level wind and SLP have often been used in analysis of ITCZ variations. Machel et al. (1998) showed that the SLP was a good parameter for determining the location of the ITCZ in the tropical Atlantic region. Their results convinced us to use SLP gradients to locate the ITCZ in the eastern equatorial Pacific. The location we used is the confluence of the SLP gradients.

The thin line in Fig. 3 shows variations of the JAS mean latitude position of the ITCZ averaged over the tropical eastern Pacific, 82°–122°W. The average JAS location of the ITCZ for 1900–98 is at 12°N with a north–south variation range of about 3°. The thick line shows the JAS total rainfall in south-central Mexico (20°–26°N). Comparison of the two lines indicates that the region's rainfall variation followed consistently with the variation in the ITCZ location, except for two short time periods in the mid-1910s and from the late 1940s to early 1950s. When the ITCZ was north of its average JAS location, its northward intrusion brought a trough to southern Mexico and enhanced tropical cyclonic flows in south-central Mexico (Reihl 1979). This feature in low-level flow anomalies related to ITCZ location was also described in Magana (2000). It contributed to active monsoon and excessive rainfall in south-central Mexico. When the ITCZ was south of its average JAS position, the monsoon rainfall was deficient.

The anomaly of the JAS ITCZ location was closely associated with the concurrent SSTA in the eastern equatorial Pacific Ocean. In the normally cool SST condition, the ITCZ was located at its average JAS location. When the SST was cooler, the ITCZ advanced northward. In warm SST years, such as during an El Niño year, it was pulled to a southern position (Fig. 3). These coherent variations were shown in Fig. 4a by a significant negative correlation of the JAS SSTA and the ITCZ location. This correlation also indicated a negative effect from the tropical Pacific SSTA on the monsoon rainfall in south-central Mexico. Warmer JAS SST would place the ITCZ south of its average location and yield less monsoon rainfall, and cooler SST would push the ITCZ to a northern location to bring more monsoon rainfall (Fig. 4b). The interannual variations in the tropical Pacific SST associated with the ENSO cycle could result in interannual variations in summer monsoon rainfall in south-central Mexico.

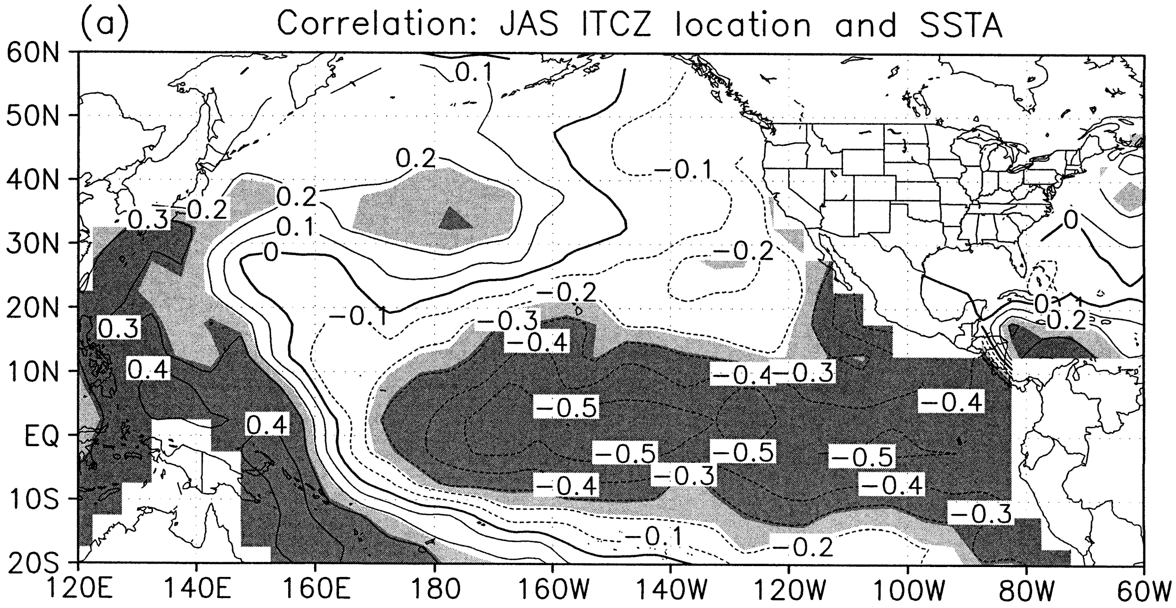
This process affecting the interannual rainfall variation in south-central Mexico had little influence on the monsoon rainfall variations in northwestern Mexico and the southwestern United States. This is demonstrated in Fig. 5, which shows the distribution of correlation of the JAS ITCZ location versus summer rainfall in the entire NAM region for 1900–98. The correlation showed hardly any effect of the ITCZ and SSTA in the eastern equatorial Pacific on monsoon rainfall variations in the southwestern United States, in quite a contrast to a significant positive effect on the monsoon rainfall variation in south-central Mexico. These results indicate that the processes affecting interannual variations in summer monsoon rainfall in the southwestern United States and northwestern Mexico are different from that affecting south-central Mexico monsoon rainfall.

5. Monsoon rainfall variations in the southwestern United States

What has affected the seasonal and interannual monsoon rainfall variations in the southwestern United States and northwestern Mexico (a region approximately in 26.0°–35.0°N, 108.75°–112.5°W)? Several previous studies attempted to answer this question using data from 1960 to 1990, as we discussed in the introduction. They suggested a link by land memory of this variation with antecedent winter precipitation and snow cover anomalies in the western United States. However, the weakening of this link (Gutzler 2000) in the most recent decade raised a concern of its robustness (Higgins and Shi 2000) and prompted reinvestigation of the causes of the variations. In this section, we will examine this robustness and provide a plausible explanation of the temporal variation in the land memory effect. The explanation along with additional supporting evidence will describe a mechanism that can partially explain the seasonal and interannual variations in the monsoon rainfall in the southwestern United States.

a. Changes in the correlation of the antecedent winter precipitation anomaly versus the summer monsoon rainfall anomaly

Our current understanding of the land memory effect on monsoon rainfall variation in the southwestern United States is based on data from 1960 to 1990. These data indicate that greater winter snow in the northwestern United States and southern Canada favored greater rainfall in the southwestern United States during the following summer. In contrast, greater winter precipitation over the southwestern United States favored decreased rainfall in the same region in the following summer. In addition, greater winter precipitation in the


(a) Correlation: JAS ITCZ location and SSTA

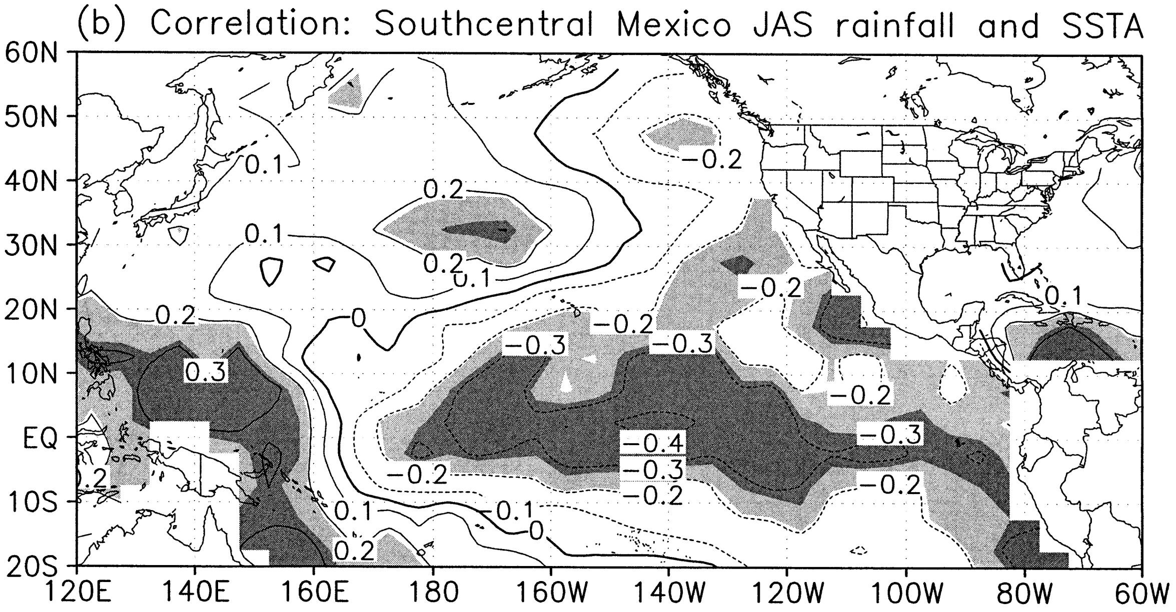

(b) Correlation: Southcentral Mexico JAS rainfall and SSTA

FIG. 4. (a) Distribution of the correlation of the JAS average ITCZ location vs the same-time SSTA in the North Pacific Ocean, and (b) distribution of the correlation of south-central Mexico JAS rainfall vs the same-time SSTA in the North Pacific Ocean (contour interval is 0.1, solid line for positive correlation, and dashed line for negative correlation). Light (dark) shading indicates 95% (99%) confidence level of correlation.

northwestern United States coexisted with less winter precipitation in the southwestern United States. These relationships can be written as $P' \sim P'_{\mathrm{NW}}$, $P' \sim -P'_{\mathrm{SW}}$ and $P'_{\mathrm{NW}} \sim -P'_{\mathrm{SW}}$, where P' is the southwestern U.S. summer rainfall anomaly, P'_{NW} and P'_{SW} are winter precipitation anomalies in the northwestern and southwestern United States, respectively. If we use the difference of P'_{SW} and P'_{NW} to define an index, that is, $\mathrm{WP} = P'_{\mathrm{SW}} - P'_{\mathrm{NW}}$, and use it to measure the combined effect of winter precipitation anomalies in the western United States on the following summer monsoon rainfall anomalies in the southwestern United States, we can find that $\mathrm{WP} = P'_{\mathrm{SW}} - P'_{\mathrm{NW}} \sim -P' - P' = -2P'$, that is, WP is negatively correlated to P'. In the following, P'_{SW} is defined as the winter precipitation anomaly in the southwestern United States (30.0°–37.5°N, 105.0°–

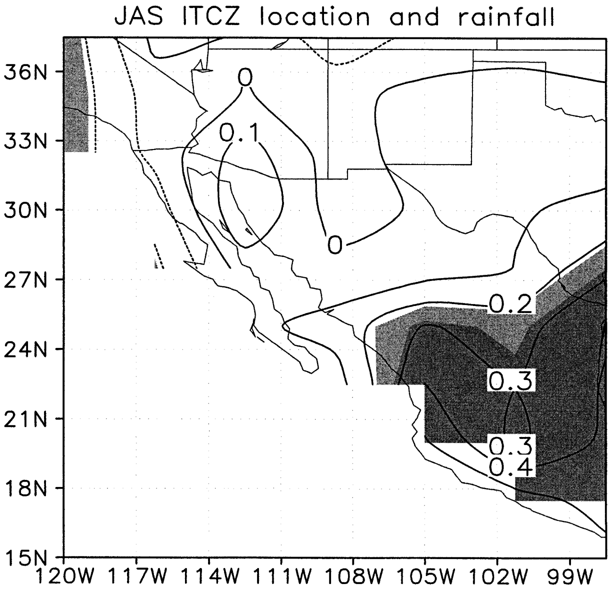


FIG. 5. Distribution of the correlation of JAS ITCZ location and the same-time rainfall in the mapped region. Light (dark) shading indicates 95% (99%) confidence level.

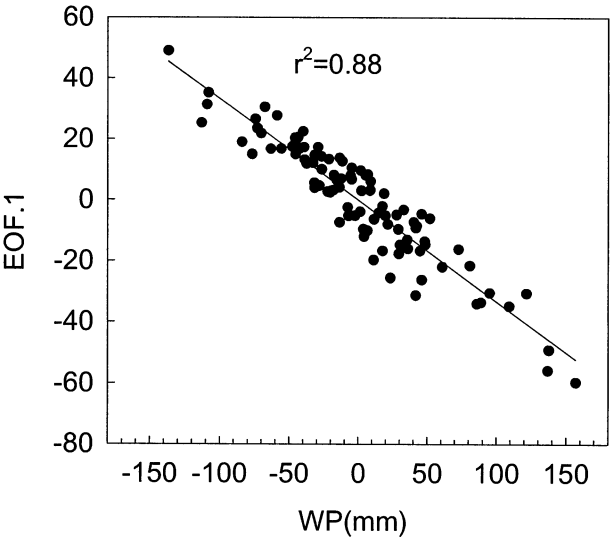


FIG. 6. Relationship of the coefficient of EOF-1 and the WP index for 1900–98.

120.0°W), and P'_{NW} as the simultaneous precipitation anomaly in the northwestern United States (42.5°–55.0°N, 108.75°–123.75°W; see Fig. 8a for these regions). With these P'_{SW} and P'_{NW}, the index WP is similar, to a large degree, to the first principal component of the winter precipitation pattern in the western United States (Fig. 6), but differs from it by having only the effects of the precipitation anomalies in the two most influential regions in the southwestern and northwestern United States identified by observations (e.g., Gutzler and Preston 1997; Higgins et al. 1998; Higgins and Shi 2000). The above negative relationship of WP and P' is based on 1960–90 observations. Temporal variation of WP over a longer period will test the robustness of this relationship and the land memory effect it describes.

We calculated WP from 1900 to 1998 and examined its correlation with the following summer monsoon rainfall in the southwestern United States (32.0°–35.0°N, 108.75°–112.50°W). The result (Fig. 7) showed a significant correlation in 1965–90, the same as in previous studies (Gutzler and Preston 1997; Higgins et al. 1998; Gutzler 2000). The negative correlation was also significant in 1920–30, but was weak in 1900–20 and broken down from 1930 to 1960. The correlation also showed a tendency of weakening since 1990. This variation of the correlation in the course of the last 100 yr revealed that the antecedent winter season precipitation anomaly in the western United States affected the summer monsoon rainfall differently in different periods, and their relationship, identified based on 1960–90 data, was not robust.

The change of the spatial correlation pattern between the early epoch (1930–60) and the recent epoch (1961–90) is further shown in Fig. 8. Figures 8a,b show the correlation of the summer monsoon rainfall versus the gridpoint precipitation in the antecedent winter in the western United States for the two epochs. The recent epoch (Fig. 8a) has significant negative (positive) correlations of summer monsoon rainfall versus antecedent winter precipitation in the southwestern (northwestern) United States. In the early epoch (Fig. 8b), this pattern was replaced by a weak positive correlation of the summer rainfall versus the antecedent winter precipitation in the southwestern United States and a vague relationship with the winter precipitation in the northwestern United States.

Details in the change of the relationship in the epochs are disclosed from comparison and contrast of the composites of annual rainfall variation in the southwestern United States in wet and dry monsoon years of the two epochs (Fig. 9). The wet (dry) monsoon years were years with monsoon rainfall departure larger (smaller) than one half of a positive (negative) standard deviation of the JAS rainfall of the epoch. Figure 9a shows that summer monsoon rainfall in the wet years was virtually

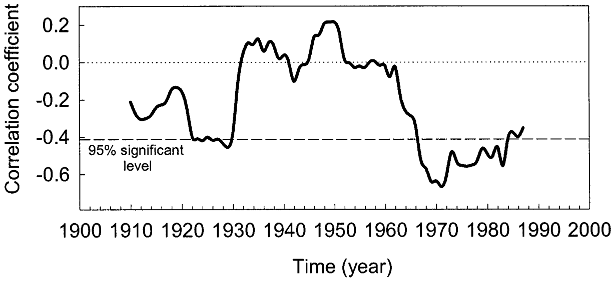


FIG. 7. Variation in the 21-yr moving correlation of JAS rainfall in the southwestern United States vs the WP index. The dashed line indicates the 95% confidence level.

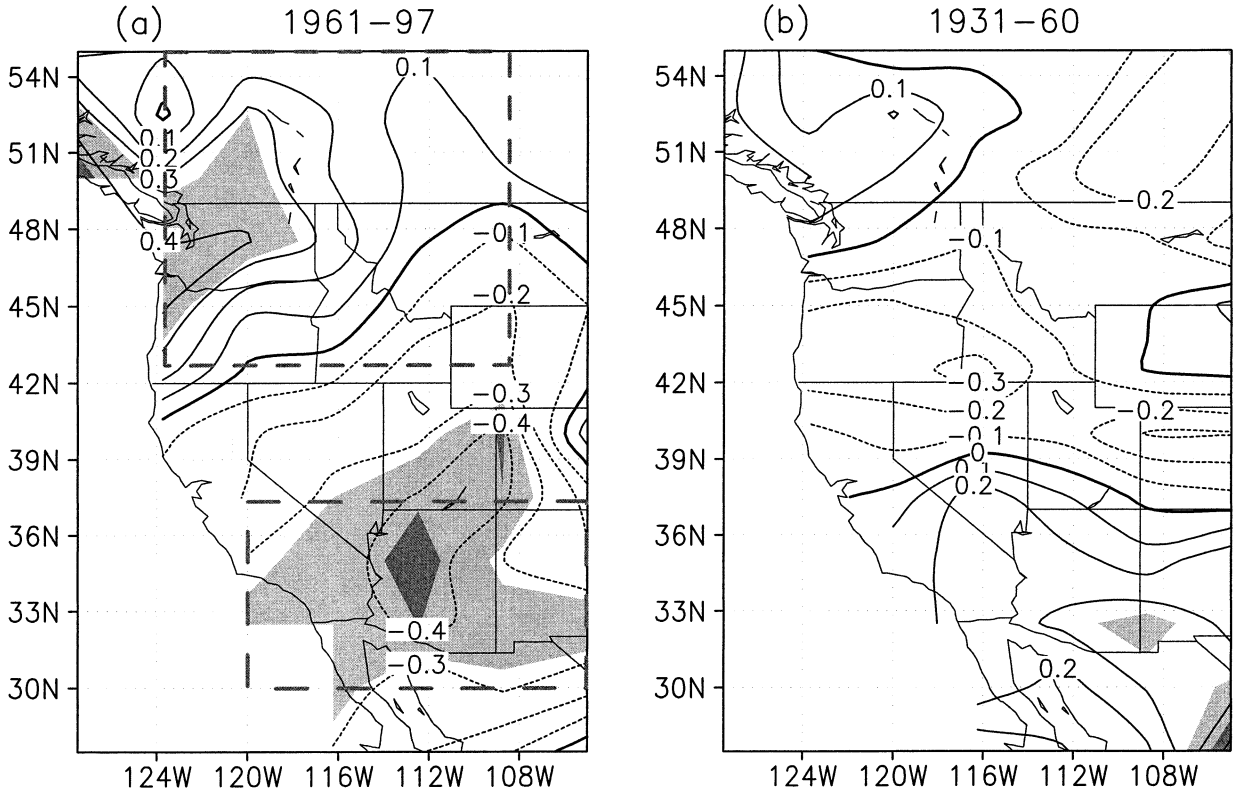


FIG. 8. Distribution of the correlation of JAS rainfall in the southwestern United States vs the gridded Jan–Mar precipitation in the mapped area during (a) 1961–97 and (b) 1931–60. Light (dark) shading indicates 95% (99%) confidence level of correlation.

the same for the two epochs. The winter precipitation was also close, if we take an average over the months of December, January, and February. Figure 9b shows that the winter precipitation was about the same in dry monsoon years between the different epochs, but their monsoon rainfall was very different; the dry summers in the recent epoch were much drier than the dry summers in the early epoch. From comparisons of the precipitation variation between wet and dry summer years in the same epochs (Figs. 9c and 9d), we see that the large summer rainfall difference between wet and dry summers in the recent epoch corresponded to a small but persistent difference in antecedent winter precipitation. A wetter summer followed a slightly drier winter. In the early epoch, a smaller rainfall difference between wet and dry summers corresponded to a larger difference in the preceding winter precipitation. However, a wetter summer followed a wetter winter, and the negative correlation broke down.

In addition to showing the changes of the relationship between the epochs, the differences in Fig. 9 raised some important questions: why in the early epoch (Fig. 9c) did the wet winters not produce dry summers as in the recent epoch (Fig. 9d), and why was the response of the monsoon rainfall so dramatic for such a small difference in the antecedent winter precipitation anomaly in the recent epoch (Fig. 9d)? Apparently, these questions cannot be explained by the land memory effect alone because the march of the land surface processes from winter to summer associated with similar winter precipitation anomalies in both the epochs should be alike. The systematic change in the relationship may be accounted for by a change in atmospheric circulations between these epochs.

b. Role of large-scale circulation in the correlation and its variation

To examine the circulation variation and its role in the land memory change between the epochs, we used singular value decomposition (SVD; Bretherton et al. 1992) and compared covariance structures of summer and winter SLP in different epochs. The SLP was used because it has data in the early epoch and it represents reasonably well the low-level circulation (Hu and Feng 2001). The SVD analysis of SLP can reveal the covariance structure in the winter and summer circulation and depict the summer circulation anomalies corresponding to the circulation anomalies in the antecedent winter. Differences of the covariance structures in different epochs can reveal the role of the atmospheric circulation in change of the relationship of the southwestern U.S. summer rainfall anomaly versus the antecedent winter precipitation anomaly.

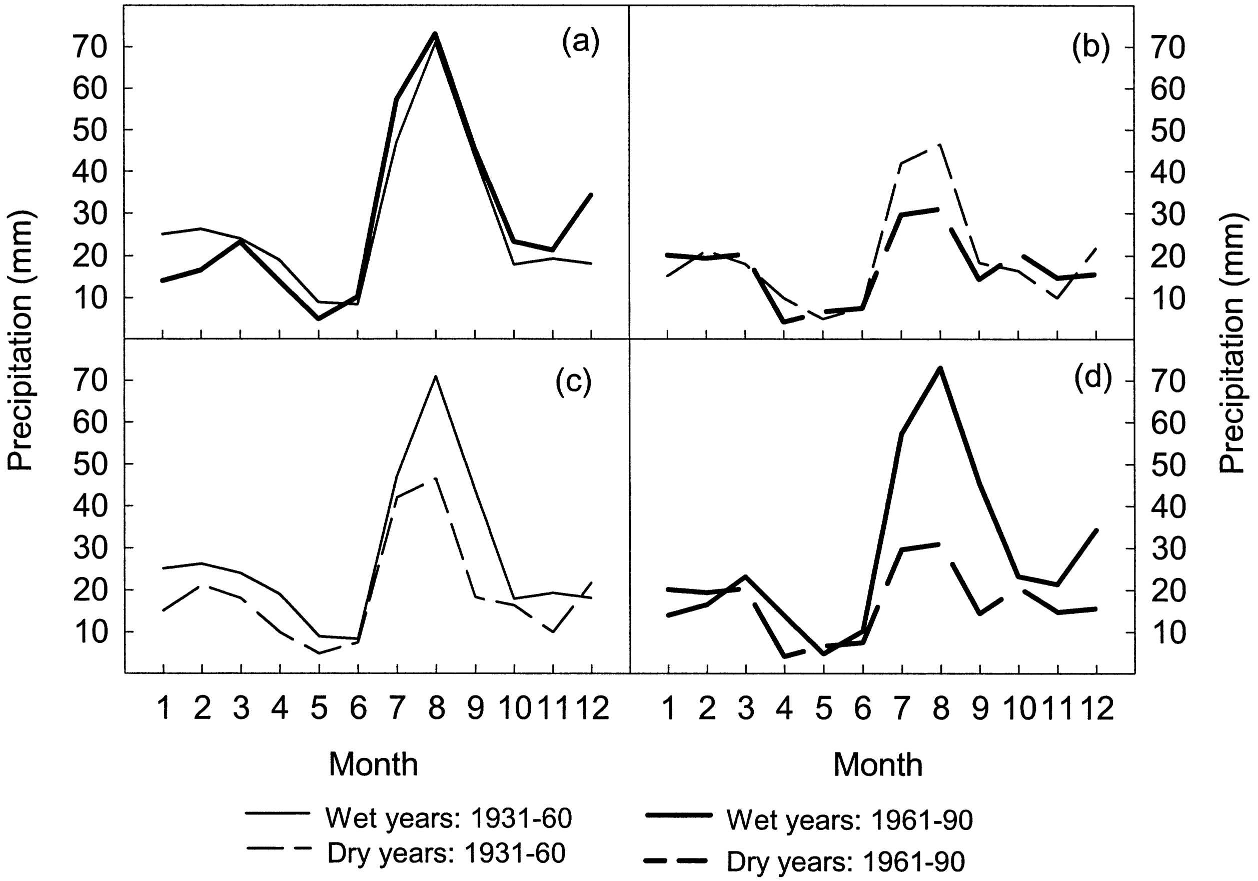
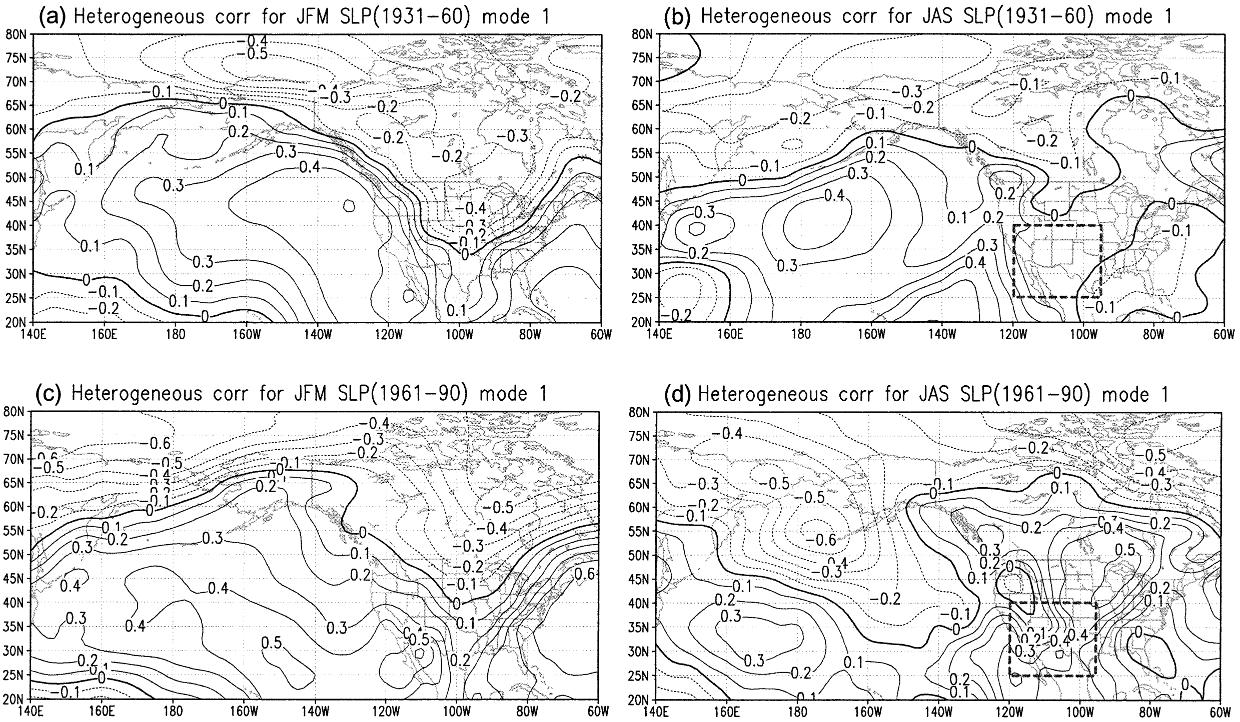


FIG. 9. Comparison and contrast of annual rainfall distributions of (a) the wet monsoon years between the early and recent epoch, (b) dry monsoon years between the two epochs, (c) wet and dry monsoon years in the early epoch, and (d) wet and dry monsoon years in the recent epoch. [In the panels, the thin solid line is the composite annual precipitation variation for wet years (1931, 1935, 1939, 1941, 1946, 1951, 1954, 1955, 1959) in the southwestern United States in the early epoch; the thin dashed line is the composite annual precipitation variation for dry years (1932, 1934, 1938, 1942, 1944, 1945, 1947, 1948, 1950, 1952, 1953, 1956, 1960) in the epoch for the same region. The thick solid line is the composite annual precipitation variation for wet years (1963, 1964, 1967, 1970, 1983, 1984, 1986, 1988, 1990) for the recent epoch; the thick dashed line is the composite annual precipitation variation for dry monsoon years (1962, 1968, 1972, 1973, 1978, 1979, 1980, 1987, 1989) in the epoch for the same region.]

The leading modes of the SVD covariance matrix of SLP in the Pacific and North America are shown in Fig. 10 for the two epochs. They are distinctly different. In the early epoch, the heterogeneous correlation (Figs. 10a and 10b) of SLP shows that the winter anomalies in the mid- and high-latitude northeastern North Pacific region strongly affected the summer SLP pattern in the North Pacific basin. But the circulation anomalies in this as well as others regions had very little influence on the low-level circulation in the southwestern United States and northwestern Mexico (see the boxed area in Fig. 10b). This is also consistent with the result in Fig. 7 for the epoch. This correlation structure changed dramatically in the recent epoch. As shown in Figs. 10c and 10d, the leading modes of the heterogeneous correlation showed a strong response of the summer circulation in the southwestern United States and northwestern Mexico (boxed region) to antecedent winter circulation anomalies in the midlatitude eastern North Pacific.

These different relationships show that the large-scale circulation and its variation were the essence of the observed correlation of the summer monsoon rainfall anomaly versus the preceding winter precipitation anomaly in the western United States. The circulation regime in the recent epoch contained temporally persistent components connecting the antecedent winter circulation in the North Pacific–North American sector with the summer circulation variation in the southwestern United States. Thereby, the monsoon rainfall responded to the antecedent winter precipitation anomalies in the western United States. The circulation regime in the early epoch did not have such circulation features. Although it is undisputable that the land surface condition anomalies resulting from the winter precipitation anomaly can affect regional circulations, these results indicate that a ‘‘right’’ or ‘‘supporting’’ large-scale circulation is essential for the observed cross season correlation of precipitation in the western United



(a) Heterogeneous corr for JFM SLP(1931−60) mode 1

(b) Heterogeneous corr for JAS SLP(1931−60) mode 1

(c) Heterogeneous corr for JFM SLP(1961−90) mode 1

(d) Heterogeneous corr for JAS SLP(1961−90) mode 1

FIG. 10. The SVD leading mode of heterogeneous correlation of (a) the Jan–Mar SLP vs (b) the JAS SLP for the early epoch. The modes for the recent epoch are shown in (c) and (d). The box in (b) and (d) focuses correlation changes between the epochs in the study area.

States. The large-scale circulation can maintain or erase the effect of land surface anomalies on the monsoon rainfall and result in variations of the correlation. In this regard, the land memory effect is a part of the circulation feature.

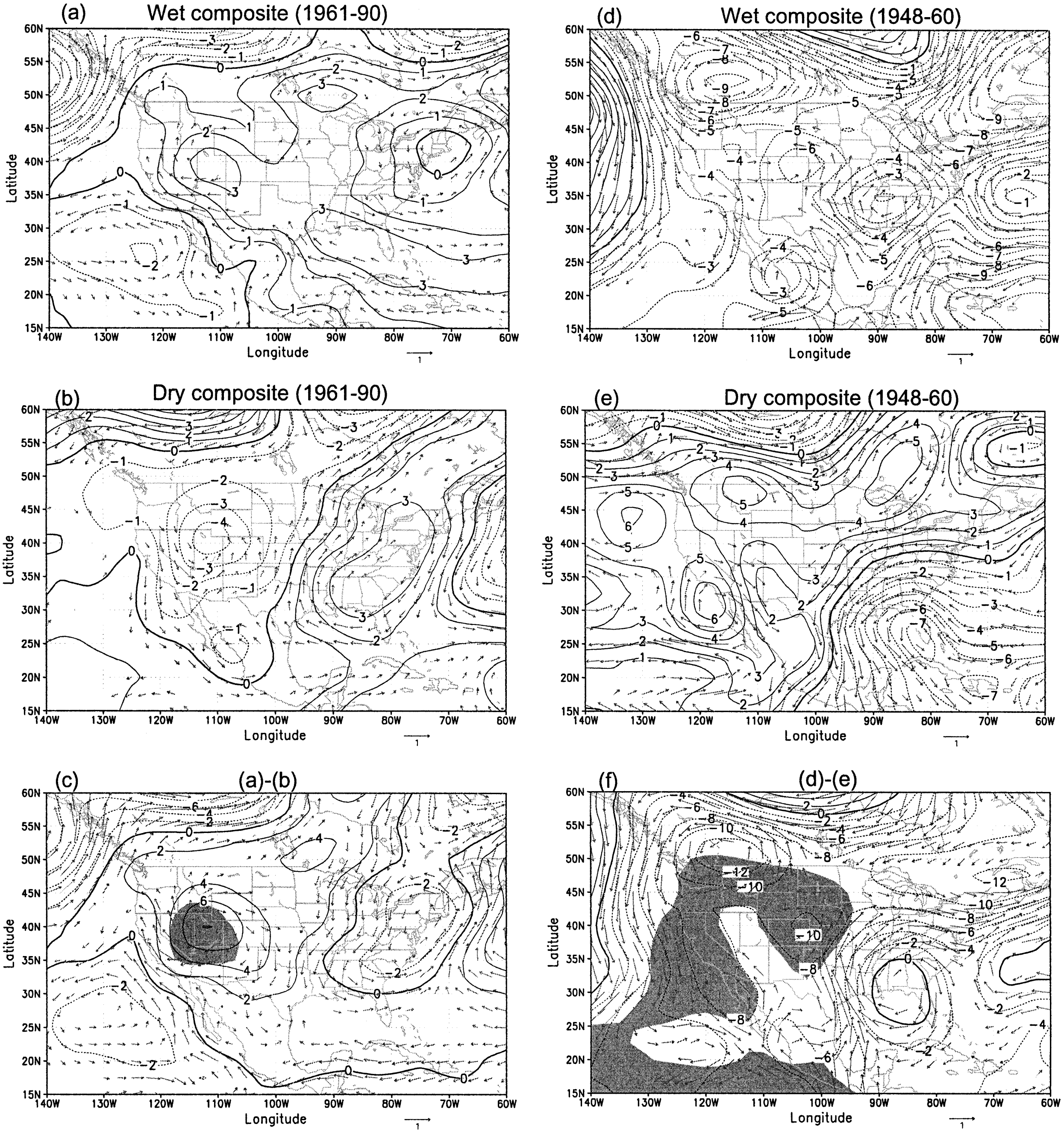
c. Low-level circulation features in the interannual variations in monsoon rainfall in different epochs

To show the circulation features in the interannual variation of the monsoon rainfall in the different epochs, we plotted in Fig. 11 the composites of JAS 850-hPa geopotential height and wind anomalies for wet and dry monsoon years in the two epochs. The differences of the large-scale circulation in the two epochs also help to disclose different causes of the interannual variation in the summer monsoon rainfall in the southwestern United States and northwestern Mexico.

In the recent epoch (Fig. 11a), the 850-hPa circulation anomaly in wet monsoon seasons featured a strong geopotential gradient from northeast to southwest across the costal line of the southwestern United States. The flow field was easterly and southeasterly from the Gulf of Mexico region through the orographic gap between the Rocky Mountain plateau and the Mexican plateau to the monsoon region. This anomaly pattern reversed in dry monsoon seasons (Fig. 11b). Their difference (Fig. 11c) revealed significant changes in geopotential height centered to the north of the monsoon region and associated motion field in the monsoon region. In dry seasons, dry and stable westerly and northwesterly flows, associated with a low-geopotential anomaly, entered the monsoon region from cool SST areas in the eastern North Pacific. The dry stable air discouraged rainfall development and produced rainfall deficit. In wet seasons, easterly and southeasterly moisture flows associated with a high-geopotential anomaly entered the monsoon region from the Gulf of Mexico and Gulf of California and created instability for convection and storm and produced more rainfall.

In the early epoch, the entire circulation was different; the monsoon region had low-geopotential anomalies relative to the geopotential to its east and west and converging flows in both the wet and dry monsoon seasons (Figs. 11d and 11e). A major feature separating the circulation anomalies between wet and dry seasons is that in wet seasons, enhanced low-geopotential anomalies in eastern foothills of the Rockies established southerly and southeasterly flows converging from the Gulf of Mexico into the monsoon region (Fig. 11d), causing a rise of the monsoon rainfall. In dry monsoon seasons, enhanced high-geopotential anomalies over the cool ocean water off the southwest coast of California established strong northerly and northwesterly flows into the monsoon region (Fig. 11e). The stable northerly and northwesterly flows from the cool ocean areas suppressed storm development and monsoon rainfall.

The contrast of Figs. 11c–11f indicates different ac-


(a) Wet composite (1961-90)

(b) Dry composite (1961-90)

(c) (a)-(b)

(d) Wet composite (1948-60)

(e) Dry composite (1948-60)

(f) (d)-(e)

FIG. 11. Composite anomalies of JAS 850-hPa geopotential height (m) and wind (m s^{-1}) for (a) wet years and (b) dry years for 1961–90 and (c) their difference. Similar composite and difference for 1948–60 are shown in (d)–(f). The composite years in each epoch are the same as those listed in Fig. 9. The shading in (c) and (f) indicates statistically significant change in geopotential between wet and dry composites. Wind arrows were omitted when wind speed is weaker than 0.2 m s^{-1}.

tivity/anomaly centers in the two epochs responsible for interannual monsoon rainfall variations in the southwestern United States. In the recent epoch, the sole anomaly center in the north of the monsoon region directly controlled the circulation and rainfall anomalies. Its alternation resulted in interannual variation in the monsoon rainfall. In the early epoch, the monsoon region was between two major anomaly centers on its northeast and southwest, and did not have a clear and dominant flow anomaly between wet and dry monsoon seasons as in the recent epoch. Thereby, a small imbalance between the two large anomaly centers *within* a summer can change the course of the monsoon rainfall development in the monsoon season. This situation un-

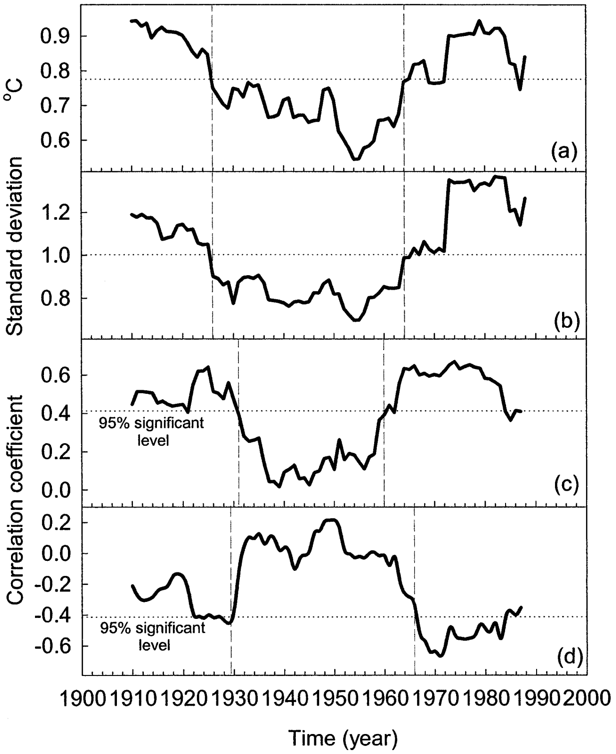


FIG. 12. (a) Variation in the std dev of the 21-yr sliding window period for the Niño-3.4 SST and (b) for the SOI. The dashed lines in (a) and (b) indicate the mean value of the entire period. (c) Variation of the 21-yr moving correlation of the WP vs the Niño-3.4 SST. (d) Variation of the 21-yr moving correlation of the WP vs summer monsoon rainfall in the southwestern United States. The dashed line in (c) and (d) indicates the 95% confidence level of the correlation.

dermined the dependence of the summer monsoon rainfall anomaly on the antecedent winter precipitation anomalies in the western United States. It also explains the small difference in monsoon rainfall intensity between wet and dry years in the early epoch (Fig. 9c).

d. The circulation change versus ENSO variation

We found that the change of dynamics and circulation in the different epochs was related to the intensity variation of ENSO, which possesses interannual and decadal scales (Trenberth and Hoar 1997; Zhang et al. 1997). The variation in ENSO intensity for the twentieth century is shown in Figs. 12a and 12b in terms of the standard deviation of winter Niño-3.4 SST and the Southern Oscillation index (SOI). These figures show that the amplitude and intensity of ENSO were large in two periods—one before 1925 and the other from the early 1960s to the late 1980s. Between them was a period of weak ENSO.

Effects of the ENSO intensity variation on precipitation in the monsoon region are indicated in Fig. 12c, which shows the relationship of the ENSO intensity and the winter precipitation index (WP). This relationship varied and its variation was nearly in phase with the variation in ENSO intensity except for some phase difference in the transition time.[2] During the periods of strong ENSO activity, the ENSO effect on the winter precipitation and distribution in the western United States was significant. This effect could be reached via the Pacific–North American (PNA) teleconnection (Wallace and Gutzler 1981) as described in Carleton et al. (1990). The associated circulation anomalies further developed to affect the following summer monsoon rainfall in the southwestern United States and northwestern Mexico (Fig. 12d), causing ENSO-like interannual variations in monsoon rainfall in that region. In the period when ENSO activity was weak (e.g., 1931–60), a different circulation was dominant in the North Pacific–North American sector (Fig. 10). The ENSO teleconnection with winter circulation and precipitation in the western United States weakened, and the connection between the winter circulation anomalies and summer monsoon circulation and rainfall variation in the southwestern United States and northwestern Mexico broke down. Interannual variations in monsoon rainfall in such epochs would result from processes different from that in the recent epoch.

6. Concluding remarks

Major questions answered in this study are 1) does the North American monsoon region have a single dominant monsoon system; 2) if it has more than one, what are they; and 3) what are the major causes of the interannual monsoon rainfall variations in the different monsoon systems? Results show a significant component in the variation of the summer monsoon rainfall in the southwestern United States and western Mexico. It explains more than 13% of the rainfall variance and has a north–south seesaw pattern in the NAM region. This pattern suggests that the summer monsoon rainfall in south-central Mexico, primarily the region south of 26°N is affected by processes different from that in the southwestern United States and northwestern Mexico. Monsoon rainfall anomalies in the two regions have a tendency of being opposite to each other, consistent with the paleoclimatic records in Mexico (Metcalfe et al. 2000).

The significant interannual variations in monsoon rainfall in south-central Mexico were highly correlated with interannual variations in the SST and the ITCZ in the eastern tropical Pacific region; cooler (warmer) than normal SST coexisted with the more northern (southern) position of the ITCZ in the region and more (less) monsoon rainfall in south-central Mexico.

Interannual variations in summer monsoon rainfall in the southwestern United States were affected by much

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[2] The phase difference may have resulted from nonsynchronous changes of processes, during the transition, in the ocean and atmosphere involved in the multidecadal variations in the climate.

more complex processes of both ocean and land origin. In agreement with previous studies, we found strong linkages of the summer monsoon rainfall anomalies in the region with antecedent winter precipitation anomalies in the western United States. Moreover, we found that this relationship was not robust. It was strong from approximately 1920 to 1930 and disappeared from 1931 to 1960. It regained its strength from 1961 to 1990 but weakened again since 1990.

This multidecadal variation of the relationship questioned the role of the land memory effect on interannual monsoon rainfall variations. The key issues are why in only some epochs winter precipitation anomalies in the western United States could be stored in the land memory and released in the following summer through land surface condition anomalies and associated energy and water fluxes, and why such memory failed repeatedly in winters of other epochs when a similar magnitude of winter precipitation/snow anomaly developed in the same region. Our explanation of this paradoxical situation is that the large-scale circulation in the North Pacific–North American sector changed in those epochs. As a circulation feature, the land memory process also changed. Putting it in a different perspective, we assert that the multidecadal variation in large-scale circulation has regulated the apparent land memory effect on monsoon rainfall, enhancing them in some epochs and weakening them in the other.

In the epochs of enhanced land memory effect, the preceding winter circulation in the North Pacific region and in the western United States was highly correlated with the summer circulation anomalies in the southwestern United States. Consequently, the summer monsoon rainfall showed consistent variations with the winter precipitation anomalies in the western United States. The winter precipitation anomaly was a good precursor of summer monsoon rainfall anomaly, and the ENSO cycles affecting the winter precipitation variations also brought the interannual variations to the summer monsoon rainfall in the southwestern United States. In the opposite epochs, quite different circulations weakened the connection between the monsoon rainfall variation and the antecedent winter circulation anomalies in the North Pacific and western United States. In those epochs, the mechanisms causing the interannual monsoon rainfall variations in the other epochs could not operate, and the sources of the observed interannual monsoon variations remain unknown.

These answers to the questions have identified some key sources of monsoon variations and are useful to improve prediction of the North American monsoon rainfall. They demonstrate the critical role of the multidecadal variation in alternating the mechanisms of seasonal and interannual variations in the North American monsoon rainfall, and indicate that successful prediction methods of the interannual monsoon rainfall variation will rely on their ability to correctly account for the multidecadal variations in the circulation.

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