Decadal Hydroclimatic Variability in the Western Coastal United States: Temporal and Spatial Variations in Precipitation, Streamflow, and Lake Level

Hong-Chun Li and Teh-Lung Ku

Abstract: We have analyzed streamflow variations recorded at 15 USGS gauging stations in California during the past 90 years or so. The anomalies (departures from the 1960-1990 mean discharge) of streamflow on annual-to-decadal time scales are strongly correlated with precipitation anomalies in each drainage basin. The temporal variations of the 5-year running averages of these records clearly show high/low runoff cycles with a periodicity of about 11±3 years, representing a decadal climate (precipitation) variability. High runoff periods (wet climate) centered around 1982, 1969, 1956, 1940, and 1915. Low runoff periods (dry climate) centered around 1989, 1976, 1962, 1946, and 1932. In addition, streamflow intensity during the high runoff periods reveals different spatial patterns. For example, runoff around 1956 was much stronger at the northern California stations than at the southern California stations. In 1993, all stations (four) in southern California showed very high runoff, while the other stations showed weakly increased runoff. Although causes of the decadal climate (precipitation) variability are not known with certainty, the use of streamflow records may help us understand the relative strengths of moisture sources and shift of the jet stream in atmospheric circulation. Precipitation regimes in California are influenced by three moisture sources: northwesterly flow (polar front) related to the Pacific/North America anomaly, southwesterly flow controlled by the tropic ENSO pattern, and southeasterly flow governed by the summer monsoon. A preliminary assessment shows that variations of California runoff on decadal time scale, but not on annual time scale, are strongly correlated with ENSO. This implies that the northwesterly flow may be blocked by the subtropical high-pressure system with descending, dry air in mid-latitude zones when the Southern Oscillation is strong, causing drought in California. When the Southern Oscillation is weak, the northwesterly flow can penetrate farther south and the El Niño event can bring more precipitation from the equatorial Pacific to California. Summer monsoon mainly affects the climate and streamflow in southern California. Strong runoff in 1969 and 1993 recorded by gauging stations in the south may indicate the strengthening of the summer monsoon.

Data

This study uses annual precipitation data along the climatic divisions in the west coast regions of the United States, including Washington, Oregon, and California (Figure 1). The data are extracted from the WeatherDics Associates, Inc., World WeatherDisc CD-ROM 1994. The climatic division boundaries are defined by the National Climatic Data Center, including stations subjectively considered to exhibit similar climatic properties. Precipitation data are the averages of several stations in each division so that they can represent the best feature of each division. All divisions are along the coast regions so that the effect of topography on precipitation pattern is minimized. Records employed for precipitation extend from 1895 to 1991. Three other rainfall records

In: C.M. Isaacs and V.L. Tharp, Editors. 1997. *Proceedings of the Thirteenth Annual Pacific Climate (PACLIM) Workshop, April 15-18, 1996.* Interagency Ecological Program, Technical Report 53. California Department of Water Resources.

extended farther back are those of Los Angeles (1887), the southern San Joaquin Valley (1872), and Nevada City (1864), for longer time comparison. All data are expressed as departure from 1895-1991 mean precipitation.

The Southern Oscillation Index, defined as the sea level pressure difference Tahiti minus Darwin shown as departure from 1951-1980 annual mean of 2.8 mb, are adopted from bimonthly values in Hastenrath (1991). A low (negative) value of the index corresponds to a weaker east-west pressure gradient and correlates to a high sea surface temperature anomaly in the equatorial Central Pacific. The SOI data extend from 1902 to 1988.

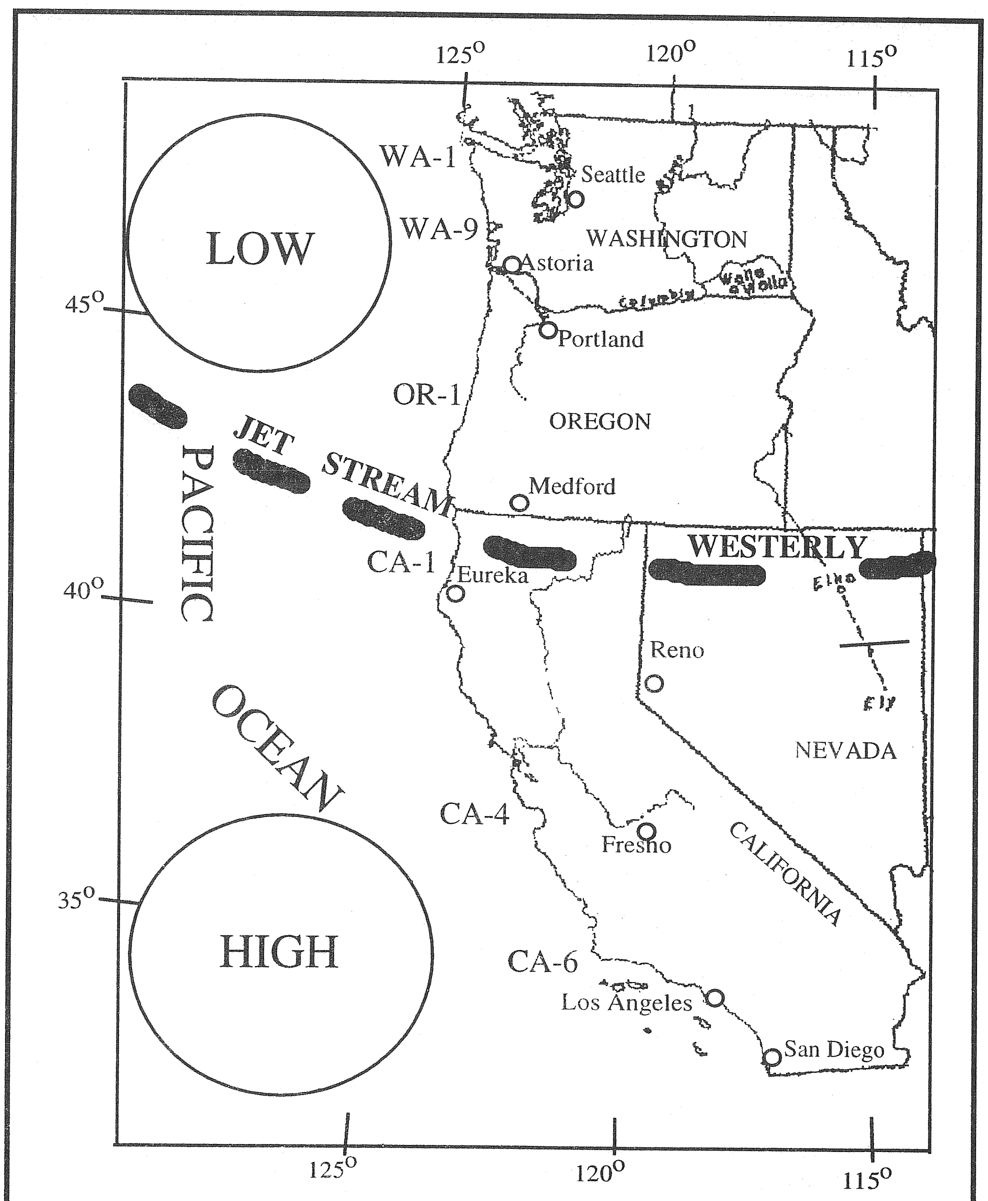


Figure 1. Map of western United States showing six precipitation regions along the coast and climatic pattern of jet stream westerly.

Subtropics High and North American/Pacific Low are simplified.

The streamflow data are recorded at 14 U.S. Geological Survey gauging stations in California. They are classified as three groups from the coastal region (west) to inland area (east) — coast, central valley, and mountain — and one group in southern California. In each group, three to four gauging stations are listed from north to south (or from west to east). These records extend from as early as 1902 to 1994 (Water Resources Data — California, 1994). The data are expressed as departure from 1960-1990 mean discharge.

Mono Lake is a hypersaline, alkaline lake in the Mono Basin at the eastern base of the California Sierra Nevada (Figure 1). Its lake-volume history since 1912 has been recorded instrumentally, showing dramatic fluctuations due to climatic variations and large decline of lake-surface elevations initiated by the 1941 artificial diversion of stream inflow (Blevins *et al* 1987). A 76-cm-long sediment core was collected in 1991 from the deepest part of Mono Lake at 39 meters, using a rectangular freeze corer (Li *et al* 1996). We have made high-resolution (0.5- to 3-year intervals) oxygen isotopic measurements on total carbonates of the deionized water washed lake sediments. The sedimentary chronology was determined from the distributions of ^{210}Pb and $^{239+240}Pu$ in the sediments and extended from 1991 to about 1840 with 5 to 10% uncertainty (Li *et al* 1996). Our previous study shows that the $\delta^{18}O$ record simulates the lake-volume fluctuations rather well. The objective of using the lake volume and the $\delta^{18}O$ record is to demonstrate that closed-basin lake sediment $\delta^{18}O$ provides an effective means of probing decadal climatic variability in the past while historical records are absent.

Precipitation Anomalies, ENSO, and Jet Stream Shift

The comparison of annual rainfall records of Los Angeles and south coast region of California with El Niño events and SOI variations shows that only half of the strong El Niño (weak SOI) years correspond to precipitation anomalies above average (Figure 2). Some of the strong El Niño years actually show precipitation anomalies below average. Some non-ENSO years (*eg*, 1889, 1909, 1938, 1978, 1980) have strong positive precipitation anomalies. This observation raises questions regarding how the ENSO system influences climatic variability in mid-latitude, and on what time scale we can correlate ENSO pattern with the climatic variability in a better way.

Five-year running averages of rainfall records in the western United States reveal apparently decadal/interdecadal climatic variability (Figure 3). In coastal California, with wet periods corresponding to the weak SOI except during 1917-1927, when the entire west coast was dry. Dry periods in this region correlate with the strong SOI. Therefore, on the interannual-to-decadal time scales, precipitation anomalies in coastal

California, but not limited to southern California, can be well correlated to the ENSO pattern.

The spatial variations of the decadal precipitation patterns on the west coast show opposite trends between the southern and northern parts except in two periods, 1917-1927 and 1978-1984. When the northern part is wet, the southern part tends to be dry, and vice versa. This observation may indicate that Jet Stream Westerly has migrated south or north depending on the intensity of the Southern Oscillation. Normally, Jet Stream Westerly meets the cold, moist air of the polar easterly at about 45-50°N above the west coast. Low pressure systems in the polar front zone generate most winter precipitation, which is the dominant rainfall along the west coast. During weak Southern Oscillation periods, the warm water of El Niño at the equatorial Pacific causes the inter-tropical convergence zone (ITCZ) to shift south from its usual position. Hence, positions of the Subtropic Highs (high pressure) and the Pacific/North America Lows (low pressure) probably migrate southward and cause Jet Stream Westerly to shift south. Under this condition, perhaps both polar front and subtropic jet streams bring more moisture to the southern part,

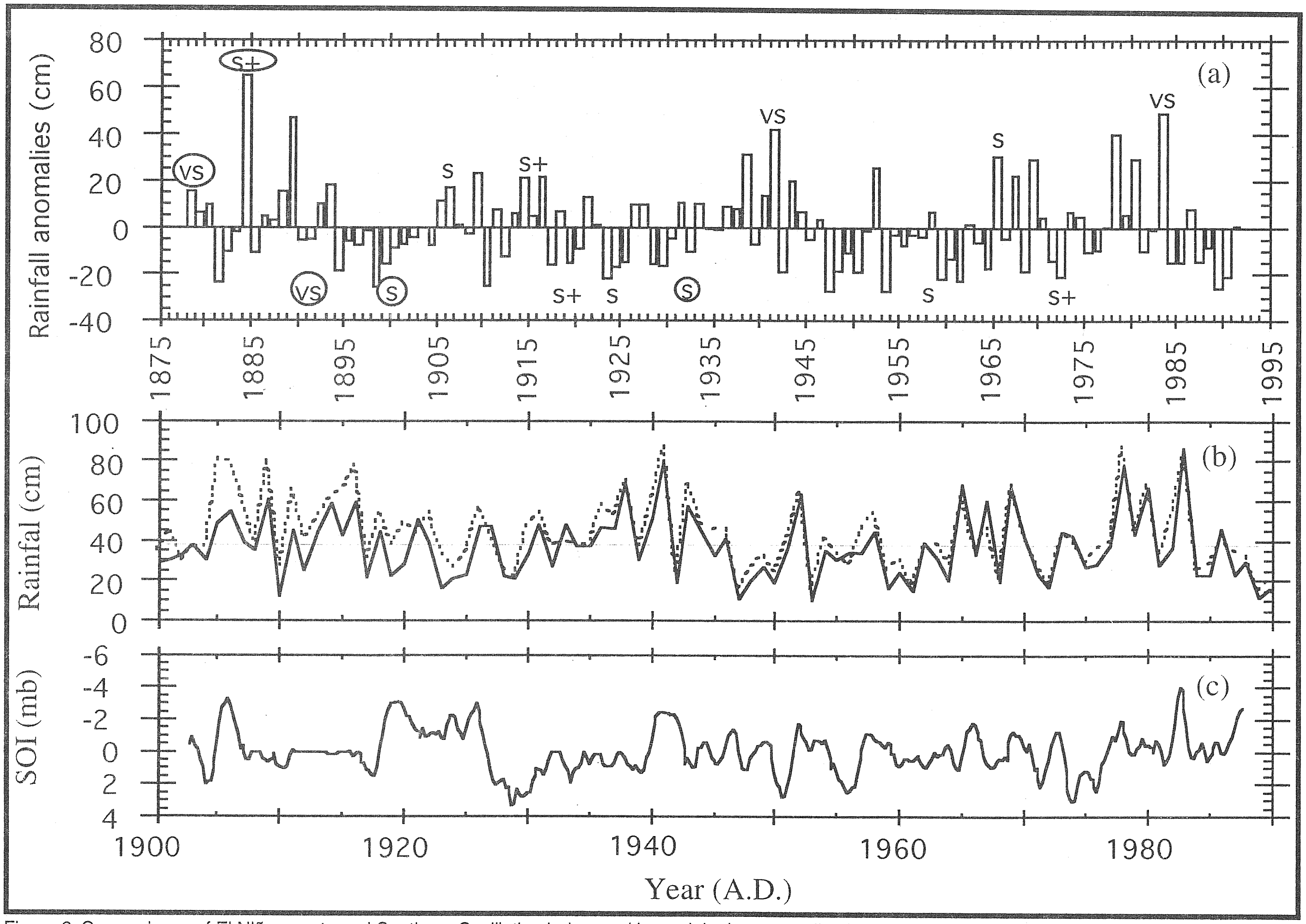


Figure 2. Comparisons of El Niño events and Southern Oscillation indexes with precipitation anomalies in southern California:
(a) rainfall anomalies in Los Angeles compared with El Niño events classified by Quinn and Neal (1987) (S=strong, VS=very strong);
(b) historical precipitation records in Los Angeles (solid) and southern California (dashed);
(c) mean annual Southern Oscillation Index averaged from bimonthly values as departure from 1951-1980 mean of 2.8 mb.

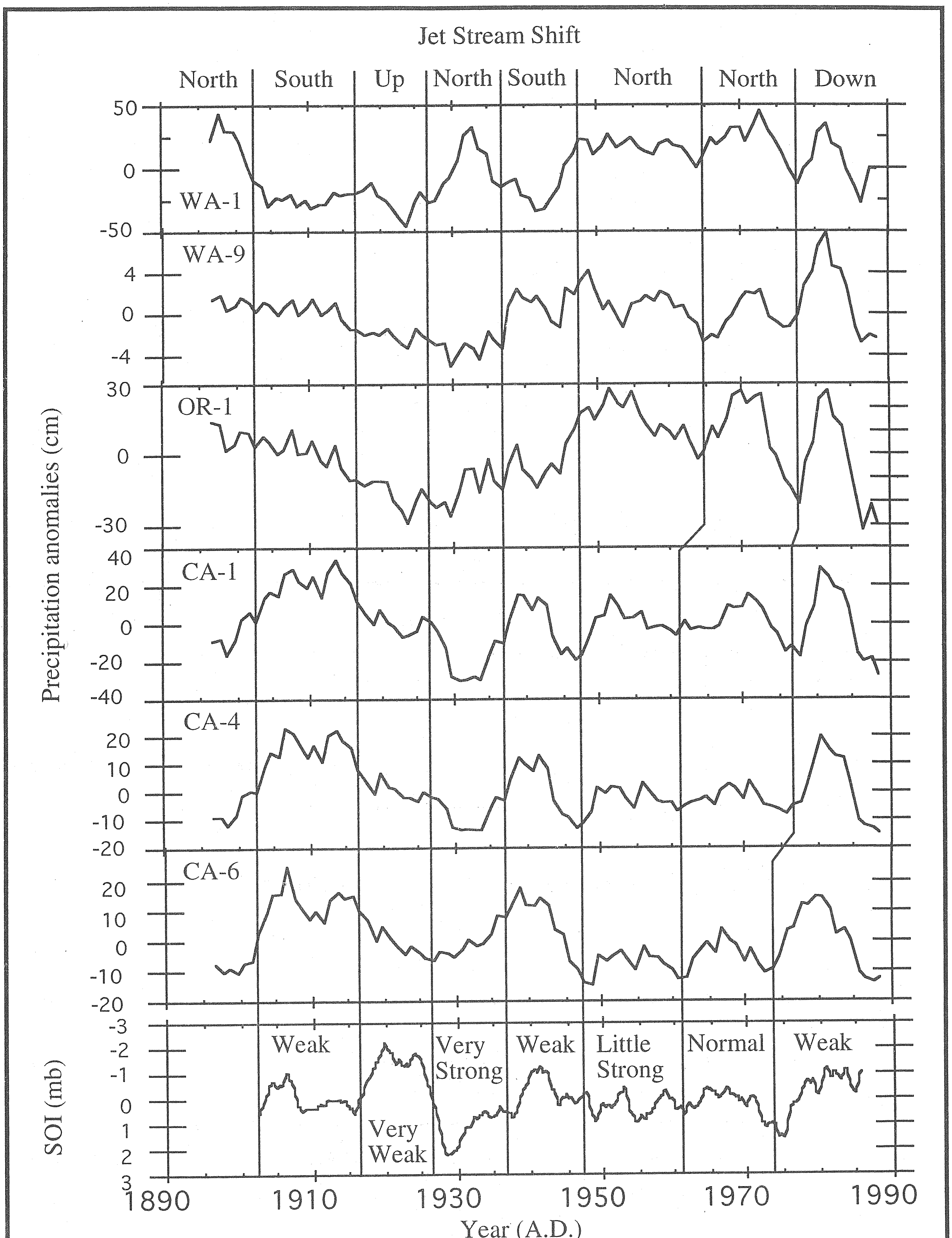


Figure 3. Comparison of 5-year running average precipitation anomalies with 5-year running average Southern Oscillation Index.

Precipitation stations (*eg*, WA-1, CA-6) shown in Figure 1 are plotted from north to south.
North/south and up/down shifts of jet stream are indicated on the top of the plot.

so that the southern part is wet and the northern part is dry. In contrast, during strong Southern Oscillation periods, the cold water of La Niña at the equatorial Pacific causes ITCZ to shift north. This shift leads to the Jet Stream Westerly persisting in the northern part and causes more storm activity there. The northwesterly moisture from the northern part is diminished when it migrates southward, perhaps blocked by the subtropical high-pressure system with descending, dry air in mid-latitude zones when the Southern Oscillation is strong, so the southern part tends to be drought.

Two specific periods (1917-1927 and 1978-1984) are different from the above observation and cannot be explained by horizontal shift of the Jet Stream Westerly (Figure 3). Close examination indicates that both periods show very weak Southern Oscillation patterns. However, while the entire west coast experienced a dry climatic regime during 1917-1927, the entire region experienced a very wet climatic regime during 1978-1984. A hypothesis that has been made for understanding this observation is probably the vertical movement of the atmospheric circulation. Although the mechanism caused the vertical movement of the atmospheric circulation is unclear, drought along the entire west coast of the United States may reflect an upward shift of low pressure systems (polar jet and subtropic jet?), and the situation reverses when extreme wetness occurs along the entire west coast.

Correlation Between Streamflow and Precipitation Anomalies

The anomalies (departures from the 1960-1990 mean discharge) of streamflow recorded at 14 USGS gauging stations in California during the past 90 years or so are strongly correlated with precipitation anomalies in each drainage basin on annual-to-decadal time scales (Figures 4-7). This means the streamflow anomaly on annual-to-decadal time scales reflects chiefly precipitation change in this arid-semiarid region. The temporal variations of the 5-year running averages of these records clearly show high/low runoff cycles with a periodicity average of 11±3 years, representing a decadal climate (precipitation) variability. High runoff periods (wet climate) are centered around 1982, 1969, 1956, 1940, and 1915. Low runoff periods (dry climate) are centered around 1989, 1976, 1962, 1946, and 1932. The high and low runoff periods correspond well to weak and strong Southern Oscillation, respectively, in all of California. Again, this indicates that variations of California runoff on decadal time scale, but not on annual time scale, correlate well with ENSO pattern. On such time scale (decadal), the study of ENSO may not be limited in southern California. In addition, the streamflow intensity during the high runoff periods reveals different spatial patterns, which are similar to the precipitation patterns. The temporal and spatial vari-

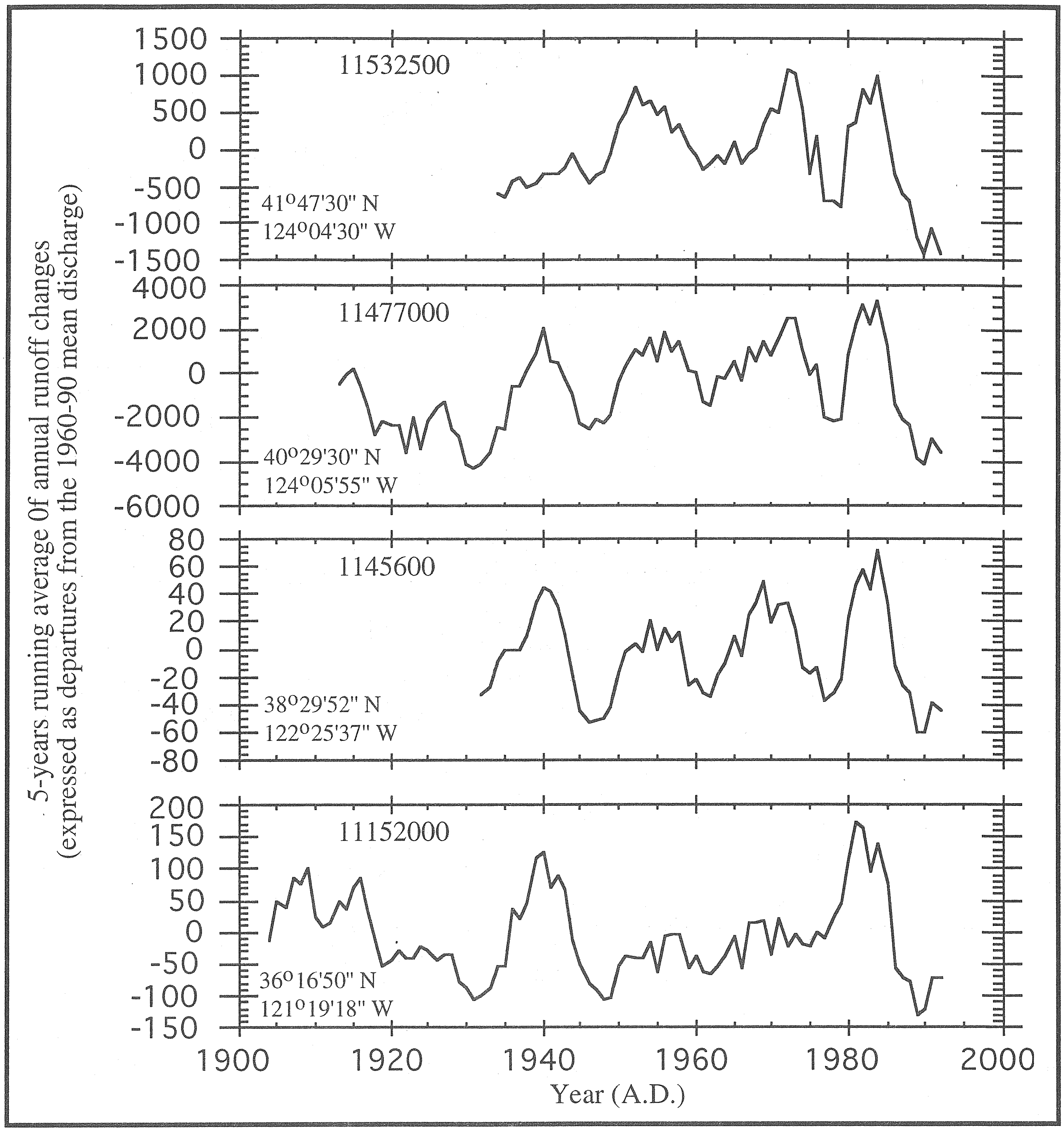


Figure 4 . Temporal and spatial variations in streamflow in the coastal area of California.
Stations are plotted from north to south.

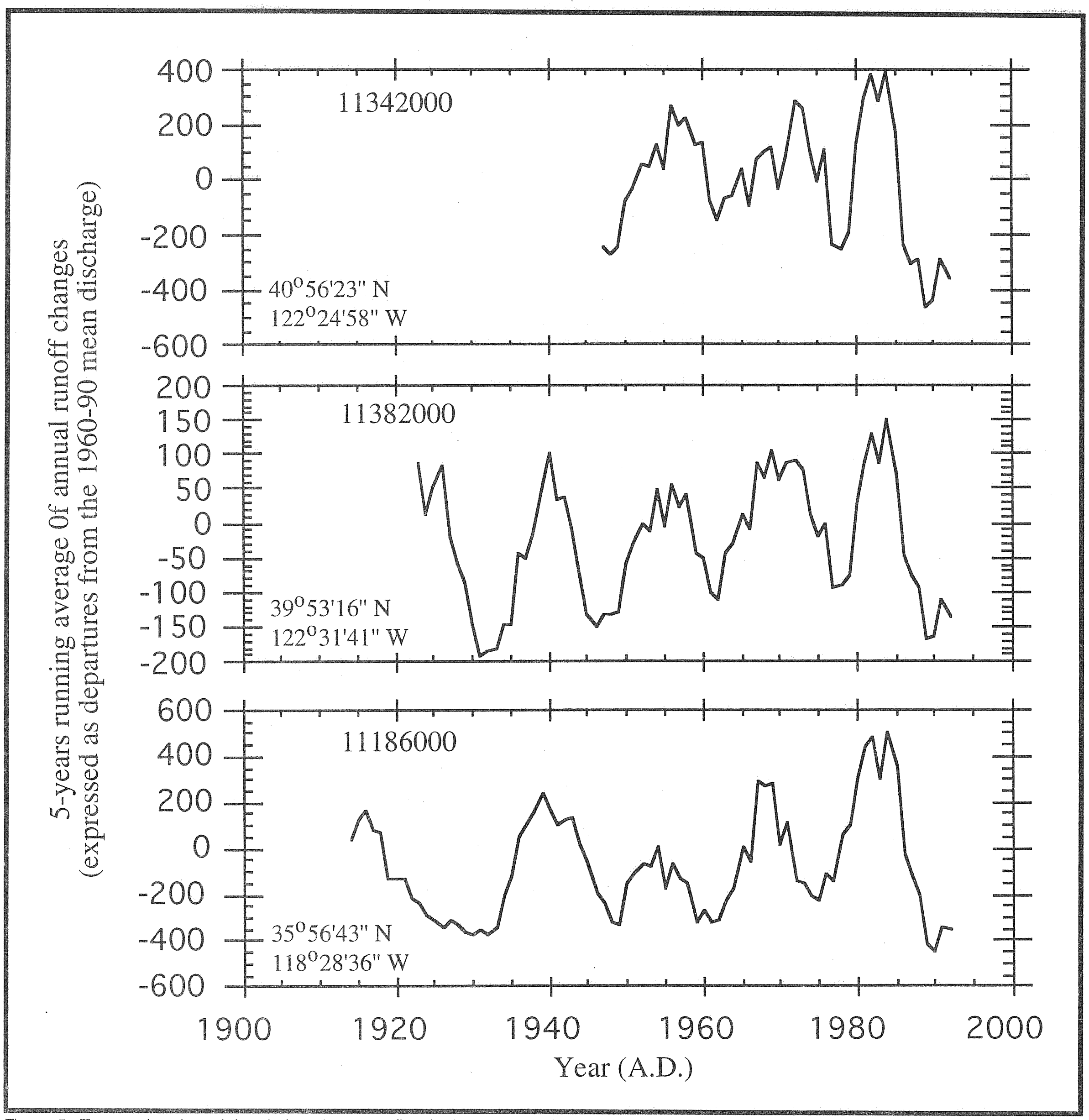


Figure 5 . Temporal and spatial variations in streamflow in the central valley of California.

Stations are plotted from north to south.

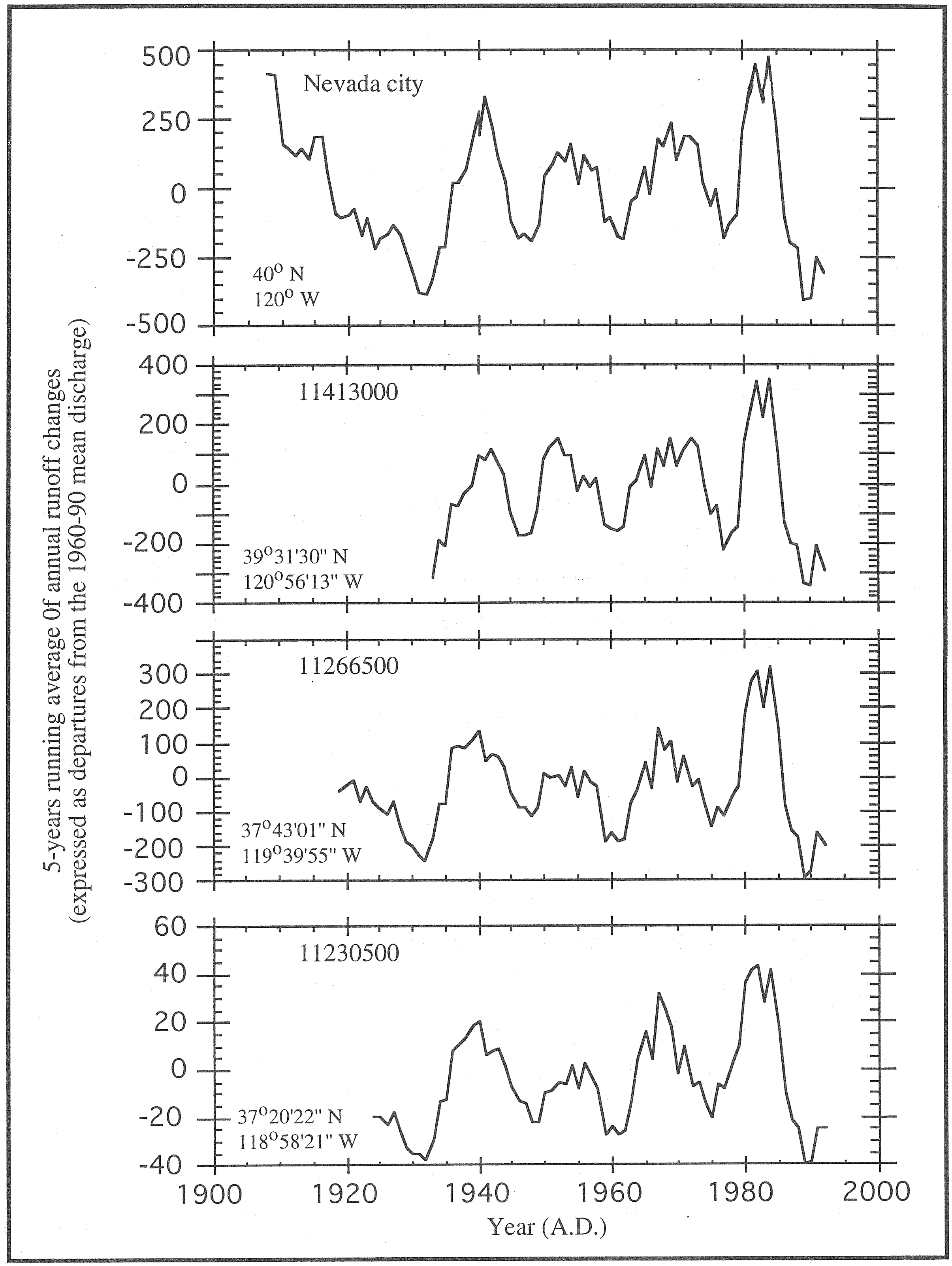
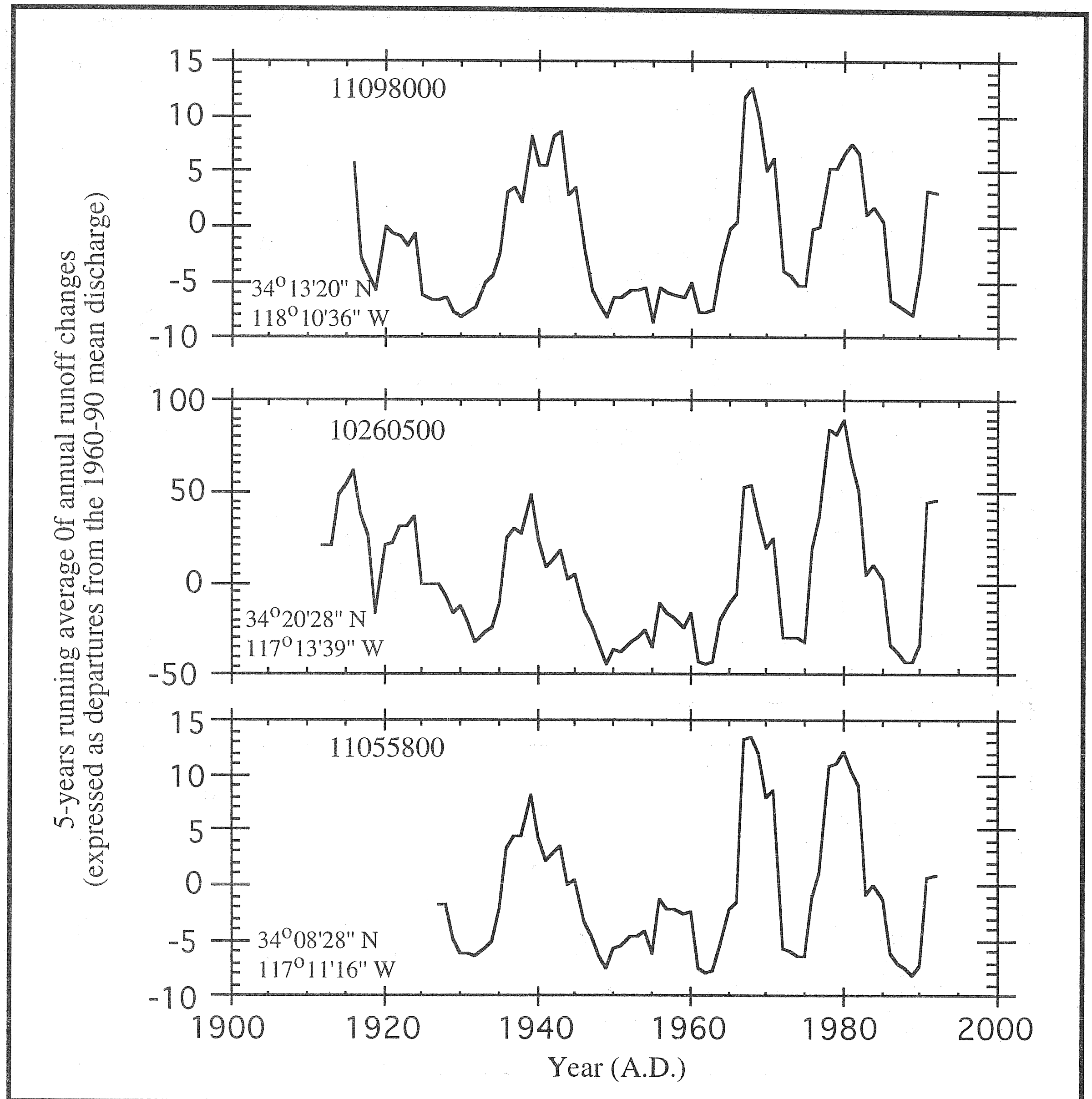


Figure 6. Temporal and spatial variations in streamflow in the mountain area of California.

Stations are plotted from north to south.



.Figure 7. Temporal and spatial variations in streamflow in the Los Angeles Basin of California.

Stations are plotted from west to east.

ations of California runoff can also be explained by the north-south and up-down shifts of polar and subtropic jet streams illustrated in Figure 3.

Runoff variations in the Los Angeles Basin and southern desert area of California are somewhat different from other regions (Figure 7). Precipitation in this region can be strongly influenced by southeasterly flow governed by the summer monsoon. Strong runoff in 1969 and 1993 recorded by gauging stations in this region may indicate the strengthening of the summer monsoon.

Lake Level Fluctuation and Anomalies of Streamflow and Precipitation

Fluctuations in lake level and volume of closed-basin lakes should serve to indicate changes in the moisture budget associated with climatic change. Water entering closed-basin lakes via rain and runoff mostly leaves by evaporation. As evaporation is highly temperature dependent, one may surmise that relatively constant average annual temperature imparts little to the runoff fluctuation. Hence, changes in the effective wetness (P-E) mainly reflect changes in precipitation on interannual-to-decadal time scales.

The level and volume fluctuations of a closed-basin lake can be recorded by the $\delta^{18}O$ of authigenic carbonates in lake sediments that is in equilibrium with the $\delta^{18}O$ of lake water. The lake $\delta^{18}O$ of a closed-basin lake gets progressively heavier as evaporation proceeds. Thus, $\delta^{18}O$ of input water is always lighter than that of the lake water. When precipitation rate increases in a closed basin, runoff and lake storage in the basin will increase and the lake $\delta^{18}O$ will be depleted. We have made high-resolution $\delta^{18}O$ measurements on the sediments of Mono Lake, a hypersaline, alkaline closed-basin lake at the eastern base of the California Sierra Nevada. The $\delta^{18}O$ record simulates the measured lake-level fluctuations rather well. From the comparison of the Mono Lake $\delta^{18}O$ record with the precipitation and streamflow records in the vicinity (Figure 8), one can see that closed-basin lake sediment $\delta^{18}O$ of relatively small lakes such as Mono Lake provides an effective means of probing decadal precipitation variations in arid-to-semiarid regions. A multi-lake study may enable us to reconstruct decadal variability of ENSO pattern and jet stream shift in the western United States.

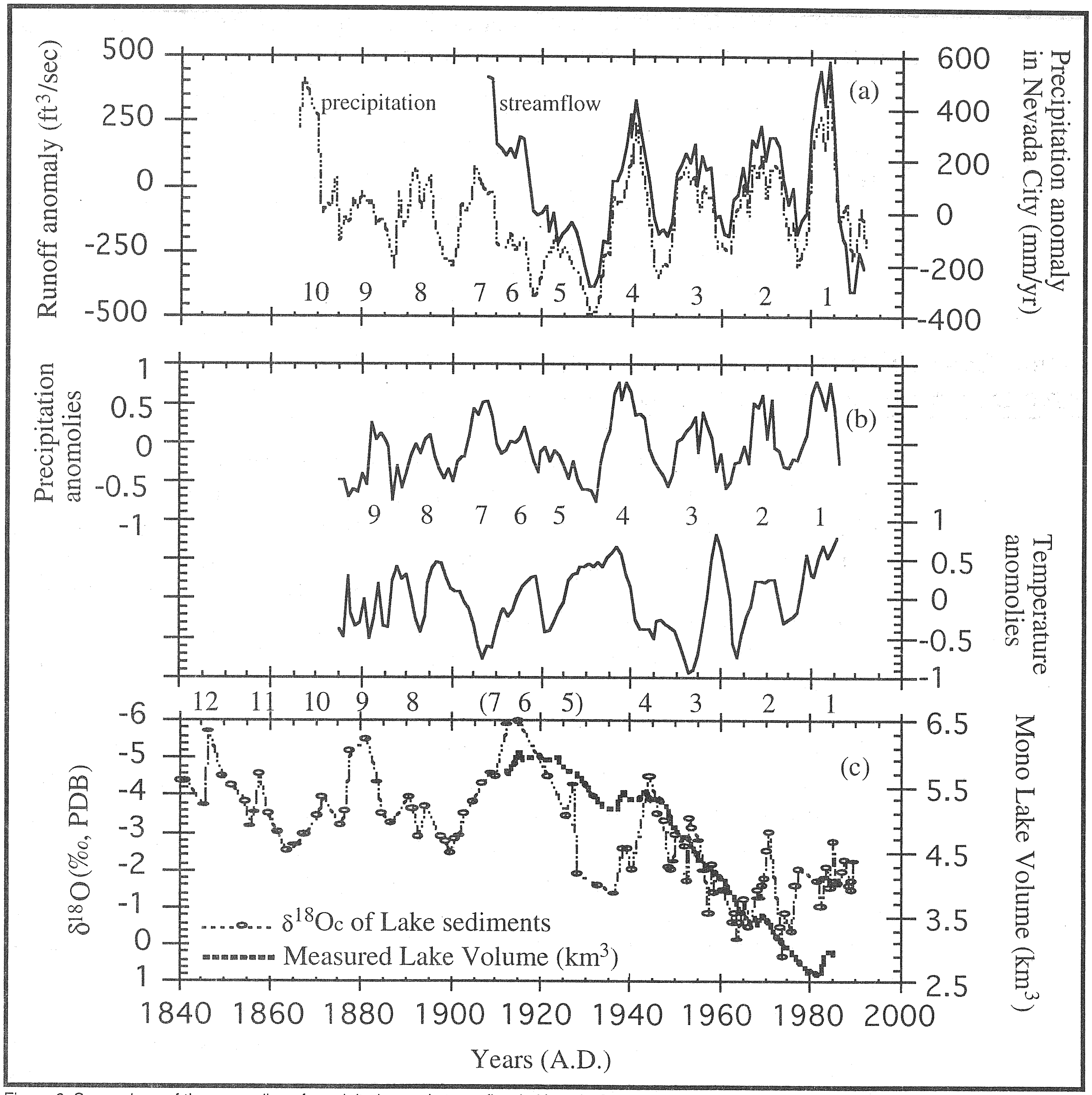


Figure 8. Comparison of the anomalies of precipitation and streamflow in Nevada City, California (top) and precipitation and temperature anomalies in the Central Valley (center) with Mono Lake fluctuations indicated by measured lake volumes and sedimentary $\delta^{18}O$ (bottom).

Summary

The teleconnection of ocean-atmospheric circulation in North Pacific and the west coastal region of the United States involves westerly flow influenced by the Pacific/North America Lows and the Subtropic Highs and southeasterly flow governed by the summer Monsoon. The dominant winter precipitation regime associated with the Jet Stream Westerly exhibits decadal variability. The temporal and spatial variability of the precipitation regime can be explained by the horizontal and vertical shifts in westerly flow. Although causes of the vertical shifts remain unknown, the south-north shifts are probably related to the intensity of the Southern Oscillation. A preliminary assessment shows that variations of California rainfall and runoff on a decadal time scale, but not on an annual time scale, are strongly correlated with ENSO. Positive SOI may cause the jet stream westerly to shift north more than normal, hence the northwestern coast is wet and the southwestern coast is dry, and vice versa. Both up and down shifts in westerly flow occur during very weak Southern Oscillation periods. This vertical shift controls a broad region of precipitation anomaly.

Streamflow anomalies in California are strongly correlated with precipitation anomalies in each drainage basin on annual-to-decadal time scales. This means that streamflow anomaly on annual-to-decadal time scales reflects chiefly precipitation change in this arid-semiarid region. The temporal and spatial variations of California runoff can also be explained by the north-south and up-down shifts of jet stream westerlies. However, strong runoff in 1969 and 1993 recorded by gauging stations in the Los Angeles Basin and the desert area of California may indicate strengthening of the summer monsoon.

Closed-basin lake sediment $\delta^{18}O$ of relatively small lakes such as Mono Lake provides an effective means of probing decadal precipitation variations in arid-to-semiarid regions. Multi-lake study may be used to reconstruct decadal variability of ENSO pattern and jet stream shift in the western United States.

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