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DECADE-SCALE HYDROCLIMATIC FORCING OF GROUND-WATER LEVELS IN THE CENTRAL GREAT BASIN, EASTERN NEVADA

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ABSTRACT: Ground-water levels in widely scattered wells in nearly pristine aquifers of the central Great Basin have risen significantly since the 1960s. The levels reflect a general filling of the basin-fill aquifers during recent wetter-than-normal conditions following drier-than-normal and near-normal conditions between the 1920s and 1950s. Surprisingly, the recent water-level rise has reflected mostly variations in summertime precipitation. These variations in precipitation have been forced by long-term shifts in summertime atmospheric circulations that increasingly have supported the inflow of moisture and less stable atmospheric conditions over Nevada beginning in the 1960s. The aquifers of the Great Basin have acted as natural filters to accentuate these relatively weak, decade-scale climate variations.
KEY TERMS: Hydroclimatology; ground water levels; precipitation; Nevada.

INTRODUCTION

The U.S. Geological Survey (USGS), in cooperation with Nevada state and local agencies, has measured ground-water levels in selected wells in Eastern Nevada since the 1960s. Most of the wells in this area penetrate consolidated to weakly consolidated deposits of gravel, sand, silt, and clay which partly fill the structural basins of the region and which derive from adjacent mountains. Most are located far from significant aquifer developments. One well has been measured nearly monthly for the last 35 years, whereas the others have been measured seasonally or annually. Together, these measurements provide a unique perspective on long-term climatic variations that have affected the hydrology of this part of the western United States.

LONG-TERM GROUND-WATER VARIABILITY

Ground-water levels in at least five widely scattered wells in eastern Nevada (Figure 1) gradually have risen between 2 and 4 m since the early 1960s. The Steptoe Valley well near Steptoe (USGS ground-water site 393310114475001, Well A in Figure 1) has the richest record of ground-water levels in the region: levels were measured intermittently in 1918, 1936, and 1949-59, nearly monthly during 1960-

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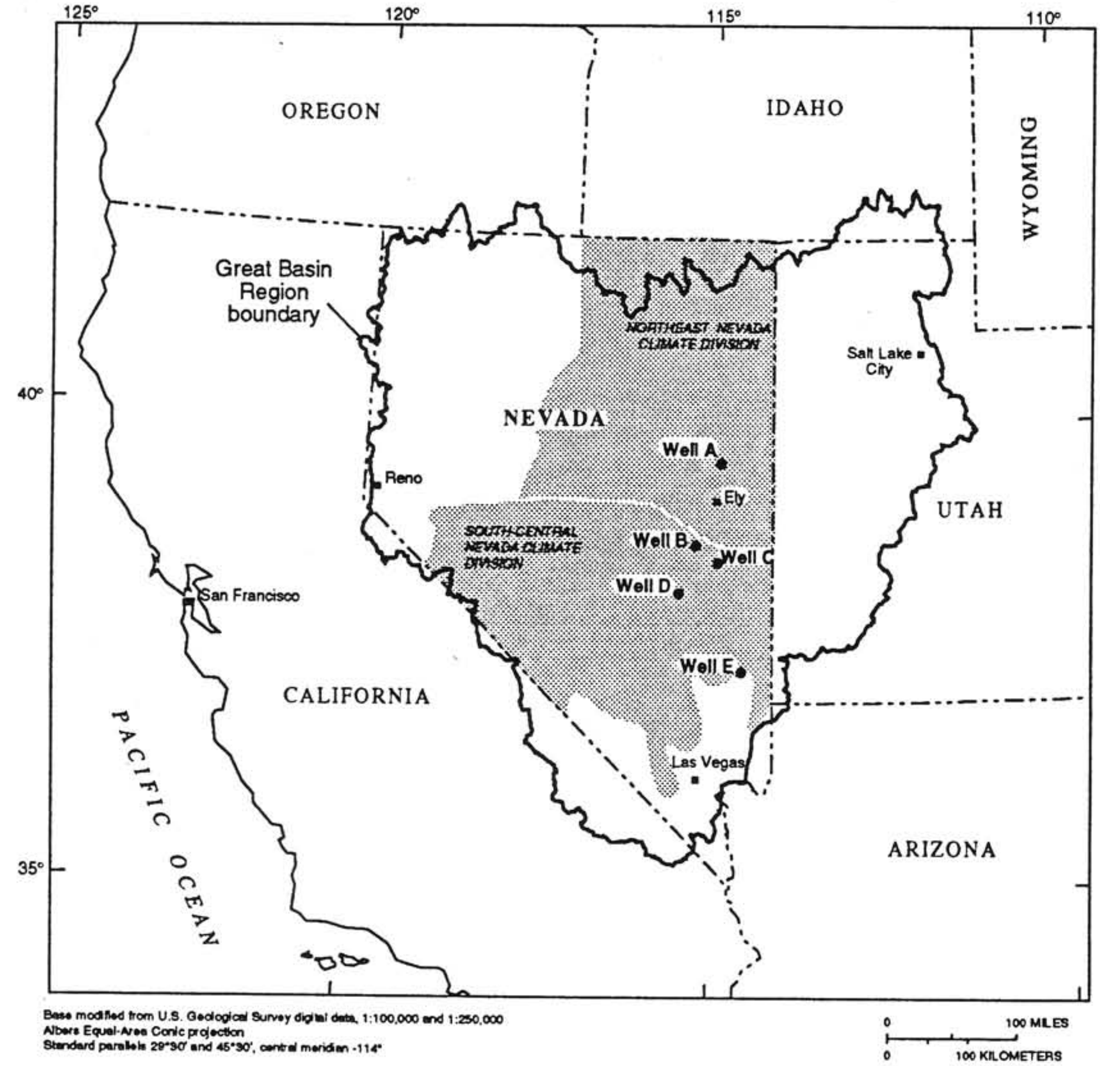
83,and continuously since 1983. The well was drilled and cased to a depth of 165 m by the USGS in 1918 (Clark and Riddell, 1920) and it still serves as a remarkable indicator of natural ground-water level variability in the high and relatively cool central Great Basin. The aquifers of Steptoe Valley are only modestly developed for agricultural and domestic uses; pumpage is about 4 million m^3 yr^{-1} (Stetson Engineers, San Rafael, Calif., oral commun., 1994), a small fraction of the estimated natural water budget of 100 million m^3 yr^{-1} (Harrill *et al.*, 1988). The Steptoe Valley well is set apart from even this limited development. As in many surrounding basins, ground-water levels in the basin-fill aquifers of Steptoe Valley rose more-or-less monotonically from 1960 until about 1988 (Figure 2A). This long-term trend amounted to a rise of 2.5 m in the Steptoe Valley, in contrast to an annual ground-water level fluctuation in the well of about 0.5 m from spring (high) to fall (low). Since 1988, levels have declined by 0.7 m.

The long-term variability in this well is corroborated as reflecting a regional trend by ground-water levels during the same period in wells in less developed basins to the east and south of Steptoe Valley (Figure 1). Records in these wells are not as complete as that of the Steptoe Valley well, but they show similar trends (Figures 2B-E). Although its record is short, intense observations at Cave Valley well since 1983 also have shown that, as in the Steptoe Valley well, the long-term water-level rise is considerably larger than annual fluctuations (Figure 2C). Water levels in the wells shown in Figures 1 and 2 range from 2 to 70 m below land surface, but all the wells are believed to penetrate water-table aquifers.



Base modified from U.S. Geological Survey digital data, 1:100,000 and 1:250,000
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Figure 1. Locations of Nevada, Great Basin, Two Climate Divisions (shaded), and Selected Wells (A, Steptoe Valley Well; B, Railroad Valley Well; C, Cave Valley Well; D, Garden Valley Well; E, Lower Meadow Valley Wash Well).

The ground-water-level trends in eastern Nevada result from relatively small climatic forcings that are "well tuned" to the low-pass filtering characteristics of the ground-water systems. Because the levels are rising, it is unlikely that the trends are responses to the (minimal) pumping from the aquifers that they penetrate: the pumping presumably would induce water-level declines. The trends also do not reflect a simple trending of precipitation or temperature during the post-1960s era. No statistically significant trends (at 95-percent confidence levels) are detected in the post-1960 climate when Kendall's-tau tests for nonstationarity are applied to monthly, seasonal, or annual temperatures and precipitation totals from the northeastern climate division of Nevada (Figure 1).

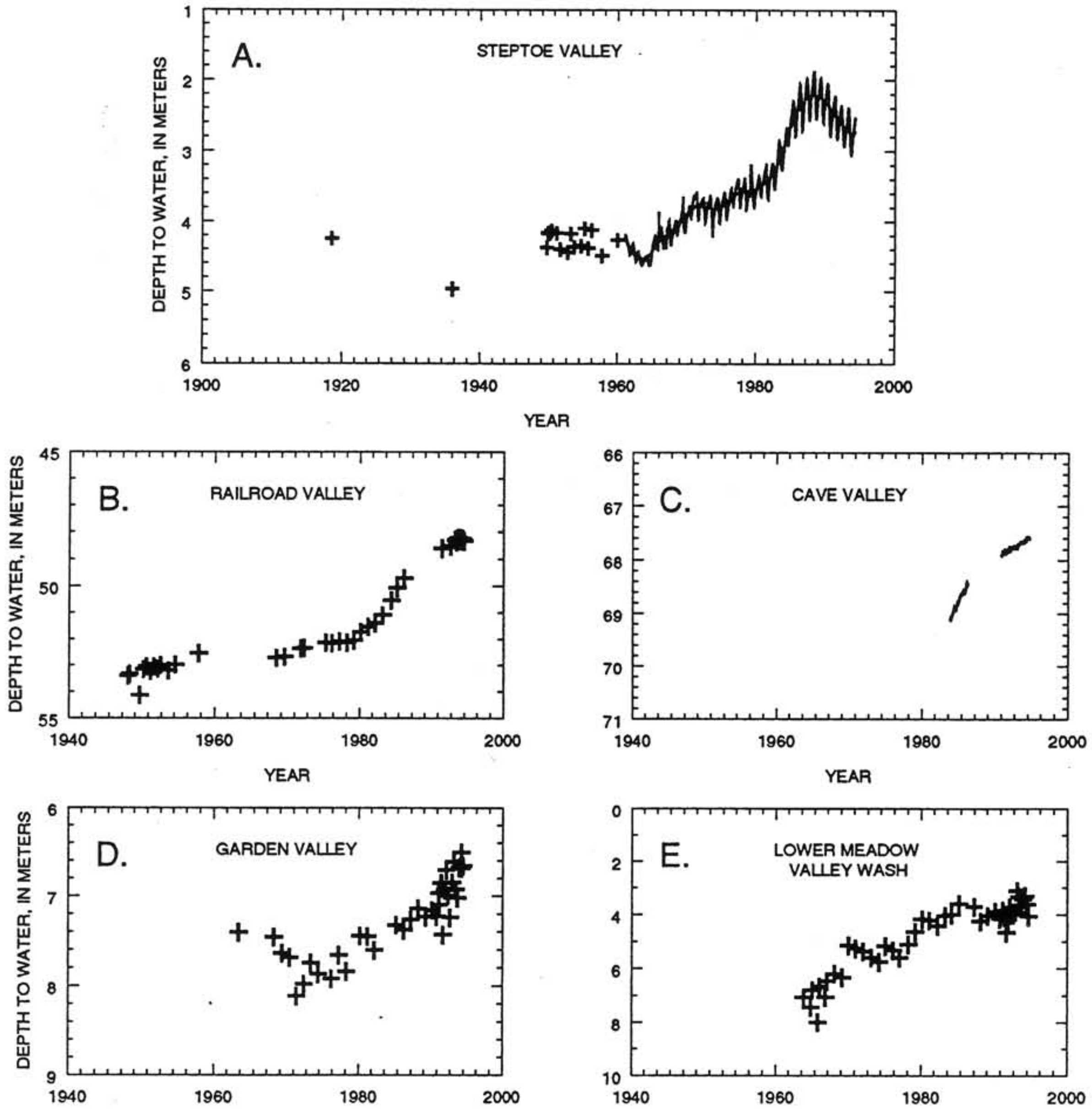

Figure 2. Ground-Water Levels in Five Wells of the Central Great Basin. Panel letters (A-E) correspond to well labels in Figure 1. Crosses indicate intermittent measurements; curves indicate regular (monthly to continuous) measurements.

Instead, the changing ground-water levels closely reflect decade-scale cumulative departures of annual precipitation from the long-term mean. Cumulative departures that were computed from precipitation totals for the northeastern climate division of Nevada are shown in Figure 3A for the period 1900 to 1993, along with cumulative departures for the south-central division of Nevada. The cumulative departure of annual eastern Nevada precipitation increased rapidly between about 1962 and 1972, increased slowly or stalled between 1972 and 1980, increased very rapidly around 1982-1984, and then slowed and declined since about 1987. The ground-water levels in the Steptoe Valley well follow the same trend and are highly correlated with the cumulative departure of annual precipitation when a 1-year ground-water lag is allowed ($\rho = 0.95$).

The cumulative departures of annual precipitation before 1960 include a 30-year period, from about 1930 to 1960, during which the precipitation totals were not sufficiently greater than normal (on average) to recover from precipitation deficits of the late 1920s and 1930s. Cumulative departures of precipitation oscillated around a value of about -50 cm between 1930 and 1960 (Figure 3A). This nearly horizontal part of the plot corresponds to long-term near-mean precipitation totals (just as does the curve for the 20 years from 1900 to 1920). It is from the precipitation deficits between these two periods, the deficits of the late 1920s and 1930s, that the positive-trending cumulative departures since 1960 are finally recovering. The rising ground-water levels probably also correspond to gradual filling of the basins during an extended wetter-than-average period since the 1960s, following the drier-than-average period centered on the 1920s and the prolonged near-average period during the 1930s-1960s.

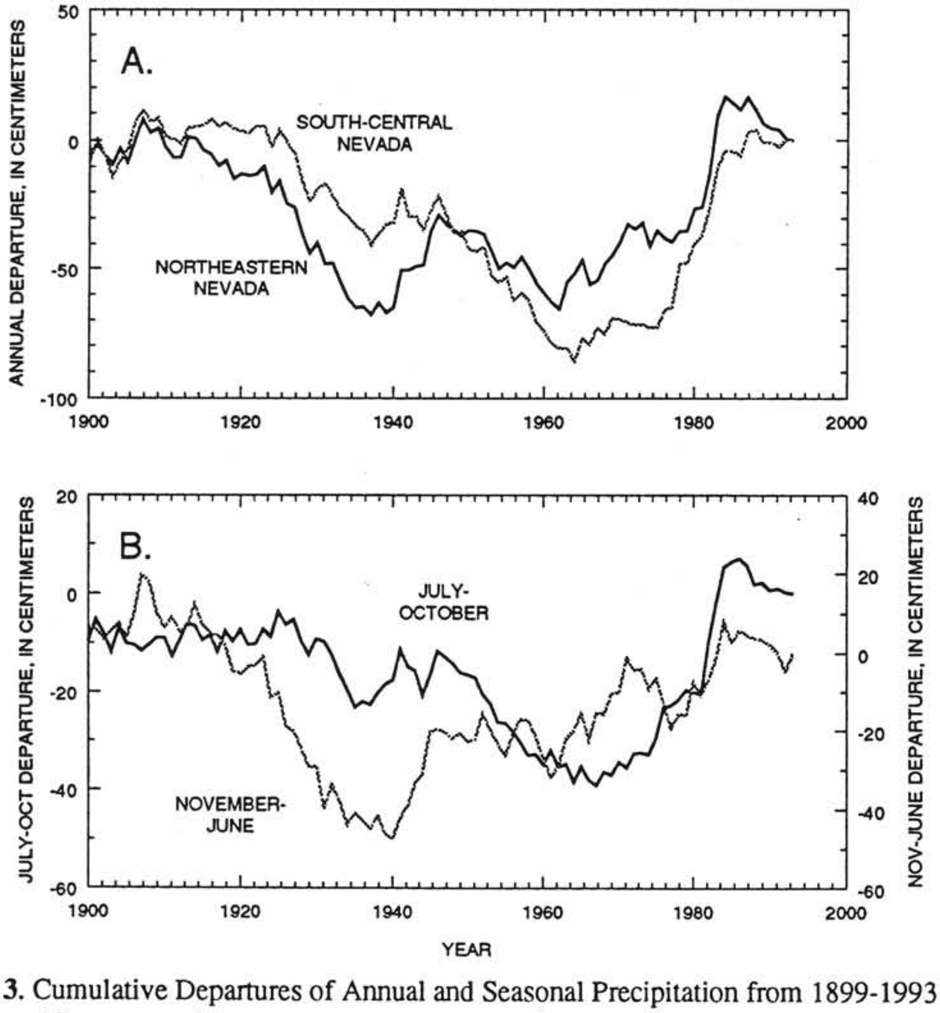

Figure 3. Cumulative Departures of Annual and Seasonal Precipitation from 1899-1993 Means, (A) Annual Departures for Northeastern Nevada Climate Division (solid) and for South-Central Nevada (dotted), (B) July-October Departures for Northeastern Nevada (solid) and November-June Departures (dotted).

The several wells considered here also reflect regional differences in the cumulative departure curves. Much of the recovery of cumulative departures in eastern Nevada occurred during the remarkably wet El Niño year of 1982-83. The volume of water in the Great Salt Lake, to the northeast in Utah, has experienced similar trends (Arnow and Stephens, 1990). In contrast, the effect of 1982-83 on the cumulative departures of annual precipitation for south-central Nevada (dotted curve in Figure 3A) was more subtle. The longer cumulative-precipitation rise during the late 1970s and early 1980s in the south probably explains less dramatic water-level rises during this period in the southernmost wells considered here (Figures 2D and 2E).

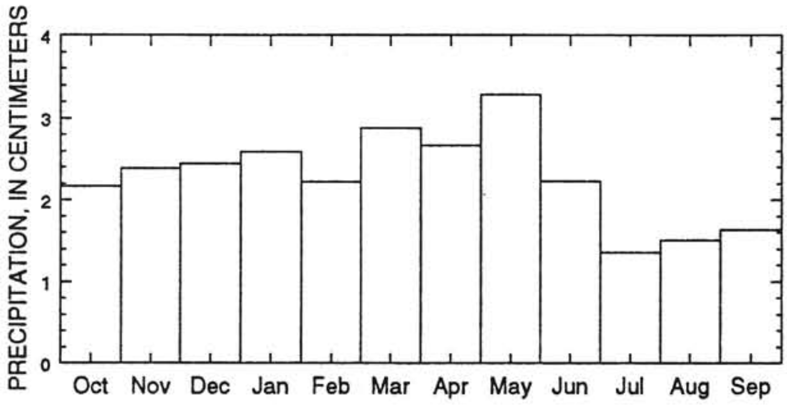

Figure 4. Mean Monthly Precipitation Rates, 1899-1993, Northeastern Nevada Climate Division.

Precipitation occurs mostly during the cool months in eastern Nevada (Figure 4); only 20 percent occurs during the July through October warm season. Surprisingly then, the shape of the cumulative-departure curve for annual precipitation since about 1950 (and also the ground-water-level trend) reflects mostly the cumulative departures of summer-precipitation totals from their long-term mean (solid curve, Figure 3B). The correlation between 1960-1993 cumulative departures of summer precipitation and the ground-water levels of the Steptoe Valley well is 0.94, despite the summer minimum in precipitation typical of this region. The recent correspondence between summer and annual cumulative departures from mean precipitation also is recognizable, amidst much more year-to-year scatter, in streamflows (not shown in figures here) of Lamoille Creek, nearby to the north. A more subtle trend of cumulative departures of precipitation during the rest of the year (November-June) does not correlate well with the ground-water levels (dotted curve, Figure 3B). Also, departures of summer temperatures, hours of sunshine, and pan evaporation (not shown) do not parallel the ground-water levels as closely as does the summer precipitation. The slight plateau in eastern Nevada annual precipitation departures around 1972 is mostly a reflection of the stronger plateau in "cool-season" precipitation departures. Notice, however, that this plateau is much subdued in the ground-water levels, which suggests that, indeed, the ground-water levels have responded preferentially to summer precipitation variability in recent decades.

Ground-water levels mostly have followed cumulative departures of summer precipitation since about 1960, as have the annual cumulative departures. The correspondence between summer and annual cumulative precipitation departures prior to about 1950 is not as striking. Indeed, prior to 1950, the most striking feature of the annual departures curve is the dry period of the 1930s, which mostly reflects dry cool seasons. The occasional measurements (Figure 2B) in the Steptoe Valley well during that earlier period indicate that the water levels were lowest in 1936 and higher, at nearly equal levels, in 1918 and the 1950s. This combination of observations is difficult to interpret but may indicate that the water levels followed the annual precipitation departures (and thus the cool-season departures) during that earlier period. Notice that the cool-season precipitation departures have recovered only recently from the dry

1930s, and thus, some of the recent water-level rise may correspond to recovery from the dry 1920-30s. None of the available ground-water level records, however, include any earlier period with levels as high as at present.

Since about 1960, the ground-water fluctuations preferentially have reflected a subtle, long-term shift from drier summers to wetter summers (on average) during the 1960s. Despite the relatively small contributions of summer precipitation to the water budgets of the Great Basin, the recent shift in summer climatology is the dominant signal in eastern Nevada ground-water levels. Possible reasons for this summer influence may be (i) the low-pass properties of the ground-water systems respond only to the longest term climatic variations, even if they are in summer months, (ii) the input of "extra" water during the summer months has helped directly to fill the aquifers or has increased indirectly the recharge of precipitation from wetter months, (iii) natural discharge from the aquifers was reduced because of cloudier or more humid weather or because more summertime evapotranspiration was supplied by soil-moisture reservoirs instead of shallow aquifers, or, most likely, (iv) some combination of these influences. Notably, the addition of "extra" water alone probably is not the entire explanation, since the "extra" cool-season precipitation in the late 1960s did not cause much water-level response. The response of deep water levels (greater than 50 m to water), however, suggests that changes in natural discharge may not be the entire explanation either. Overall, the ground-water responses seem to reflect some combination of the seasonality and duration of the precipitation anomalies.

ATMOSPHERIC-CIRCULATION CHANGES ASSOCIATED WITH GROUND-WATER FLUCTUATIONS

The shift in summer weather that ground-water levels have followed is, in turn, a reflection of subtle shifts in the population of atmospheric-circulation patterns during the corresponding summers. Short-term and long-term variations in the atmospheric-circulation patterns that influence the hydroclimatology of the western United States have been investigated by many researchers (e.g., Namias, 1978; Weare and Hoeschele, 1983; Klein and Bloom, 1987; Cayan and Peterson, 1989; Webb and Betancourt, 1992; Dettinger and Cayan, 1995) and most have found strong linkages. However, most have addressed wintertime connections because of the important hydrologic role of winter precipitation and because large-scale climatic forces are most influential during winters. Summertime hydroclimatology of the Great Basin has been studied less and is more locally forced.

Variations of summer-mean atmospheric circulations from decade to decade since 1960, however, do show shifts that are consistent with the long-term variations in mean summer precipitation and, thus, with the ground-water fluctuations. The atmospheric-circulation shifts can be illustrated with summertime 700-hPa height anomalies. These anomalies measure the seasonal-mean departures from the long-term mean height of points in the atmosphere at which pressures of 700 hPa (700 millibars) are encountered. Deviations of these constant-pressure surfaces indicate zones of higher or lower pressure, as well as deviations of wind fields and air masses from their long-term mean positions and trajectories.

Connections between 700-hPa height anomalies and local climate are most simply illustrated by maps of the correlation coefficients between local weather variables and the height anomalies over large areas (Klein and Bloom, 1987). Correlations between 700-hPa height anomalies and summer precipitation in northeastern Nevada (Figure 5) show that lower-than-normal pressures over southern Nevada correlate with higher-than-normal precipitation in northeastern Nevada. Height anomalies in the subtropics south of Nevada are positively correlated with precipitation in Nevada. Together, this "dipole" of correlations suggests that the position of the summertime subtropical high-pressure ridge over the southwestern United States (centered on the squares in Figure 5) plays a key role in determining precipitation in Nevada. When the ridge is positioned farther south than normal, the atmosphere over Nevada is less stable and moisture can enter the Great Basin from the west and northwest (Bryson and Hare, 1974) to support more precipitation there. When the ridge is located farther north, moisture is diverted and subsidence of the atmosphere suppresses the formation of precipitation-rich cumulus convection. This dependence of Nevada's summer precipitation on the subtropical ridge is in contrast to the dependence in Arizona, where a northward placement of the ridge allows more "monsoonal" moisture to enter, resulting in increased precipitation (Carleton *et al.*, 1990).

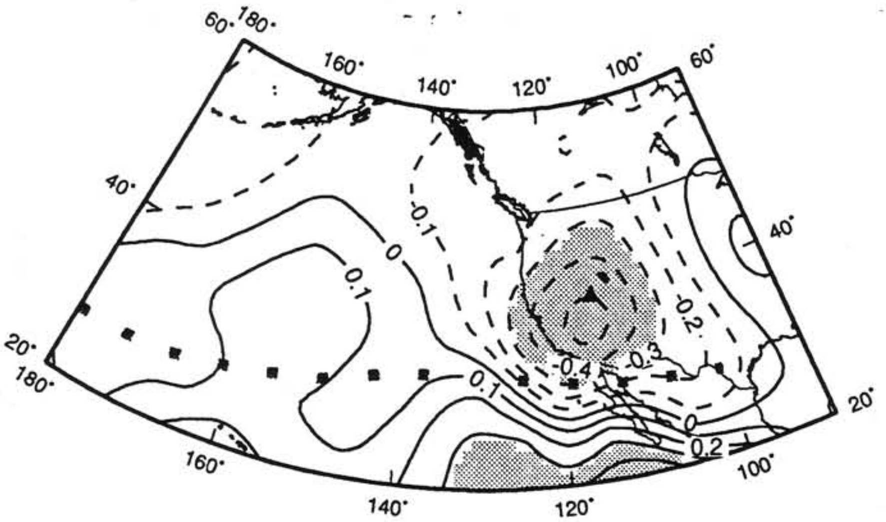

Figure 5. Cross Correlations between July-September Precipitation in Northeastern Nevada and 700-hPa Height Anomalies, 1948-1991. Contour interval, 0.1; dashed where negative and stippled where significantly different from zero at 95-percent confidence level. Triangle shows location of Steptoe Valley well and line of squares near 30°N shows the long-term mean axis of the summertime subtropical high-pressure ridge (Namias, 1979).

Elsewhere, the correlations in Figure 5 are not significantly different from zero at 95-percent confidence levels, which indicates that summer precipitation is determined mostly by local features of the atmospheric circulation. Even the local correlation (about -0.5) is small in magnitude, which illustrates the weak and local relations between summer weather and large-scale circulations. In winter, correlations of |0.8| are common.

Despite the weak summertime relation, the observed decadal fluctuations of summer precipitation owe much to observed decadal changes in the summer circulation patterns. Averaged summer 700-hPa height anomalies over the North Pacific and North America for each decade since the 1950s are shown in Figure 6. Shaded regions have average anomalies that are significantly different from zero at 95-percent confidence levels. In the 1950s, significantly positive height anomalies extended toward southern Nevada from the southeast. The positive anomalies extend into the region of significant negative correlation between height and precipitation (Figure 5); this decadal-average height anomaly is consistent with less summer precipitation in the 1950s and thus decreasing summer-precipitation departures (Figure 3B). During the 1960s, decadal-average height anomalies were not significantly different from zero in the vicinity of Nevada; this lack of significant decadal-scale forcing is consistent with the lack of an overall trend in the summertime cumulative departures during the 1960s. During the 1970s, significantly negative decadal-average height anomalies occurred over all of Nevada, and traces of positive anomalies occurred over the subtropical North Pacific, consistent with greater-than-normal summer precipitation in eastern Nevada. Finally, decadal-average height anomalies in the 1980s were strongly negative over Nevada and positive over the subtropical North Pacific Ocean to the southwest; this pattern is consistent with a southward shift of the subtropical ridge and increased precipitation over Nevada. Thus, the long-term shifts in summertime precipitation that the water levels have reflected are consistent with decade-scale circulation differences.

The same summertime fluctuations of the mean atmospheric circulation have been described by Carleton *et al.* (1990, p. 1011) in Arizona to the southeast as "runs of summers having consistently north-

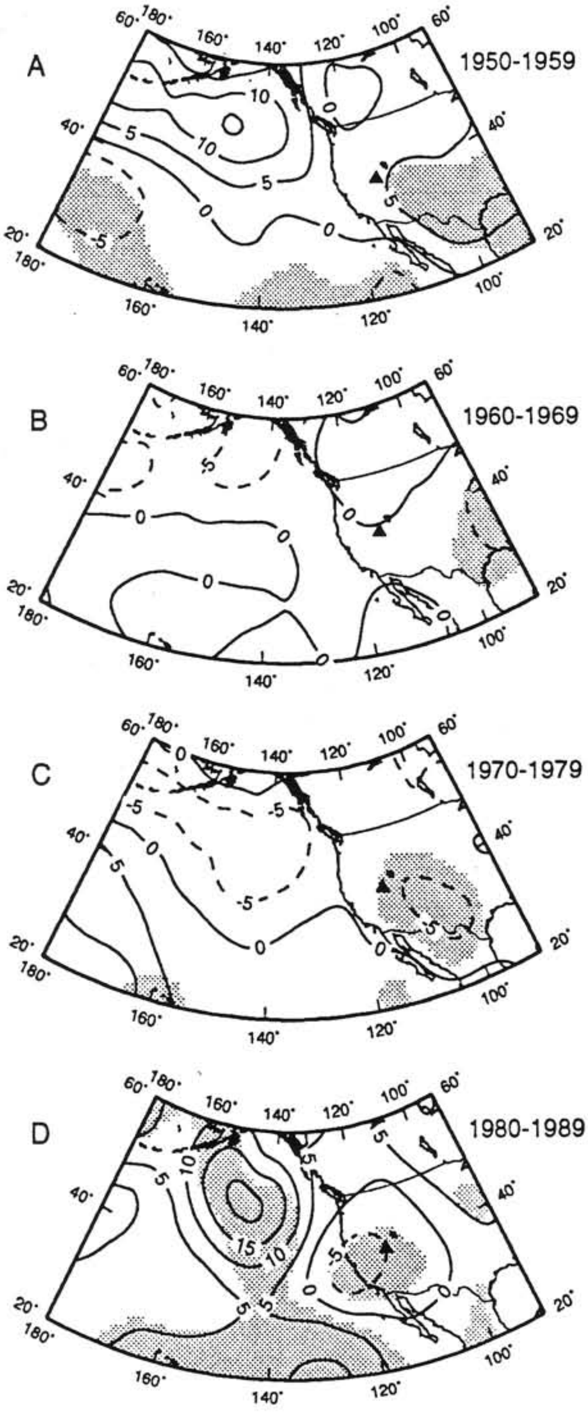

Figure 6. Average 700-hPa Height Anomalies for July-September, (A) 1950-1959, (B) 1960-1969, (B) 1970-1979, (D) 1980-1989. Contour interval, 5 meters; dashed where negative and stippled where significantly different from zero at 95-percent confidence level. Triangles show location of Steptoe Valley well.

ward- (southward-) displaced [subtropical ridge] ... in the 1950s (1970s). Similarly, there has been a tendency in recent decades toward a decrease in [Arizona] summer rainfall." Recent summer-rainfall variability in Arizona has been complicated by increasing rainfall from tropical cyclones that can enter the area when low-pressure centers form over that State, as in the 1970s and 1980s (Hereford and Webb, 1992). These changes in Arizona precipitation differ from those in Nevada but are driven by the same atmospheric fluctuations. Thus, recent decreases in monsoonal rainfall and increases in tropical-cyclone rainfall in Arizona have been tied to increased summer precipitation and rising ground-water levels of the central Great Basin by their common origins in large-scale atmospheric-circulation variations.

SUMMARY AND CONCLUSIONS

Ground-water levels in wells in nearly pristine aquifers of the central Great Basin have been monitored since the 1960s. Water levels in five selected wells have risen significantly during their periods of record. The levels correlate with cumulative departures of annual precipitation from long-term means and appear to reflect a general filling of the basin-fill aquifers during wetter-than-normal conditions, presumably following drier-than-normal and near-normal conditions in the 1920s through 1950s. Surprisingly, the recent water-level rise has reflected variations in summertime precipitation more than the precipitation variations in the remaining months. Summers since the 1960s were wetter on average than summers in several decades before 1960. The response of ground-water levels to this change in "dry-season" precipitation may be (i) a result of the low-frequency nature of the dry-season precipitation variations during the period of record, (ii) a simple reflection of the "extra" water regardless of the season in which it falls, (iii) a result of associated decreases in evapotranspiration of ground water, or (iv) a combination of these influences. The long-term variations in precipitation have been forced by concurrent shifts in summertime atmospheric circulations that have resulted in less stable atmospheric conditions and, possibly, more inflow of moisture over the central Great Basin beginning in the 1960s.

The aquifers of the central Great Basin have acted as natural filters to accentuate these relatively weak, decade-scale climate variations. Aquifers integrate climate variability in much the way that streamflow records reflect local averages of precipitation and temperature (Cayan and Peterson, 1988), but on much longer time scales and, possibly, larger spatial scales. The aquifers of the Great Basin also respond to annual and interannual climatic variations not discussed here. To the extent that they exist and can be identified, long-term observations from wells in relatively undisturbed aquifers can serve as indices of long- and short-term climatic variability in other regions as well. Thus far, however, ground-water levels have been underutilized in analysis of decade-scale climate variations.

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