DECADAL TRENDS IN RUNOFF OVER THE WESTERN UNITED STATES AND LINKS TO PERSISTENT NORTH PACIFIC SEA-SURFACE-TEMPERATURE AND ATMOSPHERIC-CIRCULATION PATTERNS

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Since the late 1940's, amid much interannual variability, snowmelt and runoff have come increasingly early in the water year in many basins of the Western United States.The geographic range of these trends is illustrated in Figure 1 in terms of (a) the fraction of annual runoff occurring during spring months and (b) the fraction of cool-season precipitation remaining on the ground as April 1 snowpack. These properties represent the part of the water supply that is available during the heavy summer demand season.The trends apparently have been driven by warmer winters and springs during the same period, as has occurred, for example, in the Sierra Nevada of California (Figure 2a). The change in surface climate, in turn, was driven most immediately by long-term changes in the mix of wintertime atmospheric-circulation patterns over the North Pacific and North America (Figure 2b). This atmospheric shift may be an expression of midlatitude air-sea interactions that have trended toward certain more-persistent winter sea-surface-temperature (SST) and atmospheric-circulation patterns identified by Namias et al. (1988). Beyond this, there may be tropical ties. Although traditional ENSO indices, such as the Southern Oscillation Index and Niño 3 temperatures, do not contain significant multi-decadal

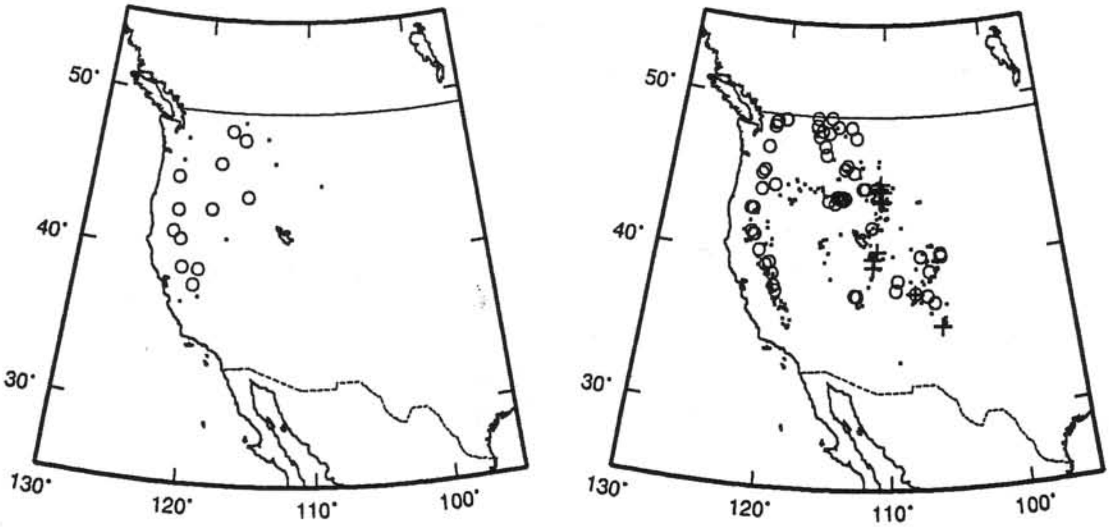

Figure 1.--Significance of trends--from Kendall's-tau statistics--in (a) April-June fraction of annual streamflows, 1948-88, and (b) ratio of April 1 snow course water contents to November-March total precipitation at nearest climate division, 1948-87. Sites with significant ($p<0.05$) increasing trends are marked with '+'; significant decreasing trends with 'o'; and no trends with '.'.

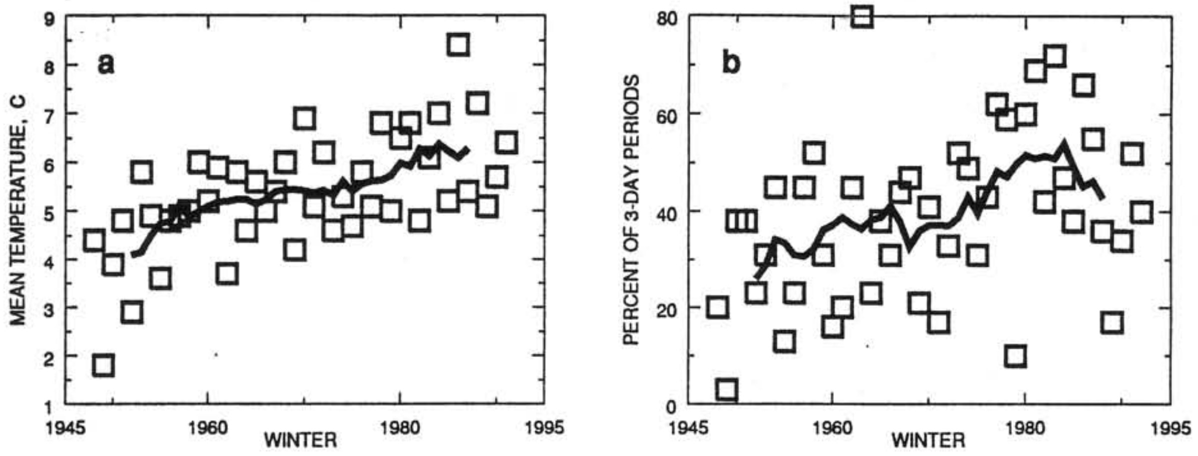

Figure 2.-- (a) January-March mean surface-air temperatures in a regionally averaged Sierra Nevada weather series. (b) Percentage of December-February time spent in circulation patterns categorized as having dominantly southerly (warm) 700-mbar wind components over the Sierra Nevada by principal-components analysis of Dettinger and Cayan (1992). Solid curves are 9-winter moving averages.

trends this century, tropical western Pacific SST anomalies have trended significantly toward warmer temperatures (not shown) beginning at the same time as the runoff trends (mid-1940's).

Month-to-month persistence of SST patterns varies from year to year but shows considerable decadal structure. Overall, pattern persistence, as shown by examination of the average of four lag-one-month pattern correlations, has increased during winters since 1947 (Figure 3). Notice the remarkable string of winters with highly persistent SST patterns during the 1980's; 8 of the 10 winters with the most persistent SST patterns occurred since 1980.

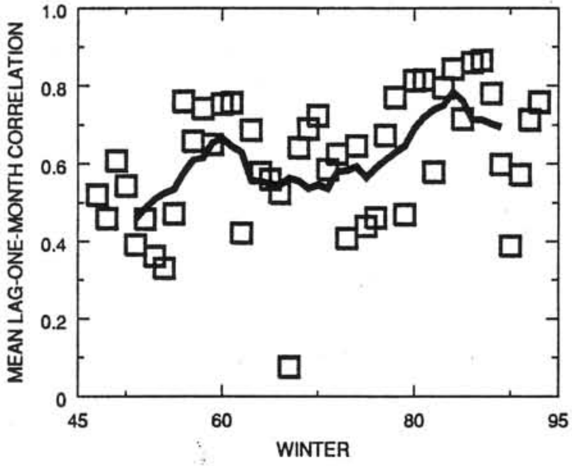

Figure 3.--Average January-May lag-one-month pattern correlations of 5°x5°-gridded sea-surface temperatures, North Pacific Ocean, 1947-93.

The most persistent winter North Pacific SST patterns feature cool water in a zonal band at about 40° N. and warm water off the west coast of North America, a pattern described from pre-1985 data by Namias et al. (1988). These persistent SST patterns usually have coincided with deep Aleutian Low phases of the Pacific-North America atmospheric pattern. Updated calculations of the most persistent SST patterns (Figure 4a), including new SST's for 1985-93, verify the Namias SST pattern, and correspond to the same atmospheric-circulation pattern

(Figure 4b) as before. Note that 4 of the 10 winters included in these composites are from the update period (Figure 3). The same atmospheric pattern also is the most persistent atmosphere condition, although persistent winter SST's and persistent atmospheric patterns have not always coincided. Two pieces of evidence suggest that the association of strong monthly persistence with these particular climatic patterns is robust. First, the average persistent sea-level-pressure patterns (not shown) for 1900-47 and for 1948-92 are remarkably similar. Second, if the 10 most persistent-SST winters prior to the 1980's are averaged, an SST pattern that is similar to but weaker than that shown in Figure 4a is obtained.

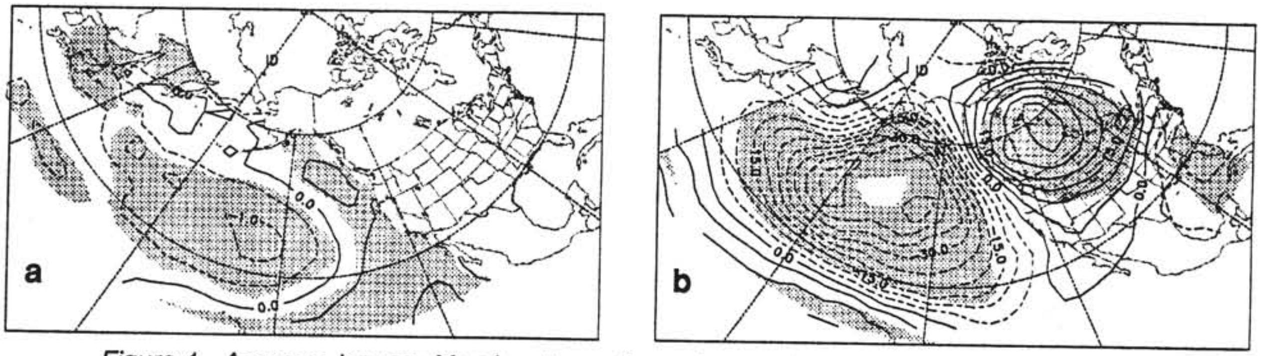

Figure 4.--Average January-March patterns from winters with most persistent sea-surface temperature patterns, 1947-93: (a) deviations of sea-surface-temperature from normal (°C), and (b) deviations of 700-mbar heights from normal (m). Shaded where significantly different from zero at 95-percent level, and dashed where negative. [Winters averaged in (a) were 1956, 78, 80, 81, 83, 84, 86, 87, 88, 93; the same winters--excluding 1993--were averaged for (b).]

The extent to which the persistent SST patterns simply reflect the associated atmospheric-circlation patterns as opposed to somehow favoring those circulation patterns is not clear. On seasonal to decadal scales, extratropical SST probably influences atmospheric circulation. On at least the shorter time scales, however, the dominant influence is in the other direction--that is, atmospheric circulation drives SST. Whatever their causality, the robustness of the patterns associated with persistence found here suggests that they are indeed linked and possibly mutually reinforcing. Because of the robust link between these particular patterns and pattern persistence, the increase in SST persistence is reflected in regional trends of both SST and 700-mbar levels (Figure 5) that echo the persistent SST patterns (Figure 4). These patterns have come to increasingly dominate winter weather in recent decades.

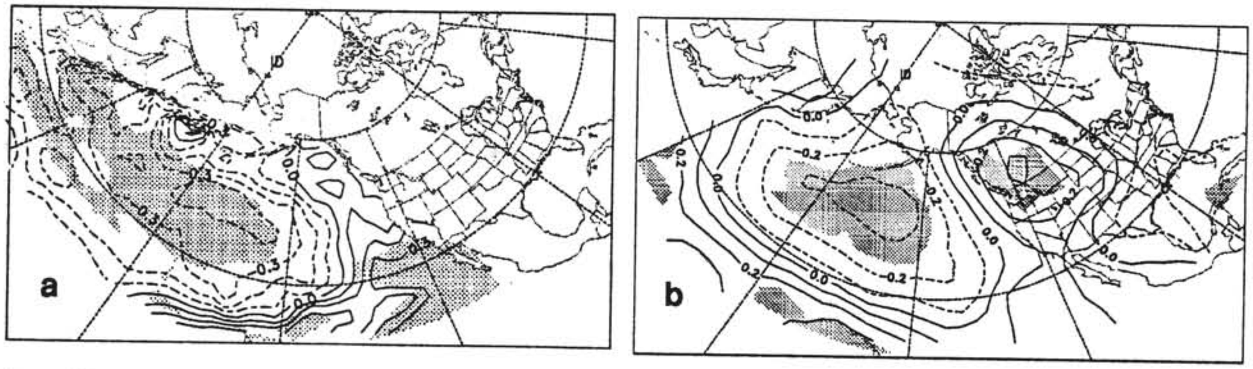

Figure 5.--Kendall's-tau trend-test values for (a) January-March SST anomalies, 1948-92, and (b) January-March 700-mbar height anomalies, 1948-92. Shaded where significantly different from zero at 95-percent level and dashed where negative. Trends computed from 5°-gridded SST and 5°x10° diamond-gridded 700-mbar heights.

The increasing persistence of SST patterns appears to be important to understanding winter weather and water supplies of the Western United States. During winters with the persistent SST patterns and its attendent atmospheric circulation, the frequency of warm-weather circulation pattern is increased in the Western United States (Figure 2a). The atmospheric patterns linked to that increase (Figure 4b) produce warm winters by inhibiting cold outbreaks and increasing subsidence and southerly wind components. (In the Northwest, these patterns also are associated with drier weather.) Thus, the trend toward earlier runoff seems to have been driven by the more frequent occurrence of these patterns. The long persistence of these particular SST patterns may even provide a basis for predicting spring snowpacks in the Northwest (and thus perhaps runoff) using SST's over the North Pacific early in the cool season (Figure 6). A considerable part of the variability of April 1 snow-water contents is reflected already in January SST's at three points in the North Pacific. However, we are uncertain as yet whether the snow variability is decribed by earlier SST's due to (1) influences that the atmospheric patterns associated with the persistent SST conditions exert on concurrent and later snow accumulation or (2) the role of SST's as an integrated measure of atmospheric circulations (and thus regional temperature and precipitation conditions) even earlier in the cool season. Finally, notice that the long-term trends faltered during the late 1980's but may be recovering in the 1990's (Figures 2 and 3).

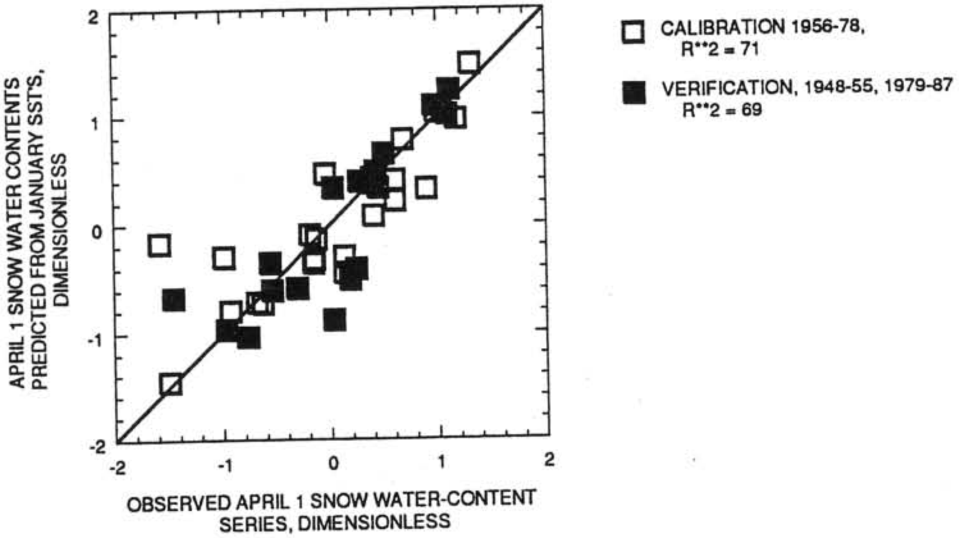

Figure 6.--Observed and predicted April 1 snow-water contents in the northwestern part of the conterminous United States, 1948-87. The observed snow-water content series is the average of standardized observations at 45 snow courses. Predictions were based on a linear regression equation linking January sea-surface temperatures (SST's) at three points in the North Pacific Ocean to the snow-water content series for 1956-78.

REFERENCES

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