Large-Scale Atmospheric Forcing of Recent Trends toward Early Snowmelt Runoff in California

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ABSTRACT

Since the late 1940s, snowmelt and runoff have come increasingly early in the water year in many basins in northern and central California. This subtle trend is most pronounced in moderate-altitude basins, which are sensitive to changes in mean winter temperatures. Such basins have broad areas in which winter temperatures are near enough to freezing that small increases result initially in the formation of less snow and eventually in early snowmelt. In moderate-altitude basins of California, a declining fraction of the annual runoff has come in April–June. This decline has been compensated by increased fractions of runoff at other, mostly earlier, times in the water year.

Weather stations in central California, including the central Sierra Nevada, have shown trends toward warmer winters since the 1940s. A series of regression analyses indicate that runoff timing responds equally to the observed decadal-scale trends in winter temperature and interannual temperature variations of the same magnitude, suggesting that the temperature trend is sufficient to explain the runoff-timing trends. The immediate cause of the trend toward warmer winters in California is a concurrent, long-term fluctuation in winter atmospheric circulations over the North Pacific Ocean and North America that is not immediately distinguishable from natural atmospheric variability. The fluctuation began to affect California in the 1940s, when the region of strongest low-frequency variation of winter circulations shifted to a part of the central North Pacific Ocean that is teleconnected to California temperatures. Since the late 1940s, winter wind fields have been displaced progressively southward over the central North Pacific and northward over the west coast of North America. These shifts in atmospheric circulations are associated with concurrent shifts in both West Coast air temperatures and North Pacific sea surface temperatures.

1. Introduction

The timing of snowmelt runoff from the mountains of California plays almost as great a role in water supply management as does its quantity and quality. As a result of large contributions from snowmelt and a Mediterranean-type climate in which most precipitation occurs during winter, the major rivers of California tend to reach peak flows during late spring or early summer, and minimum flows occur in August and September. Operations of reservoirs, irrigation-supply dispersals, flood-control management, and, more recently, fisheries management all rely to a great extent on this annual "cycle" of runoff. Water managers must balance the long-term need to store water to meet future demands against short-term needs to release water to maintain flows, deliveries, and flood-control capacity (Aguado et al. 1992). Consequently, recent indications that long-term changes in runoff timing are occurring in California have been a source of concern and some debate.

Roos (1987, 1991) observed that the fraction of Sacramento River basin annual runoff occurring during April–July has been decreasing since about 1950. Annual total runoff also may have been increasing, but confidence in this trend was low. Pupacko (1993) noted related trends in two rivers in the Sierra Nevada and found that both runoff amount and runoff variability have increased since the mid-1960s. Pupacko suggested that long-term changes in temperature and precipitation centered on about 1965 may have caused these runoff changes. Wahl (1991) and Aguado et al. (1992) considered a wider range of streams from 10 western states and found that declines in the April–July fractional runoff were common. However, Wahl found no widespread evidence of decreases in April–July runoff volumes, and he concluded that April–July runoff was not necessarily decreasing. Wahl (1992) extended the analysis to other seasons and concluded that decreases in the ratios of April–July flows to annual flows actually

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reflected trends toward more runoff in the remainder of the year.

Hydrologic trends such as those investigated in this paper have been widespread throughout the western United States. For example, significant trends in the fraction of annual streamflow during spring are indicated at 12 of 22 long-term gauging stations shown in Fig. 1a. The broad incidence of these trends in flows that have not been influenced directly by human activities suggests that the trends have a climatic source. The climatic source is indicated also by the trends shown in Fig. 1b, wherein significantly declining ratios of spring snowpack water content to total cold-season precipitation are found throughout the western states. In general, these are not trends toward less *overall* runoff and snowpack (with the notable exception of a region of decreasing flows and snowpack in the northwesternmost states). Rather the trends in Fig. 1 represent changes in runoff and snowmelt timing. Investigated in this paper are the mechanisms that have produced those timing trends, including hydrologic conditions at river-basin scales and atmospheric conditions at scales comparable to the North Pacific Ocean.

To focus this investigation, we examine the trend in runoff timing from the mountains of California. California presents a well-defined region for investigation of these trends and offers a wide range of altitudes to test the role of snowmelt mechanisms in causing the trends. Although extension of the analyses to longer time series, broader areas, and more streams adds to sample sizes and supports more apparent statistical confidence, that confidence is based on an assumption that the runoff from streams throughout the broader western states area must reflect trends in the same way as witnessed in California. This is not necessarily so. For example, the climate of the Pacific Northwest varies differently from the climates of the interior states and also from that of California (e.g., Cayan and Webb 1992), and thus climate-driven trends in runoff timing could vary significantly within the western states. Furthermore, the inclusion of more streams typically has involved inclusion of streams from a broader range of altitudes than those providing runoff to the major California river basins, and streamflow responses to climatic forcing at all timescales depend on the mix of snowmelt and rainfall runoff in total runoff. Similarly, the runoff-timing trend does not need to have been constant or continuous throughout the longest time series available in order to have important consequences today. This paper addresses observed influences of altitude on trends toward earlier runoff in California and the length of time during which those trends have been statistically significant.

In addition, we consider climatological time series representing the mountains of California and address the questions: 1) Are long-term trends present in temperature and precipitation records? 2) If so, are such trends consistent with the runoff-timing trends that have been detected? A trend toward warmer winters or springs would provide a possible explanation for earlier runoff. California has a Mediterranean-type climate; therefore, spring precipitation is low and its influence on runoff timing is less than in many areas. Streamflow, precipitation, and surface air temperature records are examined to determine whether warmer winters occurred (as has been suggested also by Pupacko 1993).

Temperature series from individual sites, however, are subject to long-term changes for many reasons that may not be climatological and that may not drive runoff timing. For example, long-term changes in observed temperatures may arise as a result of changing methods, times, or locations of measurements (Redmond 1992) or as a result of urban heat island or land-use influences (Karl et al. 1988). We therefore also address the question: Are observed trends in winter temperatures in California the result of nearby influences or of larger scale climatic changes? In particular, are the winter temperature trends consistent with long-term shifts in winter circulation patterns of the atmosphere over the North Pacific Ocean and North America?

To answer these questions, the strategy employed in this study is to analyze atmospheric circulation patterns to see if they are consistent with trends toward warmer winter weather in California since the late 1940s. The key in this analysis is the shift to lower pressure in a remote region south of the Aleutian Islands, as well as a regional rise in average pressure over the West Coast. This change is shown to be consistent with large-scale changes in North Pacific sea surface temperatures (SSTs). Observed circulation over much of the North Pacific Ocean and North America is consistent with long-term trends toward early snowmelt, more rain, and less snow during California winters, and, thus, earlier runoff overall. Together, the trends in winter circulation patterns over the North Pacific Ocean and in runoff timing in California provide a good example of how large-scale, long-term climatic fluctuations are expressed in land surface hydrology.

2. Data

Runoff timing and amount are addressed here in terms of streamflow records for the period 1948–91 from five basins in California: the low-altitude Smith River, the medium-altitude North Fork American River, the higher altitude Upper San Joaquin and Carson Rivers, and the "highest" altitude Merced River. Representative altitudes and winter temperatures for these basins are given in Table 1. With the exception of the Upper San Joaquin River, these rivers are all wild or nearly unimpaired above the gauges used in the analysis. The Upper San Joaquin River flows analyzed were corrected for reservoir effects by the California Department of Water Resources. None of the five basins has experienced much development or land-

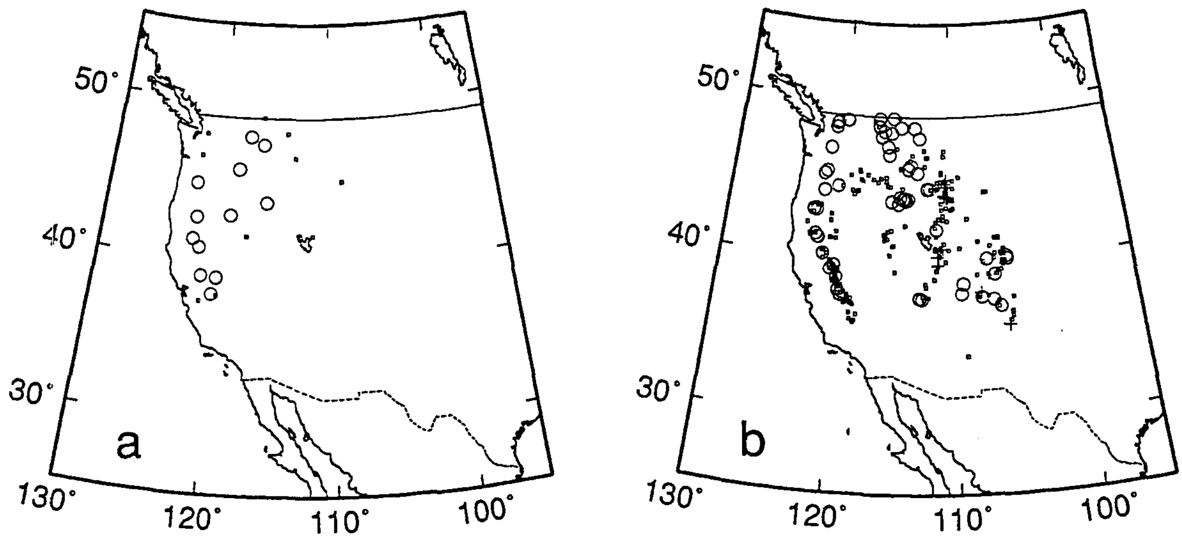

FIG. 1. Significance of trends in (a) April–June fraction of annual streamflows, 1948–88, and (b) ratio of 1 April snowcourse water contents to November–March total precipitation at the nearest climate division, 1948–87. Sites with significant (Kendall's tau with $p < 0.05$) increasing trends are marked with "+"; significant decreasing trends with "O", and no trends with "•". Most of the stations in panel (a) were described by Slack and Landwehr (1992) as being relatively free from confounding human influences such as reservoirs and land-use changes.

use change. Also analyzed is a regional runoff index that is the sum of natural or reconstructed natural monthly streamflows for the period 1906–90 at eight rivers that supply the Sacramento and San Joaquin River basins of California. Together, these two basins constitute the northern three-quarters of the Central Valley of California. The eight rivers summed are the Sacramento, Feather, Yuba, American, Tuolumne, Stanislaus, San Joaquin, and Merced Rivers, and their summed flow is called the eight rivers index (ERI). The ERI represents much of the runoff from the western slope of the Sierra Nevada and was provided by data from the California Department of Water Resources (G. Hester 1992, personal communication). These various rivers are shown, together with the four weather stations employed here, in Fig. 2.

Monthly mean temperature and monthly total precipitation are represented here by the variance-weighted averages of climate records from four long-term (1931–92) climate stations,

$$\bar{x}'_{mn} = \bar{\sigma}_m \sum_{i=1}^{4} x'_{imn}/\sigma_{im}, \quad (1)$$

where $\bar{x}'_{mn}$ is the weighted-average temperature or precipitation anomaly for a particular month m, year n, x'_{imn} is the measured precipitation or temperature anomaly for a single station i during month m, year n, σ_{im} is the monthly standard deviation of station i for months m, and $\bar{\sigma}_m$ is the root mean of variances for months m—$(\sum_{i=1}^{4} \sigma_{im}^2/4)^{1/2}$ (following a procedure from Aguado et al. 1992). The four stations used are all in and near the western slope of the central Sierra Nevada (Fig. 2) and range in altitude from near sea

TABLE 1. Mean altitudes and approximate altitude ranges, in meters above mean sea level, and mean January air temperatures (1913–86) in degrees Celsius for five California river basins (from Cayan and Riddle 1993).

River basin	Mean altitude	Altitude range	January temperature
Smith	457	30–2000	+5.1
American	1433	200–3000	−0.8
San Joaquin	2286	90–4000	−6.1
Carson	2485	1600–3000	−7.3
Merced	2743	1200–4000	−8.9

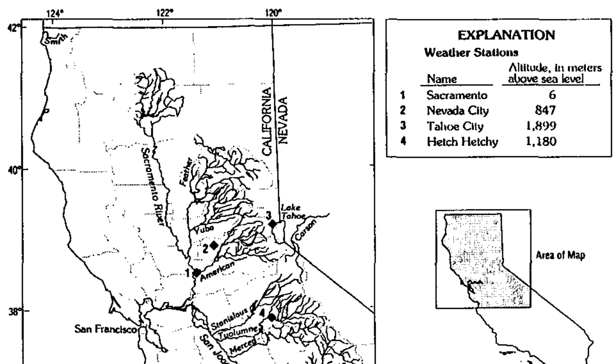

FIG. 2. Locations of selected rivers and weather stations in California.

level to 1900 m above sea level. The resulting weighted-average series represent weather trends in the mountains of central California at about 40°N. Similar winter weather trends are found in records from individual sites elsewhere in the Sierra Nevada.

Recent atmospheric circulation patterns over the North Pacific Ocean and North America are described in terms of monthly 700-mb height anomalies on a 5° diamond grid for 1948–92. For discussion of trends in the context of a longer term, sea level pressures (SLPs) on a 5° grid for 1899–1992 are used. These data were obtained from the National Oceanic and Atmospheric Administration (NOAA) Climate Analysis Center. Given the near-geostrophic conditions of the atmosphere, 700-mb heights describe directions of large-scale winds at about 3 km aloft and SLPs describe large-scale circulations near the surface. SSTs are affected also by atmospheric circulations, and trends in these temperatures provide a useful, independent check for consistency with warmer winters in California. Monthly SSTs for the North Pacific Ocean (20°–60°N) on a complete 5° grid for 1948–92 were employed. Regional average SST anomalies for 10°S–10°N and 140°–180°E and 35°–50°N and 180°–150°W over the period 1899–1993 were obtained from T. Barnett and T. Tubbs, Scripps Institution of Oceanography (Barnett 1989).

3. Methods

The nonparametric Kendall's tau statistic is used extensively in this study to test for the presence of trends (Kendall 1938; Hirsch et al. 1982). The statistic is designed to identify monotonic trends in data that need not be normally distributed. The test is insensitive to individual outliers and missing data values. It cannot distinguish between continuous trends and step changes near the middle of a time series. Furthermore, the test does not determine when a change occurred. The statistic is determined by counting, from each data value in turn, the number of subsequent values that are greater and smaller. If G is the sum of the number of values greater and S is the sum of the number of values smaller (summing over all the combinations counted), then

$$\tau = \frac{(G - S)}{n(n - 1)/2}, \qquad (2)$$

where n is the total number of data values in the series. The statistic τ is $+1$ if all values, counting forward, are larger, and τ is -1 if all values are smaller. If the numbers of larger and smaller values are equal, τ is 0. Kendall showed that if the series statistics are stationary (that is, the statistics are not time dependent), τ is approximately normally distributed with zero mean and variance equal to $(4n + 10)/9n(n - 1)$. With this result, the null hypothesis that the data are identically distributed random values with stationary mean can be tested, with no other assumptions necessary as to their distribution (Press et al. 1989). In simplest terms, τ may be viewed as a nonparametric correlation coefficient between elements of a time series and the corresponding times. In this paper, p levels associated with Kendall's null hypothesis of stationary means will be used to judge the significance of trends in monthly and seasonal runoff, temperature, and precipitation series. The p level is the significance level above which the null hypothesis would have to be rejected (Benjamin and Cornell 1970). Time series of the large-scale, gridded climate data are tested and mapped at p levels less than 5%; that is, those regions wherein τ is significantly different from zero with 95% confidence levels are highlighted.

To permit examination of associations between large-scale circulation trends and weather in California, correlations are computed and mapped between point measurements in the Sierra Nevada and gridded atmospheric series. For clarity, linear correlations are used (Press et al. 1989). Temporal correlations are computed by standard (Pearson's) methods between the point-measurement series (for example, a precipitation series) and the 700-mb height anomalies at each point in the grid, in turn. Then the resulting correlation coefficients are mapped at the grid points to which they correspond. Only correlations that are significantly different from zero at 95% confidence levels are mapped.

Finally, multiple linear regressions are used to identify the association between runoff timing and seasonal precipitation and temperatures. By performing regressions on various subsets of the historical record, we can assess quantitatively the robustness of these associations. Multiple regression methods are described by Draper and Smith (1981). A stepwise form of multiple regression also was used in which independent variables are added successively to the regression according to their contributions to the variance and to their statistical significance (Ryan et al. 1985). Finally, simple linear regressions are used to identify the association between winter temperatures and SLP anomalies.

4. Runoff-timing trends

Trends in runoff timing in California are suggested by the time series of spring (April–June) runoff as a fraction of annual flow in the ERI and the North Fork American River, shown in Figs. 3a–b. In both series, the trend is subtle and is masked by considerable interannual and interdecadal variability. However, in both, the trends between 1948–91 are statistically significant, with a τ of -0.32 ($p = 0.003$) for the ERI and a τ of -0.21 ($p = 0.05$) for the American River. The presence of a trend in the American River (and not just the ERI) is evidence that the trends are naturally occurring or, at least, not an artifact of land-use changes or reservoirs. The ERI incorporates both reconstructed and natural flows (depending on river) and thus could

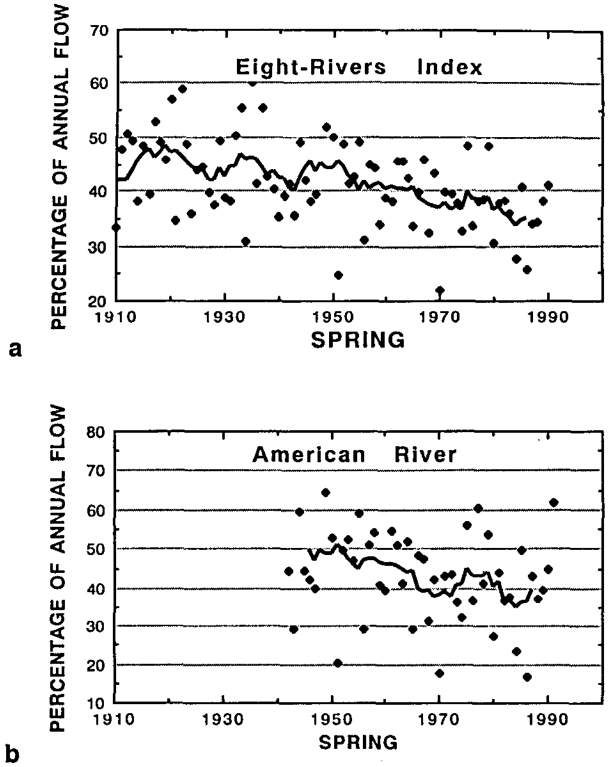

FIG. 3. Spring (April–June) runoff fractions (of annual flow) for (a) the eight rivers index and (b) the North Fork American River. Solid curves are nine-year moving averages.

contain some residual human influences. In contrast, the American River series is for a "wild and scenic" river and thus is free from such influences. Because it is a composite of flows in eight large rivers, the ERI spring fractional runoff is less variable from year to year than that of the American River alone. Thus, the trend toward smaller spring fractional flows also is more evident in the ERI series.

As noted by Roos (1991), the trend toward increasing spring fractions of the ERI seems to have begun in the late 1940s (Fig. 3a). Prior to the 1940s, the 9-yr moving average shown is more oscillatory than trending. To test the variability of the perceived trends, τs and associated p levels were computed over each 30-yr period beginning in 1906 and continuing through 1960 (plotted in Fig. 4a). Small p levels imply greater confidence that a trend is present. The progression of p levels in Fig. 4a shows that, indeed, as measured over 30-year windows, trends in spring runoff fraction have been statistically significant (at $p < 0.05$ levels) only since the mid- to late-1940s. Both earlier and later 30-year periods yield less-significant τs. The p-level variation after the 1940s is an artifact in part of the 30-year window used, and probably represents variations of longer period than the 30-year window, but shorter than the 44-yr window from 1948 to 1991 (which yielded highly significant τs).

As indicated by Figs. 3 and 4, analysis of time series beginning earlier than the late 1940s would not increase the accuracy with which the spring runoff trend is detected because the trend had not yet begun. Consequently, much of this paper will focus on the 45-yr

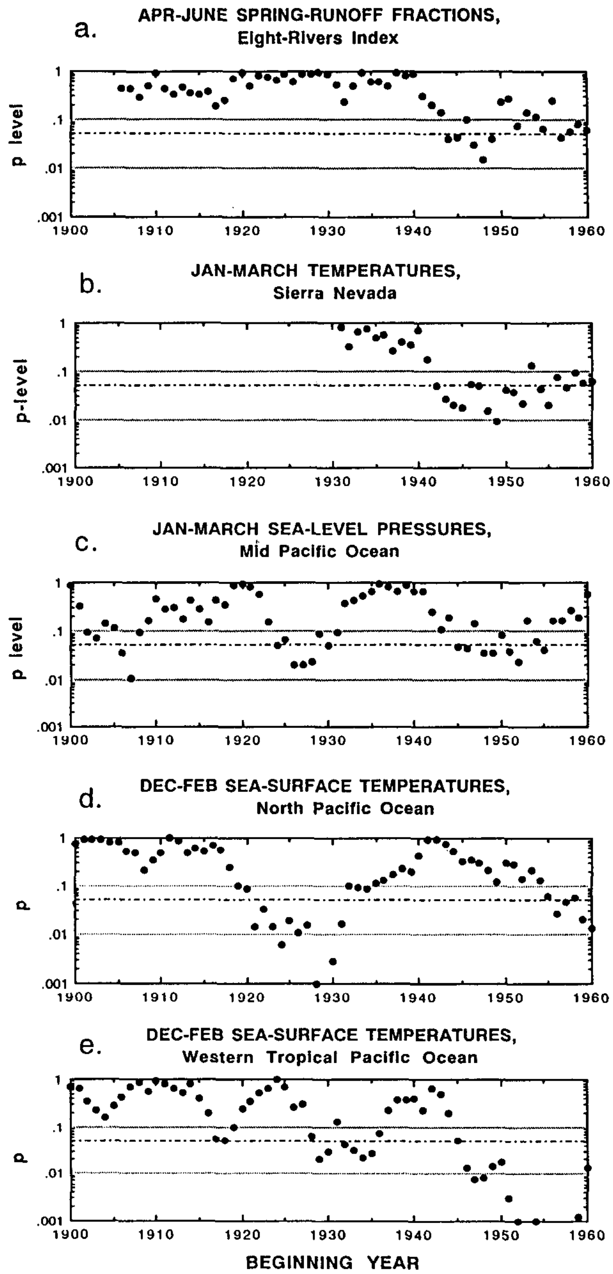

FIG. 4. Significance of trends in 30-yr moving windows of (a) eight rivers index spring runoff fraction, (b) a composite of winter-mean temperatures from central California, (c) winter-mean sea level pressures at 40°N, 160°W, (d) winter-mean sea surface temperatures between 35°–50°N and 180°–150°W, and (e) winter-mean sea surface temperatures between 10°S–10°N and 140°–180°E. Plotted are p levels for null hypothesis of stationary distribution using Kendall's tau statistic. Dot-dashed lines show $p = 0.05$ levels.

period from 1948 to 1992, when the runoff trend was strong and for which gridded 700-mb height fields are available. Later in this paper, the question, "Why did this trend begin when it did?" will be addressed by comparing long-term California temperature and SLP trends over the North Pacific Ocean from the first and second halves of this century.

The late 1940s saw the beginning of trends in streamflow timing throughout the central Sierra Nevada and much of California, as well as trends in winter temperatures (Fig. 4 and discussion in the next section). Kendall's tau values for the fraction of annual flows contributed by each month are shown in Fig. 5 for five streamflow series, along with Kendall's tau values for the total monthly flows in the ERI. In Fig. 5, negative τs imply trends (or swings) toward less of each year's runoff occurring in a given month during the 1948–91 period. Similar trends are suggested when the subperiod 1948–88 is considered, except that two recent years with "Miracle March" periods of extreme late-winter wetness (1989 with 400% of the normal March precipitation and 1991 with more than 200%) tend to amplify March trends in some of the series (as indicated by the reversals from $p < 0.05$ to $p > 0.05$ for the ERI and American River flow fractions when data from 1989–91 are removed from the analysis; see Fig. 5). Trends toward more late-summer fractional flow also are reduced when the 1989–91 period is deleted from the analysis.

No significant trends (at $p < 0.05$ levels) are found in the actual flows of the ERI, but nearly significant trends toward less total flow are suggested throughout the April–July season (especially April) together with a suggestion of increasing March runoff (even without the Miracle Marches). Overall, for annual ERI flows, no significant trend is indicated [τ equal to +0.05 (p = 0.62)]. Similarly, none of the individual streams shown experienced significant annual flow trends during the 1948–91 period. Only the Smith River was close, with τ equal to −0.19 (p = 0.08).

The trend toward decreasing spring fraction of runoff is more evident in the fractional flows shown in Figs. 5b–f. In the ERI, fractional flows during April–June decreased significantly during the 1948–88 period (p = 0.001). March fractional flow increased nearly significantly in the 1948–88 period (p = 0.08). Together with the lack of any annual flow trends, these monthly fractional flow trends imply an increasing shift in timing of runoff toward the earlier part of the water year (1 October–30 September). As indicated, this shift seems to be toward less runoff during spring (as defined by April–June) and more during late winter (and possibly autumn), although the winter and autumn trends are less statistically significant. March runoff gains the most from the spring runoff changes.

Among the individual rivers, differences are observed (Figs. 5c–f) that depend on basin altitudes and temperatures (Table 1). Notice that Figs. 5c–f is organized

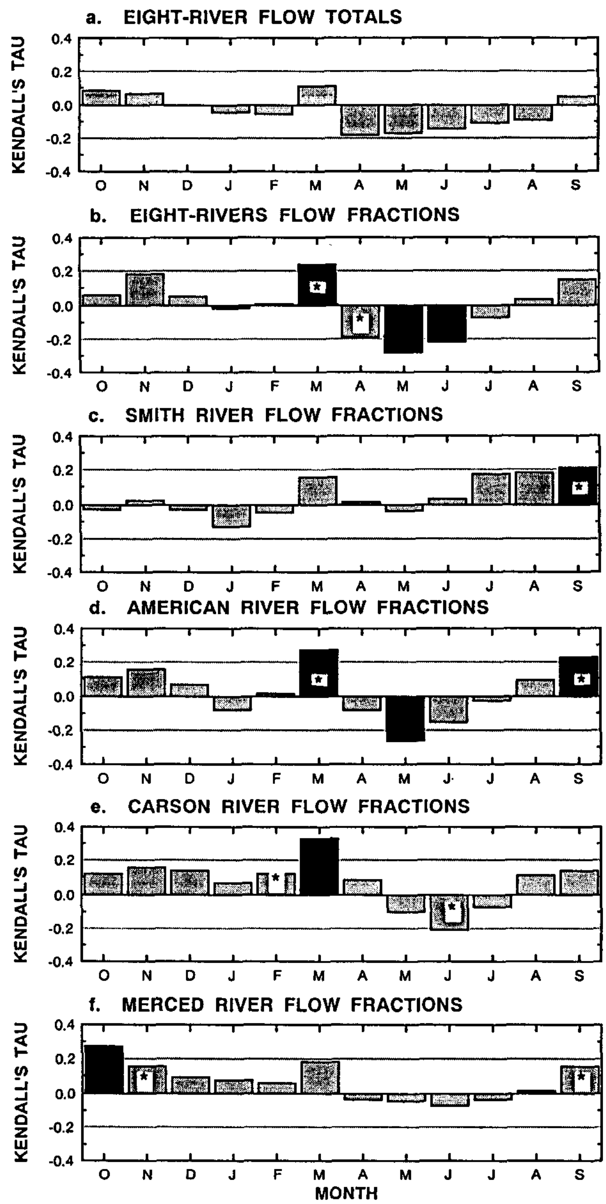

FIG. 5. Kendall's tau values for 1948–91 monthly mean (a) eight rivers index flows, (b) eight rivers index fractions of annual flows, (c) Smith River flow fractions, (d) American River flow fractions, (e) Carson River flow fractions, and (f) Merced River flow fractions. Bars are blackened where significant at $p < 0.05$ levels. Asterisks show where significance is reversed when 1989–91 data are deleted from analysis.

so that the higher, colder basins are placed closer to the bottom of the figure. Relatively significant shifts in runoff timing from the April–June season are indicated for the American and Carson Rivers. Shifts toward more March runoff are significant in the Carson and American Rivers. Winter or spring monthly fractional flows do not yield significant trends for either the Smith River (low altitude) or the Merced River (high altitude). The nearly significant trends toward more March fractional flows in the Smith River shown in Fig. 5c are much reduced when the 1989 and 1991 Miracle Marches are deleted from the analysis. Although not significant at $p < 0.05$ levels, there is a suggestion of increasing autumn and winter flows at the Merced River. Most of the rivers yielded significant trends toward increasing autumn fractional flows. Because autumn flows are minimal, however, the effect is less important (in terms of overall flow) than shifts during winter and spring. Although such changes are small in magnitude and do not influence overall water supplies much, they can be important to the freshwater ecologies of the basins.

To allow comparison of the effects of these trends on the annual hydrographs of rivers at various altitudes, mean monthly fractional runoff hydrographs are shown in Fig. 6 for the Smith, American, and Merced Rivers during the periods 1948–63 and 1978–91 (considering initial and final subsets of the study period). The Smith River is a low-altitude, rainfall runoff-dominated basin, and most streamflow occurs during the wet December–March period, which typically has about 65% of the annual precipitation. In the middle-altitude American River basin, peak runoff is delayed by two to three months, and much runoff derives from snowmelt during winter and spring. In the high-altitude Merced River basin (and Carson River basin), peak runoff is snowpack and snowmelt dominated and is delayed by four to five months relative to the peak precipitation and to the peak runoff in the Smith River. None of these three rivers has reservoirs or land-use changes upstream from their gauging stations.

Because the Smith River basin is at low altitudes throughout and therefore generally is warmer than the other basins, it has little snowpack to contribute to the shape of the annual hydrograph. Runoff shifts in this basin most likely correspond to shifts in precipitation timing or possibly to changing evapotranspiration rates during various times of year. The shift in Smith River runoff timing between the two periods summarized in Fig. 6 corresponds largely to a shift in precipitation timing (not significant at $p < 0.05$ levels, as shown later in Fig. 7) from January toward nonwinter months, especially autumn months. The shift from January runoff is not statistically significant (Fig. 5c) over the 1948–91 period. The significant trend toward more late-summer runoff on the Smith River (Fig. 5c) is not evident in Fig. 6a because the summer runoff is so small. Although late runoff from small increases in March precipitation could have masked decreases in spring runoff due to nearly significant trends toward less April–June precipitation, the Smith River hydrographs overall suggest that the influence of precipitation-timing changes on overall runoff timing has been small.

In the American River (Fig. 6b), a marked April–May snowmelt runoff peak in 1948–63 is replaced by

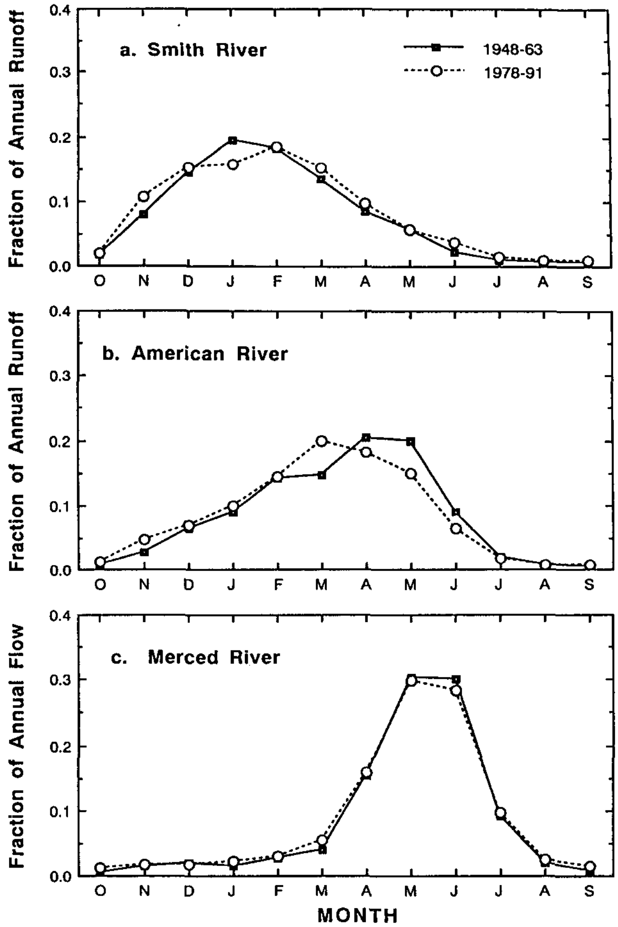

FIG. 6. Mean monthly runoff fractions for water years 1948–63 and 1978–91 in (a) the Smith River, (b) the American River, and (c) the Merced River.

a broader hydrograph with peak runoff in March. The trends toward less May and more March runoff are significant (Fig. 5d), whereas the trends toward less April and June runoff are nearly significant at $p = 0.05$ levels. (However, significance of the March trend depends on inclusion of the Miracle Marches.) Notice that the monthly trends in the ERI shown in Fig. 5b are most similar to those of the American River. Thus, the broad mix of basins contributing to the ERI approximate the response of the medium-altitude American River basin. Warmer winter temperatures could cause earlier snowmelt and thus could account for such a shift in the American River timing. Because we are considering fractional flows only, less late-spring precipitation also could lead to the shifts indicated. However, as noted for the Smith River, the precipitation-timing influence probably has been small.

The change in the average hydrograph of the Merced River between the periods 1948–63 and 1978–91 was much less dramatic than in that of the American River (see Figs. 5f and 6c). The Merced River is fed mostly by high-altitude snowpacks that form early (often by November) and do not melt until early summer. During the cool season, temperatures in most of the basin are far enough below freezing that shifts in timing of precipitation are unlikely to influence runoff timing in this basin, and temperature fluctuations have little hydrologic effect on either precipitation form or snowmelt timing. A shift is suggested (Fig. 6c) toward earlier Merced River runoff within the May–June peak runoff season, which is in keeping with cool-season temperature shifts. The Carson River is on the leeward, rain-shadowed slope of the Sierra Nevada (unlike the others) and its altitude (and temperature) is between those of the American and Merced Rivers. The Carson River shows (Fig. 5e) significant trends toward more early (February–March) runoff and less June runoff (significance of February–March and June trends are dependent on Miracle Marches). Thus, Carson River trends have elements of both the American and Merced fractional runoff trends. Not shown in Fig. 5 are trends for the Upper San Joaquin River, which is on the western slope of the Sierra Nevada and at nearly the same altitude and temperature as the Carson River basin. The monthly trends in runoff in the Upper San Joaquin River are most like those of the Carson River, with October, November, and March fractional flows increasing significantly ($p < 0.05$) during 1948–88, and with June fractional flows decreasing with a τ that is nearly significant ($p = 0.06$). Thus, in California, the runoff-timing trends vary with altitude, presumably reflecting the mean temperatures of the basins.

5. Weather trends

The runoff trends considered in the preceding section could result from winter temperature trends, shifts in precipitation timing, or both. However, weather series from central California, and especially the Sierra Nevada, are more consistent with a trend toward warmer winters than with significant shifts in precipitation timing. Shown in Fig. 7 are τs for 1948–91 monthly precipitation totals, monthly precipitation as fractions of the annual total, and monthly mean temperatures, each based on the composite weather series for the mountains of central California described in the "data" section. The most significant trends (highest τ) are associated with warmer winter temperatures. Nearly significant trends toward drier December–January and April–May conditions also are indicated. Annual precipitation totals show no significant trends (not shown), in keeping with the lack of an annual runoff trend. In contrast, annual mean temperatures have increased significantly ($p < 0.05$) in the composite weather series used here.

A similar analysis for several weather stations on the eastern slope of the Sierra Nevada also show no significant trends in monthly precipitation totals and fractions, except that a significant trend is detected to-

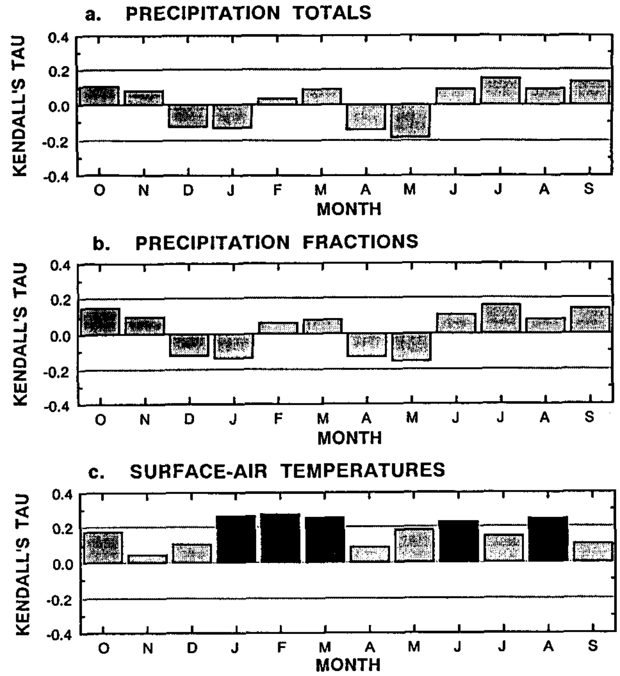

FIG. 7. Kendall's tau values for 1948–91 monthly mean composites of (a) precipitation totals, (b) precipitation fractions of annual total, and (c) mean temperatures in central California. Blackened where significant at $p < 0.05$ levels.

ward increased fractional precipitation during September. Monthly temperature trends were somewhat less pronounced on the eastern slope of the Sierra Nevada during 1948–91. Only the increases in March and August temperatures achieved significance levels of $p < 0.05$. However, the general pattern of τs for monthly temperatures are similar on both sides of the Sierra Nevada (Pupacko 1993).

Winter- (January–March) mean temperatures and spring-mean precipitation fractions for the period 1948–90 on the western slope of the Sierra Nevada are shown in Fig. 8. The trend toward warmer winters there is evident in the time series of January–March temperatures shown in Fig. 8a. Overall, the change in mean winter temperatures seems to be about +2°C between 1949 and 1990. Both the individual winter values and the nine-winter moving average indicate that the warming trend begins in the late 1940s. This impression is corroborated by the p levels of "moving" τs for winter temperatures shown in Fig. 4b. The nearly simultaneous emergence of significant trends toward warmer winter temperatures and decreasing spring runoff fractions shown in Fig. 4 clearly suggest that the two trends are linked. In contrast to the nearly monotonic trend toward warmer winter temperature, spring precipitation fractions are more random during the 1948–91 period (Fig. 8b). However, variations in spring precipitation probably accentuated some of the low spring runoff fractions in the 1970s and 1980s, with several

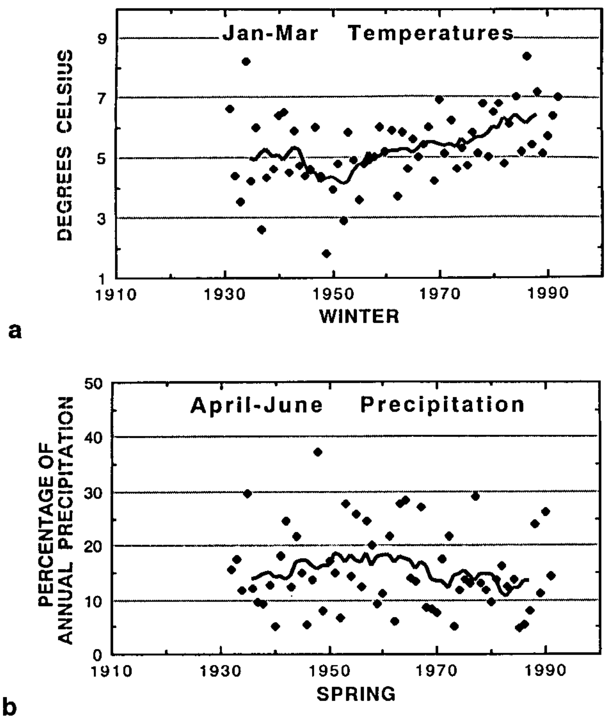

FIG. 8. Time series of composited (a) January–March mean temperatures and (b) April–June precipitation as a fraction of annual total, for central California. Solid curves are nine-year moving averages.

springs receiving less than 10% of annual precipitation during this period. Notice that April and May precipitation fractions yielded negative τs (but with $p > 0.05$) during that period, as shown in Fig. 7.

The interactions of winter temperatures and precipitation timing also help determine runoff timing in individual years. For example, consider the individual years 1969, 1972, and 1986. Both 1969 and 1986 had relatively dry springs (Fig. 8b), but 1969 had a notably cool winter and 1986 had a warm winter. The result was an early runoff in 1986 and a near-normal spring runoff fraction in 1969 (when the temperature and precipitation influences counteracted each other). Both 1972 and 1986 had warm winters, but 1972 had a relatively wet spring and 1986 a relatively dry spring. As noted, the 1986 spring runoff fraction was low, whereas (again due to counteractions) the 1972 spring runoff fraction was near normal. Thus, at timescales from annual to decadal, spring runoff fractions (and runoff timing) in general are not strictly functions of temperatures or precipitation timing. Rather, both are factors that determine runoff timing.

Stepwise linear regressions of the spring runoff fractions in both the ERI and American River help to determine the contributions of seasonal precipitation and temperatures to runoff timing. This technique was applied and discussed in much greater detail by Aguado et al. (1992). For the period 1948–91, winter-mean temperatures, together with spring (April–June) precipitation fractions, explain about 60% of the variability of the spring runoff fraction in the ERI and about 50% of the variability in the American River (both fits are significant at levels well beyond 95% confidence). Inclusion of precipitation fractions from October to December in the regression equations explains another 7% of the variability in the ERI and 15% in the American River. In the ERI, winter temperatures explain almost three times as much variability as spring precipitation fraction; in the American River, winter temperatures explain about two times as much. Winter temperatures are negatively associated with, and spring precipitation is positively associated with, spring runoff fractions in the ERI and American River (as are October–December precipitation fractions when included). The warmer the winter, or the more early warm-season precipitation that falls, the earlier will be the runoff peak and the smaller will be the spring runoff fraction. More spring precipitation contributes directly to a greater spring runoff fraction. In addition, spring-mean precipitation fractions and spring-mean temperatures are significantly correlated ($r = -0.54$), so that the usefulness of spring precipitation as a predictor of spring runoff fraction may reflect both precipitation and temperature influences. [In contrast, winter temperatures and precipitation are virtually uncorrelated ($r = -0.09$).]

Because both winter temperatures and spring runoff fractions have significant trends during the period 1948–91, a potential for spurious correlations existed. That is, any two time series that have linear trends will be correlated whether or not the series are physically related. To determine whether winter temperatures and spring runoff fractions are quantitatively consistent, two additional regression analyses were done. First, in comparison with the period 1948–91, during 1931–47 (which is mostly prior to the trends in runoff timing and winter temperatures in Figs. 4a and 4b), winter temperatures and the spring precipitation fraction explain about 76% of the variability in ERI spring runoff fractions, with most of the "extra" explanatory power (in excess of the 60% explained variance for 1948–91) appearing in the winter temperatures. Notably, the regression coefficient for winter temperatures is $-4.3\%\ °C^{-1}$ for 1931–47 (with a standard deviation of that estimate equal to $0.8\%\ °C^{-1}$) and is $-4.4\%\ °C^{-1}$ for 1948–91 (with a standard deviation of $0.6\%\ °C^{-1}$). Regression coefficients for spring precipitation fraction also are consistent for the two periods. Thus, the regressions identify quantitatively similar relations between winter temperature and spring runoff fraction whether or not the long-term trends are present. Second, returning to the 1948–91 period, the winter temperature series was separated into trend and residual components (by regressing the series against year number). Together, these two components explain the same 42% of ERI spring runoff fraction variability as

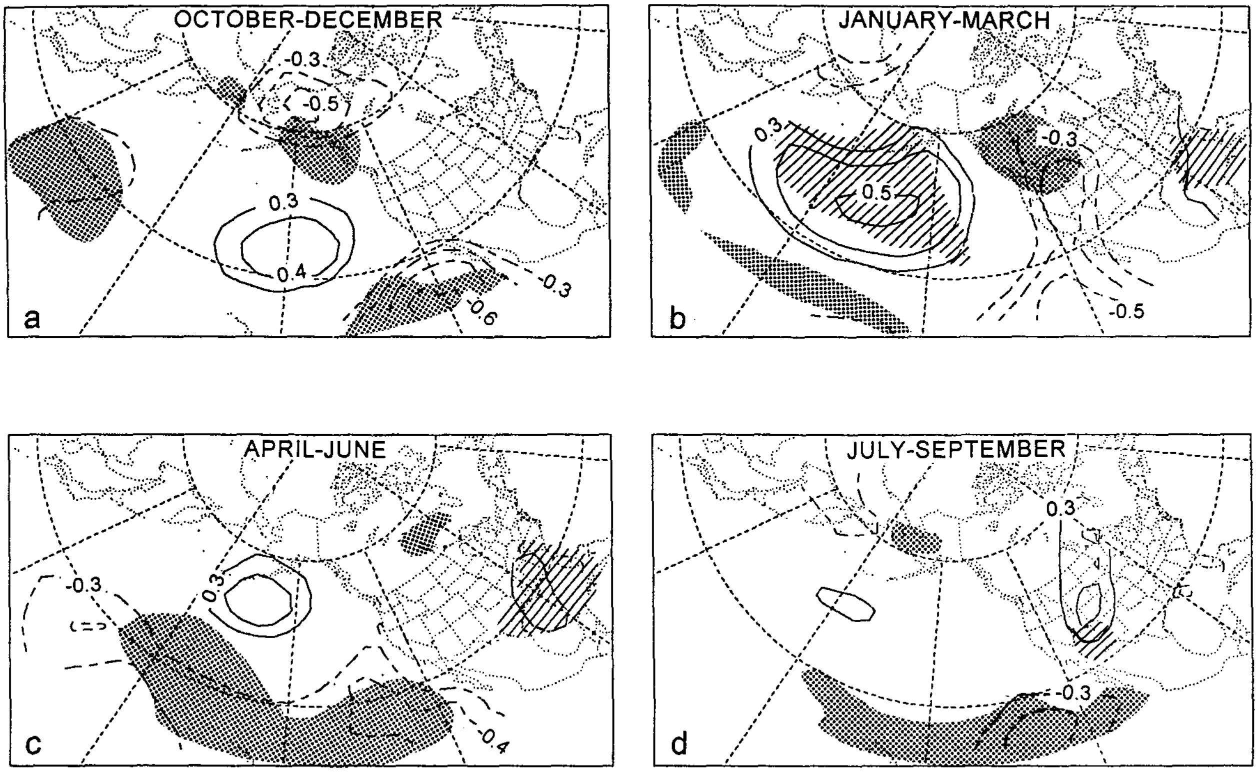

FIG. 9. Regions of significantly trending seasonal 700-mb height anomalies, 1948–91, and contoured correlations between the eight rivers index spring runoff fractions and seasonal 700-mb height anomalies for (a) October–December, (b) January–March, (c) April–June, and (d) July–September. Regions where 700-mb height anomalies have significantly declined (based on $p < 0.05$ Kendall's tau values) are hatched, and regions of significantly increasing anomalies are stippled. Correlations contoured where significantly different from zero at $p < 0.05$.

does the complete winter temperature series. The trend in winter temperatures corresponds to 16% of the variability in spring runoff fractions, and the residual component explains about 25% of that variability. In this case, the regression coefficient for the winter temperature trend is $-4.8\%\ ^{\circ}C^{-1}$ (with a standard deviation of $1.6\%\ ^{\circ}C^{-1}$) and for the residual is $-4.2\%\ ^{\circ}C^{-1}$ (with a standard deviation of $1.1\%\ ^{\circ}C^{-1}$). Once again, with or without the trend, the regressed relations between winter temperatures and spring runoff fraction are similar. Thus, we conclude that the correlations probably are not spurious and that the trends are linked.

6. Atmospheric forcing of trends

Because of the consistency of the linear-regression relations between early versus late periods and between high- versus low-frequency winter temperature and spring runoff fraction variations, it seems unlikely that the relationship between the temperature and runoff-timing trends is a spurious artifact of measurement errors or changes. The two observations are collected and analyzed independently. However, as noted in the introduction, the observed winter temperature trends might arise in response to localized influence such as the development of urban heat island effects. Alternatively, they might be produced by influences from processes at much larger scales such as long-term shifts in atmospheric circulation patterns. While a particular temperature trend may be influenced by localized influences, Wahl (1992), Aguado et al. (1992), and our Fig. 1a show that the runoff-timing trends are widespread in the western United States. Winter temperatures have trended toward warmer values over large parts of the western United States (as suggested by Fig. 1b). At this scale, runoff and temperature trends are driven by large-scale atmospheric circulations. To investigate this response, we therefore searched next for trends in historical climatic series that describe atmospheric circulation patterns at the largest scales. Several previous studies (Douglas et al. 1982; Venrick et al. 1987; Trenberth 1990; Shabbar et al. 1990; Chen et al. 1992) have addressed large shifts in the North Pacific winter circulation and have demonstrated connections to climate changes over western North America. Our search demonstrated that the winter temperature and spring runoff trends were due in large part to a long-term trend in winter climate over the North Pacific Ocean.

a. Atmospheric trends and runoff timing

Significant trends in 700-mb height anomalies for the period 1948–92 by season are shown in Fig. 9. The trend locations shown in the figure are superimposed on patterns of correlation between ERI spring runoff fraction and 700-mb height anomalies. These correlation patterns represent teleconnections between runoff timing in California and atmospheric circulations over the North Pacific Ocean and western North America. The patterns reflect the influence of basin-scale circulations over the North Pacific on weather conditions in California, which in turn drive runoff timing. Kendall's tau values for 700-mb height anomalies within the hatched regions in Fig. 9 range in magnitude from about 0.2 to 0.3. Although Fig. 9 is limited to the North Pacific Ocean and North America, similar trends can be identified in more distant parts of the Northern Hemisphere—most notably, during winters, positive trends over southern Siberia and the Mediterranean Sea. Also, although not significant at $p < 0.05$ levels (and therefore not hatched in Fig. 9), the region of declining 700-mb height anomalies persists over the central North Pacific through the spring and faintly into the summer months. Two facets of the winter (January–March) map stand out: First, the spring runoff fraction is most sensitive to winter contributions (Fig. 9b) by 700-mb height variations over the central North Pacific. Positive correlations and negative 700-mb height trends contributed to decreasing spring runoff fractions. Second, it can be seen that the regions of strongest correlations and strong atmospheric trends over the midlatitudes coincide during winter (Fig. 9b). Increasing 700-mb heights over the subtropics also coincide with strong correlations, especially during spring (Fig. 9c). In the next section, the midlatitude 700-mb trends will be seen to correspond to winter temperature trends in California, whereas the subtropical trends may have forced spring temperature and precipitation influences on the runoff-timing trends.

b. Atmospheric trends and California weather

To understand the effect of large-scale atmospheric circulation conditions on California runoff timing, teleconnections between those circulations and California weather elements were considered. Many previous investigators have demonstrated connections between seasonal precipitation and temperatures in California and large-scale atmospheric circulations over the North Pacific Ocean and North America (e.g., Namias 1978; Douglas et al. 1982; Weare and Hoeschele 1983; Cayan and Roads 1984; Klein and Bloom 1987; Cayan and Peterson 1989; Redmond and Koch 1991). Correlations between seasonal precipitation and 700-mb height anomalies, and (as in Fig. 9) regions in which the seasonal 700-mb height anomalies have displayed significant trends during 1948–92, are shown in Fig. 10. During the autumn, winter, and spring seasons, precipitation in California is negatively correlated to 700-mb height anomalies overlying and to the west of California. The negative correlations reflect tendencies for precipitation to occur when low pressure systems cross the West Coast with their associated rising motion and southwesterly winds. Dry conditions in California are associated with high pressures aloft over California and the West Coast; these conditions reflect less-frequent-than-normal passage of low pressure systems as well as large-scale atmospheric subsidence that stabilizes and dries the atmosphere. In spring, the regional negative correlation pattern continues to prevail, but remote positive correlations also appear over the Gulf of Alaska (Fig. 10e), indicating a tendency for storms to be forced to the south in wet springs.

California temperatures are positively correlated with 700-mb height anomalies over the West Coast and are negatively correlated with 700-mb height anomalies over the North Pacific, especially in winter (Fig. 10d). Notice that the spatial distribution of temperature teleconnections is broader than those of precipitation. Warm winters tend to occur when anomalously low pressures prevail over the central North Pacific and high pressures are stationed over the West Coast. Such patterns correspond to a southward displacement of westerlies over the North Pacific and a northward displacement over the western United States. During warm California winters, cold northerly winds occupy the central North Pacific and southerly winds cover much of the western United States, carrying warm air to California. The presence of wintertime high pressures over the northwestern United States, indicated by stippling there in Fig. 10d, also corresponds to decreased precipitation there. Thus, the 700-mb height anomaly trends over the Northwest are consistent with recent decreases in total runoff and snowpack. Another consequence of this configuration of large-scale winds is that ocean surface temperatures over the central North Pacific and temperatures over California tend to be negatively correlated. We will use that relation as an additional check on the observed trends in 700-mb height anomalies.

Notice the similarity of the correlation patterns of runoff timing versus winter 700-mb height anomalies (Fig. 9b), and those of winter temperatures versus winter 700-mb height anomalies (Fig. 10d). This similarity is present both in the central North Pacific and in the eastern North Pacific–West Coast regions. The areas in the central Pacific of positive correlation between autumn 700-mb height anomalies and runoff timing (Fig. 9a) coincide with the region of negative correlations between autumn temperatures and autumn 700-mb height anomalies (Fig. 10b). These coinciding patterns suggest that the correlations in Figs. 9a–b may reflect the influences of temperatures on runoff timing. (Alternatively, the patterns may reflect more complex hybrid influences of both precipitation and temperature or other seasonal influences not considered here.) In other regimes and seasons, the correlation patterns in Fig. 9 bear no obvious relations to the patterns in Fig. 10. In part, this may be due to

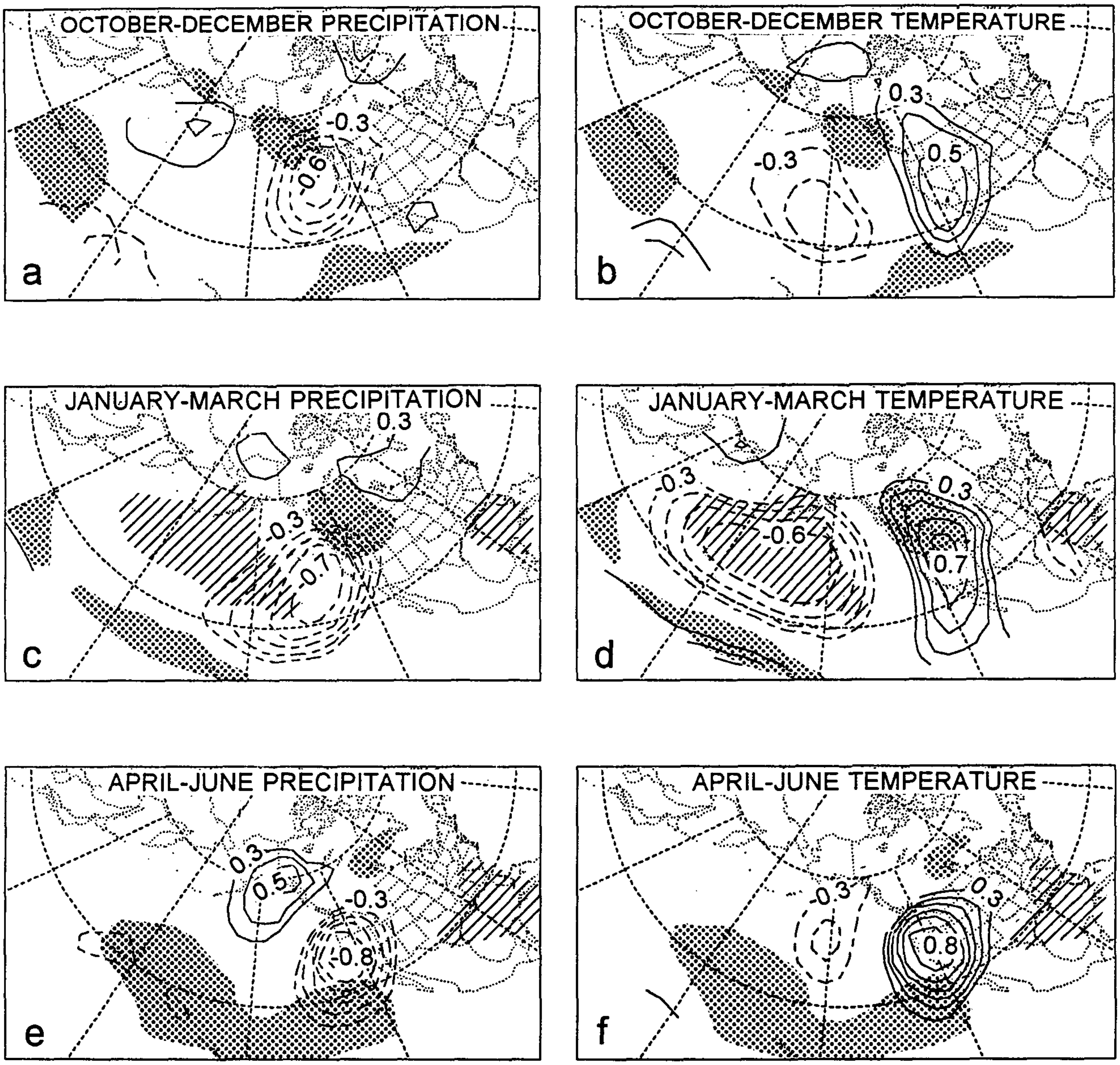

FIG. 10. Regions (shaded) of significantly trending seasonal 700-mb height anomalies, 1948–91, and contoured correlations between seasonal 700-mb height anomalies and California seasonal weather conditions: (a) October–December precipitation, (b) October–December mean temperature, (c) January–March precipitation, (d) January–March mean temperatures, (e) April–June precipitation, and (f) April–June mean temperatures. Contours, stippling, and hatching as in Fig. 9.

differences in when and where atmospheric correlations to California weather are strong enough to plot as significant in Fig. 10.

The areas that have significant trends in 700-mb height anomalies during 1948–92 and significant correlations between 700-mb heights and California weather shown in Fig. 10 differ from season to season. The winter season (Figs. 10c–d) exhibits the strongest coincidence between regions having the 700-mb height trends and regions with strong 700-mb height correlations to climatic fluctuations in California. The broad region of trends toward lower 700-mb heights over the central North Pacific is nearly centered over the regions of negative correlations with temperatures. The region of trends toward higher 700-mb heights over British Columbia overlaps the northern part of the regions of positive correlations with California temperature. The co-location of these patterns strongly suggests that increasing winter temperature trends in California (and most of the West Coast of North America) have been forced by the concurrent atmospheric circulation trends. As shown in Fig. 10c, the 700-mb height trends occurred outside the regions of strongest correlations with winter precipitation. In winter, the contributions to precipitation from the two midlatitude zones of atmospheric circulation trends tend to cancel. During spring, trends toward higher 700-mb surfaces in the subtropics of the eastern North Pacific occurred in regions that are moderately teleconnected to spring precipitation and temperatures in California (Figs. 10e–f). These spring circulation trends may have contributed to declining spring precipitation and slightly increasing temperatures in California (Fig. 7).

The pattern of trends in winter circulations (declining heights over the central North Pacific and increasing heights over British Columbia) resembles the western two-thirds of the Pacific–North American pattern (PNA) (Leathers et al. 1991). The strength of this pattern is described by the PNA index, which is defined as

$$\mathrm{PNA} = [-Z_1 + Z_2 - Z_3]/3, \quad (3)$$

where Z_1, Z_2, and Z_3 are standardized 700-mb height anomalies at 47.9°N, 170°W, at 49°N, 111°W, and at 29.7°N, 86.3°W, respectively (following Yarnal and Diaz 1986). For the present purpose, the PNA index serves as an indicator of the strength of southerly, meridional flows over the West Coast and western North America. As suggested by the trends shown in Fig. 9b, the PNA index (overall) has trended toward higher values during the winters of 1948–92, with a τ of +0.39 (p = 0.0003). However, height anomalies at Z_3 over the southeastern United States have not shown a consistent trend over the last 45 winters. Furthermore, even the trend pattern in Fig. 9b does not reflect exactly opposed trends over the North Pacific and British Columbia (Z_1 and Z_2). Rather, the strongest trends over the North Pacific were in the first half of the 1948–92 period, whereas the trends over British Columbia have been consistent throughout the period. Thus, although the PNA trend reflects and corroborates the circulation pattern trends detailed here, the PNA trend alone does not capture the character of those trends as they have influenced California. The clearest understanding of the various weather and runoff trends in California came from analysis of atmospheric trends throughout the North Pacific–North America region rather than solely those at the three PNA points.

Time series of winter-mean North Pacific SLPs (40°N, 160°W) and, also, central North Pacific SSTs are presented in Fig. 11. The seasonal SLP variations correspond closely to 700-mb height variations and are shown here because their record begins much earlier than does the 700-mb height record. In the midst of much year-to-year variability, the trends that Kendall's test recognizes in the series are evident. In the sliding 30-year series of significance levels (Fig. 4c), notice that the trend toward lower SLPs began in the late 1940s at about the same time as the California winter temperature and spring runoff fraction trends (Figs. 4a–b).

To rule out the possibility of spurious correlations between independent trends in 700-mb heights and winter temperatures in California, we generated similar correlation and trend maps (but not shown here) for the subperiod 1961–80 when the winter temperature trends (Fig. 8a) and atmospheric pressure trends (Fig. 11a) were relatively subdued. During that interval, the region of declining 700-mb heights over the Pacific shifted far to the north over the Aleutian Islands and did not overlie the region of strongest teleconnections to California temperatures and runoff timing. Meanwhile, the teleconnection patterns for winter temperature and precipitation were largely unchanged from those obtained from the longer period (1948–91) when the atmospheric trends were strong. Thus, the winter correlation patterns shown in Figs. 9c and 8d were not controlled (spuriously) by the locations of the trending variability in the 700-mb height fields, but rather correspond mostly to correlations between the higher frequency components of the height fields and weather series. Conversely, where trends in the atmospheric circulations have coincided with these regions of teleconnection, the result has been trending weather and runoff conditions in California.

c. Sea surface temperature trends, 1948–92

As described previously, the trend in winter atmospheric circulation patterns illustrated in Fig. 9c is con-

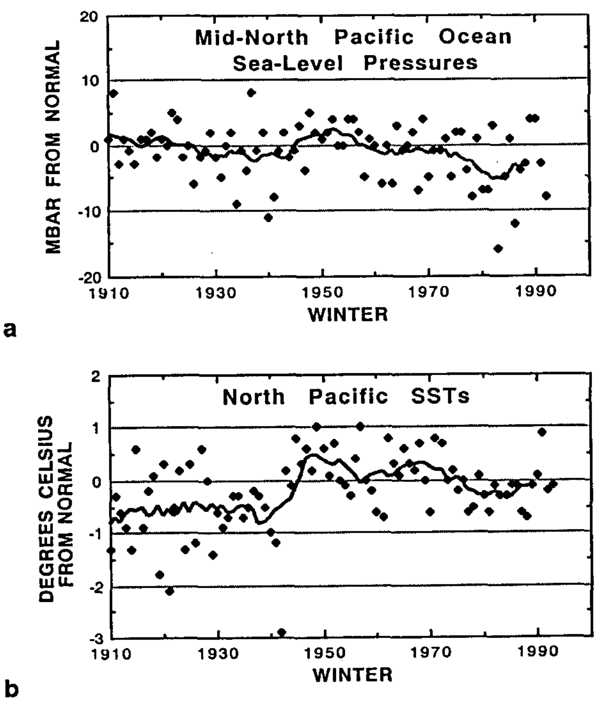

FIG. 11. Time series of January–March mean (a) sea level pressures at 40°N, 160°W and (b) sea surface temperatures between 35°–50°N and 180°–150°W. Solid curves are 9-yr moving averages.

sistent with the southward displacement of cool air over the central North Pacific and the northward displacement of warm air over the western United States. A deepened low south of the Aleutian Islands injects cool air and strengthened winds over the North Pacific Ocean and typically enhances latent and sensible heat fluxes from the sea surface, and thus leads to cooler SSTs (Cayan 1992). In addition to this immediate cooling impact by the circulation changes, Namias (1976) described other mechanisms (mixing and upwelling) by which such a circulation pattern would cool the sea surface.

Thus, the winter atmospheric circulation trends indicated in Fig. 9c should have produced attendant trends toward cooler winter SSTs in the central North Pacific. Indeed, Fig. 11b illustrates just such a trend toward cooler SSTs in recent decades since a dramatic warming in the 1940s. Figure 4d shows that the trend in SSTs in the central North Pacific began in unison with the hydrologic and weather trends in California. (Notice in Fig. 11b that the SST trends beginning during the 1920s and 1930s in Fig. 4d are mostly a result of the large temperature shift around 1940.) The spatial distribution of the trends toward cooler SSTs in the western and central North Pacific and warmer SSTs along the West Coast can be seen in Fig. 12, which shows τs for the period 1948–92. These trends are consistent with the trends in atmospheric circulation patterns since the late 1940s, including the trends toward more southerly winds at the West Coast and with warmer air temperatures over California. Thus, the SST trends provide an independent check on the reality and scale of the atmospheric changes that eventually have driven the tendency for earlier snowmelt in California.

In this interpretation of Fig. 12, we have implicitly assumed that, at the seasonal timescales considered, SSTs mostly follow and respond to atmospheric circulation rather than driving that circulation. Actually, the cause-and-effect relations between the atmospheric circulation and SSTs are uncertain at the decadal timescales considered. The preceding discussion is consistent with recent analyses of sea surface temperature tendencies (Cayan 1992), which indicate that SSTs "catch up" to changing atmospheric circulation conditions very quickly indeed. However, Namias often argued (e.g., Namias 1976) that anomalous sea surface temperature gradients of the sort implied by Fig. 12 (warm to the southeast and cool to the northwest) could induce anomalous southerly components of atmospheric circulation over the West Coast of North America. Such components would have increased the tendency for warm winters over California. Furthermore, Gray and Landsea (1992) and Dickinson et al. (1988) have speculated on the existence of multidecadal fluctuations in the operation of the heat-conveyance mechanisms of the global ocean (in particular, the global circulation of deep water). Consequently, the linkages between SST and SLP trends suggested in Figs. 9b and 11 may be much more profound than is indicated by our simple use of SST trends as a consistency check.

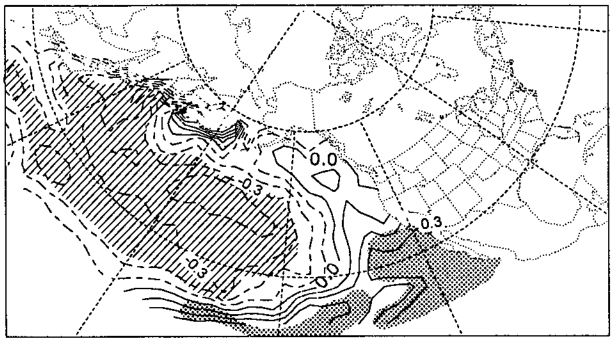

FIG. 12. Kendall's tau values for sea surface temperatures, January–March 1948–92. Contours of τ are shown, with stippling on regions where temperatures have trended significantly ($p < 0.05$) toward warmer values and hatching on regions with significant cooling trends.

Beyond these North Pacific links, there also may be tropical ties. Evidently, the tropical western Pacific sea surface has warmed in a trend that began at the same time as the runoff trends (Fig. 3e) (Barnett 1989). Thus, the recent trends considered in this paper have been coincident with long-term changes in the Tropics. It is notable that by the Kendall's tau test used here, traditional El Niño–Southern Oscillation indices of tropical variability (such as the Southern Oscillation index and SSTs in the central and eastern tropical Pacific) do not contain significant multidecadal trends. Apparently, the trends studied here are not simple responses to changes in the overall El Niño condition, but instead may be responses to changes in just the western half of that oscillation.

d. Atmospheric forcing and trends prior to 1948

Two final analyses were performed to test the linkage of California climate trends to atmospheric forcing over the North Pacific Ocean. Long-term observations of atmospheric conditions (specifically SLPs) were used 1) to determine whether atmospheric trends began as abruptly in the late-1940s as did the California temperature and runoff-timing trends, and 2) to determine whether the trends in SLP since the late 1940s have been of sufficient magnitude to explain the Sierra Nevada temperature and runoff-timing trends observed. SLP records were used because they are available in gridded form since the beginning of this century (Trenberth and Paolino 1980).

The SLP record shows an abrupt commencement of trends over parts of the North Pacific Ocean that are critical to Sierra Nevada temperatures and runoff. As indicated in Fig. 4c, there is a close synchronization of the beginning of the atmospheric trend from the

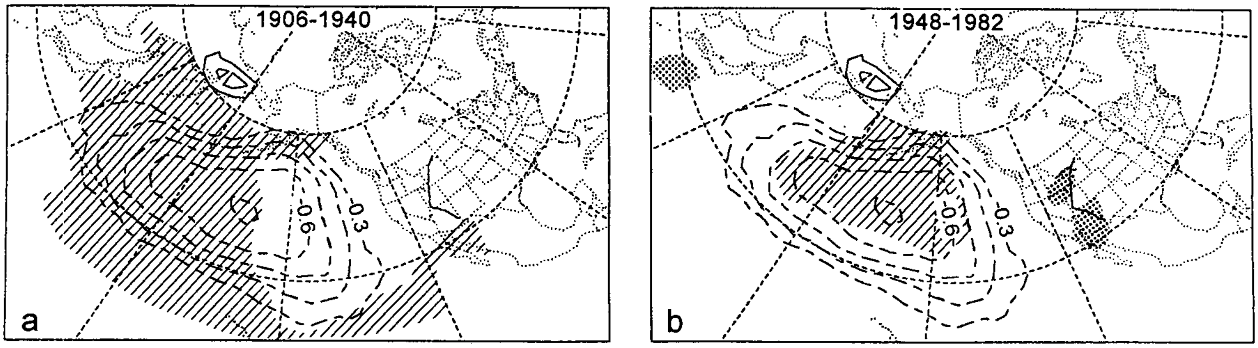

FIG. 13. Regions (shaded) of significantly trending January–March sea level pressure anomalies, (a) 1906–40, and (b) 1948–92, and contoured correlations between winter sea level pressures and temperatures in the composite weather series for central California. Contours, stippling, and hatching as in Fig. 9.

1940s–present and those of winter temperatures and spring-runoff fractions. Correlations between winter temperatures in California and SLPs (1931–92) are shown in Fig. 13, together with the regions in which winter mean SLPs trended significantly during two periods: 1906–40 and 1948–92. As previously seen (Fig. 9d), during 1948–92, atmospheric circulations trended in almost exactly the part of the North Pacific that is most teleconnected to winter California temperatures. In contrast, during the earlier (1906–40) period, SLPs underwent significant trends over a broad area west of the critical region for teleconnection to California temperatures. Thus, the recent trend toward earlier runoff timing in California is associated with the coincidence of certain winter atmospheric trends during 1948–92 with regions of maximum teleconnection to California. This implies that strong runoff-timing trends were not present in the first half of this century because atmospheric trends and teleconnections to California temperatures failed to coincide. The absence of runoff-timing trends in this early period suggests the sensitivity of regional hydrologic response to the details (e.g., the spatial phase) of large-scale climate fluctuations.

To determine whether the 1948–92 atmospheric trends are sufficient to explain observed Sierra Nevada temperature trends, winter-mean SLPs at the SLP grid point most correlated to January–March Sierra Nevada temperatures (40°N, 160°W) were regressed with those temperatures. The resulting SLP-to-temperature relation then was used to determine how large a temperature trend would be caused by the observed SLP trend. First, winter temperatures in the central-California composite were regressed with the concurrent SLPs using data from a period mostly prior to the recent trend (1931–47). During this period, a −0.24°C change occurred with each 1-mb variation (with R^2 = 70%). Then, a simple trend line for the SLP series from 1948–92 was fitted by linear regression and had a slope of about −0.15 mb winter^{-1}, although with considerable scatter (R^2 = 17%). Together these relations suggest the SLP trend would be associated with a +0.04°C winter^{-1} increase in temperature [$(-0.24°\text{C mb})^{-1} \times (-0.15 \text{ mb winter}^{-1})$.] A trend line fitted through the Sierra Nevada temperatures had a slope of +0.05°C winter^{-1} (R^2 = 38%). Thus, the SLP trend has been roughly sufficient to explain the temperature trend. Furthermore, we have seen previously that the trend component in the Sierra Nevada temperatures is sufficient to account for the runoff-timing trends. Overall, we conclude that the winter atmospheric trends since the late 1940s have been large enough to explain much of the observed temperature trends and, in turn, runoff-timing trends.

7. Summary and discussion

Runoff has come increasingly early from many basins of the western United States, including California. This trend is not a localized effect in a few basins nor an instrumental artifact. Rather, the trend is part of a broader response to large-scale atmospheric circulation changes that have forced the runoff trends primarily through long-term changes in winter temperature in the basins. The trends seem to have begun in the late 1940s and, interestingly, are most pronounced in middle-altitude river basins (roughly in the range from 1000 to 2000 m above sea level). Lower-altitude basins do not respond much to the temperature trends because they yield water mostly as rainfall runoff, which is affected little by the atmospheric forcing that caused the observed trends. Higher altitude basins also do not respond much to the trends because they are strongly snowmelt dominated and are not very sensitive to the modest changes that have occurred in cold season temperatures and precipitation timing. However, in middle-altitude basins, such as that of the American River, the timing of flow is sensitive to winter temperature changes. Middle-altitude basins in California and elsewhere in the West have broad areas with temperatures that are sufficiently near freezing that small temperature increases can result initially in the formation of less snowpack and eventually in early snowmelt. Consequently, middle-altitude basins of California, including a significant fraction of the western slopes of the Sierra Nevada, show the strongest trend toward declining April–June runoff as a fraction of the annual total. The declining spring fractions have been compensated mostly by increased runoff earlier in the water year.

Spring runoff fractions from the moderate-altitude basins are most strongly related to variations in winter temperatures and, to a lesser degree, the spring fraction of annual precipitation. Composite weather series from the central Sierra Nevada show strong trends toward warmer winter temperatures, totalling about +2°C between 1950 and 1990. Spring precipitation has shown a less remarkable trend. The winter temperature trends have been stronger and more persistent than those in other seasons. Regression analyses show that runoff timing responds equally to the observed decadal-scale trends in winter temperature and interannual temperature variations of the same magnitude, indicating that the long-term swing toward warmer winters in California is sufficient to explain the runoff-timing trends.

Although the immediate cause of the trend in runoff timing is change in winter temperatures and possibly spring precipitation in the river basins, these changes were organized by processes acting at the scale of the North Pacific. The trend toward warmer winters in California was produced largely by trends in winter atmospheric circulations over large areas of the North Pacific Ocean and western North America. Since the late 1940s, winters have seen deeper Aleutian lows and progressive southward displacement of wind fields over the central North Pacific, along with stronger southerly winds over the West Coast. This pattern resulted in colder air masses over the North Pacific and warmer air masses over the West Coast. This atmospheric pattern is evidenced by a colder sea surface in the central North Pacific and warmer sea surface along the West Coast. The initiation of the trends in runoff timing seems to have coincided with atmospheric circulation changes in a region that is particularly well teleconnected to California winter temperatures. Of secondary importance are increases in subtropical pressures in spring, which tended to promote drier warmer springs.

The trend analyses performed in this paper cannot distinguish between step changes of the mean near the center of a given time series and continual monotonic trends. Ebbesmeyer et al. (1991) identified related shifts in 40 environmental variables in the North Pacific and North America centered on 1976. Pupacko (1993) and Webb and Betancourt (1992) also identified related environmental shifts, but centered on 1965. Overall, however, the long-term series plotted in Fig. 3 and especially Fig. 8a suggest that the "trends" considered here may be as much progressive as stepwise. This progressive response of California air temperatures to changes in the climate of the North Pacific is in keeping with the conclusion of Miller et al. (1994) that the first SST empirical orthogonal function (EOF) has displayed a "trendlike" history, whereas the 1976–77 "step" in North Pacific SSTs was most prominent in the second EOF. The first EOF is similar to the pattern in Fig. 12 and is strongly correlated to California temperatures, whereas the second EOF is orthogonal (spatially uncorrelated) to that pattern. Thus, California air temperatures and runoff timing have responded mostly in a trendlike way to the long-term SST changes and, less so, to the step change of the mid-1970s.

Furthermore, inspection of data that extend to the first half of this century gives the impression that the present trends are just one episode in the low-frequency variability of the North Pacific climate system. One interpretation of Fig. 12a is that the recent hydrologic trends considered here "almost" happened before. However, this same episode of trend initiation demonstrates that the hydrologic trends are quite sensitive to details of the spatial patterns of atmospheric circulation change. The abrupt initiation of runoff timing and other trends in the 1940s also suggests that, to the extent that the trends are part of the natural variability of the region, a future retreat from recent runoff-timing regimes would not be surprising. Intriguingly, trend initiation also was coincident with changes in the western tropical Pacific. Links between these regions and trends are not well understood but merit further study.

It is important to notice that the runoff-timing trends described here do not reflect a single, monolithic warming trend that pervades the entire North Pacific/North American sector. Notice, for instance, that a vast area of the western and central North Pacific experienced increasingly cool winters (Fig. 12) during the same period that the western states experienced warming. That runoff has come earlier, rather than later, in the western states was determined by the location of these watersheds in relation to crucial features of the altered atmospheric circulation pattern rather than by a uniform global influence or trend. Thus, the incidence of warmer winters and earlier runoff in the western states does not necessarily confirm a global change.

In connection with possible climate change, however, the present study provides some possible guidance. Most importantly, the temperature trends discussed here amount to about +0.5°C decade^{-1} but have yielded fairly subtle hydrologic responses. Responses depend, apparently critically, on the altitude of the watersheds, on the seasonality of the climatic forcing, and on the location of the hydrologic settings with respect to the forcing patterns. In California's moderate-climate, midlatitude setting, hydrologic responses have been accentuated at middle altitudes—much less response was evident in the highest and lowest basins. The moderate warming experienced in winter months mostly affected snowpack development and snowmelt timing in basins where temperatures hovered near freezing. Warming concentrated in spring (and, possibly, autumn) might have induced larger runoff-timing responses, as well as responses in more basins, because many basins and their snowpacks hover even closer to freezing during those months. On the other hand, warming concentrated in summer months might have had little water supply effect in many western basins because soil moisture and runoff are minimal during those months. Finally, if climate change in the midlatitudes were to take the form of persistent changes in the populations and intensities of atmospheric circulation patterns (Held 1993), the present study suggests that hydrologic responses may be spatially variable, with "warming" responses in some regions and "cooling" in others.

The trends considered here are interdecadal, at least, and fall into what Karl (1988) described as the "gray area of climate change." In the gray area, the number of realizations provided by the instrumental record is only a few, and understanding of causes and effects is limited. Ultimately, our ability to recognize climate change and its effects on water resources will hinge upon our understanding of these slow climate variations and their influences on land hydrology.

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