Seasonal Cycle Shifts in Hydroclimatology over the Western United States

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ABSTRACT

Analyses of streamflow, snow mass temperature, and precipitation in snowmelt-dominated river basins in the western United States indicate an advance in the timing of peak spring season flows over the past 50 years. Warm temperature spells in spring have occurred much earlier in recent years, which explains in part the trend in the timing of the spring peak flow. In addition, a decrease in snow water equivalent and a general increase in winter precipitation are evident for many stations in the western United States. It appears that in recent decades more of the precipitation is coming as rain rather than snow. The trends are strongest at lower elevations and in the Pacific Northwest region, where winter temperatures are closer to the melting point; it appears that in this region in particular, modest shifts in temperature are capable of forcing large shifts in basin hydrologic response. It is speculated that these trends could be potentially a manifestation of the general global warming trend in recent decades and also due to enhanced ENSO activity. The observed trends in hydroclimatology over the western United States can have significant impacts on water resources planning and management.

1. Introduction

a. Background

There is strong evidence for persistent natural climate variation on interdecadal and century time scales (Mann et al. 1995). However, recent trends in climate, both global and regional (Folland et al. 2001), have gained much attention because of their potential links to anthropogenic causes (i.e., increased human-induced CO_2 concentrations) and their significant economic and environmental impacts. Signatures of the recent climate trends are seen in several regional and global variables, including 1) increased land and ocean temperatures, particularly over midlatitude regions; 2) increased frequency of extreme weather events (severe precipitation, floods, droughts etc.); 3) shifts in seasonal cycles—for example, early occurrence of spring (evident through early blossom of the plants and early spring flows); and 4) increased vegetation cover and an extended growing period.

The instrumental record of climate indicates that increases in land surface temperatures are widespread (Karl et al. 1991, 1993a, 1995; Weber et al. 1994; Quintana-Gomez 1999; Brunetti et al. 2000). In North America and Europe, mean surface temperatures have increased by about 0.5°C over the last 50 yr (~0.1°C decade^{-1}), consistent with global trends (Folland et al. 2001). These regional trends in surface temperatures modify the hydrologic cycle through changes in the volume, intensity, or type of precipitation (rain versus snow), and through shifts in the seasonal timing of streamflow. Increases in annual precipitation totals in Canada and in the United States (Zhang et al. 2000; Groisman and Easterling 1994; Bradley et al. 1987; Groisman et al. 2001) and a concurrent decrease in lower-latitude precipitation (Bradley et al. 1987) are observed during the twentieth century. Corresponding shifts in storm tracks from the midlatitudes to the high latitudes have also been observed (Serreze et al. 1997; Clark et al. 1999; McCabe et al. 2001). Decreases in winter precipitation over southern Europe (Brunetti et al. 2001) and the Mediterranean, and wet anomalies

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from Iceland eastward through Scandinavia, are related to the persistent positive phase of the North Atlantic Oscillation (NAO) (Hurrell 1995). Global climate model simulations of enhanced greenhouse conditions show an increase in global average precipitation of about 10%, with fewer but more intense convective events at lower and middle latitudes, and more frequent moderate- to high-intensity nonconvective events at higher latitudes (Hennessy et al. 1997). Precipitation over the contiguous United States, in line with simulation results, appears to have increased during the twentieth century as a result of an increase in the frequency of heavy precipitation events (Karl and Knight 1998; Groisman et al. 2001).

At higher latitudes, increases in surface temperature have resulted in systematic decreases in snow cover extent and changes in the amount of precipitation falling as rain versus snow (Karl et al. 1993b). Groisman and Easterling (1994) observed that there has been a 20% increase in annual snowfall and rainfall in Canada during the last 4 decades. Groisman et al. (1994) analyzed records of snow cover in the Northern Hemisphere over the period 1972–92 and found that there was approximately a 10% reduction in the area of snow cover. They linked this decrease in snow cover extent to an increase in spring temperatures and suggested the lower albedo from an increased fraction of snow-free land instigated a positive feedback that intensified the decline in snow extent.

b. Global trends and western U.S. hydroclimatology

One of the key impacts of global temperature change is the shift in the seasonal cycle of hydroclimate variables, especially precipitation and streamflow. Changes in regional hydroclimatology can have substantial economic and environmental impacts. Increasing winter temperatures reduce the amount of snow in a basin (e.g., more precipitation falling as rain than snow), as observed in several parts of the western United States (Aguado et al. 1992; Dettinger and Cayan 1995). Also, higher spring temperatures initiate earlier runoff and peak streamflows in snowmelt-dominated basins (Aguado et al. 1992; Cayan et al. 2001). These can have significant impacts on water resources management—for example, negative impacts on irrigation, nonfirm energy, recreation, flood control, and instream flow for fish (Hamlet and Lettenmaier 1999). Knowing these shifts in advance can help water managers to optimize reservoir operations to meet competing demands such as irrigation, environmental needs, and power generation.

Observations suggesting the earlier occurrence of spring are evident in shifts in several climate variables, including the phase of the annual cycle of temperature, which Thomson (1995) attributed to increased atmospheric CO_2 concentrations. Shifts in the seasonality of precipitation (Bradley 1976; Rajagopalan and Lall 1995) and streamflows (Roos 1987, 1991; Aguado et al. 1992; Wahl 1992; Lins and Michaels 1994; Dettinger and Cayan 1995; Cayan et al. 2001; Stewart et al. 2004; Stewart et al. 2005, hereafter SCD) have been observed across several regions of the western United States. Mote (2003) computed trends in snow water equivalent (SWE) in the Pacific Northwest and observed strong declines in SWE, in spite of increases in precipitation, which is consistent with an increase in spring temperatures. In an analysis of hydrologic impacts of climate change over west-central Canada, Burn (1994) found a strong shift toward the early occurrence of the spring runoff events, especially, in the last 30 yr. Dettinger and Cayan (1995) observed early flows in association with warmer winters in California. Cayan et al. (2001) documented the early onset of spring in the western United States by examining changes in the blooming of plants and the timing of spring snowmelt pulses. McCabe and Wolock (2002) observed a step increase in streamflow in the conterminous United States over the period 1941–99, with pronounced increases in the eastern United States after 1970.

Climate model simulations under CO_2 doubling show a strong seasonal shift in the snow accumulation and ablation seasons, leading to increased winter runoff and decreased spring runoff (Lettenmaier and Gan 1990). Nash and Gleick (1991) used conceptual hydrological models to simulate streamflow response to changes in temperature and precipitation in the Colorado River basin. Increases in temperature of 2°–4°C decreased mean annual runoff by 4%–20%, whereas changes in annual precipitation of ±10%–20% result in corresponding changes in mean annual runoff of 10%–20%. Seasonal shifts in flow were observed and attributed to an increase in the ratio of rain to snow. The potential effects of climate change (i.e., increased winter precipitation and warmer winter temperature) are quite pronounced in the Pacific Northwest region, where significant increases in winter flow, and corresponding decreases in summer flow, are shown under a range of different climate models (Hamlet and Lettenmaier 1999). The transitions in winter and summer flow volumes occur because of increased winter temperature and winter precipitation, with resulting reductions in snowpack (see also Mote 2003).

Recently a group of researchers evaluated future climate change impacts on western U.S. water resources management as part of the Accelerated Climate Prediction Initiative (ACPI). The climate change scenarios of projected "business as usual" (BAU) greenhouse gas emissions were simulated using the National Center for Atmospheric Research (NCAR)/Department of Energy (DOE) Parallel Climate Model (PCM). The BAU scenarios exhibited an average warming of about 1°–2°C and both decrease and increase in precipitation across the western United States. Downscaling these scenarios to the Colorado River basin, Christensen et al. (2004) find a significant decrease in April SWE (−30%), annual runoff (−17%), total basin storage (−40%), and reservoir levels (−33%) by the end of the twenty-first century. Furthermore, Barnett et al. (2004) find that these climate impacts can potentially drive the Colorado compact to the brink of failure. In the Pacific Northwest region (Wood et al. 2004) and the Columbia River basin in particular, Payne et al. (2004) and Leung et al. (2004) find that the climate change scenarios lead to a decrease in SWE, more frequent rain-on-snow events, changes in SWE accumulation/melting period and, consequently, increased likelihood of winter flooding and an earlier refill of reservoirs. This increases the competition of instream releases for hydropower generation and endangered species allocation (Payne et al. 2004; Barnett et al. 2004). Similar impacts of reduced winter and spring precipitation coupled with early spring warming and peak flows are seen in the Sacramento–San Joaquin basin (Vanrheenen et al. 2004) and several basins in the Sierra Nevada region (Dettinger et al. 2004). In general, climate change due to 1°–2°C warming and shifts in spring streamflows (Dettinger et al. 2004; Stewart et al. 2004) were found to significantly impact water resources in the western United States by the end of the twenty-first century (Barnett et al. 2004; Leung et al. 2004).

From the research efforts discussed above it is clear that there is strong evidence for climate change, as seen through trends/changes in regional hydrometeorological variables. Of course, the reported trends have to be tempered in light of short observational records. Nonetheless, given the potential socioeconomic impacts of changes in regional hydroclimatology, more research in this area is needed. The main questions that we address for the western United States are (i) What are the spatial signatures and trends in the timing of spring peak flows? and (ii) Are these trends consistent with the observed records of precipitation, temperature, and snowfall? With this as motivation, we systematically analyzed trends in precipitation, snow mass, streamflows, and timing of peak flow occurrence in snowmelt-dominated river basins throughout the western United States. Our analysis focuses on hydroclimatic trends over the last half of the twentieth century; a relatively dense network of measurement stations and consistency in datasets for this time period allows us to examine potentially complex interactions between temperature, precipitation, and streamflow over a broad geographic area characterized by diverse climatology and terrain.

2. Data and methodology

The main objective of this paper is to examine the cause-and-effect relationship between the timing of snowmelt in the mountain basins of the western United States and trends in associated hydroclimatic variables. Measurements of streamflow, SWE, precipitation, and temperature are used to assess shifts in the seasonal cycle of snowmelt runoff over the period 1950–99.

a. Streamflow

Daily streamflow data were obtained for selected unregulated basins in the western United States that are part of the U.S. Geological Survey (USGS) Hydro-Climate Data Network (HCDN) database (Slack and Landwehr 1992). This database was developed by the USGS to study climatically induced variations in U.S. surface water conditions (Slack and Landwehr 1992). The full database consists of 1659 stream gauges throughout the conterminous United States. The streams and rivers in the HCDN database are relatively free from anthropogenic influences such as watercourse regulation, diversion, groundwater pumping, and land use change. We selected stations across the western United States that have dominant spring snowmelt runoff, meaning at least 50% of the annual streamflow occurs during April–July. In addition, the stations selected have continuous records over the desired period (1950–99) and are quality checked; 89 stations satisfied the above criteria.

Several different methods have been used previously to identify changes in the timing of spring snowmelt. Burn (1994) examined trends in peak flows by selecting the Julian day on which the maximum spring flow occurred. Cayan et al. (2001) developed an algorithm identifying the day when the cumulative departure from that year's mean flow reached a minimum value, which is equivalent to finding the day after which most flows were greater than average. We found that both of these approaches performed poorly when there were rainfall or rain-on-snow events during winter or spring. In the Sierra Nevada range, for example, high-intensity rainfall events can generate floods in December or January, long before the main pulse of snowmelt. Consequently, the Julian day of peak flow may not reflect the timing of seasonal snowmelt.

Given the drawbacks of existing methods, we developed an alternative procedure that finds the date (Julian day) on which 50% of the water-year flow is equaled or exceeded. An example of the procedure is illustrated in Fig. 1, which shows daily flows of the American River near Nile, Washington (USGS gauge 12488500), for a portion of the 1974 water year. In this example, the annual peak flow in mid-January has a very sharp rising limb, suggesting it is the result of a rain event. Several subsequent peaks in May and June are characterized by slower rising limbs, reflecting separate periods of snowmelt runoff. Our procedure identifies 4 June as the cutoff date corresponding to 50% of the annual flow. This date precedes the main snowmelt peak by about 10 days. In other years it is just as likely that the main snowmelt peak will precede the date selected by our method. In most cases the date corresponding to 50% of the annual flow lies near the cen-

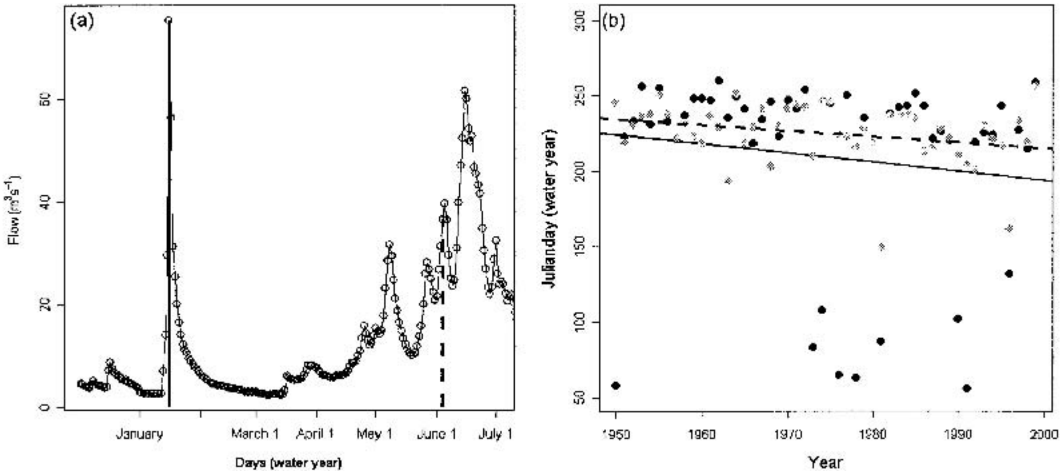

FIG. 1. (a) Daily hydrograph for water year 1974 of the American River near Nile, WA (USGS gauge 12488500). Solid line indicates the data of the annual maximum flow; this peak is likely the result of rainfall. Dashed line indicates the day corresponding to 50% of the annual flow; this date precedes the main snowmelt peak by about 10 days but coincides relatively closely to the centroid of the snowmelt hydrograph. (b) Trends in the timing (day of the water year) of peak flows on the American River for the period 1950–99. Black circles indicate dates corresponding to the annual maximum flow; a number of these flows were produced by rainfall rather than snowmelt. Gray circles indicate dates corresponding to 50% of the annual flow; nearly all of these dates fall within the period of snowmelt streamflow. The trend formed from annual peaks (solid line) is not statistically significant, whereas the trend formed by selecting peaks in snowmelt (dashed line) is significant at the 0.10 level.

troid of the snowmelt hydrograph; this date is, therefore, reflective of the annual hydrograph as a whole rather than an individual day or event. This metric also provides information on the fraction of winter precipitation that falls as rain versus snow.

The second panel in Fig. 1 shows trends in the timing of peak flows on the American River near Nile for the period 1950–99. The two time series represent dates corresponding to the annual maximum flow (black circles) and dates corresponding to 50% of the annual flow (gray circles). Both time series have negative trends, suggesting that peak flows are occurring earlier. However, the time series formed from annual peak flows is clearly influenced by the inclusion of a number of rainfall events, and the overall trend is not statistically significant. The time series formed with the procedure described above appears to be more robust in selecting the peak period of snowmelt; this trend is statistically significant at the 0.10 level.

In addition to trends in the timing of snowmelt, we examined changes in monthly and seasonal (April–July) volumes of streamflow. The streamflow analyses are used to corroborate analyses of precipitation and SWE, which may affect the timing of snowmelt independent of any change in temperature.

b. *Snow*

Trends in SWE were investigated using data from snow-course surveys conducted by the Natural Resources Conservation Service (NRCS) The snow-course surveys are conducted during the months of January–June, and SWE measurements are generally taken on or about the beginning of each month. Snow-course measurements are taken most frequently at the beginning of April, which is representative of peak SWE in many regions. Applications of SWE measurements across the western United States and limitations of the data are discussed by Clark et al. (2001). In our analysis we considered SWE data from March, April, and May, as most of the snow is melted by June. We restricted the analysis to snow-course sites that have been visited on at least 80% of the years during 1950–99. We used 469, 501, and 239 stations with SWE data for March, April, and May, respectively; however, the spatial distribution of stations has not changed much even though the number of stations varied in each month (see, e.g., Fig. 5).

c. *Precipitation and temperature*

Precipitation and temperature data were obtained from the National Weather Service Cooperative Network (COOP). Most COOP stations have records beginning from the mid-1900s. Stations with continuous daily records from 1950–99 over the western United States were selected. Approximately 75% of the stations are situated at elevations lower than 1600 m; some locations in the Rocky Mountain region of Colorado and New Mexico are at elevations greater than 1800 m.

Total winter season precipitation was computed for each COOP station for the months of November–March. Trends in spring temperatures were examined by computing the Julian day of a "warm spell" corresponding to snowmelt. A warm spell is defined here as a period of persistent daily maximum temperatures above some threshold. We calculated a 7-day moving average of daily maximum temperatures during spring and selected the first Julian day (midpoint of the 7-day window) at which the 7-day temperature average exceeds a threshold value. We examined the effects of different temperature thresholds and averaging windows and found good correspondence between the initiation of melt and a 7-day window with the threshold of 12°C.

d. Regression analysis

Trends are examined at each location using linear regression (Helsel and Hirsch 1995; Johnson 1995) for the following five variables: (i) timing of peak streamflow (as described above), (ii) monthly and seasonal flows, (iii) SWE, (iv) seasonal precipitation, and (v) temperature spell timing (described above). Standard statistical tests are used to assess the significance of individual trends (Helsel and Hirsch 1995; Johnson 1995).

3. Results

a. Peak flow timing

Changes in the timing of peak spring flow at individual gauging stations are mapped across the western United States in Fig. 2. For a majority of stations, peak spring flows are occurring earlier (negative trends in timing, indicated by circles); however, the observed trends are statistically significant primarily only in the Pacific Northwest. Later occurrences of peak flows (positive trends in timing, indicated by squares) are present over a small number of stations in the interior west and also over the Sierra Nevada region. These stations correspond to high-elevation locations, which are presumably less sensitive to temperature change. As shown in Fig. 3, shifts in peak flow timing (expressed in days) appear to vary with elevation; in basins less than 2500-m elevation, 10- to 20-day shifts in peak flow timing are common, whereas in basins greater than 2500 m little change is evident.

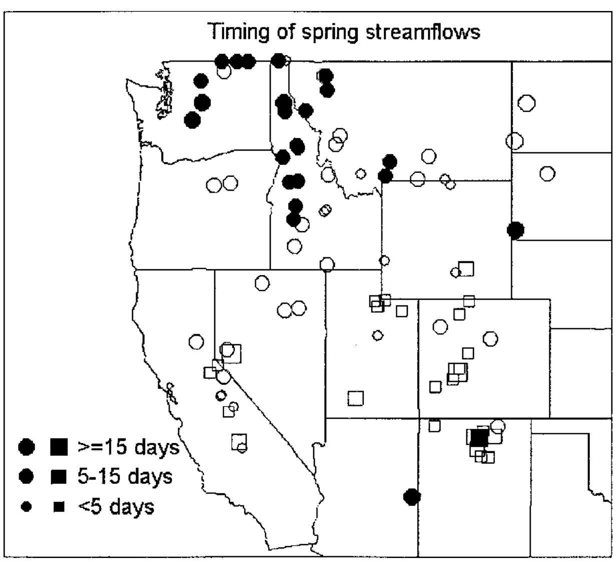

FIG. 2. Locations of gauging stations used to evaluate changes in the timing of snowmelt streamflow for the period 1950–99. Circles depict stations with earlier flow timing, and squares indicate stations with later flow timing. Filled (open) symbols represent stations passing (failing) significance tests, based on a two-tailed *t* test (Helsel and Hirsch 1995; Johnson 1995).

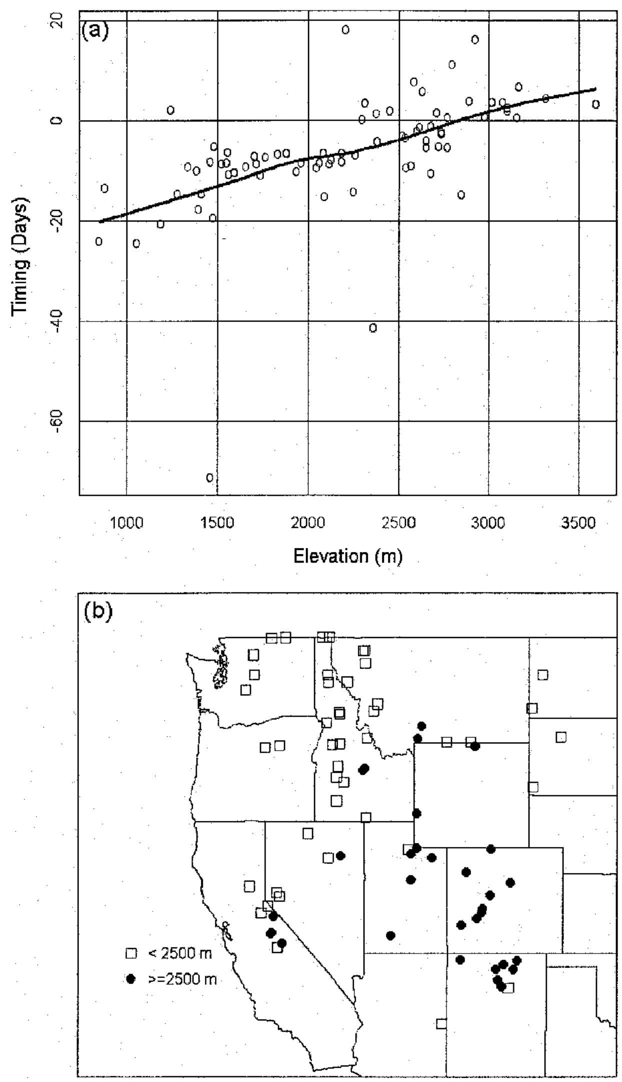

FIG. 3. (a) Scatterplot comparing the trends in the timing of 50% of annual streamflow against the mean basin elevations, and (b) a map illustrating spatial distribution of basins where the mean basin elevation (m) is above 2500 m. Note that mean basin elevations are considerably higher in the interior west.

b. Trends in accumulated snowpack

Figure 4 maps trends in SWE for the months of March, April, and May. Significant declines in monthly SWE can be seen over roughly half of the sites, with the largest declines occurring in the Pacific Northwest region and in northern parts of Idaho, Utah, Wyoming, and the Sierra Nevada region. A few locations in the northern Rockies and the southwestern United States show increasing trends in 1 May SWE.

Trends in SWE can be influenced by both temperature and precipitation (Serreze et al. 1999). One approach to separate temperature and precipitation influences is to examine the SWE trends as a function of elevation (Mote 2003). Changes in SWE due to precipitation alone should be nearly uniform with altitude, whereas changes due to temperature should be much greater at lower elevation, since at lower elevation a moderate change in temperature can dramatically change the fraction of precipitation that falls as snow (Mote 2003). SWE trends as a function of elevation are plotted in Fig. 5. This plot shows that low-elevation basins (2500 m and less) exhibit a strong decreasing trend in SWE, while there is little trend in high-elevation stations. Changes in SWE in the western United States thus appear to be sensitive to the effects of temperature, but primarily in basins below about 2500 m.

c. Trends in temperature and precipitation

Temperature plays an important role in shifting the timing of the flow peaks in snowmelt-dominated basins. Figure 6 shows trends in the timing of the spring warm spell, estimated on the basis of the 12°C threshold defined above, and trends in winter precipitation and winter temperature. Figure 6a indicates that there have been significant advances in spring warm spells over much of the western United States. Departures in spring temperature are greatest in the Pacific Northwest and Rocky Mountains regions, whereas little change is evident in California, Arizona, and New Mexico. On average there is at least a 10–15-day advancement of spring temperature spells over the entire region. Some locations in Colorado, the Sierra Nevadas, and northern Utah (at elevations of ~2500 m and above) indicate a later occurrence of temperature spell. The strong early shifts in temperature spell are consistent with early occurrence of spring flows (Fig. 2).

Figure 6b indicates that winter precipitation is increasing across much of the western United States, except in the coastal regions of Oregon and Washington and a few areas in the northern Rockies. Winter temperatures (Fig. 6c) exhibit a broad pattern of warming in the interior west but elsewhere little change. The increases in winter temperature in the interior region appear to be offset to a certain extent by the increases in winter precipitation, such that there is little change overall in the timing of snowmelt. Decreases in winter

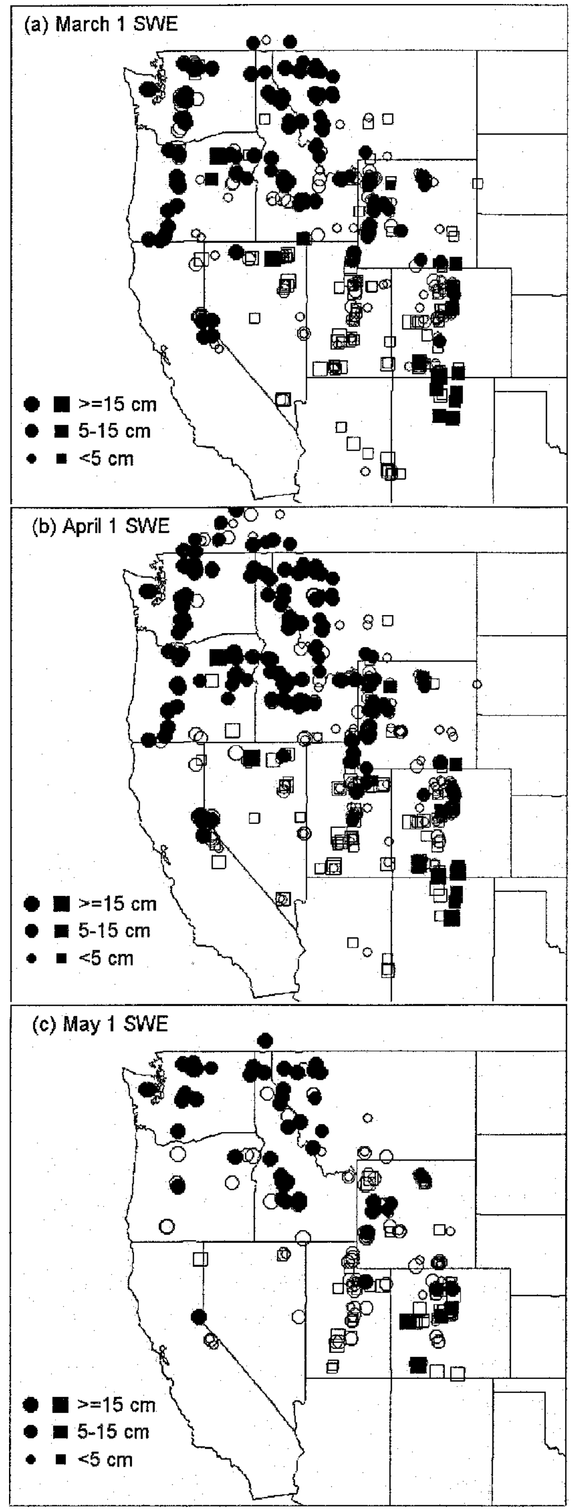

FIG. 4. Locations of snow-course measurement sites used in the analysis of SWE. Trends in accumulated snowpack (cm) for (a) 1 Mar, (b) 1 Apr, and (c) 1 May are shown. Circles indicate decreasing SWE values, and squares indicate increasing SWE values; filled (open) symbols represent stations passing (failing) two-tailed *t* tests of significance.

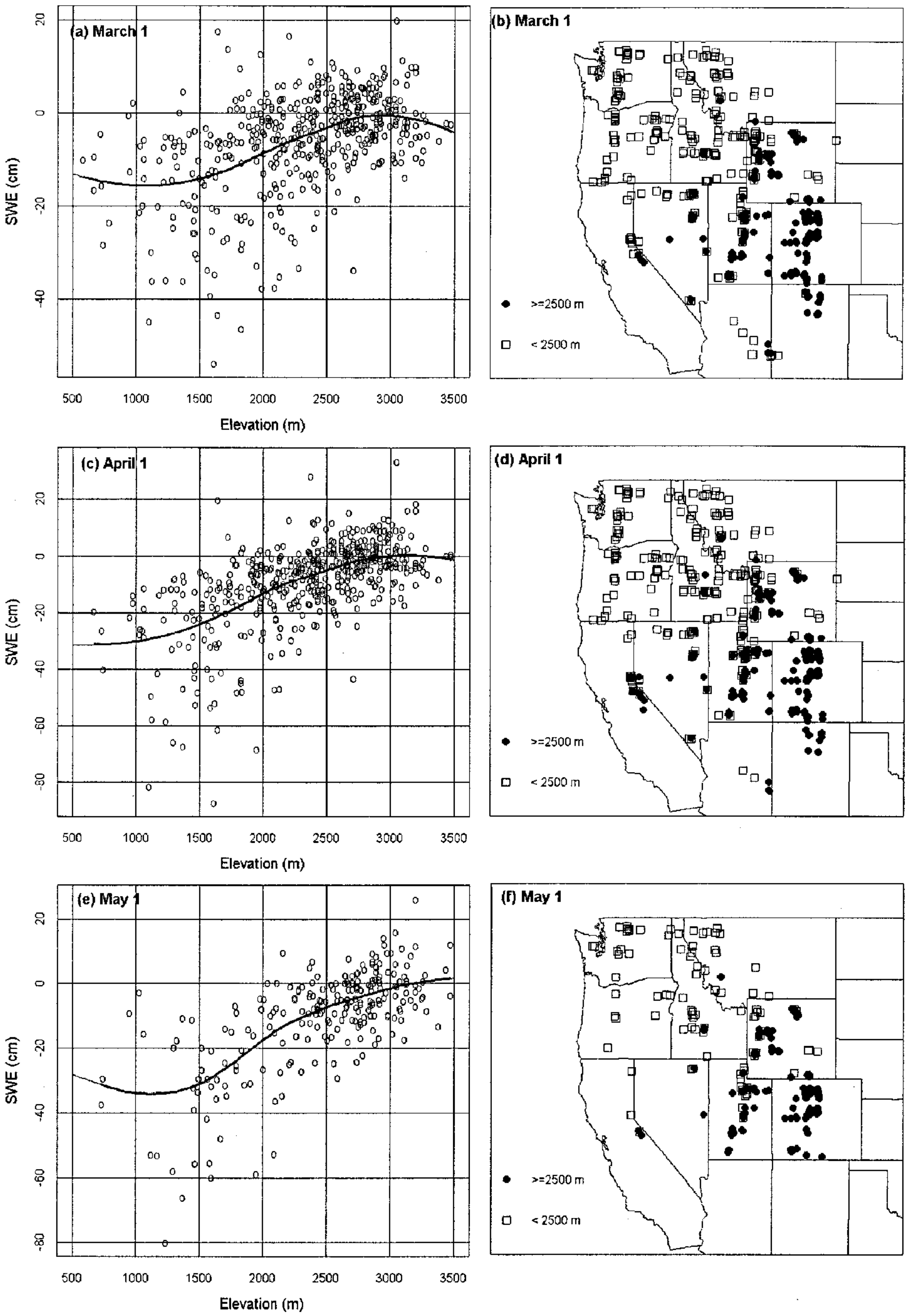

FIG. 5. Scatterplots comparing the trends in SWE (cm) against snow-course elevation (m) for measurements taken on (a) 1 Mar, (c) 1 Apr, and (e) 1 May, and (b), (d), (f) maps illustrating the spatial distribution of stations where the elevation is above/below 2500 m. Station locations are more or less preserved in each month, but the number of stations used in the analysis varies for each month.

precipitation, coupled with increases in spring warm-spell temperatures appear to have had a particularly strong effect on the timing of snowmelt in the Pacific Northwest. Implication of warmer temperatures to early occurrence of streamflows is consistent with others (Aguado et al. 1992; Cayan et al. 2001; Stewart et al. 2004; SCD). Figure 7 shows shifts in the spring temperature spell, winter precipitation, and winter tem-

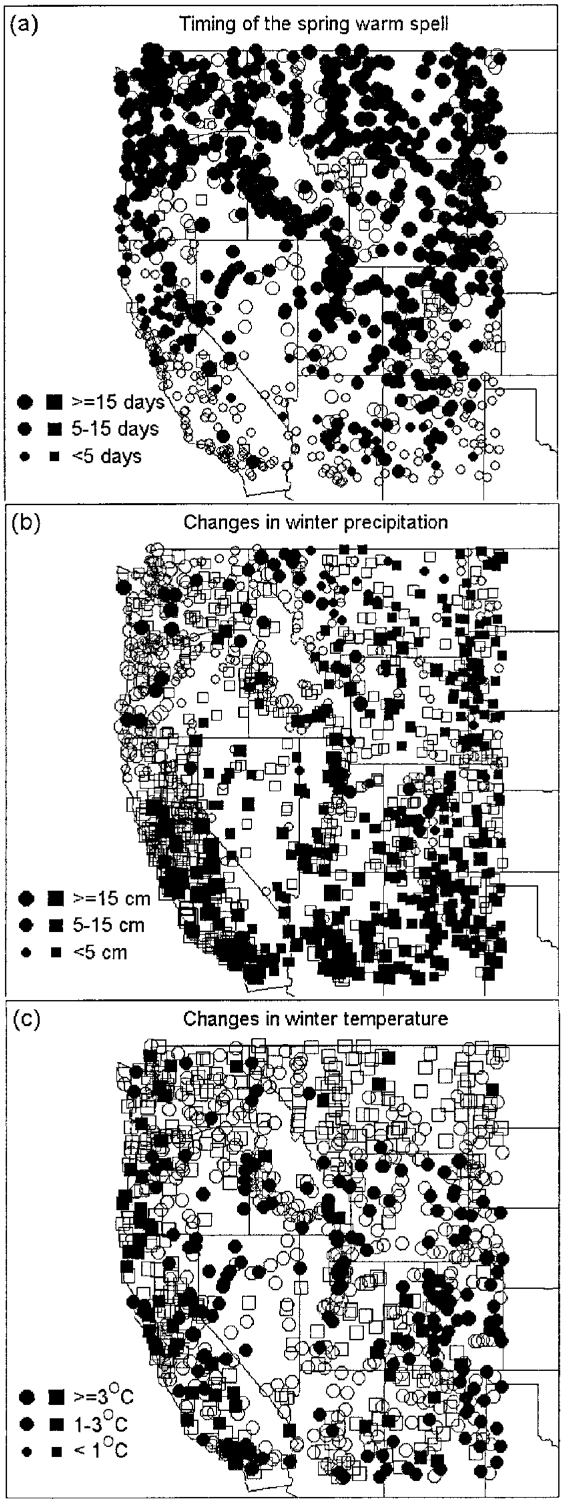

FIG. 6. Locations of weather stations used in the analysis of climate variations. (a) Changes in the timing of the spring warm spell (day); (b) changes in winter precipitation (cm); and (c) changes in winter temperature (°C). Coding is the same as in Fig. 4.

peratures as functions of elevation. There is a weak correspondence between temperature trends and elevation, but this mostly reflects the location of weather stations in low-elevation areas. Similarly, trends in winter precipitation show no obvious relation to elevation (Fig. 7b). Winter temperatures above 1500-m elevation appear to be slightly lower, again reflecting the geographic distribution of stations.

COOP data have several limitations (e.g., station relocation, changes in the timing of observations, etc.) that could cast doubt on the strength of trends obtained in this study. However, given the high spatial density of the COOP stations and, consequently, the lesser impact of isolated defective stations, we believe that the limitations do not affect the interpretation of the results. Although the U.S. Climate Reference Network (USCRN) data that are being developed by the National Oceanic and Atmospheric Administration (NOAA)/National Climatic Data Center (NCDC) are touted as the best dataset for climate change studies, they do not have the daily resolution that is required for this analysis and also lack the dense spatial coverage of the COOP data for the western United States.

d. Streamflow

To bring these results together, trends in annual streamflow were computed, as shown in Fig. 8. Basins in the Rocky Mountains in Colorado and the Sierra Nevadas in California, as well as in Utah and New Mexico, exhibit small increases in annual streamflow, while basins in Idaho and Washington exhibit small decreases. On the whole there are very few basins that pass the significance test (i.e., hardly any filled circles/squares). These results suggest that at most locations any changes in the timing or volume of snowmelt brought about by increases in temperature are offset by increases in precipitation (Fig. 6).

Interesting differences are evident when trends in streamflow are examined for individual months in spring and early summer (Fig. 9). Many stations across the western United States show significant increases in March monthly flows, with particularly large increases in the Pacific Northwest. Increasing trends in March flows in the Pacific Northwest would suggest that more precipitation is coming in the form of rain rather than snow, and also the early occurrence of spring melt. April exhibits a diffuse picture, while May and June show a strong decreasing trend over the Pacific Northwest and northern Idaho and Montana, and weak increasing trends elsewhere. A clearer picture emerges in the spatial patterns of trends in the fraction of monthly flow volumes (Fig. 10). Here the trends are computed as the fraction of monthly flow volume relative to the total annual flow. It can be seen that in the Pacific Northwest and California there is a decrease in the fraction of monthly flows going from March to June. This result suggests that, in recent decades, more of the spring flows are coming in earlier months (March and

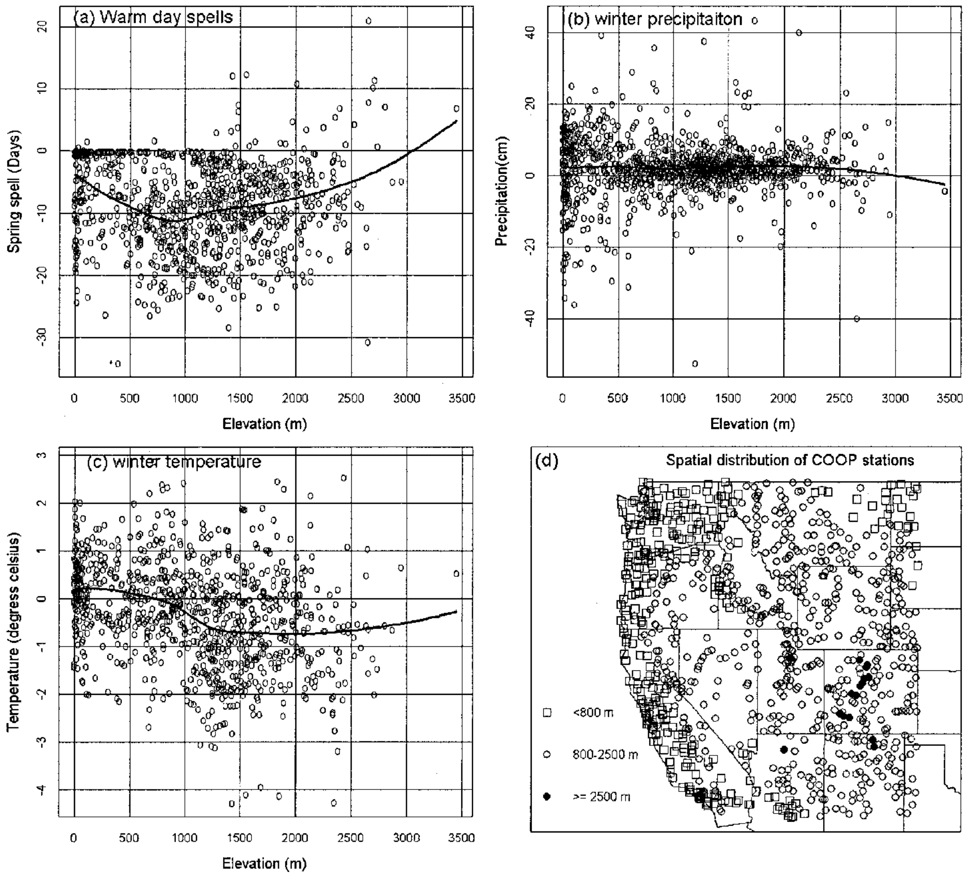

FIG. 7. Scatterplots showing relations between weather station elevation and trends in (a) warm-day spells, (b) winter precipitation, and (c) winter temperature; and (d) a map illustrating the spatial distribution of COOP stations below 800 m (squares), between 800 and 2500 m (open circles), and above 2500 m (filled circles). Note that there are very few COOP stations at high elevations.

April), which is consistent with earlier occurrence of flow peaks seen in Fig. 2.

4. Summary and discussion

The results of this analysis can be summarized in the following four points.

1) Advancement in the timing of spring temperature spells over the western United States has resulted in the earlier occurrence of peak snowmelt flows in many mountain basins. Changes in the timing of snowmelt are most evident in basins in the Pacific Northwest, which fall below 2500-m elevation. Changes in the timing of snowmelt in high-elevation basins in the interior west are, for the most part, not statistically significant.
2) Increases in March and April streamflows and decreases in May and June streamflows at a number of sites suggest a broad shift in spring peak flow timing.
3) Snowcourse measurements show a decreasing trend in the snow water equivalent (SWE) in April and

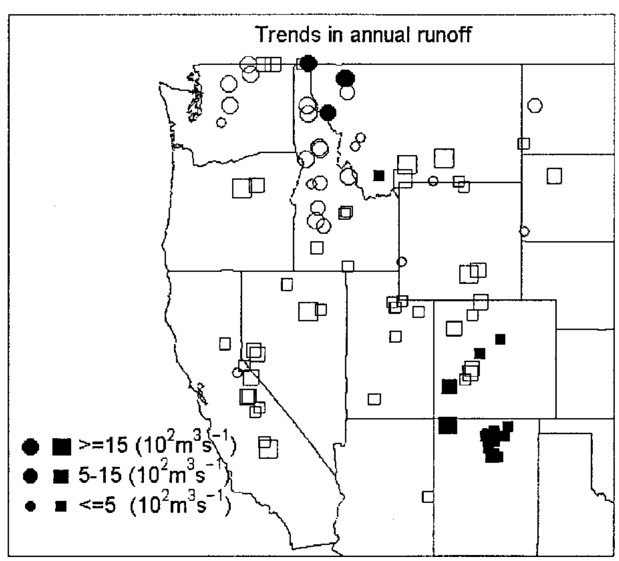

FIG. 8. Trends in annual streamflow (100 m^3 s^{-1}) at USGS gauging stations. Coding is the same as in previous figures.

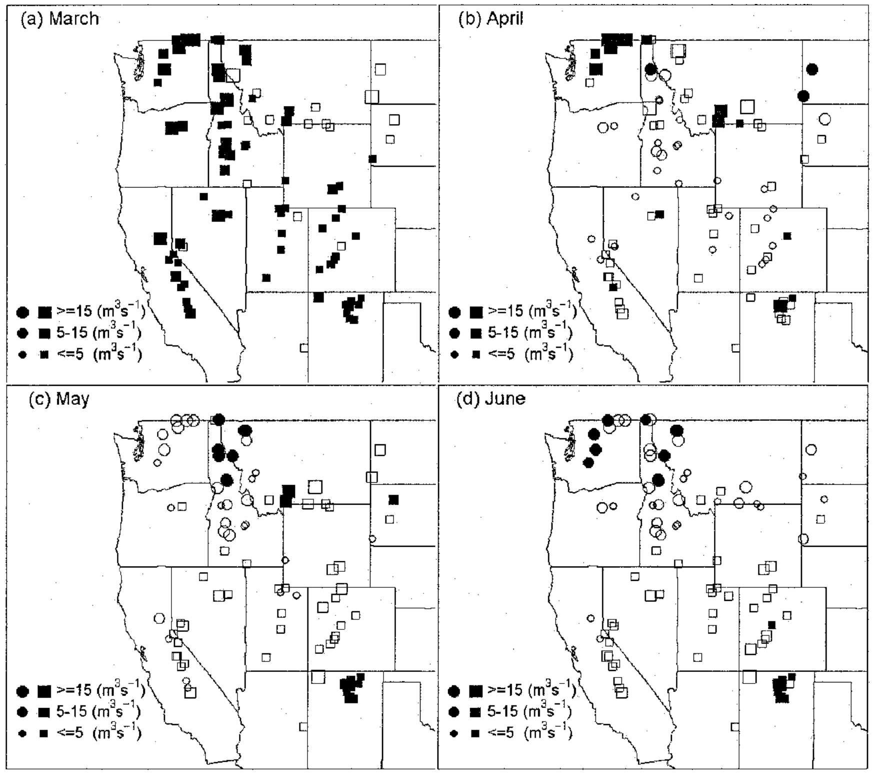

FIG. 9. Trends in monthly streamflow ($m^3\ s^{-1}$) for (a) Mar, (b) Apr, (c) May, and (d) Jun. Coding is the same as in previous figures.

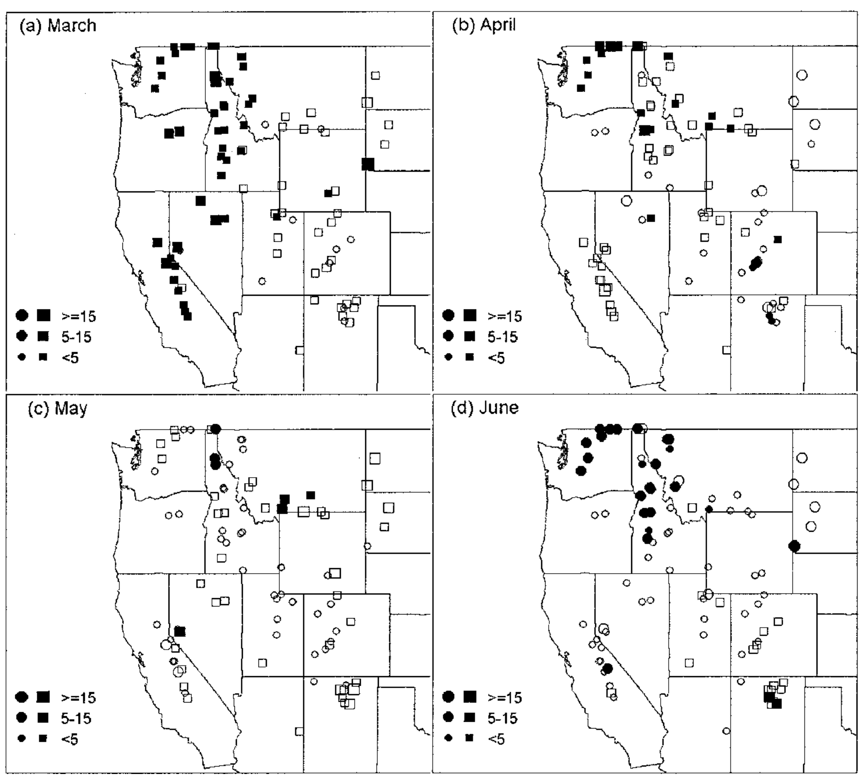

FIG. 10. Trends in the fraction of annual streamflow that occurs in (a) Mar, (b) Apr, (c) May, and (d) Jun. Coding is the same as in previous figures.

May, which is also indicative of reduced snow and early melt.

4) Winter precipitation seems to be generally increasing, but there is no clear increase in spring streamflows. This result suggests that in recent decades more of the precipitation is coming in the form of rain rather than snow.

The changes in climate and hydrology observed in this study appear to be strongly influenced by trends in the last 25 yr. Figure 11 shows trends in the timing of peak streamflow during the pre- and post-1974 periods. It can be seen that the post-1974 period shows a stronger decreasing trend (i.e., early arrival of peak flow) relative to the earlier period. Owing to small sample size, the trends are not significant, despite being higher in magnitude (size of the circles/squares).

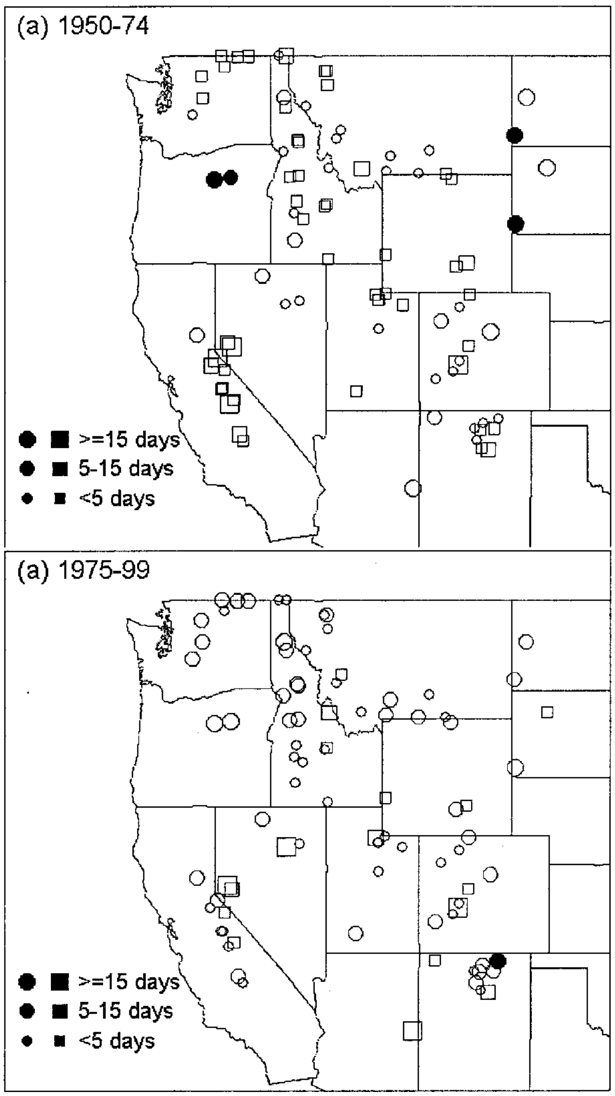

FIG. 11. Trends in the timing of 50% of the annual streamflow (day) for separate time periods: (a) 1950–74 and (b) 1975–99. Coding is the same as in previous figures.

The recent midlatitude warming, perhaps of anthropogenic origins, is a plausible cause for the shift in the spring peak flow timing. On the other hand, the trends in all the figures show an out-of-phase relationship (i.e., opposite sign) over the northwestern and southwestern United States. This is a classic El Niño–Southern Oscillation (ENSO) teleconnection pattern (Ropelewski and Halpert 1986; Redmond and Koch 1991; Cayan 1996; Cayan et al. 1999; Clark et al. 2001). There has been increased ENSO frequency in recent decades (Rajagopalan et al. 1997; Trenberth and Hoar 1996) and also a major shift in the regimes of the North Pacific oceanic–atmospheric processes (Trenberth and Hurrell 1994; Mantua et al. 1997; Zhang et al. 1997), which could affect the timing of peak flows as well. Biondi et al. (2001) observed decadal reversals of Pacific climate throughout the past 4 centuries, suggesting that the recent shifts in climate indices are not unique. McCabe and Dettinger (1999) attributed decadal variations in precipitation to shifts in the phase of Pacific decadal oscillation (PDO) and ENSO regimes. These observations, that is, the shifts in PDO/ENSO phases, could explain the trends in the hydroclimate variables. Also, there is the interesting possibility of interaction between the general warming and enhanced ENSO activity (Trenberth and Hoar 1996; Rajagopalan et al. 1997).

The concentration of negative trends in spring flow timing in the Pacific Northwest attests to the strong sensitivity of that region to climate change. In the high-elevation regions in the interior West, winter temperatures are well below freezing, and the ratio of SWE to winter precipitation is high ($>80\%$) and consistent from year to year. By contrast, in the lower-elevation Pacific Northwest, the ratio of SWE to winter precipitation is much lower and highly variable from year to year (Serreze et al. 1999). This occurs because the temperatures in the Pacific Northwest region are closer to the freezing point, and even small interannual variations in temperature can have a dramatic effect on the fraction of precipitation that falls as rain, and thus on the timing of spring melt. If the trends in temperature, snowfall, and streamflow demonstrated in this paper persist and even intensify, changes in water management practices will be necessary to adapt to the altered hydrologic regime.

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