

## Trends and Variability in Snowmelt Runoff in the Western United States

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### ABSTRACT

The timing of snowmelt runoff (SMR) for 84 rivers in the western United States is examined to understand the character of SMR variability and the climate processes that may be driving changes in SMR timing. Results indicate that the timing of SMR for many rivers in the western United States has shifted to earlier in the snowmelt season. This shift occurred as a step change during the mid-1980s in conjunction with a step increase in spring and early-summer atmospheric pressures and temperatures over the western United States. The cause of the step change has not yet been determined.

### 1. Introduction

Snowmelt runoff (SMR) is an important source of water for much of the western United States (McCabe and Wolock 1999; Stewart et al. 2004), and for snowmelt-dominated basins in the western United States spring/summer runoff can account for from 50% to 80% of total annual runoff (Serreze et al. 1999; Stewart et al. 2004). One of the expected hydrologic effects of global warming is a shift in the timing of SMR to earlier in the year (Gleick 1987; McCabe and Ayers 1988; Gleick and Adams 2000; Mote et al. 2005; Regonda et al. 2005). Consistent with this hypothesis a number of studies have identified declines in spring snowpack (Mote et al. 2005) and a shift to earlier SMR for many rivers in the western United States (Aguado et al. 1992; Wahl 1992; Pupacko 1993; Dettinger and Cayan 1995; Rajagopalan and Lall 1995; Cayan et al. 2001; Regonda et al. 2005; Stewart et al. 2004). The observed shift to earlier SMR is especially noticeable for basins in the northwestern United States (Mote et al. 2005; Regonda et al. 2005; Stewart et al. 2004). These studies also have indicated that the primary driving force of the shift in SMR timing has been increases in spring and early-

summer temperatures (Aguado et al. 1992; Dettinger and Cayan 1995; Regonda et al. 2005; Stewart et al. 2004) and possibly global warming (Regonda et al. 2005; Stewart et al. 2004).

Although a number of studies have identified a shift to earlier SMR for many rivers in the western United States, these studies have depended on trend analyses to identify these changes (Stewart et al. 2004). Trend analyses are unable to determine if a trend is gradual or a step change. Often the interpretation of trend analysis is that the change identified is gradual. Since changes in SMR timing have been identified by linear trends, there is a tendency to attribute these changes to global warming because of large correlations between linear trends in SMR timing and the increasing trend in global temperature. It often is difficult to determine the physical processes driving linear trends because so many variables with linear trends will correlate highly with one another. To better understand the climate processes driving the changes to earlier SMR timing in the western United States it is important to appropriately characterize the changes as gradual trends or as step changes (McCabe and Wolock 2002).

The objectives of this study are to 1) characterize the changes in the timing of SMR, 2) identify when changes in SMR timing have occurred, and 3) determine what climate processes are likely driving the observed changes in the timing of SMR in the western United States.

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## 2. Methods and data

Daily streamflow data for 84 stations in the western United States with complete data for water years (a water year is the period October through September) 1950–2003 were used in this study (Fig. 1). These stations were selected from the Hydroclimatic Data Network (HCDN; Slack and Landwehr 1992). The HCDN includes streamflow measurements for streams with little or no anthropogenic influences (e.g., diversions of water, reservoirs) and are thus considered natural flows. Although the original HCDN dataset ended in the year 1988, daily streamflow time series for the streams used in this study were extended through 2003. For the 84 stations included in this study the mean percentage of total water-year runoff that occurs during April through July (defined here as the SMR period) ranges from 52% to 87%, with a median value of 69%. These statistics indicate that SMR is an important, and in many cases the largest, supply of water for the rivers analyzed in this study.

For each station analyzed, the daily time series were used to compute for each water year the Julian day on which 50% of the mass of the total annual streamflow occurred [hereafter referred to as the center of mass date (CMD)]. This methodology has been used in previous studies as an index of the timing of SMR (Regonda et al. 2005; Stewart et al. 2004). Time series of the CMDs for each station then were analyzed to identify and characterize any changes in the timing of SMR.

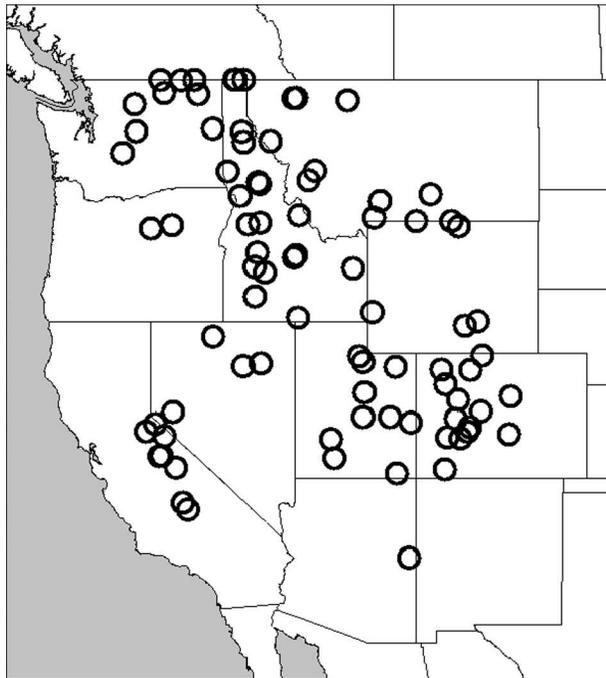


FIG. 1. Locations of streamflow sites analyzed in this study.

The time series of CMDs indexing the timing of SMR also were analyzed using a principal components analysis (PCA) to identify the primary modes of SMR timing in the western United States (Johnston 1980). The scores of the resultant principal components were plotted and analyzed.

In addition to the streamflow data, monthly temperature data for the western United States were obtained for the 84 climate divisions in the western United States (Fig. 2a). The climate divisions represent regions within states that are, as nearly as possible, climatically homogeneous (Karl and Riebsame 1984). In addition, the data for the climate divisions have been corrected for time-of-observation bias (Karl et al. 1986). Although extreme climatic variations can occur in areas of complex terrain, such as mountainous areas, standardized departures of temperature and precipitation from normal are spatially consistent within a climate division (Karl and Riebsame 1984). The monthly temperature data were used to compute mean spring/early-summer [April–May–June–July (AMJJ)] temperatures for the period 1950–2003 for each climate division in the western United States. The AMJJ months were used to rep-

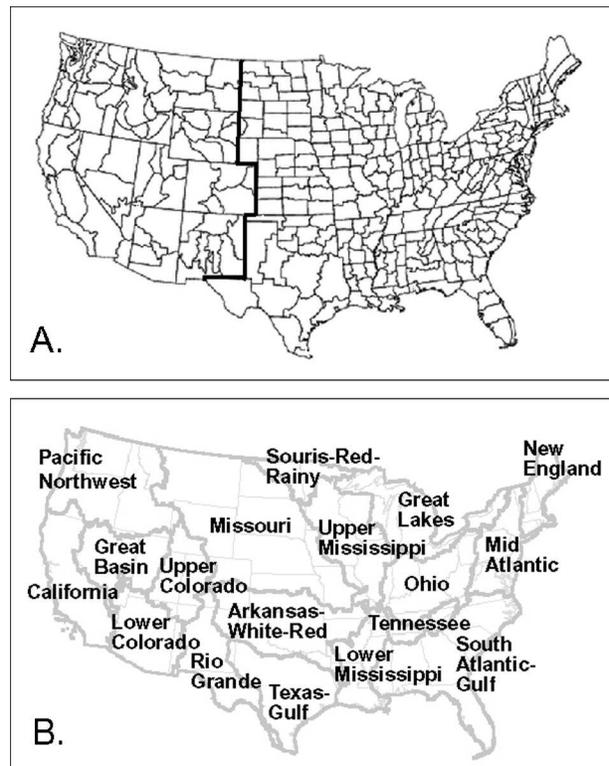


FIG. 2. (a) Climate divisions in the conterminous United States. The climate divisions to the left of the dark line were used in the analysis. (b) Water resource regions in the conterminous United States.

resent the SMR season. These time series then were averaged to compute a mean time series of AMJJ temperatures for the western United States as a whole.

Time series of common climate indices also were used in this study. Monthly values of the Pacific decadal oscillation (PDO) were obtained from the Joint Institute for the Study of the Atmosphere and Ocean at the University of Washington, Seattle, Washington ([http://tao.atmos.washington.edu/data\\_sets](http://tao.atmos.washington.edu/data_sets)). Monthly values of Niño-3.4 sea surface temperatures [indexing the El Niño–Southern Oscillation (ENSO)] were obtained from <http://climexp.knmi.nl/data/inino5.dat>.

Gridded temperature and atmospheric pressure datasets also were used in the analysis. Gridded ( $5^\circ$  by  $5^\circ$  grid) and mean global monthly temperatures were obtained from the Climate Research Unit at East Anglia, United Kingdom (<http://www.cru.uea.ac.uk/cru/data>). Monthly 700-hPa height anomalies were derived from gridded daily 700-hPa height series pressure data produced by the National Oceanic and Atmospheric Administration's Climate Analysis Center and were obtained from the Climate Research Division at the Scripps Institution of Oceanography. The 700-hPa level was chosen for analysis because this atmospheric level provides a good representation of midtropospheric atmospheric circulation above many of the complex/local influences at the earth's surface (McCabe and Dettinger 2002).

### 3. Results and discussion

As a starting point, and to be consistent with previous studies of SMR timing, linear trends in the CMDs for each of the 84 sites included in this study were computed. For most of the sites analyzed (79 sites), linear trends in CMDs (Fig. 3) indicate that the timing of SMR has become earlier (negative trends). These results are consistent with previous studies (Dettinger and Cayan 1995; Rajagopalan and Lall 1995; Cayan et al. 2001; Mote et al. 2005; Regonda et al. 2005; Stewart et al. 2004) and are consistent with the expected effects of increased temperatures observed across the western United States during recent decades (Cayan et al. 2001). Because of large interannual variability, most of the trends in CMD are not statistically significant (only 33 sites indicate trends in CMD that are statistically significant at a 90% confidence level). The trends in CMD, however, do indicate a large degree of spatial coherence (Mote et al. 2005; Regonda et al. 2005; Stewart et al. 2004). The largest trends to earlier SMR are found in the Pacific Northwest and for a few sites in the central Rocky Mountains. In addition, most of the largest trends are found for sites with the lowest elevations.

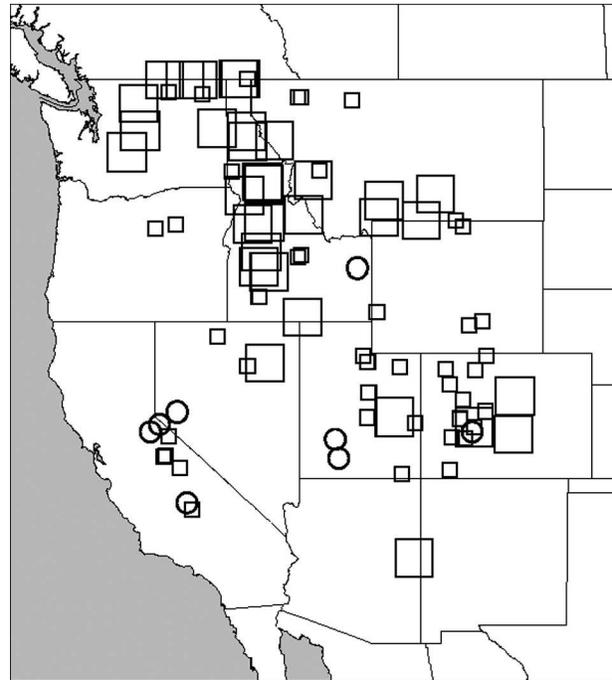


FIG. 3. Linear trends (correlations with time) in the Julian date when 50% of total annual runoff occurs, 1950–2003. Squares indicate trends to earlier dates and circles indicate trends to later dates. Large symbols indicate trends that are significant at a 90% confidence level.

The correlation between trends in SMR and elevation is 0.63 (significant at a 99% confidence level). The relation of trends in SMR timing with elevation is consistent with results presented by previous studies (Mote et al. 2005; Regonda et al. 2005; Stewart et al. 2004). Sites that indicate no trend or an increasing trend in SMR have the highest elevations of the sites analyzed. Apparently these sites have low enough winter/spring temperatures that any warming that has occurred in recent decades has not been large enough to affect SMR timing (Regonda et al. 2005).

The spatial coherence of the trends in SMR also can be seen in the distributions of trends for water resource regions. There are 18 water resource regions in the conterminous United States (Fig. 2b). These subdivisions, or hydrologic units, are used for collection and organization of hydrologic data. The hydrologic units outlined in these data represent natural and man-made stream-drainage areas. Trends of SMR timing were examined for five of the water resource regions in the western United States [i.e., Missouri, Upper Colorado, Great Basin, California, and Pacific Northwest (Fig. 2b)]. These water resource regions were chosen because they included at least six of the streamflow sites used for analysis. The distributions of trends of SMR timing in-

dicate a range of trend values within each water resource region (Fig. 4). As illustrated in Figs. 3 and 4, most sites indicate decreasing trends in SMR timing (trends to earlier SMR); however, many of the trends are not statistically significant. In addition, of the five water resource regions examined, trends are largest for the Missouri and Pacific Northwest water resource regions.

A PCA of the time series of CMDs indicates that the first principal component (PC1) explains over 44% of the variance in all of the data. The second component explains less than 15%, and subsequent components explain only approximately 8%, 6%, and 3%. The loadings of the individual CMD time series on PC1 are strongly negative for most sites in the western United States (median value =  $-0.67$ ; 25th percentile =  $-0.82$ ; 75th percentile =  $-0.50$ ). The large amount of variance of the CMDs explained by PC1, and the strongly negative loadings of CMDs on PC1 for most sites in the western United States indicates that this component represents western United States-wide covariance in CMDs. Thus, most of the sites included in this analysis have experienced similar changes in the timing of SMR. Further evidence of this large-scale covariance in CMDs is that the scores for PC1 (multiplied by  $-1$  for ease of comparison) are highly correlated ( $r = 0.99$ , significant at a 99% confidence level) with the mean time series of CMDs averaged for all 84 sites (Fig. 5). Because of the large correlation between PC1 and the mean time series of CMDs, the mean time series of CMDs is used to represent the changes in SMR timing

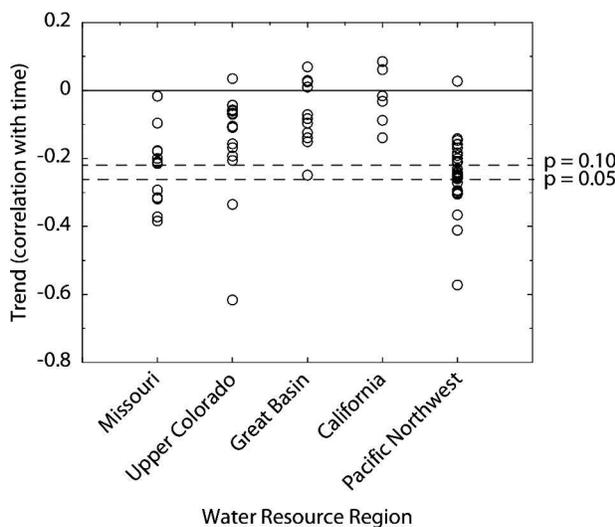


FIG. 4. Distributions of linear trends in the Julian date when 50% of total annual runoff occurs, 1950–2003, for five of the water resource regions in the western United States.

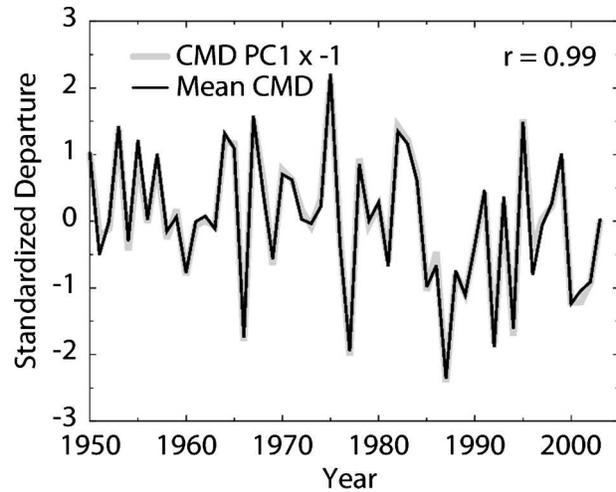


FIG. 5. Scores (gray line) for PC1 from a principal components analysis of the time series of Julian dates when 50% of annual runoff occurs (CMD) for 84 sites in the western United States, 1950–2003 (the PC1 time series was multiplied by  $-1$ ), and standardized departures (black line) of the mean CMD time series for the 84 sites.

that have occurred in the western United States during 1950–2003.

Because previous studies found that changes in CMDs were related to increases in spring and early-summer temperatures (Aguado et al. 1992; Dettinger and Cayan 1995; Regonda et al. 2005; Stewart et al. 2004) the mean CMD time series was compared with mean AMJJ temperatures for the western United States. The AMJJ temperature data were computed from monthly climate division data for the 84 climate divisions in the western United States. For 82 of the 84 climate divisions AMJJ temperatures indicate increasing trends (46 are significant at a 95% confidence level; Fig. 6). These trends in spring/summer temperatures have been reported in previous studies (Stewart et al. 2004).

A PCA of the AMJJ temperature for the western United States indicated that the first PC explains 56% of the variance in the AMJJ temperature data for the western United States. Subsequent components explain 16%, 10%, 5%, and 4% of the variance in the temperature data. Loadings on PC1 of AMJJ temperature data for the individual climate divisions in the western United States were strongly negative for all climate divisions. Thus, the first PC of the AMJJ temperature data represents a large amount of the variability in AMJJ temperatures across the entire western United States. The correlation between the first AMJJ temperature PC and mean AMJJ temperature averaged for the western United States is  $-1.0$ . Because the first PC

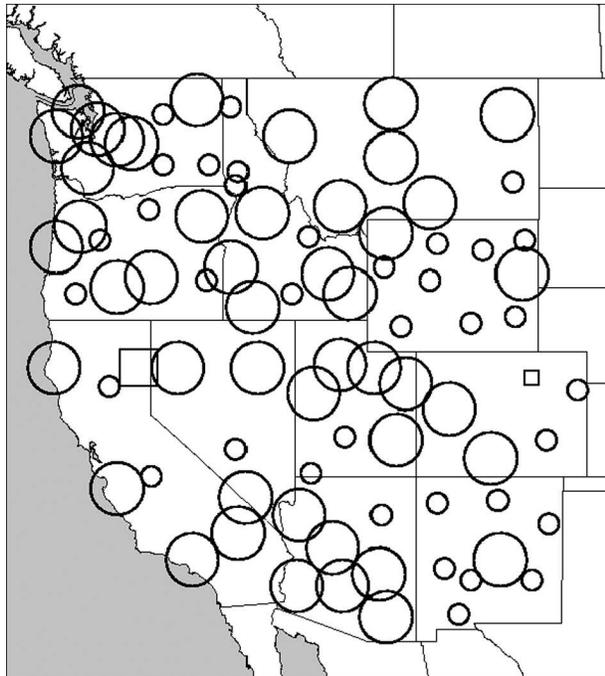


FIG. 6. Linear trends in Apr–Jul climate division temperature, 1950–2003. Squares indicate decreasing trends and circles indicate increasing trends. The large symbols indicate trends that are significant at a 95% confidence level.

for the AMJJ temperature explains so much of the variability in AMJJ temperature in the western United States, and because this PC is so highly correlated with mean western U.S. AMJJ temperature, the time series of mean AMJJ temperature averaged for the western United States is used in the remainder of this study to represent spring/summer temperature variations in the western United States.

Comparison of the mean CMD time series for the 84 sites in the western United States and the mean AMJJ temperature (multiplied by  $-1$ ) time series for the 84 climate divisions of the western United States indicates a large correlation [ $r = 0.85$ , significant at a 99% confidence level (the temperature time series was multiplied by  $-1$  for ease of comparison; Fig. 7)].

Both the CMD and temperature time series indicate a relatively abrupt (steplike) change during the mid-1980s (Fig. 7). To examine the shift in SMR timing further, moving  $t$  tests comparing sets of 10-yr moving periods were computed for each of the 84 CMD time series. For each period, the numbers of sites with statistically significant (at a 95% confidence level) increases, or decreases, in the CMD were counted. The time series of these counts (Fig. 8) clearly indicates a shift to earlier SMR timing for a large number of sites in the western United States during the mid-1980s.

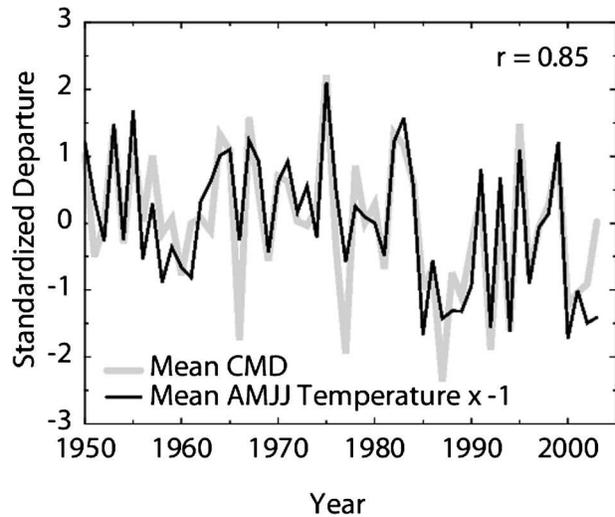


FIG. 7. Standardized departures of the mean Julian date when 50% of annual runoff occurs (CMD, averaged for 84 sites in the western United States) (gray line) and mean AMJJ temperature for the western United States (black line). The temperature time series was multiplied by  $-1$  for easy comparison with the CMD time series.

Very few sites were found to have shifts to later SMR timing for any of the periods analyzed. The large number of sites indicating a shift to earlier SMR for such a narrow period of time suggests that the change in SMR timing occurred as a step change rather than as a gradual trend.

To identify possible atmospheric driving forces of the variability in CMD and the apparent step change during the mid-1980s, the CMD time series was correlated with mean AMJJ 700-hPa heights for the region from  $140^{\circ}\text{E}$  longitude to  $60^{\circ}\text{W}$  longitude and from  $10^{\circ}\text{S}$  latitude to  $70^{\circ}\text{N}$  latitude.

Correlations between the CMD time series and mean AMJJ 700-hPa heights indicates a significant inverse

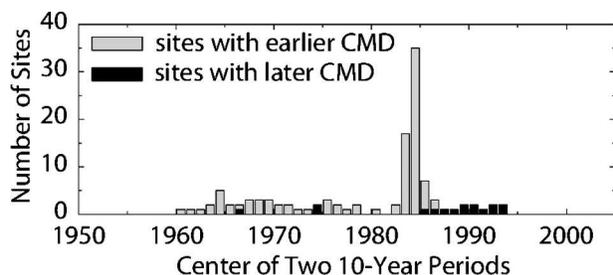


FIG. 8. Ten-year moving counts of the number of sites with statistically significant (at a 95% confidence level) increases (later timing, black bars), or decreases (earlier timing, gray bars), in the Julian date when 50% of total annual runoff occurs. The significance of the differences in mean Julian dates for sets of 10-yr moving periods was determined using a Student's  $t$  test.

correlation (significant at a 99% confidence level) centered over the western United States (Fig. 9). The pattern of correlations indicates that when atmospheric pressures are greater (lower) than average, CMDs in the western United States are earlier (later) than average. The relation between atmospheric pressure and CMDs is supported by the correlation between the mean CMD time series and mean AMJJ temperatures for the western United States (Fig. 7). When atmospheric pressures are greater than average, temperatures are generally higher than average due largely to atmospheric subsidence and the compressional heating of air (Wallace and Gutzler 1981). Correlations between the mean CMD time series and mean 700-hPa heights averaged for the western United States is  $-0.75$  (significant at a 99% confidence level), and correlations between mean AMJJ temperature for the western United States and mean 700-hPa heights is  $0.85$  (significant at a 99% confidence level).

Stewart et al. (2004) suggest that the changes in SMR timing could be related to the PDO, whereas Regonda et al. (2005) speculate that trends in SMR timing could be a response to the increased frequency of El Niño events in recent decades, or to general global warming. The first PC resulting from the PCA of the CMD data is not well correlated with either of these indices; however, the second PC is significantly correlated with both PDO ( $r = -0.51$ , significant at a 99% confidence level) and Niño-3.4 SSTs ( $r = -0.32$ , significant at a 95% confidence level). These results suggest that PDO and ENSO account for some portion (albeit small) of the variability in CMDs across the western United States.

Since AMJJ temperatures are so highly correlated with the mean CMD time series and because Regonda et al. (2005) speculated that changes in the timing of SMR may be related to global warming, correlation between the CMD time series and global AMJJ temperatures also was computed. The resulting correlation is small ( $r = -0.27$ ) and although this correlation is



FIG. 9. Correlations between the mean Julian date (averaged for 84 sites in the western United States) when 50% of annual runoff occurs (CMD) and mean AMJJ 700-hPa heights. The solid lines indicate positive correlations, and the dashed lines indicate negative correlations. The contour interval is 0.2 and the first solid isoline is the zero correlation isoline.

statistically significant at a 95% confidence level, the magnitude of the correlation suggests that the mean CMD time series has little relation with global temperatures on the time scale—and for the period—examined. An additional analysis was performed to further examine the possible connection between global temperatures and changes in SMR timing. The mean CMD time series was correlated with gridded AMJJ temperatures for the globe. The gridded AMJJ temperatures were computed from monthly temperature data for  $5^\circ$  by  $5^\circ$  grids obtained from the Climate Research Unit in East Anglia, United Kingdom (see online at <http://www.cru.uea.ac.uk/cru/data/temperature/>). Correlations were computed for grids with at least 30 yr of data during 1950–2003.

Strong correlations ( $r \geq 0.5$  or  $r \leq -0.5$ ) between the gridded AMJJ temperatures and the mean CMD time series for the western United States are only found for grids located in the western United States (Fig. 10). Correlations for other regions of the world are small and many are close to zero. Similarly, correlations between mean AMJJ temperatures for the western United States and gridded global AMJJ temperature are only strong for grids over the western United States. These results suggest that the climate factors affecting the changes observed in SMR timing are regional.

The connection between changes in SMR and global warming (i.e., anthropogenic greenhouse forcing) is a complex one. On one hand, one could develop the argument that since the changes in SMR are best represented as a step change and the trends in NH temperature are gradual, then anthropogenic greenhouse gases may not be the driving force. Similarly, one could argue against anthropogenic greenhouse forcing on the basis of the regional character of SMR variability.

However, on the other hand, one could follow the

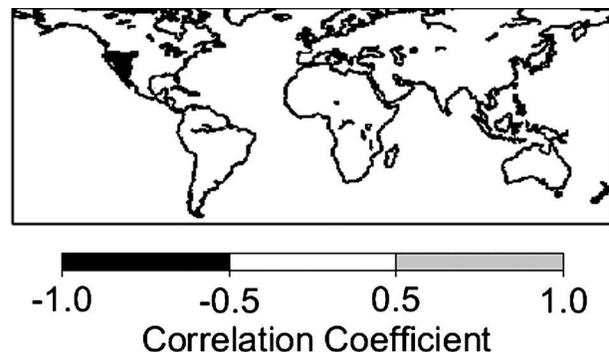


FIG. 10. Correlations between AMJJ gridded temperature and the mean Julian date (averaged for 84 sites in the western United States) when 50% of annual runoff occurs (CMD). Correlations were computed for grids with at least 30 yr of data during 1950–2003.

sequence of arguments that increased atmospheric greenhouse gases lead to warmer temperatures, and earlier SMR is a response to warmer temperatures—therefore, the observed changes illustrated in this study may be an early appearance of anthropogenic climate change. With this perspective, the step change and regional character of SMR variability in the western United States also may be explained as a nonlinear response to anthropogenic greenhouse forcing.

#### 4. Conclusions

Time series of daily runoff for 84 rivers in the western United States were analyzed to characterize changes in the timing of SMR. Results indicate that the timing of SMR for many rivers in the western United States has shifted to earlier in the snowmelt season. In addition, the shift to earlier SMR has not been a gradual trend, but appears to have occurred as a step change during the mid-1980s. The shift in SMR is related to a regional step increase in AMJJ temperatures during the mid-1980s. A small portion of the variability in the timing of SMR and AMJJ temperatures is attributable to PDO and ENSO; however, these climate indices are not sufficient to explain the changes in SMR timing. In addition, it appears that the observed change in the timing of SMR in the western United States is a regional response to natural climate variability and may not be related to global trends in temperature. It is unknown whether the shift to earlier SMR timing will continue or if there will be a change to later SMR timing.

While attribution of SMR timing variability to external climate forcings is complicated, the observed changes will have profound impacts on water resource management in the western United States. There is an urgent need to understand the societal impacts of changes in SMR and develop strategies to cope with a wide range of climate impacts that may be encountered during the next 50 years.

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