Shifts in Western North American Snowmelt Runoff Regimes for the Recent Warm Decades

HOLGER FRITZE

Institute for Geoinformatics, University of Münster, Münster, Germany

IRIS T. STEWART

Department of Environmental Studies and Sciences, Santa Clara University, Santa Clara, California

EDZER PEBESMA

Institute for Geoinformatics, University of Münster, Münster, Germany

(Manuscript received 1 September 2010, in final form 15 March 2011)

ABSTRACT

Climate change–driven shifts in streamflow timing have been documented for western North America and are expected to continue with increased warming. These changes will likely have the greatest implications on already short and overcommitted water supplies in the region. This study investigated changes in western North American streamflow timing over the 1948–2008 period, including the very recent warm decade not previously considered, through (i) trends in streamflow timing measures, (ii) two second-order linear models applied simultaneously over the region to test for the acceleration of these changes, and (iii) changes in runoff regimes. Basins were categorized by the percentage of snowmelt-derived runoff to enable the comparison of groups of streams with similar runoff characteristics and to quantify shifts in snowmelt-dominated regimes. Results indicate that streamflow has continued to shift to earlier in the water year, most notably for those basins with the largest snowmelt runoff component. However, an acceleration of these streamflow timing changes for the recent warm decades is not clearly indicated. Most coastal rain-dominated and some interior basins have experienced later timing. The timing changes are connected to area-wide warmer temperatures, especially in March and January, and to precipitation shifts that bear subregional signatures. Notably, a set of the most vulnerable basins has experienced runoff regime changes, such that basins that were snowmelt dominated at the beginning of the observational period shifted to mostly rain dominated in later years. These most vulnerable regions for regime shifts are in the California Sierra Nevada, eastern Washington, Idaho, and northeastern New Mexico. Snowmelt regime changes may indicate that the time available for adaptation of water supply systems to climatic changes in vulnerable regions are shorter than previously recognized.

1. Introduction

Surface water supplies throughout western North America hinge on a highly seasonal and variable mountain runoff pattern that is sensitive to climatic variability and change. While mountain regions in general contribute twice as much discharge to the terrestrial portion of the hydrologic cycle as the adjacent lowlands (Viviroli et al. 2007), in western North America, the largest share of that precipitation is deposited between the months of October and March, resulting in a comparatively narrow window of time during which runoff is generated for the year. In rain-dominated and mixed runoff regimes, the largest fraction of runoff comes during winter and early spring, closely following the precipitation pattern. For snowmelt-dominated basins, most of the winter precipitation is stored as snow in the higher elevations of the watershed and is released during spring and early summer. This spring snowmelt runoff pulse contributes up to 75% of total annual runoff for the snowmelt-dominated basins in the region (Dettinger 2005; Stewart et al. 2004); its start and peak are to a large degree determined by latitude and altitude of the watershed.

Corresponding author address: Iris T. Stewart, Department of Environmental Studies and Sciences, Santa Clara University, 874 Lafayette Street, Santa Clara, CA 95053-0563.
E-mail: IStewartFrey@scu.edu

DOI: 10.1175/2011JHM1360.1

Mountain runoff is captured in reservoirs during late winter and early spring and often transported over great distances to sustain large agricultural areas and urban centers through the summer drought period. Before the snowmelt runoff pulse, these reservoirs are in flood protection mode, such that earlier runoff due to timing shifts may not be captured. Thus, in this highly seasonal system, the timing of streamflow is as important as the overall quantity and quality for both ecosystem health and human uses (Dettinger and Cayan 1995). Especially in the dry Southwest, where essentially all water is already allocated, user demands continue to increase, and a situation of limited water availability has been exacerbated over the last decade (Anderson et al. 2008).

As regional climate is the dominant factor in determining the amount and timing of flows in natural river basins, the high year-to-year variability in temperatures and precipitation coupled with high demands already pose a challenge to water managers. In addition, temperatures over western North America have been warming on the order of 1°C per century (Mote 2003; Mote et al. 2005; Hamlet et al. 2007; Hamlet and Lettenmaier 2007), although some spatial and temporal variability exists. Precipitation changes are less clear. In spite of a general increase in precipitation, no regionally consistent trend over the region has been found (Mote et al. 2005; Hamlet et al. 2007; Hamlet and Lettenmaier 2007). However, changes in interannual variability, increased variance, increased autocorrelation in time, and increased synchronicity between the different regions of the western United States were described by Hamlet and Lettenmaier (2007) and Pagano and Garen (2005).

Concurrent with these climatic shifts, recent studies have identified declining spring snowpacks (Mote et al. 2005), greater fractions of precipitation coming as rain (Knowles et al. 2006), and a spring snowmelt runoff pulse that has come increasingly earlier over the past several decades (Cayan et al. 2001; Stewart et al. 2005; McCabe and Clark 2005; Dettinger 2005). While natural climatic oscillations, such as the El Niño Southern Oscillation (ENSO) and the Pacific decadal oscillation (PDO), appear to contribute to the observed widespread and regionally coherent hydroclimatic changes, several studies (Knowles et al. 2006; Stewart et al. 2005; Mote et al. 2005) concluded that shifts toward earlier melt and runoff are mainly connected to anthropogenically driven winter and spring warming. More recently, several rigorous detection and attribution studies have formally established human-induced climatic changes rather than internal natural variability as the main driver of the observed hydroclimatic shifts of the past decades (i.e., Barnett et al. 2005; Bonfils et al. 2008; Das et al. 2009).

Interestingly, the 1998–2008 decade has seen some of the warmest years on record (Bates et al. 2008; NOAA 2009), which have not been included in the previous analyses. The principal goal of the current study, therefore, is to establish whether and how streamflow timing for snowmelt-dominated, mixed, and rain-dominated regimes across the region has responded to these most recent climatic drivers. In particular we ask, if the warming experienced through 2008 has resulted in either an acceleration of timing trends compared to the previously established changes and/or a shift in the runoff regime (i.e., from snowmelt dominated to rain dominated). To this end, trends in streamflow timing indices are computed and correlated to climatic indices to indicate responses on a stream-by-stream basis and allow comparison to prior work. As these stream responses are varying greatly from one basin to another, we also take a new "category perspective," where individual basins are classified based on four snowmelt-domination categories (SDCs) and the average hydroclimatic response for each category is computed. This approach yields a description of streamflow changes for a particular runoff regime over a large spatial scale. The behavior of the combined streamflow timing trends for the region is explored with two second-order regression models applied to each SDC. In addition, the SDC perspective also allows us to determine which streams have experienced a change in runoff regime over the study period.

As our study area extends over a subcontinental scale, but each gauge represents data for a corresponding watershed on a much finer scale, we explored possibilities of an easy accessible visualization of the results and graphical outcomes. A Microsoft Windows application has been developed to enable public access to the collection of hydrographs and metadata for each gauge using concepts of virtual globe technology.

2. Data and methods

In this study, several previously established measures were applied to the most recent data to facilitate comparison to prior studies. In addition, new approaches to distinguish between rain and snowmelt pulses, as well as classifying runoff regimes, were developed as described below.

a. Stream gauges

This study is based on streamflow records for the western North American continent north of 29°N and west of 105°W for the 1948–2008 period, as earlier streamflow records are often not available or not continuous. Data sources and specifications are summarized in Table 1. Basins used in this study are generally considered

TABLE 1. Data sources.

Data	Data source	Retrieval date	Spatial extent	Spatial resolution	Time period	Temporal resolution
Stream discharge	United States: USGS, National Water Information System (NWIS)	21 Mar 2009	−170°–−105°W 31°–70°N	Point data measured at individual gauges	Water year 1948–2008	Daily averages
	Canada: Environment Canada processed by Scripps Institute of Oceanography	21 Jul 2009		United States: 309 Canada: 53		
	http://waterdata.usgs.gov/nwis/sw					
Temperature and precipitation	PRISM	27 Mar 2009	Tile at each river gauge	Tile size 2.5''	Water year 1948–2008	Temperature: monthly averages Precipitation: monthly sums
	ftp://prism.oregonstate.edu/pub/prism					
PDO	University of Washington	7 May 2009	North Pacific Ocean (north of 20°)	N/A	1948–2008	Monthly averages
	http://jisao.washington.edu/pdo/PDO.latest					
Political maps	U.S. Census Bureau	22 Mar 2009	U.S. States: AK, AZ, CA, CO, ID, MT, NM, NV, OR, UT, WA, and WY Provinces in Canada: AB, BC, NT, SK, and YT	N/A	N/A	N/A
	www.census.gov/cgi-bin/geo/shapefiles/national-files					
Digital elevation model (DEM)	USGS, GTOPO30	20 Jul 2009	100°–180°W 90°–10°W 100°–140°W 90°–10°W	Tile size 30 arc seconds	Developed over a 3-yr period	Completed in 1996
	http://eros.usgs.gov/#/Find_Data/Products_and_Data_Available/gtopo30_info					

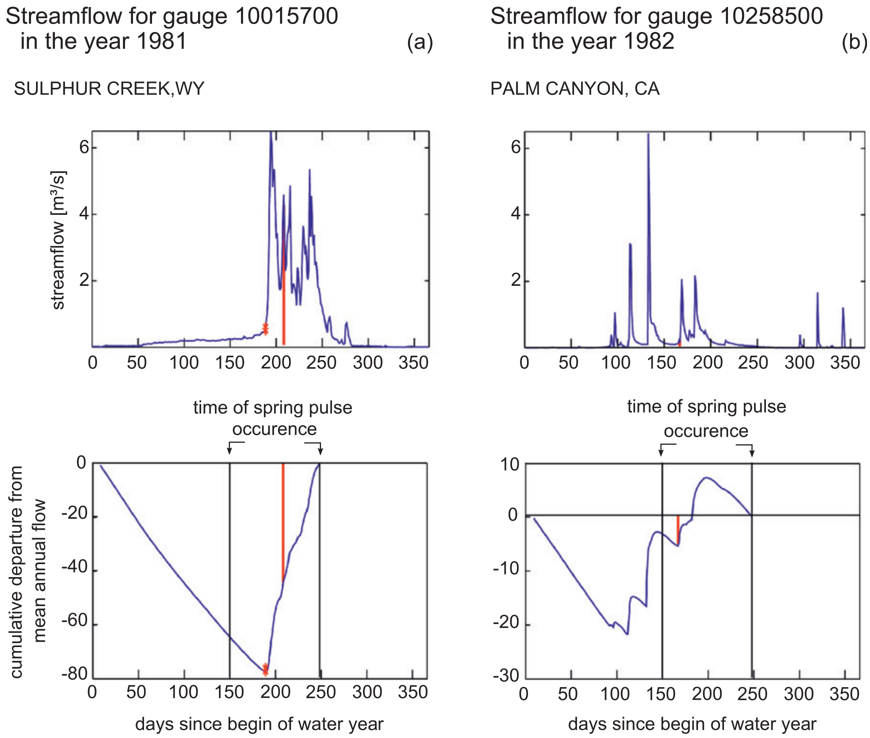

FIG. 1. Comparison of (top) hydrographs and (bottom) their corresponding cumulative departures from the mean for (a) a snowmelt-dominated stream and (b) a rain-dominated stream. The red line indicates the timing of CT, and the red asterisk denotes the start of the snowmelt runoff pulse. The hydrograph in (b) is not identified as exhibiting a snowmelt pulse because of the time constraint (see text for explanation).

to be free of anthropogenic influences, such as water diversions and land-use changes that modify flow timing and amount, and streams with less than 40 years of full records were excluded from the analysis. The resulting dataset includes a list of the 309 U.S. and 53 Canadian gauges, and can be accessed at http://webpages.scu.edu/ftp/streamflowtiming/. All analysis is based on the water year (1 October–30 September) for the region.

b. *Monthly fractions of annual streamflow*

Prior studies (i.e., Roos 1991; Dettinger and Cayan 1995; Aguado et al. 1992; Stewart et al. 2005) have used monthly fractional runoff hydrographs for individual streams with varying altitudes. Monthly fraction of the annual runoff smooths the variability of daily data by aggregation. This study used this measure not for single streams but for a collection of streams and applied it to the SDCs defined below. Trend analysis was used to investigate changes for monthly flow fractions.

c. *Start of the snowmelt runoff pulse*

An algorithm developed by Cayan et al. (2001) identified the start of the snowmelt pulse as the time of transition when low winter base flow changes into high spring flow conditions, and therefore, as the day when the cumulated departure from the year's mean flow is most negative (Fig. 1a). However, the procedure often incorrectly identified late winter–spring rain events as snowmelt pulses for rain-dominated, mixed, but also marginal snowmelt regimes. Thus, we modified the algorithm developed by Cayan et al. (2001) to distinguish the presence of a snowmelt pulse from late winter–spring rain events in any given year and for any runoff regime as follows: first, the global minimum of the cumulated departure only served as an indication of a snowmelt pulse if it fell into the period between the 150th and 250th day of the water year. Second, as the characteristics of snowmelt-dominated regimes exhibit a negative departure (Fig. 1a), while those of rainfall-dominated regimes exhibit both positive and negative departures from the year's mean flow (Fig. 1b), a snowmelt pulse was logically excluded if the ratio of the area of positive departure (indicating rainfall events) to that of the area of negative departure was ≥ 1. The introduction of these new criteria minimized the identification of "false positives" for snowmelt pulses.

It should be noted that the start of the snowmelt runoff pulse can at times not be as clearly defined as the one in Fig. 1a as several smaller melting events may lead up to the main snowmelt pulse. In these cases, several dates within a range could reasonably be defined as the start of the snowmelt runoff. This is especially true for basins that are partially snowmelt dominated, which leads to additional uncertainty in this index.

d. Center of timing

Stewart et al. (2005) characterized the discharge by the ''center of timing'' (CT), a flow-weighted timing measure representing the center of mass, which is calculated as

$$\mathrm{CT} = \frac{\sum_{i=1}^{n} t_i q_i}{\sum_{i=1}^{n} q_i},$$

with t_i the time in days from beginning of the water year and q_i the corresponding discharge for day i. This CT measure has been applied by several other studies such as Regonda et al. (2005), McCabe and Clark (2005), Clow (2010), and Luce and Holden (2009). As most precipitation falls in the winter, a later CT indicates a lower winter and a higher spring discharge and a tendency toward a greater snowmelt component for snowmelt-dominated gauges. For rain-dominated gauges, a late CT corresponds to precipitation that is centered later in the year. An earlier CT is an indication of earlier snowmelt for gauges with a snowmelt component, and/or a higher fraction of winter precipitation arriving as rain. CT and snowmelt runoff pulse, average streamflow of the year, and the average streamflow of the gauge were calculated and graphed for each gauge and year; an example is shown in Fig. 2. CT is indicated by a vertical red line and the start of the snowmelt runoff pulse by a red star.

e. Visualization

Annual hydrographs including CT and the start of the snowmelt runoff pulse for each gauge and year are provided on a virtual globe. We chose to implement an application using the open-source National Aeronautics and Space Administration (NASA) World Wind Java (WWJ) Software Development Kit (SDK) to offer functionality, which is not achievable by using common virtual globes (e.g., Google Earth). This interface offers free and public access to the measures and allows browsing through the years along with visualizations of the snowmelt pulse algorithm. The Microsoft Windows application can be downloaded at http://webpages.scu.edu/ftp/streamflowtiming. The source code is freely available, and the application can be adapted under a creative commons license.

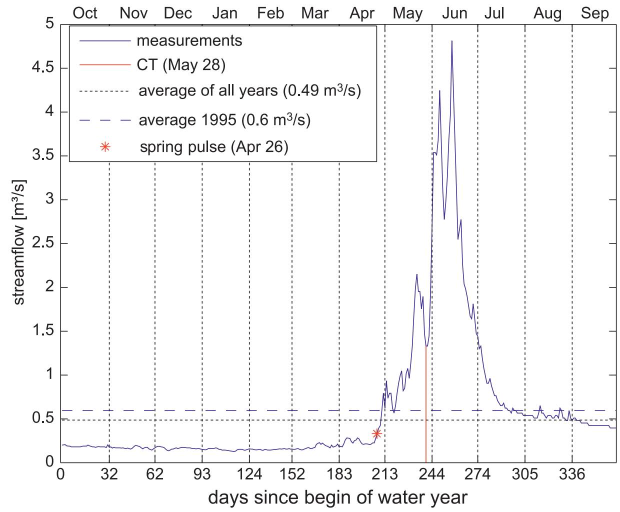

FIG. 2. Hydrograph of the 1995 discharge of the Salina Creek, Utah U.S. Geological Survey (USGS) gauge 10205030 with flow characteristics indicated. Flow characteristics for all gauges are available through the project Web site.

f. Snowmelt-domination categories

All gauges in this study were classified into one of four SDCs based on the amount of snowmelt-dominated runoff in the basin. The determining factor is the fraction of years with and without a snowmelt pulse over the 1948–2008 period:

SDC 1: clearly rain dominated; snowmelt pulses occur in <30% of the years,
SDC 2: mostly rain dominated; snowmelt pulses occur in ≥30% and <50% of the years,
SDC 3: mostly snowmelt dominated; snowmelt pulses occur in ≥50% and <70% of the years, and
SDC 4: clearly snowmelt dominated; snowmelt pulses occur in ≥70% of the years.

Shifts in snowmelt-domination regimes were assessed by splitting the observational period of 61 years into two subperiods and comparing the percentage of snowmelt runoff pulses for the first and second period. Three different pairs of subperiods were used, such that runoff characteristics in the past 10, 20, and 30 years of record can be compared to those of the earlier subperiod:

(i) 1948–78 versus 1979–2008, split at 1978/79;
(ii) 1948–88 versus 1989–2008, split at 1988/89 (cf. Fig. 12); and
(iii) 1948–98 versus 1999–2008, split at 1998/99 (cf. Fig. 13).

All periods were required to have data for at least two-thirds of the time to avoid the determination of artificial

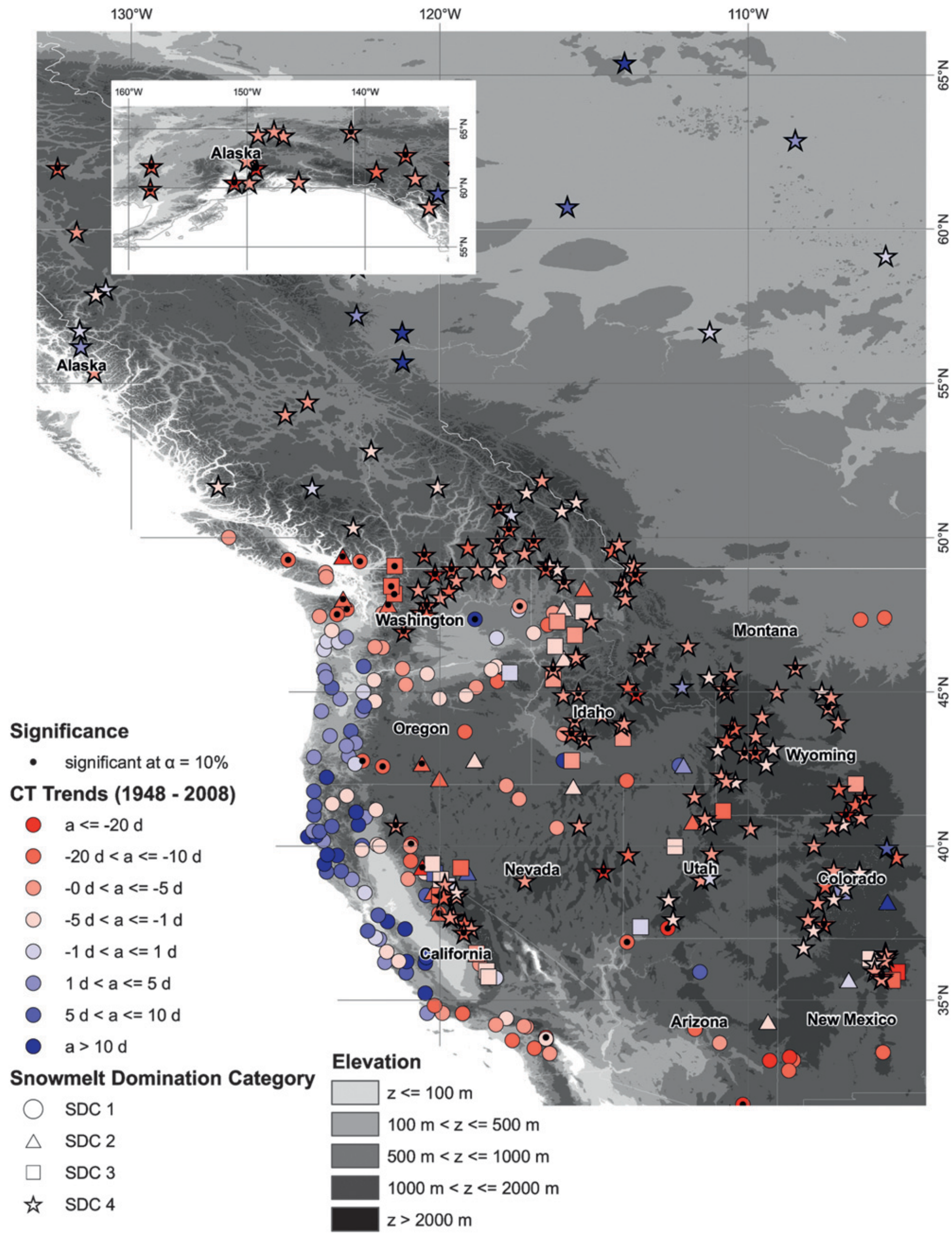

FIG. 3. Trends in CT for each SDC. Trend values are given in days over the 61-yr period.

category shifts. Sufficiently large changes in the percentage of snowmelt runoff pulses caused basins to receive different classifications for the first and second subperiod and be identified as having experienced a SDC shift.

g. Connection to climatic indices

The highly seasonal temperature and precipitation patterns reflecting climatic conditions play a key role in streamflow timing across western North America (Stewart et al. 2004). Temperature and precipitation data were obtained from the Parameter-elevation Regressions on Independent Slopes Model (PRISM), a high-quality, topographically sensitive, 2.5° minutes (4 km) climate data grid that uses a combined statistical and geographic approach to map climate that is well suited to mountainous regions (Daly et al. 2002). The extent of the grid is limited to the United States without Alaska. Monthly time series of temperature and precipitation extracted from grid tiles containing a gauge were used to calculate gauge-specific temperature and precipitation indices. To quantify the relationship between streamflow timing and

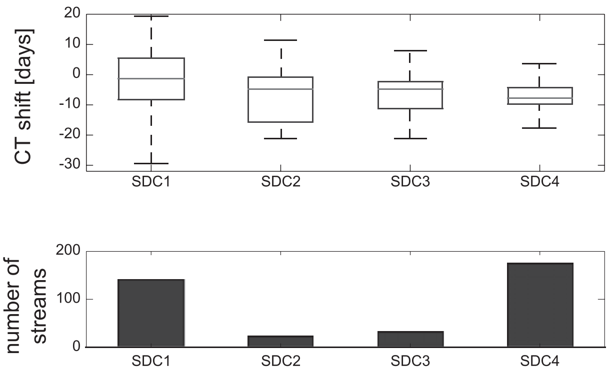

FIG. 4. Boxplot for shifts in CT for the 1948–2008 period in (top) days and (bottom) number of observations per SDC.

precipitation, we thus calculated a precipitation index (PI) that describes the anomaly of a year's October-to-March average in precipitation to the average of the observational period, and was calculated by

$$\mathrm{PI}_i = P_i - \overline{P},$$

with

- PI_i the gauge-specific precipitation index for year i ($1948 \le i \le 2008$),
- P_i the average precipitation over the months October–March of water year i ($1948 \le i \le 2008$), and
- $\overline{P}$ the average precipitation over the months October–March for the 1971–2000 reference period.

In addition, a temperature index (TI) was calculated for each gauge and year. TI represents the temperature anomaly for a gauge-specific four-month period, which includes the month in which CT in average falls, the two months prior, and the one after the CT:

$$\mathrm{TI}_i = T_i - \overline{T},$$

with

- TI_i the gauge-specific temperature index for year i ($1948 \le i \le 2008$),
- T_i the average temperature of the gauge-specific four-month period based on the average CT over all years for year i ($1948 \le i \le 2008$), and
- $\overline{T}$ the average temperature over the four-month periods for the 1971–2000 reference period.

Thus, the TI and PI indices are negative for years that are cooler (dryer) than the reference period average and positive for hotter (wetter) years.

The PDO is a decadal-scale pattern of climate variability (Mantua et al. 1997; Nigam et al. 1999) derived from North Pacific sea surface temperature anomalies. Previous studies have found a regionally varying influence of the PDO and its associated temperature and precipitation patterns on streamflow and streamflow timing (e.g., Hamlet and Lettenmaier 1999, 2007; Hunter et al. 2006; Jain et al. 2005; Pagano and Garen 2005; Stewart et al. 2005; Tootle et al. 2005; Woo and Thorne 2008), but the strength of that influence in relation to the overall continental-scale warming has not been resolved. For this study, we mapped the correlation coefficient between the PDO index and streamflow timing measures to obtain a spatial description of the strength of the influence of the PDO on streamflow timing throughout the domain.

h. *Quantifying acceleration*

Two regression models, a second-order linear trend model, and a piecewise linear regression model with two connected straight lines were fitted to establish how the streamflow timing measure CT has changed over time and whether this change has accelerated over the last decade. These models explored average changes over all or over a subset of the streams. We do recognize that first- or second-order linear models do not necessarily capture the behavior of the climatic or streamflow timing variable considered. Problems include high year-to-year variability, stepwise or other nonlinear increases, and sensitivity to the beginning and ending values. However, linear regression analysis of streamflow and climate data has been extensively used to determine monotonic trends over time (Milliman et al. 2008). These linear trends in combination with other techniques serve as an approximation of the direction of change over the observation period in the variable considered.

To remove geographic effects in all cases considered, each CT value has been normalized by subtracting the catchment mean CT value $\mathrm{CT}'_{ij} = \mathrm{CT}_{ij} - \overline{\mathrm{CT}}_j$ with i the time index, j the catchment index, and $\overline{\mathrm{CT}}_j$ the average CT value for catchment j. Time has been centered by computing $y_i = Y_i - \overline{Y}$ with y_i the centered year number, Y_i the original year number, and $\overline{Y}$ the mean year number of the series 1948–2008, (i.e., 1977.5).

The second-order linear model considered is

$$\mathrm{CT}'_{ij} = \beta_0 + \beta_1 y_i + \beta_2 y_i^2 + e_{ij}, \qquad (1)$$

with β_0 an intercept, β_1 a first-order linear component that indicates the change in CT (negative indicates a shift to earlier in the year), and β_2 a component that indicates an acceleration toward earlier in the year when negative. In the trend analysis, the e_{ij} are assumed to be normally distributed independent residuals.

As an alternative, a piecewise linear regression model was explored that consists of two connected straight

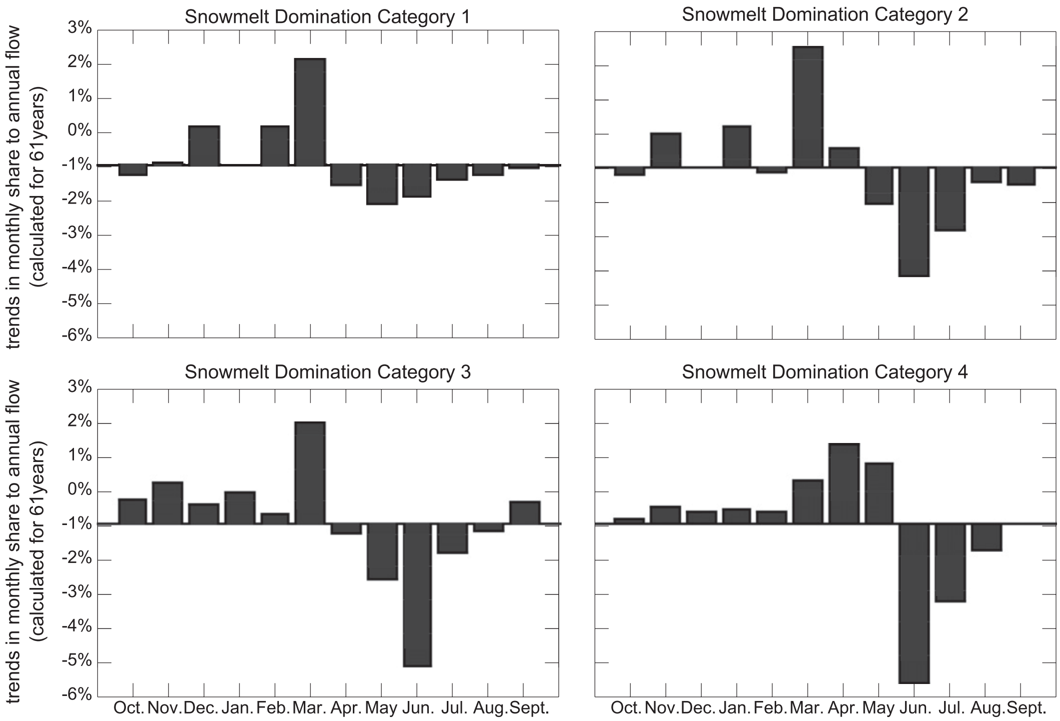

FIG. 5. Trends in fraction of annual streamflow for the 1948–2008 period, categorized by SDCs. (1–3).

lines with a change in slope after a particular time $\tilde{Y}$. In addition to y_i, we define a secondary predictor by $Y_i - \tilde{Y}$, set all the negative values of this vector to zero, and call it y'_i. The regression model then looks like

$$\mathrm{CT}'_{ij} = \beta'_0 + \beta'_1 y_i + \beta'_2 y'_i + e'_{ij}, \tag{2}$$

where β'_0 is the intercept, β'_1 the change in CT over the years up to $\tilde{Y}$, and $\beta'_1 + \beta'_2$ the slope after $\tilde{Y}$. Thus, β'_2 measures the change in slope of the lines before and after $\tilde{Y}$. Again, when β'_1 is negative, a negative value for β'_2 indicates an acceleration of CT values toward earlier in the year.

3. Results

a. Trend analysis

Streamflow timing across western North America continues to come generally earlier for snowmelt-dominated basins and generally later for the coastal rain-dominated basins across western North America, as determined by linear trend analysis for the different timing measures and the 1948–2008 period. The CT trends are regionally coherent, with the largest earlier trends occurring in the Pacific Northwest (PNW) and the southern Rocky Mountains, and the largest later trends along the coast. The magnitude of the CT shifts and gauge elevation are shown in Fig. 3. Many of the higher-elevation, snowmelt-dominated streams are now flowing earlier by 6–12 days in 2008 as compared to 1948, with a significant number experiencing earlier flows of 12–18 days, and the most vulnerable basins shifting by 18–31 days and more. These earlier flows for snowmelt-dominated gauges are taking place at the same time as the flows of low-elevation coastal rain-dominated basins are coming later by 5 to more than 10 days. Although the observed trends may not be consistently significant from a statistical perspective, there are few exceptions to earlier flows for any basins that have a snowmelt component (Fig. 3) in a region on the continental scale, even though streamflow records are comparatively short, interrupted, and possess high year-to-year variability. Analysis of trends in the start of the snowmelt pulse (not shown) indicates that snowmelt-dominated streams generally trend toward earlier snowmelt pulse start dates. These findings are consistent with those by Stewart et al. (2005). Our virtual globe application allows quick visualization of the linear trends in CT and the snowmelt pulse for each gauge during the study period (http://webpages.scu.edu/ftp/streamflowtiming/).

An acceleration of streamflow timing shifts in the very recent years may be indicated by comparing the average linear trends found for the 1948–2000 period to those of the 1948−2008. The average CT shift for all gauges and

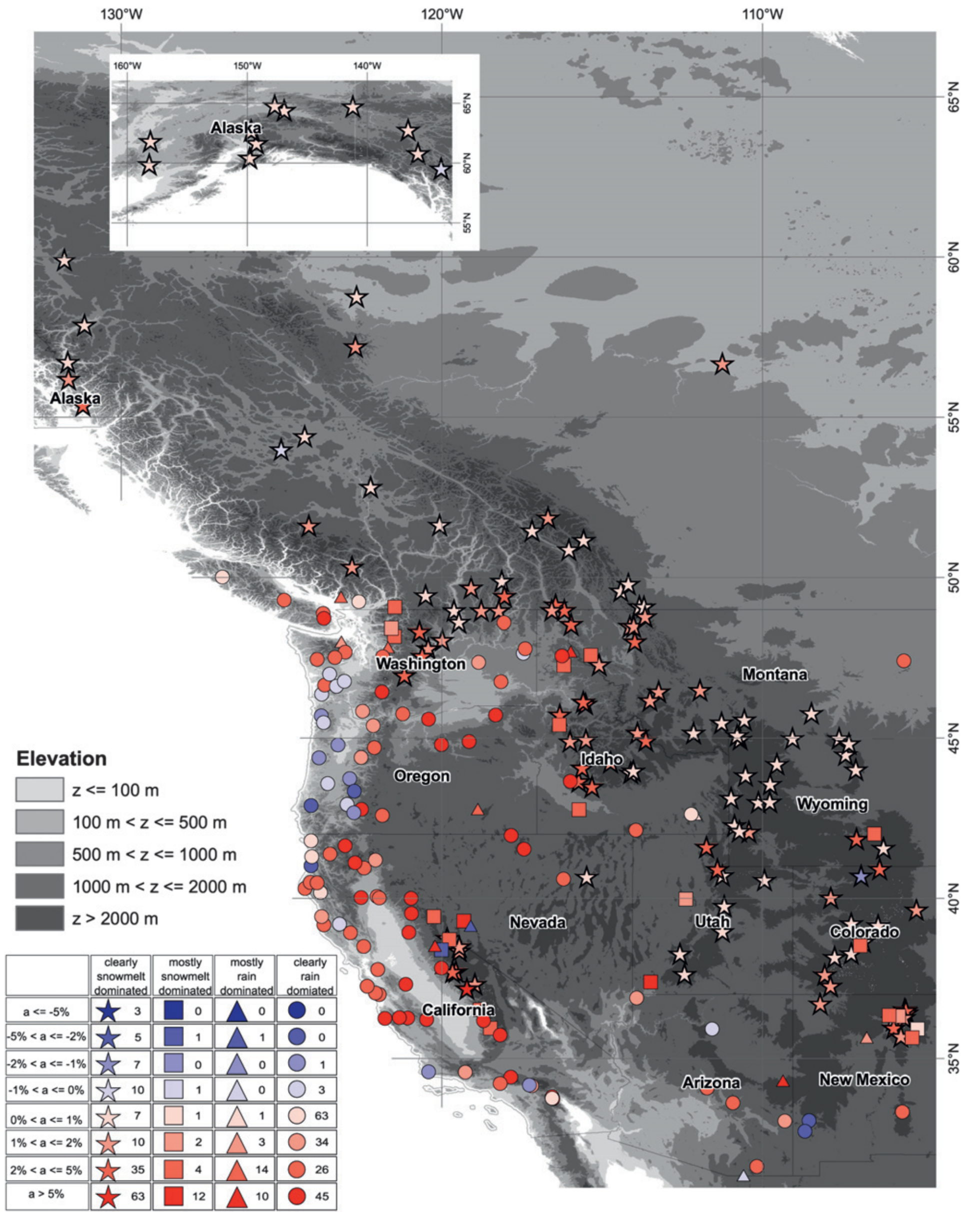

FIG. 6. Trends in fraction of March streamflow for the 1948–2008 period, categorized by SDCs.

the 1948–2000 period used by Stewart et al. (2005) was 4.8 days earlier over that period. Extrapolation of the linear regression line to include the 2001–08 period suggests that the average CT would have shifted by 5.5 days earlier overall, but in fact linear regression for the 1948–2008 observational period showed a CT shift of 6.2 days toward earlier in the year. The average trends for the start of the snowmelt runoff pulse (not shown) for all gauges for the 1948–2000 period (6.7 days earlier) and for the 1948–2008 period (6.5 days earlier), however, show almost the same magnitude shifts. In addition, the number of occurring snowmelt pulses for all gauges taken together has decreased from 56% (1948–2000) to 52% (1948–2008).

Average CT shifts by SDC are shown in the box-and-whisker plot of Fig. 4, which indicates that the largest CT shifts are taking place for SDC 4, while the spread and overall range increase with the fraction of precipitation coming as rain (from SDC 4 through 1). For SDC 1 through 4, CT is shifting by an average of 3.1, 6.9, 8.1, and 8.4 days, respectively, toward earlier in the water year. Thus, streams with the largest snowmelt component appear to respond in unison and to the largest degree at the continental scale. By contrast, those with little or no

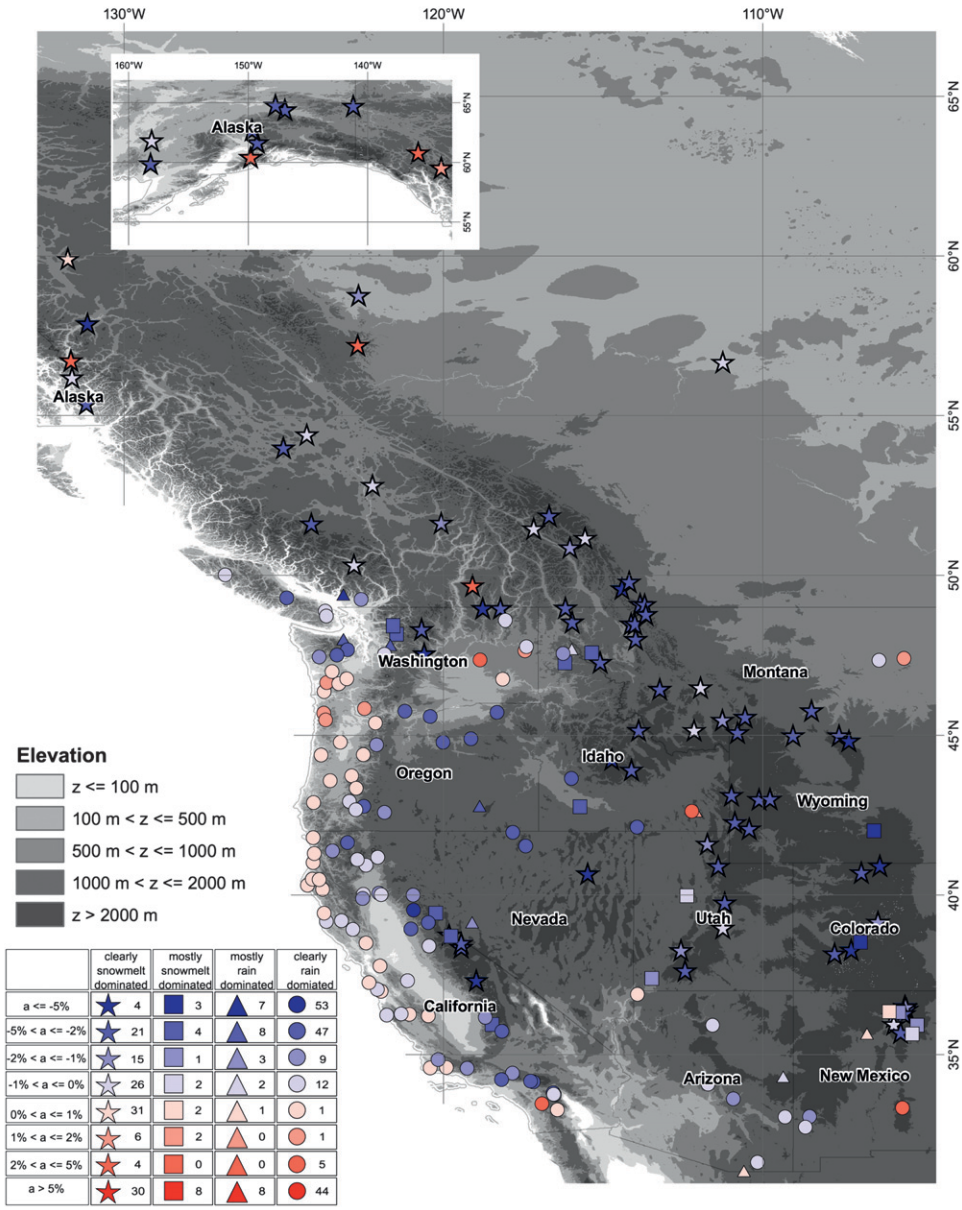

FIG. 7. As in Fig. 6, but for June.

snowmelt component exhibit the smallest overall changes, the by-far greatest range of changes, and do not consistently trend in one direction, as SDC 1 includes purely rain-dominated coastal streams as well as inland streams with a very small snowmelt component.

Consistent with earlier streamflow timing, the monthly flow fractions of annual runoff have changed over the 1948–2008 time period. The changes by snowmelt-domination period are shown in Fig. 5. An increase in the fraction of monthly to annual streamflow in the winter [December–February (DJF)] and early spring months (especially March; i.e., Fig. 6) and a decrease in the later months (especially June; i.e., Fig. 7) is common to all snowmelt categories. The snowmelt-dominated categories (SDC 3 and 4) experienced somewhat higher changes, especially in reduced flow in late spring and early summer. SDC 4, containing watersheds at more northern latitudes and higher altitudes, has experienced shifts from June, July, and August to May and June, while the shifts in the lower categories have been from May, June, and July to March and April. While a positive trend for the winter months points toward more precipitation and/or more precipitation as rain rather than snow, the summer months' decreases for all categories likely indicate earlier melt,

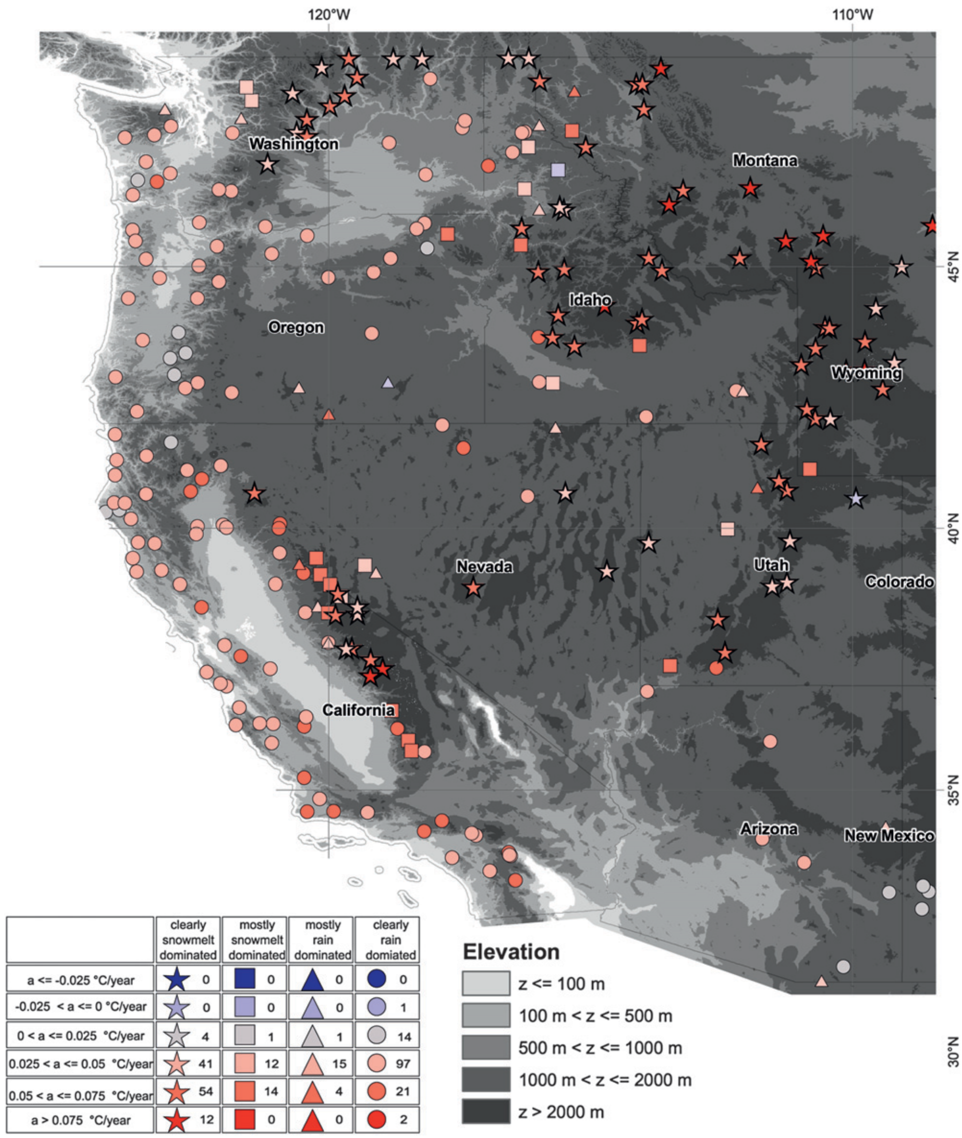

FIG. 8. Trends of temperature in March, categorized by SDC.

less watershed storage, less summer precipitation, or a combination of those factors.

b. Connection to climatic indices

Streamflow timing changes must be considered both in terms of the magnitude and timing of changes in temperature and precipitation as well as the strength of the connection between the climatic and streamflow timing shifts. Our results show that while all months except October and December have experienced warmer temperatures, the most significant warming has taken place in January, especially for the northern states, and in March throughout the region. The January and March warming has been on the order of 2°–3°C, respectively, over the 61-year study period (Fig. 8). The connection between CT and the TI and PI climatic indices varies with region and runoff regime. A negative correlation between CT and TI (Fig. 9) indicates warmer temperatures connected to an earlier CT. Essentially all but the coastal and rain-dominated southern streams are negatively correlated with TI.

Changes in precipitation have been varying with season and region over the study area. Generally, winter precipitation has increased over the Southwest and decreased over the Pacific Northwest with few consistent changes elsewhere, while March has seen precipitation decreases along the coast and increases inland. The greatest precipitation shifts have taken place in February, with decreases of more than 6 cm in the PNW and increases of more than 6 cm in the Southwest (not shown). Figure 10 graphically

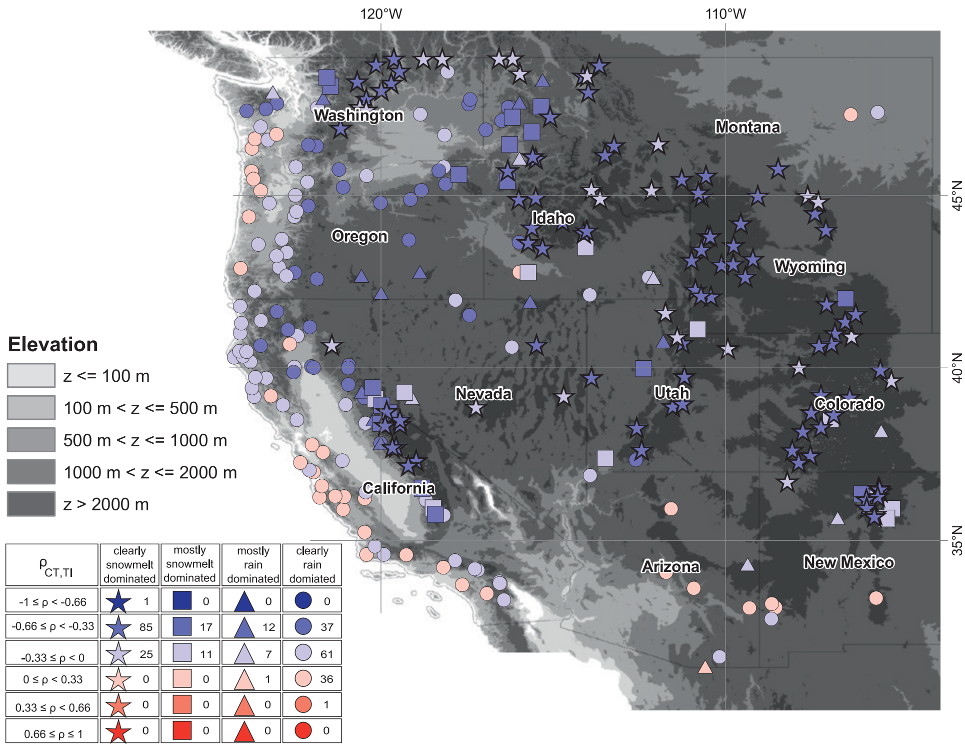

FIG. 9. Correlation between CT and the TI, categorized by SDC.

represents the correlation between CT and PI. Positive correlation coefficients for many of the snowmelt-dominated and interior basins indicate a connection of higher winter and spring precipitation (and hence larger snowpack) with later CT. Coastal and southern gauges exhibit a consistently negative correlation between CT and PI. For coastal gauges, a decrease in winter and early spring precipitation leads to a later CT. Gauges along the southern Arizona and New Mexico borders are under the influence of the summer monsoon. For those gauges, the average CT occurs in the late winter months and therefore warmer moister springs for these gauges are positively related to CT.

Correlation coefficients between CT and the PDO (not shown) are generally weak for the 1948–2008 period and not sufficiently consistent within SDCs to explain the consistent streamflow timing changes that have occurred for each SDC. Most central-to-northern Rocky Mountain, Sierra Nevada, and Alaska streams are negatively correlated, such that a positive PDO index connects to an earlier CT. All of the largest negative correlations (-0.33 to -0.66) can be found for SDC 4 and the central Rocky Mountains.

The fabric of spatially varying temperature and precipitation shifts results in several broad groups of streamflow timing responses throughout the study area. As streamflow of rain-dominated gauges is only minimally connected to temperature and mainly governed by temporal precipitation patterns, fall precipitation decreases and increases during the later winter months explain the shifts toward later CTs for the northern and southern rain-dominated coastal gauges. Streamflow for snowmelt-dominated streams is generally connected to the temperature and precipitation in the sense that warmer temperatures in the critical snowmelt months accelerate snowmelt and runoff, whereas larger snowpacks delay the discharge of the snowmelt runoff pulse. Over the California Sierra Nevada and the mountainous southwest, more precipitation has fallen in December and February and less in April and March. Earlier precipitation along with higher spring temperatures would act toward the observed earlier melt, while higher snowpacks due to increased winter precipitation may mitigate the effects of warmer temperatures. By contrast, snowmelt-dominated gauges in the PNW have experienced mixed precipitation shifts in December, January, and March, with decreases in February and small increases in April and May. Therefore, precipitation in this region has not acted consistently toward either earlier or later snowmelt runoff. However, very prominent trends toward higher January and March temperatures are likely responsible for some of the largest and most significant trends toward earlier CT in the region. In the mountainous interior, lower February and higher March precipitation acts to mitigate the

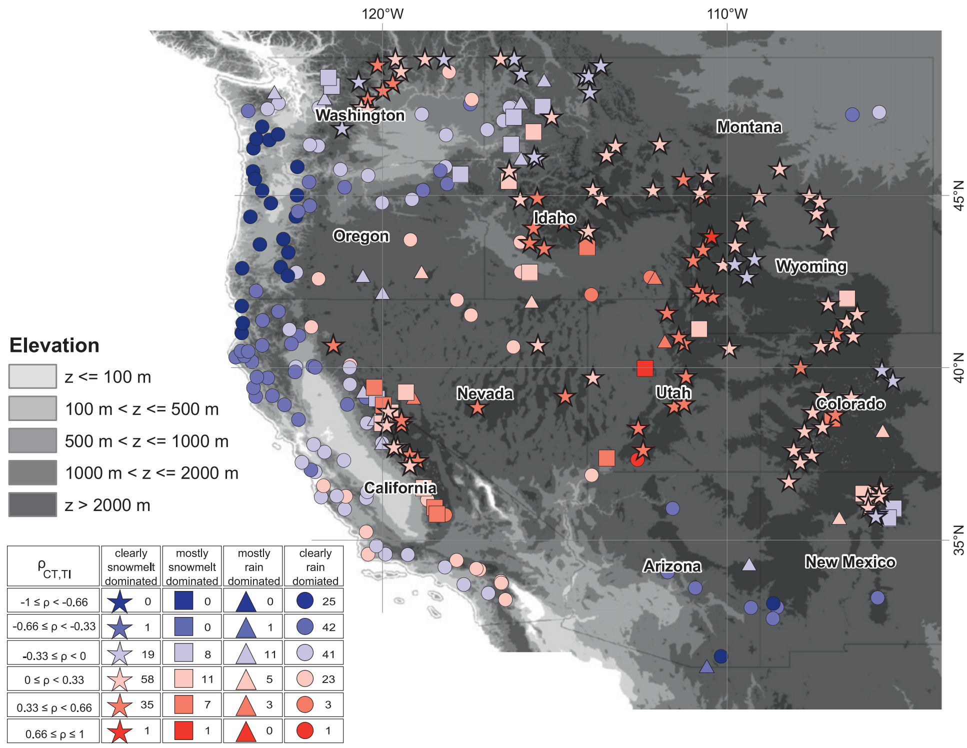

FIG. 10. Correlation between CT and PI, categorized by SDCs.

earlier runoff timing resulting from warmer spring temperatures.

c. *Acceleration of runoff timing changes*

Regression coefficients for the linear regression models of (1) and (2) were estimated by ordinary least squares. For the piecewise linear model, three different values for the changepoint $\tilde{Y}$ were chosen such that the last time segment contained 5, 10, and 20 years. For each of the snowmelt categories, estimated change coefficients for all models explored are shown in Table 2; the fit of the two models for SDC 4, with the coefficients given in Table 2, is shown in Fig. 11. The negative sign and magnitude of both (1) and (2) for SDC 4 suggest that not only is streamflow for this category coming earlier on average, but an acceleration of the changes is taking place over the past one to two decades (Fig. 11).

Although the ordinary least squares regression analysis suggests many significant effects (e.g., all coefficients of the first three models in SDC 4 of Table 2 would be significant at the $\alpha = 0.001$ level), these results may not be meaningful because spatial and temporal correlation in the data conflicts with the assumption of independent observations that underlies ordinary least squares. To more realistically assess significance of trend coefficients, we used generalized least squares regression analysis with a covariance model for residuals that addresses correlation in space and in time. Spatiotemporal covariance was modeled as the sum of a purely spatial variogram and a purely temporal variogram. The purely spatial variogram is shown in (Fig. 11). The temporal covariance was modeled as a spatiotemporal nugget effect of 30. Under the generalized linear least squares model that addresses spatiotemporal correlations, first-order linear effects were still significant at the $\alpha = 0.05$ level, but second-order effects that indicate an acceleration in the shift in the center of timing were not found to be significant (with t values between -1.5 and -1). An R script that reproduces

TABLE 2. Regression coefficients for the four linear regression models with acceleration coefficients (β_2, β_2'). For the two-piece linear model, $\tilde{Y}$ is the year where the slope of the regression line changes and β_2' is the change in slope for the second period. For a discussion of the coefficients' significance, see text.

Model		SDC 1	SDC 2	SDC 3	SDC 4
Second order	β_1	−0.039	−0.090	−0.118	−0.113
	β_2	0.0039	0.0048	0.0021	−0.0032
Piecewise linear	β_1'	−0.086	−0.201	−0.099	−0.083
$\tilde{Y} = 1988$	β_2'	0.187	0.436	−0.084	−0.131
Piecewise linear	β_1'	−0.045	−0.137	−0.106	−0.086
$\tilde{Y} = 1998$	β_2'	0.127	0.647	−0.212	−0.399
Piecewise linear	β_1'	−0.033	−0.137	−0.128	−0.110
$\tilde{Y} = 2003$	β_2'	0.086	2.30	0.166	−0.416

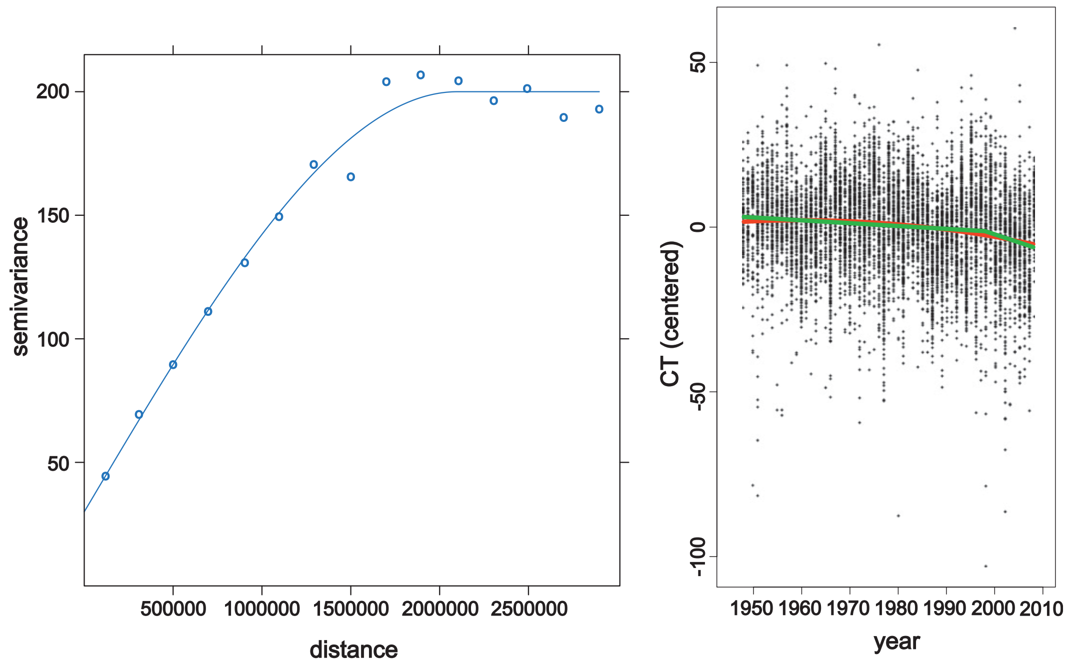

FIG. 11. (left) Sample variogram (○) and fitted model (line) of residuals from an ordinary least squares second-order linear regression model of CT with time for CT values in SDC 4. Semivariance addresses spatial correlation only; residual pairs from different years were ignored. The spherical model has a nugget of 30, a range of 2 100 000, and a partial sill of 170 (distance is in meters). (right) CT and regression models for SDC 4 for the 1948–2008 period. Here the red and green lines represent the second-order linear trend model and the piecewise linear regression model, respectively. See text for explanation of the models.

these analyses can be obtained from the authors upon request.

d. Changes in snowmelt-domination categories

The spatial distribution of each category depends on several factors, including the location in the graticule, watershed elevation, aspect, and predominant air flows. In general, the higher the latitude and the altitude, the higher is the ratio of snowmelt pulses and thus the snowmelt-domination category. As seen in Fig. 4, the majority of the basins in the region are either clearly snowmelt- or clearly rain-dominated. Intermediate categories contain comparatively few gauges.

Changes in SDCs can consistently be distinguished when considering two separate subperiods. Figures 12 and 13 illustrate the spatial distribution of the shifts within each of the four categories in the map portion of the figures for two of the subperiods and summarize the changes in an $n \times n$ matrix (where $n = 4$) within the legend. Figures 12 and 13 indicate that runoff regimes for a large number of streams change to lower SDC (toward greater rain domination) between the first and the second period—that is, 39, 48, and 40 streams for the three periods considered (the 1948–77 to 1978–2008 changes are not shown, but yielded similar results).

When comparing the 1948–88 and 1989–2008 subperiods (Fig. 12), 48 streams changed toward more rain domination. Thirty-four streams changed one category, 13 changed two, and one Sierra Nevada stream changed three categories from a mostly snow-dominated to a mostly rain-dominated regime. Comparing the first 51 years with the last 10 years (1948–98 and 1999–2008 subperiods; see Fig. 13) indicated that although the spatial distribution of regime changes somewhat differs from the previous map, the same four regions of high vulnerability to SDC shifts are generally discernible. Especially the basins of northeastern New Mexico that were already affected by category changes showed even larger shifts and more streams that changed toward greater rain domination. Category shifts in northern Idaho and northwestern Washington were less pronounced than those in the Sierra Nevada and New Mexico.

In summary, the runoff regime in some basins was altered to such a degree that previously snowmelt-dominated gauges were mostly rain-dominated in the later period. By contrast, the runoff regimes of very few streams (2, 0, and 5 for the three periods, respectively) changed into the direction of greater snowmelt domination. Four clusters of category changes can be recognized independent of the periods considered. These are northwestern

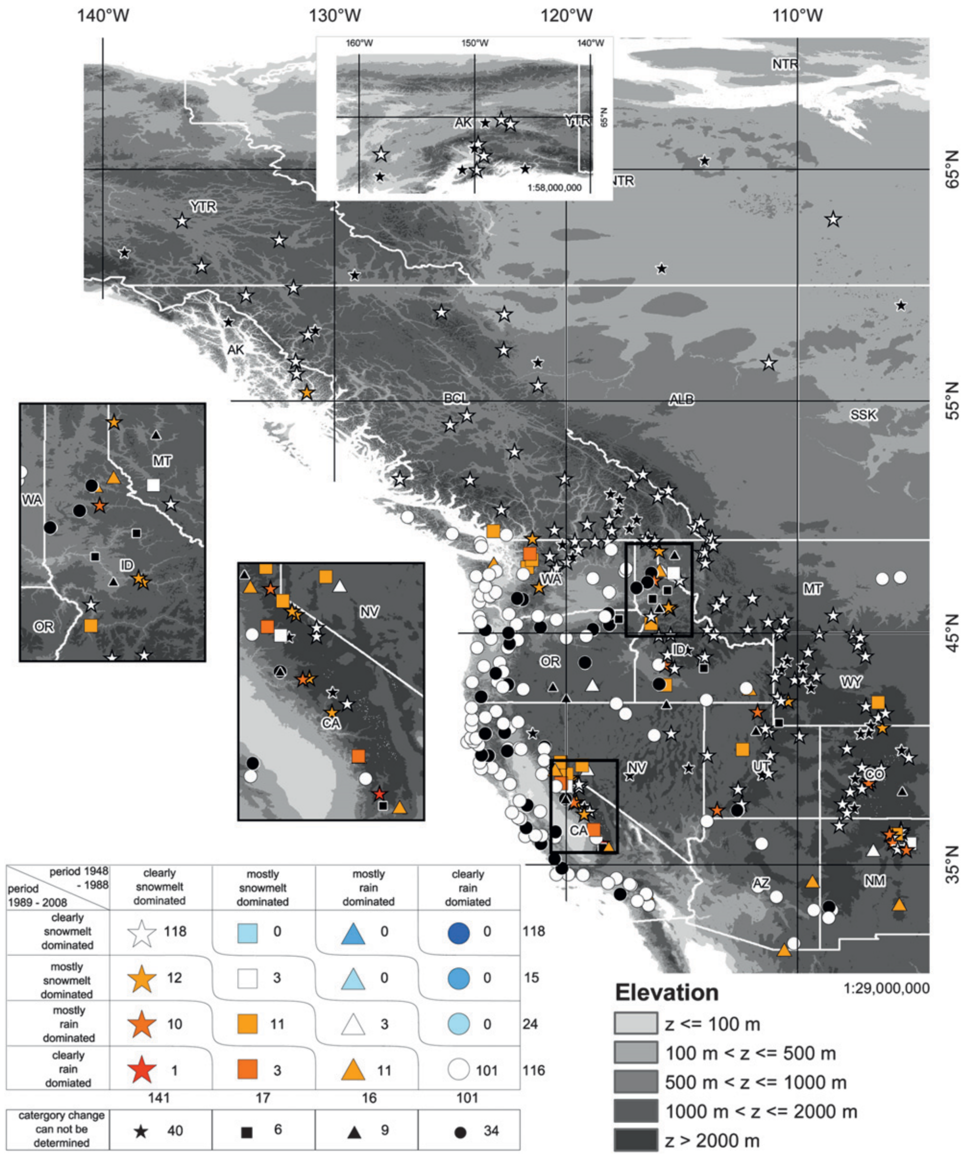

FIG. 12. Changes in SDCs between 1948–88 and 1989–2008. The main diagonal of the legend (row i = column j) contains streams that experience no change in SDC. The larger the difference $i - j$, the greater is the shift in SDCs for a given stream between the earlier and later time period. Changes to a higher (lower) category [more (less) snow dominated] are represented in the upper right (lower left) triangle of the matrix. Thus, red toned colors denote category shifts toward greater rain domination and blue toned colors indicate category shifts toward greater snowmelt domination. Category changes could not be determined for basins where the number of missing values exceeded the predefined threshold.

Washington, northern Idaho (see zoom window), the Sierra Nevada (California) (see zoom window), and northeastern New Mexico.

4. Discussion and conclusions

The overall question driving this study was whether the very warm temperatures of the 1998–2008 decade have led to continued and accelerated changes in streamflow timing compared to the earlier decades. To this end, we used linear trend analysis for different timing measures and correlated these changes to climate indices, developed an algorithm and classification method to distinguish between mostly snowmelt-dominated, mixed, and mostly rain-dominated basins, examined shifts in snowmelt-dominated regimes, and employed two generalized second-order linear regression models to determine whether an acceleration in streamflow timing changes has taken place.

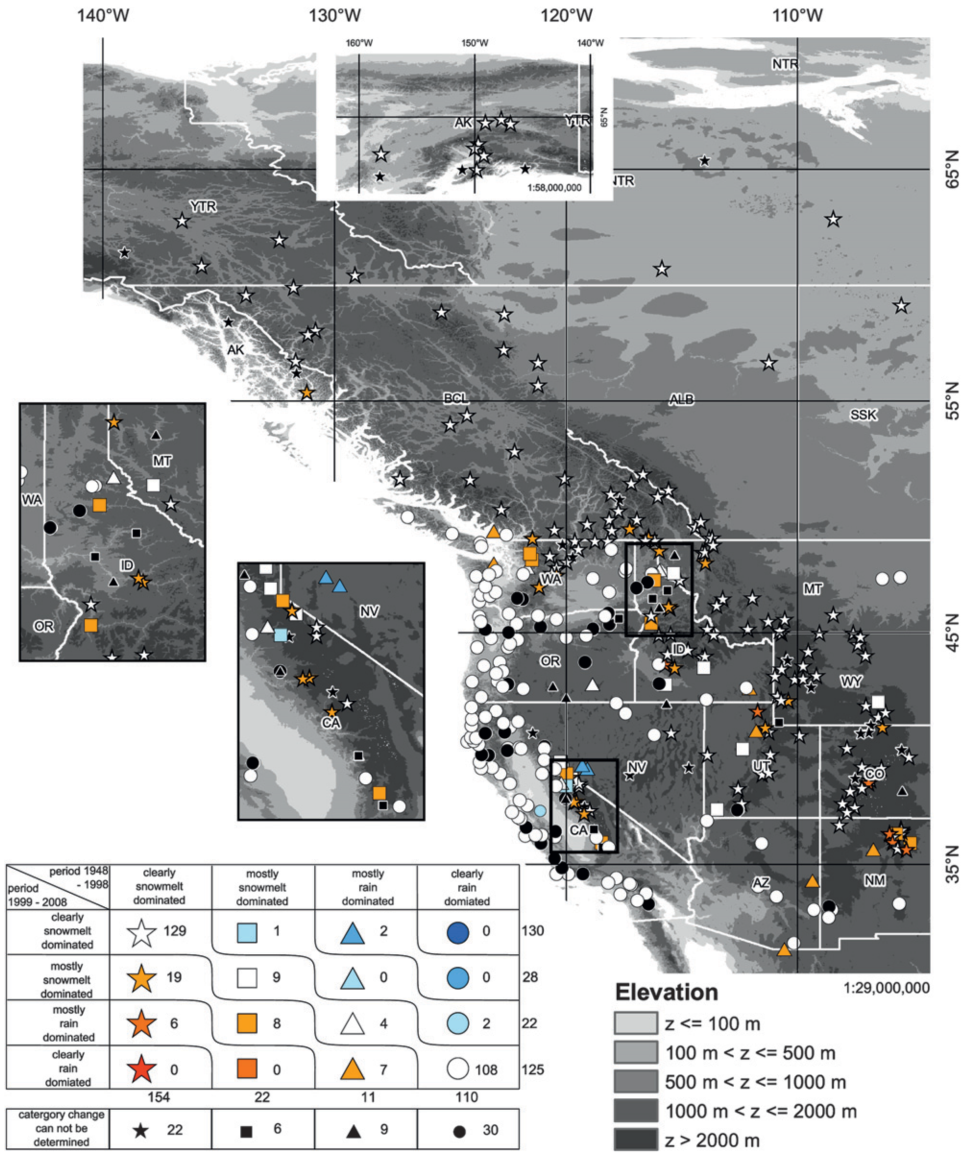

FIG. 13. As in Fig. 12, but for between 1948–98 and 1999–2008.

Shifts in runoff timing toward earlier in the year have continued with very few exceptions for most of the study area, spanning an area from Alaska to New Mexico. By contrast, runoff is consistently coming later for the coastal rain-dominated gauges from Washington to California and the snowmelt-dominated gauges in the Canadian northern interior. Interestingly, the sign in the shift is mostly dependent on geographic location rather than the elevation or the degree of snowmelt domination, while the magnitude of the change is connected to the snowmelt-domination category (SDC) of a basin. The earlier runoff timing trends have been particularly pronounced for gauges with the greatest snowmelt runoff component but are also present for mixed-regime basins. For all SDCs, these trends represent a redistribution of flow from late spring and summer toward late winter and early spring, in particular March, and appear connected to regional-scale changes in temperature and precipitation indices. Temperatures have increased throughout the study area in the late winter, spring, and summer, and correlations between warmer temperatures around the timing of peak flow and earlier melt and runoff are strong for the entire region. By contrast, precipitation has not shown any consistent trends, but coastal decreases in October, January, and March, and increases in December and April could help to explain the trends toward later streamflow timing. Correlations with the Pacific decadal oscillation (PDO) have not been consistent in sign or magnitude throughout the domain. While this and previous studies have established an influence of the PDO phase change on some areas within the region, streamflow timing changes have continued beyond the most recent PDO warm phase that ended in 1999.

In spite of the relatively warm 1998–2008 decade, our second-order linear regression models that took spatial and temporal correlation of observations into account indicated no statistically significant acceleration of streamflow timing trends when averaging over SDCs as a whole. This might be caused by the fact that acceleration is simply not present, or that it is obscured by the large variability and relatively short time series available. It should be noted in this context that the sign of the model coefficients, especially for the most snowmelt-dominated basins, does point toward earlier runoff timing and an acceleration of the shifts toward earlier timing. Future analysis with longer time series could yield more clarity on this issue.

We classified each basin into SDCs as either clearly snowmelt dominated, mostly snowmelt dominated, mostly rain dominated, or clearly rain dominated via an algorithm capable of distinguishing between runoff pulses generated by rainfall and those coming from snowmelt runoff. Based on the number of snowmelt runoff pulses occurring, basins with SDC shifts that changed their regime designation between an earlier and a later portion of the study were determined. These category shifts were almost exclusively toward greater rain domination and were consistently identified in several geographic regions that appear to possess a particular vulnerability.

We suggest, then, that streamflow has responded to the regional warming and precipitation changes over the past decades such that earlier melt is taking place in mostly snowmelt-dominated and mixed regimes on the subcontinental scale. Gauges with no snowmelt component along the coast and those in the Canadian interior responded mostly to precipitation shifts that emphasize dryer falls and wetter conditions in late winter. The observed changes have been consistent through 2008. While the climatic shifts observed to date do not appear to have clearly intensified the effects on snowmelt runoff overall, the most vulnerable basins in the region are already responding in a nonlinear way to the existing climatic drivers. In addition, several highly vulnerable regions where runoff regime shifts have taken place exist across the study area.

Acknowledgments. We thank Environment Canada and Mary Tyree of the Scripps Institution of Oceanography for providing the Canadian streamflow data. Iris Stewart gratefully acknowledges research support through the Clare Booth Luce Foundation. We also appreciated the helpful comments of three anonymous reviewers on an earlier version of this manuscript.

REFERENCES

Aguado, E., D. Cayan, L. Riddle, and M. Roos, 1992: Climatic fluctuations and the timing of west coast streamflow. *J. Climate,* **5,** 1468–1483.

Anderson, J., F. Chung, M. Anderson, L. Brekke, D. Easton, M. Ejeta, R. Peterson, and R. Snyder, 2008: Progress on incorporating climate change into management of California's water resources. *Climatic Change,* **87,** 91–108, doi:10.1007/s10584-007-9353-1.

Barnett, T., J. Adam, and D. Lettenmaier, 2005: Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature,* **438,** 303–309, doi:10.1038/nature04141.

Bates, B., Z. Kundzewicz, S. Wu, and J. Palutikof, Eds., 2008: Climate change and water. Intergovernmental Panel on Climate Change Tech. Paper 6, 200 pp. [Available online at http://www.ipcc.ch/pdf/technical-papers/climate-change-water-en.pdf.]

Bonfils, C., and Coauthors, 2008: Detection and attribution of temperature changes in the mountainous western United States. *J. Climate,* **21,** 6404–6424.

Cayan, D., S. Kammerdiener, M. Dettinger, J. Caprio, and D. Peterson, 2001: Changes in the onset of spring in the western United States. *Bull. Amer. Meteor. Soc.,* **82,** 399–415.

Clow, D. W., 2010: Changes in the timing of snowmelt and streamflow in Colorado: A response to recent warming. *J. Climate,* **23,** 2293–2306.

Daly, C., W. P. Gibson, G. H. Taylor, G. L. Johnson, and P. Pasteris, 2002: A knowledge-based approach to the statistical mapping of climate. *Climate Res.,* **22,** 99–113.

Das, T., and Coauthors, 2009: Structure and detectability of trends in hydrological measures over the western United States. *J. Hydrometeor.,* **10,** 871–892.

Dettinger, M., 2005: Changes in streamflow timing in the western United States in recent decades. USGS Fact Sheet 2005-3018, 4 pp.

——, and D. Cayan, 1995: Large-scale atmospheric forcing of recent trends towards early snowmelt runoff in California. *J. Climate,* **8,** 606–623.

Hamlet, A. F., and D. P. Lettenmaier, 1999: Columbia River streamflow forecasting based on ENSO and PDO climate signals. *J. Water Resour. Plann. Manage.,* **125,** 333–341.

——, and ——, 2007: Effects of 20th century warming and climate variability on flood risk in the western U.S. *Water Resour. Res.,* **43,** W06427, doi:10.1029/2006WR005099.

——, P. W. Mote, M. P. Clark, and D. P. Lettenmaier, 2007: Twentieth-century trends in runoff, evapotranspiration, and soil moisture in the western United States. *J. Climate,* **20,** 1468–1486.

Hunter, T., G. Tootle, and T. Piechota, 2006: Oceanic-atmospheric variability and western U.S. snowfall. *Geophys. Res. Lett.,* **33,** L13706, doi:10.1029/2006GL026600.

Jain, S., M. Hoerling, and J. Eischeid, 2005: Decreasing reliability and increasing synchroneity of western North American streamflow. *J. Climate,* **18,** 613–618.

Knowles, N., M. D. Dettinger, and D. R. Cayan, 2006: Trends in snowfall versus rainfall in the western United States. *J. Climate,* **19,** 4545–4559.

Luce, C. H., and Z. A. Holden, 2009: Declining annual streamflow distributions in the Pacific Northwest United States, 1948–2006. *Geophys. Res. Lett.,* **36,** L16401, doi:10.1029/2009GL039407.

Mantua, N., S. Hare, Y. Zhang, J. Wallace, and R. Francis, 1997: A Pacific interdecadal climate oscillation with impacts on salmon production. *Bull. Amer. Meteor. Soc.,* **78,** 1069–1079.

McCabe, G. J., and M. P. Clark, 2005: Trends and variability in snowmelt runoff in the western United States. *J. Hydrometeor.,* **6,** 476–482.

Milliman, J. D., K. L. Farnsworth, P. D. Jones, K. H. Xu, and L. C. Smith, 2008: Climatic and anthropogenic factors affecting river discharge to the global ocean, 1951–2000. *Global Planet. Change,* **62,** 187–194, doi:10.1016/j.gloplacha.2008.03.001.

Mote, P. W., 2003: Trends in temperature and precipitation in the Pacific Northwest during the twentieth century. *Northwest Sci.,* **77,** 271–282.

——, A. F. Hamlet, M. P. Clark, and D. P. Lettenmaier, 2005: Declining mountain snowpack in western North America. *Bull. Amer. Meteor. Soc.,* **86,** 39–49.

Nigam, S., M. Barlow, and E. H. Berbery, 1999: Analysis links Pacific decadal variability to drought and streamflow in United States. *Eos, Trans. Amer. Geophys. Union,* **80,** 621.

NOAA, cited 2009: 2008 global temperature ties as eighth warmest on record. [Available online at http://www.sciencedaily.com/releases/2009/01/090116163206.htm.]

Pagano, T., and D. Garen, 2005: A recent increase in western U.S. streamflow variability and persistence. *J. Hydrometeor.,* **6,** 173–179.

Regonda, S. K., B. Rajagopalan, M. Clark, and J. Pitlick, 2005: Seasonal cycle shifts in hydroclimatology over the western United States. *J. Climate,* **18,** 372–384.

Roos, M., 1991: A trend of decreasing snowmelt runoff in northern California. *Proc. 59th Western Snow Conf.,* Juneau, AK, Western Snow Conference, 29–36.

Stewart, I., D. Cayan, and M. Dettinger, 2004: Changes in snowmelt runoff timing in western North America under a ''business as usual'' climate change scenario. *Climatic Change,* **62,** 217–232.

——, ——, and ——, 2005: Changes toward earlier streamflow timing across western North America. *J. Climate,* **18,** 1136–1155.

Tootle, G., T. Piechota, and A. Singh, 2005: Coupled oceanic-atmospheric variability and U.S. streamflow. *Water Resour. Res.,* **41,** W12408, doi:10.1029/2005WR004381.

Viviroli, D., H. H. Dürr, B. Messerli, M. Meybeck, and R. Weingartner, 2007: Mountains of the world, water towers for humanity: Typology, mapping, and global significance. *Water Resour. Res.,* **43,** W07447, doi:10.1029/2006WR005653.

Woo, M.-K., and R. Thorne, 2008: Analysis of cold season streamflow response to variability of climate in north-western North America. *Hydrol. Res.,* **39,** 257–265.