Changes in the Timing of Snowmelt and Streamflow in Colorado: A Response to Recent Warming

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ABSTRACT

Trends in the timing of snowmelt and associated runoff in Colorado were evaluated for the 1978–2007 water years using the regional Kendall test (RKT) on daily snow-water equivalent (SWE) data from snowpack telemetry (SNOTEL) sites and daily streamflow data from headwater streams. The RKT is a robust, nonparametric test that provides an increased power of trend detection by grouping data from multiple sites within a given geographic region. The RKT analyses indicated strong, pervasive trends in snowmelt and streamflow timing, which have shifted toward earlier in the year by a median of 2–3 weeks over the 29-yr study period. In contrast, relatively few statistically significant trends were detected using simple linear regression. RKT analyses also indicated that November–May air temperatures increased by a median of 0.9°C decade^{-1}, while 1 April SWE and maximum SWE declined by a median of 4.1 and 3.6 cm decade^{-1}, respectively. Multiple linear regression models were created, using monthly air temperatures, snowfall, latitude, and elevation as explanatory variables to identify major controlling factors on snowmelt timing. The models accounted for 45% of the variance in snowmelt onset, and 78% of the variance in the snowmelt center of mass (when half the snowpack had melted). Variations in springtime air temperature and SWE explained most of the interannual variability in snowmelt timing. Regression coefficients for air temperature were negative, indicating that warm temperatures promote early melt. Regression coefficients for SWE, latitude, and elevation were positive, indicating that abundant snowfall tends to delay snowmelt, and snowmelt tends to occur later at northern latitudes and high elevations. Results from this study indicate that even the mountains of Colorado, with their high elevations and cold snowpacks, are experiencing substantial shifts in the timing of snowmelt and snowmelt runoff toward earlier in the year.

1. Introduction

High-elevation (≥2500 m) mountains in the western United States receive the majority of their annual precipitation as winter and spring snow (Serreze et al. 1999), as is true for most midlatitude, high-elevation basins globally (Barnett et al. 2005; Stewart 2009). Most of this snow accumulates in seasonal snowpacks, which represent a natural storage reservoir that, in many river basins, exceeds the storage capacity of manmade reservoirs (Nijssen et al. 2001; Mote 2006). Arid regions, such as the western United States, that receive relatively little precipitation during summer months are heavily dependent on natural and manmade storage to provide water for agriculture, industry, and drinking during the dry summer and fall seasons (Barnett et al. 2005).

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Recent studies have documented that in most of the western United States, changes in the accumulation and melt of seasonal snowpacks are causing substantial reductions in the natural storage of water in snowpacks. Observed changes include decreases in the proportion of precipitation falling as snow (Knowles et al. 2006), decreases in 1 April snow-water equivalent (SWE) in snowpacks (Mote 2006), and earlier runoff during the spring snowmelt period (Cayan et al. 2001; McCabe and Clark 2005; Regonda et al. 2005; Stewart et al. 2005). These studies indicated that in the west, changes were most pronounced in the Cascade Mountains, the northern Sierra Nevada, and the northern Rocky Mountains, where snowpack temperatures usually are not far below freezing. In the southern Rocky Mountains of Colorado, however, only minor changes in snowpack accumulation and melt were documented (Stewart et al. 2005; Knowles et al. 2006; Mote 2006).

The apparent lack of change in snowmelt properties and streamflow timing in Colorado was attributed to the area's cold continental climate and high elevations, and it has been inferred that the state's snowpack may be relatively immune to the effects of climate warming. Recent observations, however, suggest otherwise. Water managers and hydrologists have perceived early snowmelt and runoff in many of the state's river basins since 2000, indicating that even Colorado's relatively cold snowpack may be susceptible to a warming climate.

The objective of this study was to analyze recent trends in snowmelt and streamflow timing and evaluate potential linkages with trends in air temperature and precipitation in the state. This study builds upon previous research on trends in snowpack water content and streamflow timing by using daily snow-water equivalent data to directly evaluate trends in snowpack accumulation and melt, and by analyzing statistical relations between snowmelt timing, streamflow timing, and climate. Trends were analyzed using a relatively new, robust statistical method, the regional Kendall test (RKT), which provides an increased power of trend detection by combining data from multiple sites within a region (Helsel and Frans 2006).

2. Data

a. Snowpack

Previous studies have used streamflow timing to infer changes in snowmelt timing (Cayan et al. 2001; McCabe and Clark 2005; Stewart et al. 2005); however, few or no published studies have evaluated trends in snowmelt timing itself. One reason for this is that daily records of SWE are relatively short, which makes trend detection difficult using standard linear regression. The primary daily SWE record comes from the Natural Resource Conservation Service (NRCS), which has operated an automated network of snowpack monitoring [snowpack telemetry (SNOTEL)] sites in the western United States since 1978; at each SNOTEL site the weight of snow on a liquid-filled pillow is measured by a pressure sensor and converted to SWE at an hourly time step. Although the SNOTEL record is short when compared to snow course datasets, its daily temporal resolution makes it uniquely suited to analysis of snowmelt timing trends. It also covers a time frame that is of substantial interest to water resource managers concerned with recent and possible future trends in precipitation and runoff.

In this study, daily SWE values for SNOTEL sites in Colorado were used to directly assess changes in the timing of snowmelt from the beginning of available records through the 2007 water year (water years begin on 1 October and end on 30 September). Most SNOTEL sites began operation soon after the SNOTEL network was established in Colorado in October 1978, and the median length of record used in this study was 27 yr; sites with less than 18 yr of data were excluded, leaving 70 sites for the analysis (Fig. 1; 97% of sites had ≥21 yr of data). SNOTEL sites ranged in elevation from 2560 to 3536 m, and the average elevation was 3079 m (data and site information are available online at http://www.wcc.nrcs.usda.gov/snotel/Colorado/colorado.html). The SNOTEL network also reports daily temperature and precipitation at each site; these data were used to assess trends in air temperature, the percentage of winter precipitation falling as snow, 1 April SWE, and maximum SWE. Although precipitation data covers the period of record at each station, air temperature records at most sites did not begin until 1986/87.

SNOTEL data were screened for outliers using time series plots of daily and monthly averages, and by comparing data from sites located geographically near each other while accounting for differences in elevation. Few outliers were identified in the SNOTEL SWE and precipitation dataset; however, SNOTEL air temperature data had a higher number of anomalies that required additional screening steps. Most of the air temperature anomalies were obvious errors or flagged data, but more subtle changes, such as those that might be caused by changes in sensors or in sensor location, were of concern as well. Multiple regression models of daily average air temperature were created for each of 14 geographic regions in Colorado (see below) using elevation and daily average air temperature from all SNOTEL sites within each region as explanatory variables. Outliers were identified in residuals plots based on Mahalanobis distance (Mahalanobis 1938), and spurious values were deleted. In some cases, station metadata were useful for identifying effects of changes in sensors or in sensor location. At most sites, less than 5% of the data were deleted.

Regions usually are defined as spatially contiguous areas, and there should be similar numbers of sites within regions to provide balanced statistical power when performing trend tests using the RKT (Helsel and Frans 2006). In this study, SNOTEL and streamflow sites were grouped into 14 regions, which roughly corresponded to major mountain ranges in Colorado (Fig. 1). In some cases, sites could have been included in either of two regions based on geographic proximity; in those cases, the decision about which region to place the site in was based on balancing the number of sites within regions.

b. Streamflow

Daily streamflow data were obtained for 58 headwater streams in Colorado with long-term gauges operated by the U.S. Geological Survey (USGS) or the Colorado Division of Water Resources (Fig. 1). Data and site

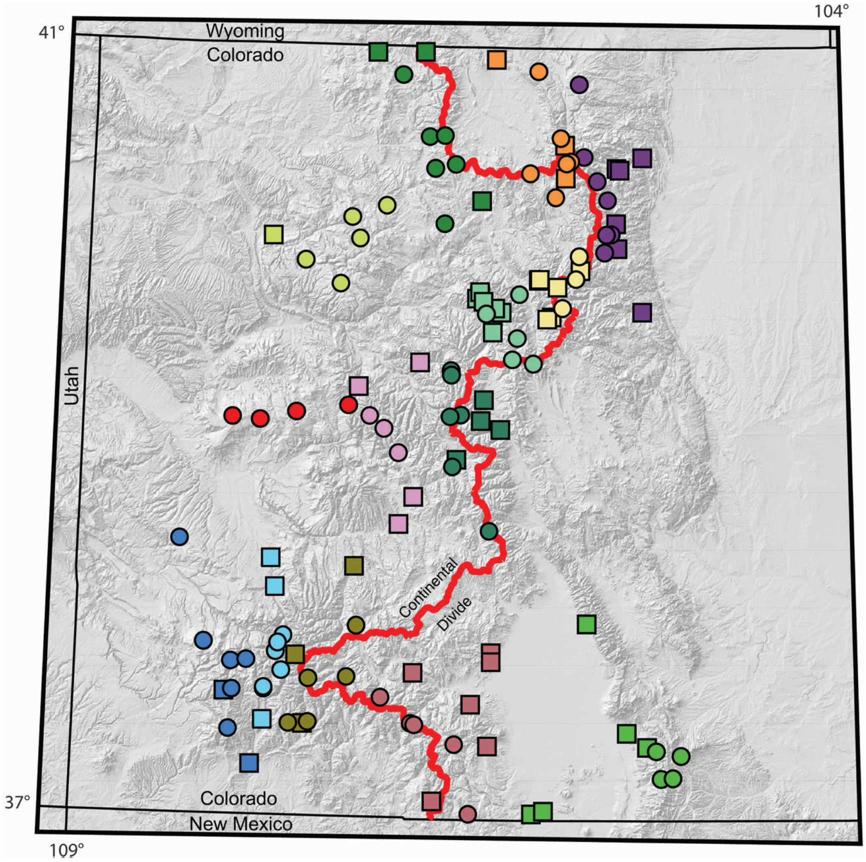

FIG. 1. Map showing locations of SNOTEL (circles) and stream sites (squares) used in study. Colors indicate regions used in the trend analyses.

information for USGS and the state of Colorado gauges are available online (http://waterdata.usgs.gov/co/nwis/rt and http://www.dwr.state.co.us/), respectively. Sites were selected based on the requirements that 50% or more of annual flow occurs during April–July, diversions and impoundments were minimal, and complete years of data were available for at least 18 yr of the 29-yr study period (the median record length was 29 yr, and 98% of sites had ≥21 yr of data). Most stream gauges used in this study began operating during the early to middle part of the twentieth century. Elevations of the stream gauges ranged from 1859 to 3179 m, and the average elevation was 2543 m. Sites included the 14-stream gauges in the USGS Hydro-Climatic Data Network (HCDN) used by Stewart et al. (2005) and McCabe and Clark (2005) in their analyses of streamflow timing trends in the western United States.

3. Methods

a. Indices of snowmelt timing and streamflow timing

In snowmelt-dominated catchments, the majority of streamflow occurs during the spring–summer snowmelt period. An example annual time series plot of cumulative discharge (Fig. 2) shows that the slope of the cumulative discharge curve is shallow during the winter low-flow period, increases sharply during spring in response to snowmelt, and then gradually becomes shallow again during the receding limb of the snowmelt hydrograph. The changes in slope of the cumulative discharge curve can be used to quantify the timing of the beginning of snowmelt-induced runoff, its midpoint, and its end. The timing of inflection points can, however, be sensitive to short-term climate variability (Stewart et al. 2005). It is more reproducible to use quantiles of cumulative annual flow that approximate the beginning, middle, and end of snowmelt (Moore et al. 2007).

At each stream site, streamflow timing indices were calculated for each year based on cumulative discharge calculated from the daily streamflow records. For a given site and year, the indices Q20, Q50, and Q80 corresponded to the dates on which 20%, 50%, and 80% of total annual flow for the water year had passed by the stream gauge (Fig. 2). These values approximate the beginning, middle, and end of the snowmelt period. For reference, Q50 is equivalent to the center of mass index

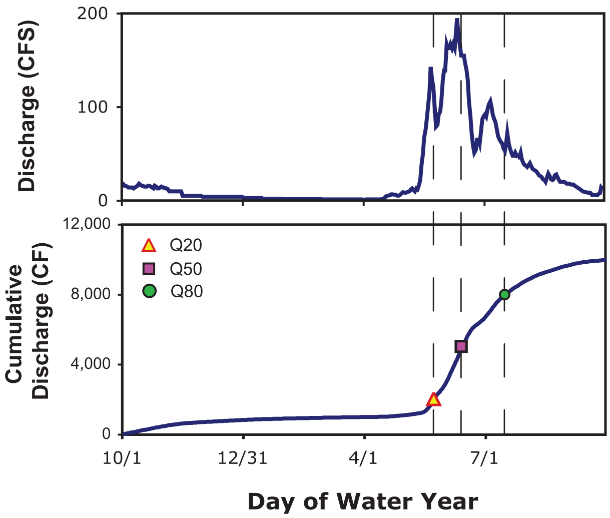

FIG. 2. Example of annual snowmelt-dominated hydrograph and associated cumulative discharge plot. Q20, Q50, and Q80 are 20th, 50th, and 80th percentiles of cumulative annual flow during the water year.

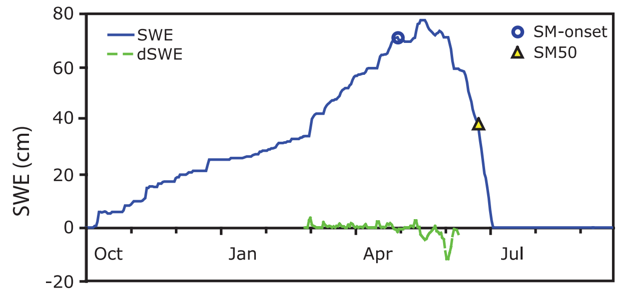

FIG. 3. Example of seasonal accumulation and melting of snowpack. SWE increases and the change in SWE (dSWE) is positive until snowpack begins to melt. Date of snowmelt onset is SM onset; and date when half of snowpack has melted is SM50 (based on maximum SWE/2).

(CT) used by Stewart et al. (2005) and the center of mass day (CMD) of McCabe and Clark (2005).

Snowpack melt indices were calculated for each SNOTEL site and year in a similar manner; SM50 refers to the day of the year on which half the snowpack had melted (based on maximum SWE; see Fig. 3, e.g.). The onset of snowmelt (SM onset) was calculated as the beginning of the first 5-day period during which SWE declined by more than 2.5 cm (Fig. 3). Although sublimation also can cause declines in SWE, they would rarely be as much as 2.5 cm over a 5-day period (Strasser et al. 2008).

Monthly averaged air temperatures were calculated for each SNOTEL site from daily average temperatures. Monthly precipitation was calculated for each SNOTEL site by summing daily precipitation totals.

b. Regional Kendall test

Most previous studies of streamflow timing have used parametric linear regression to test for trends at individual sites (e.g., McCabe and Clark 2005; Stewart et al. 2005). Linear regression has several disadvantages; however, including the propensity for results to be affected by outliers, which are common in hydrologic data (Helsel and Hirsch 1992), and limited power of trend detection in short datasets. A relatively new nonparametric test, the regional Kendall test (RKT), is resistant to outliers and missing data and provides the ability to group data from sites within a region, thus gaining statistical power for detecting trends (Helsel and Frans 2006). The increase in statistical power is an important advantage when analyzing short records with substantial interannual variability, such as the SNOTEL data.

The RKT evaluates whether there is a monotonic (single direction) trend over time, and because it is a nonparametric test, no assumptions of linearity of trends or normality of data are required. Trends are tested on individual sites using the Mann–Kendall test, which evaluates whether values increase or decrease with time based on pairwise comparisons, and results are combined for all sites with a region. Trends slopes are calculated using the nonparametric Sen slope estimator, which is the median slope between all of the pairwise comparisons. The RKT and its application are described in detail in Helsel and Frans (2006).

In the present study, trends in snowmelt and streamflow timing were tested for the 1978–2007 water years using the RKT with a 0.05 level of significance unless otherwise stated. Trend tests were performed on SM onset, SM50, Q20, Q50, Q80, monthly averaged air temperature, the percentage of winter precipitation falling as snow, 1 April SWE, and maximum SWE. For comparison, trends also were tested on individual sites using linear regression with a 0.05 level of significance.

c. Multiple regression

Previous studies have noted the strong influence of winter and spring climate on streamflow timing (Cayan et al. 2001; McCabe and Clark 2005; Stewart et al. 2005). In this study, the influence of winter and spring air temperature and precipitation on snowmelt timing was investigated using multiple linear regression (MLR; Helsel and Hirsch 1992). The MLR technique allows separation of the influences of competing variables, such as air temperature and precipitation, on trends (Mote 2006). This is important because precipitation can affect air temperature and vice versa (Serreze et al. 1999), and both can affect snowmelt timing.

To determine the relative importance of air temperature and precipitation in determining snowmelt timing, stepwise multiple regression was used to develop predictive models of SM onset and SM50, with seasonal and monthly climate variables (air temperature and precipitation, maximum SWE), latitude, longitude, and elevation as input. Values of the climate variables varied temporally and spatially, while latitude, longitude, and elevation varied only spatially. The variable that explained the most variance entered the model first. The variances explained by the remaining explanatory variables were recalculated, and the variable that explained the next greatest amount of variance entered the model next. This iterative process was repeated until no additional variables showed statistically significant correlations to the snowmelt timing indices variable at $p \leq 0.1$. Multicollinearity among the explanatory variables was evaluated using the variance inflation factor (Hair et al. 2005), with a threshold for exclusion of 0.2. The resulting beta coefficients (partial regression coefficients) for the explanatory variables represent independent contributions of each explanatory variable (Kachigan 1986). Residuals plots were used to identify and screen outliers. Residuals plots and normal probability plots were used to check for violation of assumptions of normality, linearity, and homoscedasticity (Kachigan 1986). The residual plots indicated no homoscedasticity; however, there was a small positive bias in predicted SM onset and SM50 at low values. Residuals plotted along a linear diagonal line in the normal probability plots, indicating that they were normally distributed.

4. Results

a. Changes in snowmelt and streamflow timing

At individual SNOTEL sites, snowmelt timing indices exhibited substantial interannual variability (Fig. 4). Few trends in SM onset and SM50 were detected at individual sites using linear regression (Table 1), as expected given the large interannual variability and short period of record; however, 95% of the regression slopes in SM onset and SM50 were negative, which is indicative of earlier melt (Table 1).

In contrast with results from the linear regression analyses, results of the regional Kendall analyses indicated strong, pervasive trends toward earlier snowmelt throughout the mountains of Colorado (Figs. 5a,b). Thirteen of the 14 regions of SNOTEL sites had statistically significant trends in SM onset and SM50 toward earlier melt. Trends in SM onset ranged from 1.9 to 7.5 days earlier per decade, and the median change among the regions was 4.8 days decade^{-1}. Trends in SM50 were similar, as expected, because the two snowmelt timing indices are affected by the same climatic variables. SM50 ranged from 1.1 to 5.6 days earlier per decade, with a median of 4.3 days per decade. Over the 29-yr study period, the median changes in SM onset and SM50 were 14.4 and 12.9 days, respectively.

Trends in SM onset were smaller at sites in the north-central mountains than in western and southern parts of Colorado (Fig. 5a), probably reflecting relatively weak trends in 1 April SWE in that area (see section 4b). Strong upward trends in air temperatures during April and May in the north-central mountains, however, caused trends in SM50 in that area to "catch up" to the rest of the western mountains (Fig. 5b, section 4b).

Trends in SM onset and SM50 were not significantly related to elevation. Previous studies have noted inverse correlations between elevation and trends in 1 April snowpack SWE (Mote et al. 2005) and trends in streamflow timing (McCabe and Clark 2005). It was inferred that snowpacks at low elevations were more susceptible to early melt than snowpacks at higher elevation, which is reasonable given that low-elevation snowpacks generally are much closer to 0°C than high-elevation snowpacks. The difference in results from previous studies may reflect the much smaller range in elevations of sites used in the present study, or SM onset and SM50 may have responded primarily to regionally extensive weather patterns rather than elevationally dependent trends in air and snowpack temperatures.

There were coherent temporal patterns in snowmelt timing, indicating that snowmelt timing responded similarly among SNOTEL sites in Colorado (Fig. 6). Snowmelt was relatively late during 1982–84, possibly reflecting the cooling influence of volcanic eruptions, including El Chicon, in the Northern Hemisphere (Santer et al. 2003). Snowmelt timing also was late during the mid-1990s, which was a relatively wet period in most of the Colorado mountains (Ray et al. 2008). Early snowmelt occurred during the late 1980s and early 2000s, which were relatively warm and dry periods in western Colorado (Ray et al. 2008).

Linear regression analyses on data from individual stream sites indicated a moderate percentage of statistically significant trends in streamflow timing during 1978–2007; regression slopes were negative at 95% or more of the sites (Table 1). In contrast, results of the regional Kendall analyses on streamflow data indicated nearly ubiquitous trends toward earlier streamflow throughout the mountains of Colorado (Figs. 5c–e). The trends were strongest early in the season and declined as snowmelt progressed; the trend in median Q20 was 7.1 days earlier per decade, whereas the trends in median Q50 and Q80 were 5.0 and 3.8 days earlier per decade,

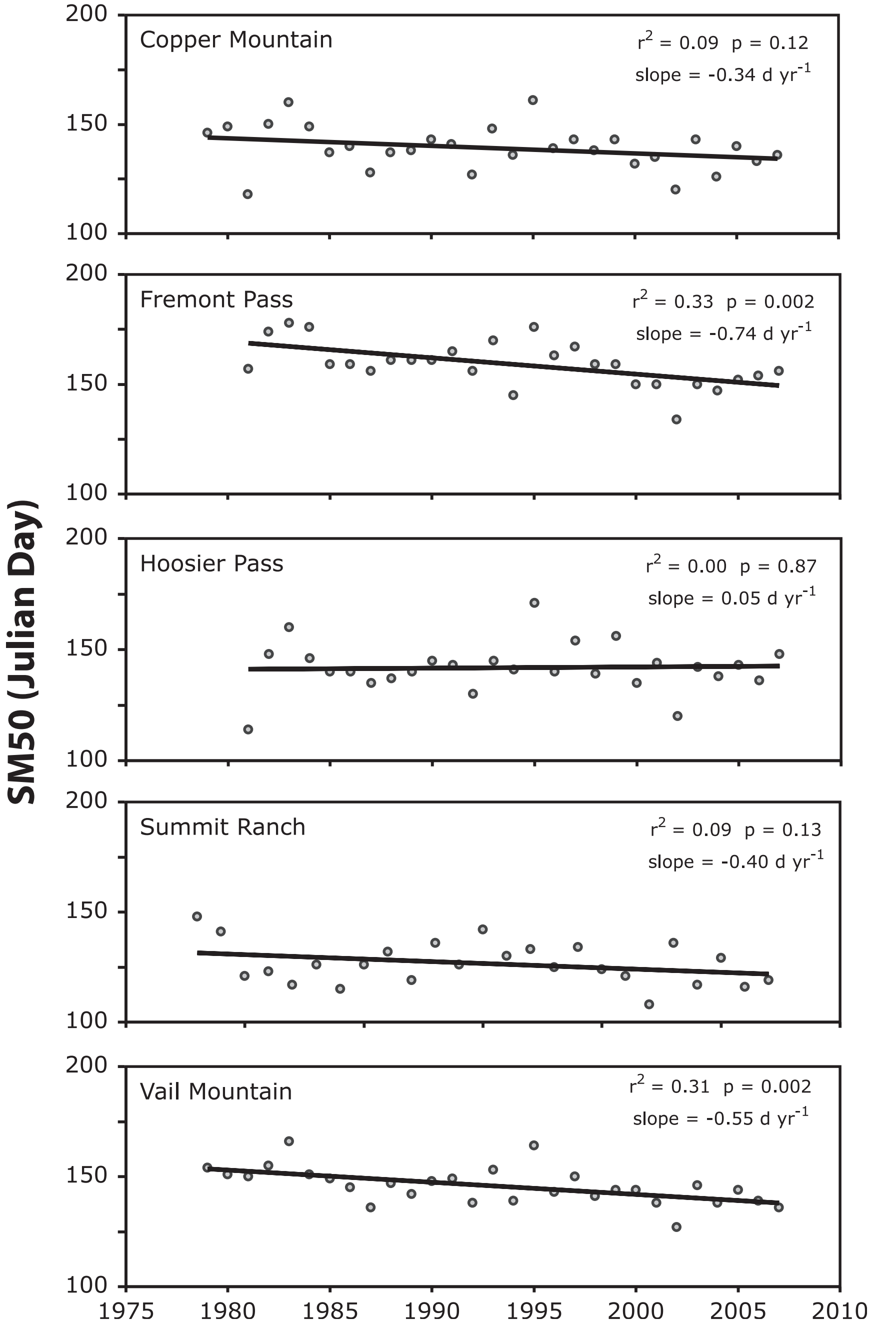

FIG. 4. Snowmelt center of mass (SM50) at SNOTEL sites near the Continental Divide in north-central Colorado. These sites comprise 1 of 14 regions used in the RKT.

respectively. Thus, the length of the snowmelt runoff season increased in duration. The increase in runoff duration might be due to an increase in the relative importance of summer rain; October–April precipitation declined in 8 of 14 regions during 1978–2007, but there were no statistically significant changes in May–September precipitation over that period. October–April coincides with the snowfall season; precipitation during May–September is primarily in the form of rain. Rainfall helps sustain streamflow through the summer period, and the lack of trend in rainfall may explain why shifts in Q20, Q50, and Q80 were progressively smaller. The reason for the change in seasonal precipitation is uncertain, but the increase in runoff duration identified in this study is consistent with regional model projections by Rauscher et al. (2008). These trends may

TABLE 1. Results from linear regression analyses of SM onset, SM50, Q20, Q50, and Q80 against year at individual SNOTEL and stream sites during 1978–2007 water years. Trends were considered statistically significant at $p \leq 0.05$.

	Significant upward trends	Significant downward trends	Positive regression slopes	Negative regression slopes
SM onset	0%	29%	5%	95%
SM50	0%	13%	5%	95%
Q20	0%	43%	2%	98%
Q50	0%	62%	0%	100%
Q80	0%	36%	5%	95%

have important implications for management of water storage systems and for water rights that are linked to specific times of year.

The most notable spatial pattern in streamflow timing was that trends in the north-central mountains initially were relatively weak, similar to those of SM onset (Figs. 5a,c). This pattern disappeared as snowmelt progressed, however, and trends were more evenly distributed by the end of the snowmelt period (Figs. 5d,e).

The differences in results of trend tests using linear regression and RKT analyses were noteworthy; far fewer trends in snowmelt timing and streamflow timing were detected using linear regression than using RKT (Table 1, Fig. 5). In one of the regions in north-central Colorado, for example, RKT analysis indicated a strong downward trend in SM50 of 4.2 days decade^{-1}, with $p \leq 0.001$, but significant trends were detected at only two of five sites in the region using linear regression. The greater statistical power of the RKT method is largely attributable to grouping of the data (Helsel and Frans 2006), although resistance to outliers and missing values is an additional benefit of this nonparametric test.

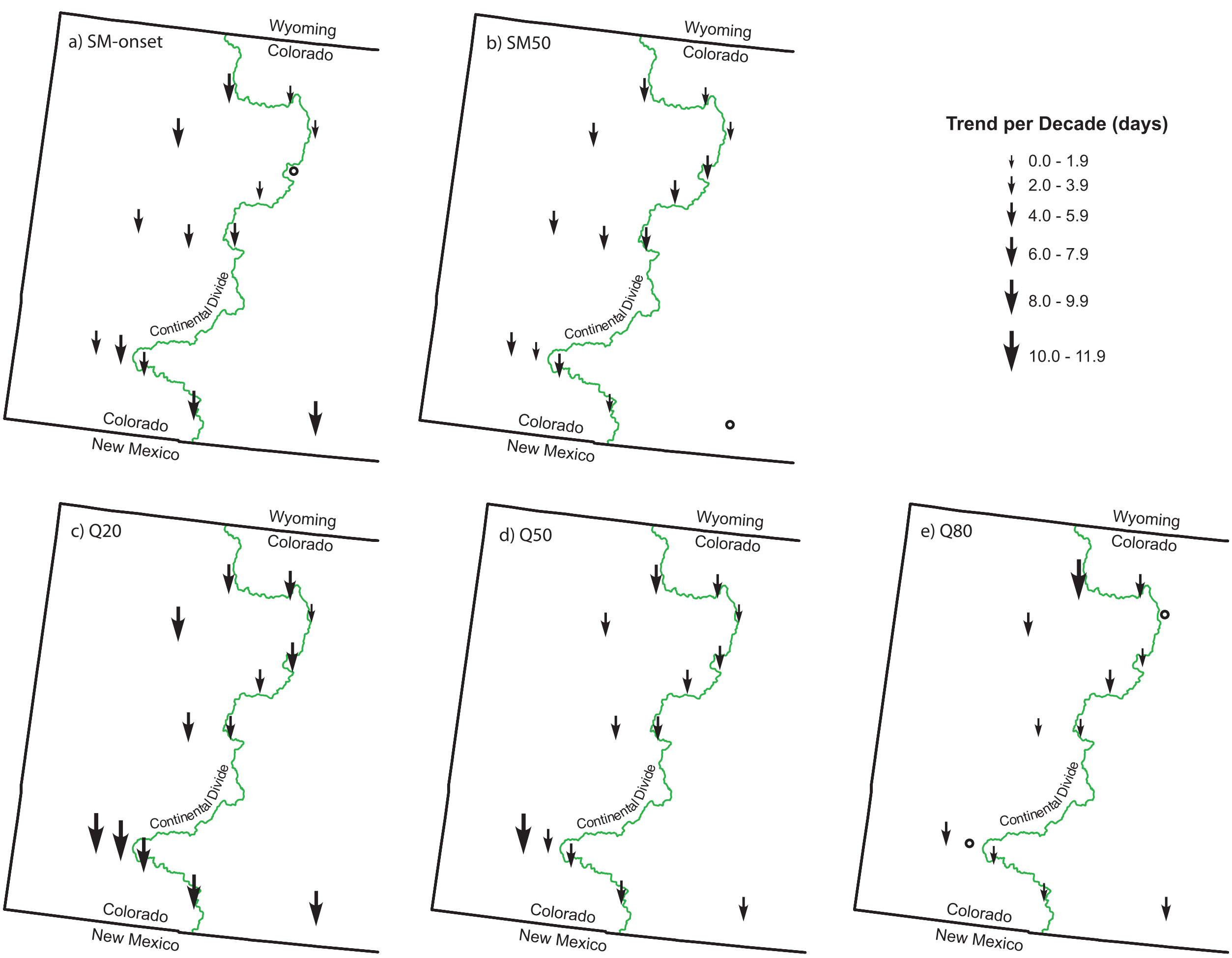

FIG. 5. Trend in timing of (a) day of snowmelt onset (SM onset), (b) day when half of snowpack has melted (SM50), (c) day when 20% of annual flow has passed gauge (Q20), (d) day when 50% of annual flow has passed gauge (Q50), and (e) day when 80% of flow has passed gauge (Q80). Arrows indicate trends significant at $p \leq 0.05$; circles indicate no significant trend.

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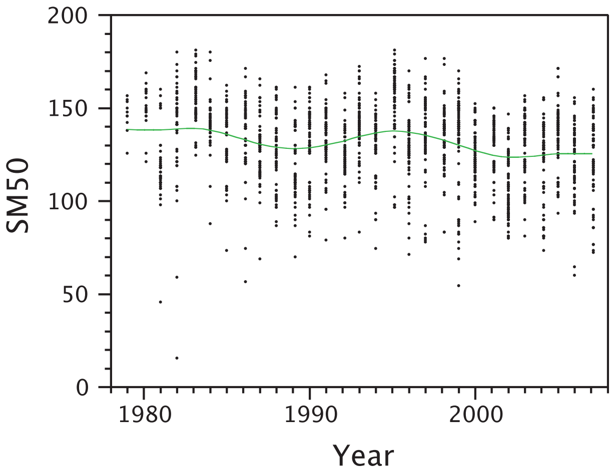

FIG. 6. Annual variations in snowmelt center of mass (SM50) at 70 SNOTEL sites in Colorado during 1978–2007 water years. Line is locally weighted scatterplot smooth (LOWESS) fit to the data (Helsel and Hirsch 1992).

b. *Trends in air temperature and precipitation*

1) Air temperature trends at SNOTEL sites

There were strong upward trends in monthly average air temperatures during the snow accumulation/melt season in the Colorado mountains during 1986–2007 (Fig. 7). Trends were strongest during November–January, with median increases ranging from 1.0 to 1.5°C decade^{-1}. Air temperatures trended upward in March–May by 0.6°–0.9°C decade^{-1}, and trend magnitudes increased as spring progressed (Fig. 7). The upward trends in air temperature during March–May are noteworthy because of the inverse relation between springtime air temperatures and snowmelt timing observed in previous studies (Cayan et al. 2001; Stewart et al. 2005). There also were strong increases in temperature during July and August (0.7°–1.3°C decade^{-1}), which would be expected to lead to increased drought stress in forested ecosystems, unless there is an increase in summer precipitation. The median increase in November–May air temperatures at the SNOTEL sites in Colorado during 1986–2007 was 0.9°C decade^{-1}; the median increase in annual air temperatures was 0.7°C decade^{-1}.

The observed air temperature increases at the SNOTEL sites in Colorado are similar to those estimated for Colorado mountains over the 1979–2006 period by Diaz and Eischeid (2007) from the 4-km-resolution gridded Parameter–Elevation Regressions on Independent Slopes Model (PRISM) dataset (Daly et al. 2002). They are, however, substantially greater than those estimated for Colorado as a whole, based on linear regression analyses performed on data collected at National Weather Service (NWS) cooperative observer stations in Colorado over a similar time period (1977–2006; see Ray et al. 2008). Linear regression analysis of air temperature data from the Global Historical Climatology Network (GHCN) indicate an average warming in the Northern Hemisphere of 0.34°C decade^{-1} during 1979–2005 (Trenberth et al. 2007). Differences in analyzed time periods may explain part of the difference in trends, but differences in station locations may be important as well. Sites used in the current study and in Diaz and Eischeid (2007) included SNOTEL stations, which often are located on hill slopes and at relatively high elevations. In contrast, most of the NWS and GHCN sites are located in valleys at lower elevations than the SNOTEL sites. In an analysis of PRISM data, Diaz and Eischeid (2007) noted a strong increase in the magnitude of air temperature trends with elevation, from approximately 0.4°C decade^{-1} at 2000 m to 0.8°C decade^{-1} at 4000 m; thus, differences in elevation could be an important reason for differences in trend results.

2) Air temperature trends at Loch Vale and Niwot Ridge

Although the SNOTEL air temperature data used in this study underwent extensive screening to eliminate outliers and biased values, independent long-term measurements are needed to help corroborate the observed trends in SNOTEL data. Long-term climate data are extremely sparse for high elevations in Colorado; however, high-quality datasets are available at two research watersheds in the northern Front Range. The USGS has monitored climate in Loch Vale (elevation 3159 m) since 1983 (http://co.water.usgs.gov/lochvale/; http://www.nrel.colostate.edu/projects/lvws/pages/homepage.htm), and the University of Colorado has monitored climate at two locations (C1 elevation = 3048 m and D1 elevation = 3749 m) on Niwot Ridge since 1952 (http://culter.colorado.edu/NWT/).

During 1983–2007, average annual air temperatures at Loch Vale increased by 1.3°C decade^{-1} (Fig. 8). During the same period at Niwot Ridge, average annual air temperatures increased by 1.1°C decade^{-1} at C1 and by 1.0°C decade^{-1} at D1. All of the trends were statistically significant at $p \leq 0.01$.

It is worth noting that the results of trend analyses may be strongly affected by the time period used in the analyses (Ray et al. 2008). Trend tests on air temperatures at Niwot Ridge, for example, indicate a decrease in air temperatures from 1952 through the mid-1970s (Williams et al. 1996; Pepin and Losleben 2002), and an increase in air temperatures since then. This illustrates the importance of short-term climate oscillations, which may overlay on and obscure long-term climate change

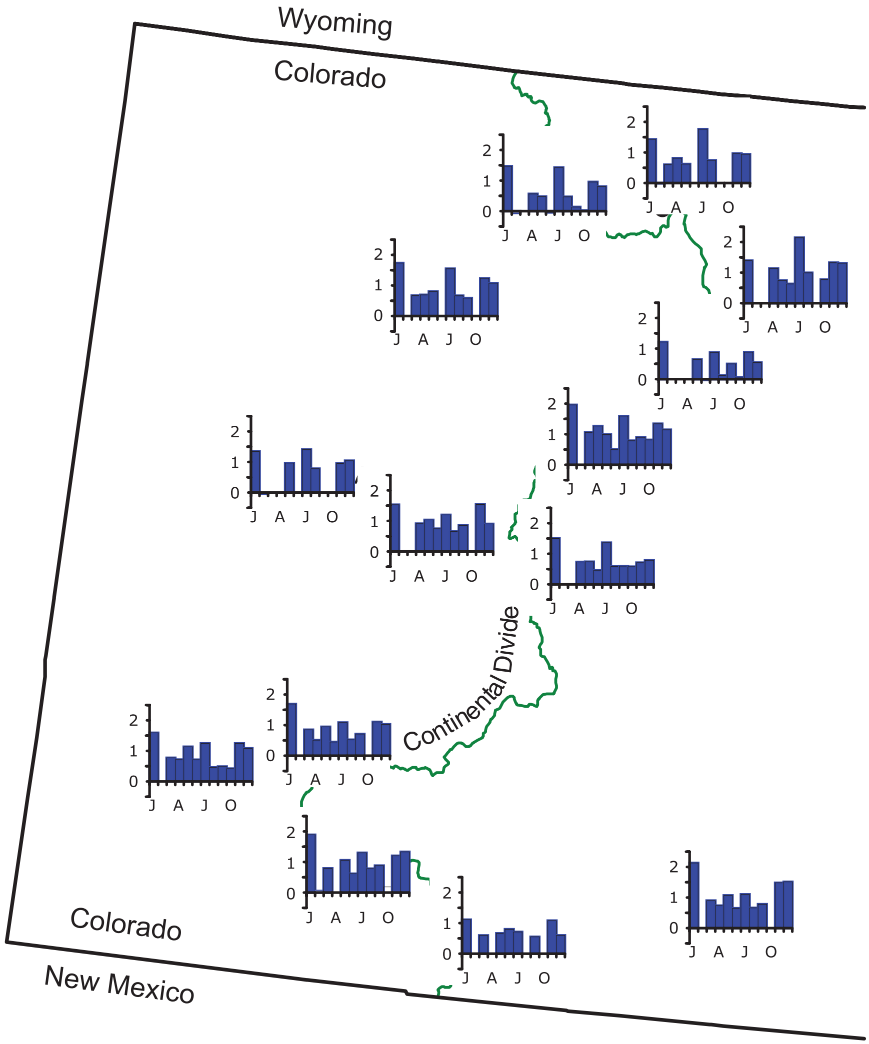

FIG. 7. Trends in monthly averaged air temperatures during 1986–2007 (°C decade^{-1}) at SNOTEL sites in Colorado. Trend tests were performed using the RKT, with sites grouped by regions as in Fig. 6. Filled columns indicate trends significant at $p \leq 0.05$.

signals. Trends in other hydroclimate variables, including precipitation, runoff, and snowmelt timing, may be strongly affected by short-term climate variations as well.

3) SWE AND PRECIPITATION TRENDS AT SNOTEL SITES

The 1 April SWE was highly correlated with maximum SWE ($r^2 = 0.88$), and both declined during the 1978–2007 water years, particularly in western and southern Colorado (Fig. 9a). The median declines in 1 April SWE and maximum SWE were 4.1 and 3.6 cm decade^{-1}, respectively. Over the 29-yr study period, this amounts to about one-fifth of the average maximum SWE. Declines in 1 April SWE and maximum SWE were much smaller in the north-central mountains than in the western and southern mountains, which might reflect changes in the prevalence of synoptic weather patterns affecting Colorado during the study period. The north-central mountains receive winter/spring precipitation under several types of weather patterns. One pattern that is relatively unique to the Front Range compared to other parts of the state is that upslope snowstorms can occur when low pressure forms to the southwest and cyclonic flow brings abundant moisture to the Front Range (Changnon et al. 1993; Marwitz and Toth 1993). On a broader scale, winter precipitation in the southwestern United States (including southern Colorado) has been shown to be correlated with El Niño–Southern Oscillation (ENSO; see Dettinger et al. 1998; McCabe and Dettinger 1999) and the Pacific decadal oscillation (PDO; Knowles et al. 2006). Correlations between winter

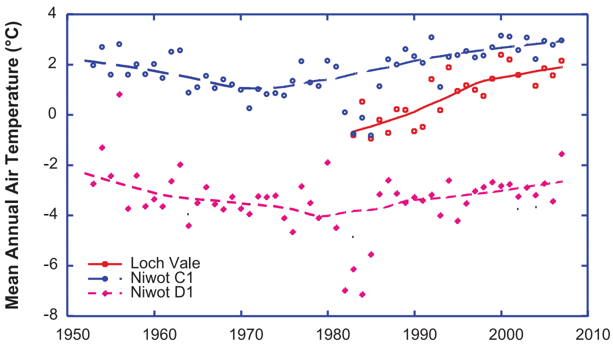

FIG. 8. Average annual air temperatures at Loch Vale and Niwot Ridge weather stations. Lines are LOWESS fits to the data (Helsel and Hirsch 1992).

precipitation and climate indices in other parts of the state are weaker and more variable (Ray et al. 2008).

Mote et al. (2005) reported widespread declines in 1 April SWE in the western United States during 1950–97. Most of the change in 1 April SWE in the Rocky Mountains was attributed to increasing air temperatures rather than changes in precipitation, which were relatively small (Hamlet et al. 2005; Mote et al. 2005). Time series plots indicated that while changes in 1 April SWE in the Rockies were modest during 1950–2004, there was a substantial decline between the mid-1970s and 2004 (Mote et al. 2005).

In the current study, significant declines in winter precipitation (not shown) were detected at 11 of the 14 SNOTEL regions during the 1978–2007 water years ($p \leq 0.05$), which explains part of the decline in SWE in Colorado. Changes in the ratio of snow-water equivalent to total precipitation (SWE:P) for the winter season were important as well; six SNOTEL regions had significant downward trends in the SWE:P ($p \leq 0.05$), and changes elsewhere were not statistically significant (Fig. 9b). All of the significant trends in SWE:P occurred in the western and southern parts of the state, which is similar to the spatial pattern of declines in 1 April SWE and maximum SWE. A multiple regression analysis indicated that SWE:P accounted for 60% of the variance in maximum SWE, and the correlation was positive. Other factors that were less important, but still added significant explanatory power to the MLR, were winter air temperature (positive correlation), and April and May air temperatures (negative correlation). Warm winter air temperatures allow air to hold more moisture, promoting increased snowfall. Warm springtime air temperatures, however, can cause early melt and reduce water stored in the snowpack.

Knowles et al. (2006) documented widespread changes in SWE:P for the winter season in the western United States during 1949–2004, based on data from cooperative

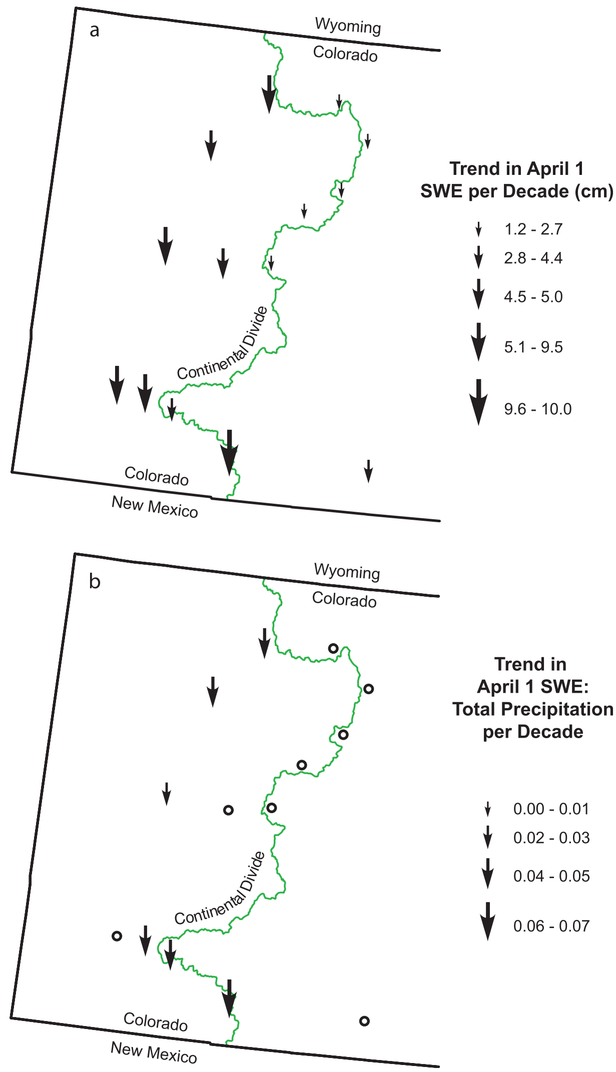

FIG. 9. Trend per decade in (a) 1 Apr SWE and (b) 1 Apr SWE:total precipitation. Total precipitation refers to the amount of precipitation in the water year by 1 Apr. Trends significant at $p \leq 0.05$ (arrows) and no significant trend (circles) are noted.

weather stations. The changes in SWE:P were linked to regional warming, and were most pronounced in areas where the majority of winter precipitation fell at temperatures ≥ -5°C (Knowles et al. 2006). Trends in SWE:P in Colorado were variable, with about half the sites showing declines (Knowles et al. 2006), which is consistent with results from the present study.

c. *Influence of climate on snowmelt timing*

Multiple regression models developed for SM onset and SM50 provide useful information about the relative importance of trends in air temperature and precipitation in controlling trends in snowmelt timing. The MLR models for SM onset and SM50 differed in their predictive

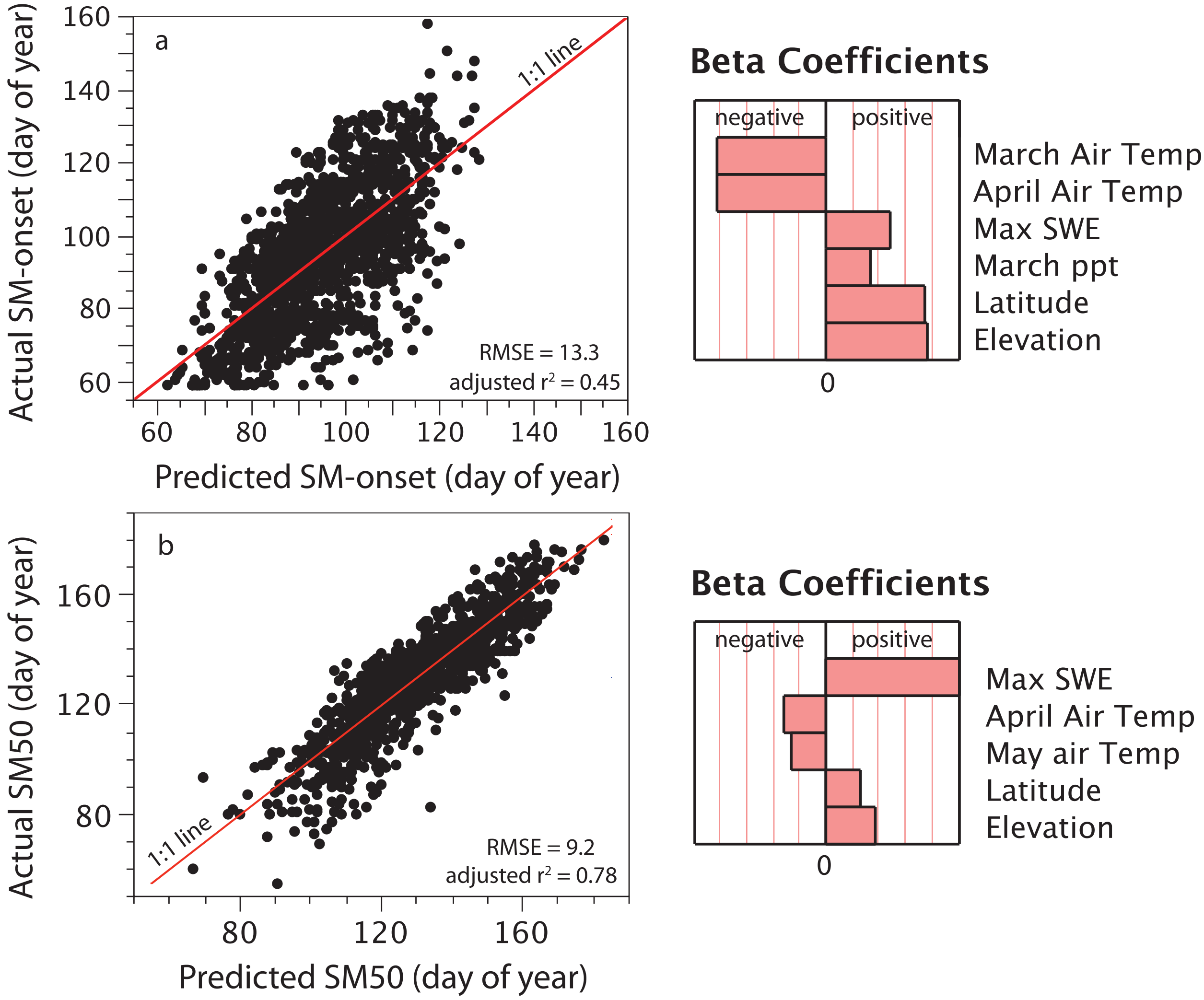

FIG. 10. Comparison of actual and predicted (a) Julian date of SM onset and (b) Julian date of SM50. Beta coefficients show the relative importance of explanatory variables, and are centered around the parameter mean and scaled by the parameter range/2 (Kachigan 1986). Residuals were normally distributed based on linearity of normal probability plots (not shown).

power. The date of SM onset proved to be difficult to model using the climate variables employed in this study. The "best" model, which used March and April air temperatures, maximum SWE, March precipitation, latitude, and elevation, was able to explain only 45% of the variance in SM onset at Colorado SNOTEL sites and had a root-mean-square error (RMSE) of 13.3 (Fig. 10a). March and April air temperatures were the most important explanatory variables and were inversely related to SM onset, indicating that warm springtime temperatures lead to earlier melt (Fig. 10a). Latitude and elevation were positively related to SM onset; note that these variables do not vary temporally and serve primarily to account for spatial variations in temperature (later melt would be expected at high latitudes and elevations because of cooler temperatures). March precipitation and maximum SWE also were positively related to SM onset due to the fact that more energy is required to heat deep snowpacks up to their melting point (0°C) than that needed for shallow snowpacks. The SM onset model overpredicted SM onset for early melt situations and underpredicted SM onset for late melt situations. This suggests that the model does not account for an important, but unknown, process.

Efforts to model SM50 were more successful; a model incorporating many of the same variables as the SM-onset model, plus May air temperature, explained 78% of the variance in SM50 and had a RMSE of 9.2 (Fig. 10b). Maximum SWE was the most important explanatory variable, and it was positively correlated with SM50, as were elevation and latitude. April and May air temperatures were negatively related to SM50 (Fig. 10b).

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The lesser amount of variance explained by the SM-onset model might reflect the influence of short periods of rapid warming on snowmelt onset (Regonda et al. 2005), which are not captured by the monthly and seasonal climate indices used here. Short warming periods are likely to affect shallow, warm snowpacks more than deep, cold snowpacks. The SM50 model probably is less influenced by short-term climate fluctuations, and thus may be a more robust index of snowmelt timing. The performance of the regression models might improve if indices for aeolian dust deposition on snowpacks are included. Aeolian dust deposited on snow can affect snowmelt timing by decreasing snowpack albedo (Painter et al. 2007). Although this effect was not included in the models in the present study, it might be possible to use snowpack chemistry (e.g., calcium or alkalinity) or remote sensing data [e.g., Moderate Resolution Imaging Spectroradiometer (MODIS) snow albedo] as indicators of dust deposition in the future.

Multiple regression models can be used to assess the relative importance of the explanatory variables in determining the response of SM onset and SM50 to recent changes in climate. Holding maximum SWE constant and changing springtime air temperatures by the amount observed over the past 29 yr yields advances in SM onset and SM50 of 7 days and 8 days, respectively. If air temperatures are held constant and maximum SWE is allowed to change as observed, SM onset and SM50 advance by 1 and 6 days, respectively. These results indicate that the dominant influence on SM onset was trends in air temperature; SM50 was influenced almost equally by trends in air temperature and maximum SWE.

d. Implications for water resources in Colorado

Recent model projections using a high-resolution nested climate model indicate that air temperatures in the mountains of Colorado are likely to warm by an additional 3°–5°C by the end of this century (Rauscher et al. 2008). Modeled air temperature increases were greatest during winter and at high elevations because of a snow–albedo feedback, in which warming causes decreased snow cover and increased absorbance of solar radiation by bare ground. This subsequently causes additional warming and melting, which amplifies the signal. The projected increases in air temperature from the nested climate models are greater than those previously estimated using downscaled general circulation models (GCMs) because the nested modeling approach is better able to account for local topography (Rauscher et al. 2008). The higher-resolution modeling results are consistent with observations of strong upward trends in air temperature at high elevations documented in the present study.

Projected changes in precipitation for Colorado generally are small and have high uncertainty (Christensen et al. 2004; Ray et al. 2008). Over the long term, most GCMs predict that high latitudes will see an increase in precipitation, whereas the desert Southwest will see a decrease resulting from a northward shift in the midlatitude storm track (Dettinger et al. 1998; McCabe et al. 2001). Running through northern Colorado, 40°N latitude appears to be a pivot point in a north–south precipitation ''see-saw'' (Dettinger et al. 1998). When precipitation is high north of the pivot, it tends to be low to the south, and vice versa. In the high-resolution nested simulations of future climate conducted by Rauscher et al. (2008), cyclonic flow increases over the Southwest, resulting in increased upslope flow over western mountain ranges and a decreased rain shadow effect. This pattern is in good agreement with the spatial pattern of trends in 1 April SWE and maximum SWE observed in the present study, in which declines in SWE were much smaller in the north-central mountains than elsewhere in the study area. Even with no change in precipitation, evapotranspiration is expected to increase because of warmer temperatures, causing runoff in the Colorado River basin to decline by 10%–30% by 2050 (Milly et al. 2005).

If the shifts in snowmelt timing observed in this study continue, they have important implications for reservoir operation and flood risk, water rights, wildfire severity, and forest ecology in Colorado. Snowmelt will occur earlier, but the runoff season may increase in length, which could reduce the risk of flooding during snowmelt. On the other hand, flood risk might increase if warming temperatures cause Colorado to experience more rain-on-snow events, which have been relatively uncommon in the state compared to the Pacific Northwest. Changes in snowmelt timing may affect water rights whose seniority varies with time of year. Stakeholders whose water rights are senior late in the year, but are more junior early in the year, may be losers under scenarios of increased springtime warming. Earlier snowmelt may cause soil moisture to decline during summer, increasing drought stress in trees, making them more susceptible to wildfires and insect infestation (Westerling et al. 2006). A mountain pine beetle epidemic currently is decimating lodgepole forests in Colorado, and drought stress and increased winter temperatures probably are important contributing factors (Hicke et al. 2006).

Controls on temporal patterns in climate in Colorado are complex. Periodicity is evident in air temperatures, precipitation, and snowmelt timing in Colorado, but the links to oceanic and atmospheric indices are complicated and not well understood (Redmond and Koch 1991; Cayan 1996; McCabe and Dettinger 1999). The cyclical climate patterns make detection of a greenhouse gas–induced warming signal difficult; however, using multivariate analysis techniques, Barnett et al. (2008) were able to demonstrate that most of the long-term trends in streamflow, winter air temperatures, and SWE in the western United States are related to greenhouse warming.

5. Conclusions

In this study, trends in the timing of snowmelt and associated runoff were evaluated for the state of Colorado during the 1978–2007 water years using the regional Kendall test (RKT) on daily snow-water equivalent (SWE) data from SNOTEL sites and daily streamflow data from headwater streams. Trends also were tested using linear regression on data from individual sites for comparison. RKT was much more powerful at detecting trends than linear regression was, largely because of the ability to group data from sites within geographic regions. The RKT results indicated pervasive trends toward earlier snowmelt; the median change in snowmelt onset was 4.8 days decade^{-1}, and the median change in the snowmelt center of mass (the day on which half the snowpack had melted) was 4.3 days decade^{-1}. Streamflow timing advanced by similar amounts. RKT analyses indicated that November–May air temperatures increased by a median of 0.9°C decade^{-1}, while 1 April SWE and maximum SWE declined by a median of 4.1 and 3.6 cm decade^{-1}, respectively.

Multiple regression models indicated that increasing springtime air temperatures and declining snowpack SWE could account for a large portion of the variance in snowmelt timing (45% of the change in snowmelt onset, and 78% of the change in snowmelt center of mass). It may be useful to include other possible controls on snowmelt timing, such as dust deposition, in regression models in the future.

Results from this study indicate that even the mountains of Colorado, with their high elevations and cold snowpacks, are experiencing substantial shifts in the timing of snowmelt and snowmelt runoff toward earlier in the year. Addressing the observed and potential future changes in snowmelt runoff will require careful planning by water resource managers and policy makers (Barnett et al. 2004; Barnett et al. 2005). Long-term climate monitoring at high elevations has been, and will continue to be, key to detecting trends in snowmelt and streamflow timing.

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