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On the Origin of Recent Changes in Western North American Snowpack

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Abstract Monthly snow water equivalent station observations and gridded temperature data are used to identify mechanisms by which warming affects the temporal and geographical structure of changes in western North American mountain snowpack. We first exploit interannual variability to demonstrate the sensitivity of snowpack to temperature during the various phases of the snow season. We show that mechanisms whereby temperature affects snowpack emerge in the mid to late portion of the snow season, but are nearly absent during the earliest phase, when temperatures are generally well below freezing. The mid to late snow season is precisely when significant loss of snowpack is seen at nearly all locations over the past few decades, both through decreases in snow accumulation and increases in snowmelt. At locations where April 1st SWE has been increasing over the past few decades, the increase is entirely due to a significant enhancement of accumulation during the earliest phase of the snow season, when the sensitivity analysis indicates that temperature is not expected to affect snowpack. Later in the snow season, these stations exhibit significant snowpack loss comparable to the other stations. Based on this analysis, it is difficult to escape the conclusion that recent snowpack changes in western North America are caused by regional-scale warming. Given predictions of future warming, a further reduction in late season snowpack and advancement in the onset of snowmelt should be expected in the coming decades throughout the region.

Keywords snow water equivalent · climate change · climate sensitivity · trends · surface observations

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1 Introduction

The yearly recurrence of cold season mountain snowfall is a critical aspect of water resources in western North America. The water supply from spring and summer snowmelt runoff supports agriculture, urban areas, and the ecological health of coastal ocean and riverine environments. The mountain snowpack provides natural storage of precipitation from the cold season months until it gradually melts during the warm season and subsequently flows to sea level through rivers and aqueducts. Water supply and springtime runoff predictions are necessary for intra-annual water use planning and flood management, as well as for longer term planning, design, and operation of water resource systems (Brekke et al, 2009). Recent studies have documented the precarious balance between current water supply and a growing demand (Gleick and Palaniappan, 2010, Rajagopalan et al, 2009) with the potential for climate change to require significant changes to water resource management (Brekke et al, 2009, Barnett et al, 2005). An understanding of the mechanisms causing changes in the mountain snowpack over the last half-century is of paramount importance to understanding future changes, and developing credible adaptation strategies to avert water shortages or flooding.

Given that global temperature has been increasing over the past century and that the warming is expected to accelerate due to anthropogenic forcing (Solomon et al, 2007), understanding how temperature affects snowpack is of the utmost importance if we hope to project future snowpack changes in western North America. As temperatures vary across the freezing point of water, snowpack in a mountainous region such as western North America would be directly affected through: (1) changes to the percentage of precipitation falling as rain or snow, and (2) melt anomalies.

These two direct temperature influences on snowpack would vary in importance over the snow season. The first mechanism, where temperature modulates precipitation partitioning between rain and snow, should be detected through anti-correlations between changes in SWE and temperature anomalies. This should mainly be observed during the accumulation phase of the snow season. Several papers examine snowpack as a fraction of accumulated precipitation to assess this mechanism. Barnett et al (2008) forced a hydrologic model with output from two general circulation models over the Cascades, Northern Rockies, and Northern Sierras to show that simulated January through March minimum temperatures are anti-correlated with April 1st SWE as a fraction of accumulated winter precipitation. Feng and Hu (2007) similarly showed that there are strong observed trends in seasonal mean SWE/precipitation ratios and November-March wet-day temperature over the Pacific Northwest and central to eastern United States with almost uniform negative correlations between the two metrics. Knowles et al (2006) complements this work by exploring the phase of the seasonal cycle when temperature has its greatest influence on observed precipitation partitioning over western North America.

The second mechanism, where temperature modulates snowmelt, should also be detected through anti-correlations between changes in SWE and temperature anomalies, particularly during the melting phase of the snow season when temperatures rise above freezing during the day. However, unlike the first mechanism, this should mainly be observed during the later, melting phase of the snow season. Previous studies have utilized submonthly SWE measurements to ascertain the relationship between snowmelt and temperature. This work focuses on data available since the late 1970s; these include daily snowpack measurements from automated snow telemetry sites (Serreze et al, 1999) and snow cover products from the more recent satellite record (McCabe and Wolock, 2010, Leathers and Robinson, 1997). Streamflow measurements have also been used as a proxy for SWE to explore the relationship between temperature and snowmelt over the longer streamflow record, and show a trend towards earlier streamflow (Stewart et al, 2005, 2004, Lundquist et al, 2004). Studies using the available SWE record (from 1930 to present) have used linear regressions to connect mean temperatures with SWE for observations (Mote, 2006, Cayan, 1996) and variables derived from a hydrologic model (Mote et al, 2005). Kapnick and Hall (2010) used four monthly SWE measurements during the snow season to calculate a proxy for melt timing in California. They examined its relationship to temperature and found strong anti-correlations.

In spite of all these studies of the two main temperature-driven mechanisms affecting snowpack, it is not clear whether and how they have manifested themselves in snowpack trends. Increasing temperatures should lead to a lower percentage of precipitation falling as snow and enhanced snowmelt; however, these mechanisms are likely strongest during different phases (accumulation versus melt) of the snow season. Moreover, internally-generated or anthropogenic changes in accumulation at any phase of the snow season may also affect snowpack trends. For all these reasons it is difficult to interpret trends in time-integrated snowpack variables physically. This makes it all the more challenging to ascribe such trends to a clearly warming climate.

Studies of April 1st SWE provide a vivid illustration of this problem. They show that April 1st SWE has been decreasing over the historical record in most places. However, it is not clear that this decrease is due to simultaneous warming. Moreover, April 1st SWE has been increasing at a few locations, in particular over the southern California Sierras and southern Rockies (Mote, 2006, Mote et al, 2005, Regonda et al, 2005). This has raised further questions about the robustness of the warming signal in the snowpack (Christy and Hnilo, 2010, Howat and Tulaczyk, 2005). All of this evidence could be consistent with a warming climate if strong evidence for the two mechanisms by which temperature can affect snowpack were found at all locations, including those where April 1st SWE is increasing.

In this study, we exploit interannual variability to demonstrate the sensitivity of snowpack to temperature during the various phases of the snow season. We show that the two mechanisms whereby temperature affects snowpack emerge in the mid to late portion of the snow season, but are nearly absent during the earliest phase. The mid to late snow season is precisely when significant loss of snowpack is seen at nearly all locations over the past few decades. At locations where April 1st SWE is increasing, the increase is entirely due to a significant enhancement of accumulation during the earliest phase of the snow season, when the sensitivity analysis indicates that temperature is not expected to affect snowpack. Later in the snow season, when temperature is expected to affect snowpack according to the sensitivity analysis, these stations also exhibit significant snowpack loss comparable to the other stations. Based on this analysis, it is difficult to escape the conclusion that recent snowpack changes in western North America are caused by regional-scale warming.

We present our study by first providing a description of observational data in Section 2 and the methods for analyzing the data in Section 3. We discuss the links between snowpack and temperature in Section 4. The trends in snowpack, accumulation, snowmelt, and temperature are discussed in Section 5. We summarize our main findings in Section 6. The physical interpretations of our findings and implications of our work are found in our concluding remarks in Section 7.

2 Data

Snow station data were collected from three sources to provide maximum geographical coverage over western North America. Data for 12 western US states were taken from the National Resources Conservation Service ("NRCS") and Water and Climate Center (www.wcc.nrcs.usda.gov/snowcourse/). Over California, the majority of stations (73%) were given by a second source, the California Department of Water Resources (http://cdec.water.ca.gov/misc/SnowCourses.html), with the remaining stations (27%) coming from the NRCS. Station data for British Columbia were taken from the British Columbia Ministry of the Environment River Forecast Centre (http://bcrfc.env.gov.bc.ca/). A total of 670 stations, each with at least 29 years of SWE data from at least one month over the snow record (mid-January to mid-May), are used in this paper (see Figure 1). Monthly station measurements were taken within roughly 2 weeks of the 1st of each month (February, March, April, and May). These stations vary in their years of available data, as measurements were sometimes not regularly taken in years before automatic measurements began in the late 1970s, and some stations were also only operational for a specific time period. Because of minimum data coverage requirements for statistical analysis, fewer than the 670 available stations are sometimes used in the various aspects of this study.

Temperature data are also used to diagnose changes in SWE and melt timing. Maximum and minimum daily gridded temperature data from 1930 to 2003 were downloaded from the web site of the Surface Water Modeling group at the University of Washington (www.hydro.washington.edu/Lettenmaier/Data/gridded/). The development of this data set is described by Hamlet and Lettenmaier (2005). It was chosen for its long temporal coverage (1915 to 2003) and high spatial resolution (1/8 degree) relative to other temperature products that include the pre-satellite era. This product has also been used in previous snowpack studies (Kapnick and Hall, 2010, Casola et al, 2009, Das et al, 2009, Mote et al, 2005, Hamlet et al, 2005). It covers four main regions: the Pacific Northwest and Columbia River, California, the Great Basin, and the Colorado River. (Figure 7 shows the geographical coverage.) Unfortunately, some Wyoming and Colorado snow stations used in Section 5 fall outside of these regions, and are thus left out of Section 4 where snow observations are compared to temperature data.

3 Methods

3.1 Calculations

We use the SWE centroid date (SCD), a metric developed in our previous work on California snowpack (Kapnick and Hall, 2010), to assess interannual variations in snowpack timing when only monthly snowpack snapshots are available. The SCD for any particular year is calculated according to:

$$SCD = \frac{\sum t_i SWE_i}{\sum SWE_i} \quad (1)$$

Monthly measurements within the year are distinguished by i. The SWE measurements (in centimeters) are given by SWE_i. The variable t_i is the exact date of the measurement (given in day of the year, with January 1st as 1). This metric is similar to streamflow metrics used in previous studies of changes in the onset of spring (Stewart et al, 2005, 2004, Lundquist et al, 2004). For the SCD to shift earlier (later), either the fraction of snow accumulation later in the season must decrease (increase), or there must be an increase (decrease) in the fraction of snow melt later in the season.

To provide a physical interpretation of SCD, we tested the relationship between SCD and the actual peak date of SWE at a limited number of stations with daily SWE data. These stations are in California and were analyzed in Kapnick and Hall (2010). We first calculated the date of maximum SWE from February 1st to May 1st using daily data. For years with days of sustained maximum SWE, we averaged the measurement days of sustained maximum SWE to find the peak SWE date. We then aggregated the data from all the years and all available stations for correlation analysis. The monthly SCD, calculated with 1st-of-the-month snapshots, and date of maximum SWE from daily data have a correlation coefficient of $r=0.71$ ($p<0.05$) and regression coefficient of 1.33 (peak days per SCD days). Thus it appears that SCD anomalies are roughly proportional to anomalies in peak date, and that peak date variability can be assessed without the need for daily data through the SCD technique. Because of this close relationship between peak date and SCD, we use the terms interchangeably in the rest of this paper.

3.2 Temperature Adjustments

The daily gridded temperature data were adapted for comparison to snow station data by averaging in time and adjusting temperatures for station elevations. Given that our snow station data is generally only available at monthly intervals, we converted the daily temperature data into monthly means of daily maximum and minimum temperatures. In analyses involving both temperature and snow station data, the local gridcell temperature is adjusted for elevation differences between the gridcell and snow station by assuming a constant lapse rate of 6.5°C/km. If a station is equidistant from two or more gridcells, an average lapse-rate adjusted temperature is calculated over the relevant gridcells. Only stations within 2 grid cells (roughly 28km) of available temperature data are included in these analyses.

3.3 Linear Trends

To understand how the western North American snow pack has changed over the past few decades, we calculated linear trends from observations. Individual snow station and temperature gridcell linear trends (found in Figures 4-7) were calculated for each station or gridcell using all years with available data over the specified time period. Snow trends were only calculated at snow stations with records covering at least 75% of the time period being considered. Trend analysis was conducted using: (a) monthly SWE values, (b) month-to-month changes in SWE, (c) the centroid date of SWE over the snow season (discussed in more detail in Section 3a), and (d) monthly maximum daily temperature. The calendar dates associated with the time dimension of the trend calculations are different for each of these variables: (a) monthly SWE trends use each observation's measurement date, (b) month-to-month changes in SWE trends use the midpoint of the measurement dates of the adjacent months, (c) trends in the centroid dates of SWE use the mean of the measurement dates of the four observations over each snow season from mid-January to mid-May, (d) temperature trends are calculated based simply on the year of measurement, as the measurement dates do not change.

Tables 2 and 3 provide western North American climate trends using two different methods to combine individual observations and aggregate them to create regional trends. For snowpack variables, the linear trend corresponding to all available snowpack data over a given time period was calculated. Rather than average snowpack trends of individual stations found in Figures 4-6 to create a regional trend, we treated the entire set of snowpack observations as one variable for trend analysis. This method gives equal weight to each snowpack measurement and is well-suited for a data set like snowpack that is inhomogeneous in space and time. A similar technique was used in the regional trend calculations of Kapnick and Hall (2010) and Cayan et al (2001). In contrast to snow variable trends, regional western North American temperature trends (found in Table 3) were calculated by finding the mean of all gridcell trends at elevations above 1000m, where nearly all snow stations are located (see Figure 1). Equal weight is given to each gridcell in determining the combined regional trend in temperature. This technique is more appropriate for a data set like temperature that is spatially and temporally homogenous. Trend analysis can be affected by the choice of start date due to availability of data (for snowpack variables) and interdecadal and inter-annual variability (for all climate variables). To determine the consistency of trends and to allow for comparison against studies using other time periods, we have also provided information on sensitivity of trend calculations to start date in these tables.

Previous studies have noted that historical monthly snow course measurement dates may vary (Cayan, 1996), with a potentially systematic shift in the actual date of measurement towards later in the season (Mote et al, 2005). Thus if snow measurement is assumed to take place on a specific and unvarying date, typically the first of the month, errors could result. In reality the measurement can be taken within two weeks of the first of the month (Cayan, 1996, Mote et al, 2005), resulting in approximately 29 potential measurement dates. To avoid this source of error in our analyses, we use the actual measurement date rather than assuming the measurement date is the first of the month. However, even if measurement dates are accounted for correctly, spurious positive or negative trends in SWE could still occur. For example, a systematic shift in measurement dates could result in a corresponding shift in the sampling of SWE to a significantly different point in the seasonal cycle (e.g. to earlier or later in the melt phase). To assess this potential error, we calculated the SWE-related analyses presented in this study using subsets of observations that were taken within either 5, 10, or 14 days from the first of the month (not shown in analysis). We found that including the measurements taken more than 5 days away from the first of the month does not alter our results. Since this error source appears insignificant, we have chosen to utilize measurements taken within 14 days of the first of the month to maximize the number of stations available for analysis.

4 Temperature Sensitivity

We explore the relationship between snowpack and temperature in this section. We exploit interannual variability to identify the phases of the snow season when SWE is most sensitive to temperature. All results rely on monthly means of daily maximum temperatures.

4.1 SWE

In this section we combine temperature and snowpack data to characterize the sensitivity of SWE to temperature. Our goal is to understand how the influence of temperature on SWE changes over the course of the snow season. To accomplish this, we examine the relationship between month to month SWE changes and temperature over the same time interval. Individually, most stations exhibit statistically significant anti-correlations between temperature and inter-month SWE (Figure 2a-c) for all inter-month intervals. The magnitudes of anti-correlations between month-to-month SWE changes and temperature systematically increase over the course of the snow season (i.e. from February to May, see also Table 1). Stations at higher elevations (mainly in Colorado, Utah, and Wyoming) do not exhibit statistically significant anti-correlations with temperature in February (Figure 2a), though this pattern largely disappears in subsequent months (Figures 2b and 2c). No stations have statistically significant positive correlations between snowpack changes and temperature.

The distribution of station correlations between monthly temperature and changes in SWE and the steadily increasing correlations between temperatures and SWE changes as the snow season progresses can be explained by the relationship of the mean station temperature to the freezing point of water. In Figure 2d-f the same correlations displayed in Figure 2a-c are plotted against the mean maximum station temperature (i.e. the average for the entire record of monthly mean maximum daily temperatures at each individual station). During the colder months of February and March (panels d and e) mean temperatures cluster near the freezing point, and nearly all stations experience accumulation (green circles). For these accumulating stations, there is a strong linear relationship between mean temperature and the correlations between temperature anomalies and SWE changes. As mean station temperatures increase, the correlations depart from zero, becoming more and more negative. This is because the mean maximum temperature is a surrogate for the frequency with which maximum temperatures breach the freezing point. The more frequently maximum daily temperature rises above freezing, the more likely it is that precipitation will fall as rain rather than snow, and the stronger the negative influence of temperature on SWE changes. If the mean maximum temperature falls below about -2°C, precipitation almost always falls as snow. The changes in SWE are controlled almost exclusively by precipitation anomalies and the anti-correlation with temperature disappears. This pattern may be interpreted as a confirmation of the emergence of the first temperature mechanism, as temperatures increase and move beyond the freezing point.

Most stations generally experiencing melt are found in April, and to a lesser extent March (grey circles in Figures 2d-e). At these stations and during these months, mean temperatures are enough above freezing that changes in SWE and temperature anomalies are consistently anti-correlated, no matter what the mean temperature. (See the tight cluster of grey circles on the left side of Figure 2f). Warmer temperatures therefore consistently result in more melt. This may be interpreted as the emergence of the second temperature mechanism as the snow season progresses to the melt phase. There is also a small population of grey circles generally associated with very high mean temperatures and relatively low correlations. These may correspond to stations where the change in SWE simply represents the final loss of snowpack through melt and thus is determined by the amount of SWE remaining rather than any other factor such as temperature.

4.2 SCD

As we showed in Section 4a, the relationship between temperature and SWE changes becomes progressively stronger over the course of the snow season, as the first, and then the second temperature mechanism (snowmelt and precipitation partitioning respectively) become increasingly important. This is also reflected in the relationship between monthly temperature anomalies and SCD. When individual station SCD time series are correlated with the various monthly temperature time series (Table 1), it becomes apparent that mean spring temperatures have the greatest influence on peak snowmass timing. Interestingly, mean spring temperatures (mean March and April) have a greater influence on SCD (r= -0.58 for all stations) than either month separately (r= -0.40 and r= -0.50 for all stations in March and April respectively).

Figure 3 provides a perspective on how consistently the mean spring temperatures influence peak timing over the population of stations. It shows a histogram of correlation and regression coefficients between individual station SCD time series and elevation-adjusted local gridcell monthly temperatures from 1950 to 2003. The mean March and April maximum daily temperatures (thick line) have the most negative distribution of correlations and regression coefficients with SCD. This is because temperatures during these months have the greatest influence on snowmelt and snow versus rain accumulation, which shifts the peak timing later (earlier) in cases of cooler (warmer) years. The correlation coefficients are tightly clustered in the -0.5 to -0.9 range, while the corresponding regression coefficients vary from close to 0 days per degree to about -4 days per degree. The correlations and regressions for the months of March and April individually (starred and dashed lines) are also very negatively skewed, but are generally somewhat smaller in magnitude than the combined March and April correlations. This is likely due to a lack of autocorrelation between monthly temperature anomalies in these two months (the mean temperature autocorrelation for gridcells above 1000m from March to April from 1950 to 2003 is r=0.21 with a standard deviation of 0.09). Averaging mean spring temperatures thus better captures the integrated effect of temperature variations across both months.

The distributions of correlation and regression coefficients seen in Figure 3 are expected from our analysis of the relationship between temperature and monthly changes in SWE from Figure 2. In contrast to the late season correlations, February correlations (Figure 3; circled line) have a nearly bell-shaped station distribution centered over 0. This is consistent with the relatively weak influence of February temperature anomalies on inter-month SWE changes (Figure 2a and 2d). The generally greater anti-correlations between mean record temperature and monthly change in SWE over March and April (Figures 2e, 2f, and Table 1) is similarly mirrored in Figure 3 with greater negative distributions between mean spring temperatures and SCD.

5 Trends

In this section we explore the simultaneous trends in snowpack variables and temperature. Combined with the results of Section 4, we can identify the mechanisms underpinning the relationships between trends in snowpack and temperature.

5.1 SWE

The first four rows of Table 2 show the aggregate SWE trends for each month from February to May over the entire population of stations in western North America. Negative trends in SWE are seen in February, and these increase in magnitude monthly until May. This table also shows trends associated with various start dates. Statistically significant negative trends in monthly SWE are found for all months with start dates prior to 1950. For start dates since 1960, two months (February and March) do not have statistically significant trends. However, the trends for the later months (April and May) are entirely robust to choice of start date.

We also explore the geographic distribution of monthly SWE trends from 1950 to 2008 in Figure 4. Consistent with the data in Table 2, negative trends are common throughout western North America in each month. With the possible exception of February, a similar geographical pattern is seen in each month. The negative trends overwhelmingly predominate north of 45°N and are generally statistically significant. Meanwhile, positive SWE trends, when they do occur, are generally confined to stations below 45°N. A relatively small proportion of the positive trends are statistically significant. The southern portion of the California Sierras and southern Rocky Mountains (mainly in Colorado and along its border with New Mexico and Wyoming) are the only regions that exhibit statistically significant positive trends in monthly SWE through April. The general pattern found in Figure 4c has been noted in previous studies of April 1st SWE trends

(Mote, 2006, Mote et al, 2005, Hamlet et al, 2005). Looking at each month individually, we find that the positive trends in these areas generally emerge in February and persist through April. Positive trends in February and March are found in a few stations over Oregon, Idaho, Nevada, and Utah, but generally do not persist through April.

It is difficult to interpret the trends shown in Figure 4 physically, because the SWE values for each month are the integral of snow accumulation and melt over all previous months of the snow season, and therefore may fold in effects of the two main mechanisms whereby temperature affects SWE discussed in Section 1. To determine when in the snow season the SWE changes leading to the trends in Figure 4 occur, and whether they are attributable to melt or accumulation processes, we calculated the trends in inter-month SWE changes for stations with data for two consecutive months. Figure 5 provides the results for February to March, March to April, and April to May, segregated by stations that on average experience accumulation (top row) and snowmelt (bottom row) during the respective time periods. Most stations accumulate SWE from February to April (98% and 77% of stations from February to March and March to April respectively) and then lose SWE from April to May (82% of stations).

Together Figures 4a and 5a allow us to assess how snow accumulation has changed over the time period ending with March. The positive trends prior to February found mainly in California and the southern Rocky Mountains (Figure 4a) were discussed above. Positive trends are also seen from February to March at many more stations, and snow accumulation seems to be increasing at more locations than it is decreasing during this time period. Positive accumulation trends continue to be most pronounced in the California Sierras and southern Rocky Mountains, with most other stations exhibiting weakly positive accumulation trends.

A dramatic reversal occurs during the month of March at nearly all stations, countering any increased snowfall occurring earlier in the season. Nearly all accumulating stations exhibit large negative trends indicating strong reductions in snowfall (Figure 5b). Meanwhile, at melting stations, trends are also very negative during this time period, indicating large increases in melting (Figure 5e). Since April SWE trends are more consistently negative than the trends in accumulation from February to March (compare Figures 4c and 5a), the large and significant decreases in snowfall and increases in snowmelt during the month of March (Figures 5b and 5e) must overwhelm any positive trends seen earlier in the snow season.

During April, many stations also show reduced accumulation and increased melt (Figures 5c and 5f), though the trends are generally smaller than during March and exhibit less statistical significance. There is one station in California, "Lower Lassen Peak", with a significant increase in accumulation from April to May (Figure 5c) over the record (6 cm/decade). This value is driven in large part by an extreme snowfall event from April to May in 2003. (More than 250 cm fell between April and May; the average is only 9 cm.) The trend is reduced to 2 cm/decade if this one extreme year is removed from the station data. This station is also anomalous because it experiences snow accumulation later in the season than other stations in the Feather River basin due to its unique combination of topographic variables (Jost et al, 2007, Regonda et al, 2005). Neglecting this station, accumulating stations (Figure 5c) either experience reduced or neutral accumulation from April to May. Melt is either enhanced, neutral, or slightly reduced during this time period (Figure 5f). Overall, Figure 5 shows that the dominant change to the snowpack occurs during the month of March. The strong and widespread decreases in snowfall and increases in snowmelt in March to April SWE, even at stations showing significant positive trends in April 1st SWE, are highly suggestive of a coherent and strong forcing during this part of the season.

The last three rows of Table 2 provide a quantitative aggregation of individual trends shown in Figure 5. The region exhibits some positive statistically significant trends from February to March and from April to May over different time periods. In later decades, February to March trends in inter-month changes in SWE become more positive, consistent with the general predominance of stations with accumulation increases in Figure 5a. April to May trends become consistently negative for later periods. However, these trends are generally small in magnitude compared to the March to April figures, which are on the order of -1 to -2 cm/decade, and increase with later analyses periods. And, the only inter-month interval with consistent statistically significant trends for every start year is March to April. The information in this table is consistent with the idea that a modest increase in accumulation generally occurred during February followed by a strong and coherent forcing during March causing a much more significant snowpack loss.

5.2 SCD

Figure 6 shows the geographical distribution of trends in SCD. They are overwhelmingly negative. The only positive trends are found at a few stations in California and Colorado, and the only statistically significant positive trend is found in Colorado. The regional linear trend in SCD based on data from all of western North America from 1950 to 2008 is -0.7 days/decade (Table 3). Given the regression coefficient between SCD and daily peak date (from Section 3a), this translates to a change in the actual date of peak SWE of roughly -0.9 days/decade. We similarly calculated SCD trends for different start years in Table 3 to explore the effect of start date on SCD trends. Even when different start years are chosen, the western North American SCD trend remains on the order of -1 day/decade and is statistically significant no matter what start date is chosen.

5.3 Temperature

Temperatures in western North America have predominantly increased over the available record. However, there are seasonal and geographical variations in temperature trends. Figure 7 displays monthly-averaged maximum daily temperature trends from 1950 to 2003 for: (a) February, (b) March, (c) April, and (d) mean spring temperature (mean March and April). A few isolated areas exhibit negative trends, especially in February, which also exhibits the weakest warming trends. The month of March generally exhibits the largest warming—on the order of 0.5°C/decade at almost all locations, creating a similar pattern in the mean March and April temperature trend. Table 3 gives the mean trends for gridpoints with elevations above 1000m, where nearly all snow stations are located (see Figure 1). Sensitivities for various start years are also provided. For March, April, and mean March and April temperatures, the warming trends are larger when start dates are chosen from later decades. There are no large scale cooling trends, and all but 2 entries show warming trends, with March generally exhibiting the strongest trends and February the weakest, consistent with Figure 7. We discuss the relationship between trends in SWE metrics and temperature in the final two sections.

6 Summary

In this paper, we examined the interannual variability in snowpack and explored its relationship to monthly temperature during different phases of the snow season. This analysis allows us to interpret the recent changes in mountain snowpack over western North America. The strength of the temperature influence on SWE is directly proportional to mean station temperatures as they approach the freezing point of water in the early part of the snow season (Figures 2d,e). In particular, during the month of February, the mean daily maximum temperatures have had an almost equal probability of being below or above freezing (56% of the record exhibits mean daily maximum temperatures above freezing). For stations with mean subfreezing temperatures during February, temperature has little influence on snowpack. As a result, snow accumulation has increased at these unique locations in California and the southern Rocky Mountains until March while total precipitation has increased.

After February, there is a greater direct influence of temperature on snowpack (as measured by absolute correlations in Table 1). The region is dramatically warmer; mean maximum daily temperatures are almost always above freezing (98.6% of the mean March and April record exhibits temperatures above freezing). Above-freezing temperatures lead to strong anti-correlations with SWE as temperatures rise significantly above freezing in March (Figure 2). The regression coefficients corresponding to the correlations shown in Figure 3b support the strong influence of late season temperature on the timing of the snowpack peak. Individual stations exhibit an SCD sensitivity of up to -6 days/°C, which translates into a peak SWE date or snowmelt onset sensitivity of up to -8 days/°C (using the relationship between SCD and peak SWE found in Section 3a).

The analysis of the relationship of interannual variability in snowpack to temperature anomalies allows us to interpret the relationship between trends in SWE metrics and temperature. During February, any snowpack trends are unlikely to be attributable to the weak February warming trend, given the lack of sensitivity of snowpack variables to temperature during this phase of the snow season. Instead, February snowpack trends are likely attributable to accumulation trends. However, after February significant warming has been observed over the last few decades. And given the high degree of sensitivity of snowpack to temperature during the mid to late snow season seen in the interannual variability analysis, it seems very unlikely that the simultaneous loss of snowpack is not closely related to this warming. During the month of March, uniform warming has probably resulted in reduced accumulation and enhanced snowmelt at all stations (Figures 5b,e). With the exception of a few high elevation stations in California and the southern Rocky Mountains, these secular, temperature-driven changes in snowpack combine to form a mainly negative trend in April SWE across western North America in all locations that is enhanced through May (Figures 4c,d). As springtime temperatures continue to warm, the onset of snowmelt will continue to shift earlier and post-February snowpack values will continue to decline.

The majority of warming has thus far happened during months when maximum temperatures are above freezing (March and April, Table 3). These are also the months when the snowpack shifts into the melt phase of the season (as measured by the distribution of stations exhibiting melt in Figures 5d-f). The warming in these months may have been enhanced through surface albedo feedback due to the loss of snowpack and increased patchiness of existing snow cover. In the future, the much larger warming signal currently seen in March and April may shift to earlier in the season as snowpack decreases also shift earlier through increased snowmelt and increased percentage of precipitation falling as rain.

7 Discussion

As a result of the intraseasonal changes in the influences of precipitation and temperature on snowpack and variable elevations across western North America, certain geographical and temporal trends in SWE measurements may at first appear to be at odds with the idea that a warming climate is influencing snowpack. These include the positive trends in April SWE seen in Figure 4c and noted in previous literature (Kapnick and Hall, 2010, Barnett et al, 2008, Mote, 2006, Howat and Tulaczyk, 2005, Mote et al, 2005). Here we show that these trends can be attributed to increased accumulation prior to March. These positive snowpack trends do not prove that temperature has little influence on snowpack however. In fact, during the months when snowpack is expected to be sensitive to temperature, these stations show comparable snowpack loss to other stations in association with warming. For example, stations with strong April SWE trends generally show reduced accumulation or enhanced melt trends from March to April (Figures 5b and 5e) when there have also been significant warming trends (Figure 7). The peak date of SWE is also shown to shift earlier in the season at these locations. Given the sensitivity of peak date to temperature at all locations (Figure 3), this is likely the result of warming. By analyzing monthly SWE measurements using inter-month changes in SWE and the SCD metric, we can isolate various phases in the seasonal cycle to show that the direct influences of temperature increases on snowpack can be detected in the observational record at nearly all locations.

A few locations appear to be experiencing hydrologic intensification, particularly prior to March. For example, high altitude stations in California and the southern Rocky Mountains have experienced enhanced accumulation in the early part of the snow season (Figures 4a and 5a). These precipitation increases could be the result of anthropogenic intensification of the global hydrologic cycle. However, the increases in accumulation and their expression in the positive April 1st SWE trends shown in Figure 4c may also arise from internally-generated accumulation anomalies in the early part of the season. In some cases these may be large enough to counter the significant loss of snowpack during the later part of the season due to a warming climate. These unique locations may continue to experience increased snowfall during months of sub-freezing temperatures particularly given the lower warming rates in February. However, given our analysis of the influence of temperature on snowpack at the same stations later in the season and lower elevation stations in the early snow season, we can conclude that as temperatures rise above freezing more often, these locations will eventually exhibit statistically significant negative correlations between inter-month SWE and temperature, and rising temperatures would therefore eventually cause snowpack loss.

The message of a declining late season western North America snowpack parallels findings of other studies using observations (Barnett et al, 2008, Mote, 2006, Mote et al, 2005, Cayan, 1996), hydrologic models (Barnett et al, 2008, Hamlet et al, 2005), regional models (Kim et al, 2009, Leung et al, 2004), and global climate models (Das et al, 2009, Pierce et al, 2008, Maurer, 2007). They underscore a fundamental shift in the availability of water coming from late spring and summer snowmelt towards earlier in the season. This shift has various implications, including: changes to the statistics of flood risk from rain on snow events (McCabe et al, 2007), less warm season water supply in regions without sufficient water reservoir capacity, reduced effectiveness of hydroloelectric dams in the absence of pumping water upstream (Vicuna et al, 2008, Christensen et al, 2004), and increased risk of dry season wild fires (Westerling et al, 2006).

The potential negative impacts of increased runoff during February and March and reduced warm season snowmelt runoff highlight the need for confident predictions of future snowmelt timing and snowpack values. Future changes to total precipitation and thus early snowpack values however remain unclear and do not show as consistent or significant of a signal in this observation study or in other global climate modeling studies (Solomon et al, 2007). Even if snow accumulation in the early cold season increases or remains unchanged, continued warming in March and April will very likely significantly shift the onset of melt earlier and reduce late season snowpack and summer snowmelt runoff.

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Table 1 Correlation between SWE metrics and temperature from 1950 to 2003. For the inter-month SWE metric, the observations were correlated with temperatures for the time period covered (first three rows). For the SCD metric, the observations were correlated with temperatures for each month of changing SWE and the mean spring temperature (last four rows). The number of stations used in analysis and mean correlation of all stations and stations with statistically significant correlations ($p<0.05$) are given. When we performed the same analysis using monthly means of daily minimum temperatures, somewhat lower correlations were found.

SWE Metric Observation	Month of Temperature	Total No. of Stations	Mean Correlation	No. of Significant Stations	Mean Correlation
Feb to Mar	Feb	239	-0.35	138	-0.59
Mar to Apr	Mar	351	-0.53	308	-0.58
Apr to May	Apr	216	-0.63	196	-0.69
SCD	Feb	160	0.00	9	-0.18
SCD	Mar	160	-0.40	115	-0.51
SCD	Apr	160	-0.50	138	-0.55
SCD	Mean Mar & Apr	160	-0.58	144	-0.62

Table 2 Trends in monthly SWE and delta SWE with variations in start date. Trends are given as centimeters per decade for all combined stations from start date (denoted in columns) to 2008. Stations must have data for a minimum of 75% of years over the given time period. Cells without data do not have trends that are statistically different than 0 using the Student's T-test at $p<0.05$. The bolded cells represent the combined trends found in Fig. 4 and Fig.5.

Calculation	1930	1940	1950	1960	1970
February SWE	-0.3	-0.3	**-0.6**		
March SWE	-0.6	-0.5	**-0.6**		
April SWE	-1.1	-1.3	**-1.8**	-1.0	-1.6
May SWE	-1.5	-2.1	**-2.0**	-1.9	-2.6
February to March Change in SWE	-0.3		**0.1**	0.4	
March to April Change in SWE	-0.8	-0.8	**-1.0**	-1.1	-1.6
April to May Change in SWE	0.3		**-0.2**	-0.8	-1.1

Table 3 Trends in SCD and temperature with variations in start date. Trend in SCD (days/decade) for all combined stations from start date (denoted in columns) to 2008. Trend in peak timing is given for stations with data for a minimum of 75% of years over the given time period. The bolded cells represents the combined trend in SCD and number of stations found in Fig. 6. The number of stations in each time period is provided. Trend in average monthly maximum daily temperature at elevations above 1000m (elevation minimum for snow stations used in the bulk of this analysis) is given from start date to 2003 (due to the limitation of the available temperature data set) for the months of February, March, April, and averaged March and April.

Calculation	1930	1940	1950	1960	1970
All Station SCD (-2008)	-0.7	-0.9	**-0.7**	-0.9	-0.8
Number of Stations	47	99	**135**	194	274
Select Station SCD (-2003)	-0.8	-0.9	-1.0	-0.9	-0.6
Number of Stations	66	115	160	256	508
February Temperature	0.2	0.1	0.1	0.1	0.0
March Temperature	0.2	0.3	0.5	0.5	0.6
April Temperature	0.0	0.1	0.2	0.4	0.6
Averaged March & April Temperature	0.1	0.2	0.4	0.4	0.6

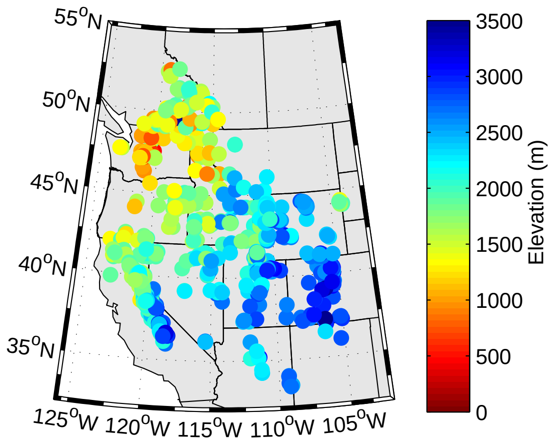

Fig. 1 Location of 670 snow stations with available SWE measurements for a minimum of 29 years from 1930 to 2008 and used in our analysis. Stations are colored by elevation in meters.

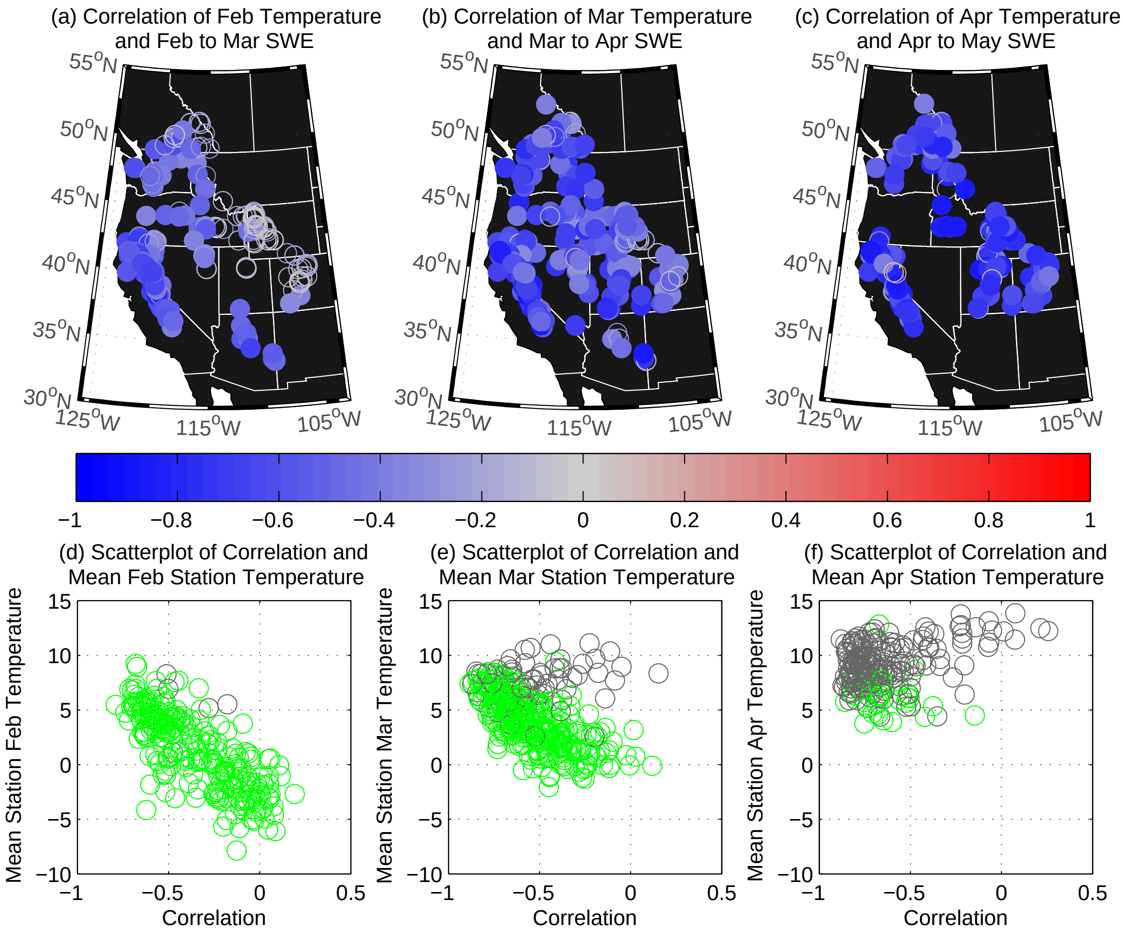

Fig. 2 Correlation analysis between monthly mean maximum daily temperatures and inter-month SWE values. Maps given of station correlations between monthly temperature and inter-month SWE for: (a) February temperature and February to March SWE (b) March temperature and March to April SWE, and (c) April temperature and April to May SWE. Scatterplots shown between correlations found in panels a-c and mean station temperatures for: (d) February, (e) March, and (f) April. Green (grey) points are those that on average experience snow accumulation (snowmelt) during the month. There are 239, 351, and 216 stations for the respective columns used in this analysis with data for 75% of the years available from 1950 to 2003. When we performed the same analysis using monthly means of daily minimum temperatures, somewhat lower correlations were found.

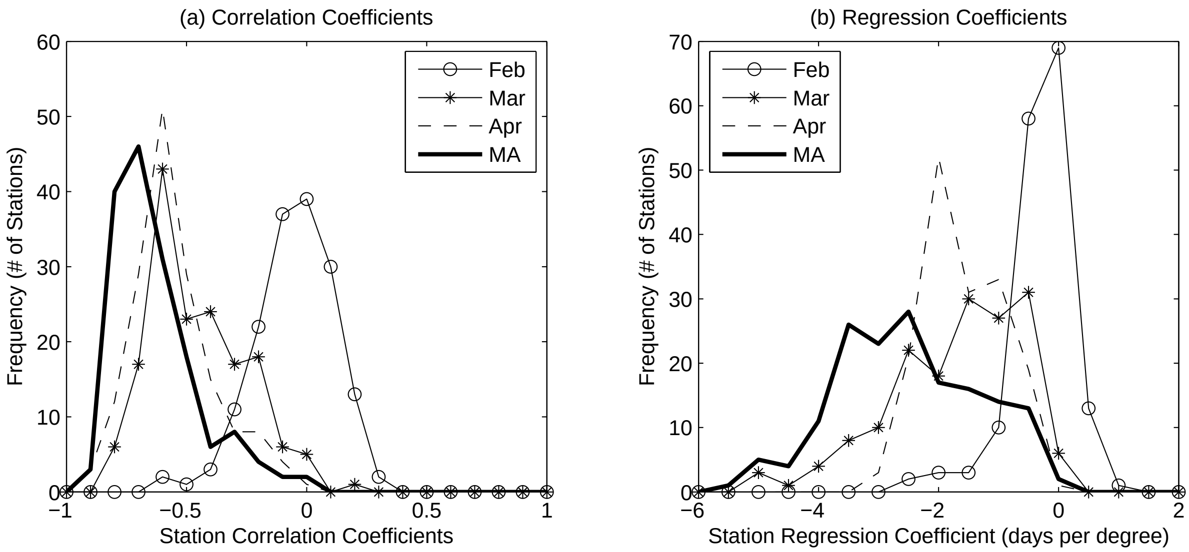

Fig. 3 Frequency given in number of stations for: (a) correlation coefficients between SCD and monthly mean maximum daily temperature, and (b) regression coefficients between SCD and temperature. There are 160 stations in total used in this analysis for stations with 75% of years available for all months from February to May from 1950 to 2003. Temperatures used are mean maximum daily temperature over February, March, April, and the average of March and April. When we performed the same analysis using monthly means of daily minimum temperatures, somewhat lower correlations were found.

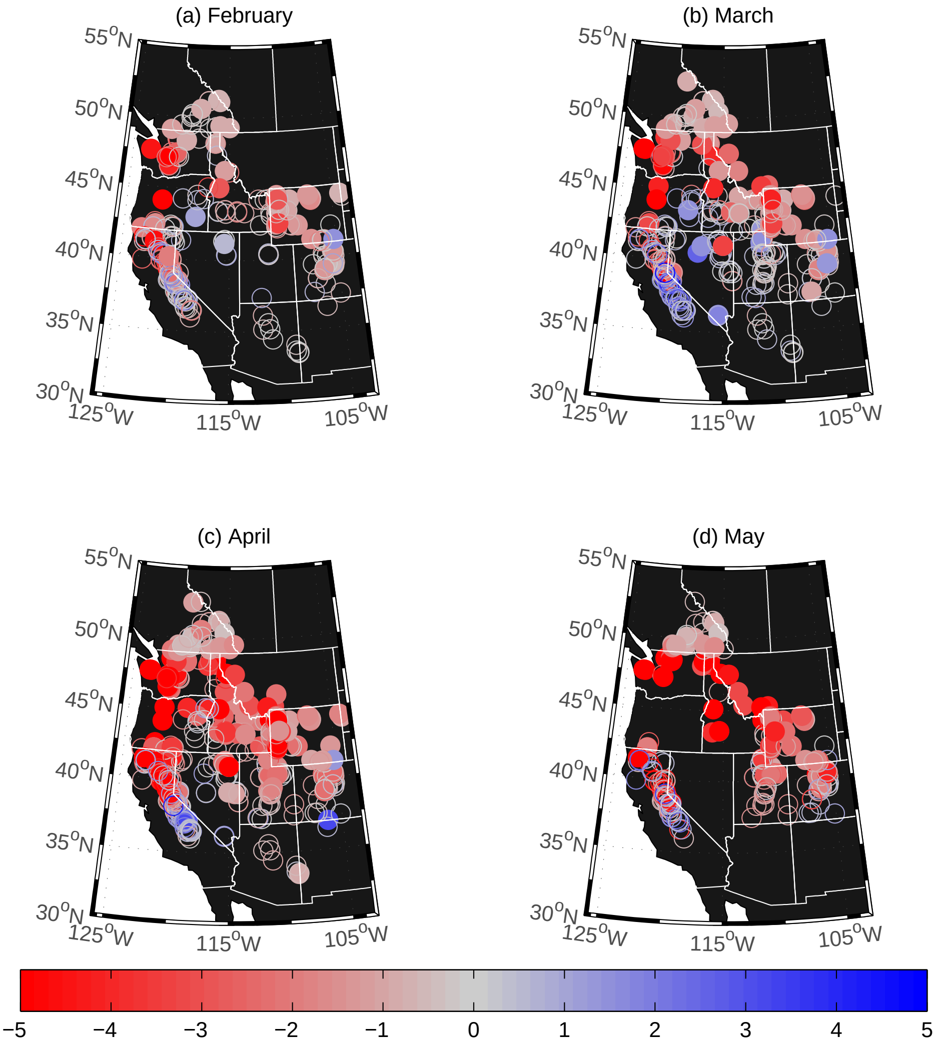

Fig. 4 Trends in monthly SWE values for February through May for stations with 75% of years available from 1950 to 2008. Trends given in centimeters per decade. There are 269, 358, 447, and 228 stations for February, March, April, and May respectively. Stations with trends that are statistically different than zero (student's T-test, $p<0.05$) are filled dots; stations with trends not statistically different than zero are open circles. Changing the end year to 2003 (to correspond with the time period of available temperature information) includes some additional stations, but the overall spatial pattern and magnitudes of trends are not altered.

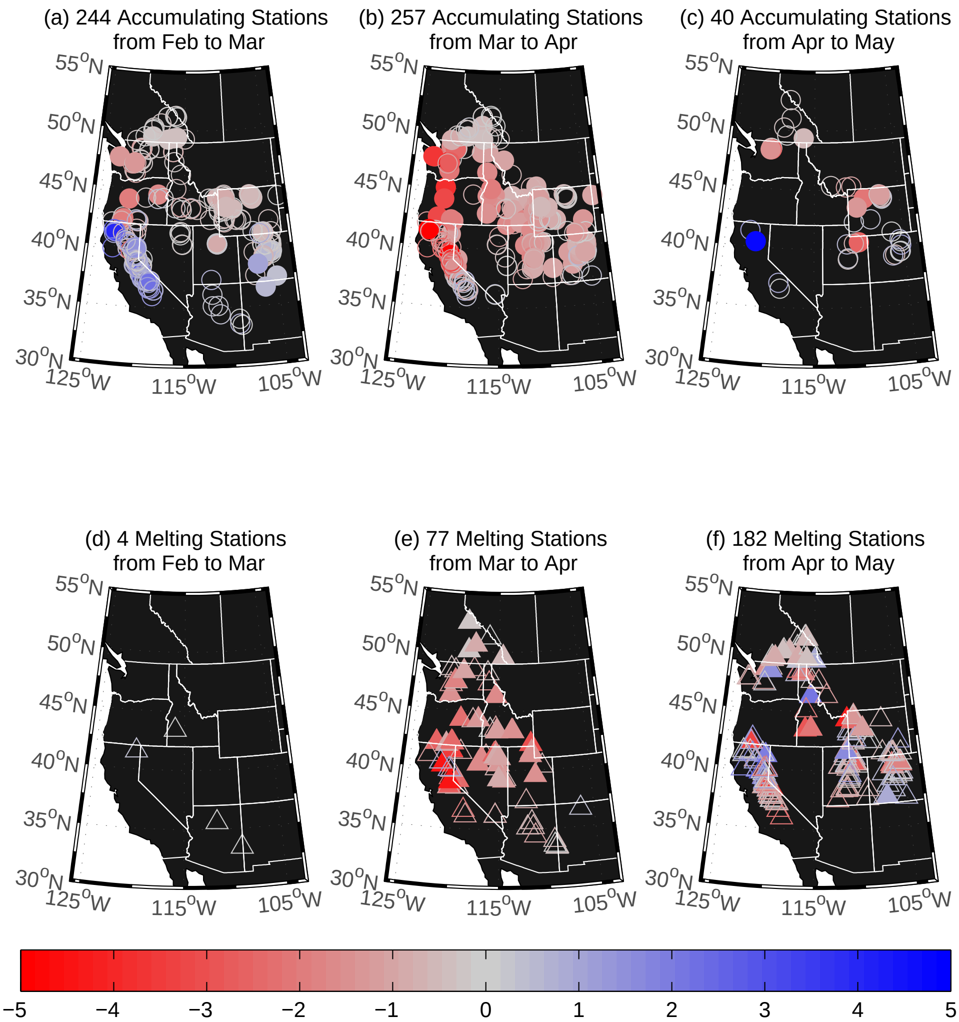

Fig. 5 Trends in changes in monthly SWE values for February through May for stations with 75% of years available from 1950 to 2008. Trends given in centimeters per decade. There are a total of 248, 334, and 222 stations available for February to March, March to April, and April to May respectively. The top row (panels a through c) shows stations with mean monthly differences in SWE greater than zero (on average they experience snow accumulation over the month). The bottom row (panels d through f) shows stations with monthly differences in SWE less than zero (on average they experience snowmelt over the month). Filled symbols denote stations with trends that are statistically different than zero (student's T-test, $p<0.05$); stations with trends not statistically different than zero are open. Changing the end year to 2003 (to correspond with the time period of available temperature information) includes some additional stations, but the overall spatial pattern and magnitude of trends are not altered.

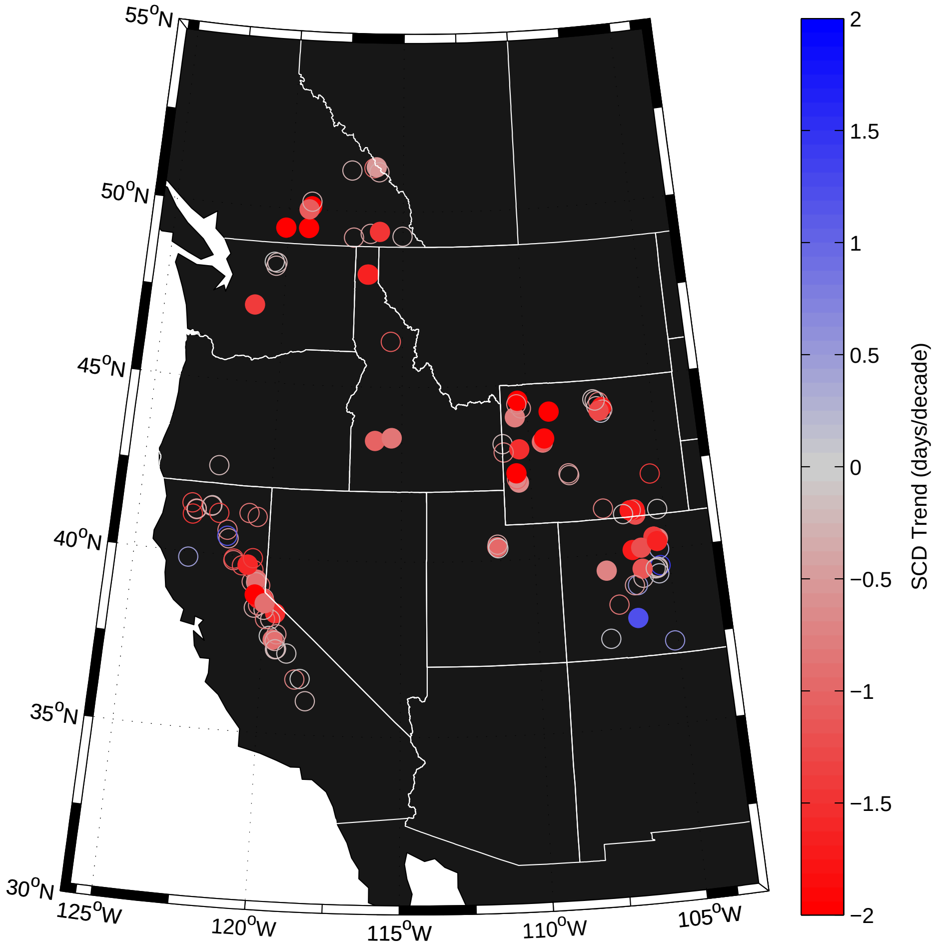

Fig. 6 Trends in SCD for 135 stations with 75% of years available from 1950 to 2008. Trends given in days/decade. There are significantly fewer stations used in the SCD analysis is that not all stations have measurements continuously from February to May with sufficient years for analysis. Changing the end year to 2003 (to correspond with the time period of available temperature information) includes some additional stations, but the overall spatial pattern and magnitude of trends are not altered.

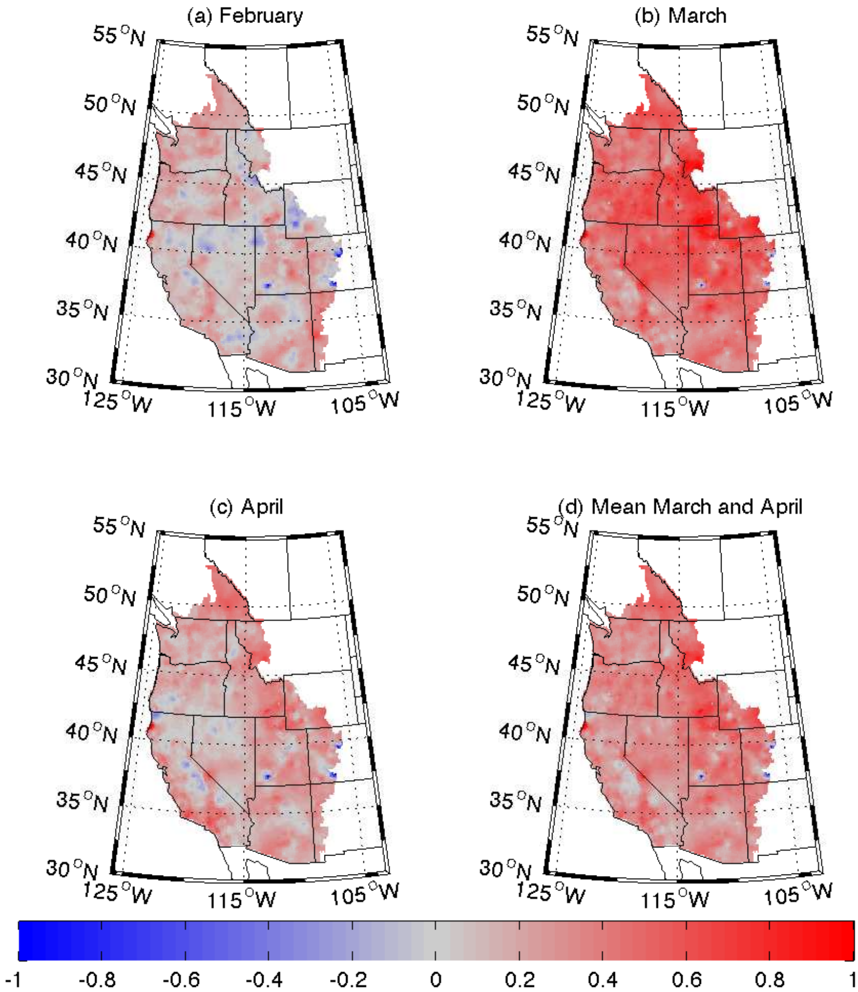

Fig. 7 Surface mean maximum daily temperature trends from 1950 to 2003 for the months of: (a) February, (b) March, and (c) April, and (d) mean March and April. Trends given in degrees per decade.