Recent Declines in Western US Snowpack in the Context of 20th Century Climate Variability

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ABSTRACT: A monthly snow accumulation and melt model was used with monthly PRISM temperature and precipitation data to generate time series of April 1 snow water equivalent (SWE) for 1900 through 2008 in the western United States (US). Averaged across the western US, SWE generally was higher than long-term (1900-2008) average conditions during the periods 1900-1925, 1944-1955, and 1966-1982; SWE was lower than long-term average conditions during the periods 1926-1943, 1957-1965, and 1984-2008. During the period 1900-2008, the temporal pattern in winter precipitation exhibited wetter-than-average and drier-than-average decadal-scale periods with no long-term increasing or decreasing trend. Winter temperature generally was below average from 1900 to the mid-1950s, close to average from the mid-1950s to the mid-1980s, and above average from the mid-1980s to 2008. In general, periods of higher-than-average SWE have been associated with higher precipitation and lower temperature. Since about 1980, western US winter temperatures have been consistently higher than long-term average values, and the resultant lower-than-average SWE values have been only partially offset by periods of higher-than-average precipitation. The post-1980 lower-than-average SWE conditions in the western US are unprecedented within the context of twentieth century climate and estimated SWE.

Data and Methods

Monthly temperature and precipitation data for the period January 1895 through March 2008 were obtained from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) dataset (http:www.ocs.orst.edu/prism/). These data are provided on a 4-kilometer (km) by 4-km grid. Temperature and precipitation data for grid cells in the western US (west of 102 degrees west longitude, 209584 PRISM grid cells) were used as input to a monthly time step snow accumulation and melt model (snow model), which was used to estimate monthly SWE at each grid cell. Model-estimated SWE for the years 1900 through 2008 were used for analysis.

April 1 SWE observations made at snow courses across the western US are used in this study to calibrate the snow model. At most snow course locations in the western US, SWE reaches its peak at about April 1 and has been found to be highly correlated with annual streamflow in nearby rivers. In addition, SWE is measured most frequently on or near April 1. Thus, April 1 SWE is the focus of this study and is estimated by the snow model using accumulated SWE at the end of March. All snow courses with complete records for the 1941–1990 period were used, defining a set of 314 sites across the western US for model verification (Figure 1).

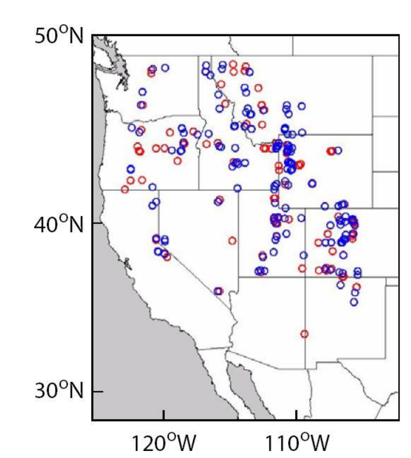


Figure 1. Location of snow courses used for snow model verification. Red circles indicate sites used to calibrate the snow model, and blue circles indicate sites used to verify the snow model.

The snow model: inputs to the model are monthly temperature (T) and precipitation (P); the occurrence of snow is computed as:

$$S = \begin{cases} P \text{ for } T_a \le T_{snow} \\ P\left(\dfrac{T_{rain} - T_a}{T_{rain} - T_{snow}}\right) \text{ for } T_{snow} < T_a < T_{rain} \\ 0 \text{ for } T_a \ge T_{rain} \end{cases}$$

where S is monthly snow fall in millimeters (mm), P is monthly precipitation in mm, T_a is monthly air temperature in degrees Celsius (°C), T_{rain} is a threshold above which all monthly precipitation is rain, and T_{snow} is a threshold below which all monthly precipitation is snow. When the monthly air temperature is between T_{rain} and T_{snow}, the proportion of precipitation that is snow or rain changes linearly.

In the snow accumulation and melt model, snow that occurs during the month is added to the snowpack and is subject to melt if the air temperature is warm enough for snow melt. Thus, for some cases, snow, rain, and snow melt can occur in the same month.

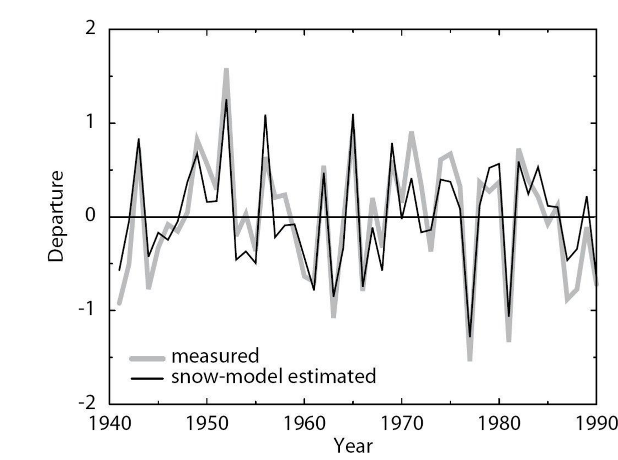
Snow melt is computed using a degree-day method of the following form:

$$M = \alpha(T_{air} - T_{snow})d$$

where M is the amount of snow storage that can be melted in a month, α is a melt rate coefficient, and d is the number of days in a month

To verify the snow model, the selected snow parameters were used with the snow model to compute April 1 SWE for the PRISM grid cells within 5.6 km of the sites of measured SWE that were not used for the calibration procedure (sites indicated by blue circles in figure 1). Time series of April 1 SWE for these PRISM grid cells were standardized and averaged to create a time series of mean standardized departures of model-estimated April 1 SWE. This time series then was compared with mean standardized departures of SWE for the sites of measured SWE not used in the calibration procedure. Figure 2 illustrates these two time series. The correlation between these two time series is 0.91 and the Nash-Sutcliffe statistic is 0.82. These results indicate that the snow model provides a reliable simulation of the temporal variability of mean April 1 SWE for the western US.

Figure 2. Times series of mean measured (gray line) and mean snow-model estimated (black line) mean standardized departures of April 1 snow water equivalent (SWE) for the western US during 1941 through 1990. These time series were computed using data for the sites not used for the calibration procedure (sites indicated by blue circles in figure 1).



Using the calibrated parameters, the snow model was used to estimate April 1 SWE for the years 1900 through 2008 for each of the PRISM grid cells in the western US. Grid cells with large numbers of years with zero SWE cause numerical problems for some statistical analyses. Therefore, only grid cells with April 1 SWE values (hereafter referred to as April 1 SWE) greater than zero for at least 50 percent of the years during 1900 through 2008 were kept for analysis. This filtering of grid cells provided 85476 grid cells for analysis (Figure 3).

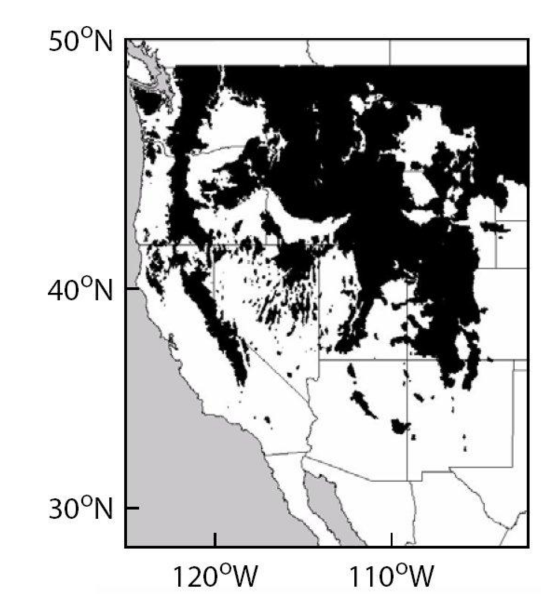
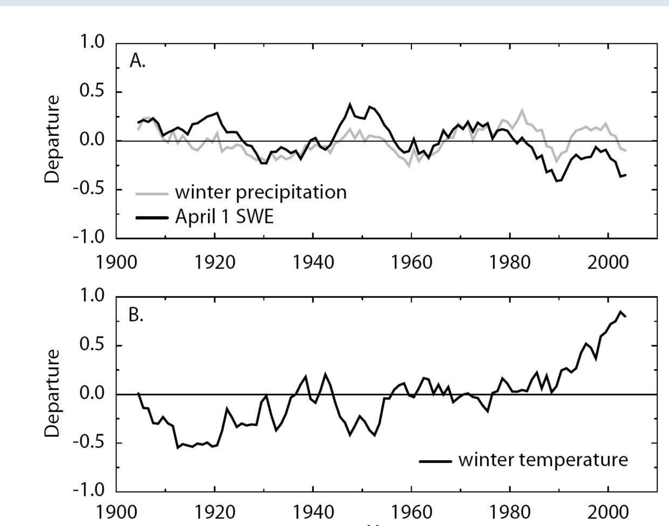


Figure 3. PRISM grid cells (black dots) with snow-modeled April 1 SWE for at least 50 percent of the years during 1900 through 2008. (85476 grid cells).

Results

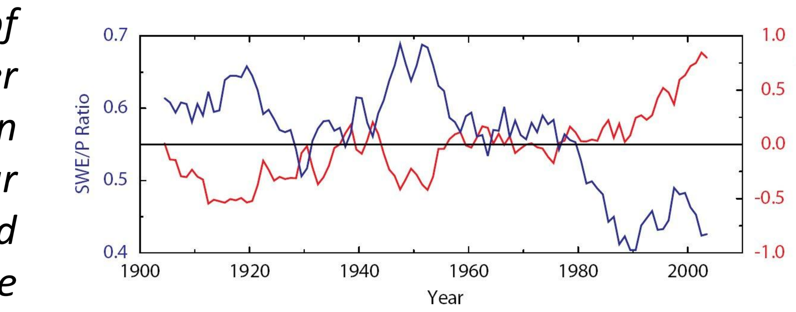
The SWE departures are greater than or equal to the precipitation departures from 1900 to 1980; after 1980, however, the SWE departures are less than the precipitation departures (Figure 4a). Temperature departures are mostly negative or neutral during the period 1900 to 1980 (Figure 4b); thus, when winter temperatures are average or cooler than average, April 1 SWE departures are more positive than are winter precipitation. After 1980, when winter temperatures are higher than average, the April 1 SWE departures are less than the precipitation departures implying that a smaller fraction of winter precipitation accumulates as snow (Figure 4a). Mote et al. (2005) also reported that declines in SWE since the mid-20th century exceeded declines in winter precipitation.

Figure 4. 10-year moving averages of mean standardized departures of western United States (A) snow-model estimated April 1 snow water equivalent (SWE) (black line) and November through March precipitation (gray line), and (B) November through March temperature.



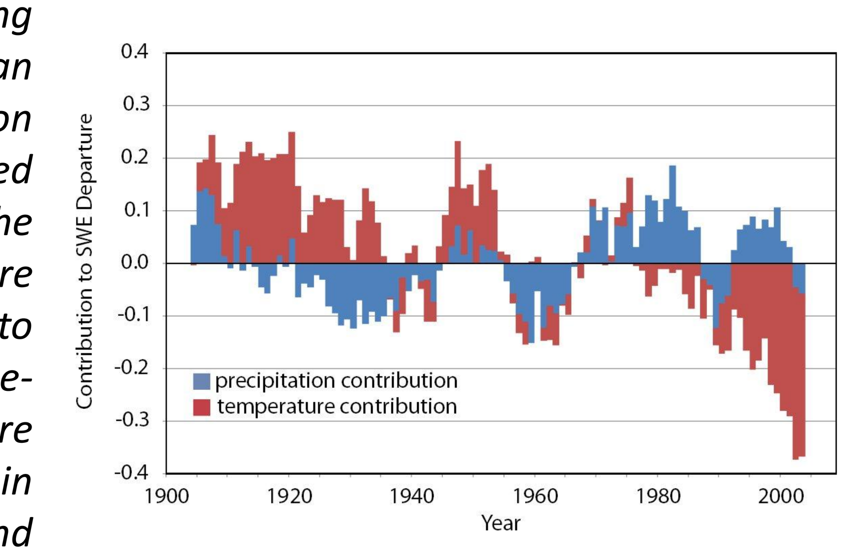
The hypothesis that a smaller fraction of winter precipitation accumulated as snow during years after 1980 was explored by averaging the ratio of April 1 SWE to winter precipitation (SWE/P) on a year-by-year basis. The results (Figure 5) show that SWE/P during the period 1900-1980 never was less than 0.5. After 1980, however, SWE/P decreased to levels below 0.5. The relation of temporal variability in SWE/P is clearly related to average winter temperature (Figure 5).

Figure 5. 10-year moving average ratio of April 1 snow water equivalent to winter precipitation (SWE/P Ratio) for the western United States (US) (blue line) and 10-year moving average mean standardized departures of winter temperature for the western US (red line).



Through regression analysis the contributions of temperature and precipitation to SWE departures were computed (Figure 6). The time series of temperature and precipitation contributions to SWE shows how precipitation and temperature interact in their effects on SWE. Two of the high SWE periods (1900-1925 and 1944-1955) in the twentieth century were associated more with cold winter temperature (red histogram bars greater than zero) than high precipitation (blue histogram bars greater than zero); the third high SWE period (1966-1982) was related mostly to high winter precipitation (blue histogram bars greater than zero). The first two low SWE periods (1926-1943 and 1957-1965) in the twentieth century were associated primarily with low winter precipitation (blue histogram bars less than zero); the final period of low SWE (1984-2008) is characterized by high winter temperature (red histogram bars less than zero) and high winter precipitation (blue histogram bars greater than zero). During this most recent period, the negative departures in SWE caused by high temperature were only partially offset by higher than average precipitation. Before 1980, when winter precipitation departures were positive (negative) April 1 SWE departures also were positive (negative). However, after 1980, even though winter precipitation departures have primarily been positive, the April 1 SWE departures have primarily been negative. The relations between the winter precipitation and April 1 SWE departures since about 1980 indicate a possible change in the hydro-climate of the western US. This change in climate appears to be connected with the increase in winter temperatures around 1980.

Figure 6. Time series of the 10-year moving average values of the contributions of mean standardized departures of winter precipitation and winter temperature to mean standardized departures of April 1 SWE. The heights of the individual precipitation (blue) and temperature (red) histogram bar segments are proportional to their contribution to the SWE departure. Positive-valued precipitation and temperature contributions are associated with increases in SWE; negative-valued precipitation and temperature contributions are associated with decreases in SWE.



Conclusions

Based on snow model estimates, western US April 1 SWE values during the years 1900 to 1980 were close to or greater than its long-term (1900-2008) mean value. Since 1980, however, SWE values were below the long-term mean because this period was marked by widespread increases in temperature in the western US. These results suggest that, during recent decades, temperatures have increased to a point that they have had a significant effect on SWE. These results are an indication of a warmer climate regime in the western US.

McCabe, G.J., and Wolock, D.M., 2009, Recent declines in western US snowpack in the context of 20th century climate variability, Earth Interactions, 13, 12 p.