Trends in Snowfall versus Rainfall for the Western United States, 1949-2004

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ABSTRACT

The water resources of the western U.S. depend heavily on snowpack to store part of wintertime precipitation into the drier spring and summer months. A well-documented shift towards earlier runoff in recent decades has been attributed to 1) more precipitation falling as rain instead of snow, and 2) earlier/faster snowmelt. The present study addresses the former, documenting a regional trend during the period 1949-2004 toward smaller ratios of winter-total snowfall water equivalent (SFE) to winter-total precipitation (P). The most pronounced reductions in this ratio have occurred in the Sierra Nevada and the Pacific Northwest, with more varied changes (still predominantly reductions) in the Rocky Mountains.

The trends toward reduced SFE are a response to warming across the region, with the most significant reductions occurring where winter-average wet-day minimum temperatures were warmer than -5°C. Most of the SFE reductions were associated with winter wet-day temperature changes between 0 and +3°C over the study period. Larger warmings have occurred mainly at sites where the mean temperature was cool enough that precipitation form has been less vulnerable to warming trends.

At the monthly scale, trends toward reduced SFE/P have been most pronounced in March regionwide and near the West Coast in January, corresponding to widespread warming in these months. Mean temperatures were colder in January at higher elevations, restricting SFE/P impacts to the lower elevations near the West Coast, whereas warmer mean temperatures in March allowed the recent warming to produce SFE/P declines across the study region.
1. Introduction

One of the most common, and common-sense, projections of the impact of global warming on the western United States are that warming will reduce the volumes and persistence of snowpacks across the region (e.g., Gleick 1987, Lettenmeier and Gat 1990, Dettinger et al. 2004, Knowles and Cayan 2004, Stewart et al. 2004). Warming in the western states is expected to reduce the fraction of precipitation that falls as snow rather than rain and accelerate rates of snowmelt once snowpacks have formed.

In this context, recent observations in many rivers of the mountainous western United States and Canada indicate an alarming tendency for streamflow from snow-dominated basins to arrive progressively earlier in recent decades in response to large-scale warming (Roos 1991, Dettinger and Cayan 1995, Cayan et al. 2001). Widespread trends towards less winter’s-end (April) snowpack water content have also been reported (Mote 2003, Mote et al. 2005). Trends in the dates of onset of rapid snowmelt runoff in spring (Cayan et al. 2001, Stewart et al. 2005) indicate that an important part of the changes in runoff timing has been earlier onset of springtime snowmelt across the region, but the possible contribution of shifts towards more rainfall and less snowfall has received less attention to date. In the northeastern states, trends toward increases in the fraction of precipitation as rainfall have already been documented (Huntington et al. 2004). To better understand the nature of the streamflow-timing changes in the West, historical changes in the relative contributions of rainfall and snowfall are assessed here.

Western warming trends historically have been (and presumably will continue to be) marked by strong seasonal and geographic patterns (e.g., Diaz and Quayle 1980,
Dettinger et al. 1995, Cayan et al. 2001). Because of the general wintertime maximum of snowfall and precipitation in the region, contributions of snow to western precipitation are likely to be most vulnerable to wintertime (November-March) temperatures, whereas changes in onset of snowmelt (once snow is on the ground) have been more sensitive to springtime temperatures. Thus snow deposition and snowmelt have been sensitive to warming trends in different seasons, and the warming trends associated with snowfall and snowmelt changes may be distinguished by the differences in their geographic patterns and rates of change. Much work has been accomplished to map trends in the latter (snowmelt responses); this study documents a parallel set of trends that has changed the relative contributions of snowfall to western precipitation.

2. Data and Methods

The measure of snowfall that will be used in this study is the snowfall liquid-water equivalent (SFE), defined as the precipitation totals on days for which newly fallen snow was recorded. These data and the temperature data used in this study were derived from the historical Summary of the Day (SOD) observations from cooperative weather stations in the 11 westernmost states of the conterminous U.S. (Fig. 1), obtained from the National Climatic Data Center (NCDC). The observations used here comprise daily snowfall depth (S, actual depth as opposed to liquid equivalent), precipitation (P, regardless of form), maximum (TMAX) and minimum (TMIN) surface air temperature, from October 1948 to September 2004. Precipitation and snowfall totals were recorded at 1,653 stations during this period; temperatures were recorded at 1,517 stations. Emulating the approach developed by Huntington et al. (2004) for similar analyses in the northeastern U.S., the
records of precipitation and snowfall at the western stations were culled according to the following sequential steps:

1) Any cool-season during which precipitation or snowfall data were missing for 10 or more days between November and March was considered incomplete and was excluded from the analysis.

2) Any station that was missing >50% of its November-March records in any given 10-year period was excluded.

3) Any station at which the mean winter snowfall total (described here by the November-March sums of daily snowfall water equivalents—SFE, described below) was less than 25mm was excluded.

This study focused on a winter season, defined here as November-March, because, on average over all the stations, 80% of snowfall occurred during that season. The analyses below were repeated using the period October-May, which accounted for 98% of snowfall aggregated over all stations, and greater than 90% of snowfall at every individual station. No substantial changes in the results were obtained by using this longer season, except that fewer stations survived the completeness tests and the relative contributions of snow to overall precipitation were numerically smaller due to the inclusion of the warmer months.

Steps 1-2 were also applied to TMAX and TMIN. These criteria ensure that the data analyzed here are sufficiently serially complete that seasonal totals, trends and other long-term patterns in temperature and snowfall can be reliably calculated without undue interference from sampling errors and seasonal effects. This culling retained 634 stations...
that contained temperature, 261 stations with precipitation and snowfall, and 207 stations that contained temperature, precipitation and snowfall. The analyses presented here used the largest appropriate data set in each case (i.e., analysis of temperatures used all 634 stations, but joint analysis of temperature and precipitation used 207 stations).

To further ensure robustness of results, the remaining data were examined for trends in the number of days with missing data, in the average date of the missing values each winter, and in the standard deviation of the dates of missing values each winter. Significant trends were found in the number of missing days at many stations, and the analysis presented below was repeated with those stations excluded. The analysis was also repeated using more stringent criteria in steps 1-2 above—thresholds of 3 days in step 1 and 25% in step 2. In both cases, the conclusions of this analysis were unchanged, albeit with fewer data points. Finally, repeating the analysis without the Great Plains stations (described in Section 3c) did not change the findings of this paper.

The depth of newly fallen snow (S) is recorded each day by cooperative observers using a variety of methods, including simple measuring sticks, snow boards which are wiped clean after each measurement, and tall snow stakes where large snow accumulations occur. Liquid (equivalent) precipitation depth (P) is typically measured with precipitation gages. The daily accumulated precipitation is either melted and the depth measured, or in the case of recording gages, the precipitation is weighed (National Weather Service 1989).

In some cases, however, P was not measured directly by observers, but was estimated on snowy days by applying some fixed multiplier to the depth of snow (S), typically 10 (Kunkel et al. 2005). To test this possibility and to determine whether such observations
adversely affect the results presented here, the precipitation and snowfall depth (S) data were examined for overabundances of integer values of the ratio S/P. The most frequently reported integer ratio was 10, which was reported (within a roundoff tolerance of 0.05) on an average of 0.4% of snowy days, followed by 20 on 0.1% of the snowy days. The station with the largest fraction of snowy days with S/P = 10 was a site in Montana where such ratios were reported 6% of the time. Removing those stations (36 stations out of 261) whose fraction of November-March days with S/P=10 was greater than 2% from the analysis resulted in no substantial changes to this paper’s conclusions.

In this study, the liquid water equivalent of newly fallen snow on each day (SFE, not to be confused with SWE, the liquid equivalent of the season-to-date’s accumulated snowpack) is defined as equal to P on days when S>0, and equal to zero when S=0. While this definition can overstate the amount of precipitation as snowfall (since precipitation on many days is a mixture of snow and rain), it avoids reliance on the reported snowfall amounts, which are notoriously unreliable and observer-dependent. Additionally, overestimation of SFE/P on mixed-form days will underestimate the contributions of those days (or trends in the number of those days) to trends in seasonally totaled SFE/P, so that this choice ensures that, if anything, the present analysis underestimates the magnitude of trends in snowfall (as a fraction of total precipitation). This definition also does not distinguish between rainfall and snowfall that melts completely on the same day it falls (before it can be measured by the cooperative observer).

The sums of SFE and P over all days with data in each winter form time series of winter and monthly totals of SFE and P, from which winter and monthly ratios SFE/P
were calculated. A Kendall's-tau nonparametric trend analysis (Kendall 1938) was performed on each time series. Additionally, a least-squares regression line was fitted to each time series to estimate the magnitudes of changes over the 56-year study period. In the rare cases when the linear fits produced negative values, the negative values were not included in the estimated magnitudes of SFE, P, or SFE/P changes.

The analyses below were initially performed with a dataset restricted to sites in the U.S. Historical Climatology Network Daily collection (HCN/D: Easterling et al. 1999), as in Huntington et al. (2004). That dataset was selected from among the SOD sites according to various quality assurance criteria, in order (where possible) to minimize such data quality concerns as inconsistencies of daily maximum and minimum temperature measurement times and heat island effects. However, in order to achieve desired spatial coverage in the HCN/D dataset (compared to the original HCN monthly dataset), these criteria were not strictly applied, nor were any corrections for nonclimatic effects applied as with the larger monthly HCN dataset (HCN: Easterling et al. 1996). When steps 1-3 were applied to the HCN/D subset for the western U.S., the number of stations that survived was barely sufficient to discern spatial patterns in the data. Rather than relax the completeness criteria, the present analysis applied the completeness criteria to the full SOD dataset as described above rather than to its HCN/D subset. This strict culling of a larger initial dataset yielded enough stations to discern spatial patterns. Similar patterns were evident in trend analyses of the HCN/D dataset (not shown here), but with much more sparsely populated maps. This replication of the results presented here offers us much confidence in the present results, but notably, nonclimatic effects such as heat island bias (Karl et al. 1988), measurement time changes, and
instrumentation changes have not been corrected in the present analysis and may influence results locally. This limitation should be of particular concern with respect to the temperature trends reported here. Ultimately, however, the results will be related to large-scale climatic patterns that are not influenced by local data discrepancies.

3. Results

a. Seasonal SFE/P Trends

The SFE/P ratio trended towards smaller values over the course of water years 1949-2004 at 192 (74%) of the 261 SOD sites analyzed (Figure 1a) and increased at the other 69 sites. Many of these trends did not rise to the level of statistical significance (p<0.05, under the standard Student-t test that applies to Kendall’s-tau analyses); however, of the sites with trends that did rise to this level, the snowfall fraction decreased at 94 sites (87%) and increased at only 14. Trends toward decreasing snowfall fractions were largest (in terms of the year-to-year standard deviations) at lower-elevation sites in the Sierra Nevada and the Pacific Northwest.

The 2004 and 1949 intercepts of the linear fits to the 56-year series of winter SFE/P values for each station were plotted (Figure 1b) to show changes over the record. A straight-line fit to all stations in Figure 1b reveals that on average, stations across the full range of initial SFE/P values have experienced remarkably uniform (slope≈1) reductions of 0.09 in their SFE/P ratios (y-intercept=−0.09). Note that most of the trends reported here are quantified as the difference of the linearly fitted values at the end and beginning of the study period. Where trend strength is the focus, standard deviations are used as in
Long-term mean values of winter SFE/P (Figure 2a) exhibit an east-west pattern, a combined result of generally increased station elevations to the east (Figure 2b) and geographic differences. Relatively little winter precipitation occurs as snow at many of the westernmost stations, which tend to be at lower altitudes and thus somewhat warmer in winter, whereas nearly all precipitation in the higher, cooler interior Rockies is snow. Elevation relationships are discussed more in Section 3c.

Changes in SFE/P could occur because of disproportionate changes in either SFE or P. Figure 3 shows the corresponding trends (in terms of year-to-year standard deviations) for P and SFE. The P trends (Figure 3a) vary considerably in magnitude and direction over the spatial domain and are not generally in accord with the widespread pattern of SFE/P declines. Of the 48 sites with significant P trends, 15 also had significant trends in SFE/P, only 3 of which trended in concordant directions for SFE/P and P (P increasing, SFE/P decreasing or vice-versa). In contrast, changes in SFE (Figure 3b) more closely parallel the pattern of SFE/P trends in Figure 1a. Of the 261 sites considered, 94 sites had significant SFE trends and 69 also had significant trends in SFE/P. SFE and SFE/P at 67 of these stations had trends of the same sign. In New England, Huntington et al. (2004) also found that trends towards smaller SFE/P ratios have reflected SFE declines rather than P trends.

The primary area where there are disagreements between the signs of SFE trends and SFE/P trends is in the southern Rocky Mountains in the southeastern portion of the study region. There, trends toward more SFE are mostly responses to increases in P. Because, at many sites there, increases in SFE have not kept pace with P, the SFE/P ratios
decreased, though some increasing trends are also found. Shifts in the relative timing of the annual cycles of precipitation and temperature have played a secondary role in determining the SFE/P trends in this region. Precipitation in the southern Rockies has shifted into colder months, counteracting the warming trends and contributing to mixed SFE/P trends there.

To clarify the relationships between the trends in SFE/P, SFE, and P, Figure 4 plots the trend magnitudes against one another in pairs. In this figure, pairs in which both trends were significant are plotted as squares. Aside from several sites that report very large reductions in P, changes in SFE/P have not been well correlated with changes in P. Reductions in SFE have generally coincided with reductions in SFE/P, and some increases in SFE have coincided with increases in SFE/P, although the relation is not simple or linear. Where both P and SFE have trended significantly, the two trends have had nearly the same magnitudes in most cases. Although changes in SFE/P and P are quite strongly correlated with changes in SFE ($r=0.40$, $p<0.01$, and $r=0.57$, $p<0.01$, respectively, over all stations), the changes in SFE/P have not been consistently related to those in P ($r=0.02$, $p=0.80$). Notably, Figure 4a indicates that decreasing P trends have generally coincided with decreasing SFE/P trends and increasing P trends have been associated with either decreasing or increasing SFE/P trends, depending on location.

The significant trends identified by squares in the three panels of Figure 4 are not necessarily the same stations in each panel. Some sites that do not exhibit jointly significant SFE and P trends in Figure 4c do correspond to significant trends in the ratio SFE/P in the other panels. As a consequence, the strong correlation between SFE and P changes shown in Figure 4c does not translate into equally strong relations with SFE/P.
changes in Figures 4a and 4b. To illustrate this, Figure 5 is a version of Figure 4c in which symbols indicate the corresponding trends in SFE/P. This version shows that significant trends in SFE/P occurred for many “off-axis” SFE and P trend pairs that lacked the jointly significant SFE and P trends indicated in Figure 4c. In particular, most significant SFE/P trends occurred at stations where the change in P was greater than the change in SFE (below the one-to-one line in Figure 5), despite the relative weakness of the individual SFE or P trends (Figure 4c).

b. Temperature Dependence

Several studies have linked declining snow packs and earlier runoffs in the West to increasing temperatures (Dettinger and Cayan 1995, Cayan et al. 2001, Hamlet et al. 2005, Mote et al. 2005, Regonda et al. 2005, Stewart et al. 2005). The present analysis suggests that one mechanism by which warming has caused these changes has been to diminish the amount of snow deposited. To understand the relevant temperature changes, Figure 6 shows trends (expressed in standard deviations) in winter-mean wet-day minimum- and maximum-daily temperatures. Wet-day TMINs have generally warmed more than have wet-day TMAXs, with average (over all western U.S. stations) 1949-2004 increases of +1.4°C and +1.0°C, respectively. Trends in dry-day TMAX and TMIN (not shown) have been similar in magnitude and spatial distribution to the wet-day trends. The remainder of this analysis will focus on wet-day minimum temperatures (TMINw).

The changes in SFE/P are plotted against the TMINw changes in Figure 7a. 77% of all the significant SFE/P trends are at sites where TMINw has warmed and the SFE/P ratio has declined, indicating that reductions in SFE/P have coincided very
(geographically) closely with TMINw warming.

The relationships between P changes and TMINw changes, and between SFE changes and TMINw changes, are shown in Figures 7b-c. Due to the strong correlation between the P and SFE changes (Figure 4c), these figures are similar. Most stations with relatively moderate TMINw changes have experienced reductions in SFE, although some such stations have experienced SFE increases. Notably, at stations where TMINw warmed by more than about +3ºC, SFE changed relatively little (increasing in most cases). Although this seems to contradict the explanation of trends by warming, the stations that warmed most also were the coolest overall so that even these greater warming rates were not enough to change the precipitation from snow to rain, as shown below.

To distinguish between the effects on SFE of changing P totals and changing TMINw, Figure 8 shows an analog of Figure 7c in which the changes in SFE have been adjusted to remove the influence of the change in P at each site. This was accomplished by subtracting the direct effect of the precipitation trend at each station from the SFE trend there. This precipitation correction was estimated as the product of the P trend magnitude and the long-term mean of SFE/P. The assumption that changes in SFE due to changes in P can be removed in this manner is a simplification, but as will be shown, a useful one.

Once adjusted for P trends (Figure 8), the fact that the most significant reductions in SFE have occurred at sites that experienced moderate (<3ºC) TMINw warming (Figure 8) is more obvious (than in Figure 7c). The most significant reductions in SFE/P (Figure 7a) occurred at stations with roughly the same magnitude of temperature trends (<3ºC) as those that yielded the most significant SFE changes. The reason that these more moderate
temperature changes resulted in the largest SFE (and SFE/P) declines is clear when viewed yet another way: Figure 9a plots the P-adjusted SFE changes against long-term mean November-March TMINw values at each site. The largest SFE reductions occurred at relatively warm locations (TMINw > -5°C), where temperatures were closer to freezing and warming by even a few degrees was enough to have a substantial impact. Averaged over sites with significant winter SFE trends, the P-adjusted winter SFE reduction was 51mm. Averaged over all sites, the reduction was 26 mm.

The relationship between TMINw changes and the long-term mean wet-day winter temperatures (Figure 9b) explains another feature of Figure 8, the very small P-adjusted SFE changes at sites that have warmed by more than +3°C. The stations that warmed this much were generally among the coldest stations, with long-term November-March mean TMINw values less than -5°C. In these cold settings, even the largest warmings in the West—more than +4°C—were apparently not sufficient to yield significant SFE reductions. Geographically, these larger warmings (> +3°C) occurred at a broad range of elevations and throughout the interior West, but were especially prevalent in the Great Plains of Montana and Wyoming. In the SFE-versus-P plot in Figure 4c, these stations tend to cluster around the one-to-one line, since these large warmings occur at cold sites where changes in P produce nearly equal changes in SFE. Stations that warmed less were generally at historically warmer sites, and are more widely scattered in that plot.

c. Elevation Dependence

The relationships with mean TMINw in Figure 9 generally reflect differences with respect to elevation. Figure 10a shows that the largest warmings have occurred at mid- to
high-elevation sites, while Figure 10b shows the decrease of mean TMINw with elevation. The main exceptions are bulges around 500-1200m where increased warming has coincided with colder mean temperatures. These exceptions, indicated in Figure 10 by different symbols and shading, correspond exclusively to the Great Plains of Montana and Wyoming, which have warmed more than other sites at similar elevations elsewhere in the West but which are also much colder. Because the average temperatures at these sites are so cold, the larger warming in this (northeast) corner of the study area yielded little change in snow deposition.

The Pearson’s correlation coefficient for the relation between the trends in TMINw and elevation (Figure 10a) is \( r=0.10 \) (\( p=0.10 \)) when only stations with significant (\( p<0.05 \)) trends in TMINw are included. When the northern Great Plains stations are left out, the correlation is \( r=0.11 \) (\( p=0.08 \)). The linear fit in Figure 10a is to significant TMINw trends, excluding the Great Plains stations, and corresponds to an increase in TMINw warming of about +0.2ºC per kilometer altitude.

Figure 11a shows that, over the period of study, winter P totals have generally declined at lower elevations, substantially so at the lowest elevations. P has generally increased at higher elevations, with increasing trends becoming common above 1500m except for a few decreasing trends at the highest elevations. These changes are echoed in a similar pattern of SFE changes (Figure 11b), such that SFE also has tended to increase above ~1800m, again excepting a few of the highest stations.

As with Figure 7c, Figure 11 can be adjusted to isolate the effects on SFE of changes in P by accounting for the expected contributions due to P trends (the P trend magnitudes multiplied by long-term mean SFE/P ratios), as shown in Figure 12. Although P declines
below 1500m have contributed to reductions in SFE, and increases in P at higher elevations have been responsible for SFE increases at higher elevations, larger SFE declines have been associated with the warming below about 1500 m. The largest reductions in P-adjusted snowfall occurred at the lower, warmer elevations, where moderate temperature changes had a significant impact. Above approximately 1800m, SFE changes are essentially all attributable to changes in P—essentially no change in snow deposition has occurred as a result of warming.

*d. Monthly Patterns*

Mapping trend magnitudes for SFE/P by month (Figure 13) reveals that the most widespread declines in snowfall fractions occurred in March, across the entire western US. Important declines in SFE/P also occurred in January along the West Coast (in stations associated with the Sierra Nevada and the Pacific Northwest). On average, January is the top snow-producing month at most of the Sierra Nevada and Pacific Northwest stations, whereas March is a top snow-producing month throughout the Rockies. Thus these changes are of considerable concern.

The seasonality of the monthly SFE/P changes echoes that of changes in TMINw (Figure 14). In particular, January and March have warmed most significantly across the West. Monthly patterns of TMAXw trends were very similar to those in Figure 14, though with smaller increases in general.

Monthly trend patterns in P were generally less organized than the January and March temperature trends, with net reductions in P over the course of the study period in the
Northern Rockies and Cascades in December, January and February, and net increases in the Southern Rockies in most months, leading to the winter-average pattern (Figure 3a).

Three conditions must be met for temperature-driven SFE reduction to occur: 1) snowfall must be occurring, 2) warming must take place, and 3) the mean temperature must be warm enough for warming to have an effect. The fraction of stations satisfying each of these conditions varied seasonally, with corresponding influences on the abundance of P-adjusted snowfall declines and the SFE/P trend patterns (Figure 13). Snowfall occurred at most stations during all winter months, with a sharp dropoff in spring. On average, the percentage of stations that warmed peaked in January and March (about 90% and 96%, respectively), and the percentage of stations that were warm enough for warming to affect SFE (historical mean TMINw>-5°C) was a minimum of 38% in January. This last factor explains why similar warming patterns in January and March (Figure 14) resulted in different SFE/P responses (Figure 13). January TMINw were too cold at higher elevations for the warming to affect SFE (Figure 15). In March, most stations were warm enough for the broad warming trends to yield broad SFE/P declines.

Despite the broadness of March SFE/P reductions, the West Coast January declines represented a greater total SFE reduction. Averaged over all stations with significant November-March SFE trends, the P-adjusted SFE reductions were 19mm in January and 10mm in March, with smaller reductions during the other winter months. These reductions amounted, on average, to 32% and 14%, respectively, of the long-term average winter SFE totals at these sites. The larger January SFE declines reflect the fact that West Coast stations receive much more P (and, at moderate elevations, more SFE)
than interior stations, with peak P and SFE in January. The combination of large (historical mean) snowfall, significant warming, and sufficiently warm mean January temperatures at these sites resulted in the largest monthly SFE declines in the West occurring at West Coast sites in January.

4. Conclusions

The fraction of winter precipitation that fell as snow declined across most of the western U.S. during the period 1949-2004. The largest reductions were due to a significant temperature-driven shift from snowfall to rainfall at low to moderate elevations (Figure 12b). Many more stations exhibited significant changes in the November-March seasonal total snowfall water equivalent (SFE) than exhibited changes in seasonal total precipitation, and most of the significant changes in SFE were reductions. The temperature trends driving the SFE reductions were widespread, but warmer low- and mid-elevation sites were affected most. Precipitation trends also contributed to changes in the amount of snowfall, especially at higher altitude stations (Figure 12a).

Trends in both precipitation and snowfall amounts varied from northwest to southeast and varied with elevation. Care must therefore be taken in interpreting the trend patterns as purely elevational or geographic relationships. In particular, the apparent elevation dependence of precipitation trends (Figure 11a) may be an aliased regional pattern (Figure 3a), because of the strong tendency for the highest stations to be in the southern Rockies, in the southeastern part of the study area where precipitation increased (Figure
However, SFE changes due to warming also exhibited a clear dependence on elevation (Figure 12b), but this relationship does not appear to have been regionally dependent. The present study shows that the (precipitation-adjusted) trends in snowfall amounts reflected both the warming trends and the long-term mean winter temperatures at each site (Figures 8 and 9a). The relationship between both of these factors and elevation was consistent throughout most of the study region (Figure 10). Temperatures warmed throughout the West (Figure 6), and SFE at low- to moderate-altitude sites, which were warmer than higher stations, responded most to warming, even though warming was typically greater at the higher stations. At the low- to moderate-elevation stations, warming by less than about +3°C during the study period was sufficient to reduce the fraction of precipitation that falls as snow. At higher stations, even larger warmings have not (yet) been sufficient to induce as much change in the snowfall fraction. Because warming has been widespread and because higher elevation stations are cooler than lower stations throughout most of the study region, the relationship between the precipitation-adjusted trends in snowfall amounts and elevation found here are probably applicable throughout the West, so that the snowfall declines reported here are probably also occurring at most other such (as-yet undocumented) low- to moderate-elevation settings throughout the West.

If warming trends across the western U.S. continue, as projected in response to increasing greenhouse-gas concentrations in the atmosphere, snowfall amounts are likely to continue to diminish. More warming may be expected to produce a rightward drift of the stations plotted in Figure 9a. When a station’s mean November-March wet-day
minimum temperature rises above about -5°C in that figure, the station’s snowfall amounts begin to respond to the warming trends that bring the temperatures closer to freezing, and continued warming forces precipitation to shift from snow to rain. Figure 9b indicates that the coldest stations on Figure 9a have been warming more quickly than lower stations. Month-by-month trend analyses have demonstrated that the effect of future warming on snowfall amounts will depend critically on warming in specific months (e.g., January and March, to date), yielding largest impacts when the greatest warming coincides with greatest (historical) snowfall amounts and suitably warm mean temperatures. Continued warming in the peak deposition season of December through March would have the largest impact on snow deposition, while warming in March through June will be more strongly expressed as accelerations of snowpack melting like those projected by Stewart et al. (2001).

If continued warming raises more of the mean winter wet-day minimum temperatures in the West above about -5°C, snowfall declines (and rainfall increases) may be expected to combine with more rapid melting of the remaining accumulations of snowpack to further diminish the West’s natural freshwater storage capacity. The shift from snowfall to rainfall also may be expected to increase risks of winter and spring flooding. This combination of greater flood risk and reduced natural storage threatens to exacerbate the tension between flood control and freshwater storage priorities that many western reservoir managers face. Increased understanding of how flood risks will change, of the atmospheric conditions that control precipitation form, and of possible trends in those conditions are needed to better project and accommodate changes in the West’s water supplies.
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Figure Captions

Figure 1. a) Winter (Nov-Mar) SFE/P trends: symbol area is proportional to study-period changes, measured in standard deviations as indicated; circles indicate high trend significance (p<0.05), squares indicate lower trend significance (p>0.05). b) Water year 2004 winter SFE/P vs. WY 1949 winter SFE/P, with significant SFE/P trends highlighted. Dashed line is least-squares fit to all data points.

Figure 2. a) Mean winter (Nov-Mar) SFE/P values, and b) station elevations.

Figure 3. Trends in winter a) P and b) SFE; significance of trends is shown by circles and squares as in Figure 1a.

Figure 4. a) 1949-2004 changes in winter SFE/P versus changes in winter P. b) Changes in SFE/P vs. changes in SFE. c) Changes in SFE vs. changes in P. In each plot, stations with statistically significant (p<0.05) trends in both quantities plotted are indicated with squares.

Figure 5. Same as Figure 4c but with symbols determined by the corresponding changes in winter SFE/P. Circles indicate decreasing SFE/P and squares are increasing SFE/P, with significant (p<0.05) SFE/P trends in black.

Figure 6. a) Trends in winter-mean daily-minimum wet-day air temperatures, b) Trends
in winter-mean daily-maximum wet-day air temperatures. Circles and squares indicate significance as in Figure 1a.

Figure 7. a) Changes in SFE/P vs. changes in TMINw, with significant trends in SFE/P (p<0.05) highlighted as squares. b) Changes in P vs. changes in TMINw, significant P trends highlighted. c) Changes in SFE vs. changes in TMINw, significant SFE trends highlighted.

Figure 8. Precipitation-adjusted trends in SFE vs. trends in TMINw, with significant (p<0.05) SFE trends highlighted.

Figure 9. a) Precipitation-adjusted SFE trends vs. winter mean TMINw. b) TMINw trends vs. winter mean TMINw.

Figure 10. a) Trends in TMINw vs. elevation, with p<0.05 trends highlighted. In both panels, MT and WY Great Plains stations are indicated with different symbols and lighter coloring. The linear fit is to all non-Great-Plains stations which have significant trends. b) Long-term mean TMINw vs. elevation.

Figure 11. a) Precipitation trends vs. elevation, b) SFE trends vs. elevation. Significant (p<0.05) trends are highlighted.

Figure 12. a) Products of the P trend magnitudes and long-term mean SFE/P ratios,
versus elevation, with stations where SFE trends are significantly different from zero highlighted, b) P-adjusted SFE changes versus elevation.

Figure 13. Monthly trend magnitudes for SFE/P.

Figure 14. Monthly trend magnitudes for TMINw.
Figure 1. **a**) Winter (Nov-Mar) SFE/P trends: symbol area is proportional to study-period changes, measured in standard deviations as indicated; circles indicate high trend significance (p<0.05), squares indicate lower trend significance (p>0.05). **b**) Water year 2004 winter SFE/P vs. WY 1949 winter SFE/P, with significant SFE/P trends highlighted. Dashed line is least-squares fit to all data points.
Figure 2. a) Mean winter (Nov-Mar) SFE/P values, and b) station elevations.
Figure 3. Trends in winter a) P and b) SFE; significance of trends is shown by circles and squares as in Figure 1a.
Figure 4.  

a) 1949-2004 changes in winter SFE/P versus changes in winter P.  
b) Changes in SFE/P vs. changes in SFE.  
c) Changes in SFE vs. changes in P. In each plot, stations with statistically significant (p<0.05) trends in both quantities plotted are indicated with squares.
Figure 5. Same as Figure 4c but with symbols determined by the corresponding changes in winter SFE/P. Circles indicate decreasing SFE/P and squares are increasing SFE/P, with significant (p<0.05) SFE/P trends in black.
Figure 6. a) Trends in winter-mean daily-minimum wet-day air temperatures, b) Trends in winter-mean daily-maximum wet-day air temperatures. Circles and squares indicate significance as in Figure 1a.
Figure 7. a) Changes in SFE/P vs. changes in TMINw, with significant trends in SFE/P (p<0.05) highlighted as squares. b) Changes in P vs. changes in TMINw, significant P trends highlighted. c) Changes in SFE vs. changes in TMINw, significant SFE trends highlighted.
Figure 8. Precipitation-adjusted trends in SFE vs. trends in TMINw, with significant (p<0.05) SFE trends highlighted.
Figure 9. a) Precipitation-adjusted SFE trends vs. winter mean TMINw. b) TMINw trends vs. winter mean TMINw.
Figure 10. **a)** Trends in TMINw vs. elevation, with p<0.05 trends highlighted. In both panels, MT and WY Great Plains stations are indicated with different symbols and lighter coloring. The linear fit is to all non-Great-Plains stations which have significant trends. **b)** Long-term mean TMINw vs. elevation.
Figure 11. **a)** Precipitation trends vs. elevation, **b)** SFE trends vs. elevation. Significant (p<0.05) trends are highlighted.
Figure 12. a) Products of the P trend magnitudes and long-term mean SFE/P ratios, versus elevation, with stations where SFE trends are significantly different from zero highlighted, b) P-adjusted SFE changes versus elevation.
Figure 13. Monthly trend magnitudes for SFE/P.
Figure 14. Monthly trend magnitudes for TMINw.
Figure 15. Precipitation-adjusted SFE changes vs. mean TMINw for January and March.