

Trends in Snowfall versus Rainfall in the Western United States

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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 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 snowmelt. The present study addresses the former, documenting a regional trend toward smaller ratios of winter-total snowfall water equivalent (SFE) to winter-total precipitation (P) during the period 1949-2004.

The trends toward reduced SFE are a response to warming across the region, with the most significant reductions occurring where winter wet-day minimum temperatures, averaged over the study period, were warmer than -5°C . Most SFE reductions were associated with winter wet-day temperature increases between 0 and $+3^{\circ}\text{C}$ over the study period. Warmings larger than this occurred mainly at sites where the mean temperatures were cool enough that precipitation form was less susceptible to warming trends.

The trends toward reduced SFE/P were most pronounced in March regionwide and in January near the West Coast, corresponding to widespread warming in these months. While mean temperatures in March were sufficiently high to allow the warming trend to produce SFE/P declines across the study region, mean January temperatures were cooler, with the result that January SFE/P impacts were restricted to the lower elevations near the West Coast.

Extending the analysis back to 1920 shows that although the trends presented here may be partially attributable to interdecadal climate variability (PDO), they also appear to result from still longer-term climate shifts.

1. Introduction

One of the most common, and common-sense, projections of the impact of global warming on the western United States is 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 hasten the onset 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 observed changes in snowpack and streamflow timing 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 affected by wintertime (November-March) temperatures, whereas changes in onset of snowmelt (once snow is on the ground) are more likely to be sensitive to springtime temperatures. Thus snow deposition and snowmelt are expected to be differently sensitive to warming trends in different seasons, and the warming trends associated with snowfall and snowmelt changes may be distinguishable by differences in their geographic patterns and rates of change. Much work has been accomplished to map trends in snowmelt response; this study documents a parallel set of trends that has changed the relative contributions of snowfall to western precipitation.

In Section 2, the data used and the methods applied are discussed, and the robustness of the approach is addressed. In Section 3a, trends in winter precipitation form are presented, and in Section 3b, the influence of temperature on these trends is examined. In Section 3c, the monthly patterns underlying the seasonal trends are presented. In Section 3d, the role of climate variability in generating trends in precipitation form is investigated. Finally, the main results are summarized in Section 4, and their implications discussed.

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 US (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. Because S is not a reliable proxy for snowfall liquid equivalent because snow density can vary significantly, and because P observations have no associated data flags indicating the precipitation form (i.e., solid, liquid, or mixed), in this study, a non-zero value of snowfall depth (S) is used to assign a solid form to any measured precipitation (P), thereby estimating snowfall water equivalent (SFE).

Precipitation and snowfall totals were recorded at 1,653 stations during some or all of 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 daily observations 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 interval. 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 261 stations with precipitation and snowfall, 634 stations that contained temperature, and 207 stations that contained temperature, precipitation and snowfall. The analyses presented

here used the largest appropriate data set in each case (i.e., joint analysis of temperature and precipitation used 207 stations, while analysis of temperature alone used all 634 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 liquid depth measured, or, in the case of recording gages, the precipitation is weighed (National Weather Service 1989).

A potential problem with the use of precipitation gage measurements to compare snowfall to total precipitation is that catch efficiency is typically lower for snow than for rain. The influence on the results presented below of this phenomenon of undercatch were estimated by assuming all solid precipitation was associated with a gage efficiency of 50%, and all liquid precipitation with an efficiency of 90%, then repeating the analyses of this study. The results suggest that undercatch had relatively little effect on the trends reported here, and, if anything, results in an underestimation of trends in SFE/P and SFE. A more rigorous treatment of these effects was not possible due to the absence of catch efficiency data for the individual stations studied.

Although they have been selected to have recorded snowfall (criterion 3 above), the SOD station subset is generally representative of lower and middle elevations. For example the median elevation from the snow/precipitation SOD subset is 1380m, while the median elevation of snow pillows in the same region is 2380m. However, as will be brought out in the results, the elevational distribution of the SOD stations is quite well situated to record changes in precipitation form from relatively modest climate fluctuations or changes. This is because elevations below 2000m are nearer to freezing and thus more sensitive to temperature changes than are the higher, colder elevations that are generally characteristic of snow courses and snow pillows.

In a relatively small number of cases, P was not measured directly, but was estimated on snowy days by applying some fixed multiplier (corresponding to an assumed snow density) to the depth of snow (S), typically 0.1 (Kunkel et al. 2005). To test this possibility and to determine whether such cases 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 percentage of snowy days for which 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 percentage 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 some days is a mixture of snow and rain), it avoids over-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 would result in underestimation of 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).

The sums of SFE and P over all days with data in each winter (after the culling process described above) form time series of winter and monthly totals of SFE and P, from which winter and monthly ratios SFE/P, the fraction of precipitation falling as snow, 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 a linear fit produced negative values, only the positive segment of the fit was used to determine magnitude 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 they were in 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. To include a fuller network of stations, the present analysis applied the completeness criteria, as described above, to the full SOD dataset 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.

Most of the analyses presented are from the primary precipitation, snowfall depth, and temperature datasets taken from 1949-2004. However, to obtain a better understanding of the temporal variability of the snowfall fraction and its linkage to temperature, selected analyses use two smaller subsets of stations beginning in 1930 and 1920, respectively.

3. Results

a. Seasonal SFE/P Trends

The fraction of winter precipitation falling on snowy days (SFE/P) trended towards smaller values during 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 standard deviations of the yearly ratios) at the lower-elevation sites in the Sierra Nevada and the Pacific Northwest.

The 2004 and 1949 intercepts of linear fits to the time series of winter SFE/P values for each station were plotted against each other (Figure 1b) to show the magnitude of changes during the 56-year study period. A straight-line fit to all stations, in Figure 1b, reveals that stations across the full range of initial SFE/P values have experienced remarkably uniform (slope \approx 1) reductions in the fraction of precipitation falling as snow. The linear fit corresponds to an SFE/P decline of 9% during the study period. In this paper, most trends will be discussed in terms of the difference of the linearly fitted values at the end and beginning of the study period; where trend strength is the focus (as opposed to trend magnitude), standard deviations are used (Figure 1 and Figure 3).

Long-term mean values of winter SFE/P (Figure 2a) increase from west to east, responding to generally higher station elevations in the east (Figure 2b), cooling with increasing latitude, and other geographic effects. 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. Geographic relationships, including elevation, are discussed more in Section 3c.

Changes in SFE/P can occur because of disproportionate changes in either SFE or P. To better understand how these two factors influence observed SFE/P trends, Figure 3 shows the corresponding trends (in terms of year-to-year standard deviations) in P and SFE. The P trends (Figure 3a) vary considerably in magnitude and sign over the spatial domain and are not generally in accord with the widespread pattern of SFE/P declines. Of the 48 stations with significant P trends, 15 also had significant trends in SFE/P. Of these, SFE/P trends were of the same sign as the P trends at 12 stations but, since P contributes inversely to SFE/P, this means that in most cases P trends did not dictate the sign of the SFE/P trends. In contrast, changes in SFE (Figure 3b) more closely parallel the pattern of SFE/P trends shown 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 trends at 67 of these stations shared the same sign. In New England, Huntington et al. (2004) also found that SFE declines have generally reflected trends towards smaller SFE/P ratios.

The primary area where there have been disagreements between the signs of SFE trends (Figure 3b) and SFE/P trends (Figure 1a) is in the southern Rocky Mountains, in the southeastern portion of the study region. At most sites there, SFE increased in response to increasing P. At many of these sites, increases in SFE have not kept pace with P, and thus SFE/P ratios decreased. Relative within-season differences in when and how much precipitation and temperature changed (not shown) 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 the mixed SFE/P trends there.

To further clarify the relationships between the trends in SFE/P and trends in SFE and P, Figures 4a-b show trend magnitudes plotted against each other, with stations exhibiting significant SFE trends plotted as squares. Aside from a few sites that experienced large reductions in P, changes in SFE/P have not been well correlated with changes in P (Figure 4a). Notably, decreases in P have generally coincided with *decreases in* SFE/P and increases in P have been associated with either decreases or increases in SFE/P, depending on location. 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 (Figure 4b).

The relative roles of trends in SFE and P in determining trends in SFE/P can be summarized as follows: if nothing else changes, a change in P should produce a change in SFE equal to the initial value of SFE/P (i.e., the 1949 intercept of the linear fit) multiplied by the change in P. If the change in SFE is less than this as a result of factors other than P, then SFE/P should decrease; if greater, it should increase. This relationship is verified in Figure 4c, where the change in SFE at each station has been plotted against the initial SFE/P intercept multiplied by the change in P. The symbols differ based on whether the trend in the ratio SFE/P was positive or negative. The $(SFE/P)_{init} * \text{trend-in-P}$ value predicts the sign of the trend in SFE accurately at over 90% of sites, and is accurate within a small tolerance at all 261 sites.

For the ratio SFE/P to have changed, then, some factor other than P must have influenced SFE. The next section discusses the role of temperature in producing SFE trends and attempts to distinguish contributions to the trends due to precipitation changes from those due to temperature changes.

b. Temperature Dependence

Several studies have linked declining snowpacks 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, among other possible mechanisms, warming has contributed to these changes by increasing the temperature during precipitation events, thus reducing the amount of snow deposited. To understand the relevant temperature changes, Figure 5a shows trends in winter-mean wet-day minimum-daily temperatures. Wet-day TMINs have generally warmed more than have wet-day TMAXs (not shown), with average (over all western U.S. stations) increases of +1.4°C and +1.0°C between 1949 and 2004, 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 winter (November-March) wet-day minimum temperatures (TMINw).

Long-term mean TMINw values are mapped in Fig. 5b. A clear southwest-northeast gradient is apparently in contrast to the northwest-southeast gradient in station elevations shown in Figure 2b. Part of the reason for this is that Figure 2b includes only stations from the precipitation-snowfall dataset, while 5b shows the larger set of temperature stations. Most stations in the warm southwest did not have enough snowfall to qualify for the precipitation-snowfall data set, so these warm stations, which are included in the temperature data set, yield a more accentuated SW-NE pattern. Also, the Great Plains (GP) stations of Montana, Wyoming, and eastern Colorado are distinctly colder than other stations at comparable elevations and latitudes, further contributing to the SW-NE pattern of Figure 5b. The anomalously cold temperatures of the GP stations are very apparent when mean TMINw values for each station are plotted against station elevations (Figure 5c). In general, Figure 5c demonstrates a clear-cut relationship between TMINw and elevation, with the spread of temperatures at a given elevation associated primarily with a spread of latitudes. However, the GP stations (highlighted as light gray squares) show quite different behavior, with an inverted lapse rate and much colder temperatures.

Although some of the GP stations have had the largest warmings in the West (Figure 5a), they are also among the coldest sites in the West (Figures 5b and 5c) and have exhibited correspondingly little change in winter snowfall to date. This relationship between mean temperature and amount of warming holds for non-GP stations as well, though less dramatically. Figure 5d shows trends in TMINw plotted against mean TMINw, with significant trends highlighted, and significant GP trends identified as gray diamonds. Though the GP stations stand out as some of the coldest and most warmed in

the West, many of the coldest non-GP stations have also warmed more than other, warmer non-GP sites. 79% of non-GP stations with significant TMINw trends and that warmed more than +3°C had mean TMINw values less than 0°C; 70% of these had mean TMINw less than -5°C. In comparison, for non-GP with significant TMINw trends and that warmed *less* than +3°C, these values were 47% and 40%, respectively.

To understand how these temperature changes have affected snowfall, fractional changes in SFE, expressed as the ratio of SFE change over the record to the initial SFE value (i.e., the 1949 intercept of the linear fit to the SFE time series) at each station, are plotted against the TMINw changes in Figure 6a. Most stations with moderate TMINw changes experienced reductions in SFE. The outliers with large fractional SFE increases correspond to sites which had very small initial snowfall and which experienced only moderate increases in snowfall. Many sites lost most of their snowfall over the course of the 56-year study period. However, at stations where TMINw warmed by more than about +3°C, SFE changed relatively little (increasing in most cases). This is a result of the larger warmings that occurred at very cold sites (Figure 5d), and is discussed further below.

To distinguish between the effects on SFE of trends in P totals and trends in TMINw, Figure 6b shows an analog of Figure 6a in which the changes in SFE have been adjusted to remove the influence of any P trend at each site. This was accomplished by subtracting the first-order effect of the precipitation trend at each station from the SFE trend there. This first-order precipitation correction was estimated as the product of the P trend magnitude and the long-term mean of SFE/P. Earlier, the *initial* value of SFE/P was used to calculate the expected change in SFE/P due to P trends in the absence of other factors. Here, the use of the record-length mean of SFE/P is necessary because, as indicated by Figure 4c, other factors have been influencing SFE/P. SFE/P has thus been changing over the course of the record, and the record-length mean must be used to calculate a first-order approximation to the changes in SFE/P due to P trends. 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, it is even clearer (than in Figure 6a) that the most significant reductions in SFE have occurred at sites that experienced moderate (<3°C) TMINw warming (Figure 6b). The reason that smaller temperature changes resulted in the largest SFE declines is clear when viewed another way: Figure 6c shows the P-adjusted SFE changes plotted against long-term mean November-March TMINw values at each site. The largest SFE reductions occurred at the warmest locations (TMINw > -5°C), where temperatures were closer to freezing and warming by even a small amount was enough to have a substantial impact. Because mean TMINw values are strongly related to elevation (Figure 5c), P-adjusted SFE trends (Figure 6d) as well. Most P-adjusted SFE reductions occurred at sites with elevations below 2000m, corresponding to the warmest temperatures in Figure 6c. The few stations that exhibited appreciable fractional increases were largely located above about 1200m and experienced relatively little snowfall; hence small positive trends produced large fractional increases. At sites

with significant winter SFE trends, the average P-adjusted winter SFE reduction was 51mm over the 56-year study period. Averaged over all sites, the reduction was 26 mm.

As noted above, the relationship between TMINw changes and the long-term mean wet-day winter temperatures (Figure 5d) explains another feature of Figures 6a and 6b, the very small SFE changes at sites that have warmed by more than +3°C. The stations that warmed this much tended to be 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.

Since mean TMINw and, to a lesser degree, trends in TMINw exhibit regional patterns, Figures 6b-c also were plotted separately for individual regions, splitting the study domain into east-west, north-south, and northwest-southeast halves to test for effects of continentality, latitude, and elevation (Figure 2a), respectively. In all three cases, the halves showed considerable overlap and the relationships were consistent with those in Figures 6b-c, indicating that P-adjusted SFE trends were not controlled by continentality, latitude, or elevation effects, but rather were driven by temperature trends.

The geographic pattern of P-adjusted SFE trends resulting from the TMINw trends (Figure 5a) and mean TMINw (Figure 5b) are shown in Figure 7. P-adjusted SFE was reduced at 75% of all stations in the West, with 20% of all stations experiencing reductions of greater than one-half of their initial snowfall. The largest reductions occurred at stations in the coastal Northwest. Although these sites experienced only moderate warming (Figure 5a), were also among the warmest sites (Figure 5b) and therefore had the largest fractional SFE reductions, consistent with the relationships revealed by Figures 6b-c. Sites in central and northern California received, on average, considerably more snow than any other region, and in terms of magnitude, they showed the largest snowfall reductions in the West.

The pattern of Figure 7 therefore results from the patterns of Figures 5a-b, which are in turn dependent on elevation, latitude, and other geographic factors responsible for temperature patterns. Another key factor was the relationship between warming and mean wet-day daily-minimum temperatures—the sites that warmed the most tended to have the coldest mean temperatures. The relationships expressed in Figures 6b-c are fundamental in determining the change in snowfall, and they hold throughout the study region.

c. Monthly Patterns

Mapping trend magnitudes for SFE/P by month (Figure 8) reveals that the most widespread declines in snowfall fractions occurred in March, with declines spanning the western U.S. 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 in the Rockies. Thus the declines are of considerable concern.

The seasonality of the monthly SFE/P changes echoes the monthly changes in TMINw (Figure 9). In particular, January and March have warmed most significantly across the West. Monthly patterns of TMAXw trends were very similar to those in Figure 9, 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 have initially occurred, 2) warming must take place over the study period, 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 8). Historically, snowfall occurred at most stations during all winter months, with a sharp drop in the number of stations that normally received snow in springtime. On average, the largest percentages of stations experienced warming in January and March (about 90% and 96%, respectively), and the smallest percentage of stations were warm enough for warming to affect SFE (historical mean TMINw > -5°C) in January (38%). This last factor explains why similar warming patterns in January and March (Figure 9) resulted in different SFE/P responses (Figure 8). January TMINw values were too cold at higher elevations for the warming to affect SFE (Figure 10). In March, most stations were warm enough for the broad warming trends to yield broad SFE/P declines.

Although January SFE/P reductions were not as widespread as those in March, the average January SFE declines were slightly greater. Averaged over *all* stations, the P-adjusted SFE reductions were 10mm in January and 8mm in March, with smaller reductions during the other winter months. These reductions amounted, on average, to 14% and 9%, respectively, of the long-term average winter SFE totals. 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.

d. Climate variability

So far, only linear trends have been examined. Using an empirical orthogonal function (EOF) analysis, the temporal evolution of the system can be examined in more detail and farther back in time. Figures 11-12 show the first modes and associated amplitude time

series from 6 different EOF analyses. To produce these results, the TMINw and SFE/P time series were extended back first to WY1930 and then to WY1920. In the WY1930-2004 series, 91 precipitation/snowfall stations and 330 temperature stations satisfied the completeness criteria; in the WY1920-2004 series, there were 45 and 251 stations, respectively. The time series at all stations were standardized to have zero mean and a standard deviation of one over each of the time intervals analyzed. The EOF analyses were then applied to these four datasets as well as to the original WY 1949-2004 datasets.

For each of the three time periods, the first EOFs of November-March average TMINw are everywhere positively weighted (except for one station in Colorado), capturing variations shared by all stations. In each analysis, the first EOF explains around 40% of the overall TMINw variance (Figure 11, top). The first EOFs of SFE/P explain around 20% of SFE/P variance, with most stations varying in unison but a few in opposition (Figure 11, bottom). Despite the much sparser data sets for the longer analysis periods, Figure 11 shows that the same basic patterns dominated all three analyses. Indeed, when the first-EOF amplitudes for all three are plotted on top of each other, they agree remarkably well (Figure 12), with correlation coefficients for overlapping time periods greater than 0.94 in all cases. The first-EOF amplitudes for TMINw and SFE/P are also strongly anti-correlated, with correlations more negative than -0.87 for all three time periods. Thus, on time scales from annual to long-term trends, temperature increases produce decreases in SFE/P.

The first EOFs are of particular interest because they represent spatially coherent variations on the largest scale, a scale that characterizes the trends presented above. The lower-order EOFs reflect smaller spatial scales, such as spatial dipoles, and are not presented here. The EOF1 amplitudes in Figure 12 are strongly related to the time series of TMINw and SFE/P averaged over all stations (not shown) and to each other. The correlations between TMINw EOF1 amplitudes and the time series of all-station-average TMINw are 0.99 for all three time periods. The corresponding correlations for SFE/P are 0.86 for 1920-2004, 0.89 for 1930-2004, and 0.92 for 1949-2004.

Also shown in Figure 12 are smoothed versions of the first EOF amplitudes. These were generated from the annual EOF amplitudes using a low-pass filter with a 10-year cutoff period (Mann 2004). While the smoothed versions were generated for the full time period corresponding to each EOF amplitude time series, the smoothed versions shown in each period in Figure 12 are the smoothings from the richest data sets with temporal coverage appropriate for the 10-year smoothing period used. That is, the smooth solid line from 1954-2004 is the filtered version of the 1st EOF amplitude from the 1949-2004 data set, the smooth dashed line from 1935-1954 is from the 1930-2004 EOF analysis, and the smooth dotted line from 1920-1935 is from the 1920-2004 analysis. This approach provides an optimal representation of low-frequency behavior for each period of the record, as more stations came online.

The positive temperature trend and the shift from snowfall to rainfall during WY1949-2004 presented earlier are evident in the smoothed amplitudes (Figure 12). It also appears

that the changes composing the trends occurred largely in the 1950's and after the late 1970's.

One reason for extending the analysis back to 1920 was to determine whether the trends presented here are artifacts of the 1949-2004 study period that supplied most of the data for the analyses. That widespread meteorological observations did not become available until 1948 is an unfortunate constraint on the present analysis. 1949 was a particularly cold year in the historical record, and SFE/P ratios were correspondingly high. Also, during approximately the first half of the 1949-2004 study period, the Pacific Decadal Oscillation (PDO, Mantua et al. 1997) was in its cool phase, after which it transitioned to a warm phase that persisted throughout most of the second half of the study period. More recently still, the PDO may have re-entered its cool phase, though its present status is not clear.

Though the amplitudes become more uncertain as fewer stations were existent further back in time, it does appear that some of the trends detected since 1949 may be attributable to low-frequency climate variability, since the 1947-1976 cool phase was characterized by cooler temperatures and higher SFE/P ratios than both the 1925-1946 and the 1977-1998 warm phases. These conclusions were also borne out by a separate examination of the all-station means of TMINw and SFE/P (Table 1).

However, the PDO warm phase lasting from about 1925 through 1946 was characterized by lower temperatures and higher SFE/P values than the most recent 1977-1998 PDO warm phase (Table 1), suggesting that the trends reported here are at least partially attributable to still longer-term climate shifts. Indeed, when the entire analysis presented in Sections 3a-b was repeated using the 1930-2004 data and again using the 1920-2004 data, although the plots contained fewer data points, the resulting trend maps and plots were essentially unchanged.

4. Conclusions

The fraction of winter precipitation that fell as snow declined across most of the western U.S. during the period 1949-2004. Significant changes in November-March seasonal total snowfall water equivalent (SFE) were much more common than changes in seasonal total precipitation during this period, and most of the significant changes in SFE were reductions unrelated to changes in total precipitation. The largest reductions were shifts from snowfall to rainfall driven by warming, and occurred at relatively warm, low- to moderate elevations (Figures 6b-d).

Warming trends were widespread across the western U.S. However, the sites that warmed most tended to have relatively cold climatologies. As a result, some of the largest warming trends in the West ($>4^{\circ}\text{C}$) did not cause shifts in precipitation form (from snow to rain) because, despite the warming, temperatures remained well below freezing. The largest shifts from snowfall to rainfall, actually, occurred at sites that warmed less (from 0°C to $+3^{\circ}\text{C}$), because these sites had mean temperatures warm enough that moderate

warming was sufficient to impact precipitation form (Figure 6d).

In summary, the mean temperatures (Figure 6c) and the magnitude and sign of the surface temperature trends (Figure 6b) were the fundamental determinants of the amount of precipitation shifting from snow to rain at each site. Although mean temperatures and, to a lesser extent, temperature trends exhibit regional patterns, it was verified that the temperature dependencies expressed in Figures 6b-c hold throughout the study region; i.e., they are not simply aliased regional patterns. This fact, combined with the widespread nature of the warming trends (Figure 5a) and the strong elevational dependence of mean temperatures (Figure 5c), suggests that the east-west pattern of fractional precipitation-adjusted snowfall reduction of Figure 7 is primarily a reflection of station elevation (Figure 2a), and is not indicative of some other regional control on snowfall reductions. Thus, the snowfall declines seen at the cooperative stations included in the present study are probably also occurring at most other (as-yet undocumented) sufficiently warm, low- to moderate-elevation sites in the West.

We found that while PDO fluctuations may have influenced wet-day temperatures and snowfall fractions at the interdecadal time scale, it also appears that longer-term changes have been occurring. This result is consistent with recent findings of reduced spring snowpack by Mote et al. (2005) and advanced snowmelt runoff by Stewart et al. (2004), who suggest that these changes can only be partially explained by fluctuations in PDO, with another portion of variability that may be a response to broader-scale anthropogenic warming. If warming trends across the western U.S. continue, as projected in response to increasing greenhouse-gas concentrations in the atmosphere (IPCC 2001), the snowfall fraction of precipitation is likely to continue to decline. More warming may be expected to produce rightward drifts of the points in Figure 6c. 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 temperatures closer to freezing, and continued warming shifts precipitation from snow to rain. Figure 5d indicates that the coldest stations in Figure 6c have been warming more than the warmer stations. Month-by-month trend analyses showed that the effect of future warming on snowfall amounts will depend critically on warming in specific precipitation-rich 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. Warming during December through March would have the largest impact on snow deposition, while warming in April through June will be more strongly expressed as accelerations of snowpack melting like those projected by Stewart et al. (2004).

If warming continues and raises mean winter wet-day minimum temperatures in more of the West above about -5°C , snowfall declines (and rainfall increases), combined with earlier melting of the remaining accumulations of snowpack, will 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 in many settings. The combination of greater flood risk and reduced natural storage threatens to exacerbate the tension between flood control and storage priorities that many western reservoir managers

face. Better 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 project and accommodate future changes in the West's water supplies.

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Figure and Table Captions

Figure 1. **a)** Trends in fraction of winter (Nov-Mar) precipitation falling on snowy days (SFE/P), 1949-2004: red indicates decreasing snowfall fractions; symbol radius is proportional to study-period changes, measured in standard deviations as indicated; circles indicate high trend significance ($p < 0.05$), and squares indicate lower trend significance. **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. 1949-2004 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, with significant SFE/P trends highlighted. **b)** Changes in SFE/P vs. changes in SFE. **c)** Observed SFE changes versus SFE changes predicted due to changes in P (absent other factors). Sites above the one-to-one line had increasing SFE/P (circles); at sites below the line the ratio decreased (x's).

Figure 5. **a)** Trends in winter-mean daily-minimum wet-day air temperatures for 1949-2004. Symbol size is proportional to trend magnitude; circles indicate significant ($p < 0.05$) trends, squares indicate less significant trends. **b)** Winter-mean wet-day minimum temperatures TMINw. **c)** TMINw vs. station elevation. Great Plains stations are represented by gray squares. **d)** Trends in TMINw vs. mean TMINw, significant trends highlighted. Great Plains stations are identified in gray, with significant trends as diamonds.

Figure 6. **a)** Fractional changes in SFE vs. changes in TMINw over the period 1949-2004, with significant trends in SFE ($p < 0.05$) highlighted as squares. **b)** Fractional changes in precipitation-adjusted SFE vs. trends in TMINw, significant SFE trends highlighted. **c)** Fractional changes in precipitation-adjusted SFE vs. winter mean TMINw. **d)** Fractional change in precipitation-adjusted SFE vs. station elevation.

Figure 7. 1949-2004 fractional change in winter snowfall water equivalent after removing the effects of trends in precipitation. 75% of stations have experienced snowfall reductions as a result of widespread warming (Figure 5a).

Figure 8. Trend amounts for monthly averaged SFE/P. January and March have shown the largest reductions in response to warming trends (Figure 9).

Figure 9. Trend amounts for monthly averaged TMINw. January and March have had widespread warming trends.

Figure 10. Fractional precipitation-adjusted SFE changes vs. mean TMINw for January and March. January temperatures were too cold at many stations for warming to have any impact, but March was warm enough for most stations to show reductions in P-adjusted snowfall.

Figure 11. First EOFs for six time series: TMINw and SFE/P for the periods WY1949-2004, WY1930-2004, and WY1920-2004. Percent of overall variance explained is in lower left of each panel.

Figure 12. EOF amplitudes representing spatially broad patterns of variability in winter wet-day minimum temperature (**top**) and fraction of winter precipitation falling as snow (**bottom**), with PDO phases indicated. These amplitudes correspond to the spatial loading patterns in Figure 11. The thick, wavy lines are low-pass filtered versions of each amplitude. The portion of the low-pass curve which best describes a given period is used for that period. See text for further explanation.

Table 1. Mean (over all stations) TMINw and SFE/P for three phases of the PDO. The differences between the two warm phases are of the same order of magnitude and in the same direction as the overall WY1920-2004 trends.

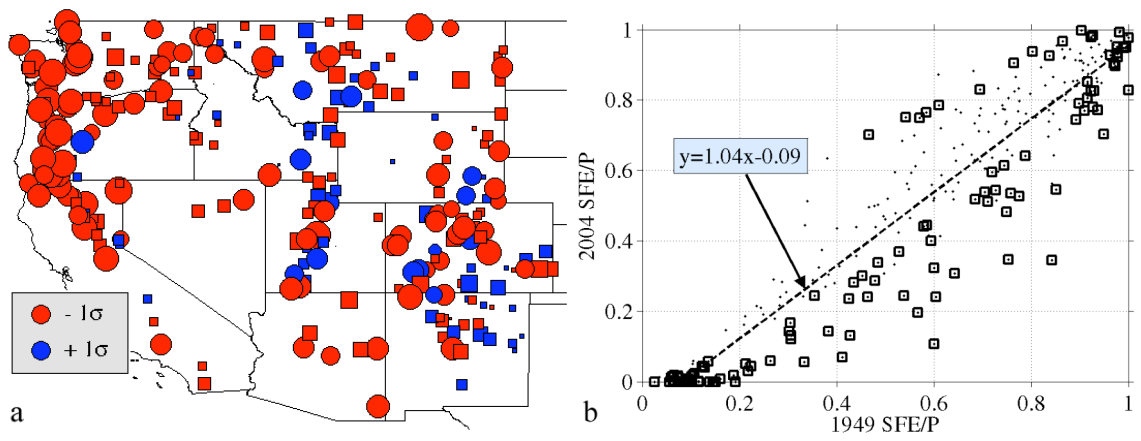


Figure 1

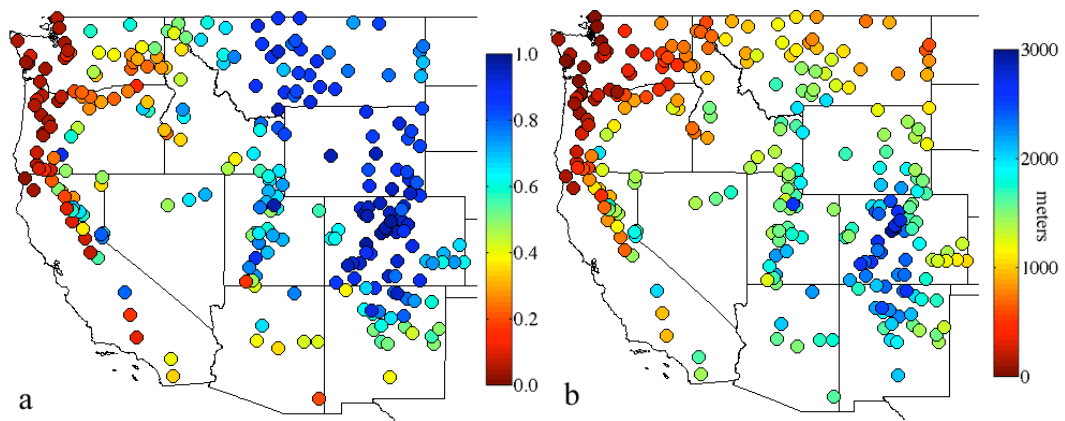


Figure 2

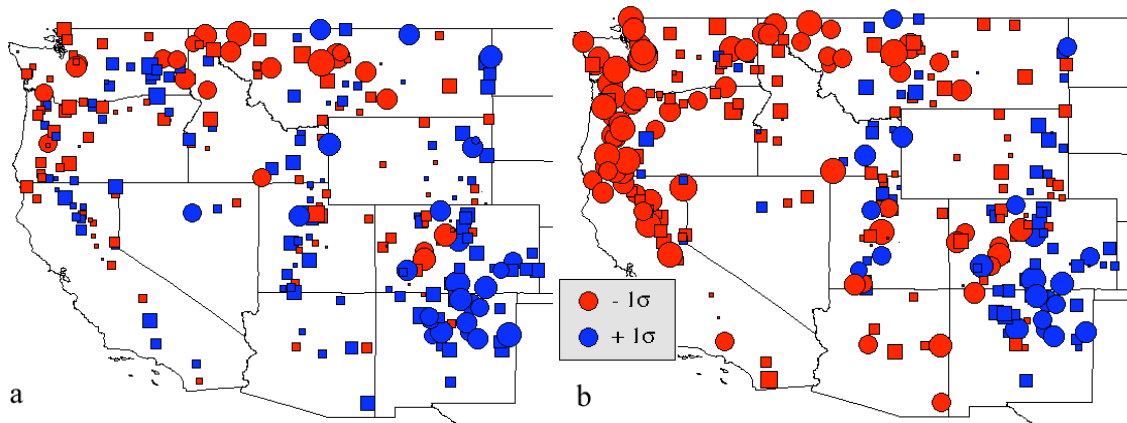


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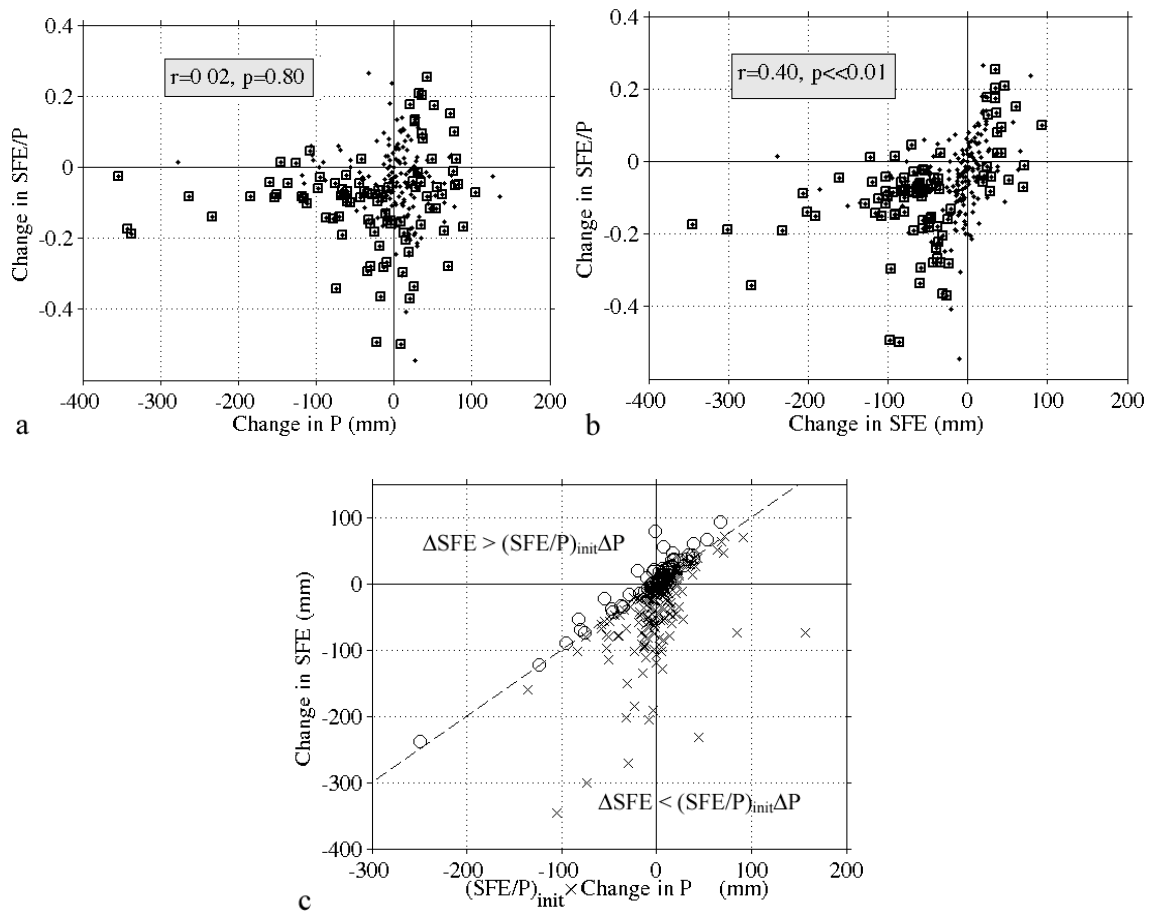


Figure 4

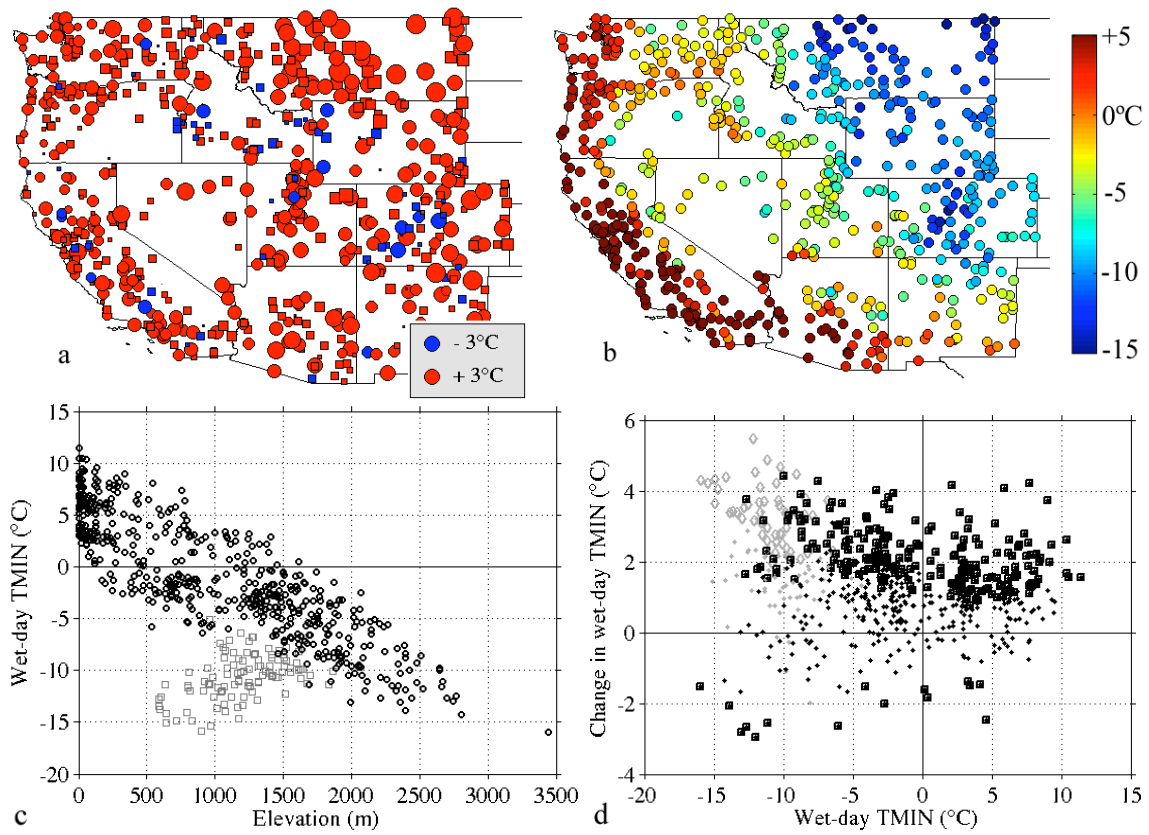


Figure 5

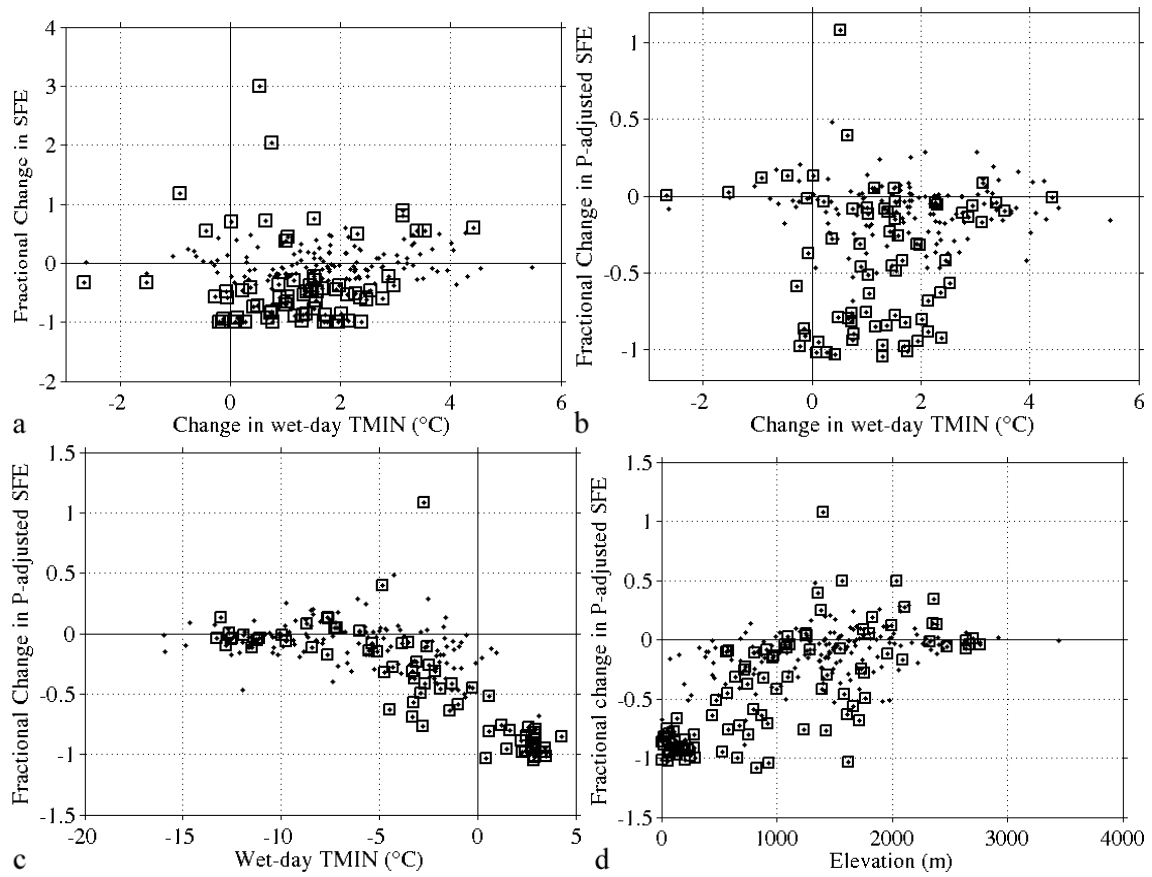


Figure 6

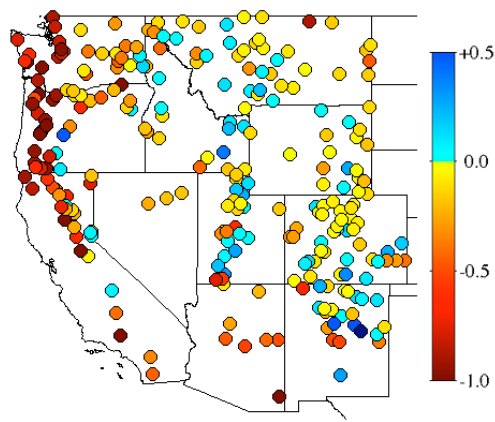


Figure 7

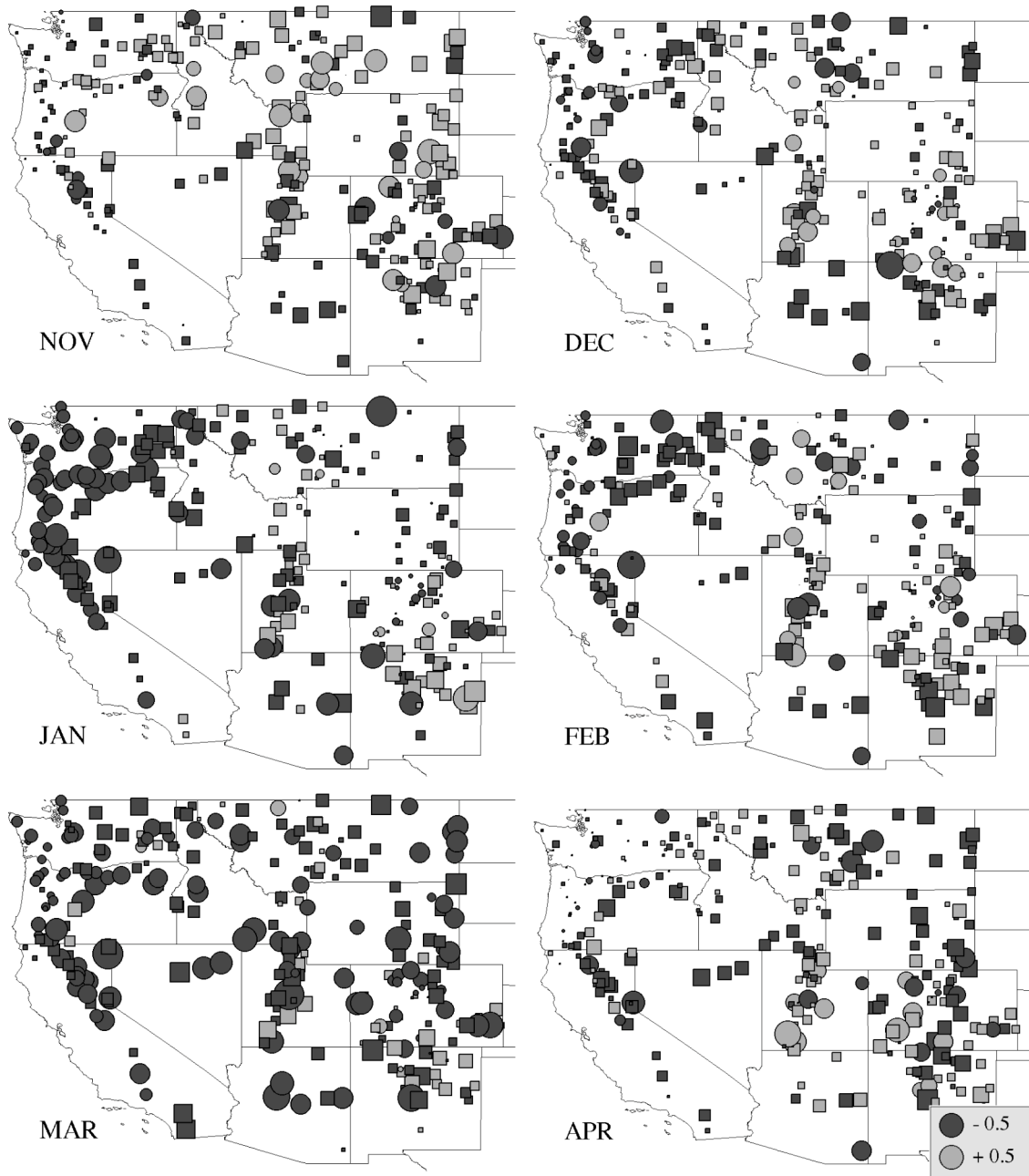


Figure 8

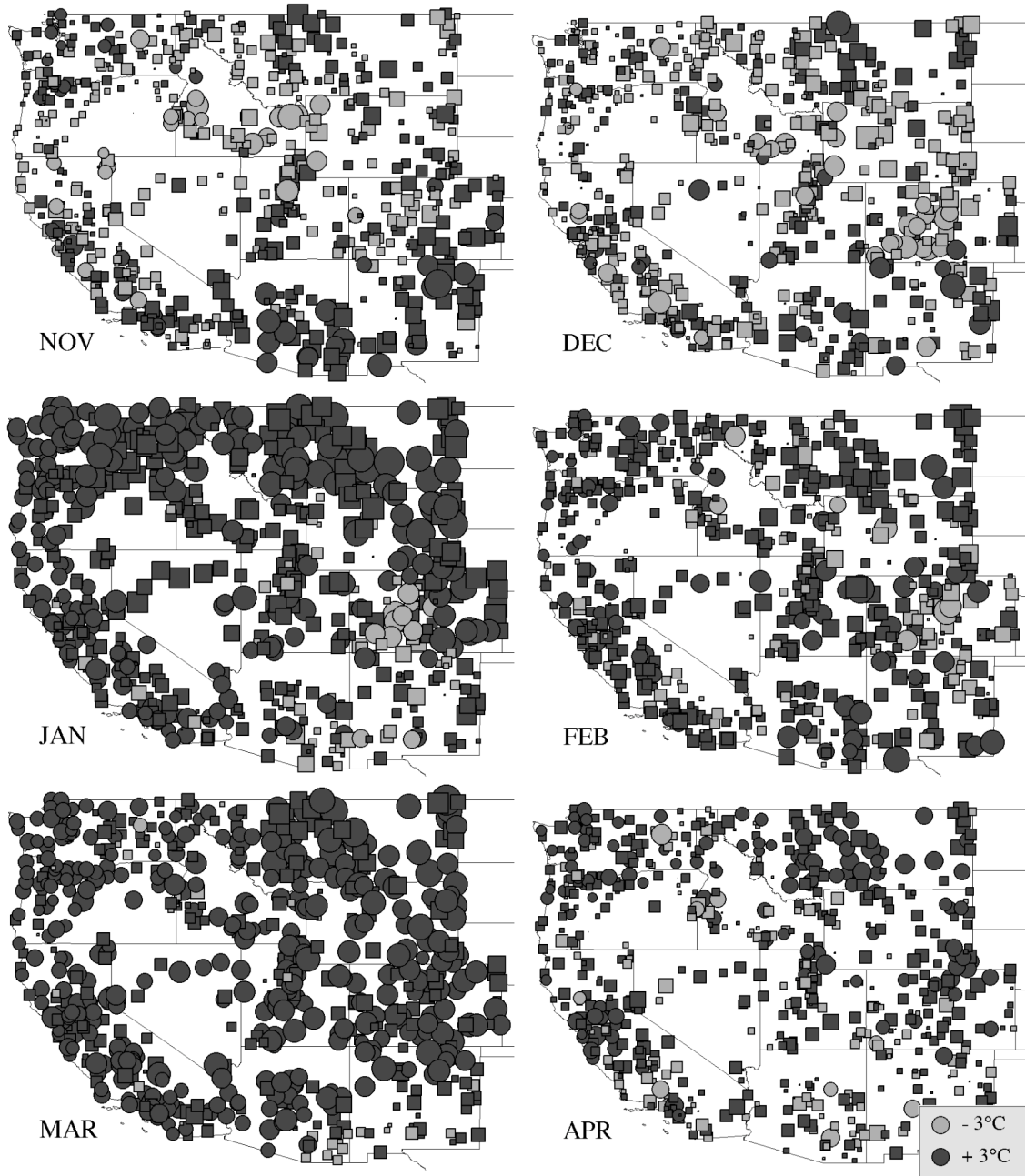


Figure 9

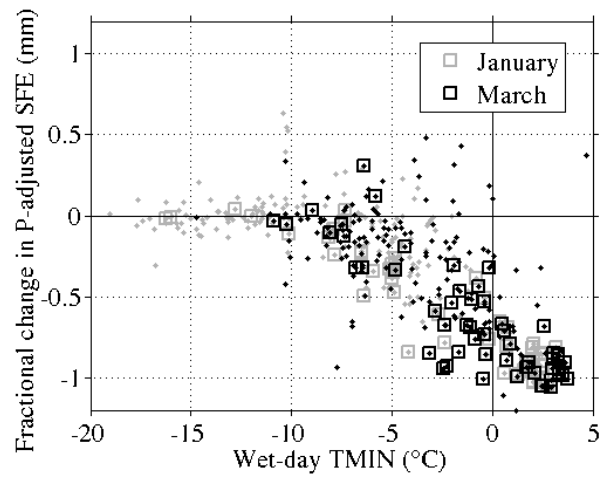


Figure 10

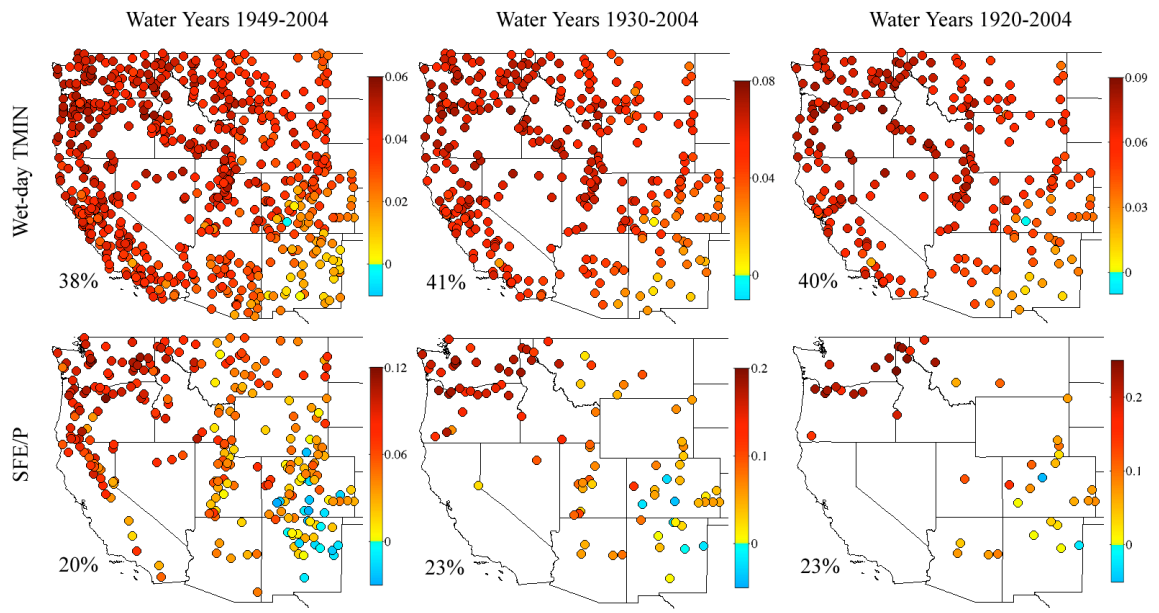


Figure 11

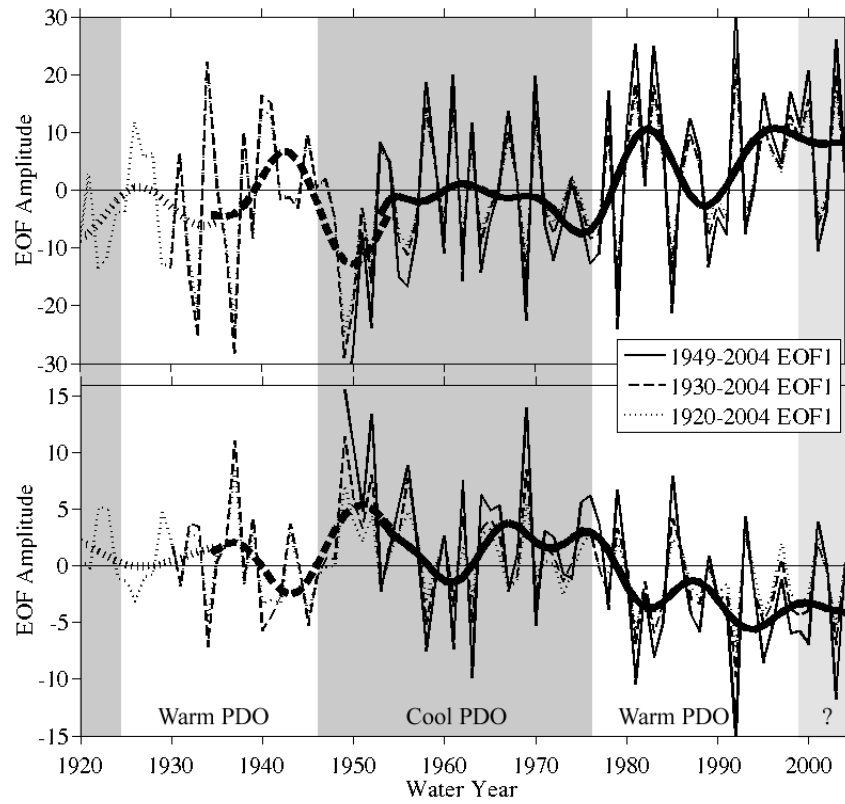


Figure 12

Table 1. Mean (over all stations) TMIN_w and SFE/P for three phases of the PDO. The differences between the two warm phases are of the same order of magnitude and in the same direction as the overall WY1920-2004 trends.

	TMIN _w (°C)	SFE/P
WY1925-1946 (warm)	-2.8	0.56
WY1947-1976 (cool)	-3.0	0.57
WY1977-1998 (warm)	-2.4	0.54
Warm-Phase Difference	+0.4	-0.02
WY1920-2004 trend	+1.1	-0.06