Arnold Schwarzenegger
Governor

TRENDS IN SNOWFALL VERSUS RAINFALL FOR THE WESTERN UNITED STATES, 1949–2001

PIER PROJECT REPORT

Prepared For:
California Energy Commission
Public Interest Energy Research Program

Prepared By:
United States Geological Survey
Scripps Institution of Oceanography

April 2007
CEC-500-2007-032

California Climate Change Center
Report Series Number 2007-011

Prepared By:
Noah Knowles, U.S. Geological Survey
Menlo Park, California

Michael Dettinger and Daniel Cayan, U.S. Geological Survey and
Scripps Institution of Oceanography
La Jolla, California 92093-0224

Commission Contract 500-02-004
Commission Work Authorization MR-025

Prepared For:
Public Interest Energy Research (PIER) Program
California Energy Commission

Beth Chambers
Contract Manager

Kelly Birkinshaw
Program Area Lead
Energy-Related Environmental Research

Laurie ten Hope
Office Manager
Energy Systems Research

Martha Krebs
Deputy Director
ENERGY RESEARCH & DEVELOPMENT DIVISION

B.B. Blevins
Executive Director

DISCLAIMER

This report was prepared as the result of work sponsored by the California Energy Commission. It does not necessarily represent the views of the Energy Commission, its employees or the State of California. The Energy Commission, the State of California, its employees, contractors and subcontractors make no warrant, express or implied, and assume no legal liability for the information in this report; nor does any party represent that the uses of this information will not infringe upon privately owned rights. This report has not been approved or disapproved by the California Energy Commission nor has the California Energy Commission passed upon the accuracy or adequacy of the information in this report.

Acknowledgments

Thanks to Alexander Gershunov and Emelia Bainto for assistance in retrieving and processing Summary of the Day (SOD) data, and to Kelly Redmond for feedback and advice concerning Coastal Ocean Observations Panel (COOP) observations. Support for Noah Knowles came from the National Research Council Research Associateship Program at the United States Geological Survey (USGS) and the CALFED Ecosystem Restoration Program. Support for Dan Cayan was from the National Oceanic and Atmospheric Administration (NOAA) Office of Global Programs through the California Applications Program, the Department of Energy, and the California Energy Commission's Public Interest Energy Research Program (PIER) through the California Climate Change Center at Scripps Institution of Oceanography. Michael Dettinger's support was from the USGS Hydroclimatology Program and PIER.

Please cite this report as follows:

Knowles, N., M. Dettinger, and D. Cayan. 2007. *Trends in Snowfall Versus Rainfall for the Western United States, 1949–2001.* California Energy Commission, PIER Energy-Related Environmental Research Program. CEC-500-2007-032.

Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Energy Commission), conducts public interest research, development, and demonstration (RD&D) projects to benefit California's electricity and natural gas ratepayers. The PIER Program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

In 2003, the California Energy Commission's Public Interest Energy Research (PIER) Program established the **California Climate Change Center** to document climate change research relevant to the states. This Center is a virtual organization with core research activities at Scripps Institution of Oceanography and the University of California, Berkeley, complemented by efforts at other research institutions. Priority research areas defined in PIER's five-year Climate Change Research Plan are: monitoring, analysis, and modeling of climate; analysis of options to reduce greenhouse gas emissions; assessment of physical impacts and of adaptation strategies; and analysis of the economic consequences of both climate change impacts and the efforts designed to reduce emissions.

The California Climate Change Center Report Series details ongoing Center-sponsored research. As interim project results, the information contained in these reports may change; authors should be contacted for the most recent project results. By providing ready access to this timely research, the Center seeks to inform the public and expand dissemination of climate change information; thereby leveraging collaborative efforts and increasing the benefits of this research to California's citizens, environment, and economy.

Trends in Snowfall Versus Rainfall for the Western United States, 1949–2001 is the final report for the Climatic Data Collection, Analyses, and Modeling project (contract number 500-02-004, work authorization number MR-025) conducted by the United States Geological Survey and Scripps Institution of Oceanography.

For more information on the PIER Program, please visit the Energy Commission's website www.energy.ca.gov/pier/ or contract the Energy Commission at (916) 654-5164.

Table of Contents

Preface iv
Abstract viii
Executive Summary 1
1.0 Introduction 3
2.0 Data and Methods 5
3.0 Results 9
3.1. Seasonal SFE/P Trends 9
3.2. Temperature Dependence 12
3.3. Elevation Dependence 15
3.4. Monthly Patterns 17
4.0 Conclusions 23
5.0 References 25
6.0 Glossary 27

List of Figures

Figure 1. (a) Winter (Nov–Mar) SFE/P trends: Symbol size 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 (WY) 2001 winter SFE/P vs. WY 1949 winter SFE/P, with highly significant SFE/P trends highlighted. Dashed line is least-squares fit to all data points. 9

Figure 2. (a) Mean winter (Nov–Mar) SFE/P values, and (b) Station elevations 10

Figure 3. Trends in winter (a) P, and (b) SFE. Significance of trends is shown by circles and squares as in Figure 1a. 10

Figure 4. (a) 1949–2001 changes in winter SFE/P versus changes in winter P. Stations with significant ($p < 0.05$) trends in both SFE/P and P are indicated with squares. (b) Changes in SFE/P) vs. changes in P. (c) Changes in SFE vs. changes in P. 11

Figure 5. Same as Figure 4c but with symbols determined instead 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. 12

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. 13

Figure 7. (a) Trends in SFE/P vs. trends in TMINw, with significant trends in SFE/P ($p < 0.05$) highlighted as squares. (b) Trends in P vs. trends in TMINw, significant P trends highlighted. (c) Trends in SFE vs. trends in TMINw, significant SFE trends highlighted. ... 14

Figure 8. Precipitation-adjusted trends in SFE vs. trends in TMINw, with significant ($p < 0.05$) SFE trends highlighted 14

Figure 9. (a) Precipitation-adjusted SFE trends vs. winter mean TMINw. (b) TMINw trends vs. winter mean TMINw 15

Figure 10. (a) Trends in TMINw vs. elevation, with $p < 0.05$ trends highlighted, (b) Long-term mean TMINw vs. elevation. In both plots, Montana and Wyoming Great Plains stations are indicated with different symbols and lighter coloring. 16

Figure 11. (a) Precipitation trends vs. elevation, (b) SFE trends vs. elevation. Significant ($p < 0.05$) trends are highlighted. 16

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, and (b) P-adjusted SFE trends (SFE trends due to temperature changes) versus elevation.. 17

Figure 13. Monthly trend magnitudes for SFE/P 18

Figure 14. Monthly trend magnitudes for TMINw 19

Figure 15. Precipitation-adjusted SFE changes vs. mean TMINw for January and March 20

Abstract

The water resources of the western United States depend heavily on snowpack to store part of wintertime precipitation into the drier spring and summer months. A well-documented shift towards earlier runoff can be 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 1949–2001 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 (but still predominantly reductions) in the Rockies. The trends in this ratio correspond to shifts toward less SFE rather than to changes in overall precipitation, except in the Southern Rockies, where both snowfall and precipitation have increased.

The trends toward reduced snowfall water equivalent are a response to warming across the region, with the most significant reductions occurring where winter-average wet-day minimum temperature changes have been less than +3°C over the course of the study period. Warming of this (limited) magnitude has occurred primarily at warmer, lower elevation stations where precipitation form is particularly sensitive to warming. Stations at altitudes above about 1800 meters have colder, less vulnerable mean conditions and have not exhibited SFE responses, despite greater warming of greater than +3°C at many of these higher altitude stations.

At the monthly scale, the trends toward reduced snowfall water equivalent/precipitation are most pronounced in March regionwide and near the west coast in January. These monthly trends correspond to the observed seasonality of warming trends in wet-day temperatures during the same period, with widespread warming in January and March. Mean temperatures were colder in January at higher elevations, restricting snowfall water equivalent/precipitation impacts to the lower elevations near the west coast; whereas warmer mean temperatures in March enabled the warming to produce broad SFE/P declines.

Keyword: Climate change and California, precipitation trends. rain and snow trends, rainfall and climate, regional climate change impacts

Executive Summary

Introduction

Water systems in California and much of the western United States rely on winter snowpack to provide water in the drier months, as the snow melts in the higher elevations. However, studies have documented a shift toward earlier runoff in the western states, which could result in shrinking water supplies in the late summer months. Two potential causes for this trend have been identified: (1) more precipitation falling as rain instead of snow, and (2) earlier and/or faster snowmelt. Both situations result in more water during wet spring months when it is least needed.

Purpose

This study's purpose was to determine if there has been a change in the fraction of precipitation falling as rain instead of snow.

Project Objective

Specifically, this study's objective was to document the regional trend during 1949–2001 toward smaller ratios of winter snowfall water equivalent (SFE) to winter precipitation (P). *Snowfall water equivalent* is the amount of water present in the snow.

Project Outcomes

The Sierra Nevada and the Pacific Northwest have shown the most pronounced reductions in the SFE/P ratio. The Rocky Mountains have shown more varied changes (but still predominantly reductions). The trends in this ratio correspond to shifts toward less SFE rather than to overall precipitation changes, except in the Southern Rockies, where both snowfall and precipitation have increased.

Conclusions

The trends toward reduced SFE are a response to warming across the region of study. The most significant reductions have occurred where winter-average wet-day minimum temperature changes have been less than +5.4°F during the 1949–2001 study period. This magnitude of warming has occurred mostly at warmer, lower-elevation weather stations, where the form of precipitation (that is, snow or rain) is particularly sensitive to warming. Stations at altitudes above about 5900 feet have colder, less vulnerable mean conditions and have not exhibited changes in SFE—even at stations that have experienced warming greater than +3°C.

Trends toward reduced SFE/P are the most pronounced in March regionwide and near the west coast in January. These monthly trends correspond to the observed seasonality of warming trends in wet-day temperatures during the same period, with widespread warming in January and March. 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 enabled the warming to produce broad SFE/P declines.

Recommendations

This study should be updated periodically to determine if the reported trend continues, as expected with a warming climate.

Benefits to California

The documentation that more of the precipitation in California is falling as rain instead of snow has enormous water management implications. This project has alerted water managers about the need to plan for potentially reduced runoff levels in the spring and summer seasons.

1.0 Introduction

Some of the most common, and common-sense, projections of the impact of global warming on the western United States are changes that reduce the volumes and persistence of snowpack across the region (e.g., Gleick 1987; Lettenmeier and Gan 1990; Dettinger et al. 2004; Knowles and Cayan 2004; Stewart et al. 2004). The primary warming-induced changes that might reduce western snowpacks are reductions in the fraction of precipitation that falls as snow rather than rain, and accelerations of the rates or timing of snowmelt once snowpacks have formed.

In this context, observations from across much of the mountainous western United States and Canada indicate an alarming tendency for runoff 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). 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 rather than snow 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 need to be assessed.

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 broad wintertime maxima of snowfall and precipitation in general in the region, trends in the contribution 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) are more sensitive to springtime (March–May) temperatures across much of the region. Thus the processes controlling snow deposition and snowmelt may be subject to different warming trends, and trends in these processes may be distinguished by differences in their progress and patterns. Much work has been accomplished to map trends in the latter (snowmelt responses); this study documents a parallel set of trends that have changed the relative contributions of snowfall to western precipitation.

2.0 Data and Methods

Historical Summary of the Day (SOD) observations from cooperative weather stations in the 11 westernmost states of the conterminous United States (Figure 1a) were obtained from the National Climatic Data Center (NCDC) for the present study. The observations comprise daily snowfall depth, precipitation (P, regardless of form), maximum (TMAX), and minimum (TMIN) surface air temperature, from October 1948 to September 2001. 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 United States, 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 discarded.
3. Any station at which the mean annual snowfall total (described here by the annual sums of daily snowfall water equivalents—SFE, described below) was less than 50 millimeters (mm) was discarded.

This study focused on a winter season, defined here as November–March, because, on average over all the stations, 80% of snowy days occurred during that season. The analyses below were repeated using the period October–May, which accounted for 98% of snowfall, which included greater than 90% of every station's snow. 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 the pair TMAX and TMIN. These criteria ensure that the data analyzed here are sufficiently complete so 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 224 stations with precipitation and snowfall data, and 647 temperature stations. Both sets of data were retained at 173 stations. The analyses presented here used the largest appropriate data set in each case—that is, data from all 647 stations were used for temperature analysis, but joint analysis of temperature and precipitation only used data from 173 stations).

To 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 three days in Step 1 and 25% in Step 2. In both cases, the conclusions of this analysis were unchanged, albeit with fewer data points.

The precipitation and snowfall depth (S) data that remained after the criteria above were applied were also examined for overabundances of integer values of the ratio S/P, which could indicate the use by cooperators of fixed snowfall-depth-to-precipitation conversions (Kunkel et al. 2005) instead of the mandated practice of melting the snow to determine liquid precipitation amount P. The most frequently reported integer ratio was 10, which was reported (within a roundoff tolerance of 0.05) on an average of 0.42% of snowy days, followed by 20 on 0.07% of the snowy days. The station with the largest fraction of snowy days (with S/P = 10) was a site in Wyoming where such ratios were reported 6.7% of the time. Repeating the analysis presented below after removing stations with significant trends in the number of winter days for which S/P ≈ 10 resulted in no substantial changes to this study's conclusions. Finally, repeating the analysis without the "Great Plains bulge" stations (described in Section 3.2) did not change the findings of this paper.

Daily SFE (the liquid water equivalent of snowfall accumulated each day, not to be confused with SWE, the water equivalent of the season-to-date's accumulated snowpack) was defined, for the present analysis, as being equal to the total precipitation measured on a day when snowfall was reported. While this definition can overstate the amount of precipitation as snowfall (since precipitation on many days is a mixture of snow and rain), it also avoids giving too much credence to the reported snowfall amounts, which are notoriously unreliable and observer-dependent. Additionally, overestimation of SFE/P on mixed-form days will tend to yield underestimates of the contributions 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 toward less snowfall (as a fraction of total precipitation).

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, and 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 53-year study period. In the rare cases when the linear fits gave 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 United States, 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.

3.0 Results

3.1. Seasonal SFE/P Trends

The SFE/P ratio trended towards smaller values over the course of water years 1949–2001 at 155 (69%) of the 224 SOD sites analyzed (Figure 1a) and increased at the remainder (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 62 sites (77%) and increased at only 18. 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 2001 and 1949 intercepts of the linear fits to the 53-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 stations with smaller initial SFE/P ratios are reduced by a larger percentage than stations with high initial SFE/P ratios. According to the linear fit, stations with initial SFE/P ratios of 0.1 had SFE reductions of 73%, while stations with initial ratios of 1.0 had an average reduction of 4%. Averaged over all stations, the average reduction in SFE/P is 13%, and averaged over stations with significant SFE/P trends, the average reduction is 26%.

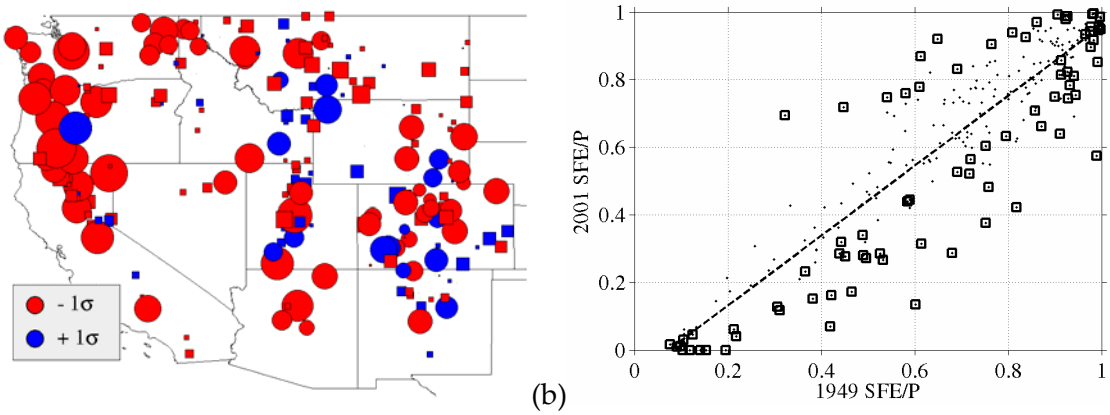
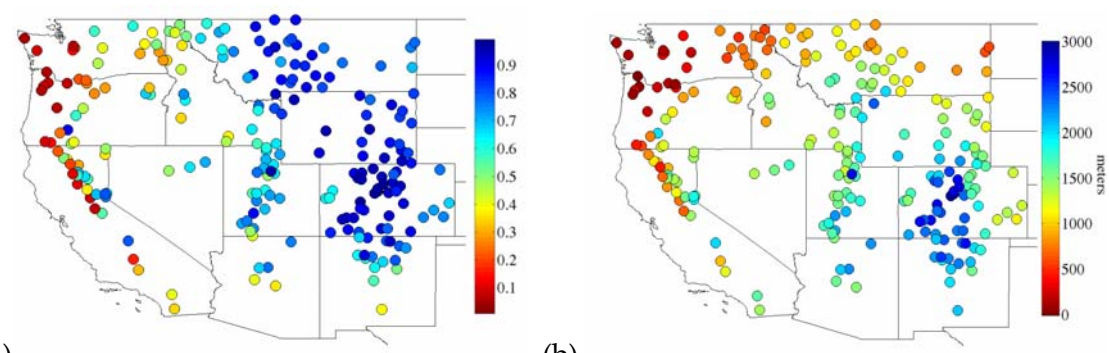


Figure 1. (a) Winter (Nov–Mar) SFE/P trends: Symbol size is proportional to study-period changes, measured in standard deviations as indicated; circles indicate high trend significance ($p < 0.05$), squares indicate lower trend significance ($p > 0.05$). (b) Water year (WY) 2001 winter SFE/P vs. WY 1949 winter SFE/P, with highly significant SFE/P trends highlighted. Dashed line is least-squares fit to all data points.

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

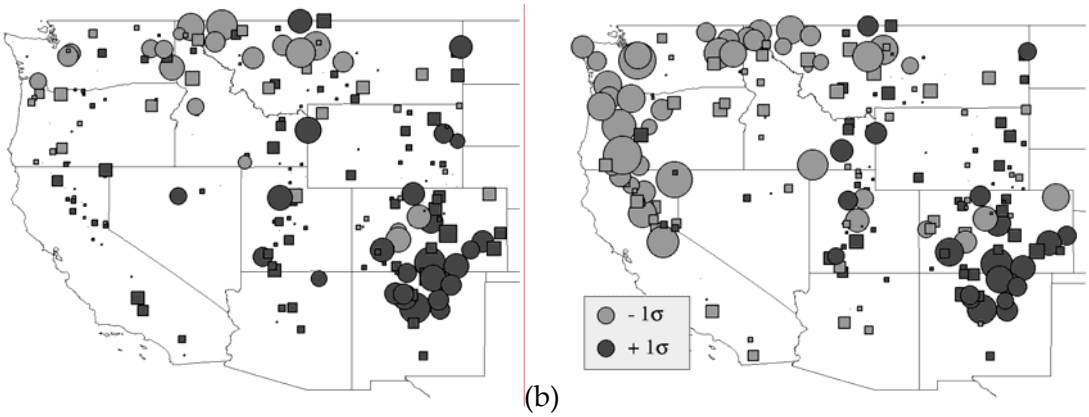
warmer in winter; whereas nearly all precipitation in the higher, cooler interior Rockies is snow. Elevation relationships are discussed more in Section 3.3.



(a) (b)

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

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 over the spatial domain and do not generally concur with the widespread pattern of SFE/P declines. Of the 47 sites with significant trends, 18 also had significant trends in SFE/P, 13 of which trended in the same direction for both SFE/P and P. In contrast, changes in SFE (Figure 3b) more closely echo the pattern of SFE/P trends in Figure 1a. Significant SFE trends were observed in 65 sites, 40 of which also had significant trends in SFE/P; 39 of these trended in the same direction. The primary area of disagreement between the SFE trends and the SFE/P trends is in the southeastern portion of the study region, the southern Rockies. There, trends toward higher SFE appear to be responses to increases in P. Because the increases in SFE have not kept pace (at many sites) with P, the SFE/P ratios generally decreased, though some increasing trends are also evident. Trends toward smaller S/P ratios in New England have similarly been shown to reflect SFE declines rather than P trends (Huntington et al. 2004).



(a) (b)

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

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, trend pairs in which both trends were highly significant are plotted as squares. Aside from several sites that report very large reductions in P, trends in SFE/P have not been well-correlated with trends in P. Positive trends in SFE have generally coincided with positive trends in SFE/P, and negative trends in SFE with negative trends in SFE/P, although the relation is not simple or linear. Where both P and SFE have trended significantly, the two trends have been essentially equal in nearly all significant cases. Overall, while trends in SFE/P and P are quite strongly correlated with the trends in SFE ($r=0.46$, $p \ll 0.01$, and $r=0.65$, $p \ll 0.01$, respectively), the relationship between the trends in SFE/P and P is ambiguous ($r=0.07$, $p=0.26$).

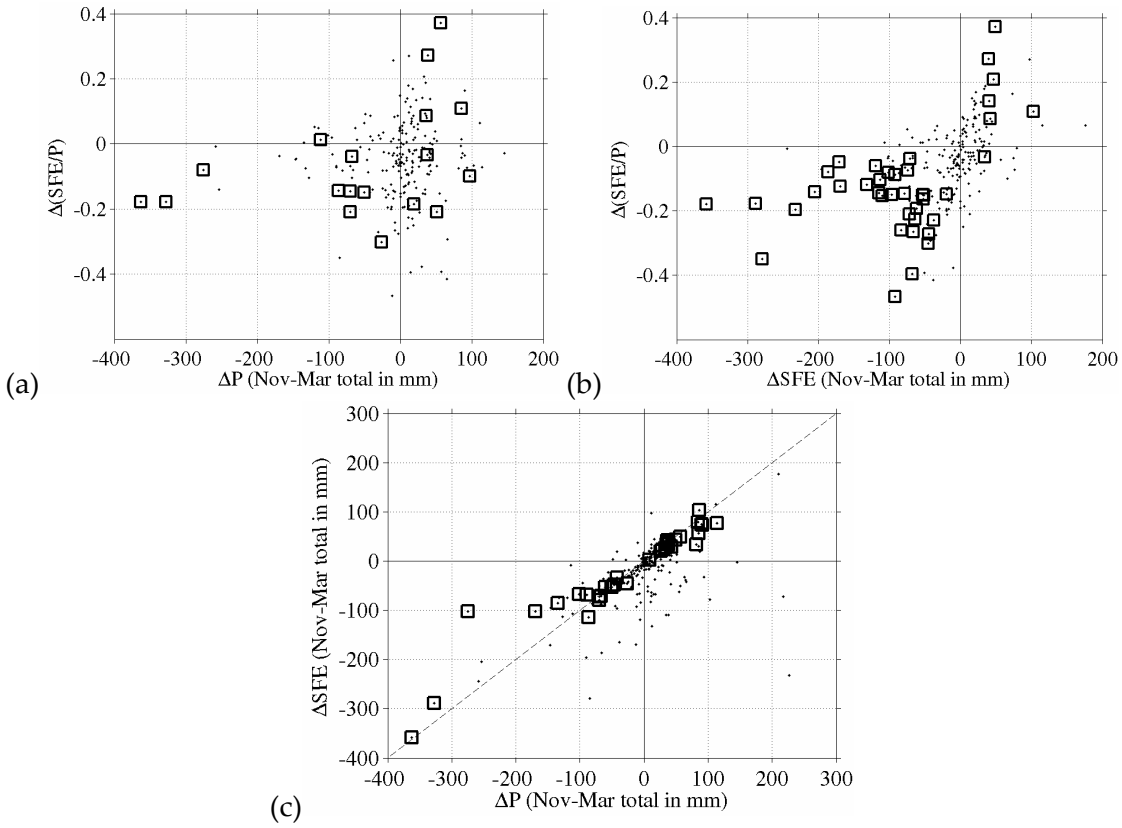


Figure 4. (a) 1949–2001 changes in winter SFE/P versus changes in winter P. Stations with significant ($p < 0.05$) trends in both SFE/P and P are indicated with squares. (b) Changes in SFE/P) vs. changes in P. (c) Changes in SFE vs. changes in P.

The trends indicated with heavy squares in the three panels of Figure 4 are not necessarily the same stations in each case. There are cases in Figure 4c that do not have jointly significant SFE and P trends but do correspond to significant trends in the ratio SFE/P in the other panels. In particular, cases in which SFE and P trend in opposite directions can produce significant SFE/P trends even if the individual trends are not

both significant. As a consequence, the strong correlation between SFE and P trends shown in Figure 4c need not (and does not) translate into equally strong relations with SFE/P trends 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 occur for many "off-axis" SFE and P trend pairs that lacked the jointly significant SFE and P trends indicated in Figure 4c. In particular, many stations with SFE reductions and P increases yielded strong, decreasing SFE/P trends, despite the relative weakness of the individual SFE or P trends.

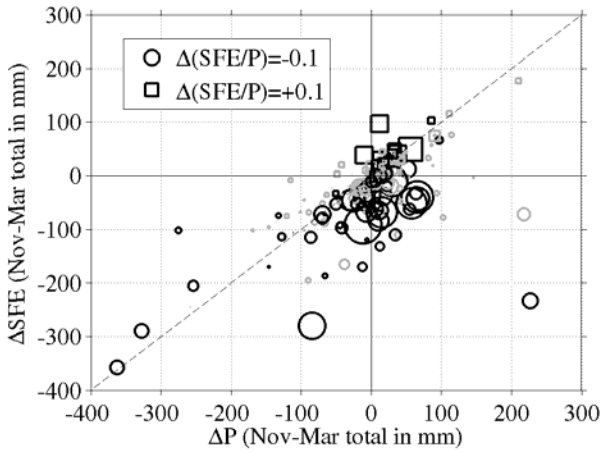


Figure 5. Same as Figure 4c but with symbols determined instead by the corresponding changes in winter SFE/P. Circles indicate decreasing SFE/P and squares are increasing SFE/P, with significant ($p < 0.05$) SFE/P trends in black.

3.2. Temperature Dependence

Several studies have linked declining snowpacks and earlier runoffs in the West with 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 demonstrates that warming has also diminished 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- (TMINw) and maximum-daily (TMAXw) temperatures. Wet-day TMINs have generally warmed more than have TMAXs, with average (over all western U.S. stations) 1949–2001 increases of +1.4ºC and +1.0ºC, 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 TMINw.

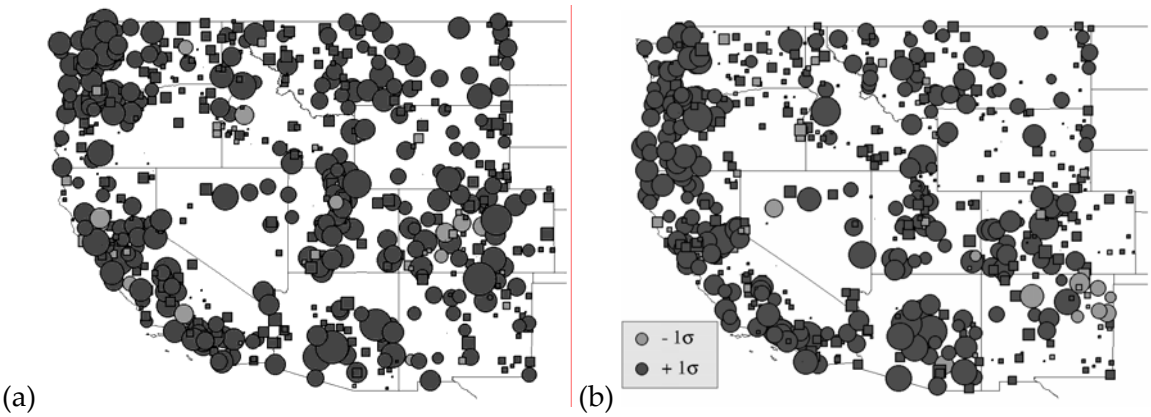


Figure 6. (a) Trends in winter-mean daily-minimum wet-day air temperatures, (b) Trends in winter-mean daily-maximum wet-day air temperatures. Circles and squares indicate significance, as in Figure 1a.

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

The relationships between P trends and TMINw trends, and between SFE trends and TMINw trends, are shown in figures 7b–c. Due to the strong correlation between the P and SFE trends (Figure 4c), these figures are similar. Some stations with moderate TMINw trends have experienced reductions in SFE; whereas others such stations have experienced SFE increases. Notably, at stations where TMINw has warmed more than about +3ºC, SFE has trended relatively little (increasing in most cases).

To distinguish between the effects on SFE (and hence on SFE/P) of changing P totals and changing TMINw, Figure 8 shows an analog of Figure 7c, with the difference that, in Figure 8, the trends in SFE have been adjusted to remove the influence of the trend in P at each site. This was accomplished by subtracting the expected effect of precipitation trends from the overall SFE trend magnitude at each station, with that expected contribution estimated as the product of the P trend magnitude and the long-term mean of SFE/P. The remainder is assumed to be the part of the SFE trend due to temperature changes. The assumption that changes in SFE due to trends in P and TMINw are additive is an oversimplification, but, as will be seen, it is a useful one.

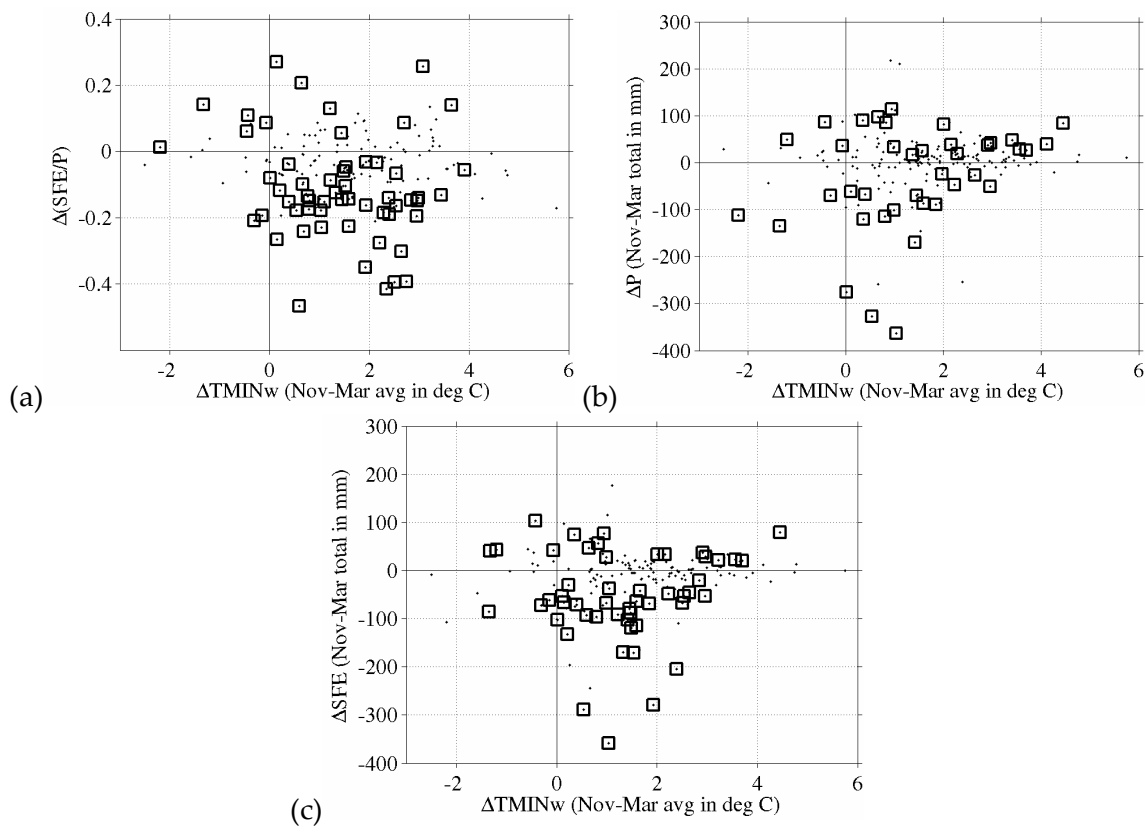


Figure 7. (a) Trends in SFE/P vs. trends in TMINw, with significant trends in SFE/P ($p < 0.05$) highlighted as squares. (b) Trends in P vs. trends in TMINw, significant P trends highlighted. (c) Trends in SFE vs. trends in TMINw, significant SFE trends highlighted.

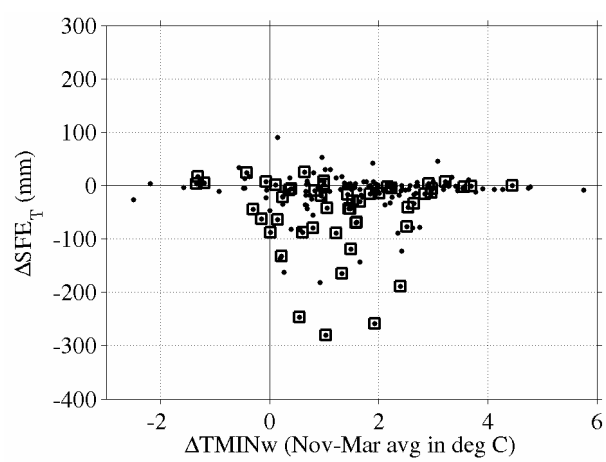


Figure 8. Precipitation-adjusted trends in SFE vs. trends in TMINw, with significant ($p < 0.05$) SFE trends highlighted

Once adjusted for the P trends, it is even clearer than in Figure 7c that the most significant reductions in SFE have been at sites that have experienced moderate TMINw warming (< 3ºC) (Figure 8). Stations with roughly the same range of temperature trends were also associated with the most significant reductions in SFE/P (Figure 7a). The reason that these temperature changes resulted in the largest SFE (and SFE/P) declines is clear when viewed another way: Figure 9a plots the P-adjusted SFE trends against long-term mean TMINw values at each site. The largest SFE reductions occurred at relatively warm locations (TMINw > -5ºC), where temperatures were closer to freezing and warming by even a few degrees was enough to have an impact.

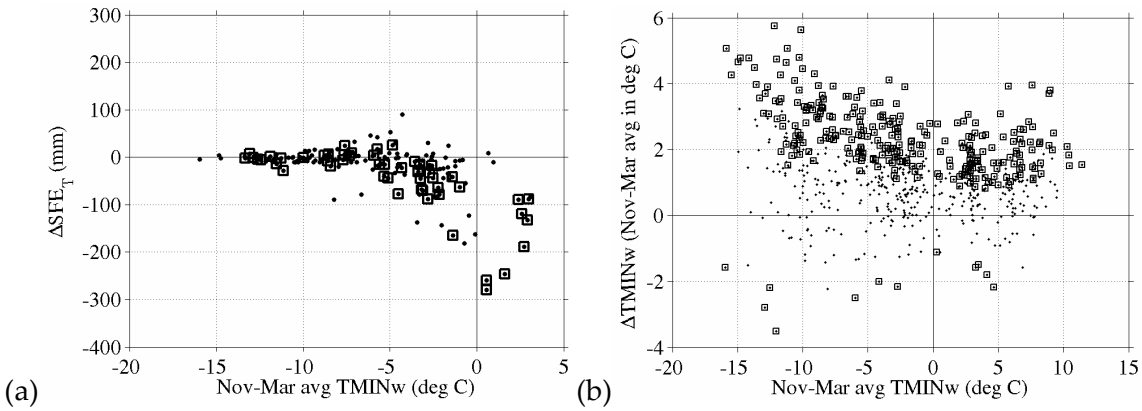


Figure 9. (a) Precipitation-adjusted SFE trends vs. winter mean TMINw. (b) TMINw trends vs. winter mean TMINw.

The relationship between TMINw trends and the long-term mean wet-day winter temperatures (Figure 9b) offers an explanation for another notable feature of Figure 8, the very small P-adjusted SFE trends at sites where the TMINw warming has been greater than +3ºC. Stations that have warmed this much are generally among the coldest stations with long-term mean TMINw values less than -5ºC. In these cold settings, even the largest warmings in the West, more than +4ºC, were not enough to cause significant SFE reductions.

Geographically, these larger warmings (> +3ºC) have occurred at a broad range of elevations and throughout the interior West, but have been especially prevalent in the Great Plains of Montana and Wyoming. In Figure 4c, these stations tend to cluster around the one-to-one line. Stations that have warmed less are more widely scattered in that plot.

3.3. Elevation Dependence

The relationships with mean TMINw in Figure 9 generally reflect differences with respect to elevation. Figure 10a shows that warming has tended to increase with elevation, while Figure 10b shows the decrease of mean TMINw with elevation. The main exceptions are bulges around 500–1000 meters (m) 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 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) are r=0.08 (p=0.05) when all stations are considered and r=0.15 (p=0.01) when only stations with significant ($p < 0.05$) trends in TMINw are included. When the northern Great Plains stations left out, the correlations are r=0.09 (p=0.02) and r=0.18 (p=0.004), respectively.

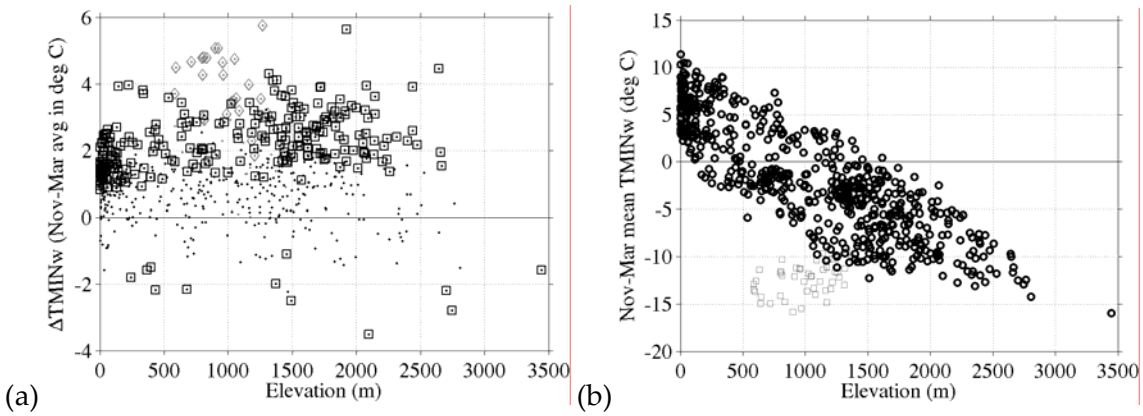


Figure 10. (a) Trends in TMINw vs. elevation, with $p < 0.05$ trends highlighted, (b) Long-term mean TMINw vs. elevation. In both plots, Montana and Wyoming Great Plains stations are indicated with different symbols and lighter coloring.

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

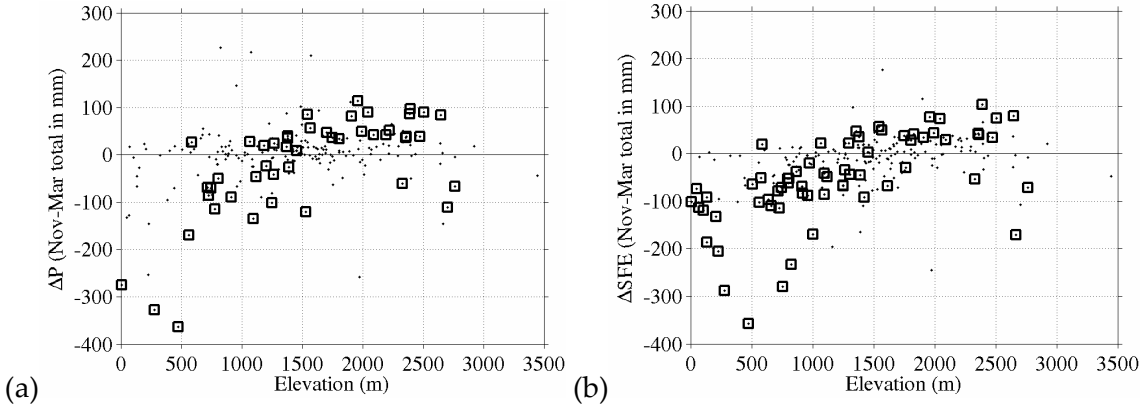


Figure 11. (a) Precipitation trends vs. elevation, (b) SFE trends vs. elevation. Significant ($p < 0.05$) trends are highlighted.

As with Figure 7c, Figure 11b can be adjusted to isolate the changes in SFE due to TMINw trends by subtracting 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 1500 m have contributed to reductions in SFE, and increases in P at higher elevations have been responsible for SFE increases at higher elevations, much larger SFE declines have been associated with the warming below about 1500 m. The largest reductions in snowfall due to warming occurred at the lower, warmer elevations, where moderate temperature changes had a significant impact. Above approximately 1800 m, essentially no change in snow deposition has occurred as a result of warming, despite greater warming at those elevations (Figure 10a). Above about 1800m, SFE changes are essentially all attributable to changes in P.

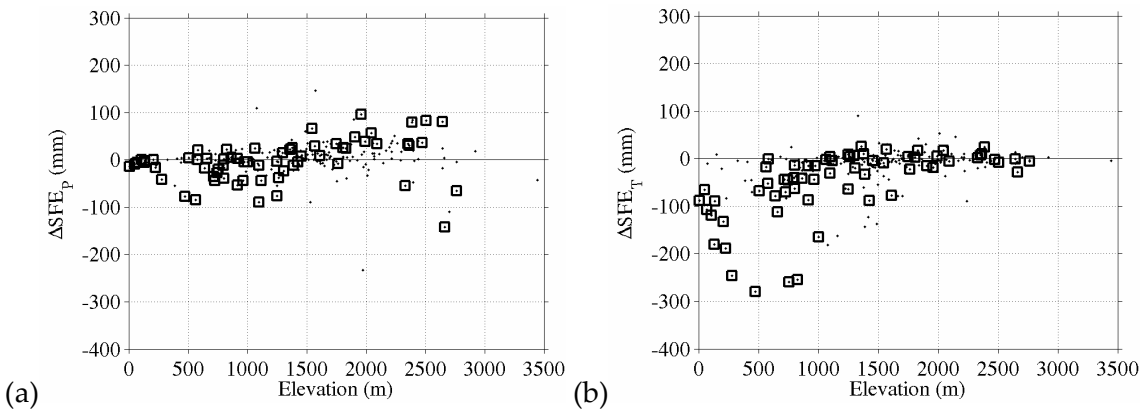


Figure 12. (a) Products of the P trend magnitudes and long-term mean SFE/P ratios, versus elevation, with stations where SFE trends are significantly different from zero highlighted, and (b) P-adjusted SFE trends (SFE trends due to temperature changes) versus elevation

3.4. Monthly Patterns

Plotting trend magnitudes for SFE/P by month (Figure 13) reveals that the most widespread declines in snowfall fractions have occurred in March, across the entire western United States. Important declines in SFE/P have also occurred in January along the West Coast (in stations associated with the Sierra Nevada and Pacific Northwest). 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 trends are of considerable concern.

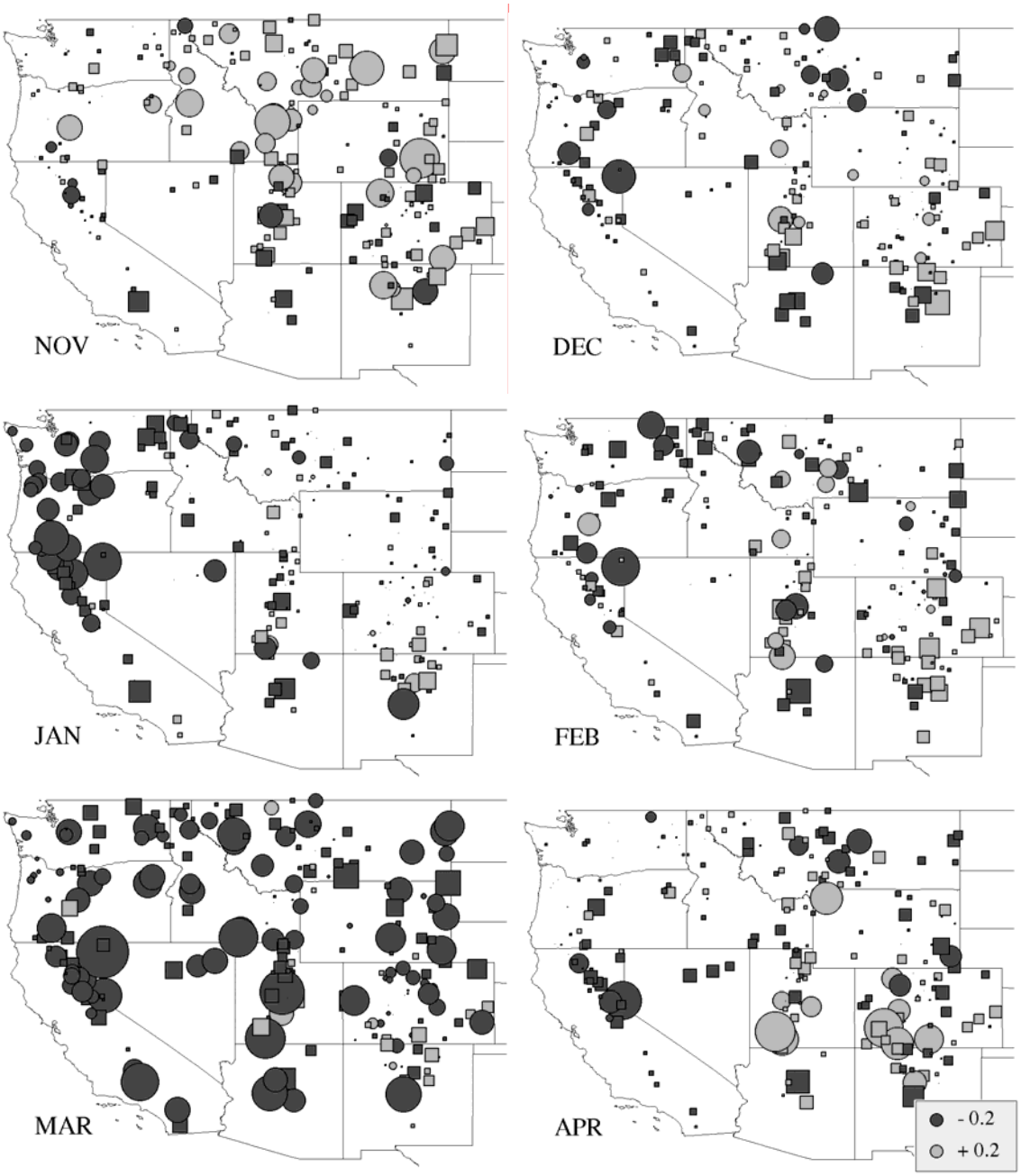


Figure 13. Monthly trend magnitudes for SFE/P

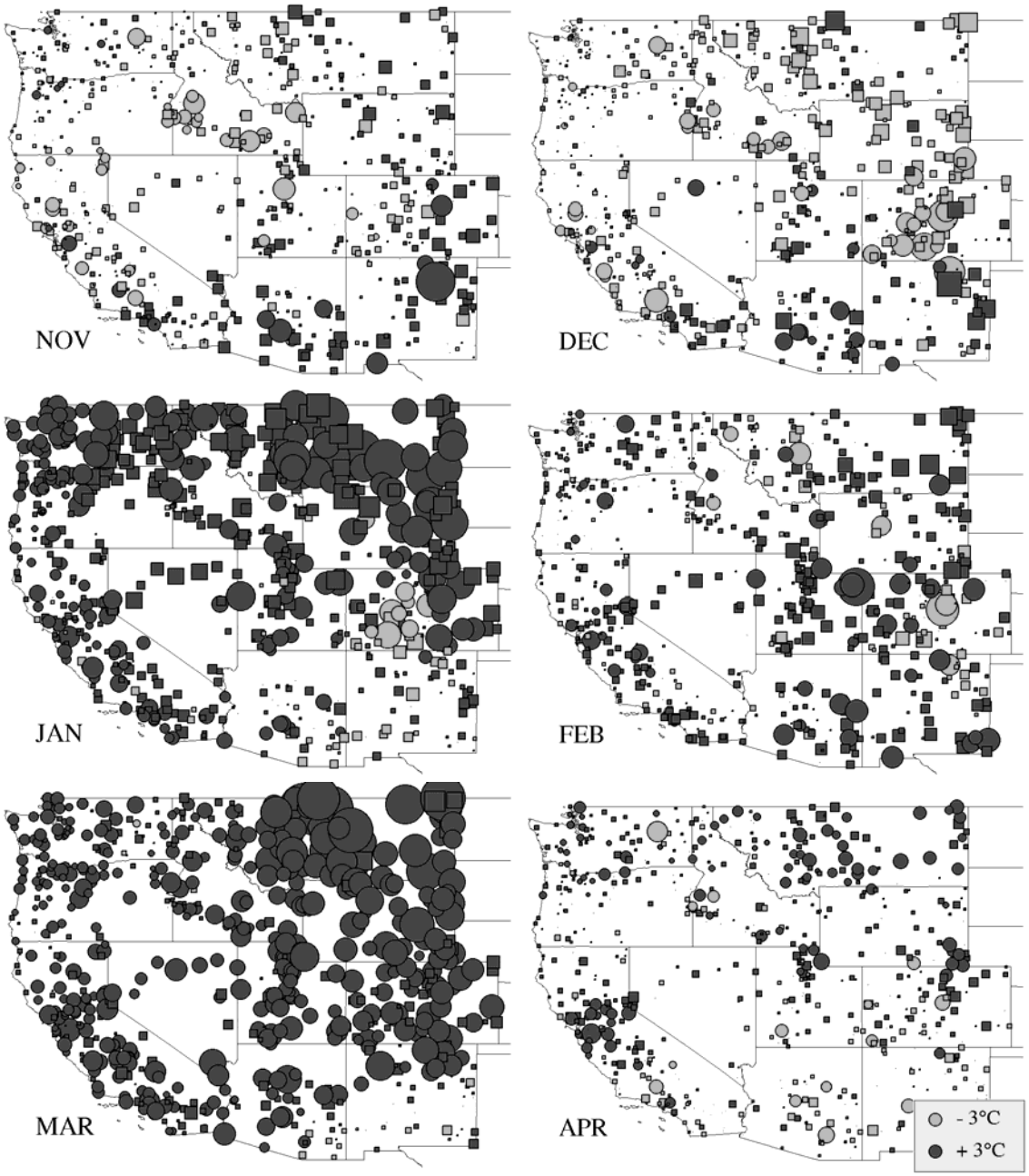


Figure 14. Monthly trend magnitudes for TMINw

The seasonality of the monthly SFE/P trends echoes that of changes in TMINw (Figure 14). In particular, January and March have shown significant warming across the West. Monthly trends in TMAXw were very similar to those in Figure 14, though with weaker trends 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 November and March, 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 varies seasonally, with corresponding influences on the abundance of P-adjusted snowfall declines and the SFE/P trend patterns (Figure 13). Snowfall was present at most stations during all winter months, with a sharp dropoff in spring. On average, the percentage of stations which warmed had peaks in January and March (about 88% and 98%, respectively), and the percentage of stations which were warm enough for warming to have an effect (TMINw > -5°C) reached a minimum of 28% 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 have an effect on SFE (Figure 15). In March, most stations were warm enough for the broad warming to yield broad SFE/P declines.

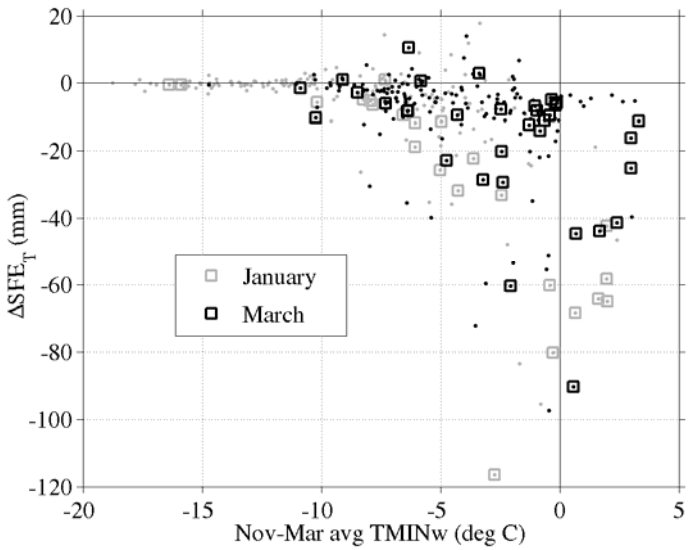


Figure 15. Precipitation-adjusted SFE changes vs. mean TMINw for January and March

However, in addition to the more widespread March trends, the average P-adjusted SFE declines also reflect the fact that west coast stations receive much more P (and, at moderate elevations, more SFE) than the interior stations, with peak P and SFE in January. Averaged over all stations with significant winter SFE trends, the P-adjusted SFE reductions were 17 mm in January and 11 mm in March, with smaller reductions during the other winter months. These reductions amounted, on average, to about 18% and 10%, respectively, of the long-term average winter SFE totals at these sites. Averaged over all stations, the reductions were 9 mm (8% of winter SFE total) in January

and 10 mm (8%) in March. Total winter reductions for stations with significant winter SFE trends averaged 49% of their total winter SFE. Averaged over all stations, the P-adjusted winter SFE reduction was 23%.

4.0 Conclusions

The proportion of winter precipitation that falls as snow has declined throughout most of the western United States during the period 1949–2001. The largest reductions were due to a significant temperature-driven shift from snowfall to rainfall at low to moderate elevations (Figure 12b). Smaller, precipitation-driven snowfall changes have also contributed to more localized increases or decreases in the fraction of precipitation falling as snow, especially at higher elevation stations (Figure 12a). Trends in both precipitation and snowfall amounts exhibit northwest to southeast differences, and have varied with elevation. Care must therefore be taken in interpreting the SFE/P 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. However, warming trends have been strong throughout the West (Figure 6), and the present study shows that the magnitude of (precipitation-adjusted) trends in snowfall amounts have been functions of both the extent of warming and the long-term mean winter temperature at each site (Figures 8 and 9a). Low- to moderate-elevation stations, being relatively warmer than other higher stations, have responded to warming most, even though warming has typically been greater at the higher stations. At the low- to moderate-elevation stations, warming by less than about +3ºC during the study period has been sufficient to reduce the fraction of precipitation that falls as snow. At higher stations, even greater warming has 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 on average than lower stations—almost regardless of geographic setting, in this study—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 may be expected to also be occurring at other such (as-yet undocumented) low- to moderate-elevation settings throughout the West.

If warming trends across the western United States continue, as projected in response to increasing greenhouse-gas emissions at global scales, snowfall amounts are likely to change in a manner suggested by Figure 9a. The warming could act, to first order, as a rightward drift of the stations shown in Figure 9a. When a station's mean winter TMINw rises above about –5ºC, 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 already been warming more quickly than lower stations. This is in agreement with other studies that show increased warming at higher elevations, both historically and in climate change projections. 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 important to accelerations of snowpack melting like those projected by Stewart et al. (2004).

As continued warming brings more of the mean winter wet-day minimum temperatures in the West above about -5ºC, snowfall declines 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 enhances the risk of winter flooding. This combination of increased 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 understandings of how flood risks will change with increasing shifts from snowfall to rainfall, of the atmospheric conditions that control precipitation form, and of possible trends in those conditions are needed to better project and accommodate the changes in store for the West's water supplies.

.

5.0 References

Cayan, D. R., S. A. Kammerdiener, M. D. Dettinger, J. M. Caprio, and D. H. Peterson. 2001. "Changes in the Onset of Spring in the Western United States. *Bull. Am. Met. Soc.* 82, 399-415.

Dettinger, M. D., and D. R. Cayan. 1995. "Large-scale atmospheric forcing of recent trends toward early snowmelt in California." *Journal of Climate* 8(3), 606–623.

Dettinger, M. D., D. R. Cayan, M. K. Meyer, and A. E. Jeton. 2004. "Simulated hydrologic responses to climate variations and change in the Merced, Carson, and American River basins, Sierra Nevada, California, 1900–2099." *Climatic Change* 62, 283–317.

Dettinger, M. D., M. Ghil, and C. L. Keppenne. 1995. "Interannual and interdecadal variability of United States surface-air temperatures, 1910–1987." *Climatic Change* 31, 35–66.

Diaz, H. F., and R. G. Quayle. 1980. "The climate of the United States since 1895—Spatial and temporal changes. *Monthly Weather Review* 108, 249–266.

Easterling, D. R., T. R. Karl, J. H. Lawrimore, and S. A. Del Greco. 1999. *United States Historical Climatology Network Daily Temperature, Precipitation, and Snow Data for 1871–1997.* ORNL/CDIAC-118, NDP-070. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee. 84 pp.

Easterling, D. R., T. R. Karl, E. H. Mason, P. Y. Hughes, and D. P. Bowman. 1996. *United States Historical Climatology Network (U.S. HCN) Monthly Temperature and Precipitation Data.* ORNL/CDIAC-87, NDP-019/R3. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee. 280 pp.

Gleick, P. H. 1987. "The Development and Testing of a Water Balance Model for Climate Change Impact Assessment—Modeling the Sacramento Basin." *Wat. Resour. Res*. 23, 1049–1061.

Hamlet, A. F., P. W. Mote, M. P. Clark, D. P. Lettenmaier. 2005. "Effects of Temperature and Precipitation Variability on Snowpack Trends in the Western United States." *J. of Climate* 18(2), 4545–4561.

Huntington, T. G., G. A. Hodgkins, B. D. Keim, and R. W. Dudley. 2004. "Changes in the Proportion of Precipitation Occurring as Snow in New England (1949–2000)." *J. Climate* 17(13), 2626–2636.

Karl, T. R., H. F. Diaz, and G. Kukla. 1988. "Urbanization—Its detection and effect in the United States climate record." *J. Climate* 1, 1099–1123.

Kendall, M. G. 1938. "A new measure of rank correlation." *Biometrika* 30, 81–93.

Knowles, N., and D. Cayan. 2004. "Elevational Dependence of Projected Hydrologic Changes in the San Francisco Estuary and Watershed." *Climatic Change* 62, 319–336.

Lettenmaier, D. P., and T. Y. Gan. 1990. "Hydrologic Sensitivities of the Sacramento-San Joaquin River Basin, California, to Global Warming." *Wat. Resour. Res*. 26, 69–86.

Mote, P. W. 2003. "Trends in snow water equivalent in the Pacific Northwest and their climatic causes." *Geophysical Research Letters* 30, DOI 10.1029/2003GL0172588.

Mote, P. W., A. F. Hamlet, M. P. Clark, and D. P. Lettenmaier. 2005. "Declining Mountain Snowpack in Western North America." *BAMS* 86(1) 39–49.

Regonda, S., M. P. Clark, B. Rajagopalan, and J. Pitlick. 2005. "Seasonal cycle shifts in Hydroclimatology over the western United States." *Journal of Climate* 18(2), 372–384.

Roos, M. 1991. A Trend of Decreasing Snowmelt Runoff in Northern California. *Proc. 59th Western Snow Conference*, Juneau, Alaska, 29–36.

Stewart, I., D. R. Cayan, and M. D. Dettinger. 2004. "Changes in snowmelt runoff timing in western North America under a 'Business as Usual' climate change scenario." *Climatic Change* 62, 217–232.

Stewart, I. T., D. R. Cayan, M. D. Dettinger. 2005. "Changes towards earlier streamflow timing across western North America." *Journal of Climate* 18(8), 1136–1155.

6.0 Glossary

COOP	Coastal Ocean Observations Panel
HCN	Historical Climatology Network monthly dataset
HCN/D	Historical Climatology Network Daily dataset
m	meter
mm	millimeters
NCDC	National Climatic Data Center
NOAA	National Oceanic and Atmospheric Administration
P	precipitation
S	snowfall depth
SOD	Summary of the Day
TMAX	maximum surface air temperature
TMIN	minimum surface air temperature
USGS	United States Geological Survey