EXTREME SNOWFALL EVENTS IN THE WESTERN UNITED STATES:

VARIABILITY, CHANGE, AND IMPLICATIONS FOR WATER RESOURCE MANAGEMENT

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Abigail C. Lute

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Major Professor: John Abatzoglou, Ph.D.

Authorization to Submit Thesis

This thesis of Abigail Lute, submitted for the degree of Master of Science with a Major in Water Resources and titled "Extreme Snowfall Events in the Western United States: Variability, Change, and Implications for Water Resource Management," has been reviewed in final form. Permission, as indicated by the signatures and dates below, is now granted to submit final copies to the College of Graduate Studies for approval.

Major Professor: ______________________________ Date: ________________
John Abatzoglou, Ph.D.

Committee
Members: ______________________________ Date: ________________
Tim Link, Ph.D.

______________________________ Date: ________________
Peter Goodwin, Ph.D.

Department
Administrator: ______________________________ Date: ________________
Jan Boll, Ph.D.

Dean of the
College of Science: ______________________________ Date: ________________
Paul Joyce, Ph.D.

Final Approval and Acceptance

Dean of the College
of Graduate Studies: ______________________________ Date: ________________
Jie Chen, Ph.D.

Abstract

In the western United States, seasonal snow accumulation largely determines water resource availability. Climate variability and anthropogenic climate change present challenges to water managers who must distribute a highly allocated water supply to satisfy many competing objectives. Extreme snowfall events are found to contribute 20-38% of annual snowfall water equivalent (SFE) and shape nearly 70% of interannual variability in annual SFE on average. Increasing temperatures are projected to decrease the SFE of extreme snowfall events in most locations, although extremes are projected to decline less than small and moderate snowfall events. Fewer snow days and increases in the interannual variability of extreme snowfall events are expected to enhance interannual variability in annual SFE, resulting in less and more variable snowfall in the future. We present a SFE analysis tool that utilizes the strong relationships between annual SFE and extreme events to provide probabilistic guidance for seasonal SFE forecasts.

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Dedication

To the adventurous spirit, to exploring new territory.

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Chapter 1:

Introduction

1. Snow in the West

In the western United States, the bulk of annual precipitation occurs during the winter and falls preferentially in the mountains due to orographic enhancement. In the mountains up to 70% of annual precipitation falls as snow [*Serreze et al.,* 2001], providing natural water storage and delayed release as demand from ecosystems and human institutions increases into the spring and summer. Snowpack and seasonal snowmelt runoff furnish many services on which ecosystems and society depend, including cool water for aquatic species, insulation of temperature sensitive crops, recreation possibilities, and enhanced infiltration and groundwater recharge. Snowpack accumulation and ablation are monitored throughout the winter and spring to inform water management decisions including spring reservoir releases, cropping choices, water supply commitments, and water rights curtailments. Limited and highly allocated water supply must satisfy demands from many competing interests including irrigation, hydropower, and in-stream flows. Year-to-year snowpack variability and the potential impacts of anthropogenic climate change present daunting challenges for water management in this region where the hydrologic cycle is largely snowmelt driven and water resources are highly allocated [*Bales et al.,* 2006].

A substantial portion of annual snowfall occurs in a few heavy snowfall events [*Serreze et al.,* 2001] which may present infrastructure, transportation, and avalanche hazards [*Qui and Nixon,* 2008; *Changnon,* 2007; *Mock and Birkeland*, 2000], in addition to contributing to seasonal water resource availability. *Serreze et al.,* [2001] showed that the single largest snowfall event each year, termed the leading event, accounts for 10-23% of the annual liquid equivalent of snowfall (snowfall water equivalent, SFE). In the Sierra Nevada, *Guan et al.* [2010] found that a few large snowfall events associated with atmospheric rivers contribute 30-40% of annual SFE. Despite their importance to annual SFE, extreme snowfall events have received relatively little attention in the literature and are largely unaccounted for in water resource management and water supply forecasting.

2. Climate Variability

Large interannual variability in annual SFE in a highly allocated system means that water supply does not always meet demand, necessitating difficult prioritization of operational objectives and users. Annual anomalies of April 1 snow water equivalent (SWE), a metric of annual water resources, are often 25-60% of the long-term average across the western U.S., indicating large interannual variability in water resources [e.g., *Cayan,* 1996*; Mote,* 2006]. Snowpack variability is a function of seasonal temperature and precipitation anomalies which have been linked to large-scale modes of climate variability including the El Niño-Southern Oscillation (ENSO), the Pacific North American pattern, and the Pacific Decadal Oscillation [*Cayan,* 1996; *Kunkel and Angel*, 1999; *McCabe and Dettinger,* 2002; *Abatzoglou*, 2011]. More directly, ENSO phase is known to influence the frequency of strong winter cyclones, annual snowfall totals, and the size of leading snowfall events [e.g. *Cayan et al.,* 1999; *Kunkel and Angel,* 1999; *Serreze et al.,* 2001].

At smaller scales, interannual variability in SFE is a function of the frequency and intensity of snowfall events which are linked to variations in winter temperature and precipitation as well as mid-latitude cyclones. Most event-scale research has focused on precipitation rather than snowfall [*Higgins et al*., 2007]. *Serreze et al.* [2001] demonstrated the importance of the leading event to annual SFE; however, they showed that annual SFE was more strongly correlated with number of snowfall days than extreme snowfall events. These findings suggest that extreme snowfall events may play a significant role in shaping annual SFE totals and variability.

A robust analysis of the role of number of snowfall days and extreme snowfall events in determining interannual variability in annual SFE is lacking; the initial analysis by *Serreze et al.* [2001] relied on only 5 to 18 years of data, limiting a thorough analysis of interannual variability in SFE. Linkages between ENSO, the primary determinant of seasonal (> 6 months) hydroclimatic variability, and extreme snowfall events have the potential to further enhance our understanding of interannual variability in SFE. Knowledge of event-scale determinants of annual SFE is particularly relevant to short-term water management decisions which are typically made at cyclical daily to monthly intervals that reflect event-scale developments. A better understanding of the importance of extreme snowfall events to annual SFE anomalies and their relationship to ENSO phase promises to further our understanding of interannual variability in SFE, potentially benefiting hydroclimatic forecasting and water management efforts.

Chapter 2 addresses the gaps in the literature identified above. More specifically, Chapter 2 has five main objectives: 1) to determine the magnitude of interannual variability in annual SFE, 2) to calculate the percent of annual SFE contributed by extreme snowfall events, 3) to identify the relative importance of annual number of snowfall days and extreme snowfall events in shaping interannual variability in annual SFE, 4) to evaluate the portion of interannual variability in annual SFE that can be attributed to extreme snowfall events, and 5) to demonstrate the influence of ENSO phase on extreme snowfall events and number of snowfall days relative to annual SFE anomalies.

3. Climate Change

Significant changes in the hydrologic cycle as a result of anthropogenic climate change have already emerged in the western United States [*Knowles et al.,* 2006; *Mote et al.,* 2005; *Stewart et al.,* 2005]. Declines in April 1 SWE, earlier snowmelt, and earlier peak streamflow have been observed across much of the region [*Mote et al.,* 2005; *Stewart et al.,* 2005] and are expected to become more acute over the next century as rising temperatures continue to decrease the fraction of precipitation falling as snow and increase snowmelt [*Collins et al.,* 2013; *Ashfaq et al.,* 2013; *Pierce and Cayan,* 2013; *Hamlet and Lettenmaier,* 1999]. Precipitation is projected to become more variable both spatially and temporally, with wet regions and seasons generally becoming wetter and dry regions and seasons generally becoming drier [*Held and Soden,* 2006; *Chou et al.,* 2013]. The frequency and intensity of heavy precipitation events are expected to increase at the expense of small and moderate precipitation events, increasing the importance of heavy events to annual precipitation totals [*Trenberth et al.,* 2003; *Trenberth,* 1999; *Allen and Ingram,* 2002; *Wilby and Wigley,* 2002; *Seneviratne et al.,* 2012].

Snow metrics are sensitive to changes in temperature and precipitation, making them interesting, albeit complex, mediums for studying climate change. The response of snow metrics to climate change is projected to be strongly temperature dependent and complicated by large interannual variability in precipitation [*Pierce and Cayan,* 2013; *Ashfaq et al.,* 2013; *Krasting et al.,* 2013]. Nonetheless, drastic declines in April 1 SWE of up to 60% are expected by midcentury for warmer locations including the Cascades [*Ashfaq et al.,* 2013; *Pierce and Cayan,* 2013]. Decreases in snowfall accumulation combined with warmer spring temperatures are projected to result in significantly earlier snowmelt and subsequent runoff, lower summer baseflow, and decreased summer surface runoff [*Ashfaq et al.,* 2013; *Hamlet and Lettenmaier*, 1999; *Stewart et al.,* 2004]. These developments have serious implications for water availability and demand, flood risk, water quality, reservoir capacity, in-stream flows, wildfire potential, agriculture, and water resource management [e.g. *Barnett et al.,* 2004; *Barnett et al.,* 2005; *Westerling et al.,* 2006; *Milly et al.,* 2008; *Brekke et al.,* 2009].

Projections of increased winter temperatures, decreased snowpack, and more extreme precipitation regimes suggest that the impact of climate change on extreme snowfall events may be profound. The importance of extreme snowfall events in shaping both annual SFE and interannual variability in annual SFE (Chapter 2) combined with the potential for significant impacts from climate change and the lack of previous research on this topic motivate the question of how these events will respond to climate change. The ability to predict these changes and their implications for future variability in water supply will be enormously helpful in adapting current management practices to future conditions and in making changes to infrastructure in a timely manner [*Raff et al.,* 2013]. In the only study to consider this question, *López-Moreno et al.* [2011] found that projected changes in heavy snowfall events in the Pyrenees were strongly elevation dependent with decreases in the frequency and intensity of these events at lower elevations and no change or even increases in event frequency and intensity at higher elevations. The response to climate change of extreme snowfall events in the western United States remains to be assessed. Chapter 3 addresses this gap by asking two central questions: 1) how will climate change impact extreme snowfall events, particularly in the context of changes in annual SFE and frequency of snowfall days, and 2) how will changes in extreme snowfall events reinforce or counteract changes in annual SFE and interannual variability of annual SFE.

4. Implications for Water Management

As discussed above, water availability and management in the western United States revolve around snowpack. Snowpack provides natural storage and delayed release of the bulk of annual precipitation, thereby filling reservoir systems so that water can be used when demand increases and precipitation decreases in the dry summer months. Snowpack is carefully monitored throughout the snow accumulation and melt seasons in order to formulate seasonal water supply forecasts which are essential for managing reservoir systems and informing water supply commitments. Water management is challenged by interannual variability in snowpack which necessitates careful orchestration of snowmelt, reservoir releases, year-to-year storage, and prioritization of operational objectives. In Chapter 2 we demonstrate that extreme snowfall events contribute a large portion of annual SFE and explain the majority of annual anomalies in annual SFE. Water management currently does not consider extreme snowfall events in decision making [*Raff et al.,* 2013; *R. Abramovich,* personal communication, January 31, 2014]. Our findings suggest that understanding of extreme snowfall events could provide insight into and enhance forecasting of interannual variability in annual SFE, benefiting water management and those dependent on water resources.

Anthropogenic climate change also has serious implications for water resource infrastructure and management, including potential loss of a large portion of annual water supply due to insufficient reservoir capacity [*Barnett et al.,* 2004; *Barnett et al.,* 2005]. Current water management practices are built on the assumption of stationarity which holds that annual SFE (as well as other hydroclimatic variables) function within the scope of variability that can be estimated from the observational record. It has been argued that this assumption is already invalid and will only become less appropriate with time [*Bates et al.,* 2008; *Milly et al.,* 2008]. Chapter 3 provides insight into projected changes in extreme snowfall events, supporting the conclusion that future extreme snowfall events will include events outside the historic range of variability. These findings can inform water managers' expectations of future change. Furthermore, we posit that a better understanding of the recently *observed* magnitude of extreme snowfall events and the role of these events in shaping interannual variability in annual SFE can improve the ability of water managers to adapt to future climate changes [*Raff et al.,* 2013; *Bates et al.,* 2008].

In light of the joint challenges of climate variability and climate change, we have sought to develop this research into actionable science that could potentially be operational within the institutional decision space of water resource management. The resulting analysis tool uses classical statistical forecasting based on analog annual SFE years and extreme snowfall event occurrence to indicate the likelihood of achieving below-, near-, or above-normal annual SFE and of experiencing additional extreme snowfall events in the remainder of the snow accumulation season. This tool was developed through interactions with a variety of potential users in an ongoing attempt to better address user needs. The concepts behind the tool, the development process, and the tool itself are presented in Chapter 4.

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Chapter 2:

Role of Extreme Snowfall Events in Interannual Variability of Snowfall Accumulation in the Western United States

A. C. Lute and J. T. Abatzoglou

Abstract

Water resources in the western United States are contingent on interannual variations in snowpack. Interannual snowpack variability has been attributed to large-scale climate patterns including the El Niño-Southern Oscillation (ENSO), however the contribution of snowfall frequency and extreme snowfall events to this variability are less well quantified. Long term records from Snowpack Telemetry and Cooperative Observer Program stations in the eleven western states were used to investigate these relationships by considering the number of snowfall days and snowfall water equivalent (SFE) of extreme snowfall events. The top decile of snowfall events contributed 20-38% of annual SFE, depending on the region. An average of 65% and 69% of the interannual variability in annual SFE was explained by snowfall days and SFE of top decile snowfall events, respectively, with extreme events being a more significant predictor at most stations. The latitudinal dipole in SFE during ENSO phases results from changes in snowfall frequency and extreme events. In the Pacific Northwest, above normal SFE during La Niña winters was a product of both larger contributions from extremes and more snowfall days, while below normal SFE during El Niño winters was primarily associated with a substantial reduction in extremes. Conversely, annual SFE during ENSO phases in the mountains of Arizona was more closely linked to fluctuations in snowfall days than extremes. Results indicate the importance of extreme snowfall events in shaping interannual variability in water resources and suggest that improved predictive ability may inform better water resource management now and in the coming decades.

Index terms and Keywords: *snow, climate variability, extreme events, hydroclimatology*

1. Introduction

Interannual variability in water resources presents a challenge to water resource managers in the western United States (U.S.) where water is highly allocated and demand often exceeds supply. Interannual variability in cool-season precipitation is particularly important because the majority of annual precipitation occurs during the winter and preferentially as snow at higher elevations through orographic enhancement [*Dettinger et al.,* 1998]. The accumulation of snow across the elevated watersheds of the western U.S. and its delayed release is essential in synchronizing the asymmetric timing of water supply with demand by ecosystems and consumptive water users [*Bales et al.,* 2006]. For example, the majority of flow in the Colorado and the Columbia Rivers, associated with snowmelt runoff during spring, coincides with increased water demand and seasonal decline in precipitation [*Barnett et al.,* 2005*; Hamlet and Lettenmaier,* 1999]. Observations of mountain snow are used operationally to inform spring reservoir releases and water supply commitments. Likewise, changes in mountain snow are of great concern to water resource managers due to increased water demands by growing populations and water availability challenges posed by climate change.

In contrast to the water content of all fallen snow, or snowfall water equivalent (SFE), snow water equivalent (SWE) is the water content of snow on the ground and provides an integrated measure of accumulation and ablation processes. Annual maximum SWE, or peak SWE, is an indicator of seasonal snowmelt runoff useful for water management applications and is typically calculated as April 1 SWE [*Serreze et al.,* 2001]. Annual anomalies of April 1 SWE are often 25-60% of the long-term average across the western U.S., and are partially attributable to interannual variability in seasonal temperature and precipitation [e.g., *Cayan,* 1996*; Mote,* 2006]. In most of the montane western U.S., winter precipitation exerts the greatest influence on spring SWE [*Cayan*, 1996*; Mote et al.,* 2005*; Mote* 2006]. However, winter temperatures at lower elevations of the Sierra Nevada and Cascades affect the partitioning between rain and snow as well as ablation processes, suggesting that SWE in transient watersheds is more sensitive to temperature [*Mote et al.,* 2005].

The frequent use of April 1 SWE as a surrogate for peak SWE is based on the historical bimonthly collection of snow course measurements. The introduction of widespread daily data from Natural Resources Conservation Service Snowpack Telemetry (SNOTEL) stations in the 1980's helped elucidate the temporally dynamic nature of SWE via both accumulation and ablation processes. Daily data from SNOTEL highlight the rich spatial and temporal variability in the magnitude and timing of peak SWE, particularly in the context of changing snow cover duration and snow melt timing with climate change [*Harpold et al.,* 2012; *Stewart et al.,* 2004]. The separation of accumulation and ablation processes at daily resolution using the distinction between SFE and SWE enables a detailed analysis of snow accumulation characteristics important to snowpack dynamics including peak SWE [*Kumar et al.,* 2012].

Snowfall events, combined with ablation, determine SWE throughout the season and thus water resource availability. The frequency and intensity of snowfall events are a function of joint variability in temperature and precipitation and are mechanistically linked to the frequency and intensity of mid-latitude winter cyclones. Most prior research on how event-scale processes contribute to seasonal and interannual moisture variability has primarily focused on precipitation rather than snowfall [e.g. *Cayan et al.,* 1999]. *Serreze et al.* [2001] showed that the leading, or largest, snowfall event each year contributed an average of 10-23% of annual SFE at SNOTEL stations, with the largest contributions in the southwestern U.S. They also found that annual SFE was more strongly correlated with number of snowfall days than the leading one day event or the event defining the 75th percentile each year. However, the analysis by *Serreze et al.* [2001] relied on stations with only 5 to 18 years of data, thus limiting a full analysis of relationships between snowfall frequency, extreme snowfall events, and interannual variability in SFE.

Large-scale climate patterns, including the El Niño-Southern Oscillation (ENSO), the Pacific Decadal Oscillation, and the Pacific North American pattern have a strong influence on winter temperature and precipitation across the western U.S. [*Cayan,* 1996; *Kunkel and Angel*, 1999; *McCabe and Dettinger,* 2002; *Abatzoglou*, 2011]. ENSO phase has been found to influence the frequency and duration of heavy precipitation events and strong winter cyclones, as well as the number of snowfall days and the size of leading snowfall events [e.g. *Cayan et al.,* 1999; *Kunkel and Angel,* 1999; *Serreze et al.,* 2001; *Higgins et al*., 2007]. While ENSO is often used prognostically in the development of seasonal water supply projections, understanding relationships between ENSO phase and both snowfall frequency and extreme snowfall events may help further our understanding of the seasonal link between ENSO and mountain snow accumulation.

This study seeks to understand the role of snowfall event frequency and intensity in shaping interannual variability in snowpack and water resources across the western U.S. The objectives of this research are 1) to determine the magnitude of interannual variability in annual SFE, 2) to calculate the percent of annual SFE contributed by extreme snowfall events, 3) to identify the relative importance of annual number of snowfall days and extreme snowfall events in shaping interannual variability in annual SFE, 4) to evaluate the portion of interannual variability in annual SFE that can be attributed to extreme snowfall events, and 5) to demonstrate the influence of ENSO phase on extreme snowfall events and number of snowfall days relative to annual SFE anomalies.

2. Data and Methods

Two observational datasets covering the 11 westernmost states in the contiguous U.S. (Figure 2.1) were used: (i) SNOTEL data with records as early as water year 1983 (October 1982-September 1983) through water year 2012, and (ii) National Weather Service Cooperative Observer Program (COOP) data with records as early as water year 1948 through water year 2012. SNOTEL stations are a unique resource for studying montane climate and snow processes as stations are located in high elevation, snow-prone areas and report temperature, precipitation, and SWE using an automated network. The daily SFE at SNOTEL stations was defined as the daily change in SWE. This method may underestimate daily SFE on days when melt is followed by snowfall accumulation. Attempts to correct for this bias involve considerable uncertainty. Conversely, this method may overestimate daily SFE by not accounting for the augmentation of snowpack by precipitation that falls as rain and subsequently freezes in the snowpack and results in positive gains in SWE. To address this, we identified days when SWE increased and minimum temperature was greater than 3.7C (based on *Dai*, [2008]) and eliminated SFE for these days (0.05% of days). COOP stations have a more extensive record, but are located primarily at lower elevations and collect daily temperature, precipitation, snowfall, and snow depth data. While snow accumulation at many COOP stations can affect water resources, it is often more significant for transportation and hazard impacts, therefore results for COOP stations are presented as supplemental material. Since data from COOP stations include only snow depth, but not SWE or snow density, and changes in snowfall measurement practices at COOP stations have been shown to affect long-term records [*Kunkel et al.,* 2007], we used an approach to estimate daily SFE that extends the empirical precipitation phase probability function of *Dai* [2008] to daily time scales using daily mean temperature and daily precipitation amount (see Appendix 1 for details). Resulting daily SFE values estimated at COOP stations less than 2.54mm (the resolution of SNOTEL SFE measurements) were set to 0 for compatibility with SNOTEL data.

SNOTEL and COOP data are subjected to initial quality control procedures by NRCS and the National Climatic Data Center. We conducted subsequent quality control checks for temperature, precipitation and daily SFE to eliminate unrealistic data (outlined in *Serreze et al.* [1999]). This process eliminated 0.15% of temperature observations, 0.14% of precipitation observations, and 0.07% of SFE observations. Stations missing more than 10% of temperature, precipitation, or SFE data during a given cool season (Oct-May) were excluded. We further restricted our analysis to stations with at least 20 years of data meeting aforementioned criteria, and excluded COOP stations with average annual SFE less than 25.4 mm or an average of less than 10 snowfall days per year. These qualifications resulted in 513 SNOTEL stations and 108 COOP stations. Statistics presented in the text with no subscript or subscript S refer to relationships for just SNOTEL stations and statistics with subscript CS refer to relationships for both SNOTEL and COOP stations.

For each station we calculated the total water year (annual) SFE, the coefficient of variation (CV) of annual SFE, the number of snow days, and the CV of the number of snow days. The number of snow days was defined as the number of days per water year at each station with SFE greater than or equal to 2.54mm, the resolution of SNOTEL measurements.

The principle publication on extreme snowfall events in the western U.S. is the work of *Serreze et al.* [2001] who analyzed data from 569 SNOTEL stations with at least five years of data from 1980-1998 to examine the characteristics of extreme snowfall events. Hereafter, we refer to snowfall events as the cumulative SFE over a three-day period as *Serreze et al.* [2001] found that a three-day span comprised 75-89% of snow events in the western U.S. We extended the protocol of *Serreze et al.* [2001] by using nearly twice the length of record of SNOTEL stations and by incorporating low elevation COOP stations. The longer record of SNOTEL stations (requiring at least 20 years of complete data) allows for a more thorough analysis of interannual variability.

While there is no exact definition of a snowfall extreme, studies of extreme weather and climate commonly rely on absolute thresholds, percentiles, or return values (see *Seneviratne*, [2012] for discussion of metrics for extremes). Absolute thresholds (e.g. *Patten et al.,* 2003) are not able to reflect extremes across the range of climates in the western U.S. Instead, percentile based indices, such as the sum of all precipitation events greater than the 90th percentile of precipitation events, are often used in the extreme precipitation literature [see *Peterson et al.,* 2001; *Klein Tank et al.,* 2009]. *Serreze et al.* [2001] examined the largest 3-day SFE accumulation each year, termed the 'leading event'. The present study considers the cumulative SFE each year at each station for three different classes of extreme snowfall events in order to illustrate the sensitivity of results to different metrics: (i) the leading, or largest, event each winter, (ii) the top three non-overlapping events each winter, and (iii) top decile events, defined by the top 10% of snowfall events over the historical record. The first two metrics are annual maximum series that consider a fixed number of events per year while the third is a partial duration series which considers only the most extreme historical events. The number of top decile events each year was between 0 and 5 most years for most stations.

A decomposition of the relationship between interannual SFE, number of snow days, and extreme snowfall events was accomplished using multiple linear regression combined with simple linear regression and semipartial correlation at each station. First, we created three multiple linear regression models (one for each extreme event class) with two predictors ('days': annual number of snow days and 'events': annual sum of extreme snowfall events) and one dependent variable ('SFE': annual SFE) where i is years:

$$SFE(i) = \alpha + \beta(days(i)) + \gamma(events(i)) \tag{1}$$

Second, simple univariate linear regression was performed between annual SFE and number of snow days as well as annual SFE and the size of each extreme event class. Models were evaluated using an F statistic (alpha = 0.05) and t-statistics (alpha = 0.05) for each coefficient in the multiple regression models. The similarity of Pearson and non-parametric Spearman correlations between these variables indicated that the variables were sufficiently linearly related. We calculated squared semipartial correlations indicating the percent of variability in SFE in the full model that is attributable to variability in one predictor after the common variance with the other predictor has been removed. The squared semipartial correlations for number of snow days and for extreme events are sr^2_{days} and sr^2_{events}, respectively. In equation form:

$$sr_{days}^2 = R^2 - r_{SFE,events}^2 \tag{2}$$

$$sr_{events}^2 = R^2 - r_{SFE,days}^2 \tag{3}$$

R^2 and r^2 indicate the regression r-squared values from multivariate and univariate models, respectively.

Although correlation analysis evaluates covariability, it fails to reflect the actual magnitudes of variation of annual SFE and extreme snowfall events. In consideration, the percent of annual SFE anomalies attributable to anomalies in annual cumulative SFE coincident with extreme snowfall events (α) for each event class was calculated using the following equation:

$$\propto = \sum_i^n \frac{\beta_i |E_{anom(i)}|}{|SFE_{anom(i)}|} \times 100 \tag{4}$$

summed over all years (n) where β_i is defined as:

$$\beta_i = \begin{cases} +1 & if\ E_{anom} * SFE_{anom} > 0 \quad \& \quad |E_{anom}| < |SFE_{anom}| \\ \dfrac{SFE_{anom(i)}}{E_{anom(i)}} & if\ E_{anom} * SFE_{anom} > 0 \quad \& \quad |E_{anom}| > |SFE_{anom}| \\ -1 & if\ E_{anom} * SFE_{anom} < 0 \end{cases}$$

Anomalies of annual SFE (SFE_{anom}) and anomalies of cumulative SFE of extreme events (E_{anom}) were computed with respect to their averages over the period of record in units of mm of SFE. Positive contributions to alpha occur for years where E_{anom} and SFE_{anom} are of the same sign, whereas negative contributions to alpha occur for years where E_{anom} and SFE_{anom} are of the opposite sign. The reward for E_{anom} and SFE_{anom} being the same sign was capped at the value of SFE_{anom} to avoiding overestimating the contribution of events.

Winter (Oct-Mar) means of the Multivariate ENSO Index (MEI, *Wolter and Timlin*, [1993]) were computed. El Niño (La Niña) years were defined as years with MEI greater than 1 (less than -1). We calculated the percent change in annual SFE, snowfall days, and cumulative SFE of extremes as the difference between mean quantities for El Niño or La Niña winters versus all other winters, divided by the climatological mean. Changes were only computed for stations that had at least 4 years with MEI exceeding the threshold. Statistically significant differences were determined using two sample t-tests (alpha=0.05).

3. Results

3.1. General Snowpack Characteristics and Variability

Climatological water year SFE accumulations were highest in the Sierra Nevada, Cascades, and Northern Rockies and lowest at the low elevation COOP stations and stations at lower latitudes (Figure 2.2a, 2.S1a). The coefficient of variation (CV) of annual SFE was greatest at lower elevations and in the Sierra Nevada and the southwestern U.S. (defined as Arizona and New Mexico) and lowest along the eastern sections of the Northern Rockies. Average mean winter temperature (Oct-May) and CVs of annual SFE were positively correlated (r_s=0.58, p_s<0.0001; r_{cs}=0.70, p_{cs}<0.0001). This suggests that snowfall accumulation at locations where average winter temperature is above freezing, such as low latitudes and stations in the Cascades, require slight temperature changes to differentiate between rain and snow. While average cumulative winter precipitation was not correlated with CVs of annual SFE, CVs of cumulative winter precipitation were correlated with CVs of annual SFE (r_s=0.73, p_s<0.0001; r_{cs}=0.64, p_s<0.0001), most notably for stations with average winter temperature below -2˚C.

The greatest number of days with snowfall occurred at high elevations and high latitudes (Figure 2.2b, 2.S1b) where cooler winter temperatures maximize the percent of precipitation falling as snow and winter cyclones are more frequent [*Changnon et al.,* 1995]. The fewest number of days with snowfall were found at low elevations and lower latitudes where higher winter temperatures decrease the fraction of precipitation falling as snow and winter cyclones are less frequent. The spatial pattern of the CV of snow days was similar to that of annual SFE. The least variability in number of snow days was found at locations with the greatest number of snow days.

3.2. Magnitude of Extreme Snowfall Events

The Sierra Nevada, Cascades, and Northern Rockies, the areas of greatest annual SFE, experienced the largest leading events whereas the high elevation interior and low elevation COOP sites experienced the smallest leading events (Figure 2.3, 2.S2). The sum of the top three events each year adhered to a spatial pattern similar to the leading event and was 2 to 2.6 times the magnitude of the leading event. The sum of top decile events each year was between 2 and 4 times the size of the leading event for most stations. Regions with fewer snow days (such as low elevations) generally had smaller differences between the leading event, the top three events, and the top decile events, indicating greater relative size of the leading event.

One measure of the relative importance of extreme snowfall events to annual SFE and water resources is the percent of annual SFE contributed by these events (Figure 2.4, 2.S3). Similar to the results of *Serreze et al.* [2001], leading events at SNOTEL stations in the interior contributed 6-17% of annual SFE, although at lower elevation COOP stations we found greater contributions (up to 43%). There was a strong negative correlation between the average number of snow days and average percent contribution by the leading event (r_s = -0.80, p_s < 0.0001; r_{sc}=-0.86, p_{sc}<0.0001). For example, the leading event contributed 6-14% of annual SFE at SNOTEL stations that averaged at least 80 snow days per year and 12-35% at stations with fewer than 50 snow days per year. The top three events contributed 20-45% of annual SFE at most SNOTEL sites, up to 60% in the Sierra Nevada and Arizona. Top decile events contributed approximately one third of annual SFE in the Sierra Nevada, Arizona, Central Idaho, and the east side of the Middle Rockies, and more than 20% at all other SNOTEL sites.

3.3. Factors in Interannual Variability of SFE

The portions of interannual SFE variability attributable to variability in the number of snowfall days and SFE coincident with extreme snowfall events are reported in Table 2.1 (Table S1 for COOP stations). Multiple linear regression models containing both the number of snow days and the leading, top three, and top decile events as predictors explained on average 81%, 88%, and 91% of interannual variability in SFE at SNOTEL stations, respectively, and were significant at all stations.

Simple linear regression showed that the number of snow days explained on average 65% of annual SFE, with r^2 values greater than 0.7 at many stations throughout the Rockies (Figure 2.5a, 2.S4a). Simple linear regressions between annual SFE and the leading, top three, and top decile events explained on average 37%, 57%, and 69% of the interannual variability in SFE. Relationships between annual SFE and the leading event (Figure 2.5b, 2.S4b) were relatively weak ($r^2<0.5$), while relationships between annual SFE and the top three events (Figure 2.5c, 2.S4c) were strongest in the Wasatch Range, Sierra Nevada, Cascades, and the mountains of southwestern Utah and Arizona. At the majority of stations throughout the West, top decile events explained more than 70% of variability in annual SFE (Figure 2.5d, 2.S4d). The spatial variability in interannual SFE explained by top decile events was not significantly correlated with the climatological percent of annual SFE contributed by top decile events for COOP or SNOTEL stations. Extreme snowfall events were the least correlated with interannual variability in annual SFE across southwestern Montana and northern Nevada, albeit corresponding to regions of relatively low SFE variability (Figure 2.2a, 2.S1a).

Comparatively, the number of snow days uniquely explained more of the variability in annual SFE than the leading or top three events on average (Table 2.1). However, top decile events uniquely explained more of the variability in annual SFE (26%) than the number of snow days (22%) on average and top decile events were more significant predictors of annual SFE than number of snow days at 58% of stations.

3.4. Extremes and Interannual Variability of SFE

The interannual relationship between annual SFE, number of snow days, and extreme snowfall events is illustrated through a regional example from the Sierra Nevada (Figure 2.6). Anomalies in annual SFE, SFE of top decile events, and the number of snow days for water years 1990-2012 at 4 SNOTEL stations with continuous records were averaged each year across all stations. Annual SFE (black bars) had a standard deviation of 280mm, indicative of the challenges faced by water managers. The correlation between annual SFE and number of snow days (gray diamonds) for this time series was $r^2=0.89$ ($p<0.0001$) while the correlation between annual SFE and the SFE of top decile events (white bars) was slightly stronger ($r^2=0.90$, $p<0.0001$). Averaged across the 4 stations, anomalies in the top decile events accounted for an average of 52% of anomalies in annual SFE (Eq. 4).

Annual anomalies in the leading and top three snowfall events accounted for an average of 18% and 33% of annual SFE anomalies (Eq. 4) at SNOTEL stations, though substantially more across the southwestern U.S. (Figure 2.7a, 2.7b). The top decile events were generally more important to interannual SFE variability and accounted for more than a third of interannual variability in annual SFE at most SNOTEL stations and up to 75% of annual SFE variability at many stations in the Rockies. We conclude that anomalies in annual SFE are in large part due to variation in the size of the top decile of snowfall events.

3.5. ENSO

During El Niño winters annual SFE increased by more than 40% at most Arizona stations and decreased by 20-60% at many stations in the Middle Rockies and the Pacific Northwest (PNW, defined as Washington, Oregon, and Northern Idaho) (Figure 2.8a, 2.S6a). During La Niña winters, annual SFE declines in the southwest were not statistically significant whereas significant increases of 30-70% in annual SFE were observed in the PNW and Middle Rockies (Figure 2.9a, 2.S7a). The number of snow days in the Sierras and Southwest increased 25-50% during El Niño winters compared to non-El Niño winters with comparable, though generally less coherent, reductions in snowfall days in the PNW and Northern Rockies (Figure 2.8b, 2.S6b). Conversely, during La Niña winters widespread increases in snowfall days were found across the PNW, while generally non-significant decreases were found across the Southwest (Figure 2.9b, 2.S7b). SFE concurrent with top decile events was significantly enhanced (reduced) in the PNW during La Niña (El Niño) winters, with few statistically significant differences in other areas (Figure 2.8c, 2.9c). Anomalies in the size of the leading and top three events had similar spatial patterns.

In the Southwest, more stations had significant differences in the number of snow days than in the SFE of extreme snowfall events. For SNOTEL stations in the mountains of Arizona (n=12) the mean anomaly in annual SFE for El Niño and La Niña winters was +46% and -28%, respectively. The average anomaly in snowfall days was +30% and -34% for El Niño and La Niña winters, respectively, whereas the average anomaly in SFE of the top decile of snowfall events was +60% and -18% for El Niño and La Niña winters, respectively. These findings suggest that fewer snow days may be a more important contributor to below normal SFE in La Niña years whereas snowfall extremes may play a more important role in contributing to high annual SFE in El Niño years. The contribution from snowfall frequency and extremes to annual SFE anomalies during ENSO phases for SNOTEL stations in the Cascades (n=62) was the most spatially coherent across the study area. Below normal SFE during El Niño winters (-21%) was primarily a consequence of a substantial reduction in extreme snowfall contribution (-60%) rather than a reduction in snowfall days (-8%). Conversely, above normal SFE during La Niña winters (+40%) was a product of substantial increases in contributions from extreme snowfall events (+69%) and snowfall days (+27%).

4. Discussion

Climatologies of annual SFE were strongly correlated with peak SWE ($r^2 \geq 0.80$ at more than 70% of SNOTEL stations) and were broadly consistent with summaries of April 1 SWE from SNOTEL and snow course stations [e.g., *Serreze et al.,* 1999]. Spatial variability in annual SFE was primarily attributed to cool season precipitation and temperature patterns. Large interannual variability in cumulative SFE was found at low elevations and low latitudes and is attributed to relatively warm winter temperatures, consistent with prior studies that have shown that the portion of precipitation that falls as snow is sensitive to temperature anomalies in transient watersheds [*Cayan,* 1996]. At colder locales (average winter temperature below approximately -2˚C), annual SFE variability was dominated by variability in winter precipitation [*Cayan,* 1996; *Selkowitz et al.,* 2002]. Winter precipitation variability is latitudinal in nature, associated with the displacement of the jet stream. The northward movement of the jet stream during winter results in less opportunity for snowfall at lower latitudes and consequently larger SFE variability. These results reinforce the findings of *Cayan* [1996], *Dettinger et al.* [1998], and *Mote* [2006] and suggest that anomalous winter precipitation is the main factor influencing snowpack variability at high elevations locations above freezing height, whereas anomalous winter temperature has a strong influence at lower elevations.

The magnitude of extreme snowfall events was greatest in the Cascades, Sierra Nevada, and Northern Idaho, areas reached by moist Pacific air masses. Leading snowfall events contributed up to 43% of annual SFE at COOP stations in California, Oregon, and Washington. Similar to the results of *Serreze et al.* [2001], leading events at SNOTEL stations in the interior contributed 6-17% of annual SFE. Lower elevation and lower latitude SNOTEL stations, including those in the Sierra Nevada and mountains of the Arizona and southwestern Utah, received the largest SFE contributions from extreme snowfall events (13-35% from leading events). Top decile snowfall events contributed 20-38% of annual SFE at SNOTEL stations, highlighting the importance of extremes in shaping the annual snowpack. Similar to leading events, top decile events contributed the largest portions of annual SFE in Arizona and the Sierra Nevada, but unlike the leading events, top decile events also made large contributions (>30%) in central Idaho and on the east side of the Middle Rockies. Large contributions of extreme snowfall events to annual SFE in the Sierra Nevada compliment the findings of *Guan et al.* [2010], who showed that a few extreme snowfall events in the Sierra Nevada, associated with atmospheric rivers, contribute 30-40% of annual SFE. While this study did not explicitly examine synoptic processes associated with extreme snowfall events, we found that more than 70% of leading events from 1998-2008 at stations in the Sierra Nevada coincided with land-falling atmospheric rivers identified by *Dettinger et al.* [2011]. Projections of warming and increased snowpack temperature sensitivity [*Ashfaq et al.,* 2013] combined with our findings that the warmest locations generally have the highest CV of annual SFE and the largest SFE contributions from extremes suggest that the CV of annual SFE and contributions from extremes may be greater in the future, making the need to understand annual SFE variability increasingly important.

A multiple linear regression model containing number of snow days and SFE of the top decile events explained more than 90% of variability in annual SFE, on average, and was significant for all stations. We found that interannual variability in the number of snow days was generally more strongly correlated with annual SFE than the leading or top three events. Conversely, SFE of top decile events was more strongly correlated with annual SFE than number of the snow days for the majority of SNOTEL stations. This more temporally extensive analysis qualifies and expands on the findings of *Serreze et al.* [2001] who showed that snow days was more strongly correlated with annual SFE than the leading one day event or the event defining the 75th percentile each year. Our analysis has shown that, when defined as a partial duration series, extreme snowfall events are a stronger predictor of annual SFE than number of snow days.

The covariation of annual SFE and top decile snowfall events ($\overline{r^2}$=0.69) suggests that extreme snowfall events play a substantial role in shaping water year SFE anomalies. This was confirmed by the fact that 18-75% of SFE anomalies at SNOTEL stations were accounted for by anomalies in the top decile events. Additionally, unusually high and low numbers of top decile events were strongly related to high and low SFE years, respectively. Averaged over all stations, there were 75% more (60% less) top decile events than the long-term average for years in the top (bottom) quartile of annual SFE. These results elaborate on *Serreze et al.* [2001] who found that locations with enhanced extreme snowfall events in a given year are likely to experience above average snowfall while locations with fewer extreme snowfall events in a given year are more likely to experience below average snowfall. The strong correlations between annual SFE and April 1 SWE ($r^2 \geq 0.70$ at more than 65% of SNOTEL stations) suggest that extreme snowfall events may be indicative of seasonal snowmelt runoff as well as annual accumulation.

Robust increases (decreases) in annual SFE were found in the southwest (PNW) during El Niño while during La Niña, significant increases in SFE were found in the PNW but decreases in the southwest were not statistically significant. The spatial patterns of annual SFE anomalies at SNOTEL and COOP stations compliment earlier findings of April 1 SWE anomalies at snow courses [*McCabe and Dettinger,* 2002; *Cayan,* 1996] and are partly attributed to a southward (northward) shift in the jet stream during El Niño (La Niña) which alters the probability of precipitation. The Cascades were the most sensitive to ENSO phase; during El Niño winters below normal annual SFE (-21%) was primarily due to a substantial reduction in extreme snowfall contribution (-60%) rather than a reduction in snow days (-8%), whereas above normal SFE during La Niña winters (+40%) was a product of substantial increases in contributions from extremes (+69%) and snow days (+27%). Many states, including Utah, Colorado, Nevada, New Mexico, and California showed little difference in the SFE of extreme events between ENSO phases. Our findings compliment prior research on changes in wet day frequency and heavy winter precipitation events with ENSO phase [*Higgins et al.,* 2007; *Cayan et al.,* 1999; *Gershunov and Barnett,* 1998]. However, we generally find stronger relationships at mountainous SNOTEL sites than in previous research using lower elevation stations [*Higgins et al.,* 2007; *Gershunov and Barnett*, 1998], suggesting stronger relationships between mountain precipitation and ENSO phase which may be partly due to differential orographic enhancement [*Luce* *et al.,* 2013]. These results can augment the existing utility of ENSO forecasts for water resource management by increasing confidence in the likelihood of a top decile snowfall event occurring.

5. Conclusions

Analysis of three classes of extreme snowfall events indicated that these events are pivotal in shaping interannual variability in snowpack across the western U.S. Considering that water availability in most of the West is contingent on snowmelt, the presence or absence of extreme snowfall events in a given year can mean the difference between a water surplus year and a drought year, respectively. Furthermore, for the same annual SFE, extreme snowfall events can increase annual maximum SWE, potentially partially compensating for losses in snowpack via enhanced snowmelt and higher rain to snow ratios in a warming climate [*Kumar et al.,* 2012]. Complementary to our results on accumulation processes via extremes, analysis of ablation processes at daily timescales and the sensitivity of these processes to climate variability is needed to characterize variability in snowpack evolution and consequent runoff, particularly later in the snow accumulation season [*DeBeer and Pomeroy,* 2009; *Hood et al.,* 1999].

The frequency of snowfall days and contributions via extreme snowfall events was shown to correspond with ENSO phase, facilitating a link between atmosphere-ocean variability and April 1 SWE [*Serreze et al.,* 2001; *Patten et al.,* 2003]. Although research remains to be done on the synoptic factors responsible for extreme snowfall events [see *Guan et al.,* 2010; *Uccellini and Kocin*, 1987] and their linkages to large-scale climate variability, the tie between ENSO phase and extreme snowfall events has the potential to inform water management decisions. Quantifying the importance of these events provides an as yet not fully recognized mechanism for understanding interannual SFE variability. This knowledge can inform avalanche forecasting efforts as well as spring reservoir releases and early season water supply commitments, all of which depend on reliable forecasts of snowpack accumulation and ablation.

Projections of decreased snowpack and more extreme precipitation regimes resulting from anthropogenic climate change [*Pierce and Cayan,* 2013; *Kunkel,* 2003; *Seneviratne et al.*, 2012] portend changes in the significance of extreme snowfall events to annual SFE totals and interannual variability in SFE. Given that extreme snowfall events typically occur at temperatures above -2C at many stations in the Cascades, Sierra Nevada, Arizona, and Idaho, these events will likely transition to heavy rain events within the 21st century [*Bales et al.,* 2006], contributing substantially to the drastic declines in total snowpack projected for these regions. In colder areas, such as the Middle and Southern Rockies, extreme snowfall events typically occur at temperatures below -4C, suggesting that the SFE of extreme events in these regions may increase in accordance with the Clausius-Clapeyron relationship until climatological winter temperatures increase by a substantial amount. The future importance of extreme snowfall events in shaping interannual variability in annual SFE remains unexamined. Potential changes in the size and relative importance of extreme snowfall events to annual SFE totals and interannual variability in annual SFE will challenge water resource management and the assumption of stationarity on which it is based [*Milly et al.,* 2008]. Improvements in our ability to seasonally forecast, prepare, and manage for extreme snowfall events now will make water resource management more capable of adapting to potential changes in snowfall regimes in the future.

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Table 2.1 Regression analysis r^2 values for SNOTEL stations

	R^2 values[a]				Semipartial Correlations[e]	
Event	R^2 AES	r^2 ES	r^2 AE	r^2 AS	sr^2 AE	sr^2 AS
leading	0.81 *(100)*[b]	0.11 *(28)*	0.37 *(85)*	0.65 *(99)*	0.16	0.44
top three	0.88 *(100)*[c]	0.19 *(50)*	0.57 *(99)*	0.65 *(99)*	0.23	0.31
top decile	0.91 *(100)*[d]	0.25 *(67)*	0.69 *(100)*	0.65 *(99)*	0.26	0.22

[a] Average R-squared values from regressions between annual SFE (A) and each event size (E) and number of snow days (S) where the first letter indicates the dependent variable and the following letters indicate independent variables. The percent of stations for which the regression model was significant by F-test is indicated in parentheses ().

[b] The leading event is a significant variable at 92.01% of stations, snow days significant at 99.81% of stations.

[c] Top three events are a significant variable at 100% of stations, snow days significant at 100% of stations.

[d] Top decile events are a significant variable at 100% of stations, snow days significant at 100% of stations.

[e] Squared semipartial correlations computed using Equations 2 and 3.

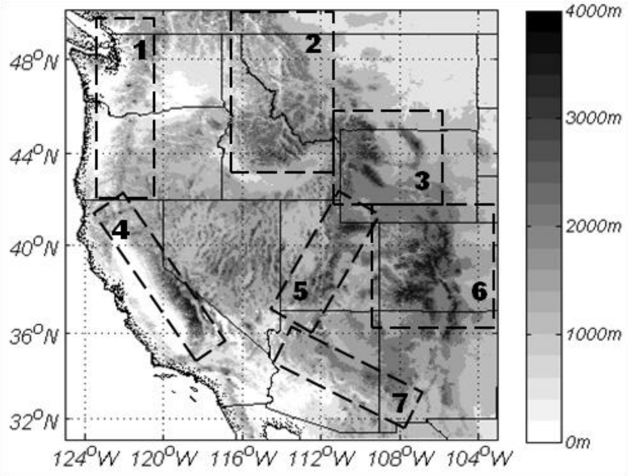

Figure 2.1 Map of study area. Color bar indicates elevation (m). Major mountain ranges referred to in the text are labeled: 1) Cascades, 2) Northern Rockies, 3) Middle Rockies, 4) Sierra Nevada, 5) Wasatch Range, 6) Southern Rockies, and 7) mountains of Arizona.

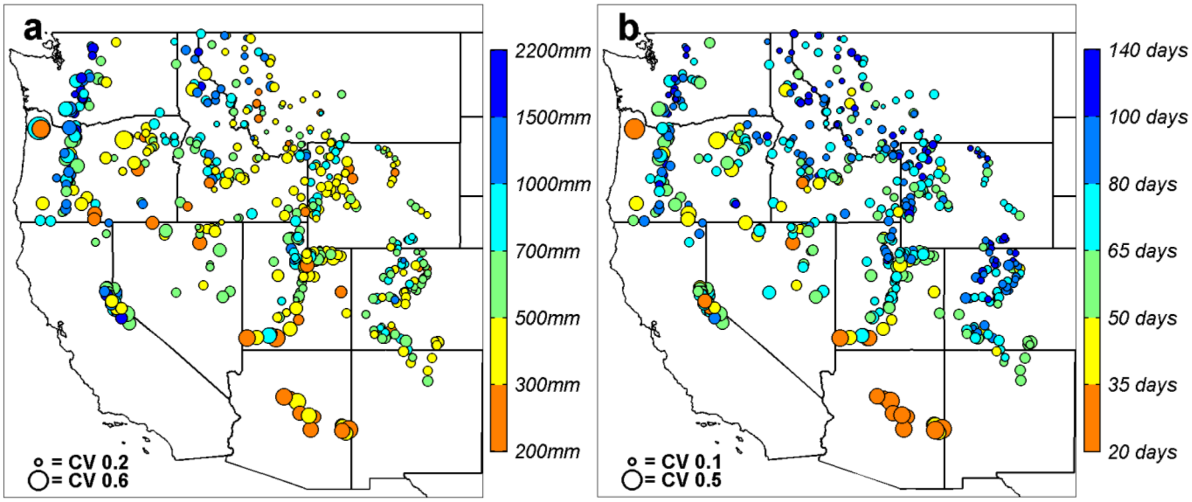

Figure 2.2 For SNOTEL stations: a) Average annual SFE (mm, indicated by color) and coefficient of variation of annual SFE (indicated by marker size) and b) average annual number of snow days (indicated by color) and coefficient of variation of number of snow days (indicated by marker size.)

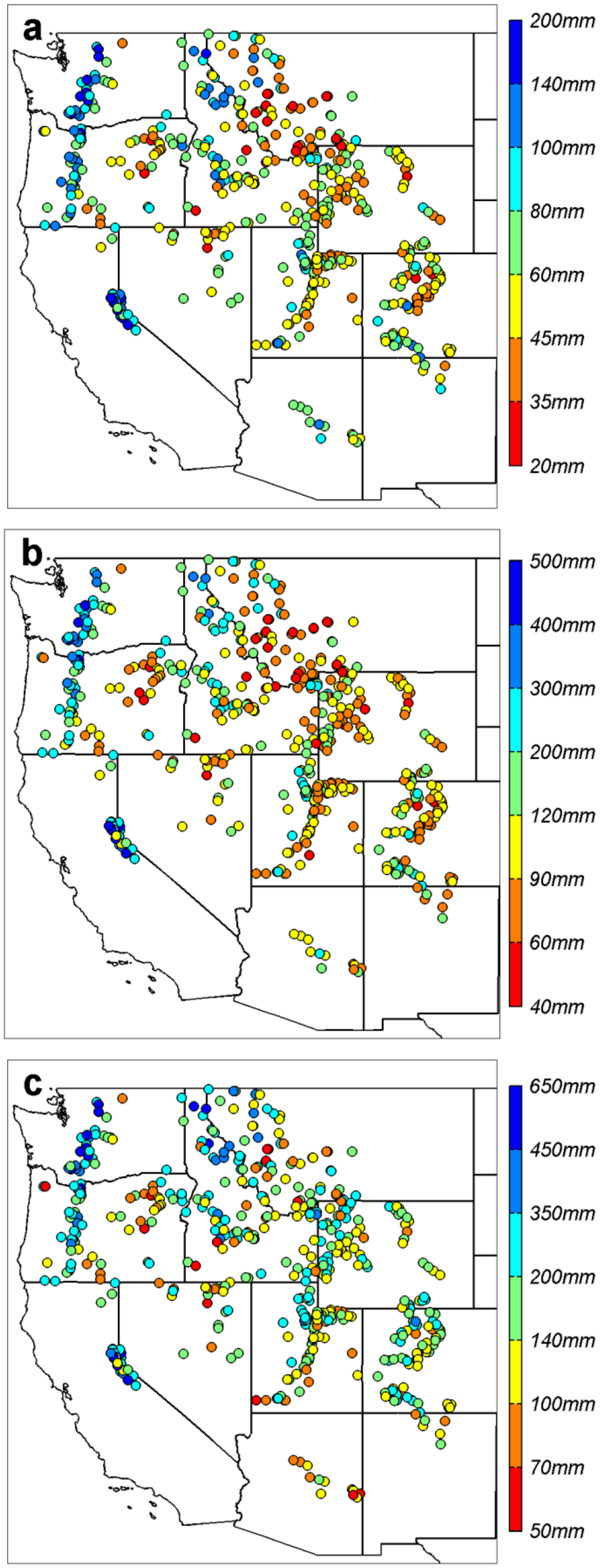

Figure 2.3 For SNOTEL stations: Average magnitude (mm) of a) the leading event, b) the three biggest events, and c) the average SFE of the top decile of snowfall events each year. Note different color bar scales.

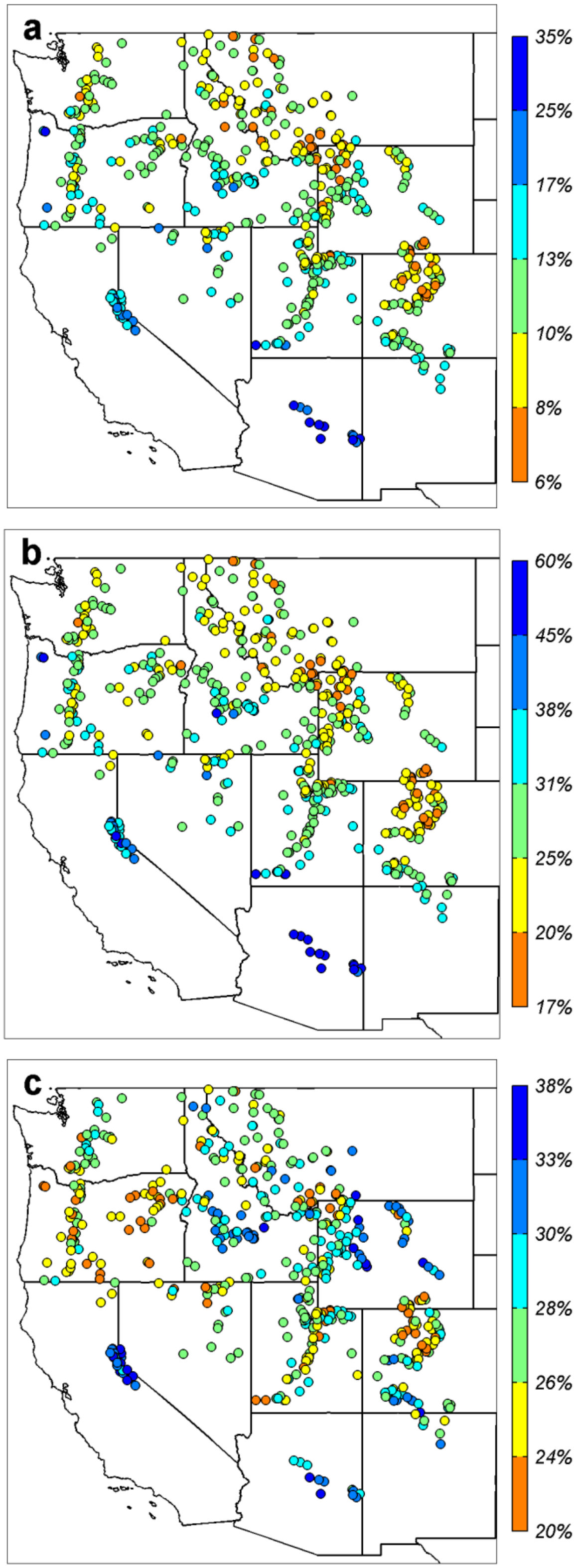

Figure 2.4 For SNOTEL stations: Average percent of annual SFE contributed by a) the leading event, b) the top three events, and c) the top decile events each year. Note different color bar scales.

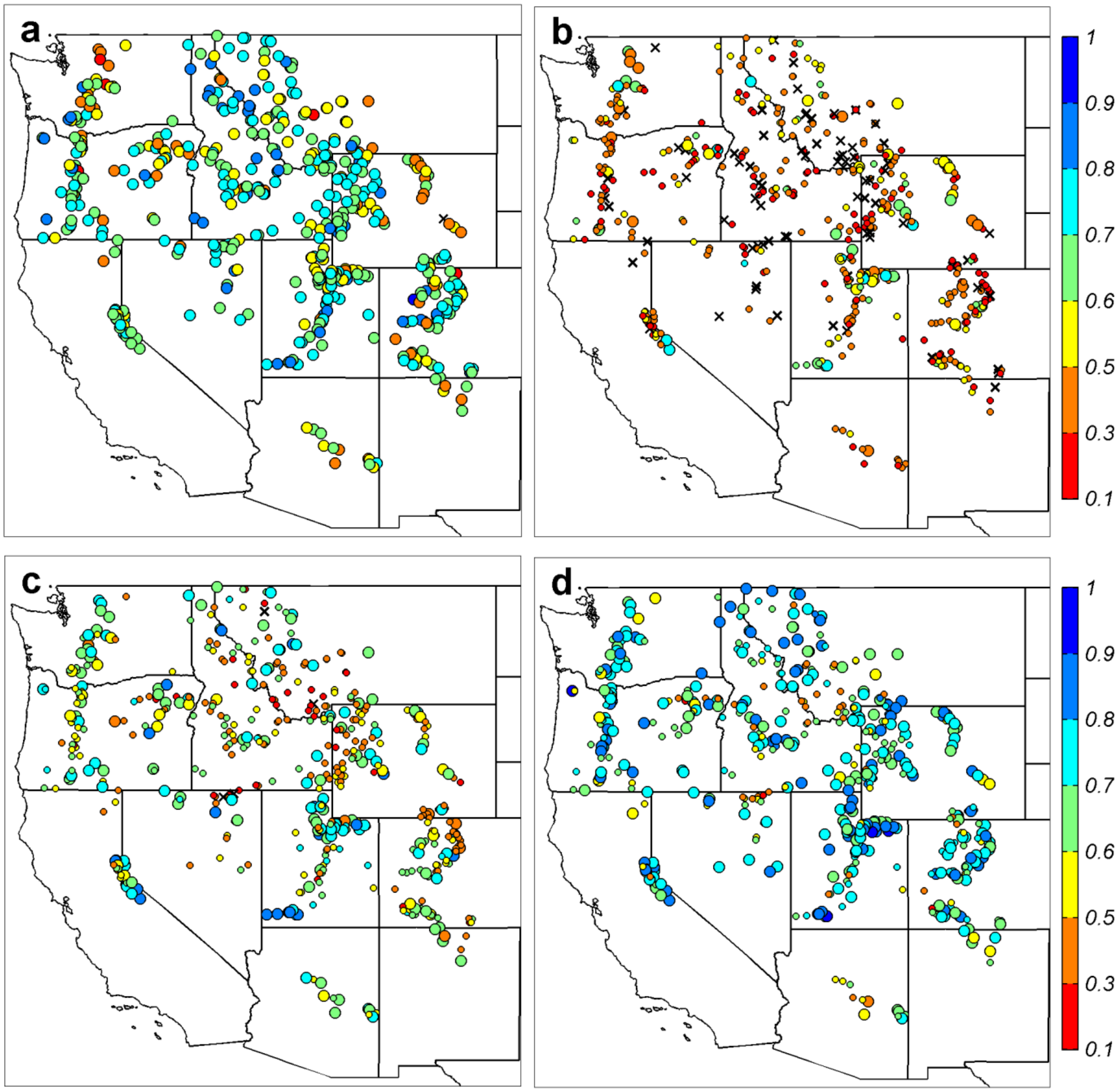

Figure 2.5 r^2 values of simple linear regression between annual SFE and a) number of snow days, b) SFE of the leading event, c) SFE of the top three events, and c) SFE of the top decile events. Stations at which the regression was not significant (alpha =0.05) are marked with x's. For b), c), and d), larger (smaller) markers indicate that the r^2 value is greater (less) than the r^2 value in a).

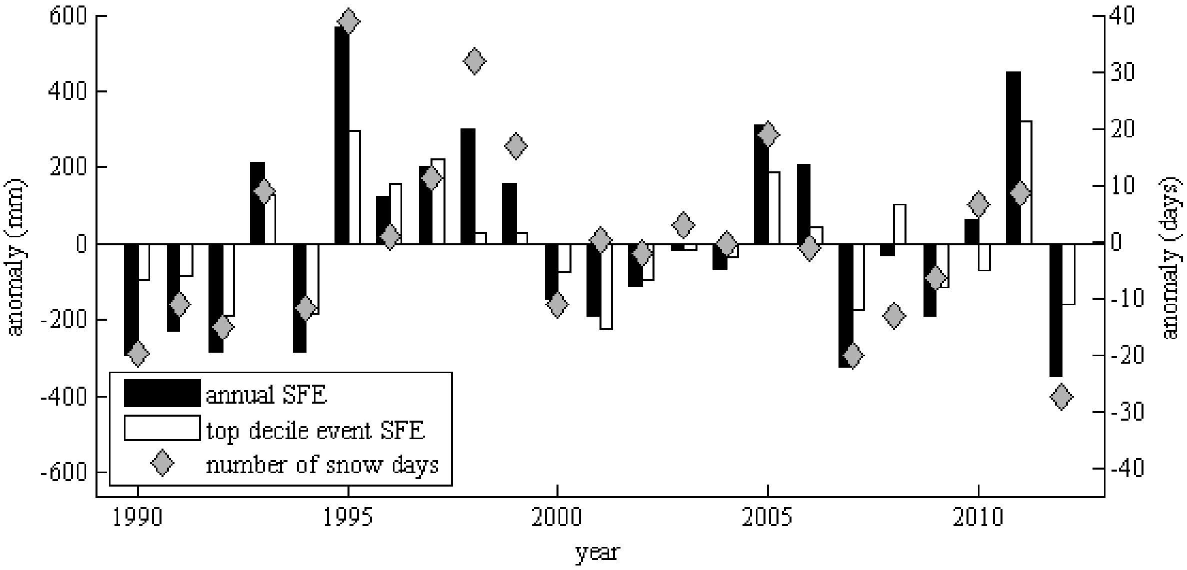

Figure 2.6 Time series of anomalies of annual SFE, top decile events, and number of snow days, averaged across Sierra Nevada SNOTEL stations (n=4) for water years 1990-2012. Anomalies of annual SFE (mm) are indicated by black bars with values on the left y-axis, anomalies of SFE of top decile events (mm) are indicated by white bars with values on the left y-axis, and anomalies of number of snow days (days) are indicated by gray diamonds with values on the right y-axis.

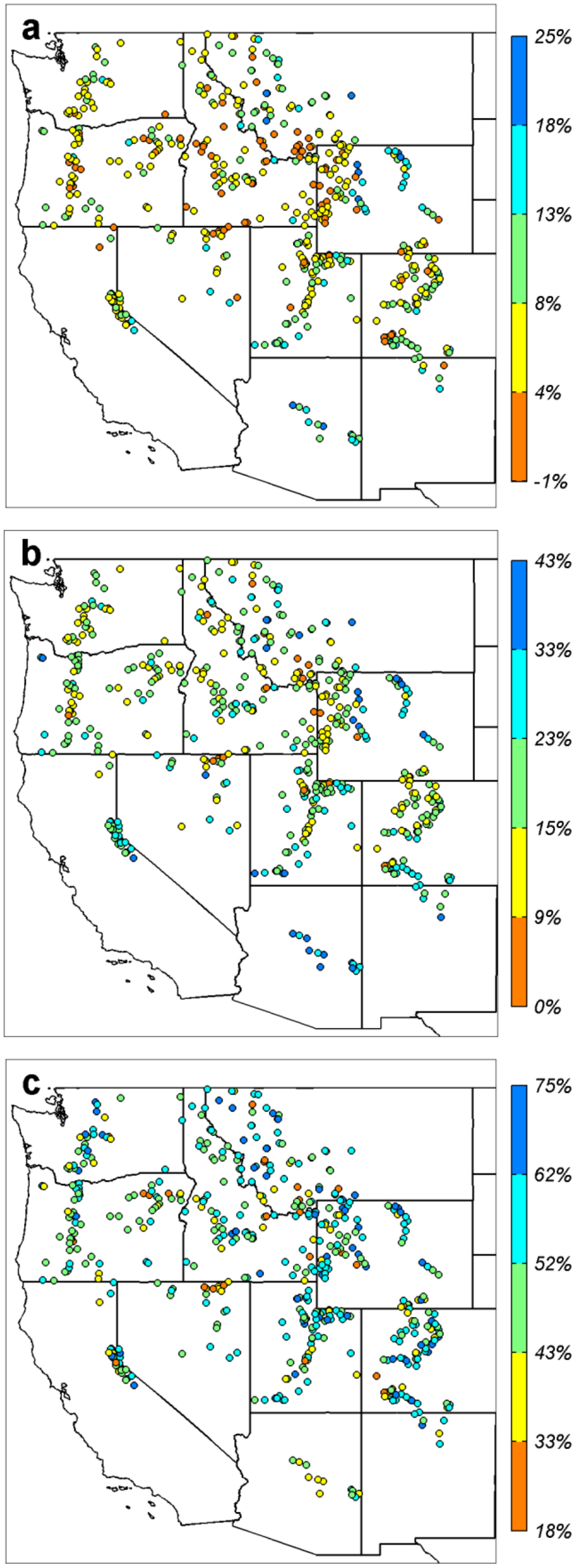

Figure 2.7 For SNOTEL stations: Percent of anomalies in annual SFE contributed by anomalies in the SFE of a) the leading event, b) the top three events, and c) the top decile events. Note different color bar scales.

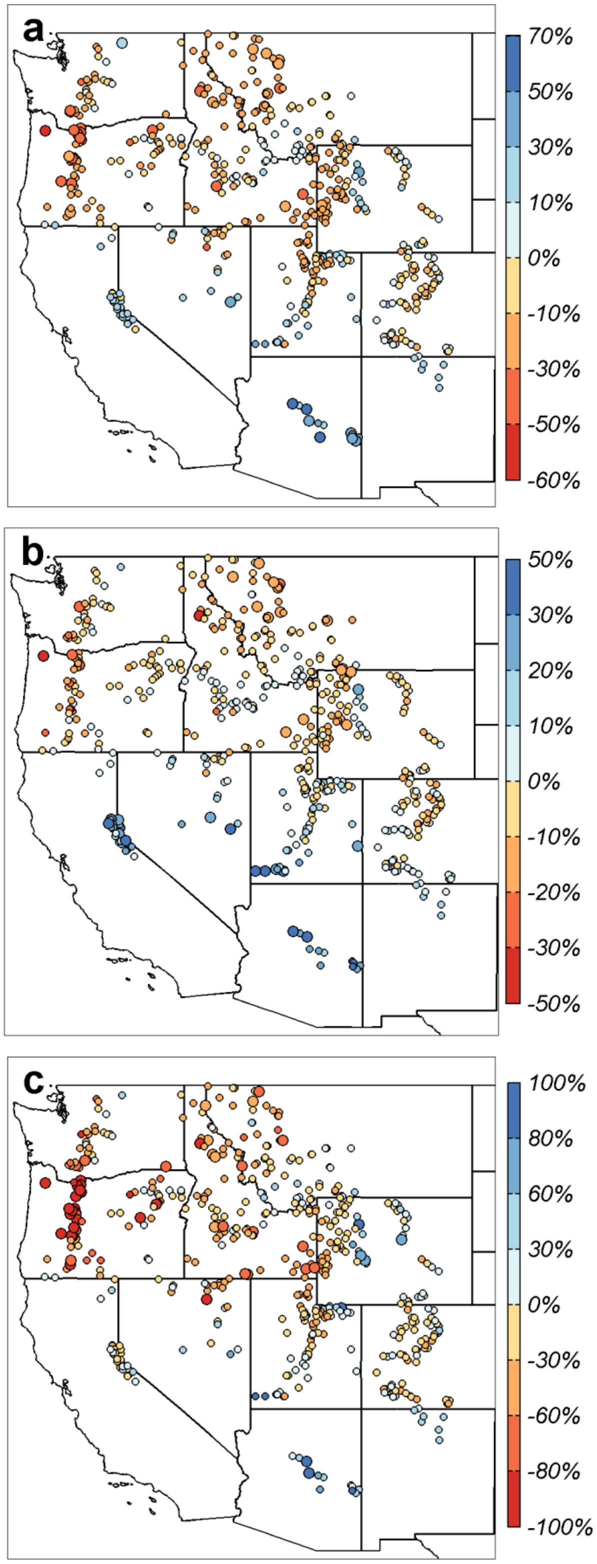

Figure 2.8 For SNOTEL stations: Percent change between El Niño and all other years in a) annual SFE, b) the number of snow days, and c) the SFE of top decile snowfall events. Larger markers indicate a statistically significant difference between El Niño and other year values (alpha=0.05). Note different color bar scales.

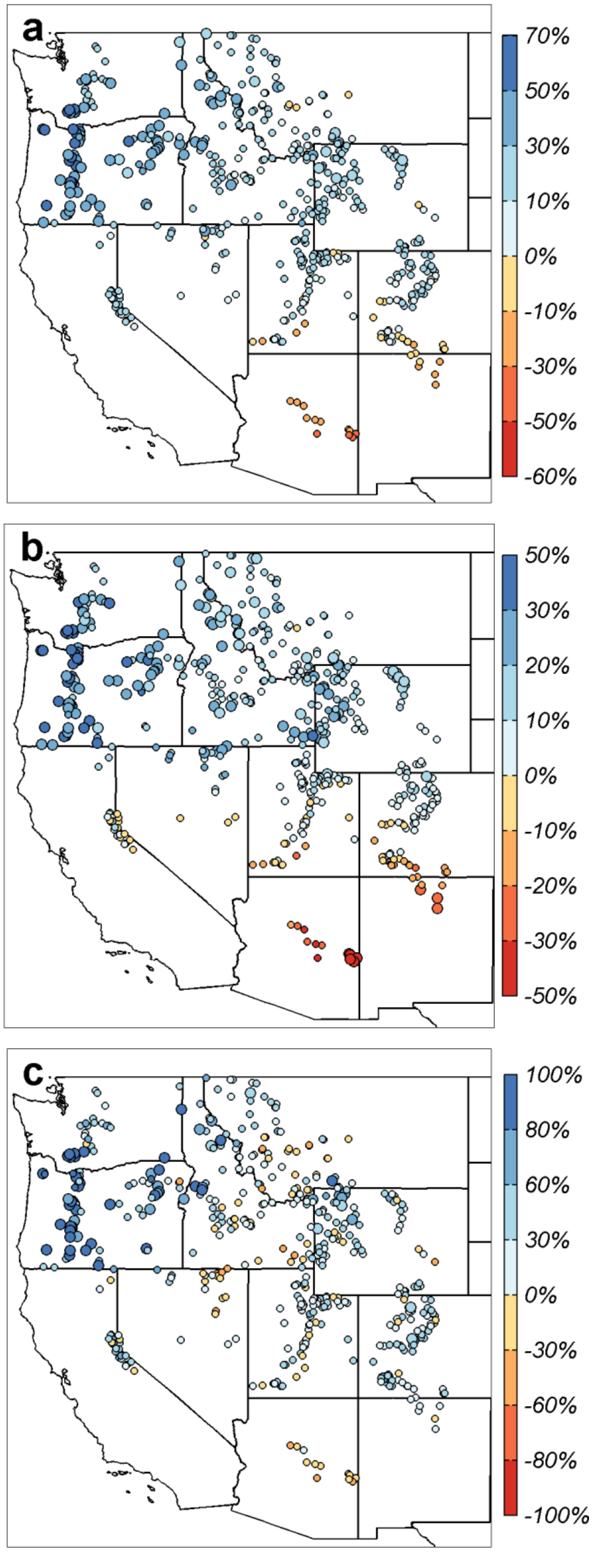

Figure 2.9 For SNOTEL stations: Percent change between La Niña and all other years in a) annual SFE, b) the number of snow days, and c) the SFE of top decile snowfall events. Larger markers indicate a statistically significant difference between La Niña and other year values (alpha=0.05). Note different color bar scales.

Table 2.S1. Regression analysis r^2 values for COOP stations

	R^2 values[a]				Semipartial Correlations[e]	
Event	R^2 AES	r^2 ES	r^2AE	r^2 AS	sr^2 AE	sr^2 AS
leading	0.90 *(100)*[b]	0.21 *(76)*	0.47 *(100)*	0.79*(100)*	0.11	0.44
top three	0.95*(100)*[c]	0.38 *(98)*	0.72 *(100)*	0.79*(100)*	0.16	0.22
top decile	0.94 *(100)*[d]	0.30 *(91)*	0.63 *(100)*	0.79 *(100)*	0.15	0.31

[a] Average R-squared values from regressions between annual SFE (A) and each event size (E) and number of snow days (S) where the first letter indicates the dependent variable and the following letters indicate independent variables. The percent of stations for which the regression model was significant by F-test is indicated in parentheses ().

[b] The leading event is a significant variable at 100% of stations, snow days significant at 100% of stations.

[c] Top three events are a significant variable at 100% of stations, snow days significant at 100% of stations.

[d] Top decile events are a significant variable at 100% of stations, snow days significant at 100% of stations.

[e] Squared semipartial correlations computed using Equations 2 and 3.

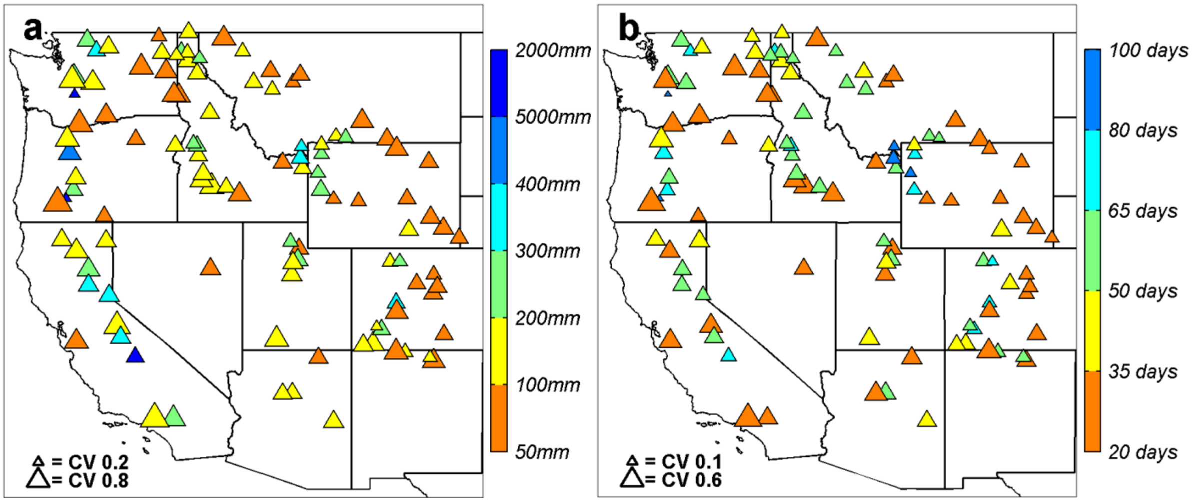

Figure 2.S1 For COOP stations: a) Average annual SFE (mm, indicated by color) and coefficient of variation of annual SFE (indicated by marker size) and b) average annual number of snow days (indicated by color) and coefficient of variation of number of snow days (indicated by marker size.)

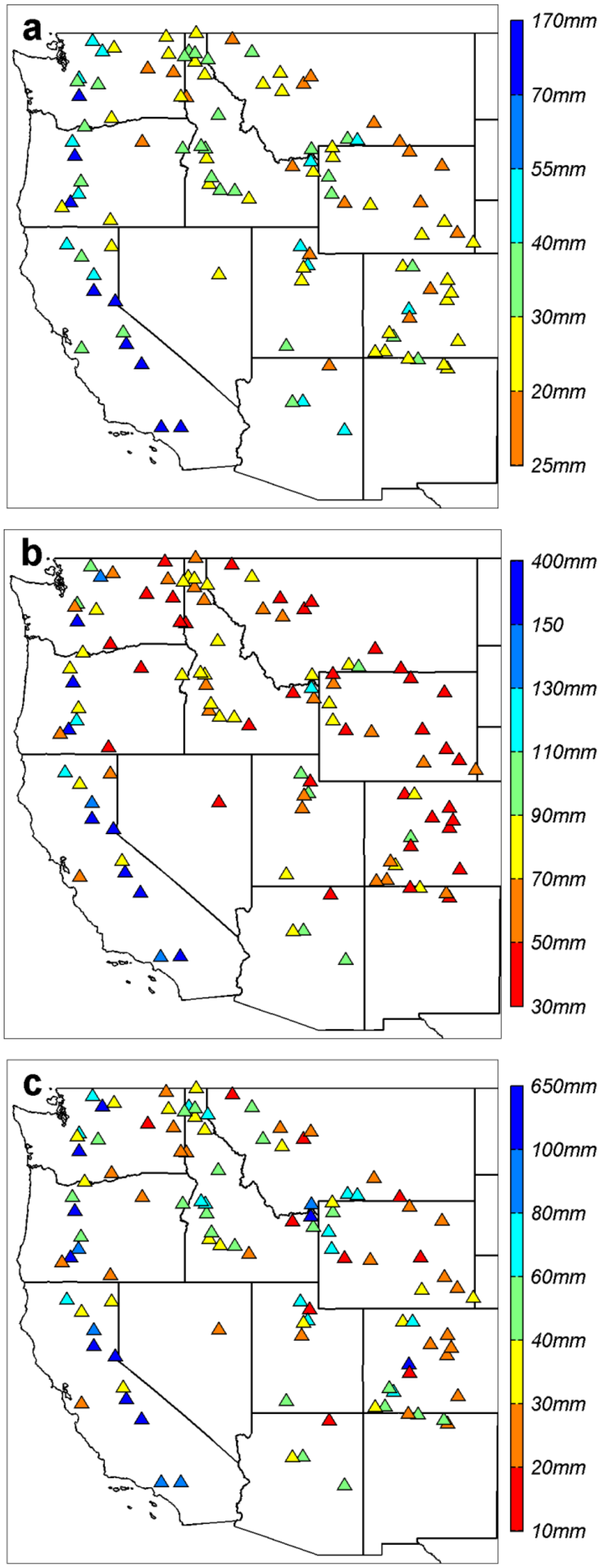

Figure 2.S2 For COOP stations: Average magnitude (mm) of a) the leading event, b) the sum of the three biggest events, and c) the sum of events in the top decile each year. Note different color bar scales.

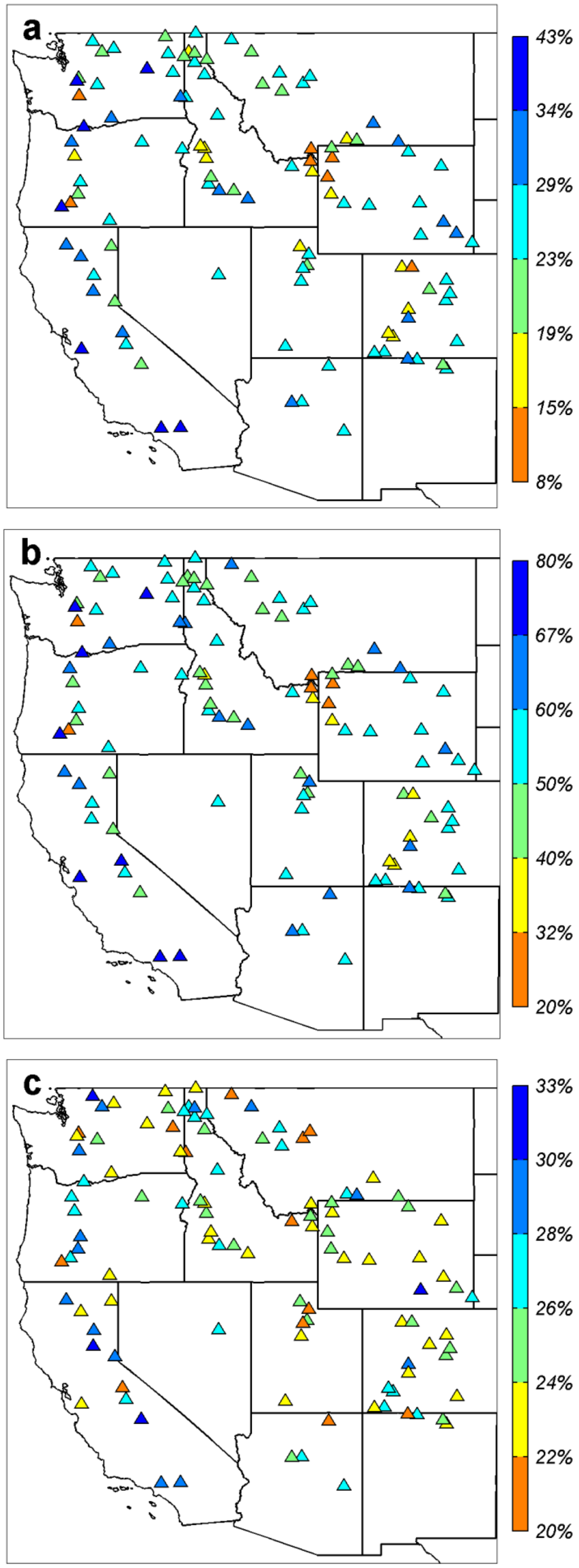

Figure 2.S3 For COOP stations: Average percent of annual SFE contributed by a) the leading event, b) the top three events, and c) the top decile events each year. Note different color bar scales.

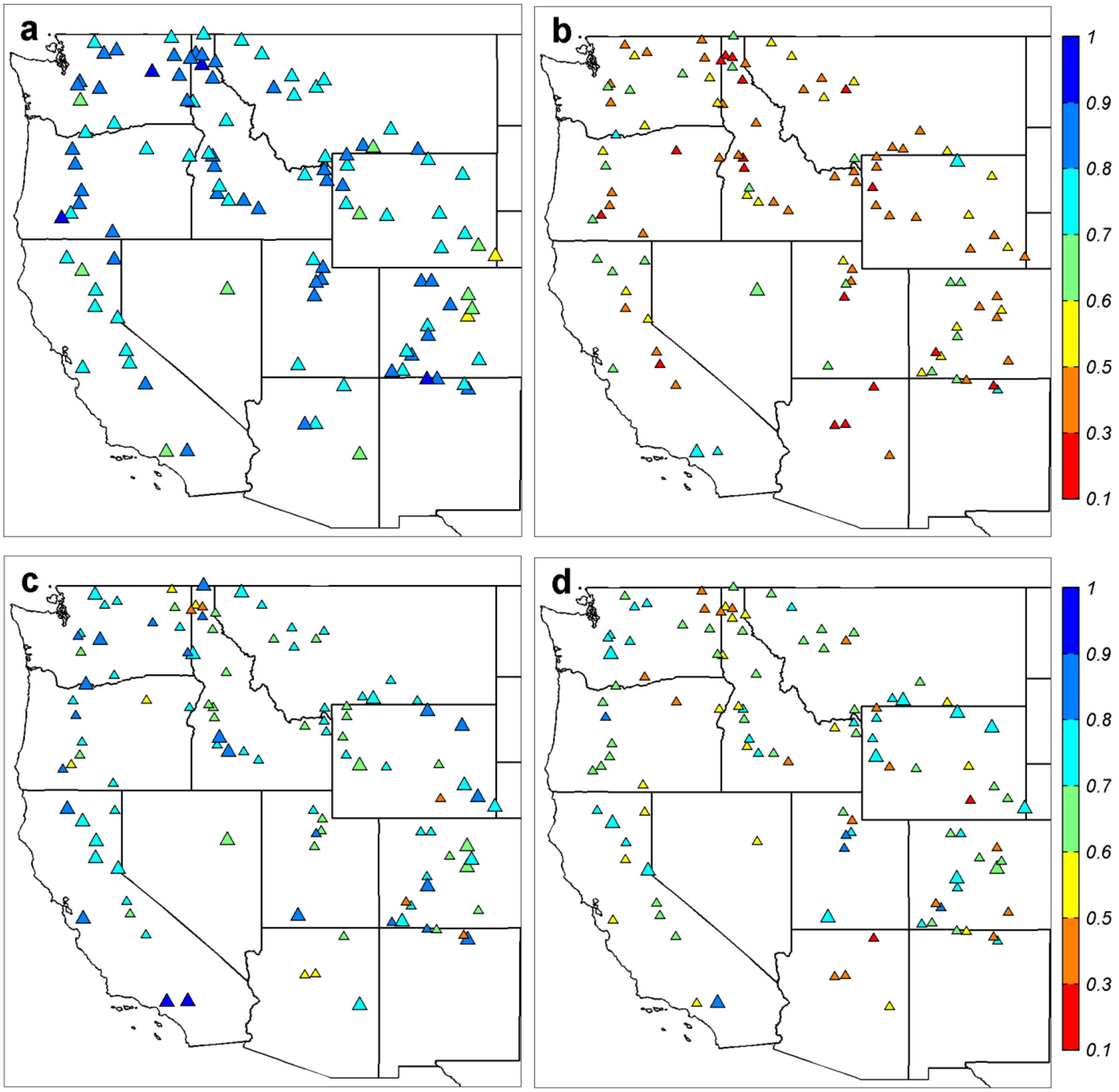

Figure 2.S4 For COOP stations: r^2 values of simple linear regression between annual SFE and a) number of snow days, b) SFE of the leading event, c) SFE of the top three events, and c) SFE of the top decile events. Stations at which the regression was not significant (alpha =0.05) are marked with x's. For b), c), and d), larger (smaller) markers indicate that the r^2 value is greater (less) than the r^2 value in a).

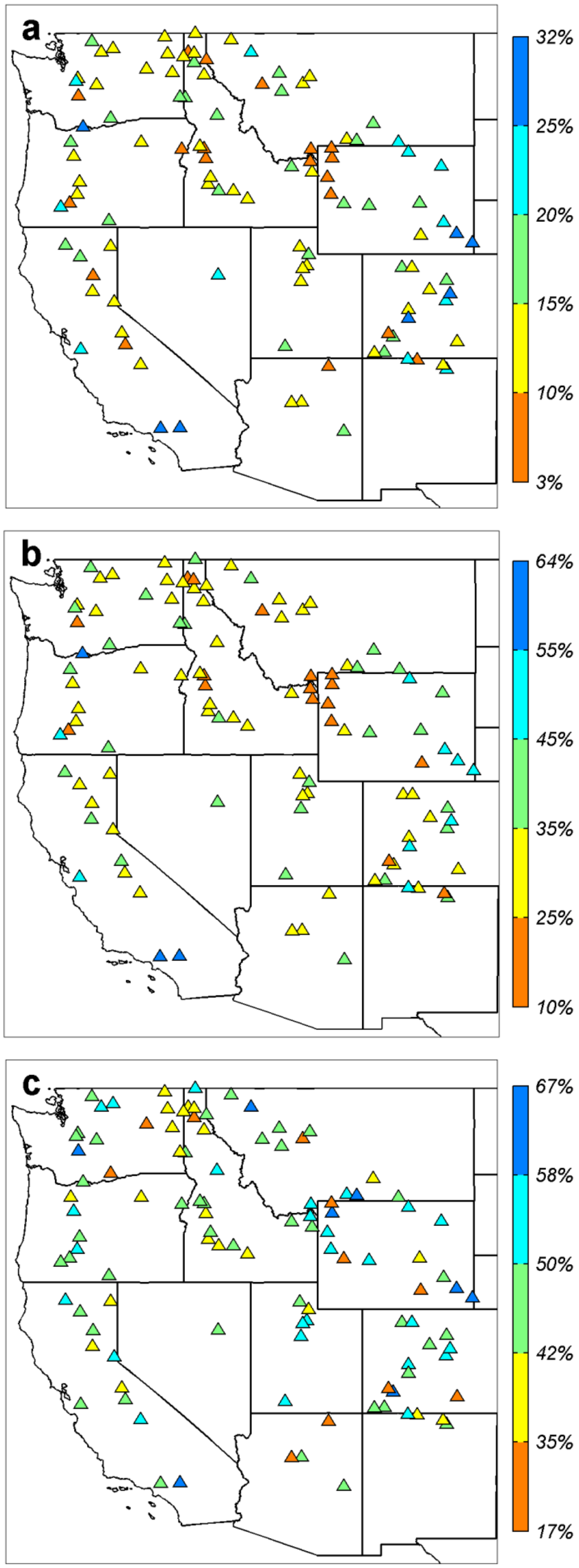

Figure 2.S5 For COOP stations: Percent of anomalies in annual SFE contributed by anomalies in the size of a) the leading event, b) the top three events, and c) the top decile events. Note different color bar scales.

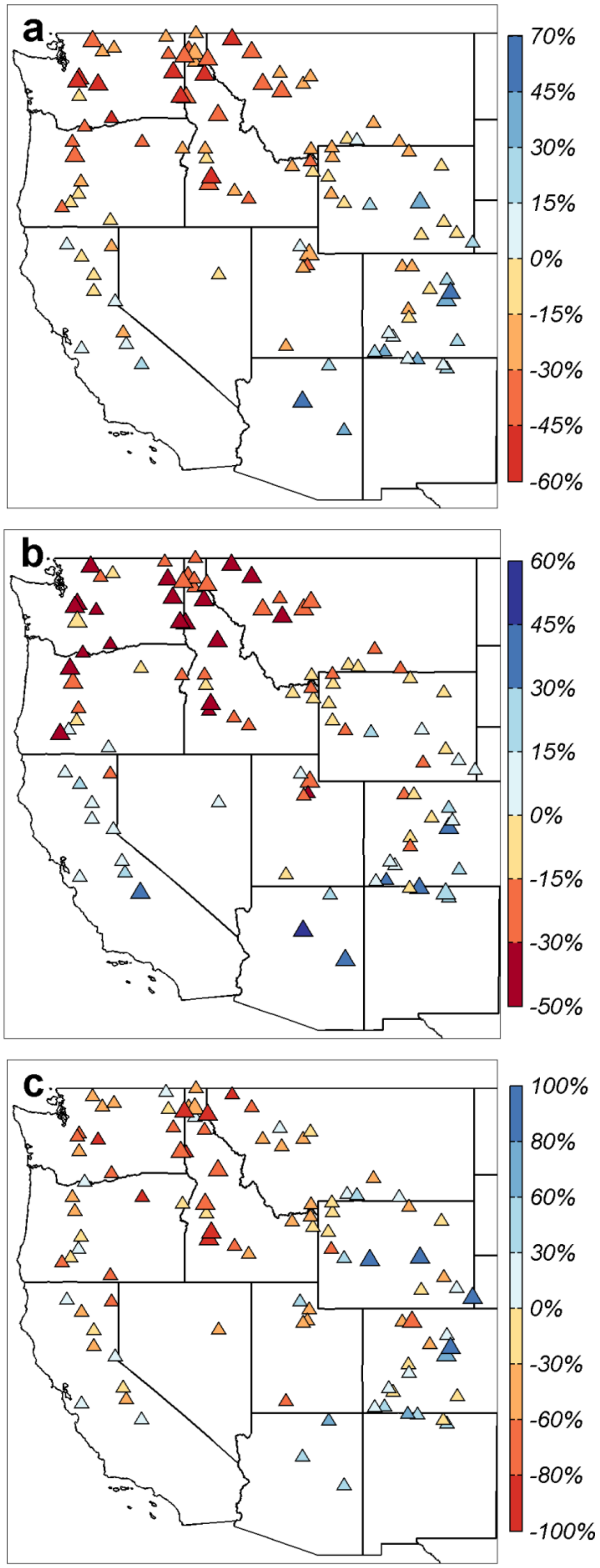

Figure 2.S6 For COOP stations: Percent change between El Niño and all other years in a) annual SFE, b) the number of snow days, and c) the size of top decile snowfall events. Larger markers indicate a statistically significant difference between El Niño and other year values (alpha=0.05). Note different color bar scales.

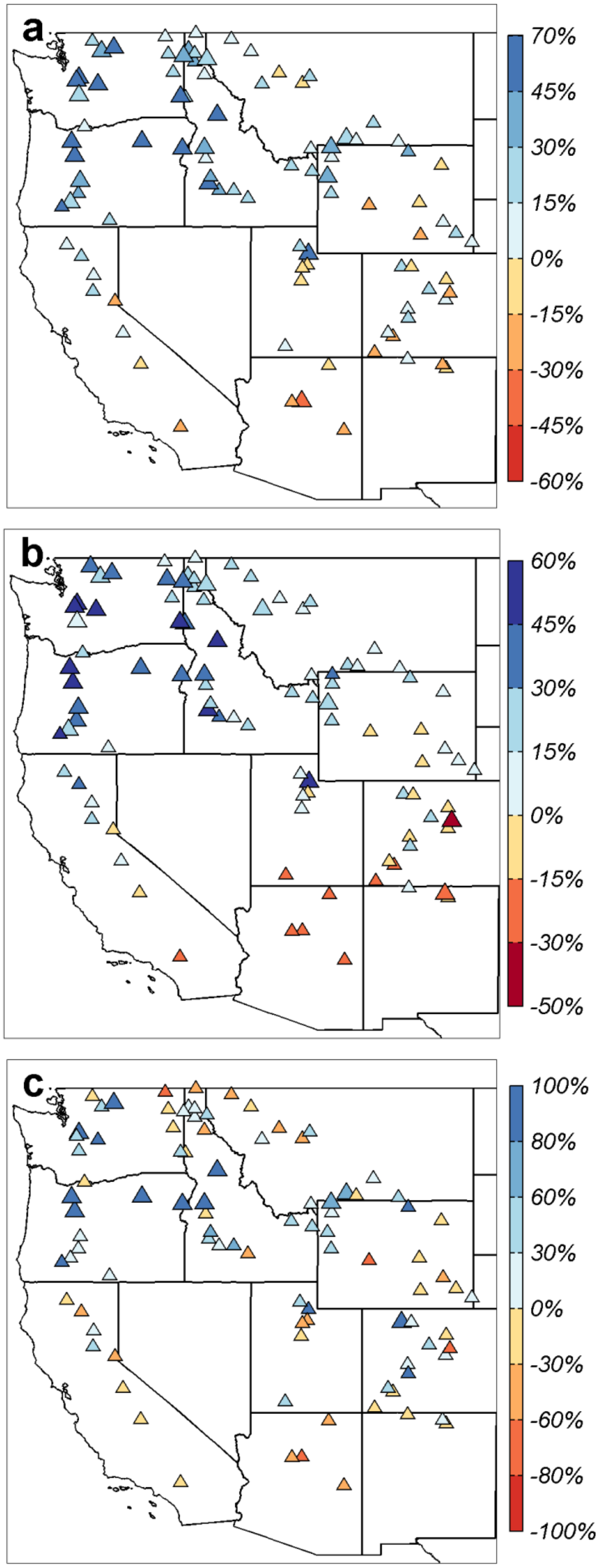

Figure 2.S7 For COOP stations: Percent change between La Niña and all other years in a) annual SFE, b) the number of snow days, and c) the size of top decile snowfall events. Larger markers indicate a statistically significant difference between La Niña and other year values (alpha=0.05). Note different color bar scales.

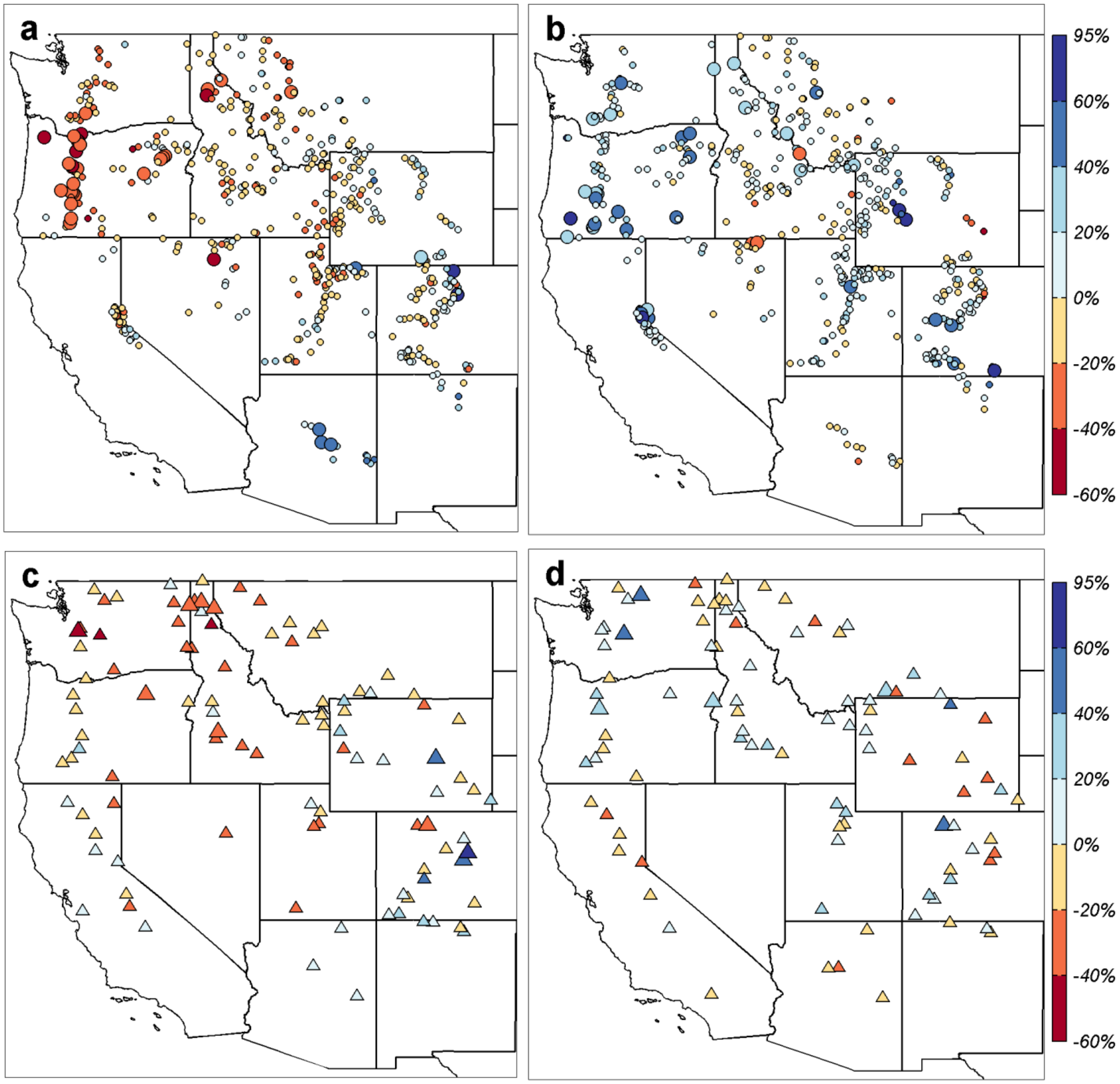

Figure 2.S8 Percent change in the size of the leading snowfall event for SNOTEL (a and b) and COOP (c and d) stations. S8a and S8c show difference between El Niño and all other years, S8b and S8d show difference between La Niña and all other years. Larger markers indicate a statistically significant difference between El Niño/La Niña and other year values (alpha=0.05).

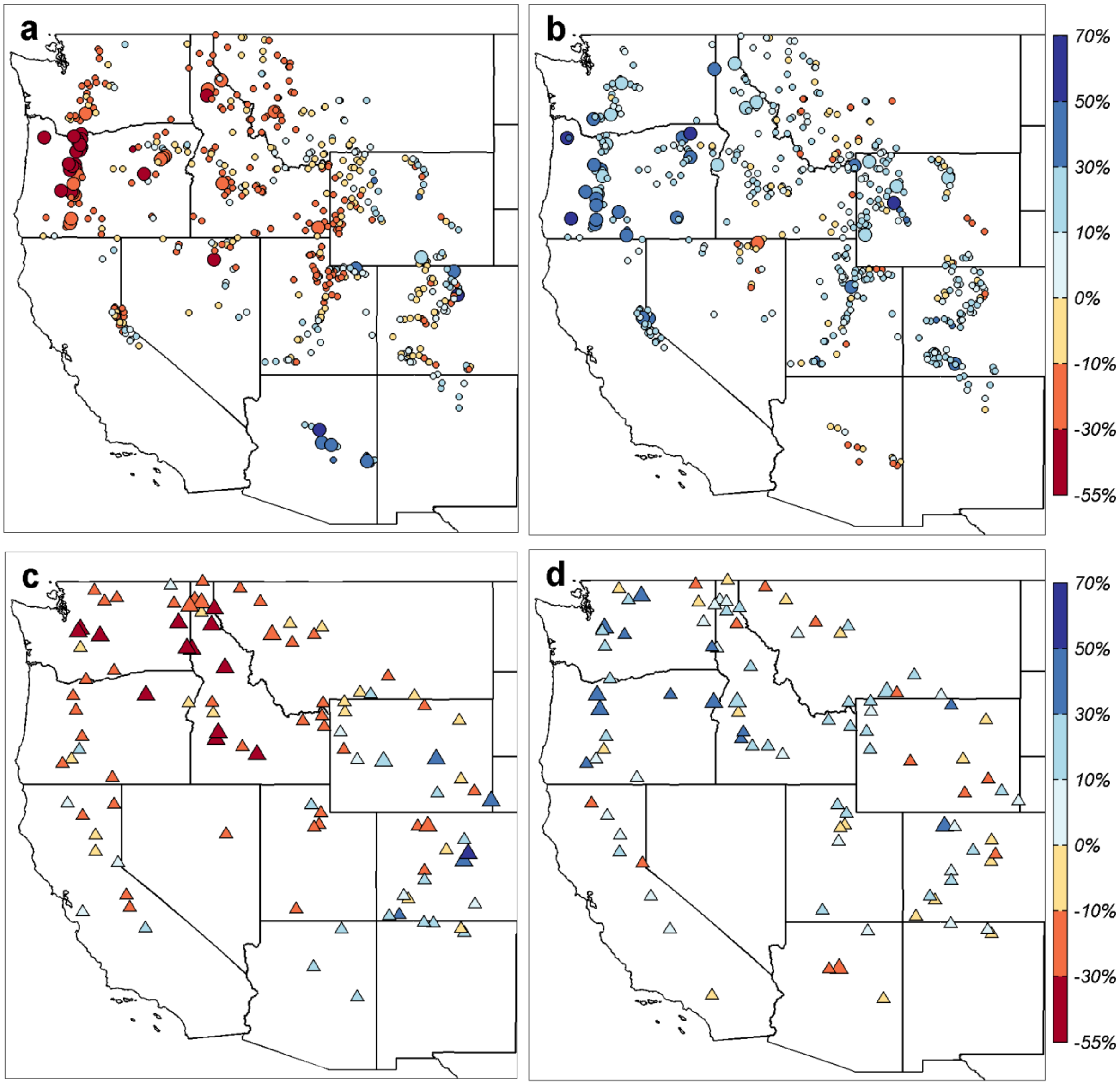

Figure 2.S9 Percent change in the size of the top three snowfall events for SNOTEL (a and b) and COOP (c and d) stations. S9a and S9c show difference between El Niño and all other years, S9b and S9d show difference between La Niña and all other years. Larger markers indicate a statistically significant difference between El Niño/La Niña and other year values (alpha=0.05).

Chapter 3:

Differential temperature sensitivity of extreme snowfall events in the context of climate change: implications for annual snowfall accumulation and variability

A. C. Lute and J. T. Abatzoglou

Abstract

Projected warming and more spatially and seasonally variable precipitation will have significant impacts on snowfall accumulation and melt, with implications for water availability and management in snow-dominated regions. Projected changes in extreme snowfall events, which constitute 20-38% of annual snowfall water equivalent (SFE) in the western U.S., are confounded by projections of more extreme precipitation and the differential temperature sensitivities of extreme snowfall events and small to moderate size snowfall events. Data from 20 global climate models downscaled to the western U.S. and bias corrected to Snowpack Telemetry stations are used to assess projected changes in extreme snowfall events and the mean and variability of annual SFE by the mid-21st century. Annual SFE is projected to decrease at all stations while the mean SFE of extreme snowfall events is projected to increase in the regions with the coldest climatological winter temperatures, including the Middle and Southern Rockies. In these regions, changes in the distribution of snowfall events mirror changes in the distribution of precipitation events, with substantial increases in the most extreme events and smaller changes in small and moderate events. In regions with climatological winter temperatures closer to freezing, all snowfall event percentiles are projected to decline, however large events are projected to be far more resilient than small and moderate events due to differential temperature sensitivities and changes in the distribution of precipitation. The coefficient of variation (CV) of annual SFE is projected to increase by as much as 80% in climatologically warmer regions due to fewer snowfall days, increasing importance of heavy snowfall events, and increasing CV of extreme snowfall events. In the coming century, water management will be challenged by reduced and significantly more variable snowpack.

1. Introduction

Snow is a particularly climate sensitive component of the hydrologic cycle due to its codependence on precipitation and temperature. Increased temperatures resulting from anthropogenic climate change will decrease the portion of precipitation falling as snow and increase snowmelt [e.g. *Collins et al.,* 2013], whereas changes in precipitation are less certain and more regionally and seasonally dependent [e.g. *Collins et al.,* 2013]. In the western United States (U.S.), the implications of these changes for snow metrics have already been observed in the form of less precipitation falling as snow, decreased April 1 snow water equivalent (SWE), earlier snowmelt, decreased spring snow cover extent, and shortened snow cover duration [*Knowles et al.,* 2006; *Mote et al.,* 2005; *Stewart et al.,* 2005; *Groisman et al.,* 2004; *Harpold et al.,* 2012; *Kunkel et al.,* 2009; *Kapnick and Hall,* 2012].

Hydroclimatic changes in the western U.S. are expected to accelerate in the coming decades as human-induced changes in temperature and precipitation become more profound [*Ashfaq et al.,* 2013]. The responses of various snow metrics are projected to be strongly temperature dependent and complicated by large interannual variability in precipitation [*Pierce and Cayan,* 2013; *Ashfaq et al.,* 2013; *Krasting et al.,* 2013; *Kapnick and Delworth,* 2013]. Decreases in the ratio of snowfall to precipitation are expected to be most pronounced at lower elevations including the Cascade Mountains, contributing to declines in April 1 SWE of up to 60% by midcentury with more modest declines in climatologically cooler regions including the Wasatch Range and Colorado Rockies [*Ashfaq et al.,* 2013; *Pierce and Cayan,* 2013]. Changes in snowfall accumulation combined with warmer spring temperatures are projected to result in significantly earlier snowmelt and subsequent runoff, lower summer baseflow, and decreased summer surface runoff [*Ashfaq et al.,* 2013; *Hamlet and Lettenmaier*, 1999; *Stewart et al.,* 2004]. These developments have serious implications for water availability and demand, water quality, flood risk, reservoir capacity, in-stream flows, wildfire potential, irrigated and dryland agriculture, and water resource management more generally [e.g. *Barnett et al.,* 2004; *Barnett et al.,* 2005; *Westerling et al.,* 2006; *Milly et al.,* 2008; *Brekke et al.,* 2009].

Projections of hydroclimatic change are complicated by shifts in the distribution of precipitation events resulting from the intensification of the hydrologic cycle [e.g., *Giorgi et al.,* 2011]. The moisture holding capacity of the atmosphere increases at a rate of approximately 7% per degree Celsius, in accordance with Clausius-Clapeyron relationship, suggesting that the globally averaged intensity of heavy precipitation events should increase at roughly the same rate [*Trenberth et al.,* 2003]. Observations and theoretical arguments support the conclusion that this will result in an increase in heavy precipitation events at the expense of light and moderate precipitation events [*Westra et al.,* 2013; *Karl et al.,* 1995; *Karl and Knight,* 1998; *Trenberth et al.,* 2003; *Allen and Ingram,* 2002; *Giorgi et al.,* 2011; *Trenberth,* 1999] although climate variability can mask statistically significant trends [*Mass et al.,* 2011; *Duliere et al.,* 2013]. Numerous studies using global climate model projections also predict increases in heavy precipitation events [*Singh et al.,* 2013; *Meehl et al.,* 2005; *Tebaldi et al.,* 2006].

The potential impact of higher temperatures and changes in precipitation intensity, seasonality, and quantity on heavy snowfall events remains largely unexamined. Extreme snowfall events contribute 20-38% of annual SFE in the western U.S. and account for more than 70% of interannual variability in annual SFE in most montane locations [*Lute and Abatzoglou*, in press], indicating their importance to water resource availability. In the sole known study to consider the effects of climate change on extreme snowfall events, *Lopez-Moreno et al.* [2011] projected decreases (increases) in event frequency and intensity at the lowest (highest) elevations of the Pyrenees. The complex dependency of extreme snowfall events on the coincidence of temperature and precipitation, as well as precipitation intensity suggests that these events may be particularly sensitive to climate change. Furthermore, given the importance of extreme snowfall events to annual snowfall totals and variability, changes in these events may have a disproportionate impact on water resources.

Interannual variability in snowfall accumulation presents one of the largest sources of uncertainty in contemporary water resource management [*Raff et al.,* 2013], challenging water management, infrastructure, society, and ecosystems. Understanding the impact of climate change on interannual variability in snowfall has been identified as a high priority by western U.S. water management agencies [*Brekke,* 2011] but has yet to be addressed. The bulk of studies have focused on changes in mean or seasonal snowfall metrics rather than interannual variability of snowfall [e.g., *Pierce and Cayan,* 2013; *Ashfaq et al.,* 2013]. However, occurrences of extreme low and high snowfall years, which typically have the biggest impacts on society and ecosystems, may be more sensitive to changes in snowfall variability than changes in mean annual snowfall [following *Katz and Brown,* 1992]. Analogous to the findings of *Polade et al.,* [2014] that more dry days will increase annual precipitation variability, fewer snowfall days resulting from higher temperatures will decrease the sample size of snowfall events which contribute to annual SFE, likely increasing interannual variability in snowfall. The role of changes in snowfall event intensity in counteracting or reinforcing these changes has not been considered. Given the significant role that extreme snowfall events play in shaping historical interannual variability in annual snowfall [*Lute and Abatzoglou,* in press], changes in these events may significantly alter future snowfall variability.

In this study we explore the effects of climate change on extreme snowfall events and interannual snowfall variability in the western U.S. using twenty global climate model projections downscaled to montane Snowpack Telemetry (SNOTEL) stations. We seek to answer two primary questions: 1) how will climate change impact extreme snowfall events, particularly in the context of changes in annual SFE and frequency of snowfall days, and 2) how will changes in extreme snowfall events reinforce or counteract changes in annual SFE and interannual variability of annual SFE. These questions are addressed with respect to the temperature sensitivity of extreme snowfall events.

2. Data and Methods

Daily minimum and maximum temperature and precipitation from twenty global climate models (GCMs, Table 3.1) participating in the fifth phase of the Climate Model Intercomparison Project (CMIP5) [*Taylor et al.,* 2012] were downscaled for the historical period (1950-2005) and a mid-21st century period (2040-2069, hereafter referred to as midcentury). CMIP5 outputs were statistically downscaled using the Multivariate Adaptive Constructed Analogs (MACA) method [*Abatzoglou and Brown,* 2012] using the surface meteorological dataset of *Livneh et al.,* [2013] as training data across the continental United States and the Canadian portion of the Columbia Basin (downscaled outputs last accessed: January, 2014). We used the MACA approach over other statistical downscaling methods for its ability to capture daily meteorology as simulated by GCMs and its ability to show skill in regions of complex terrain, rather than simpler methods such as bias corrected statistical downscaling (BCSD) that temporally disaggregate monthly data. We modified the MACA method by applying joint bias correction to temperature and precipitation [e.g., *Zhang and Georgakakos,* 2013], enabling a more realistic derivation of temperatures coincident with precipitation and thus snowfall. We consider just a single experiment for future runs (RCP 8.5) rather than several experiments since model uncertainty generally exceeds scenario uncertainty during the first half of the 21st century, particularly at regional scales [*Hawkins and Sutton,* 2009].

Downscaled data were further bias corrected to 513 Natural Resources Conservation Service SNOTEL stations in the 11 westernmost states in the contiguous U.S. SNOTEL stations are regularly used in water resource management decision-making tools and hydrologic models and thus are relevant to the water resource management community. We applied a set of quality control procedures to the daily SNOTEL data before bias correction following *Lute and Abatzoglou,* [in press]. We bias corrected co-located gridded data to each of the stations using the non-parametric EDCDFm quantile-mapping method [*Li et al.,* 2010].

We estimate daily SFE using the empirically based precipitation phase probability function of *Dai* [2008], extended to daily timescales. Daily temperature, calculated as the average of downscaled minimum and maximum temperature, is used to calculate the percent of precipitation that falls as snow, which is multiplied by the downscaled precipitation amount to estimate daily SFE. Daily precipitation and SFE values less than 2.54mm (the resolution of SNOTEL SFE measurements) were set to 0. Daily SFE values are used to compute the snow metrics discussed below and listed in Table 3.2. We calculate the total water year (annual) SFE, the coefficient of variation (CV) of annual SFE, and the number of snow days for each station. The number of snow days is defined as the number of days per water year at each station with positive daily SFE.

Snowfall events are defined as three-day periods with net positive SFE as in *Serreze et al.,* [2001] and *Lute and Abatzoglou*, [in press] and snowfall event SFE is the cumulative SFE of the three-day period. Precipitation events are defined similarly. The extreme snowfall event metric considered here, T_{90}, is similar to extreme precipitation metrics used by *Diffenbaugh et al.,* [2005] and *Bell et al.,* [2004]. T_{90} is defined for each station separately for the historical and midcentury periods as the 90th percentile of non-overlapping snowfall events. The average SFE of an extreme snowfall event, $\overline{SFE}_{90}$, is computed as the mean SFE of a snowfall event exceeding T_{90}. The SFE of all extreme snowfall events each year, $\sum SFE_{90}$, is the cumulative SFE that fell during non-overlapping snowfall events exceeding T_{90} each year. We also compute the CV of $\sum SFE_{90}$.

The observed temperature coincident with snow days, $Tavg_{snow}$, and the observed temperature coincident with extreme snowfall events, $Tavg_{90}$, are derived from SNOTEL data. $Tavg_{90}$ and $Tavg_{snow}$ are compared using one-sided t-tests (alpha=0.05). The observed mean winter (November through March) temperature is used to divide stations into six 2°C temperature bins between -9°C and +3°C. Bins are labeled by the midpoint temperature (e.g. the bin between -9°C and -7°C was labeled -8°C) and are used to group stations in subsequent analyses. Although temperature binning groups together diverse climates (such as the Cascades and Arizona in the warmest bin), the groupings are useful for examining the differential temperature sensitivities of snowfall events.

For each station and model, for all non-overlapping three-day snowfall events in both the historical and midcentury periods, we compute the 25th, 50th, 75th, 90th, 95th, and 99th percentiles. We computed the ratio of midcentury percentiles to historical percentiles by considering all stations in each temperature bin. The multi-model mean of event percentile ratios for each temperature bin is plotted as well as the 10th and 90th percentiles of model percentile ratios. Changes in the distribution of cold season (October through April) precipitation events are evaluated in the same manner.

Results are generally presented through the multi-model mean difference between the midcentury period value and the historical period value. The multi-model mean has been shown to be superior to any single model in regional climate change studies due to the tendency for opposing errors in the individual models to off-set one another [*Pierce et al.,* 2009]. For variables defined on an annual basis (all variables except T_{90} and CV) we quantify uncertainty in model projections using an approach similar to *Tebaldi et al.,* [2011] whereby robust changes are denoted where a majority of models project a significant change and at least 80% of these models project a change of the same sign. Significance is computed using a t-test (alpha=0.05) comparing historical period values to midcentury period values. We recognize that this approach considers changes uncertain both when only a minority of model projections are significant and when model projected changes are significant but of opposite signs [*Tebaldi et al.,* 2011; *Collins et al.,* 2013]. To address this we have also included plots of the model spread in projected changes. Since there is only one value of T_{90} and CV for the historic and future periods for each model, we employed a Monte Carlo resampling approach. For T_{90}, a sample of 75% of historical years was randomly selected 1000 times and T_{90} was recomputed each time. The same procedure was applied to midcentury years. The resulting T_{90} values for the historical and midcentury periods were then compared with a t-test (alpha=0.05). The same procedure was applied to CV except instead of calculating T_{90} from each sample, CV was calculated. Certainty in changes in T_{90} and CV was then calculated using the method outlined above for the other metrics.

3. Results

Projected changes, averaged across the stations, in mean winter (November through March) temperature by midcentury ranged from 1.5°C to nearly 5°C with the most warming projected by the MIROC-ESM and MIROC-ESM-CHEM models and the least warming projected by the GFDL-ESM2M and MRI-CGCM3 models (Figure 3.1), although there is considerable spatial heterogeneity in temperature projections across the region. All models projected increases in station-averaged cumulative winter precipitation, although projected increases varied from approximately 2% to more than 20%. Increases in precipitation were largest in the CanESM2 model while the Inmcm4, CSIRO-Mk3-6-0, and NorESM1-M models were the driest. The spread in model projections of winter temperature and precipitation highlights the importance of using a range of GCMs when evaluating plausible changes in climate and potential hydroclimate impacts.

Historical mean winter (November through March) temperatures were above freezing at stations in the Cascades and Arizona and coldest at stations in the high elevation continental mountains (Figure 3.2a). The spatial pattern of temperatures coincident with extreme snowfall events, $Tavg_{90}$, was characterized by a longitudinal gradient similar to that of mean winter temperature (Figure 3.2a) with warmer temperatures (-3°C to 0°C) over the Sierra Nevada, Cascades, and Arizona and cooler temperatures (-7°C to -3°C) over the more continental mountains (Figure 3.2b). Conversely, temperatures coincident with snowfall extremes in parts of the Cascades, Blue Mountains, and Sierra Nevada were significantly cooler than temperatures on all snow days ($Tavg_{snow}$), and significantly warmer than $Tavg_{snow}$ in the Middle and Southern Rockies (Figure 3.2c). These findings suggest that while extreme snowfall events in the Middle and Southern Rockies are less temperature sensitive than extreme snowfall events in other regions, they are relatively more temperature sensitive than typical snowfall events in cold regions.

Annual SFE was projected to decline most severely in climatologically warmer areas including the Cascades and Arizona, with a 35-70% reduction by midcentury (Figure 3.3a). By contrast, declines in annual SFE were 5-20% in the coldest locations, including the Middle and Southern Rockies. Declines in annual SFE were significant for all but a few stations in the coldest regions, where the impacts of warming are largely offset by increases in winter precipitation (Figure 3.1) and the small magnitude of change limits the signal to noise ratio. Both projected declines and the range of model projections were greatest for locations with higher climatological winter temperatures where model projections of change in annual SFE spanned a range of up to 40% (Figure 3.4a). The inter-model spread in projections of annual SFE, averaged across all stations within each bin, was smallest for bins with the smallest change projected, corresponding to the coldest locations. The MRI-CGCM3 model was the only model to project increases in annual SFE in the coldest bin and the smallest reductions in annual SFE in all other temperature bins. This can be attributed to the combination of this model projecting the second least overall warming across the stations and increases in precipitation greater than the multi-model mean (Figure 3.1).

Projected changes in number of snow days showed a similar spatial pattern to changes in annual SFE with the smallest declines (10-20%) in the Middle and Southern Rockies and parts of Utah and the largest declines (up to 50%) in the Cascades and Arizona (Figure 3b). Changes in number of snow days were significant for all stations. As with projected changes in annual SFE, projected declines and the inter-model range of projections in number of snow days were greatest for the warmest stations (Figure 3.4b). The MRI-CGCM3 model was again the greatest outlier, projecting the smallest declines in number of snow days in every temperature bin. Percent declines in number of snow days were generally greater than percent declines in annual SFE for the coldest bins and lesser for the warmest bins.

Projected percent changes in T_{90} were characterized by the longitudinal gradient evident in the previous results (Figure 3.5a). Changes in the extreme snowfall event threshold, T_{90}, and the mean SFE of extreme snowfall events, $\overline{SFE}_{90}$, were strongly positively correlated with elevation and strongly negatively correlated with $Tavg_{90}$. At stations in the Cascades, Sierra Nevada, and the mountains of Arizona, which correspond to the warmest temperature bins, T_{90} was projected to decline by 20-50% by midcentury. At the highest elevations, including the Middle and Southern Rockies, T_{90} was projected to increase by up to 10%. The spread of model projected percent changes in T_{90} was relatively small compared to other snow metrics and there were no obvious outlier models (Figure 3.6a). Projected percent changes in the mean SFE of extreme snowfall events, $\overline{SFE}_{90}$, were similar to those of T_{90} (Figure 3.5b). Modest increases in $\overline{SFE}_{90}$ were projected for the Middle and Southern Rockies, while decreases of 30-50% were projected for some stations in the Cascades, Sierra Nevada, and Arizona. By definition, percent changes in the mean number of extreme snowfall events per year will change at the same rate as number of snow days (Figure 3.3b). All models projected increases or no change in $\overline{SFE}_{90}$ for stations in the coldest (-8°C) bin (Figure 3.6b). The inter-model range was again smallest for the -6°C bin where projected percent changes were smallest.

We contextualize changes in snowfall extremes relative to both precipitation and snowfall events across statistical moments. Generally, changes in snowfall events mirrored changes in precipitation events, although the added temperature sensitivity of snowfall events resulted in less positive changes in snowfall (Figure 3.7). With the exception of small to moderate events (25th, 50th percentile) in the warmest locations, precipitation events (blue) were projected to intensify. The greatest increases were projected for the most extreme precipitation events and for the coldest regions. Multi-model mean changes in precipitation indicated increases of nearly 20% in the size of 99th percentile precipitation events for the coldest bins. Across all temperature bins the mean annual number of precipitation events was projected to change very little (blue text). In contrast, the mean annual number of snowfall events was projected to decrease substantially, with declines of nearly 30% in the warmest (2°C) bin (black text). In general, changes in snowfall event percentiles (black/gray) were less positive than changes in precipitation events and were characterized by particularly large declines in warmer locations. Small and moderate snowfall events (25th and 50th percentiles) were projected to decline in every temperature bin. The most extreme snowfall events were projected to change the least and were projected to increase by nearly 10% in the coldest bins where the greatest increases in extreme precipitation events were also found. The contrast between changes in the 99th percentile and changes in the 25th percentile of snowfall events increased with increasing temperature, indicating the differential temperature sensitivities of snowfall event percentiles.

Interannual variability in annual SFE, in terms of the CV of annual SFE, was projected to increase at all stations (Figure 3.8a). At scattered locations in the Sierra Nevada, Utah, and the Middle and Southern Rockies, projected increases in variability were modest (5-20%) and, for some stations, insignificant. In contrast, in the Cascades, Blue Mountains, and Northern Rockies variability of annual SFE was projected to increase by 50-85% by midcentury. With fewer snow days (Figure 3.3b), annual SFE will be composed of a smaller sample of snowfall events. A smaller sample size leads to increased variability about the mean. Furthermore, at the coldest stations, although annual SFE and number of snow days are projected to decrease (Figure 3.3), the standard deviation of annual SFE is projected to increase by up to 13% (not shown), further contributing to increased interannual variability.

Projected percent changes in the CV of $\sum SFE_{90}$ (Figure 3.8b) had a similar spatial pattern to that of percent changes in the CV of annual SFE, but were significant at fewer stations and were generally larger than percent changes in the CV of annual SFE. In the Cascades, Blue Mountains, and Northern Rockies the CV of $\sum SFE_{90}$ was projected to increase by 60-100%. Projected changes in the CV of $\sum SFE_{90}$ calculated using only the historical T_{90} values (i.e. a static threshold) had a similar spatial pattern but were much greater (not shown). Projected decreases in the number of snow days (Figure 3.3b) indicate that the number of extreme snowfall events will also decrease. As with annual SFE, the decreased sample size of extreme snowfall events will lead to greater interannual variability about the mean. This is compounded by the fact that, despite decreases in $\sum SFE_{90}$ projected for roughly 65% of stations (increases are found at coldest stations), the standard deviation of $\sum SFE_{90}$ was projected to increase at more than 97% of stations, with the largest increases in the Northern Rockies (up to 65%) (not shown).

4. Discussion

The coincident temperatures of extreme events (Figure 3.2b) are largely a by-product of the regional climate which is partly attributable to elevation and continentality; coincident temperature was strongly correlated with station elevation (r=-0.79, p<0.0001). Differences between temperatures coincident with extreme events and temperatures coincident with all snow days are a result of the interplay between enhanced atmospheric moisture content and potential precipitation rates with warming, and decreased proportion of precipitation falling as snow with warming. In relatively warmer regions, cooler temperatures increase the snow to precipitation ratio, resulting in larger events occurring at temperatures slightly below average snow day temperatures. In contrast, in relatively cold regions, the moisture holding capacity of the atmosphere is limited and increases at approximately 7% per degree Celsius in accordance with the Clausius-Clapeyron relationship. It follows that extreme snowfall events may be more likely to occur at temperatures slightly above average snow day temperatures in cooler regions. These concepts are illustrated by the clear longitudinal gradient in extreme snowfall event temperature anomalies (Figure 3.3b). Differences between extreme event coincident temperatures and snow day temperatures may also be a function of snowfall seasonality; west of the Rockies, heavy snowfall events primarily occur December through February when temperatures are coldest while east of the Rockies, heavy snowfall events can occur late in the Spring when temperatures are warmer [*Serreze et al.,* 2001]. We also computed extreme snowfall event temperature anomalies and snow day event temperature anomalies relative to the day of the year (using a 30 day sliding window). At most stations east of the Rockies, where extreme snowfall events often occur late in the spring, and at many stations in the Cascades, where mean winter average temperatures are above freezing at many stations, extreme snowfall event temperature anomalies were significantly colder than mean snow day temperature anomalies. In most of Idaho the opposite was true; extreme snowfall event temperature anomalies relative to day of year were significantly warmer than mean snow day temperature anomalies, suggesting that during winter temperatures are relatively cold and the atmosphere is moisture limited in this region.

Regional projections of change in annual SFE (Figure 3.3a) were comparable to those found by *Pierce and Cayan* [2013] for October through March SFE. Of the many snow metrics they analyzed, October through March SFE was the last to emerge as significant and for some regions significance was not achieved by 2100. This was attributed to the sensitivity of seasonal snowfall to large interannual variability in precipitation. The greater certainty in our projections of change in annual SFE is likely in part due to the inclusion of SFE accumulation after March 31, which is especially sensitive to warming [*Pierce and Cayan,* 2013], and in part due to differences between the uncertainty measures used. Projected declines in annual SFE indicate reduced natural storage of winter precipitation, in the context of increased total winter precipitation (Figure 3.1). Barring the creation of increased reservoir capacity, this will result in a large portion of annual precipitation being unavailable for use [*Barnett et al.,* 2005]. Declines in snowfall shown here will be compounded by earlier snowmelt [*Ashfaq et al.,* 2013; *Stewart et al.,* 2004] and will force difficult choices between hydropower, ecological, agricultural and other objectives [*Barnett et al.,* 2004].

Changes in number of snow days (Figure 3.3b) were spatially similar to changes in annual SFE. At higher elevations including the Middle and Southern Rockies, which correspond to the coldest temperature bins, percent reductions in number of snow days were typically the same or slightly greater than percent reductions in annual SFE. In most other regions including the Cascades and mountains of Arizona in particular, which correspond to the warmest temperature bins, percent reductions in annual SFE were far greater than percent reductions in number of snow days. Given that annual SFE is a function of snowfall event frequency and intensity, this suggests that mean snowfall event intensity in the coldest regions may be expected to increase while mean snowfall event intensity in the warmer regions may be expected to decrease.

Changes in snowfall event intensity will be in part a function of changes in precipitation intensity. Across all temperature bins, extreme precipitation was projected to increase more than small and moderate precipitation events (Figure 3.7), similar to the findings of *Wilby and Wigley*, [2002] and *Meehl et al.,* [2005]. Projected changes in the distribution of snowfall events reflect changes in the distribution of precipitation events while illustrating the differential temperature sensitivities of extreme snowfall events compared to the average snowfall event (Figure 3.7). The relatively cold coincident temperatures of extreme snowfall events in the Middle and Southern Rockies (Figure 3.2b) combined with expected increases in atmospheric moisture will enable larger snowfall events into the mid-21st century (Figure 3.5), despite the fact that extremes in these regions occur at significantly warmer temperatures than the average snowfall event (Figure 3.2c). In these cooler regions, the spread between percent changes in extremes and the rest of the distribution is relatively small (Figure 3.7). For the same annual SFE, fewer but more intense snowfall events have been shown to increase annual maximum SWE, partially counteracting decreased annual snowfall and increased melt rates [*Kumar et al.,* 2012]. However, projected decreases in April 1 SWE [*Ashfaq et al.,* 2013], a commonly used surrogate for peak SWE, suggest that even before midcentury the enhancement of peak SWE by more extreme snowfall events will not be sufficient to maintain peak SWE at historic levels. As winter temperatures continue to increase through the latter half of the 21st century, extreme events in the coldest regions will likely decrease in SFE similarly to warmer regions.

Many of the warmer locations, including the Cascades and the Sierra Nevada, are characterized by high moisture availability and moderate winter temperatures due to their location relative to storm tracks moving eastward from the Pacific Ocean. Mild winter temperatures increase the vulnerability of snow in terms of precipitation phase and melt rates. Extreme snowfall events at many stations in these regions historically occurred at temperatures above -3°C (Figure 3.2b), making them vulnerable to projected increases of 1.5-5°C by midcentury (Figure 3.1, Figure 3.5). However, extreme snowfall events in the warmest locations occur at significantly cooler temperatures than the average snowfall event (Figure 3.2c). The differential temperature sensitivities of snowfall events is evident in the modest declines in extreme snowfall events relative to the large declines small and moderate snowfall events in the warmest bins (Figure 3.7). These developments have implications for snowpack dynamics as well as avalanche hazards.

Changes in the event composition of annual SFE have implications for interannual variability in annual SFE. In particular, decreased number of snow days, which is projected for all stations, will decrease the sample from which annual SFE is created, resulting in greater variability about the mean. This is similar to the finding of *Polade et al.,* [2014] that increased number of dry days effectively reduces the sample from which total annual precipitation is created and therefore increases interannual precipitation variability. The effect of fewer snow days will be amplified by snowfall event distributions that are increasingly composed of extreme snowfall events. The reliance of annual SFE on fewer events which are shifting toward heavier events at the expense of light and moderate events will increase the sensitivity of annual SFE to the occurrence (or absence) of a handful of snowfall events. These developments are illustrated by the projected increases in interannual variability in annual SFE at all stations (Figure 3.8), with the largest increases generally in regions which experienced the largest historical variability in annual SFE [*Lute and Abatzoglou*, in press]. Projected percent increases in the CV of the cumulative SFE of extreme events (Figure 3.8b) outstrip those of the CV of annual SFE. The increasing tendency toward heavy events at the expense of light and moderate events (Figure 3.7) combined with increasing variability in the heaviest events will serve to reinforce the projected increases in annual SFE variability due to decreasing snow days alone.

5. Conclusion

This work relied on climate projections from 20 CMIP5 global climate models forced with the RCP 8.5 scenario, downscaled to the western U.S., and bias corrected to 513 SNOTEL stations to assess changes in extreme snowfall events and their implications for mean annual SFE and interannual variability in annual SFE. Previous studies have considered changes in mean and seasonal snowfall metrics [e.g. *Pierce and Cayan,* 2013; *Ashfaq et al.,* 2013; *Krasting et al.,* 2013] but have not considered changes in snowfall variability, although interannual variability in snowfall presents one of the greatest challenges to current water management [*Raff et al.,* 2013]. While much literature has focused on observed, projected, and theoretical changes in extreme precipitation [e.g. *Karl and Knight,* 1998; *Trenberth et al.,* 2003; *Giorgi et al.,* 2011; *Trenberth,* 1999; *Singh et al.,* 2013; *Wilby and Wigley,* 2002; *Meehl et al.,* 2005; *Tebaldi et al.,* 2006] changes in extreme snowfall events have received very little attention [with the exception of *López-Moreno et al.,* 2011] despite their importance to annual SFE totals and interannual variability in annual SFE [*Lute and Abatzoglou,* in press]. The current study demonstrates the differential temperature sensitivities of extreme snowfall events relative to other snowfall events and the ramifications changes in extreme snowfall events have for annual snowfall totals and variability.

The differential temperature sensitivities of extreme snowfall events compared to the average snowfall event were attributed to a balance between increased atmospheric moisture holding capacity at warmer temperatures and increased snow to precipitation ratio at colder temperatures. Furthermore, the differential temperatures of snowfall events were evident in the projected changes in snowfall event distributions which were characterized by greater declines in small to moderate events than heavy events, a pattern that was accentuated in warmer regions.

Both annual SFE and annual number of snow days were projected to decrease at every SNOTEL station by midcentury (2040-2069). Decreased snowpack resulting from less snowfall and higher melt rates will decrease summer streamflow and increase surface water temperature, negatively impacting aquatic species [*Isaak et al.,* 2012]. Projected increases in the interannual variability of annual SFE are partly attributable to a reduction in the number of snow days which effectively decreases the sample of events from which annual SFE is created and increases the importance of individual snowfall events to annual SFE. Shifts in the distribution of snowfall events toward heavy events at the expense of small and moderate events and increased variability of extreme snowfall events will magnify the increasing variability in annual SFE due to snow days alone. In the future, annual SFE will be composed of fewer, relatively heavy snowfall events.

Projected declines in annual SFE and snowfall days, coupled with projected increases in winter precipitation totals and intensity suggest that even at high elevation SNOTEL stations, snow events are likely to transition to rain events, increasing the likelihood of rain-on-snow events with implications for flood risk [*McCabe et al.,* 2007]. Furthermore, decreased natural water storage in snowpack will increase the need for reservoir capacity if current water availability levels are to be maintained [*Barnett et al.,* 2005]. Barring additional storage infrastructure, many regions of the West will be faced with difficult choices between conflicting objectives including ecosystem support, hydropower, irrigation, and navigation [*Barnett et al.,* 2004; *Barnett et al.,* 2005]. This situation will become more acute as snowfall continues to decline, snowmelt occurs earlier in the year [*Stewart et al.,* 2004], and populations and evaporative demand increase [*Collins et al.,* 2013]. Increasing interannual variability in annual SFE will add further complexity to future water management. The growing importance of heavy snowfall events to annual SFE totals suggests that improved understanding of the synoptic causes of these events will enable water resource managers to make the most of diminished and more variable snow water resources.

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Table 3.1. List of CMIP5 models used in this study[1]

Model	Expansion
bcc-csm1.1	Beijing Climate Center, Climate System Model, version 1.1
bcc-csm1.1(m)	Beijing Climate Center, Climate System Model, version 1.1
BNU-ESM	Beijing Normal University, Earth System Model
CanESM2	Second Generation Canadian Earth System Model
CCSM4	Community Climate System Model, version 4
CNRM-CM5	Centre National de Recherches Météorologiques Coupled Global Climate Model, version 5
CSIRO-Mk3.6.0	Commonwealth Scientific and Industrial Research Organisation Mark, version 3. 6. 0
GFDL-ESM2G	Geophysical Fluid Dynamics Laboratory Earth System Model with Generalized Ocean Layer Dynamics (GOLD) component (ESM2G)
GFDL-ESM2M	Geophysical Fluid Dynamics Laboratory Earth System Model with Modular Ocean Model 4 (MOM4) component (ESM2M)
HadGEM2-ES365	Hadley Centre Global Environmental Model, version 2 (Earth System)
HadGEM2-CC365	Hadley Centre Global Environmental Model, version 2
INM-CM4	Institute of Numerical Mathematics Coupled Model, version 4
IPSL-CM5A-LR	L'Institut Pierre-Simon Laplace Coupled Model, version 5, coupled with NEMO, low resolution
IPSL-CM5A-MR	L'Institut Pierre-Simon Laplace Coupled Model, version 5
IPSL-CM5B-LR	L'Institut Pierre-Simon Laplace Coupled Model, version 5
MIROC5	Model for Interdisciplinary Research on Climate, version 5
MIROC-ESM	Model for Interdisciplinary Research on Climate, Earth System Model
MIROC-ESM-CHEM	Model for Interdisciplinary Research on Climate, Earth System Model, Chemistry Coupled
MRI-CGCM3	Meteorological Research Institute Coupled Atmosphere-Ocean General Circulation Model, version 3
NorESM1-M	Norwegian Earth System Model, version 1

[1] One ensemble run, r1i1p1, was downscaled for each model except CCSM4 for which we used r5i1p1.

Table 3.2. List of metric abbreviations, descriptions, definitions, and units.[1]

Metric	Description	Definition	Units
Annual SFE	Annual SFE	Cumulative SFE over the water year	mm SFE
Snow days	Number of snowfall days	Number of days per water year with positive daily SFE	days
Snowfall event	Snowfall event	Three-day period with positive SFE. Snowfall event SFE is the cumulative SFE over the three days centered on the event.	
T_{90}	Extreme snowfall event threshold	The 90th percentile of all snowfall events during the historical period.	mm SFE
$\overline{SFE}_{90}$	Mean SFE of extreme snowfall events	Average SFE of snowfall events greater than T_{90}.	mm SFE
$\sum SFE_{90}$	Cumulative SFE of extreme snowfall events	Annual cumulative SFE of non-overlapping snowfall events greater than T_{90}.	mm SFE
$Tavg_{snow}$	Temperature coincident with snow days	Mean average temperature on snow days.	°C
$Tavg_{90}$	Temperature coincident with extreme snowfall events	Mean average temperature over the three day period of snowfall events greater than T_{90}.	°C

[1] All metrics are calculated as the multi-model mean of the downscaled GCM data with the exception of $Tavg_{snow}$ and $Tavg_{90}$ which use historical SNOTEL observations.

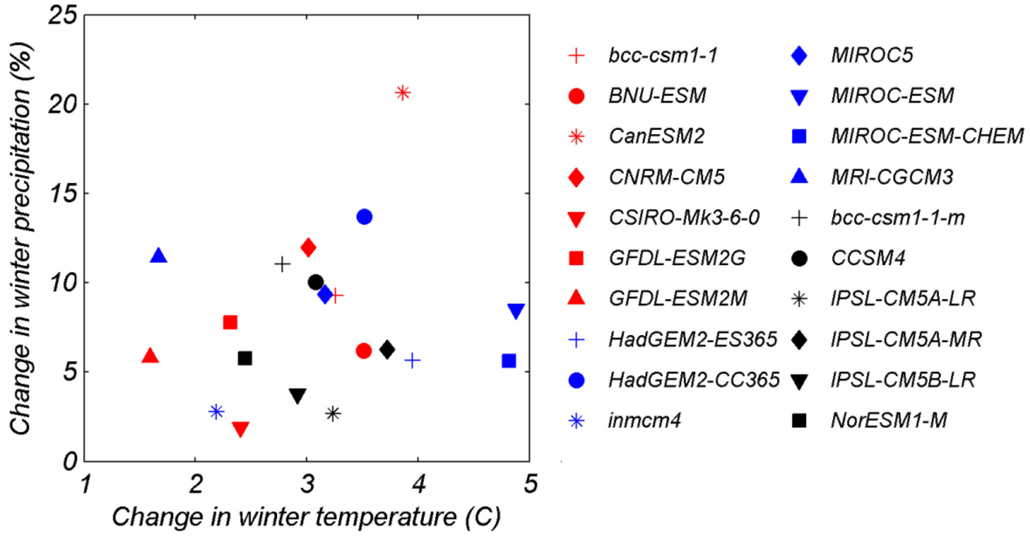

Figure 3.1 Station-averaged projected change in mean winter (November through March) average temperature (°C, x-axis) and percent change in cumulative winter precipitation (%, y-axis) between the historical (1950-2005) and midcentury (2040-2069) under RCP 8.5.

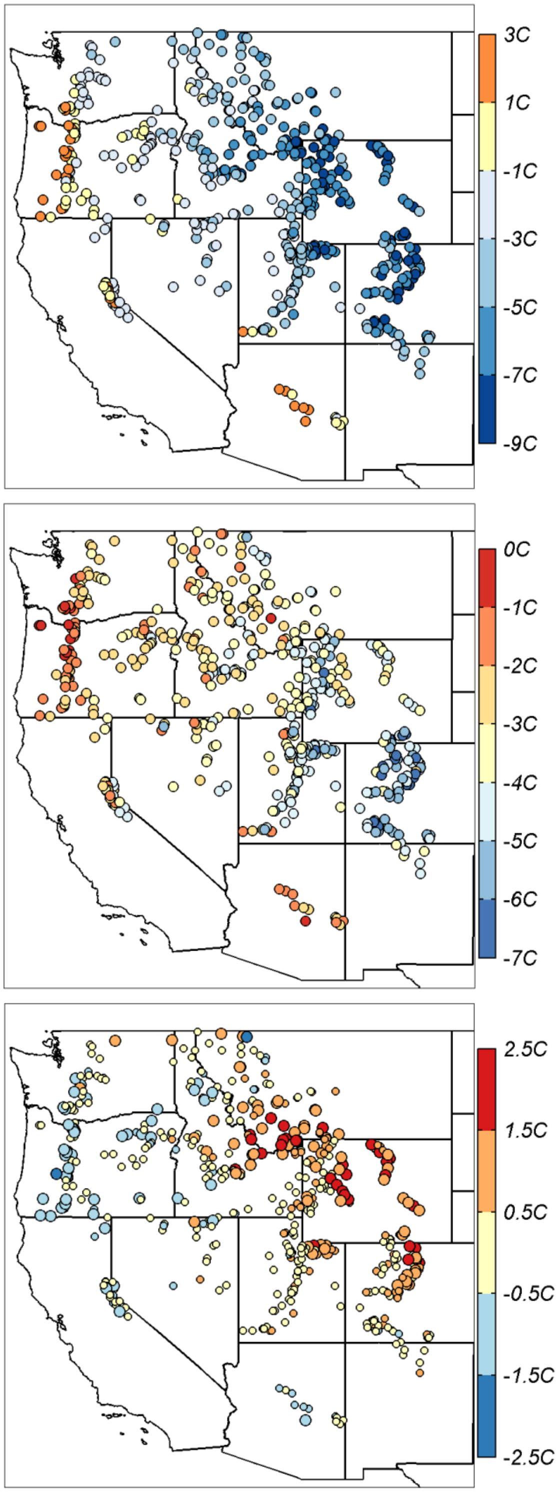

Figure 3.2 From SNOTEL observations: a) observed mean winter (November through March) temperature. Each color range identifies a temperature bin which will be referred to throughout the paper. b) Average temperature coincident with extreme snowfall events ($Tavg_{90}$). c) Difference between mean coincident average temperature of extreme snowfall events and mean coincident average temperature on snow days ($Tavg_{snow}$). Larger markers indicate that extremes occur at significantly different temperatures than all snow days by t-test (alpha=0.05).

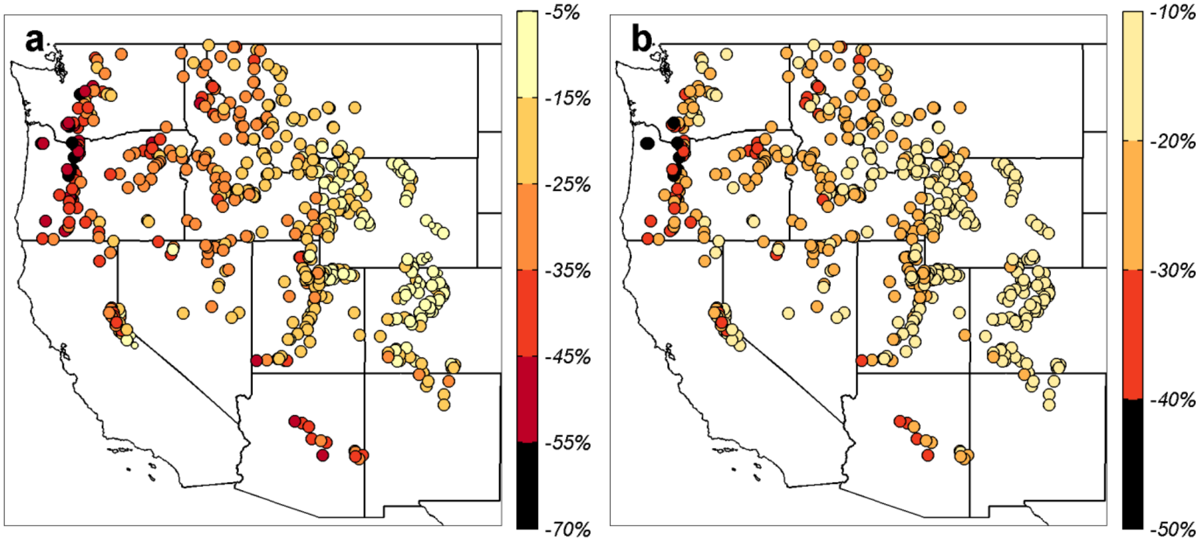

Figure 3.3 a) percent change in annual SFE and b) percent change in number of snow days. Larger (smaller) markers indicate significant (insignificant) changes.

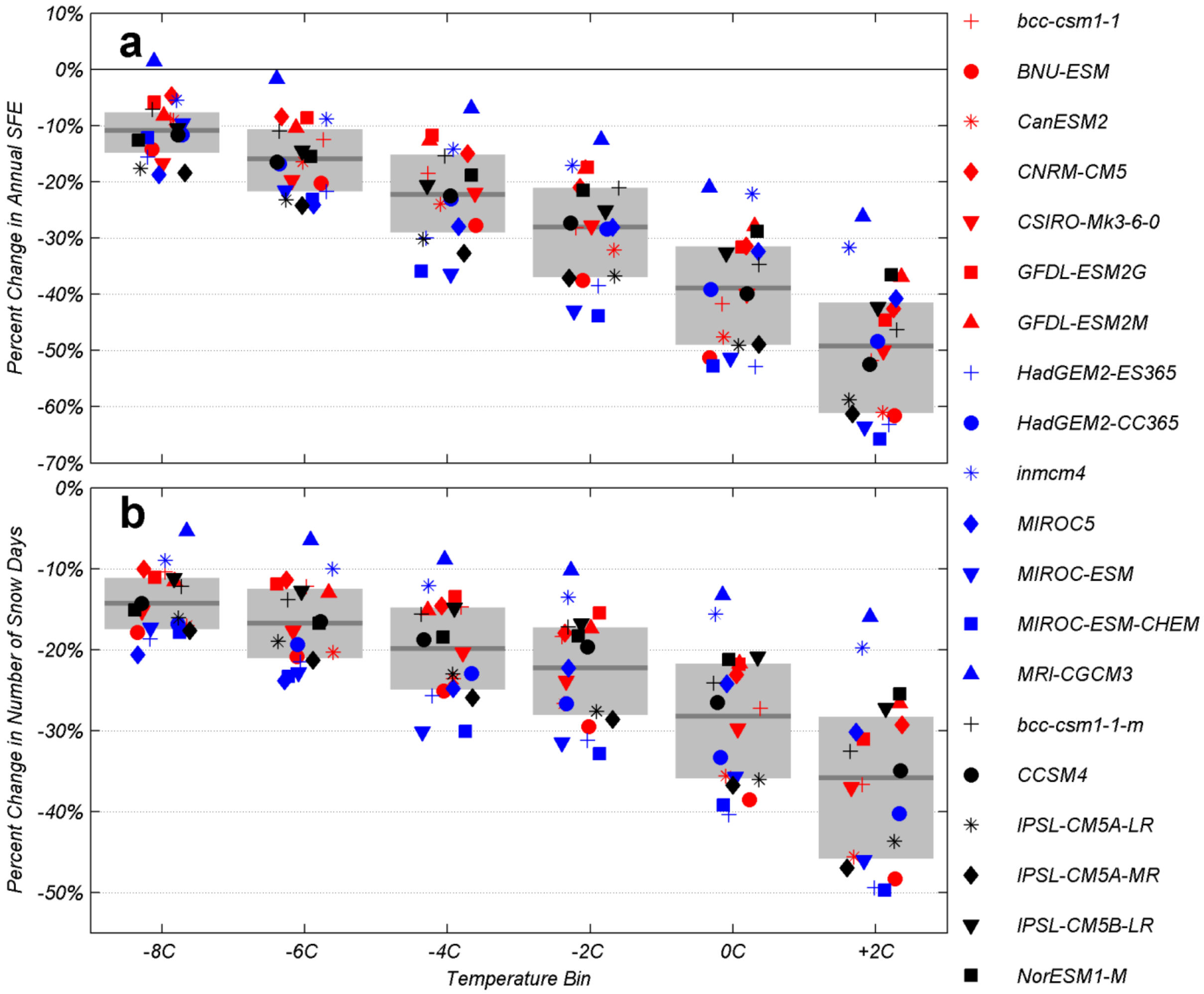

Figure 3.4 Model spread by temperature bin as indicated in Figure 3.2a for a) percent change in annual SFE and b) percent change in number of snow days. Dark grey lines represent the multi model mean value and light gray areas are delimited by the 25th and 75th percentiles of model projections.

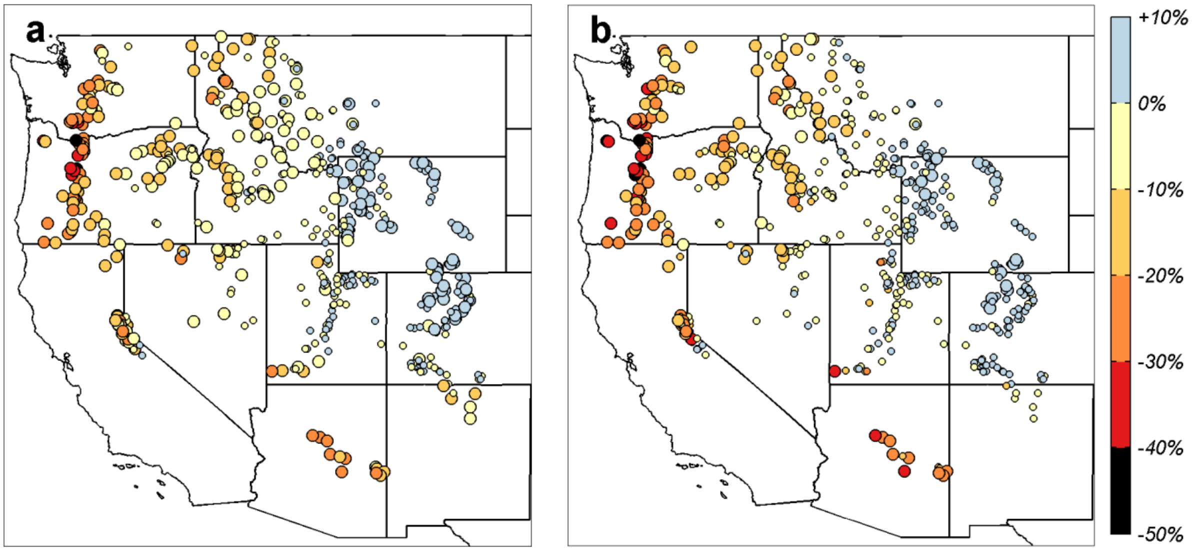

Figure 3.5 a) Percent change in 90th percentile threshold, T_{90}, and b) percent change in mean SFE of extreme snowfall events, $\overline{SFE}_{90}$. Larger (smaller) markers indicate significant (insignificant) changes.

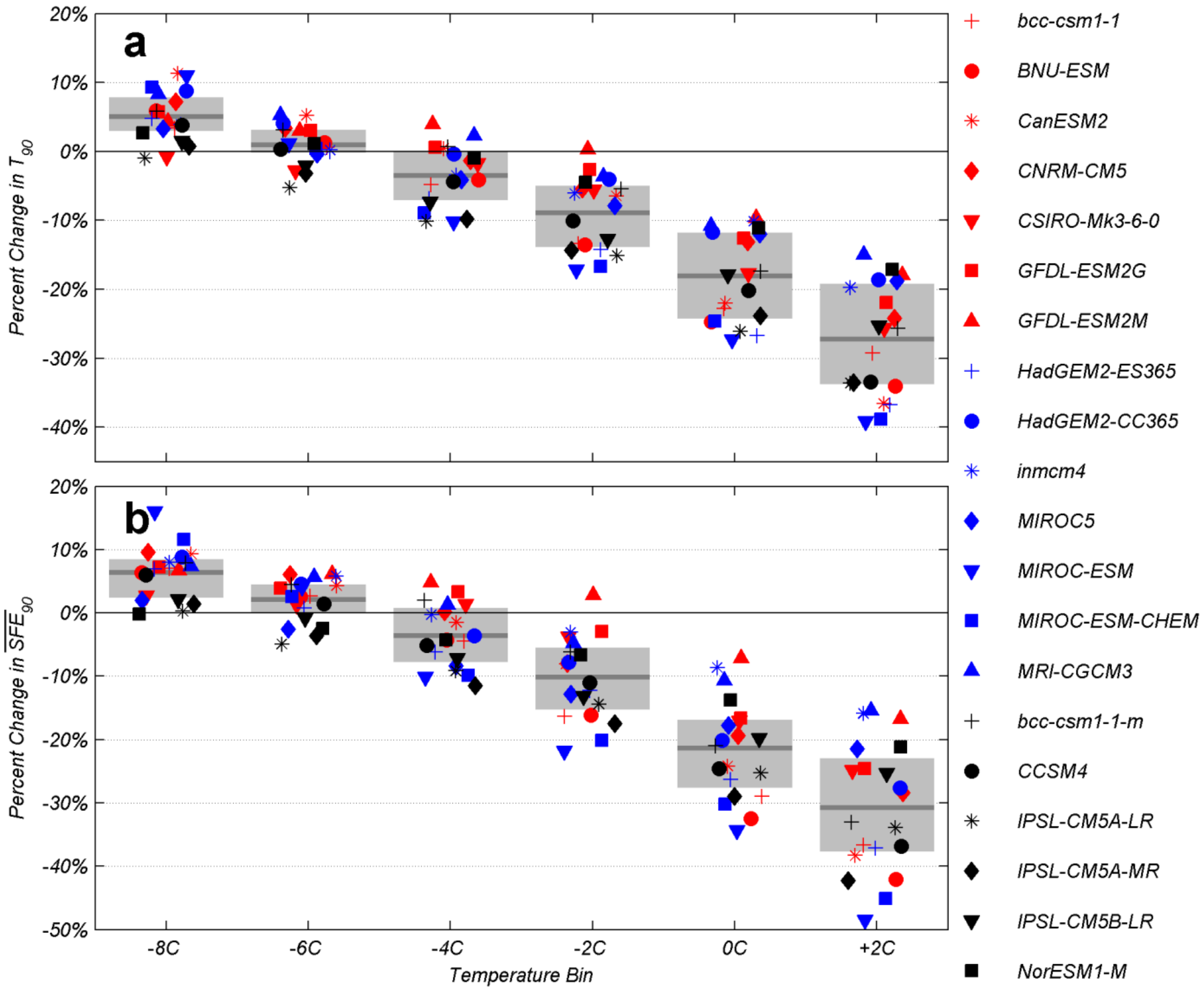

Figure 3.6 Model spread by temperature bin as indicated in Figure 3.2a for a) percent change 90th percentile threshold, T_{90}, and b) percent change in the mean SFE of extreme snowfall events, $\overline{SFE}_{90}$. Dark grey lines represent the multi model mean value and light gray areas are delimited by the 25th and 75th percentiles of model projections.

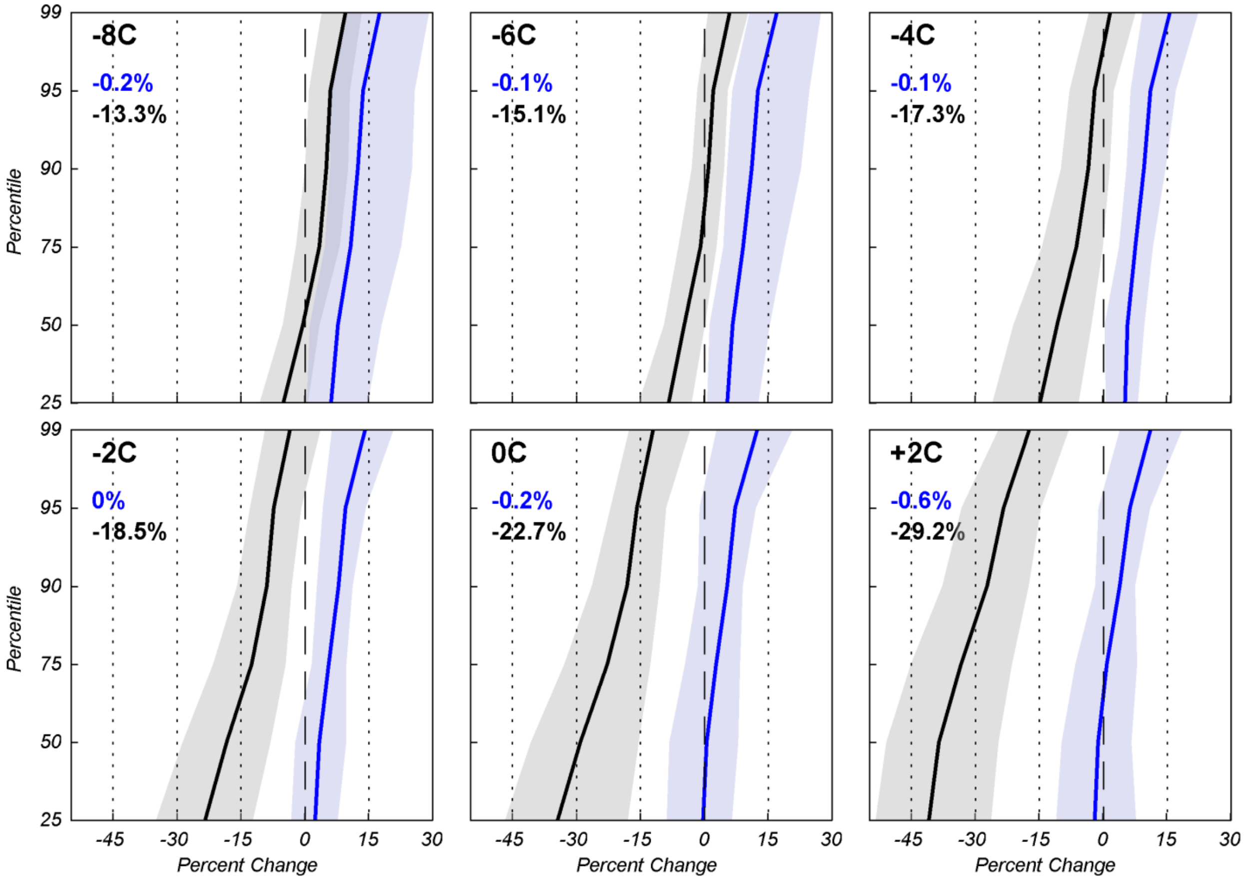

Figure 3.7 Changes in the 25th, 50th, 75th, 90th, 95th, and 99th percentiles of precipitation events (blue) and snowfall events (black) grouped by temperature bin as indicated in Figure 3.2a and labeled in the upper left of each subplot. Text the temperature bin label indicates the percent change in mean annual number of precipitation events (blue) and snowfall events (black) between the historical and midcentury periods. The station- and model-averaged percentile ratios of precipitation events (snowfall events) are represented by the blue lines (black lines). The 10th and 90th percentiles of model precipitation (snowfall) percentile ratios averaged over stations are represented by the shaded blue (gray) areas. The vertical dashed line in each subplot represents no change in the percentiles between historical and midcentury periods.

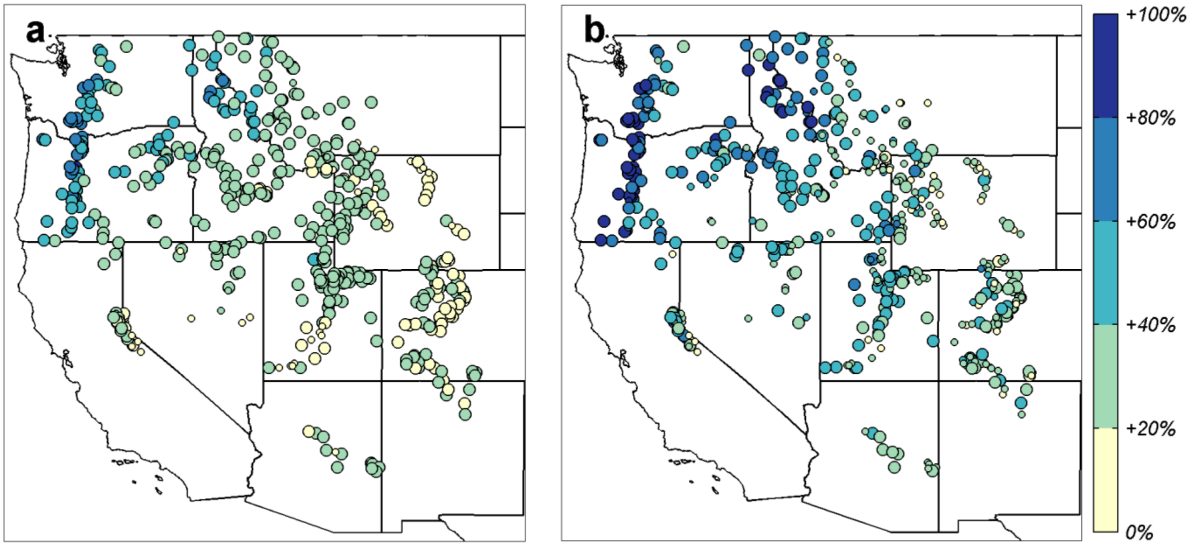

Figure 3.8 Percent change in CV of a) annual SFE and b) cumulative SFE of top decile snowfall events, $\sum SFE_{90}$ (using transient baseline). Larger (smaller) markers indicate significant (insignificant) changes.

Chapter 4:

Implications for Water Resource Management

1. Introduction

Water resources in the western United States are characterized by asynchronous supply and demand, necessitating careful orchestration of snowpack and reservoir storage. The bulk of precipitation occurs during the winter months and in montane regions up to 70% of precipitation falls as snow [*Serreze et al.,* 2001], providing natural storage and delayed release of water as temperatures increase in the spring and early summer. Water demand from ecosystems and consumptive water users peaks in the summer when precipitation is generally least and evapotranspiration greatest. Among the users of this limited water supply are ecosystems and aquatic species, hydropower, agriculture, industry, recreation, and domestic users.

This asynchrony, combined with interannual climate variability, is a challenge for water resource management in a region with limited water supply. Incorporation of climate information in water resource planning is limited due to the high uncertainty associated with climate predictions [*Raff et al.,* 2013]. The extensive system of reservoirs in the western U.S. helps buffer seasonal and interannual water shortages by storing spring snowmelt for use during the dry season and storing carry-over water for use during subsequent drought years. Despite this highly developed infrastructure and expertise, climate variability often results in less supply than demand, forcing difficult prioritization of competing users and potential water rights curtailments.

The challenges of climate variability are compounded by trends in land use and social values, population growth, and climate change [*Brekke et al.,* 2009]. Water resource management has historically been based on the assumption of stationarity which holds that future phenomena will occur within the realm of variability that can be estimated from past observations (e.g. a 100 year flood). This assumption is inappropriate in a changing climate [*Brekke et al.,* 2009; *Milly et al.,* 2008]. Climate change adaptation will require the development of new assumptions, assessment of potential impacts, and projections of changes in extreme precipitation [*Brekke et al.,* 2009]. While the ability to anticipate and manage for current hydrologic extremes will make the water resource management community more capable of dealing with future climate change, this is only a starting point for adaptation [*Raff et al.,* 2013]. Methods for determining the probability of extreme meteorological events in a changing climate are needed for reservoir management, flood risk, and infrastructure hazard implications [*Brekke et al.,* 2011]. Tools which utilize the most recent period of historical observations or which can incorporate projections of hydroclimatic change will be instrumental in managing nonstationary water resources.

2. Short-Term Water Resource Management

Ideally, water managers would be able to forecast seasonal water supply months in advance, enabling them to capitalize on available water by storing as much as possible and releasing only as much as necessary, while fulfilling the maximum amount of operational objectives (e.g. flood control, minimum flow requirements). While advances have been made in this area, seasonal water supply forecasts remain uncertain, especially at longer lead times. In practice, seasonal water supply forecasts or 'outlooks', are updated in regular cycles throughout the winter and spring. The timeframes of water supply outlooks are nested, from fine to medium to coarse temporal resolution. Each outlook resolution is focused on specific objectives, informed by data and forecasts relevant to its resolution, and informs the other outlooks in a continuing and responsive process similar to adaptive management. A summary of the outlook resolutions, update cycles, objectives, and information for each outlook is presented in Table 4.1 (modified from *Raff et al.,* [2013]).

The largest uncertainties in developing water supply outlooks are attributable to snowfall and precipitation accumulation during the winter and early spring. The 2013 technical report 'Short-Term Water Management Decisions: User Needs for Improved Climate, Weather, and Hydrologic Information' details the tools and information currently used in water resource management and assesses needs for additional tools and information [*Raff et al.,* 2013]. This document represents a collaborative assessment by the major water resource management agencies in the United States: the U.S. Bureau of Reclamation (USBR), the U.S. Army Corps of Engineers (USACE), the National Oceanic and Atmospheric Administration, and others.

2.1. Information and Tools for Water Management Decision Making

The tools and information considered for short-term water management decisions depend on the outlook resolution, region, management agency, and operational objectives relevant to the decision [*Raff et al.,* 2013]. For instance, USACE is typically focused on flood control objectives and therefore utilizes National Weather Service (NWS) River Forecast Center (RFC) flood watches, warnings, and outlooks regularly. In contrast, USBR is focused on water supply management, which requires greater consideration of observational snow products.

The outlook resolution also helps determine the type of information and tools used. Fine resolution outlooks typically consider precipitation forecasts and streamflow observations and forecasts. Precipitation forecasts may be issued by the Hydrometeorology Prediction Center, RFCs, or Weather Forecast Offices. Real-time streamflow gauge measurements are provided by the U.S. Geological Survey while RFCs issue official streamflow forecasts. In general, fine resolution outlooks consider observations that are frequently updated and forecasts that have lead times of less than 10 days. These outlooks inform decisions such as emergency response, flood risk management, hydropower, and navigation, all of which are sensitive to rapid changes in weather or streamflow.

Medium resolution outlooks are often based on current snowpack and soil moisture conditions, as well as weather and streamflow forecasts. Current snowpack and soil moisture data are available from the Natural Resources Conservation Service SNOTEL and snow course networks. RFCs develop weather forecasts based on NWS forecasts and also generate Ensemble Streamflow Predictions. Medium resolution outlooks are updated daily to weekly. These outlooks support decision making for ecosystem support (including minimum flow requirements), emergency response, flood risk management, hydropower, navigation, recreation, water supply conservation/snowmelt management, and water delivery. These outlooks are especially relevant to reservoir management in the spring and early summer when water managers aim to maximize snowmelt storage while assuming minimal flood risk.

Coarse resolution outlooks consider current snowpack and soil moisture, as discussed above, as well as antecedent weather and the cone of forecast-period weather possibilities. The cone of forecast-period weather possibilities is based on past observations and drives the hydrologic models for periods beyond about one week. Long-lead streamflow forecasts are developed from this data using methods such as the Ensemble Streamflow Prediction method, which are updated daily to monthly. This data is also input to statistical and simulation models to create seasonal water supply forecasts which are updated monthly during the winter and spring [*Garen,* 1992]. Although seasonal forecasts are able to consider seasonal climate and El Niño-Southern Oscillation (ENSO) predictions, climate predictions are typically not utilized objectively, likely because such predictions often represent the largest source of error in streamflow prediction [*Raff et al.,* 2013]. More often, climate predictions are used as subjective guidance in decision making [*Raff et al.,* 2013]. Enhanced understanding and ability to predict large-scale modes of climate variability promises to reduce this uncertainty and improve seasonal forecast accuracy. Course resolution outlooks inform decisions relevant to ecosystem support, flood risk management, hydropower, navigation, recreation, water supply allocation, and water delivery.

The 2013 assessment by *Raff et al.* identified additional information and tools that would be useful to water managers. Needs identified in the report included a) an 'enhanced suite of hydrologic predictions spanning lead times of days to seasons and consistent with the continuum of weather to climate forecast products', b) 'a multivariate suite of climate to hydrologic predictions that comprehensively characterizes the state and evolution of basin hydrologic conditions at lead times of days to seasons' including 'better anticipation of cold-season snowpack development preceding the spring-summer snowmelt and irrigation seasons', and c) improved products forecasting the probability of getting normal snowpack or the chance of recovery. These needs can be synthesized as a need for more detailed information regarding the evolution of snowpack development across a range of time scales.

3. SFE Probabilistic Analysis Tool

The research presented in Chapter 2 regarding the importance of extreme snowfall events to annual snowfall totals and to interannual variability in snowfall has the potential to partially address the needs identified above. In particular, the strong correlations between extreme snowfall events and annual SFE may enhance predictions of annual snowfall totals at daily time steps throughout the snow accumulation season. Using this research and classical statistical forecasting based on analog years we have sought to develop actionable science that could potentially be operational within the institutional decision space and outlook hierarchy of water resource management and help meet the needs of water managers identified above.

3.1. The Concept

The basin-scale daily resolution tool we developed provides qualitative guidance for forecasts of remaining water year SFE accumulation and extreme snowfall events. The tool is based on knowledge of water year to date SFE and water year to date occurrences of extreme snowfall events. The tool relies on daily-resolution SNOTEL data averaged over each 6-digit Hydrologic Unit Code (HUC6) basin in Idaho. SNOTEL stations were selected on the basis of the length, quality, and continuity of record. Using all years of continuous record, SFE on a selected day of the water year is ranked from low to high. This ranking is used to assign each year to a range relative to normal (mean) SFE. The number of top decile snowfall events (hereafter referred to simply as extreme events) that occurred before and after the date each year is also calculated.

3.2. Initial Version

The initial version of the SFE probabilistic analysis tool consisted of an information box and seven subplots, corresponding to percent of normal SFE ranges. The subplots were organized with month of the water year on the x-axis and SFE in inches on the y-axis. Figure 4.1 provides an example for the Upper Snake River Basin (USRB) based on seven SNOTEL stations with 20 years of record. Output plots were developed for the 1^{st} day of December, January, February, March, and April, and the specified date is highlighted in the output subplots. In practice, the user would be able to select the basin of interest and the month of interest. SFE was averaged over all years and all stations to calculate the normal SFE accumulation, represented by a black dashed line in the output. SFE on the date of interest was assigned to a percent of normal range based on the normal SFE accumulation on that date. The years within each percent of normal range were listed in the corresponding subplot. For instance, in Figure 4.1, SFE on February 1, 1994 was between 70 and 89% of the long-term average, so SFE accumulation in 1994 was plotted in the subplot corresponding to 70-89% of normal. The number of extreme events that occurred after the date of interest each year was listed in parentheses next to each year. At the bottom of each subplot, the station- and year-averaged number of extreme events before and after the date of interest was also listed.

3.3. Informal Feedback

The initial version of the tool was informally presented to several colleagues and Ron Abramovich, a Water Supply Specialist with the Natural Resources Conservation Service (NRCS) Snow Survey. Initial feedback was generally positive and very constructive. These conversations indicated that a clear definition of SFE and extreme snowfall events would need to be provided. The key changes that resulted from this feedback were 1) the use of only three subplots based on terciles, 2) the use of fewer SNOTEL stations with longer records, 3) color coding of years according to ENSO phase, and 4) the idea to develop this tool at daily resolution (instead of just the first day of each winter month) and make it accessible to potential users on the internet. The revised tool, incorporating these developments is shown in Figure 4.2.

In the modified tool output for the USRB, three SNOTEL stations within the basin (Togwotee Pass SNOTEL, Willow Creek SNOTEL, and Gros Ventre Summit SNOTEL) with 29 years of continuous and high quality data were selected. For each day, years were sorted from most to least cumulative SFE and divided into terciles corresponding to below-normal, near-normal, and above-normal SFE. Each year was assigned to Warm, Neutral, or Cool ENSO phase. ENSO phase was defined using the October through March mean Multivariate ENSO Index (MEI, *Wolter and Timlin,* [1993]), where MEI>1 denotes Warm phase or El Niño, 1≥MEI≥-1 denotes Neutral phase, and MEI<-1 denotes Cool phase or La Niña. Analog years and SFE were color coded in the output based on ENSO phase. Outputs were developed for each day October 1st through May 31st.

3.4. Outreach

Next, we developed a website to host the tool and elicit feedback from potential users (http://nimbus.cos.uidaho.edu/abby/SFETOOL/). The website development and subsequent outreach consisted of three main components. First, we constructed an interface where the user can select the basin and date they are interested in. The relevant output (example shown in Figure 4.2) is then displayed on the webpage. Second, we developed a suite of educational products to help users understand how the tool works and how to interpret the output. These products included a short instructional video, a written explanation of the methods behind the tool, a written guide to interpreting the output of the tool, and a frequently asked questions page. Third, we created a twelve question survey for potential users to provide feedback on the utility of the tool and potential improvements. Invitations to visit the website and evaluate the tool were sent to more than 30 representatives of potential user groups including the Bureau of Reclamation, the Army Corps of Engineers, the NRCS Snow Survey, Universities, Tribes, and private companies. An example output and the link to the website were also shared with attendees of the February Idaho Water Supply Committee Meeting in Boise (February 14, 2014).

3.5. Formal Feedback

We received five responses to our online survey. All respondents were enthusiastic about the tool, indicating that they would consider using it if it was made available for their basin(s) and that it would be useful for a variety of applications including but not limited to reservoir management, water supply commitments, flood control, business decisions, and cropping/agricultural decisions. The primary criticism of the respondents was that interpretation of the tool output relied too heavily on information provided in the video and written explanation. Ideally, the tool output would be more self explanatory, requiring less background knowledge.

In addition to the survey responses, we received a detailed formal response from the NRCS Snow Survey office in Boise. Beyond a few cosmetic and editorial comments, they made two main suggestions. First, they suggested that the name be changed from ‘Forecast Tool’ to ‘Analysis Tool’ to better reflect the qualitative rather than quantitative nature of the tool. Second, they indicated that the utility of the tool would be greatly improved if current water year SFE was plotted in the output for context. They also recommended including a brief written overview of our research findings for each basin.

Feedback from these potential users as well as conversations with the Boise NRCS Snow Survey personnel provided significant insight into the needs and values of the water management community and highlighted how the tool expands on and compliments forecast tools currently used. Through this process we determined appropriate terminology for the water resource management audience, we identified concepts that were unclear or would require additional explanation, and we learned what level of detail was desired for the tool output.

3.6. Resulting Product

The tool was modified according to user feedback and an example output is shown in Figure 4.3. The name of the tool was changed to the ‘Snowfall and Extreme Snowfall Event Probabilistic Analysis Tool.’ SNOTEL station elevations were added next to the station names and the subplots were re-ordered to be more intuitive. A paragraph summary of significant and relevant findings for each basin was developed and posted below the output plot (example shown in Figure 4.4). Helpful hints for output interpretation were also added to the output webpage. It was decided that including current water year SFE in the tool output, while likely to be very helpful, was outside the scope of the project at this time. Outputs for every 6-digit Hydrologic Unit Code basin in Idaho for each day October 1st through May 31st were made available on the website (Figure 4.5).

4. Implications for Water Resource Management

Respondents to the survey indicated that this tool would be most useful for course-resolution outlooks and decision making relevant to reservoir management, water supply commitments, flood control, water rights curtailments, business decisions, cropping/agricultural decisions, and recreation such as rafting and kayaking. The tool enhances knowledge of forecast-period weather possibilities, a consideration in course-resolution outlooks, by combining long-term qualitative forecasts of annual SFE and extreme events with daily resolution, event-scale information.

Through the continuous updating and nested hierarchy of outlook resolutions, this tool also has the potential to benefit fine- and medium-resolution outlooks. Specifically, information regarding the number of extreme snowfall events likely to occur in the remainder of the water year can provide qualitative guidance for reservoir management and flood risk decisions, particularly later in the snow accumulation season.

This tool addresses several of the user needs identified in *Raff et al.* [2013] and discussed above. Firstly, this tool sheds light on the likelihood of extreme snowfall events occurring in the remainder of the snow accumulation season, addressing the need for a better understanding of snowpack evolution and development. Secondly, this tool provides qualitative guidance on the chance of achieving near-normal SFE by visualizing SFE development in years with similar SFE to date. Forecasting chance of recovery is further enhanced by the inclusion of yearly ENSO phase classification.

The SFE probabilistic analysis tool represents the first effort that we are aware of to include extreme snowfall events in a SFE or water supply forecast guidance product. The tool is based on novel research highlighting the heretofore largely unrecognized importance of extreme snowfall events in annual SFE totals and variability. Furthermore, this tool is one of few guidance products to use daily-resolution SNOTEL information providing event-scale analysis that is relevant to water resource management timelines.

While this tool is primarily intended for short-term water management decisions in the current climate, there are several ways in which it could be adapted to serve the needs of future water management decision making. Following the Stationary System paradigm [*Brekke et al.,* 2009], this tool could be updated with the most recent years of observation on a regular basis and in this way the output would still closely reflect the contemporary climate. Alternatively, downscaled global climate model projections, such as those used in Chapter 3, could be input to the tool to provide qualitative guidance on the changing nature of the relationships between extreme snowfall events and annual SFE in the future (based in the System Projection paradigm) [*Brekke et al.,* 2009]. Finally, increasing our ability to anticipate and manage for current extreme snowfall events will enhance the ability of water management to adapt to future changes in hydrologic extremes.

5. Suggestions for Further Research and Development

Feedback from potential users revealed several ways in which this tool could be enhanced to provide either more information or easier use. Some of the more frequent suggestions included:

1. Incorporation of current water year to date SFE accumulation on the output plot, facilitating a more straightforward comparison to analog years. This would require automated downloading, processing, and updating of the output plots with up to date data from the NRCS website for the relevant stations.
2. Calculating the number, dates, and accumulations of extreme events that have occurred in the current water year to date.
3. Allowing for user interaction. For instance, being able to select years to display in the output would make it easier to view and analyze SFE accumulation.
4. Quantifying probabilities for specific target dates. For example, the probability that 1 April SFE would be at or above normal.

Finally, if the Idaho water management community finds this tool useful, it would likely be useful in other areas as well. This tool might be especially helpful in regions where annual SFE is characterized by large interannual variability or regions where annual SFE anomalies are closely tied to anomalies in the SFE of extreme snowfall events, such as the Sierra Nevada. Expanding the scope of the tool to include the entire western U.S. would be a valuable next step.

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Table 4.1 Short-Term Water Resource Management Outlook Resolutions [*Raff et al.,* 2013].

Resolution	**Update Cycle**	**Objectives**	**Information**
Fine	Hours to days	Emergency response Flood risk management Hydropower Navigation	Precipitation forecasts Streamflow volume and forecasts
Medium	Days to weeks	Ecosystem support Emergency response Flood risk management Hydropower Navigation Recreation Water supply conservation/snowmelt management Water delivery	Current snowpack Soil moisture conditions Weather forecasts
Coarse	Weeks to months, generally less than a year	Ecosystem support Flood risk management Hydropower Navigation Recreation Water supply allocation Water delivery	Current snowpack Antecedent weather Cone of forecast-period weather possibilities

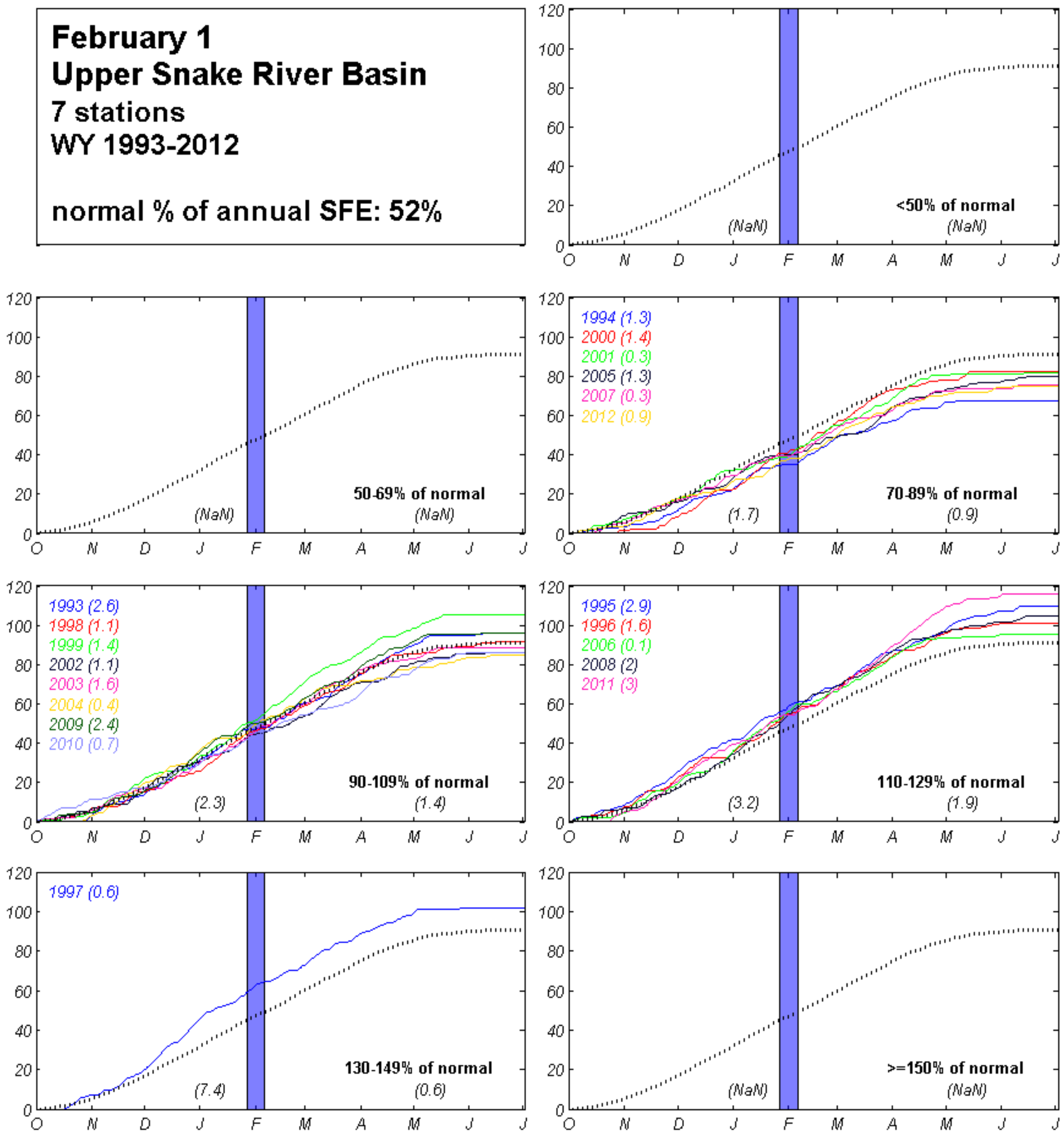


Figure 4.1 Example of the initial version of the SFE probabilistic analysis tool.

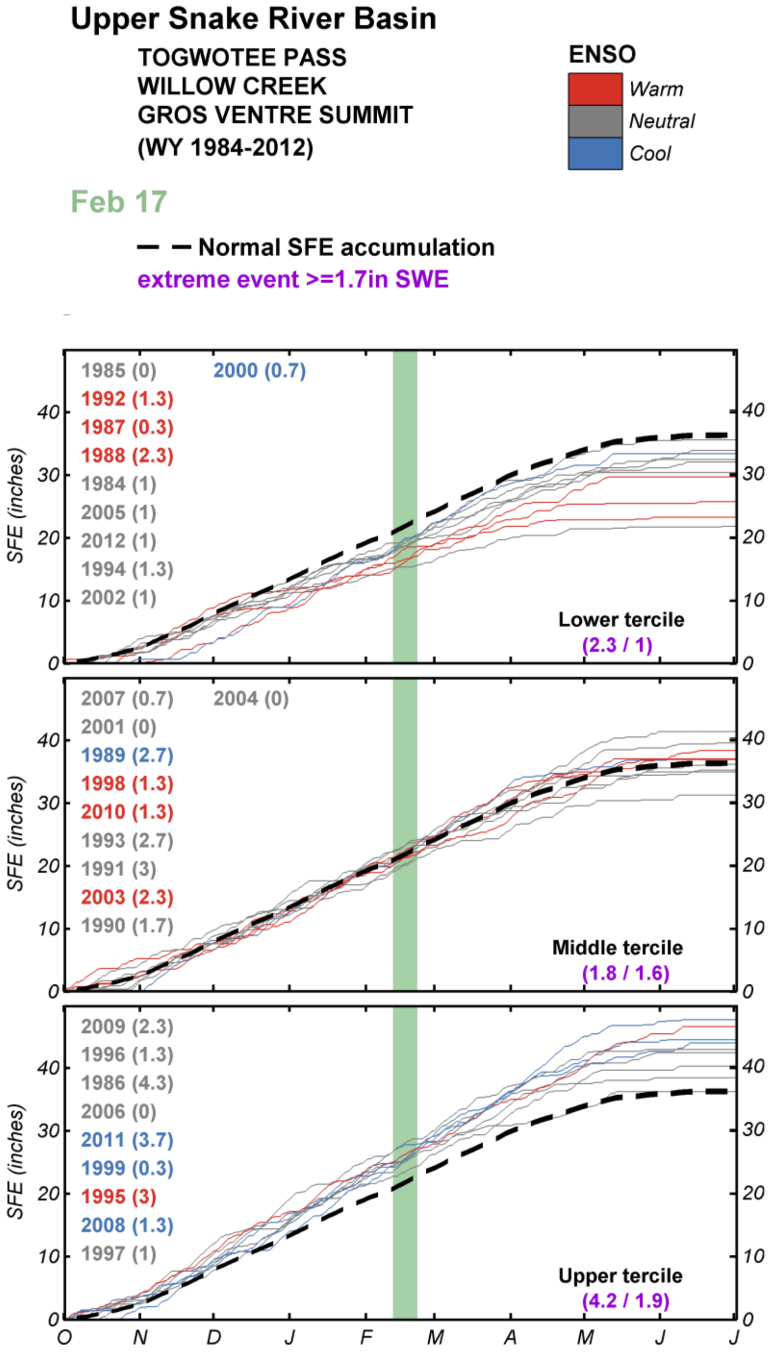


Figure 4.2 Example of second version of the SFE probabilistic analysis tool which was shared with potential users and posted on the website.

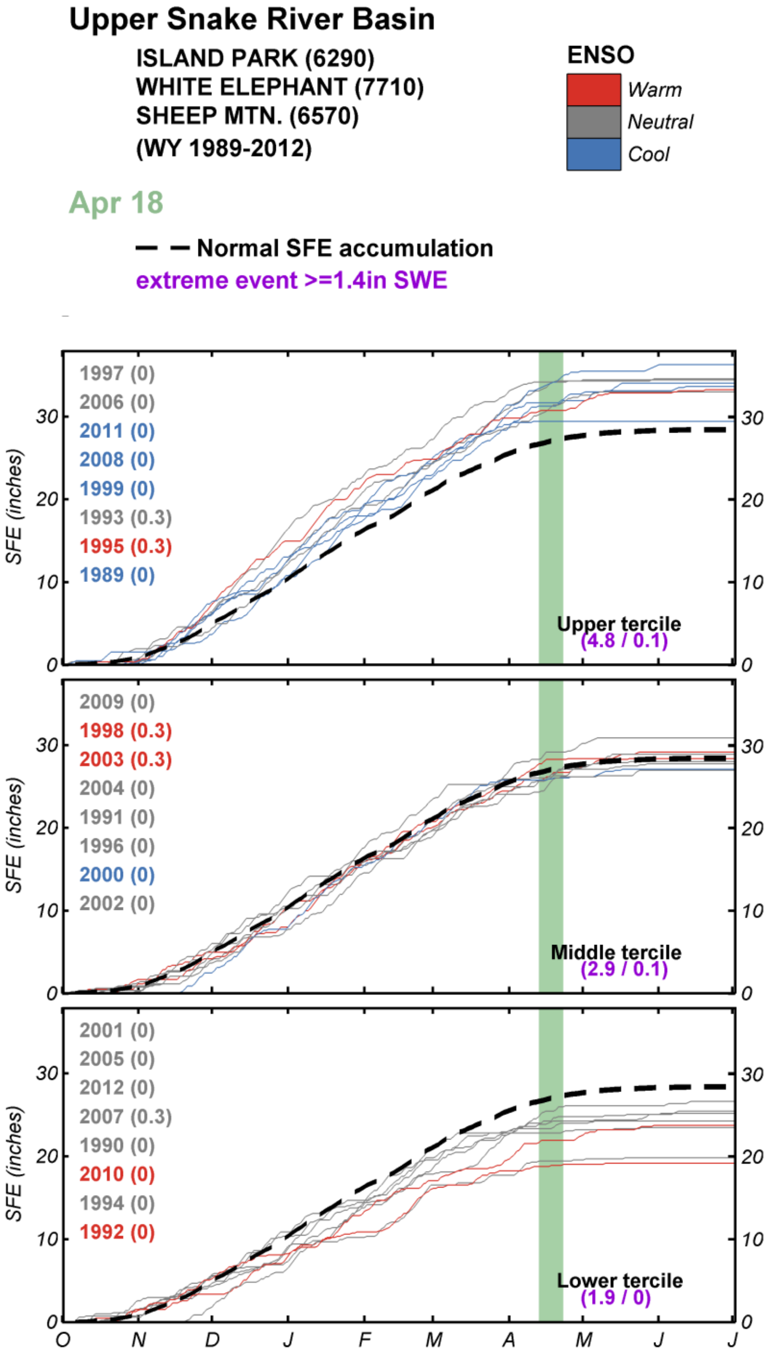
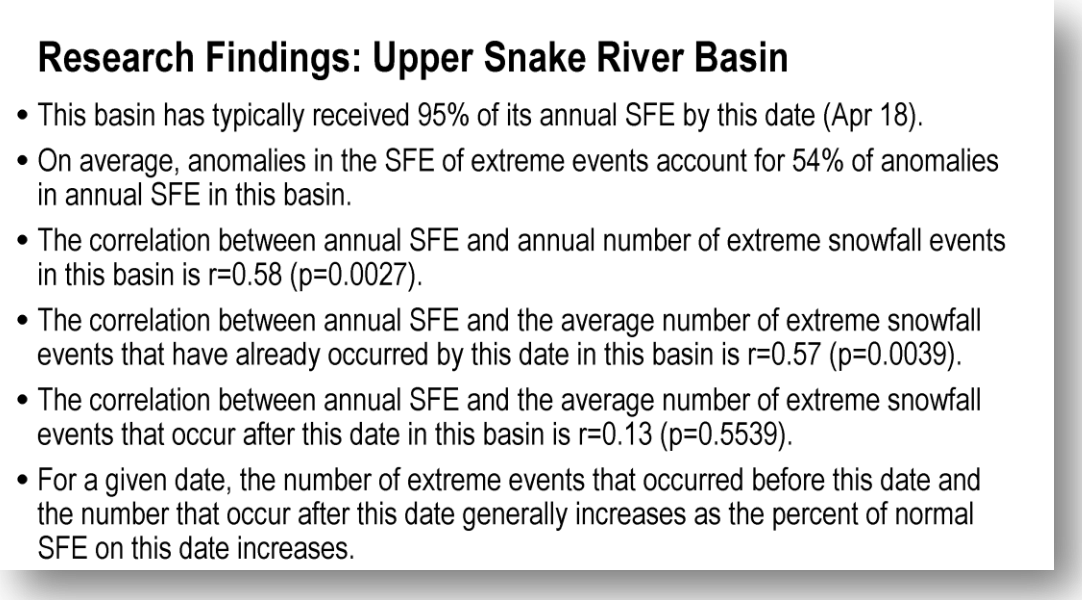


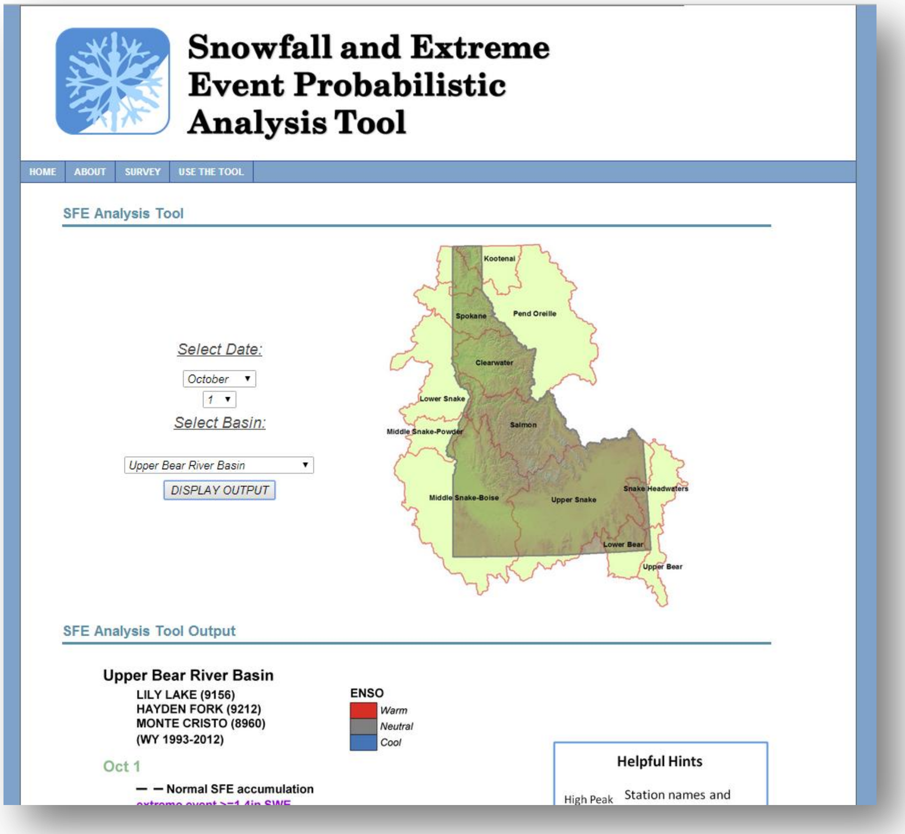
Figure 4.3 Example of the final version of the SFE probabilistic analysis tool.



Research Findings: Upper Snake River Basin

- This basin has typically received 95% of its annual SFE by this date (Apr 18).
- On average, anomalies in the SFE of extreme events account for 54% of anomalies in annual SFE in this basin.
- The correlation between annual SFE and annual number of extreme snowfall events in this basin is r=0.58 (p=0.0027).
- The correlation between annual SFE and the average number of extreme snowfall events that have already occurred by this date in this basin is r=0.57 (p=0.0039).
- The correlation between annual SFE and the average number of extreme snowfall events that occur after this date in this basin is r=0.13 (p=0.5539).
- For a given date, the number of extreme events that occurred before this date and the number that occur after this date generally increases as the percent of normal SFE on this date increases.

Figure 4.4 Example of research summary which is displayed below the tool output.



Snowfall and Extreme Event Probabilistic Analysis Tool

SFE Analysis Tool

Select Date:

October

1

Select Basin:

Upper Bear River Basin

SFE Analysis Tool Output

Upper Bear River Basin

LILY LAKE (9156)
HAYDEN FORK (9212)
MONTE CRISTO (8960)
(WY 1993-2012)

ENSO

🟥 Warm
⬛ Neutral
🟦 Cool

Oct 1

— — Normal SFE accumulation

extreme event >=1.4in SWE

Helpful Hints

High Peak Station names and

Figure 4.5 User interface on the tool website.

Chapter 5:

Conclusion

Interannual snowfall variability and climate change present tremendous challenges to water resource management in snow-dominated regions such as the western U.S. While a handful of studies have indicated that extreme snowfall events contribute a substantial portion of annual SFE [*Serreze et al.,* 2001; *Guan et al.,* 2010], the role of extreme snowfall events in shaping interannual snowfall variability and contributing to future changes in snowfall are largely unrecognized and poorly understood. Chapter 2 of this thesis evaluated the contributions of extreme snowfall events to interannual variability of annual SFE. On average, top decile snowfall events contributed 20-38% of annual SFE and accounted for 69% of interannual variability in annual SFE at SNOTEL stations. Correlations between annual SFE and top decile events were stronger than correlations between annual SFE and number of snow days, contrasting the findings of *Serreze et al.,* [2001] that annual SFE was more strongly correlated with number of snow days than leading events. In Chapter 3, projected changes in extreme snowfall events and interannual variability in annual SFE were presented. Due to differential temperature sensitivities of snowfall events and increases in precipitation intensity, extreme snowfall events were projected to decline less than other snowfall events and were even projected to increase in the coldest locations. Tendencies toward heavier snowfall events at the expense of light and moderate events, combined with projected decreases in number of snow days, will result in significant increases in interannual variability of annual SFE, challenging the assumption of stationarity in water resource management. Finally, Chapter 4 highlighted how the research in Chapter 2 was developed into actionable science for decision makers through an iterative and interactive process involving the water resource management community. The SFE Analysis Tool represents the first effort we are aware of to incorporate extreme snowfall events in water resource planning. Practical application of the tool to water management decisions will undoubtedly provide further insight into how to enhance the tool.

The analysis relied on observations from SNOTEL and COOP stations in the eleven western U.S. states. Such analysis is limited by the quality and length of the data records, particularly in montane environments. The maintenance of long-term monitoring networks, especially in high-elevation, remote environments, is essential to this work and to continued and improved evaluation of montane climate variability and change. Further technological improvements to minimize precipitation gage undercatch, snow pillow overcatch, and other instrument errors will enhance the quality of data and rigor of scientific analyses.

Extreme snowfall events represent a heretofore largely unrecognized mechanism for understanding interannual variability in snowfall accumulation. The continued importance of extreme snowfall events in shaping long-term changes in annual snowfall accumulation and changes in snowfall variability indicate that although the concept of hydroclimatic stationarity may be increasingly outdated, the relevance of extreme snowfall events to water resource management will persist. Further research is needed to understand the synoptic causes of these events across the varied climates and snow regimes of the West. Evaluation of the influence of downscaling method on snow metric projections and the skill of the MACA method in capturing observed extreme snowfall events is also needed. Development of tools such as the SFE Analysis Tool can provide a useful link between academic study and practical application. Such efforts will enhance our ability to anticipate years of high and low snowpack and to adapt to future changes in snowfall, helping to maximize available water resources in a changing climate.

Appendix 1

Discussion of precipitation phase probability function of *Dai* [2008]

Dai [2008] used 3-hourly land observations of precipitation and snow across a range of temperatures to fit a hyperbolic tangent function that calculates the percent of precipitation that is snow for an observed temperature. This percentage is multiplied by the corresponding observed precipitation to determine SFE. We used the parameters fitted to the annual land values from *Dai* [2008] with observed daily temperature and precipitation to calculate daily SFE at COOP stations. Daily SFE values less than 2.54mm (the resolution of SNOTEL SFE measurements) were set to 0.

Methods for determining SFE amounts from temperature include binomial thresholds, linear transitions, and s-shaped curve functions. The latter is theoretically the most physically plausible as it allows for mixed phase precipitation and has been shown to fit observations better than linear transitions [*Kienzle*, 2008]. Validation of any method using observations is difficult due to snow pillow overcatch and precipitation gauge undercatch (see *Goodison et al.,* [1998]; *Fassnacht* [2004]; *Sevruk et al.,* [2009]), which, even with the ideal method, would result in an underestimation of SFE. At SNOTEL stations it is not unusual for daily SFE to exceed corresponding daily precipitation or for cumulative April 1 SFE to exceed cumulative April 1 precipitation. While efforts were made to minimize this bias through quality control and outlier checks, analyses would benefit from advances in snow observing instruments that are resistant to wind effects (overcatch and undercatch) in topographically complex and elevated terrain. When applied to SNOTEL temperature and precipitation data, the Dai method underestimated SFE by 11% on average (corresponding to realistic estimates of precipitation undercatch, see *Sevruk et al.,* [2009]). Differences between calculated annual SFE and observed annual SFE at SNOTEL stations were correlated with undercatch errors (ratios of April 1 SFE to April 1 cumulative precipitation), suggesting that differences between calculated and observed SFE are least in part due to this issue. Furthermore, the Dai method replicated SNOTEL annual SFE approximately as well as the linear transition methods used in the VIC hydrologic model [*Liang et al.,* 1994] and in *Marks et al.,* [2013]. High quality data from a snow pillow site in the Reynolds Creek Experimental Watershed (RCEW), Southwestern Idaho, fit to a variety of precipitation phase functions based on average temperature, has been shown to best fit a linear threshold between 0.5C and 1.5C [*Marks et al.,* 2013]. When applied to the RCEW data, the Dai method outperformed this method.

Appendix 2

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