CHARACTERISTICS AND INTERANNUAL VARIABILITY OF EXTREME SNOWFALL EVENTS

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ABSTRACT

Extreme snowfall events provide significant contributions to total snowpack and the characteristics and variability of these events are important for interannual variability in water supply. This study assesses the characteristics of the heaviest snowfall event each winter including average amount, percent of annual snowfall accumulation, coincident mean daily temperature and relationship to ENSO using long-term records from both SNOTEL and National Weather Service Cooperative Network stations across the western United States. Results indicate that the biggest snowfall event of the year can contribute more than a quarter of total annual snowfall water equivalent (SFE) at SNOTEL stations. The size of the biggest snowfall event is strongly positively correlated with annual SFE across the West. ENSO is shown to have a northwest-southwest dipole pattern of correlation with the annual SFE, the size of the biggest event, and the percent of annual SFE contributed by the biggest event. Collectively, this analysis provides a basis for understanding the relative contribution of extreme snowfall events to water resources and provides information on the sensitivity of extreme snowfall events to interannual variability.
(KEYWORDS: snowfall extremes, event, SWE, interannual variability)

INTRODUCTION

With the exception of the wet Pacific Northwest, most of the western United States is relatively dry and receives the majority of its precipitation in the form of snow (Serreze et al., 1999). Snowpack is carefully monitored and melt is stored in reservoirs for later use. Reservoirs must be managed to balance water users' needs throughout the water year with other concerns such as flooding.

Extreme precipitation across numerous temporal scales is of concern for water management. At one end, drought raises difficult questions of allocation of scarce and valuable water resources. At the other end, extreme precipitation amounts or intensities threaten flooding and attendant damage to infrastructure, homes, and lives. Snowfall extremes, in addition to posing avalanche and road closure concerns, play a vital role in snowpack in the West and are also important for water resource availability. Results indicate that at many COOP stations in the lower latitudes and along the coast, the majority of annual snowfall comes in the single biggest snowfall event, while at most SNOTEL stations the single biggest event contributes between 10 and 20% of annual snowpack. Whereas an equivalent rain event would result in heavy runoff and likely flooding, extreme snowfall events augment the snowpack which releases this water later in the season as temperatures warm and demand increases. The contribution to snowpack received from the biggest snowfall events suggests that water resource availability is dependent on the presence or absence of the single biggest event and water resource managers must be able to manage for the presence or lack of that event.

Research on climate change indicates that many characteristics of the present hydrological regime, on which the West's water resource management systems are based, are likely to change in the coming decades. The changes for water resources can already be seen in the form of earlier snowpack melt (McCabe and Clark, 2005), decreased April 1 snow water equivalent (Mote et al. 2005), and higher freezing elevation (Abatzoglou, 2011). Furthermore, the frequency of extreme precipitation events is projected to increase, at the expense of smaller and more moderate events (IPCC, 2012). Warming temperatures may cause extreme snowfall events which occur in warmer areas or on days with temperatures close to freezing to become extreme rainfall events instead of extreme snowfall events. This will decrease snowpack water storage while increasing demand for reservoir storage (Barnett et al., 2005). Without sufficient reservoir storage, water availability will effectively decrease, leading to difficult water allocation decisions. These developments will necessitate a re-creation of our understanding of the hydrological regime and a revision of water management policy. Enhanced understanding of the characteristics and

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variability of extreme snowfall events can help water managers and users predict and manage for a large, though variable, portion of snowpack.

The present study aims to update and expand on the limited knowledge of characteristics of extreme snowfall events and their interannual variability. The first part of this study will provide a discussion of general snowpack characteristics. In the second part, the characteristics of extreme snowfall events will be analyzed in the context of general snowpack characteristics. The final part of this study will explore the role of extreme events in interannual snowpack variability. This analysis will provide valuable information to water resource managers concerning the characteristics and variability of this vital component of snow water resources.

DATA AND METHODS

Research on snow in the West has focused on snowfall (Kunkel et al., 2009), snow depth (Grundstein and Mote, 2010), April 1st SWE (Mote et al., 2005), trends in snowpack (Mote, 2006), and interannual variability of snowpack (Cayan, 1996). Very little attention has been paid to extreme snowfall events in the West, despite the fact that they are an important component of total snowpack and thus water resources. The standalone publication on this subject is the work of Serreze et al., (2001) who analyzed 18 years of SNOTEL data from 1980-1998 and examined the characteristics, spatial coherence, and interannual variability of extreme snowfall events in the West. The present study aims to update and expand on Serreze et al. (2001) by using nearly twice the period of record of SNOTEL data (1978-2012) as well as using COOP data (1948-2012) to provide an extended record and an elevational range across which these events can be analyzed. This study will also look at additional characteristics as well as provide a more in-depth analysis of the relation of these events to ENSO.

Snowpack in the western United States was initially monitored by a network of snow courses with data collected manually once or twice per month. In the late 1970s Snowpack Telemetry (SNOTEL) stations were developed to replace snow courses that were difficult to access and provide information at finer temporal scales. SNOTEL stations use an automated system and meteor burst technology to collect data and transmit it to a data collection center maintained by the Natural Resources Conservation Service. Stations provide hourly data on temperature, precipitation, and snow water equivalent (SWE). SWE is the depth of water that would result from melting the snowpack at any given time; it is therefore a function of snowfall as well as melt and sublimation. SWE is distinct from SFE or snowfall water equivalent. SFE is the water equivalent of all snowfall (not accounting for melt) at a given point in time. SFE can be calculated by summing all positive daily changes in SWE. SNOTEL sites measure SWE automatically with a snow pillow require minimal site access, making them ideal for runoff and stream flow forecasting. Furthermore, SNOTEL's daily resolution of high elevation climate data makes the network a unique resource for studying event scale snow processes and montane climates.

In addition to SNOTEL data, this study uses data from Cooperative Observer Program (COOP) stations. These stations are run by volunteer observers who collect temperature, precipitation, and snowfall data on a daily basis. Because COOP stations measure snowfall but not SWE, a procedure was developed to create SWE data from snowfall and precipitation data. For each day with an increase in snow depth and average temperature less than 2C, SWE for that day was set equal to precipitation for that day. For all other cases daily SWE was set equal to 0. COOP stations are run by the National Weather Service which trains volunteers, maintains equipment, and ensures data quality. Stations became widespread in the West in the late 1940s and today there are more than 2,000 stations in the eleven western states. They are located in a variety of terrain including urban settings, rural areas, and montane environments. COOP stations are generally at lower elevations than SNOTEL stations and their inclusion in this study will allow analysis of extreme snowfall event characteristics across a range of elevations.

Stations were selected for this study based on rigorous quality control procedures. These included screening for negative precipitation and SWE values, as well as daily precipitation and SWE values greater than 15 inches. In addition, spatial and temporal outlier checks were used to screen for errors in the data. All days of record with errors or outliers were marked as missing. For COOP stations, a minimum average yearly SFE of 1 inch was established to ensure that selected stations receive snow regularly. For a year of record to be used in this study the winter season (October through May) was required to be at least 90% complete. Finally, for a station to be selected it had to have a minimum of 10 years of data satisfying the above requirements. This procedure resulted in the selection of 598 SNOTEL stations and 277 COOP stations. The elevational and spatial distribution of the stations selected for this study is shown in Figure 1. For this figure and all subsequent figures SNOTEL stations are represented by circles and COOP stations are represented by squares.

In order to put extreme snowfall events in context, the first part of this study examines climate and general snowpack characteristics in the western United States. This includes the winter (October through March) cumulative precipitation and average temperature, total annual SFE, and the number of snowfall days. All analyses are based on water year (October 1 through September 30) values. We examine the annual SFE for each year at each station by summing all positive daily changes in SWE for the year. The yearly SFE totals are averaged for each station. The number of snowfall days is defined as the number of days each year at each station with a positive change in snow water equivalent, SWE (SWE on day i greater than SWE on day i-1).

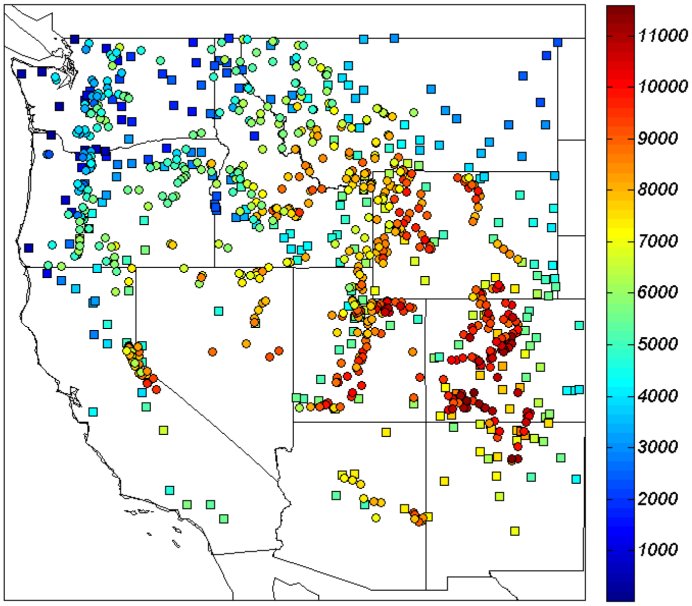

Figure 1. Elevational and spatial distribution of stations selected for this study. SNOTEL (COOP) stations are represented by circles (squares).

The second part of this study examines the characteristics of extreme snowfall events. Characteristics such as the size of the biggest snowfall events (in terms of SWE), the percent of annual SFE contributed, coincident average temperature, and seasonality will be considered. These characteristics will be evaluated in the context of general snowpack characteristics as well as spatially and elevationally.

Events are defined as the cumulative snowfall over a three-day period. A three-day time period comprises 75 to 89% of snow events in the western United States (Serreze et al., 2001). Use of a longer event period risks labeling multiple events as one event while use of a shorter period risks understating the actual magnitude of snow events. In consideration, this study defines extreme snowfall events as the largest three day accumulation of snow water equivalent of each year at each station. This results in one event for analysis for each year of record at each station. Extreme events in this study are therefore relative to the snow regime of the location. Future analysis will examine the top three events of each year at each station as well as the top 1% and top 5% of all events at each station.

Extreme events were identified through the following procedure. First, daily SWE data, SWE1, was created by taking SWE on day i minus SWE on day i-1. Then, three day snowfall accumulations were calculated by finding the three day running sum of positive SWE1 values. The maximum value of the running sums of each year at each station is the biggest event. The timing of the event is considered to be the middle day of the three day accumulation period.

The third and final part of this study explores the role of extreme events in interannual snowpack variability. This analysis uses simple linear correlation between the size of the biggest event and total SFE on a yearly basis. In addition, this paper examines correlations between extreme snowfall events and the El Nino Southern Oscillation (ENSO). These analyses will provide insight into the variability and potential predictability of extreme snowfall events.

CHARACTERISTICS

General Snowpack

To put extreme snowfall events in context, an understanding of the climate and general snowpack characteristics is necessary. This includes the winter precipitation and temperature regimes, total annual SFE, and the number of snowfall days. Average winter (October through March) temperatures and cumulative winter (October through March) precipitation are shown in Figure 2 and will be referenced throughout this section.

Cumulative winter precipitation is greatest in the Cascades, exceeding 100 inches in some locations. Winter precipitation can exceed 50 inches in the Sierra Nevada and Northern Idaho. This value generally declines in continental and lower latitudes, with lower elevation COOP stations in Eastern Montana, Wyoming, Colorado, and New Mexico receiving less than 10 inches of winter precipitation. Mean average winter temperatures are warmest near the coast and coldest inland. This is a function of both proximity to the ocean and elevation. Stations along the coast, especially COOP stations, have average winter temperatures above 6C, whereas high elevation sites in the Rockies are below -6C.

Annual SFE is an important value for water resource availability considerations because snowpack stores winter precipitation for use during the dry summer months that characterize much of the West. The Cascades, Sierra Nevada, and to a lesser extent Northern Idaho have the highest annual SFE (Figure 3). Average annual SFE at some locations in the Cascades exceeds 80 inches. High annual SFE is largely a function of precipitation; winter precipitation is greatest in the Cascades, followed by the Sierra Nevada and Northern Idaho.

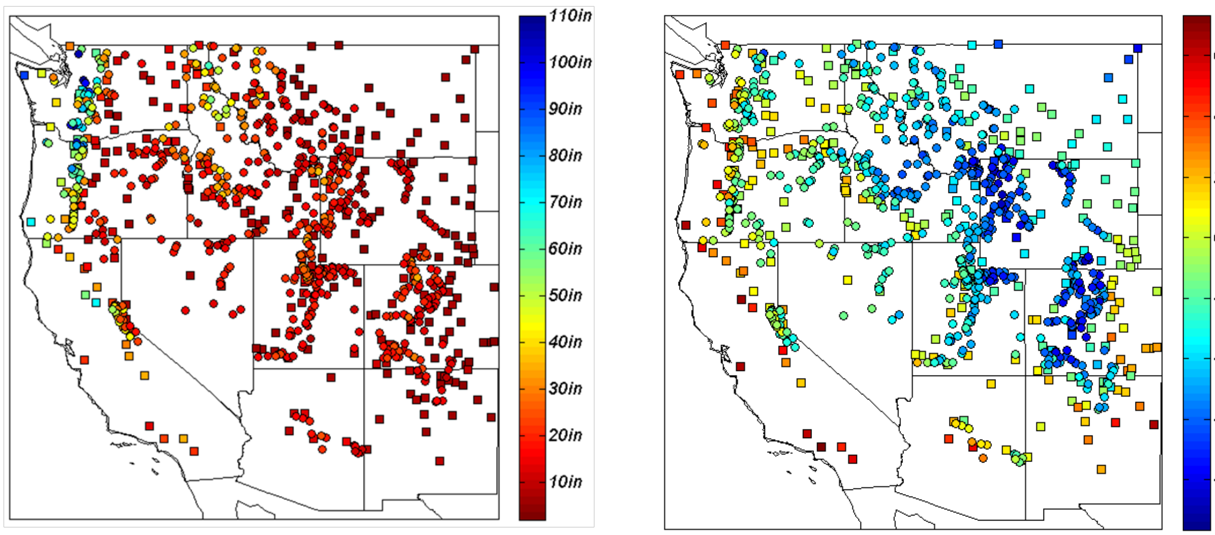

Figure 2. a) cumulative winter precipitation, b) average winter temperature

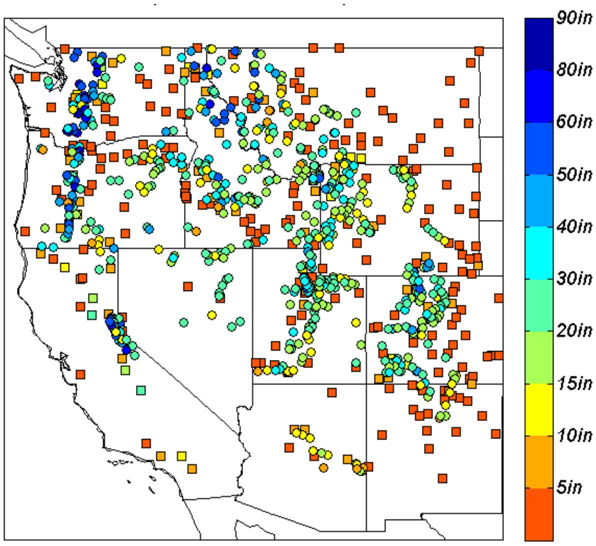

Figure 3. Average annual SFE (inches SWE)

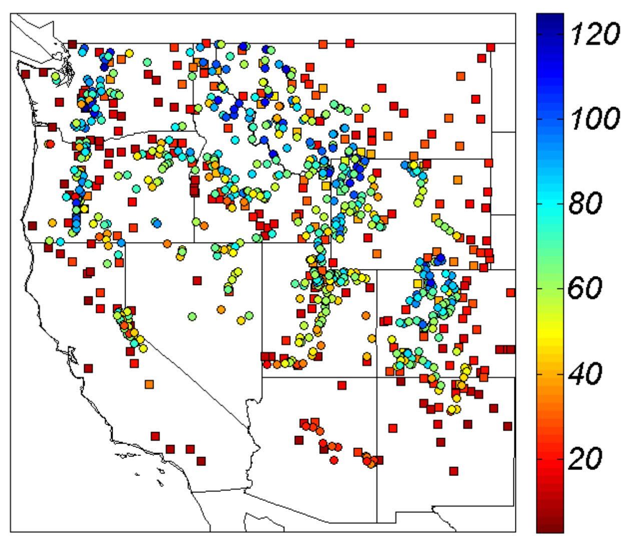

Figure 4. Average number of snowfall days

The number of snow days gives an indication of how the annual SFE at each station is achieved. The average number of snow days (days with positive change in SWE) is greatest in the Cascades and Rocky Mountains, where stations experience more than 100 snow days per water year (Figure 4). The high number of snow days in these regions is explained by relatively cold winter temperatures as well as location relative to the winter storm track. The number of snowfall days in the Cascades corresponds well with annual SFE (Figure 3), whereas the number of snow days in the Rockies is less correlated to annual SFE. Sufficiently cold winter temperatures and high winter precipitation in the Cascades combine to create both many snow days and high annual SFE. In the Rockies, although winter temperatures are cold, air masses are relatively dry. This results in lighter, drier snow which creates lower annual SFE but many snow days. The warmest winter temperatures are found in Arizona, which is reflected in the small number of snow days (less than 20 snowfall days on average per year) as well as minimal annual SFE.

As has been suggested throughout this section, annual SFE can be described as a function of cumulative winter precipitation, average winter temperature, and the number of snow days (Figure 5). Each marker in Figure 5 represents a station. Markers are plotted by average winter temperature (C) on the y-axis and cumulative winter precipitation (inches) on the x-axis. Colors, labeled on the color bar, indicate the average annual SFE at each station. The size of the marker indicates the average number of snow days; the bigger the marker the more snow days. Values for number of snow days and annual SFE increase with increasing precipitation, and to some degree with decreasing temperature. There appears to be a reasonably strong threshold at approximately 3C above which annual SFE and number of snow days are very minimal. Below the 3C threshold, the number of snow days and annual SFE are mostly a function of cumulative winter precipitation. This illustrates the sensitivity of many stations to warming temperatures. If average winter temperatures were warmed by 2C, the temperature threshold would be shifted to 1C on our current plot. This suggests that in a climate warmed by 2C, all stations with current average winter temperatures above 1C would receive minimal snow days and minimal annual SFE, regardless of any change in precipitation.

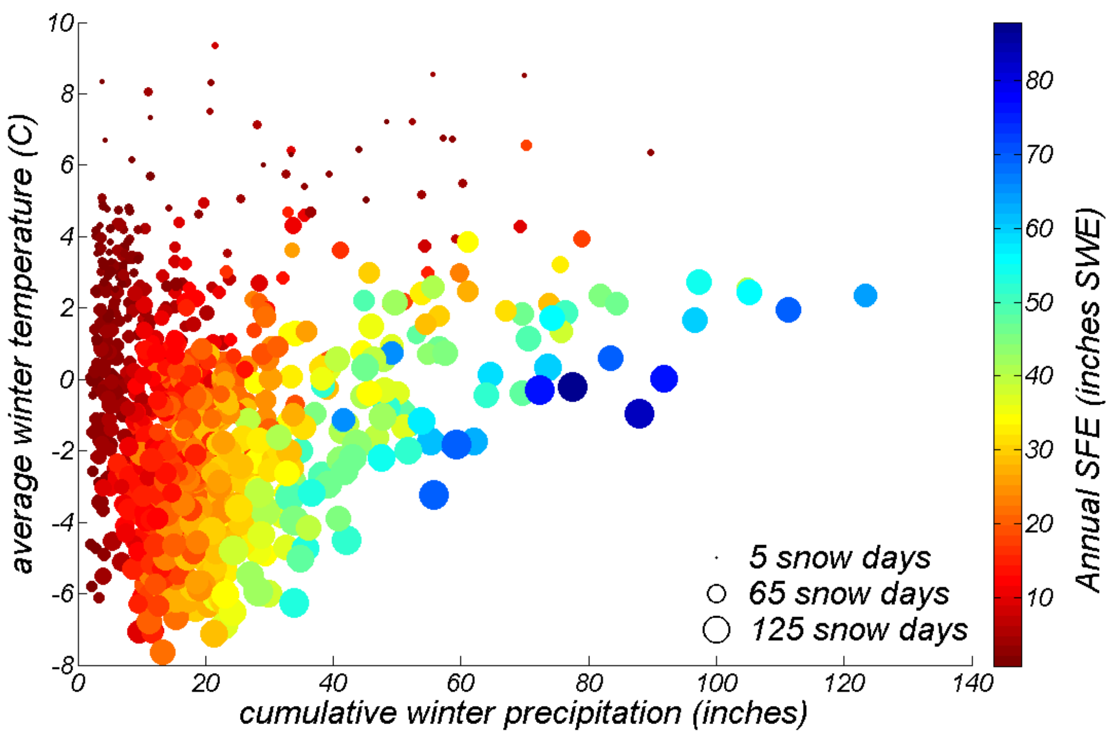

Figure 5. Relationships between cumulative winter precipitation (x-axis), average winter temperature (y-axis), average number of snow days (marker size), and annual SFE (marker color) for each station. Each marker represents one station.

Extreme Snowfall Events

Using the climatic and general snowpack characteristics discussed above as context, the following section analyzes the characteristics of extreme snowfall events. These characteristics include magnitude, percent of annual SFE contributed, seasonality, and coincident average temperature. These characteristics will be analyzed both spatially and elevationally.

The average magnitude of the biggest snowfall event ranges from about 1 inch SWE at many low elevation COOP stations, especially in the eastern (continental) regions to more than 8 inches SWE in the Sierra Nevada and Cascades (Figure 6). As with annual SFE, the greatest magnitudes of extreme events are found in the path of moisture-laden air masses coming from the Pacific Ocean, as indicated in the plot of winter precipitation (Figure 2). Most SNOTEL stations experience biggest events in excess of 1.5 inches SWE. There is a weak negative correlation between the size of the biggest event at SNOTEL stations and station elevation ($r= 0.2464$, $p<0.0001$). There is not a significant correlation between size of the biggest event and station elevation at COOP stations.

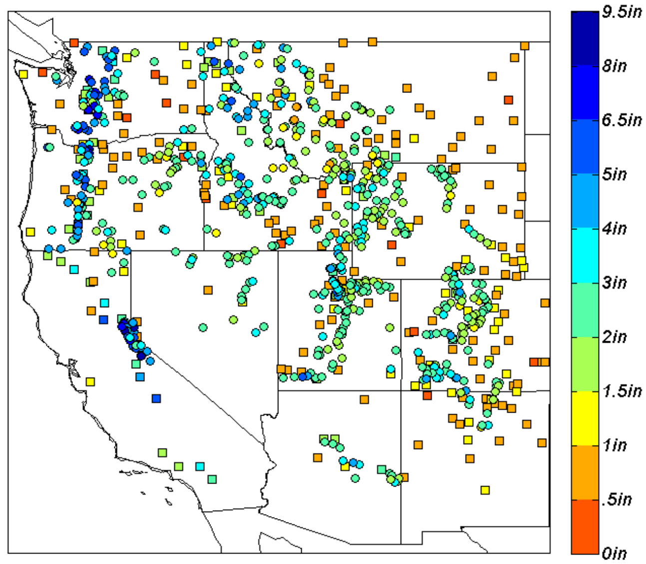

Figure 6. Average magnitude of the biggest snowfall event (inches SWE).

The biggest snowfall event of the year is extremely important to water resources, although its significance varies regionally and with elevation. The average percent of annual SFE (total snow water resources for the water year) contributed by the biggest snowfall event is shown in Figure 7. In lower latitudes and along the coast, many COOP stations receive the majority of annual SFE from the biggest event. For lower elevation COOP stations the percent contributed by the biggest event decreases moving from southwest to northeast. SNOTEL stations receive between 5 and 30 percent of annual SFE from the biggest event. Contributions are greatest in Arizona, where the biggest events contribute more than a quarter of annual SFE. The highest elevations, in the Rockies, show the smallest percent contributions. In these areas the biggest event still contributes between 5 and 20 percent of annual SFE. The high percent contributions of the biggest event indicate that water resource availability is very sensitive to the presence or absence of the biggest event, especially in low elevation and low latitude areas and coastal states. The single biggest event in these areas can make the difference between a dry and a wet year for snow water resources.

The seasonality of the biggest snowfall events for each station was computed by taking the mean of the occurrence day for all events at each station. The means were then grouped into half month increments. There are obvious caveats to this approach, for example if a station has a many events in January and another peak in frequency in March, then this method would result in a February event season. Results using the median date of occurrence had similar results. Keeping this in mind, this method still provides a useful way to examine spatial differences in seasonality. It was found that the seasonality of the biggest events varies widely across the West (Figure 8). The earliest events

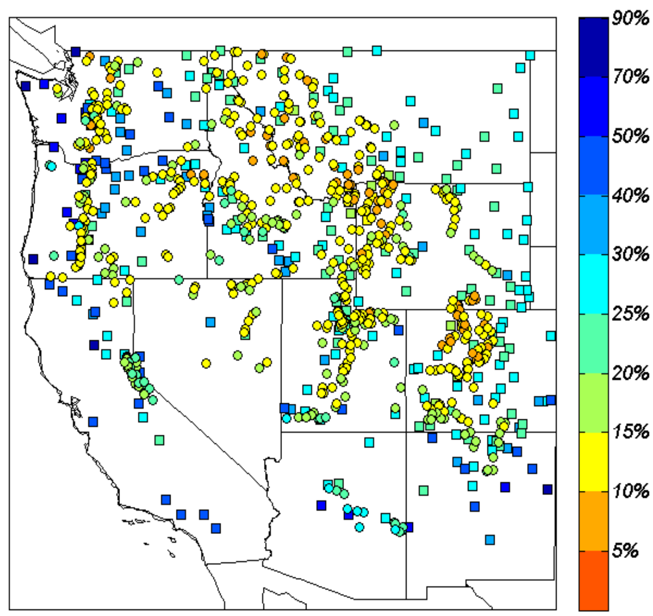

Figure 7. Average percent of annual SFE contributed by the biggest event.

occur in December at scattered locations mostly in the Pacific Northwest. California, Nevada, Arizona, New Mexico and most of the stations in the Pacific Northwest experience events in January and February. The latest events occur in the eastern regions including Montana, Wyoming and Colorado, where events typically occur in March and April, coincident with the higher late winter precipitation amounts along the eastern Rockies.

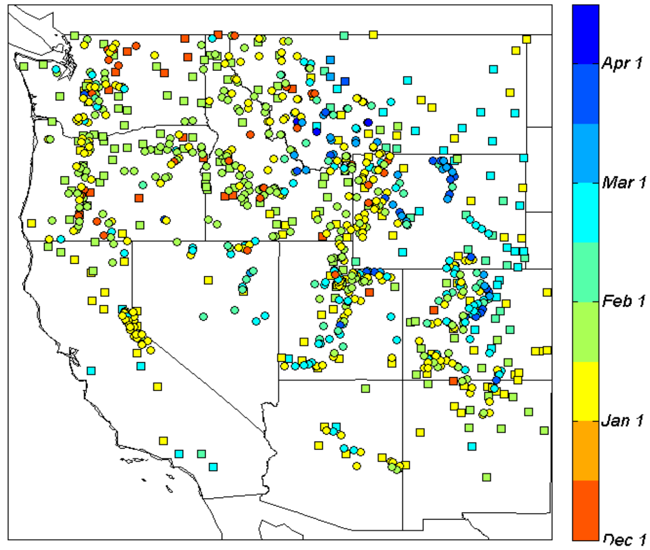

Figure 8. The mean date of the biggest snowfall event, grouped in half months.

Earlier snowpack melt (McCabe and Clark, 2005) and decreased April 1st SWE (Mote et al., 2005) suggest that the spring snow season is becoming shorter in response to climate change. Of interest is whether the biggest snowfall events, which are extremely important to annual SFE, fall during the tails of the snow season. Cumulative distributions of all snowfall events and the biggest snowfall events were computed for eight regions of the West (outlined in Serreze et al., 1999). Results (Figure 9) indicate that in many regions, including the Pacific Northwest, the Sierra Nevada, the Blue Mountains, Idaho/Western Montana, and Arizona/New Mexico, the window of biggest event occurrences is a subset of the larger snowfall season. This suggests that the biggest snowfall events in these regions may be less vulnerable to a shortened spring snow season. In the remaining three regions, Northwest Wyoming, Utah, and Colorado, the seasonality of the biggest event is very similar to the seasonality of all snowfall events.

To further explore the potential impacts of climate change on extreme snowfall events, the temperature during the events was considered. The coincident average temperature was calculated as the average temperature on the middle day of the three day event. For each station, these temperatures were averaged, resulting in one temperature value per station. Results (Figure 10) show the strong influence on continentality. Stations near the coast, in the lower latitudes, and in eastern Colorado experience the biggest snowfall events at the warmest temperatures, often above 0C. Temperatures decrease moving northeast. The coldest events occur in the high elevation intermountain region, and are often below -4C. The average event temperature is well correlated with station elevation ($r= -0.5825$, $p<0.0001$). Initial results indicate that the biggest events occur at higher temperatures than other snowfall events on average, but additional analysis is needed. With projected climate warming exceeding 2C, the biggest snowfall events in lower latitudes, coastal states, and eastern Colorado may become large rainfall events. This could result in severe flooding, possibly enhanced by a rain-on-snow situation (McCabe et al., 2007), in addition to reduced snowpack storage of winter precipitation.

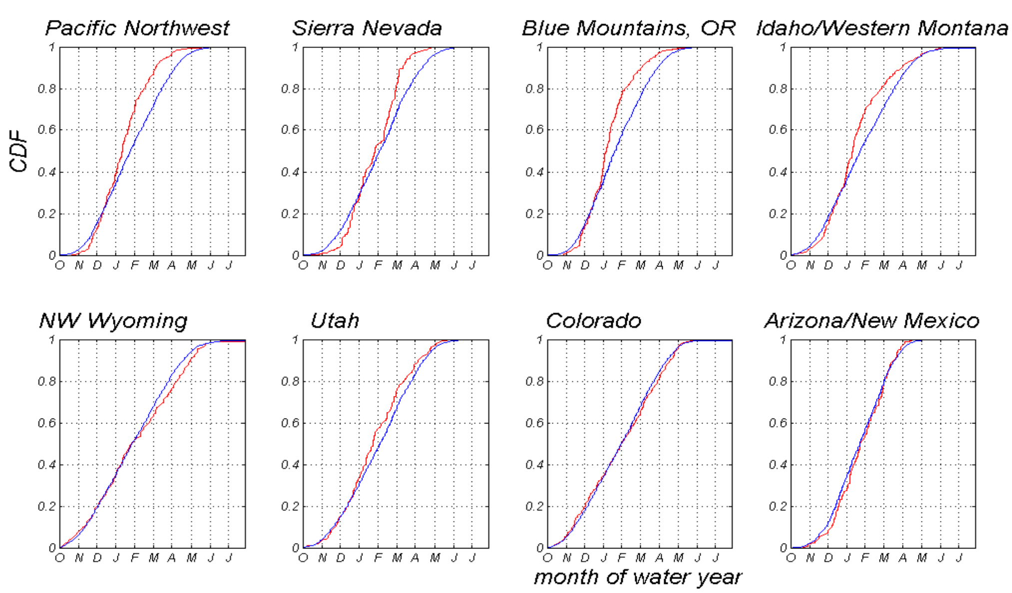

Figure 9. Cumulative distribution plots of the timing of all snowfall events (blue lines) and the biggest snowfall events (red lines) for eight regions of the western United States (regions specified in Serreze et al., 1999).

INTERANNUAL VARIABILITY

The final section of this study explores the interannual variability of extreme snowfall events. Relations of extreme snowfall events to annual SFE will be considered as well as the relationships between the characteristics of extreme snowfall events and the El Nino Southern Oscillation (ENSO). In recent years that have been several studies which examined the relationship between ENSO and various snowfall properties including snowfall (Kunkel and Angel, 1999), extreme winter precipitation (Schubert et al., 2007), and spring SWE (Cayan, 1996). The only publication considering the relationship between ENSO and extreme snowfall is by Serreze et al., (2001). They found that during strong ENSO years total SFE correlated well with the number of snow days, size of the 75th percentile event, and the size of the biggest event, although they admitted that the short period of record (18 years) limited the analysis. The following analysis expands on this by using a longer period of record as well as more diverse station locations and will consider the size of the biggest event, annual SFE, and the percent of annual SFE contributed by the biggest event.

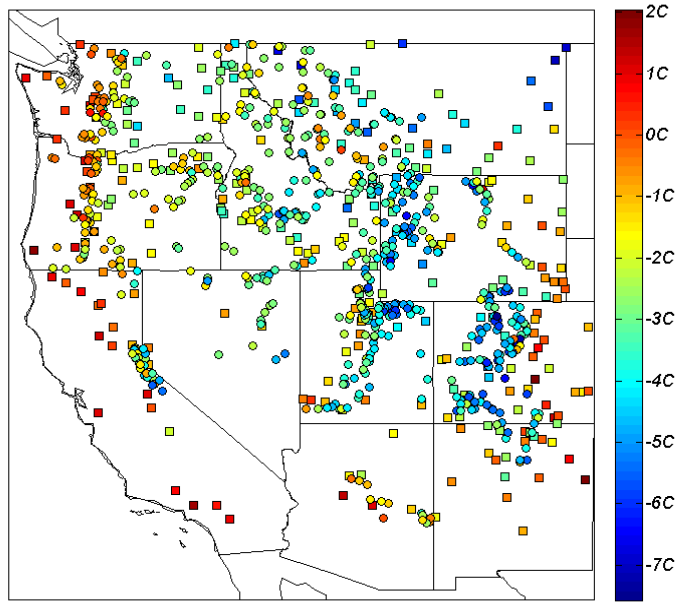

Figure 10. The mean of the average temperature coincident with the biggest snowfall event.

Extreme Snowfall Events and Annual SFE

Of interest is how annual SFE and the size of the biggest event covary. Our analysis found the correlations to be extremely strong. Figure 11 shows the R^2 value of the linear correlation between annual SFE and the size of the biggest event. Only stations with correlations significant at alpha=0.05 are shown. Approximately 40% of stations have an R^2 value greater than 0.5. This corroborates the findings of Serreze et al., (2001) who found that "years with above-average annual snowfall tend to be associated with more frequent as well as stronger snow-producing processes" which are conducive to large snowfall events. These results also reveal that during years with especially low annual SFE, the size of the biggest event tends to be less. The causal relationships are unclear and require further research. Analysis of the correlation between the size of the biggest event and annual SFE minus the biggest event (not shown) showed much weaker correlations. This further illustrates the importance of the biggest event to annual SFE.

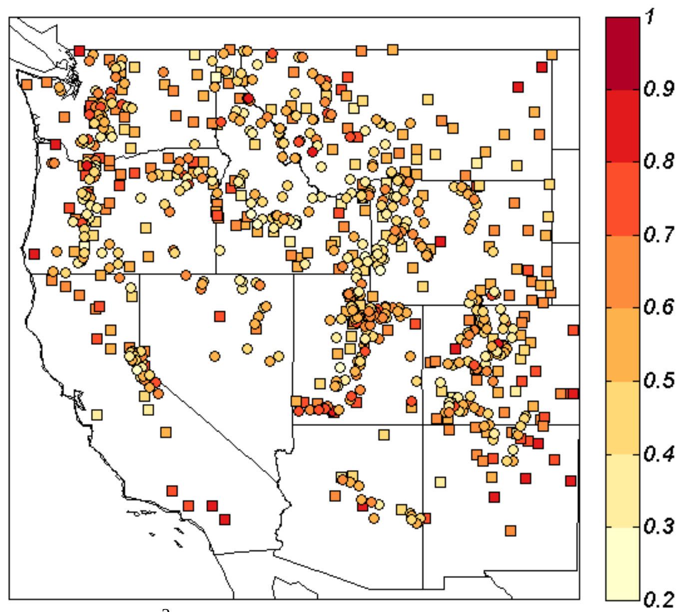

Figure 11. R^2 value of the linear correlation between annual SFE and the size of the biggest event. Stations plotted are significant at alpha=0.05.

El Nino Southern Oscillation

The El Nino Southern Oscillation (ENSO) is known to have significant impact on western United States climate and hydrology, especially during the winter months. To consider the impact of ENSO on extreme snowfall events, this study examines the correlation between the Multivariate ENSO Index (MEI) and characteristics of extreme snowfall events. The winter MEI signal was found by taking the mean of the monthly October through March MEI for each year.

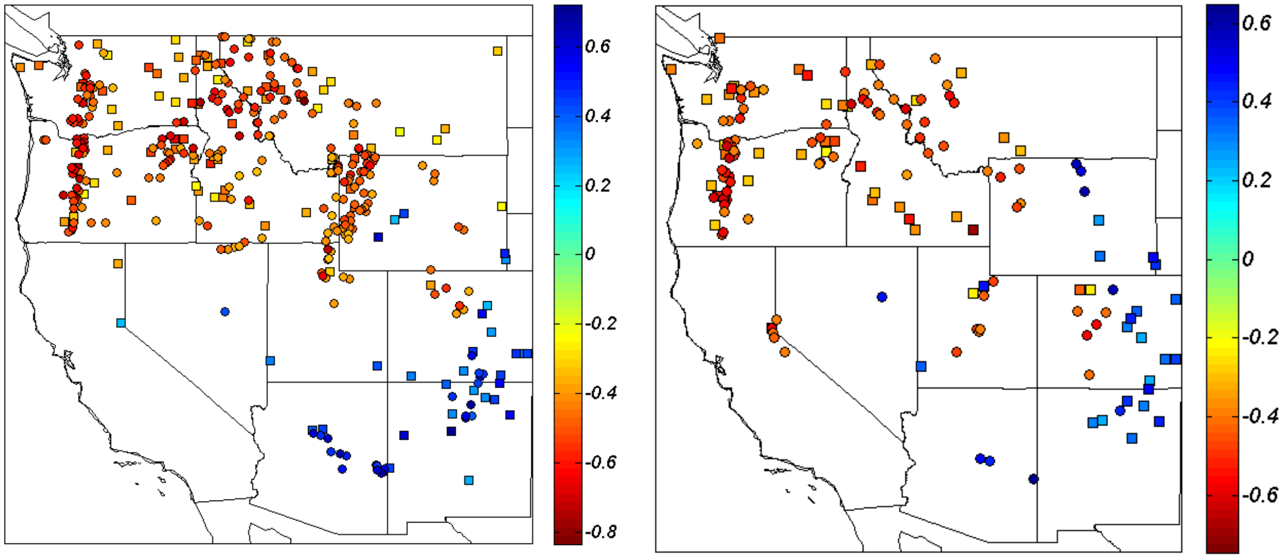

Figure 12. a) R value of the correlation between MEI and annual SFE, b) R value of the correlation between MEI and the size of the biggest event. Values plotted are significant at alpha =0.10.

Correlations were fairly strong between MEI and annual SFE (Figure 12a). Correlations (significant at alpha=0.10) display a strong dipole pattern with negative correlations in the northwest and positive correlations in the southwest. This signifies that during positive MEI or El Nino years, the northwest experiences significantly smaller snowpacks than average while the southwest experiences significantly larger snowpacks. During negative MEI or La Nina years, these situations are reversed.

Correlations between MEI and the size of the biggest event show a similar spatial pattern, although it is somewhat weaker (Figure 12b). As with annual SFE, the size of the biggest event is negatively correlated with MEI in the northwest and positively correlated in the southwest. Interestingly, stations in the Sierra Nevada are significantly correlated with MEI for the size of the biggest event but not for annual SFE. Additional research is needed to ascertain why these correlations are desynchronized. Figure 12b indicates that the biggest events are larger than average in the southwest during positive MEI or El Nino years and smaller than average in the northwest during El Nino years. The opposite situation holds for negative MEI or La Nina years.

It has been shown that ENSO has similar effects on annual SFE and the size of the biggest event; the spatial patterns of the correlations are very similar. It remains to be answered what effect ENSO has on the relative importance of the biggest event for the annual snowpack and water resources. To consider this question, the percent of annual SFE contributed by the biggest event was correlated with MEI (Figure 13). The spatial pattern of the correlations is a similar dipole pattern to the correlations with annual SFE and the size of the biggest event (Figure 12a, 12b), except that the sign of the correlations is opposite. This indicates that during positive MEI (El Nino) years, the northwest receives a greater percent of its snowpack from the biggest event. In other words, although the biggest event

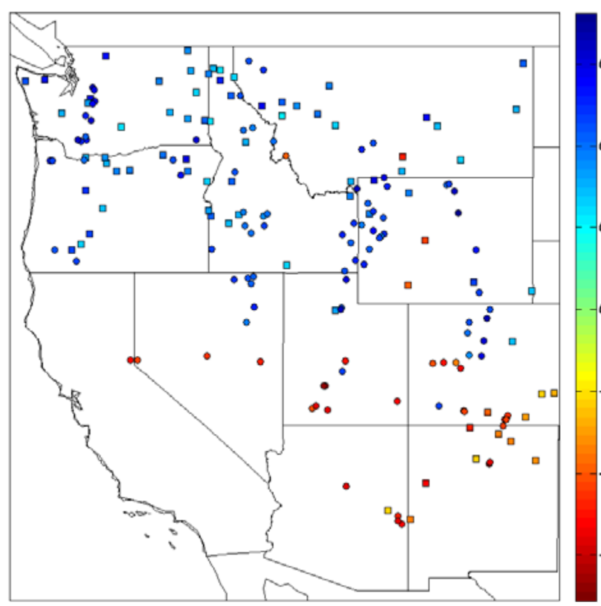

Figure 13. R value of the correlation between MEI and the percent of annual SFE contributed by the biggest event. Values plotted are significant at alpha = 0.10.

is smaller and the annual snowpack is smaller in the northwest during these years, the overall contribution of the biggest event is greater. This implies that the biggest event is especially important in these years; without it the already small snowpacks would be significantly less. In the southwest, although annual SFE and the size of the biggest event are greater in positive MEI (El Nino) years, the relative contribution of the biggest event is less.

CONCLUSIONS

This study has shown that the biggest snowfall event of the year is extremely important to water resources in the western United States, contributing upwards of 20% of annual SFE at some SNOTEL stations and often contributing the majority of annual SFE at COOP stations. The biggest events occur in the Sierra Nevada and the Cascades and the largest event becomes smaller moving from southwest to northeast.

The warmest events were shown to occur in the coastal states, low latitude regions, and eastern Colorado, where events regularly occur at above 0C. Snow water resources in these areas may be the most vulnerable to projected climate warming. This is especially true in Colorado where the biggest events tend to occur late in the snow season and maybe be affected by the same processes contributing to early snowpack melt and decreased April 1 SWE. Climate change may transition these events from extreme snowfall events to extreme rainfall events, which could result in severe flooding, possibly enhanced by a rain-on-snow situation, in addition to reduced snowpack storage of winter precipitation.

The size of the biggest was found to be strongly correlated with annual SFE, meaning that years with above average snowpack have larger biggest events. Similarly, years with below average snowpack tend to have smaller biggest events. This implies that flood and avalanche risk may be greater in high snowfall years and road closures may be even more likely due to enhanced biggest events.

Annual SFE and the biggest event are strongly correlated with MEI in a northwest-southwest dipole pattern. This suggests that with the increasing predictability of ENSO phases, some predictability of annual SFE as well as the biggest event may be possible. Furthermore it was found that the percent contributed by the biggest event was correlated with MEI in an opposing pattern to annual SFE and the size of the event. When ENSO creates larger snowpacks and larger biggest events (El Nino years in southwest, La Nina years in northwest), the relative importance of the biggest event is less.

The fact that the biggest event can make or break the annual snowpack means that water resource availability is sensitive to the presence or absence of this event and water resource managers must be able to cope with the presence or lack of this event. This study has contributed to a better understanding of extreme snowfall events, their importance to overall snowpack, and their interannual variability. This knowledge may help inform water managers of how best to manage for these events.

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