PROJECTED CHANGES IN SNOWFALL EXTREMES AND INTERANNUAL SNOWFALL VARIABILITY IN THE WESTERN UNITED STATES*

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ABSTRACT

Projected warming and more variable precipitation will impact 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 snowfall events. Data from 20 global climate models downscaled and bias corrected to western U.S. Snowpack Telemetry stations are used to assess projected changes in extreme snowfall events and annual SFE. Annual SFE is projected to decrease at all stations. In the coldest regions, changes in the distribution of snowfall and precipitation events are similar, with substantial increases in the most extreme events and smaller changes in small and moderate events. In warmer regions, reductions are projected for all snowfall events, however large events will be far more resilient than small and moderate events due to differential temperature sensitivities and changes in precipitation. Variability in annual SFE is projected to increase, particularly in warmer regions, due to fewer snowfall days and the increasing importance of heavy snowfall events. In the coming century, water management will be challenged by reduced and significantly more variable snowpack. (KEYWORDS: climate change, snowfall variability, extreme, temperature)

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*,

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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.

DATA AND METHODS

Daily minimum and maximum temperature and precipitation from twenty global climate models (GCMs, Table 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].

Table 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
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.

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 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 90^{th} 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

Table 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.	
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 on snow days	Mean average temperature on snow days.	°C
$Tavg_{90}$	Temperature during 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.

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.

RESULTS

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 1a). 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 1a) 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 1b). 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 1c). 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 2a). 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 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%. 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.

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 2b). 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. 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 mean SFE of extreme snowfall events, $\overline{SFE}_{90}$, were strongly positively correlated with elevation and strongly negatively correlated with $Tavg_{90}$. 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 2b). All models projected increases or no change in $\overline{SFE}_{90}$ for stations in the coldest (-8°C) bin. 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

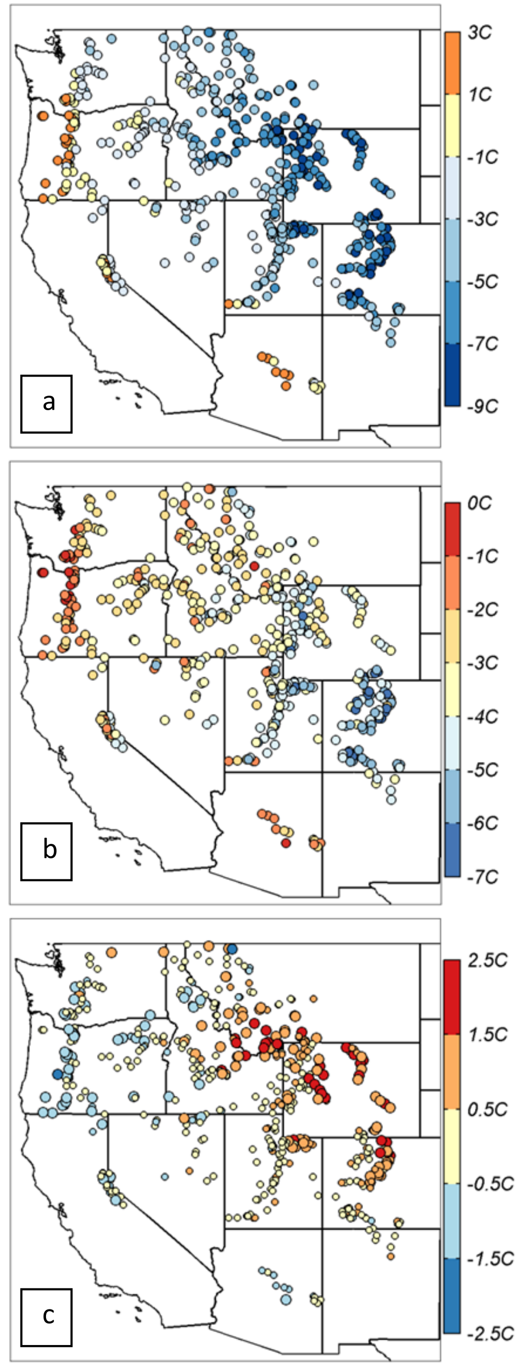

Figure 1. From SNOTEL observations: a) observed mean winter (Nov-Mar) temperature. Each color range identifies a temperature bin. b) $Tavg_{90}$ c) Difference between $Tavg_{90}$ and $Tavg_{snow}$. Larger markers indicate that extremes occur at significantly different temperatures than all snow days by t-test (alpha=0.05).

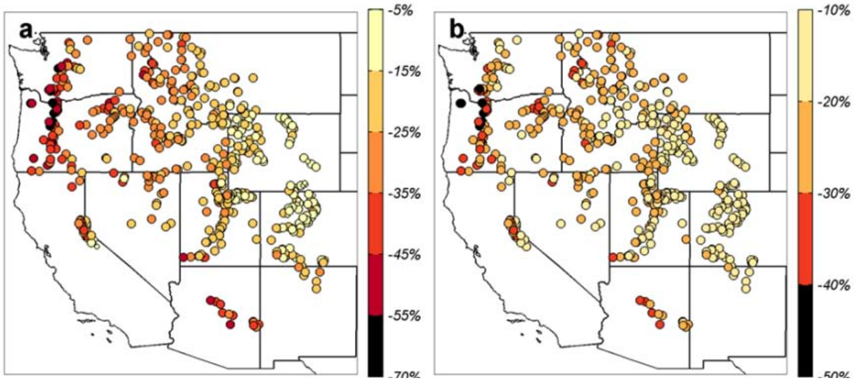

Figure 2. Percent change in a) annual SFE and b) number of snow days. Larger (smaller) markers indicate significant (insignificant) changes.

sensitivity of snowfall events resulted in less positive changes in snowfall (Figure 4). 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 5a). 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 2b), 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 2), 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 5b) 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 2b) 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).

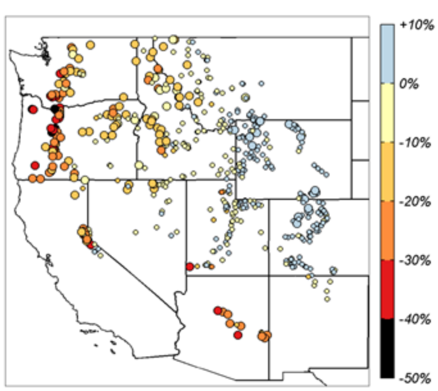

Figure 3. Percent change in SFE_{90}. Larger (smaller) markers indicate significant (insignificant) changes.

DISCUSSION

The coincident temperatures of extreme events (Figure 1b) 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

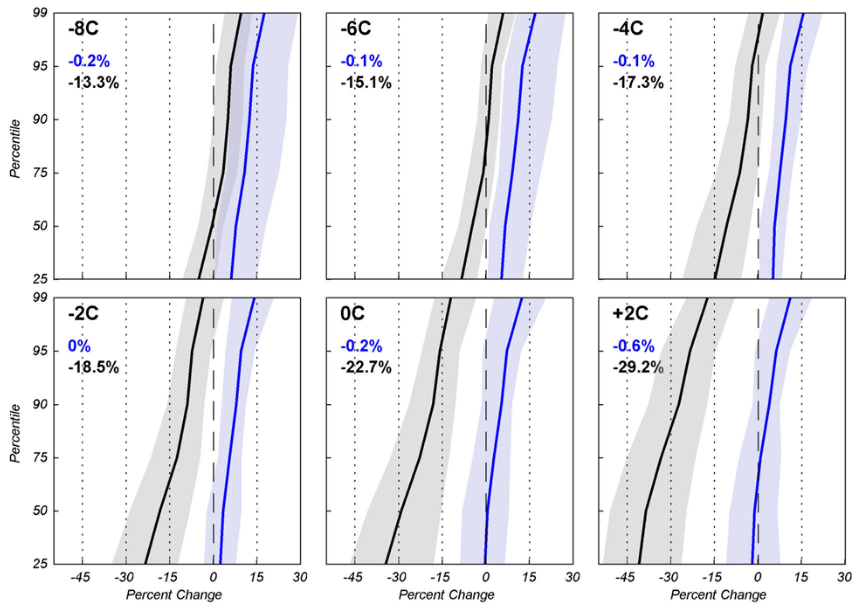

Figure 4. Changes in select percentiles of precipitation (blue) and snowfall events (black) grouped by temperature bin. Text below the temperature bin label indicates the percent change in mean annual number of precipitation (blue) and snowfall events (black). The station- and model-averaged percentile 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.

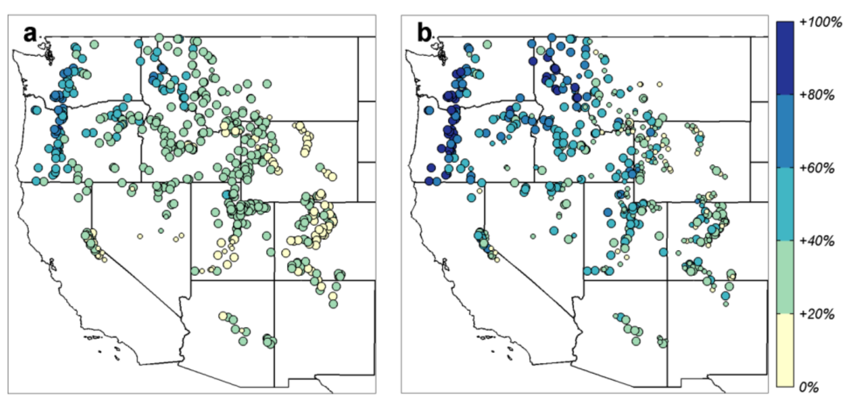

Figure 5. Percent change in CV of a) annual SFE and b) cumulative SFE of top decile snowfall events, $\sum SFE_{90}$ (using transient baseline). Larger (smaller) markers indicate significant (insignificant) changes.

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 1c). 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 2a) 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. 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 2b) 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 4), 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. The relatively cold coincident temperatures of extreme snowfall events in the Middle and Southern Rockies (Figure 1b) combined with expected increases in atmospheric moisture will enable larger snowfall events into the mid-21st century (Figure 3), despite the fact that extremes in these regions occur at significantly warmer temperatures than the average snowfall event (Figure 1c). In these cooler regions, the spread between percent changes in extremes and the rest of the distribution is relatively small (Figure 4). 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 1b), making them vulnerable to projected increases of 1.5-5°C by midcentury. However, extreme snowfall events in the warmest locations occur at significantly cooler temperatures than the average snowfall event (Figure 1c). 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 4). 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 5a), 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 5b) outstrip those of the CV of annual SFE. The increasing tendency toward heavy events at the expense of light and moderate events (Figure 4) 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.

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.

*For a more complete version of this work please see Abby Lute's Master's Thesis, 'Extreme snowfall events in the western United States: variability, change, and implications for water resource management' (2014).

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