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# The Changing Character of the California Sierra Nevada as a Natural Reservoir

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## Abstract

The mountains of the Western United States provide a vital natural service through the storage and release of mountain snowpack, lessening impacts of seasonal aridity and satiating summer water demand. However, climate change continues to undermine these important processes. To understand how snowpack may change in the headwaters of California's major reservoirs, the North American Coordinated Regional Climate Downscaling Experiment is analyzed to assess peak water volume, peak timing, accumulation rate, melt rate, and snow season length across both latitudinal and elevational gradients. Under a high-emissions scenario, end-of-century peak snowpack timing occurs 4 weeks earlier and peak water volume is 79.3% lower. The largest reductions are above Shasta, Oroville, and Folsom and between 0- and 2,000-m elevations. Regional climate model and global forcing data set choice is important in determining historical snowpack character, yet by end century all models show a significant and similar decline in mountain snowpack.

## Plain Language Summary

Mountains are natural water towers that store snowpack in winter and release it as snowmelt during spring to summer. However, climate change has and continues to undermine this natural service. To answer where and when water resource management may be impacted by a future of low-to-no snowpack, we can leverage climate models, which are able to project the future conditions of mountain snowpack under various assumptions of global greenhouse gas emissions. In this study, we use five unique climate models under a high-emissions scenario to evaluate a set of snowpack measures upstream of 10 California reservoirs. These 10 reservoirs represent nearly half of California's surface storage and by end century could face a 79% reduction in peak snowpack water volume. This work provides detailed guidance on the mountain snow conditions policymakers, water managers, and scientists will encounter in addressing adaptive resiliency in the face of climate change.

## 1 Introduction

North American mountains comprise a quarter of the continent's land surface but store 60% of the 1,365 million acre-feet (MAF) of annual peak snow water (Wrzesien et al., 2018). Water budgets of Western United States are largely dependent on mountain snowpack, which provides three fourths of the water supply via snowmelt (Palmer, 1988). In California, the Sierra Nevada mountain range supplies 60% of the consumptive water use and supplements the state's reservoir storage capacity by 72% through mountain snowpack (Bales et al., 2011; Dettinger & Anderson, 2015). The recent 2012–2016 drought, which featured record-low snowpack and subsequently strained water resources, provided a poignant reminder of the importance of mountain snowpack to California's economy and population (Belmecheri et al., 2016). Insufficient water availability during this period led to a loss of 2.7 billion dollars in agricultural revenue, 21,000 jobs, and a diminished ski season length and quality and led to a statewide mandatory urban water use reduction of 25% (Mote et al., 2016).

Long-term observational records reveal that the average volume and peak timing of mountain snowpack is decreasing and shifting earlier in the season (Kapnick & Hall, 2010, 2012; Mote et al., 2005). In addition, snow drought conditions akin to 2012–2016 could become more common and severe in the future (Berg & Hall, 2017; Harpold et al., 2017; Huang et al., 2018; Ullrich et al., 2018). Sierra Nevada mountain snowpack is largely derived from a few extreme precipitation events that arrive in the form of atmospheric rivers. Because the temperatures of these events often hover at or near freezing, climatological warming has the potential to more readily transform snow events into rain events, which are in turn counterproductive for snowpack accumulation (Bales et al., 2006; Dettinger et al., 2011; Gershunov et al., 2017; Gimeno et al., 2014; Guan et al., 2013).

Climate model simulations corroborate observed decreasing trends in mountain snowpack and show a future of consistent low-to-no snowpack largely due to surface warming and augmentation in precipitation phase associated with anthropogenic climate change (Cayan et al., 2008; Pierce et al., 2008; Pierce & Cayan, 2013). Recent work comparing bias-corrected statistically downscaled global climate model (GCM) simulations, a variable-resolution GCM simulation, and a coordinated set of regional climate model simulations concluded that the Sierra Nevada may lose between 30% and 60% of average snowpack by midcentury (Brekke et al., 2013; Maurer et al., 2007; Mearns et al., 2012, 2013; Rhoades et al., 2016; Rhoades, Ullrich, et al., 2018). These studies, in combination with others in the fourth National Climate Assessment, led to the conclusion that with little-to-no climate change mitigation, and without changes to current water management strategies, there is very high confidence that reoccurring and persistent hydrological drought will become commonplace by the end of this century (Wehner et al., 2017).

As water managers look ahead to a future with decreasing snowpack, there is a need for more detailed information about the speed with which snow conditions are changing in different geographic locations and whether the choice of downscaling methodology has important implications on this, especially within catchment regions of major reservoirs. There is also a need to understand how climate change will affect seasonal and interannual variability in snow dynamics. However, the degree to which climate models and downscaling tools can adequately characterize changing snow dynamics at the spatial and temporal scales required has not been fully investigated. The magnitude of the impact of climate change on snow dynamics is affected by a number of interacting processes such as changes in both the mean and interannual variability of storm track location, precipitation phase, and the snow-albedo feedback (Huang & Ullrich, 2017; Letcher & Minder, 2015; Mountain Research Initiative EDW Working Group et al., 2015; Qu & Hall, 2007; Rhoades, Ullrich, et al., 2018; Sun et al., 2016).

To date, Pierce and Cayan (2013) has been the only study to systematically evaluate a broad range of snow measures in the Western United States within the larger scope of climate model simulations imposed by climate change scenarios. The authors used statistical downscaling to add regional detail to 13 CMIP5 GCM simulations. By end century, they found significant decline in the fraction of snow water equivalent per precipitation event and the persistence of mountain snowpack, especially in coastal mountains such as the Cascades and Sierra Nevada. Although statistical downscaling approaches provide a computationally efficient means to downscale GCM projections to higher resolution, the relationships built into statistical downscaling during the historical training period can break down under climate change due to the lack of positive feedback loops (e.g., snow-albedo feedback) and modifications in synoptic-to-regional scale interactions (Walton et al., 2015; Walton et al., 2017). Both of these are captured by more computationally intensive dynamical downscaling and/or hybrid dynamical-statistical downscaling approaches.

In California, a series of hybrid dynamical-statistical downscaling efforts evaluated climate change influences on snow cover fraction and area and snowmelt timing and runoff throughout the Sierra Nevada as well as more focused efforts in understanding changes to precipitation phase and its influence on snowpack totals in the southern Sierra Nevada (Berg & Hall, 2017; Huang et al., 2018; Schwartz et al., 2017; Sun et al., 2016; Walton et al., 2017). More broadly, several single-model dynamical downscaling efforts have focused on various aspects of snowpack loss such as rainfall-to-snowfall ratios, frequency of rain-on-snow events, peak snow water equivalent (SWE) amount and timing, and snowmelt rate in the major mountain ranges of the Western United States using both climate change scenarios and psuedo-global warming approaches (Ashfaq et al., 2013; Minder et al., 2018; Musselman et al., 2017, 2018; Rasmussen et al., 2014; Rhoades, Ullrich, et al., 2018).

With that said, even among dynamical downscaling approaches, significant historical biases have been identified in their ability to capture key features of the seasonal snow accumulation and melt cycle including the timing and magnitude of peak SWE, mean accumulation rate, and mean melt rate, all of which vary with model resolution and subgrid-scale parameterizations (Rhoades, Jones, et al., 2018). Given the range in quantified model skill for capturing historical snow dynamics, an important question is how the choice of model, or downscaling methodology, affects future projections of snow conditions and dynamics that might be used in a water management planning context.

In this study, we aim to understand how the character of Sierra Nevada snowpack will change in a detailed fashion using process-level metrics to quantify seasonal dynamics at spatial and temporal scales of relevance for major reservoir operations in California. We further examine how historic biases in these metrics affect future projections across an ensemble of regional climate models. We employ the multimetric framework from Rhoades, Jones, et al. (2018), referred to as the SWE triangle, to evaluate snowpack in the headwater regions of 10 major reservoirs in California under a high-emissions scenario. The SWE triangle allows for a systematic evaluation of the snow season at a process level using metrics that characterize unique features of the snow season including peak water volume, peak timing, average accumulation and melt rate, and snow season length. Consequently, this framework provides a more comprehensive assessment of model veracity beyond one measure of skill (i.e., average depth of winter season snowpack) and has the potential to elucidate compensating biases that may exist. To maximize the utility of the SWE triangle multimetric framework we apply it across latitudinal and elevational gradients to understand their role in shaping mountain snowpack.

In the following sections, we aim to answer four major questions surrounding the regional spatiotemporal change in Sierra Nevada mountain snowpack:

(1) How will snowpack change in the headwater regions of major surface reservoirs?
(2) What are the latitudinal dependencies of snowpack change?
(3) How does snowpack change across elevational gradients?
(4) Does the choice of regional climate model influence future projections of snowpack?

## 2 Data and Methods

This study assesses snowpack statistics using the SWE triangle methodology of Rhoades, Jones, et al. (2018). The six SWE triangle metrics are a simple, informative means to quantify the key features of the annual snow season. These metrics include the snowpack accumulation start date, the snowpack accumulation rate (mm/day), the snowpack accumulation peak date and peak water volume at this date (MAF), the snowpack melt rate (mm/day), the complete melt date, and the length of the accumulation and melt season (days). Hereafter, the term peak water volume will refer to the volume of peak SWE in MAF (1 MAF = 1.23348 $km^3$).

To evaluate a wide range of RCM simulations, we utilize nine simulations within the North American Coordinated Regional Climate Downscaling Experiment (NA-CORDEX, Mearns et al., 2018) comprised of six RCMs that are forced by five GCM simulations. These simulations are listed in supporting information Table S1. More details about these simulations can be found in Mearns et al. (2012, 2013). The minimum requirement for inclusion in this study was that daily SWE output must be available for 20 simulated years over a historical (1985–2005), midcentury (2039–2059), and end-century (2079–2099) time period. Each of the future simulations were forced by the Representative Concentration Pathway (RCP) 8.5 (the high-emissions scenario), which assumes high population growth, modest technological changes on energy intensity, and limited-to-no globally enacted climate change policies associated with greenhouse gas emissions (Riahi et al., 2011). RCP8.5 was chosen for this analysis because our current greenhouse gas trajectory is on course with this emission scenario, the temperature response of RCP8.5 is similar to RCP4.5 (midrange emissions scenario) at midcentury and by end-century RCP8.5 likely represents an upper bound on snowpack changes (Hawkins & Sutton, 2009).

The nine NA-CORDEX simulations will be evaluated akin to Rhoades, Jones, et al. (2018) by first regridding them to a common resolution (12 km) using the Earth System Modeling Framework and then masking them across 10 headwater regions generated using U.S. Geological Survey Hydrologic Unit 8-digit Classifications and a surface water hydrologic connectivity algorithm (Tesfa et al., 2011). The headwater regions for this study were chosen as they directly feed into 10 of the major reservoirs of California: Shasta, Oroville, Folsom, New Melones, Don Pedro, Exchequer, Pine Flat, Terminus, Success, and Isabella (supporting information Figure S1). In total, these 10 reservoirs represent 40% of the surface water storage for the State. To examine the elevation dependence of snowpack loss SWE triangle metrics will also be assessed at 100-m intervals up to the median maximum elevation of 2,500 m across the 10 headwater regions.

The Landsat-Era Sierra Nevada Snow Reanalysis (SNSR) product by Margulis et al. (2016) will be used to compare the NA-CORDEX ensemble historical model skill across the SWE triangle metrics. The SNSR SWE estimates are derived from a Bayesian data assimilation method that utilizes probabilistically downscaled meteorological inputs from the North American Land and Data Assimilation Database phase 2 and snow cover area/vegetation cover fractions from the National Aeronautics and Space Administration Landsat 5, 7, and 8 satellite data across 20 watersheds in the Sierra Nevada. A more detailed comparison between SWE observation-based and model-based snow products can be found in Rhoades, Jones, et al. (2018).

Although the NA-CORDEX ensemble only provides simulation data at 25- and 50-km resolutions, coarser than generally preferred for mountain snowpack products (Ikeda et al., 2010; Letcher & Minder, 2015; Pavelsky et al., 2011; Wrzesien et al., 2015; Wrzesien et al., 2018), it is nonetheless a significant improvement over other multimodel ensembles such as the Coupled Model Intercomparison Project phase 5 (CMIP5) GCM ensemble. Further, it is at a sufficiently high resolution to still provide value for snowpack assessment when factoring in the important trade-offs between model resolution, subgrid-scale parameterizations, and global forcing data set (Rhoades, Ullrich, Zarzycki, et al., 2018; Xu et al., 2018).

## 3 How Will Snowpack Change in the Headwater Regions of Major Surface Reservoirs?

To understand the general characteristics of snowpack change in the watersheds of each major reservoir, we first evaluate the daily climatological change in snowpack from 1985–2005 to 2039–2059 and 2079–2099 across the 10 headwater regions. SWE triangles for each of the NA-CORDEX simulations are presented in Figure 1, and summary statistics are presented in supporting information Table S2. Further visualizations of interannual variability via individual water year SWE triangles for all nine NA-CORDEX simulations are presented in supporting information Figures S1 and S2.

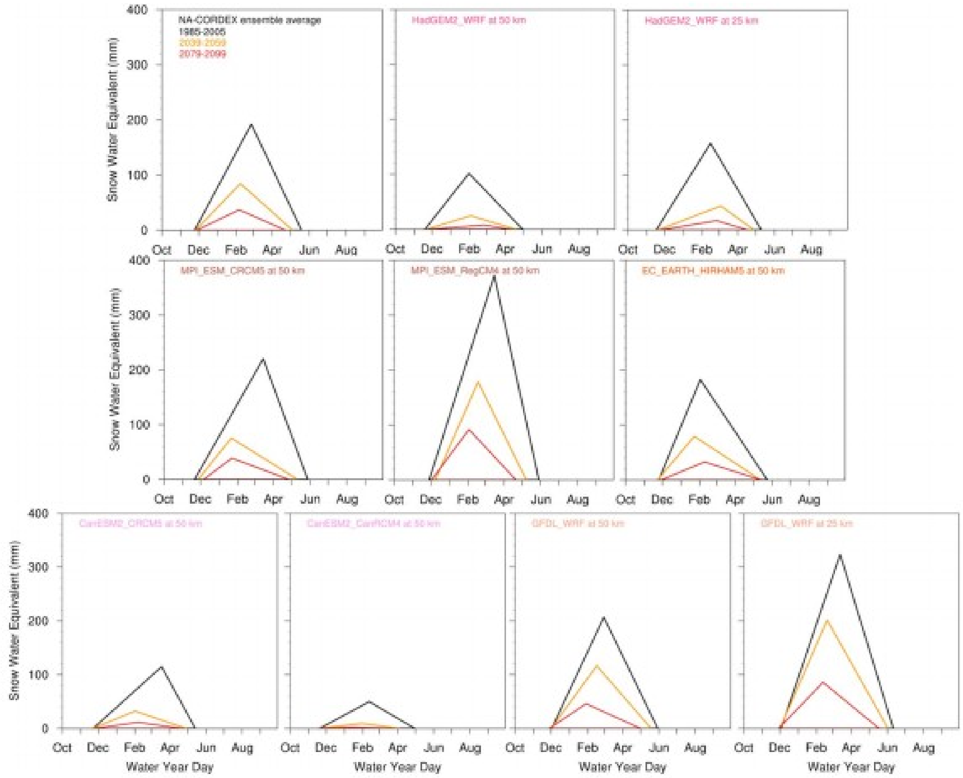


**Figure 1.** Daily climate snow water equivalent triangles for the nine NA-CORDEX simulations across the 10 reservoir headwater regions in California. Each snow water equivalent triangle represents a linearized average approximation of snowpack dynamics for 1985–2005 (black) and future climate under a high emissions scenario for 2039–2059 (orange) and 2079–2099 (red). NA-CORDEX = North American Coordinated Regional Climate Downscaling Experiment.

The peak water volume across the 10 reservoir headwater regions in 1985–2005 is 8.76 MAF for the nine NA-CORDEX simulations. Under future projections, the peak water volume declines by 54.4% to 4.00 MAF by 2039–2059 and 79.3% to 1.81 MAF by 2079–2099. This decline is accompanied by a SWE peak accumulation date that occurs 13 days earlier than historical by 2039–2059 and 25 days earlier than historical by 2079–2099 (to water year day 125 or 3 February). Snow season length, or the accumulation season plus the melt season, is shortened by 20 days by 2039–2059 and 39 days by 2079–2099, with an equally diminished accumulation and melt season. The shorter snow season is driven by a reduction in total snowfall and/or increased ablation. This is shown by the steady reduction in the snowpack accumulation rate from 1.41 to 0.72 to 0.37 mm/day from 1985–2005 to 2039–2059 to 2079–2099. The decline in the snowpack accumulation rate is mirrored by a decline in snowpack melt rate. However, the snowpack melt rate is generally twice that of the snowpack accumulation rate across all time periods.

Overall, these findings corroborate previous regional downscaling results that snowpack in California will decline substantially by midcentury and end century under a high-emissions scenario. Our analysis expands the number of regional climate models assessed in California and evaluates the simulations across a consistent set of snow metrics that elucidates agreement or disagreement in the representation of the snow season historically and under climate change forcing. The 73% to 95% decline in peak water volume by end-century across the nine simulations broadens the range of potential change but is still consistent with past literature. For example, Sun et al. (2016) calculated that 1 April SWE in the southernmost portions of the Sierra Nevada may decline by 46–74% (68–95%) across comparable elevations to this study by 2041–2060 (2081–2100). Using a variable-resolution GCM, Rhoades, Ullrich, et al. (2018) observed that Sierra Nevada mean winter SWE could decline by 30–60% by 2040–2065 across several downscaling methods and 82% by 2075–2100. Pierce and Cayan (2013) claimed a more conservative estimate of changes in winter season SWE in the Sierra Nevada with an 80% probability of a 20% decline by 2040–2069 up to a 60% decline by 2070–2099. Loss of Sierra Nevada winter season SWE will be further exacerbated during drought years as shown by Berg and Hall (2017) and Ullrich et al. (2018) through the recreation of a 2012–2016-like drought at midcentury and end century. Next, we evaluate the important spatial and temporal nuances of change in the California headwater regions.

## 4 What Are the Latitudinal Dependencies of Snowpack Change?

Climate change is hypothesized to impact California's precipitation characteristics, and therefore snowpack, via modifications to the intensity of extreme events and a northward shift in both the mean and interannual variability of winter season storm tracks (Kossin et al., 2017; Walsh et al., 2014). The latter hypothesis was shown more conclusively in GCMs in the most recent CMIP5 than in earlier CMIPs, and as shown in Neelin et al. (2013) the five GCMs used as boundary conditions to the NA-CORDEX ensemble are in agreement of increased precipitation change over northern California by end century under a high-emissions scenario.

To evaluate the potential latitudinal dependence of snowpack change across the NA-CORDEX simulations, we combine the 10 headwater regions into three aggregate regions. These aggregates include the three northern regions (i.e., Shasta, Oroville, and Folsom), which span latitudes 38.6° to 42.4°N and have a total area of 33,480 $km^2$, the three central regions (i.e., New Melones, Don Pedro, and Exchequer), which span latitudes 37.5° to 38.5°N and have a total area of 8,999 $km^2$, and the four southern regions (i.e., Pine Flat, Terminus, Success, and Isabella), which span latitudes 35.4° to 37.2°N and have a total area of 11,807 $km^2$.

A plot of each of the 10 headwater regions is given in Figure 2 along with histograms for each SWE triangle metric across all time periods. In the three northern regions, the NA-CORDEX ensemble mean peak water volume declines by 59.5% by 2039–2059 and up to 83.8% by 2079–2099, or 4.63 MAF to 1.87 and 0.75 MAF. This decline is coupled with a shorter snow season length that over 1985–2005 was 162 days and shortens 22 days by 2039–2059 and 41 days by 2079–2099. Similar changes were found in the central and southern regions as well. In the central regions, a 48.4% decline in peak water volume was found by 2039–2059 and increases to 73.4% by 2079–2099 from 2.43 MAF to 1.25 and 0.65 MAF coinciding with a reduction in the historical snow season length of 186 days by 20 and 37 days. Southern regions decline by 48.8% in peak water volume from 1.70 to 0.87 MAF by 2039–2059 and 75.6%, or 0.42 MAF, by 2079–2099 and a reduction in historical snow season length from 164 days by 18 and 38 days, respectively.

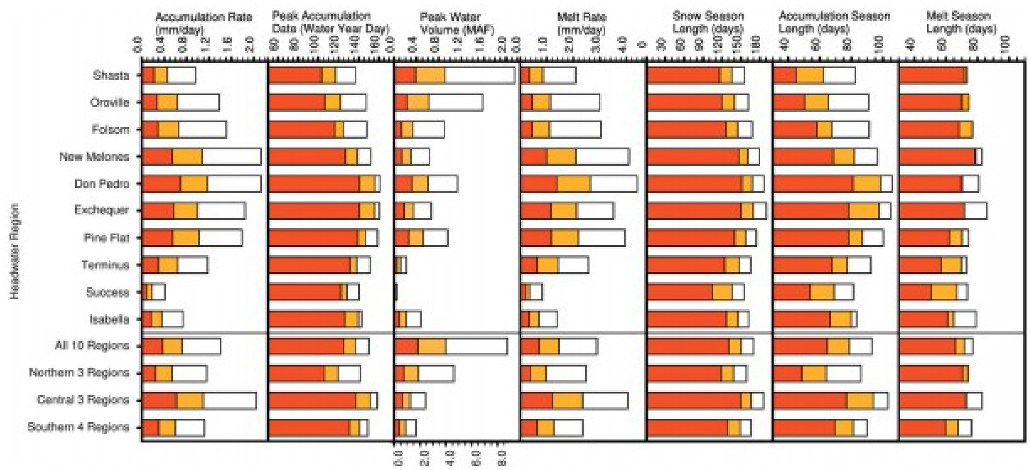


**Figure 2.** Snow water equivalent triangle metrics for the nine North American Coordinated Regional Climate Downscaling Experiment simulations across 10 reservoir headwater regions in California and the northern, central, and southern aggregate regions. Color is used to distinguish 1985–2005 (white), 2039–2059 (orange), and 2079–2099 (red). For Peak Water Volume the top *x* axis is used for individual regions and the bottom *x* axis is used for aggregate regions. MAF = million acre-feet.

The greatest loss in the NA-CORDEX ensemble average peak water volume is in the northern latitudes, nearly double that found in the central and southern latitudes combined. A latitudinal dependence is found over 2039–2059 with a 59.5% decline in the northern headwater regions and 48.4% and 48.8% in the central and southern headwater regions. Similarly, over 2079–2099 the decline was 10% higher in the northern headwater regions than in the central and southern headwater regions with reductions of 83.8%, 73.4%, and 75.6%, respectively. Therefore, given the dramatic snow loss in the NA-CORDEX simulations, especially in the northern regions of California, and the findings of Neelin et al. (2013) it is likely that projected increases in precipitation in northern California comes primarily as rainfall rather than snowfall by end century. The implications of this phenomena across elevation gradients is explored in more detail in the subsequent section.

## 5 How Does Snowpack Change Across Elevational Gradients?

Climate change is expected to impact precipitation phase through a shift from snowfall to rainfall, especially at the surface (Huang & Ullrich, 2017; Rhoades, Ullrich, et al., 2018). This is particularly important for the northern reaches of the Sierra Nevada where elevations are, on average, lower than those found in the southern portions of the Sierra Nevada. For example, across the NA-CORDEX simulations the average (maximum) elevation in the headwater regions of the northernmost reservoirs, Shasta, Oroville, and

Folsom, is 1,320 m (1,730 m), whereas the southernmost reservoirs, Pine Flat, Terminus, and Isabella, is 1,670 m (2,150 m).

Figure 3 shows the changes in the NA-CORDEX ensemble average SWE triangle metrics for the 10 headwater regions up to 2,500 m, the median maximum elevation shared across NA-CORDEX simulations. To evaluate potential impacts surrounding precipitation phase with elevation, we first evaluate snowpack accumulation rates across the 10 headwater regions. In 1985–2005, accumulation rates vary from 0.58 to 4.14 mm/day near monotonically for every 100 m of elevation gain. By 2039–2059, snowpack accumulation rates diminish 71.5% at 0–500 m, 54.4 to 64.8% between 500 and 2,000 m, and 37.1% at 2,000–2,500 m. We attribute this change to elevation-dependent warming, whereby surface temperatures warm due to anthropogenic climate change leading to more variability in the extent and duration of the freezing line and a higher propensity to snowpack ripening (Mountain Research Initiative EDW Working Group et al., 2015; Rangwala & Miller, 2012; Qixiang et al., 2018). Changes to the freezing line increase the ephemerality of snow cover, which modifies the local albedo, and can lead to further warming as more shortwave and longwave radiation is absorbed and reemitted. By 2079–2099, snowpack accumulation rates reduce to 77.1–80.3% between 0- and 2,000-m elevations from historical rates. Thus, snowpack accumulation rates found in 1985–2005 at 0–500m are equivalent to those found at 1,500–2,000 m by 2039–2059 and 2,000–2,500 m by 2079–2099.

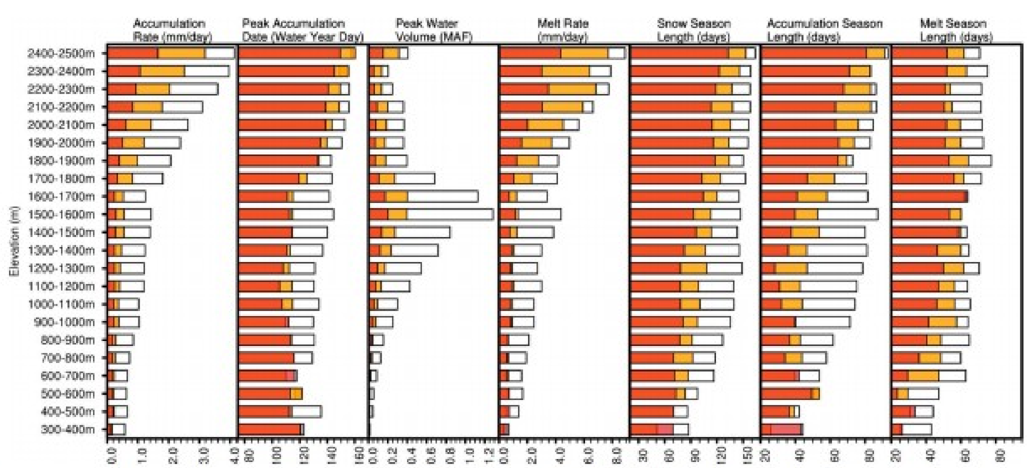


**Figure 3.** Snow water equivalent triangle metrics for the nine North American Coordinated Regional Climate Downscaling Experiment simulations across 10 reservoir headwater regions in California at 100-m elevation increments. Color is used to distinguish time-period, 1985–2005 (white), 2039–2059 (orange), and 2079–2099 (red). MAF = million acre-feet.

In addition to shifts in accumulation rates, peak snowpack timing and spring snowmelt are particularly important to water managers who are tasked with balancing competing interests between flood management, reservoir storage, and the maintenance of species habitat in the spring season. The peak timing of snowpack, often assumed to be 1 April in California, is an important indicator of the start of the melt season. Across NA-CORDEX simulations the historical snowpack peak accumulation date ranges between water year day 125 (3 February) to 154 (4 March) across 0–2,500 m. By 2079–2099, this date shifts 1 to 3 weeks earlier. Akin to snowpack accumulation rates, an elevation gradient in snowpack melt rates is also shown. However, unlike snowpack accumulation rates, unique low-to-middle and middle-to-high elevation dependencies are seen. For example, at 0- to 1,000-m, 1,000- to 2,000-m, and 2,000- to 2,500-m elevations, historical snowpack melt rates were 1.59, 3.61, and 7.37 mm/day, respectively. By 2039–2059, snowpack melt rates diminish to 15% at 0–500 m and 2,000–2,500 m and up to 65% between 500 and 1,500 m relative to 1985–2005. The smaller change in snowpack melt rates at lower elevations is likely because low-to-no snow is deposited, whereas at middle elevations, where larger changes are seen, the variability of the snowline is maximized. By 2079–2099, snowpack melt rates contract to 67–73% of historical rates across all elevations.

Thus, the NA-CORDEX ensemble projects that by midcentury and end-century snowpack accumulation at higher elevations will resemble those that were 1,500–2,000 m lower in elevation historically. Coupled with this, an earlier peak timing of 1 to 3 weeks is shown. In addition, slower snowmelt in a warming world has been corroborated by previous studies, for example, Musselman et al. (2017), and is partly due to less snow accumulation in early winter leading to less available snow to melt but also due to shortwave radiation constraints as the snowpack peak accumulation date shifts earlier in the season when seasonal latitudinal gradients in shortwave radiation are maximized. We next evaluate the influence of model choice on future projections of snow measures.

## 6 Does the Choice of Regional Climate Model Influence Future Projections of Snowpack?

Besides physical mechanisms, regional climate model choice has important implications on simulated land-atmosphere interactions through differences in atmospheric internal variability and structural and parameter decisions made in the representation of snowpack within the land surface model (Chen et al., 2014; McCrary et al., 2017; Mudryk et al., 2015; Raleigh et al., 2015; Rhoades, Jones, et al., 2018; Slater et al., 2001). To evaluate the influence of regional climate model choice on the projection of snowpack within the 10 headwater regions of California, we first evaluate each NA-CORDEX simulation independently.

Figure 4 shows the daily climate SWE triangle metrics across each of the nine NA-CORDEX simulations for 1985–2005, 2039–2059, and 2079–2099. The SNSR SWE observational product daily climate mean and 20-year min, interquartile range, median, and max are also shown. Although there were large differences in magnitude, all nine NA-CORDEX models agree on the incremental downward trend from 1985–2005 to 2039–2059 to 2079–2099 in snowpack accumulation rate, peak water volume, and snowpack melt rate. This agreement by midcentury and end century occurs despite the relatively wide range of historical results. Similarly, snowpack peak accumulation date moves earlier across most of the simulations from 1985–2005 to 2039–2059 and 2079–2099; however, nonintuitively, the two Hadley Global Environment Model 2 (HadGEM2)_Weather Research and Forecasting model (WRF) simulations highlight a later timing. All NA-CORDEX simulations are in agreement that total snowpack season length will diminish by midcentury and end century. However, there were disagreements on the portion of the total snowpack season length that led to the decline, especially at midcentury. For example, six models project a shortening of snowpack accumulation season length from 1985–2005 to 2079–2099, whereas three models project a lengthening. However, for snowpack melt season length four simulations project a shortening and five a lengthening. Even among the four WRF simulations, which all use the same dynamical core, subgrid-scale parameterizations, and Noah land surface model, there is significant divergence in snowpack melt season length. All four simulations agree to within a week of one another on the average historical melt season length. Yet by 2039–2059 and 2079–2099, the range in melt season length diverges between models by 48 and 51 days, respectively. Overall, the NA-CORDEX models are largely in agreement about the magnitude, direction, and model order in the changes in accumulation rate, peak water volume, and melt rate from historical to midcentury and end-century, indicated by the color-filled regions in Figure 4. More dispersion, even in model order, is seen in peak accumulation date and accumulation and melt season length.

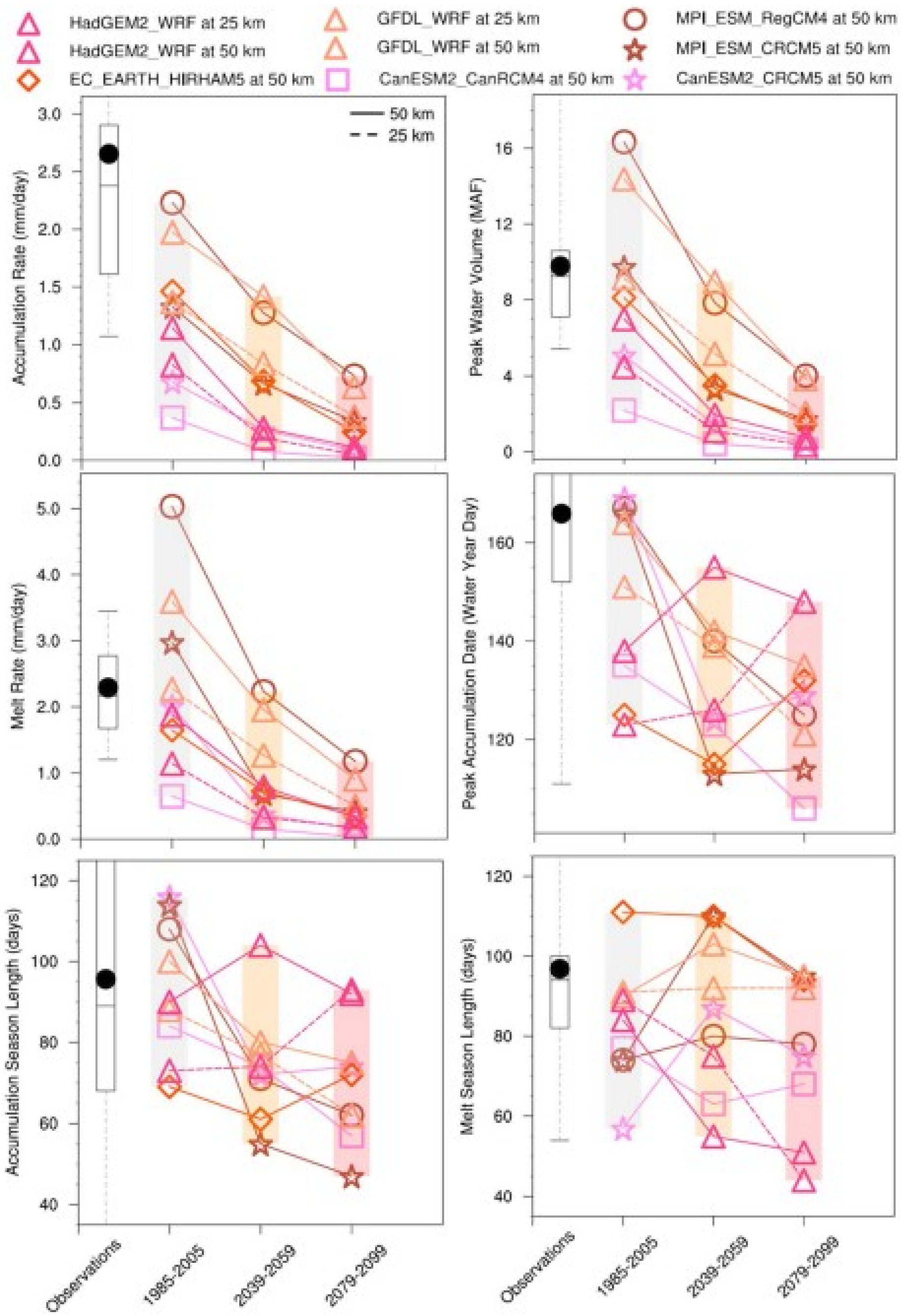


**Figure 4.** Climate average snow water equivalent triangle metrics for the nine North American Coordinated Regional Climate Downscaling Experiment simulations across 10 reservoir headwater regions in California for each of the time periods 1985–2005, 2039–2059, and 2079–2099. Symbol indicates a common regional climate model, color indicates a common global climate model forcing data set, and solid (dashed) lines indicate 50-km (25-km) horizontal resolution. For observational comparison, the Sierra Nevada Snow Reanalysis data set is plotted in black with the daily climate mean (dot) and minimum, interquartile range, median, and maximum shown.

In addition to regional climate model choice, the implications of global model forcing data set is a particularly important factor for the simulation of mountain snowpack as it determines the timing and location of storms as they enter the regional climate model domain. Further, regional climate model resolution is an important factor as it determines how well the underlying topography and land surface cover is represented. In the nine NA-CORDEX simulations, two simulations were run at 25 km and the other seven were simulated at 50 km, with the WRF model offering the only simulations that include both 50 and 25 km. Across the seven 50-km simulations, both the lowest and highest daily climate snowpack accumulation rates, peak water volumes, snowpack melt rates, and snow season lengths occur in 1985–2005. The range in NA-CORDEX model simulations is 1.86 mm/day, 14.1 MAF, 4.38 mm/day, and 21 days. For the two 25-km simulations, a spread in SWE triangle metrics is also found; however, it is less severe with differences of 0.83 mm/day, 7.4 MAF, 1.72 mm/day, and 16 days. However, when comparing the trends in SWE triangle metrics at 50 versus 25 km from 1985–2005 to 2039–2059, and 2079–2099, no significant difference is found across most of the SWE triangle metrics. For example, snowpack accumulation rate, peak water volume, and snow season length all show decreasing trends across resolutions from 1985–2005 to 2039–2059 and 2079–2099. The largest disagreement between simulations run at 50 versus 25 km is in snowpack melt rate, specifically from 1985–2005 to 2039–2059. Simulations run at 50 versus 25 km highlight that snowpack melt rate reduces by 63.4% versus 49.8% from 1985–2005 to 2039–2059. Despite model dispersion in 2039–2059, by 2079–2099, reductions in snowpack melt rates more closely align (i.e., snowpack melt rate reductions range between 77.5% and 82.3% of historical values).

Focusing on just the WRF simulations that were run at 50 and 25 km, differences between Geophysical Fluid Dynamics Laboratory model (GFDL)_WRF at 50 versus 25 km are much larger than for HadGEM2_WRF. For instance, the GFDL_WRF simulation at 25 km compared with 50 km has snowpack accumulation and melt rates that are 0.60 and 1.33 mm/day faster and peak water volumes that are 5.24 MAF larger in the historical period. Yet, by midcentury and end century, GFDL_WRF simulations at 50 and 25 km project more similar reductions in snowpack accumulation rate and peak water volume. Within the HadGEM2_WRF simulations the largest resolution-dependent difference is found at midcentury in snowpack melt rate and melt season length. When comparing the impacts of global model forcing data set between GFDL_WRF and HadGEM2_WRF some additional differences are seen. GFDL-forced WRF simulations have nearly double the snowpack accumulation rates of HadGEM2-forced WRF simulations over the historical period, which amplifies to five times at midcentury and end century. The significant difference in snowpack accumulation rate led to considerable differences in peak water volume of 6.01 MAF. Interestingly, GFDL-forced simulations project a progressively shortened accumulation season length from the historical period to midcentury and end century, whereas HadGEM2 projects the opposite. In both simulations, snowpack melt rates are nearly double snowpack accumulation rates, yet GFDL-forced simulations have snowpack melt rates that are 2 times faster than HadGEM2-forced simulations. In addition to WRF being forced by two different GCM forcing data sets CRCM5 was forced by CanESM2 and MPI_ESM but was only run at 50-km resolution. Akin to the WRF simulations, a nearly twofold difference in historical snowpack accumulation rate and peak water volume is found in CRCM5 when using CanESM2 versus MPI-ESM. Similarly, the RegCM4 simulation forced by MPI_ESM has both the fastest accumulation rate (2.23 mm/day) and largest peak water volume (16.3 MAF) across the historical NA-CORDEX simulations.

Therefore, it appears the snowpack accumulation season is dominated more by the choice of global model forcing data set than by regional climate model choice and/or resolution when looking across WRF, CRCM5, and RegCM4. It should be noted that a comprehensive assessment of regional climate model resolution was not possible using the NA-CORDEX ensemble and resolution did appear to play a role in constraining the magnitude of change in SWE triangle metrics from 1985–2005 to 2039–2059 in simulations that were both run at 50 and 25 km. With that said, the combination of global forcing data set and regional climate model choice had more of a determination in the historical representation and future projection of the SWE triangle metrics.

## 7 Conclusions

In this study, nine regional climate model simulations are analyzed using the SWE triangle multimetric framework in order to understand how the character of Sierra Nevada snowpack will change over the coming century under a high-emissions scenario. The use of the NA-CORDEX multimodel ensemble expands the number of regional climate models assessed in California and allows us to answer how the choice of regional climate model shapes future projections of mountain snowpack. The use of our multimetric framework allows for a more fine-grained analysis of the character of the changing snowpack and how these changes differ across the community of models.

The ensemble average of the nine NA-CORDEX simulations show that by end-century SWE peak timing may occur 4 weeks earlier coupled with a 79.3% reduction in peak water volume upstream of 40% of California's surface water storage. Given that Sierra Nevada snowpack approximately doubles California's surface water storage and releases the water gradually into downstream reservoirs during arid months, a 79.3% reduction presents a major challenge that likely will require fundamental changes in the way that water resources are managed in California.

Despite a slight projected increase in future northern California precipitation (Neelin et al., 2013), the greatest loss in simulated peak water volume at peak timing occurs in the northern latitudes, nearly double that in the central and southern latitudes combined. By end century, the headwaters of Shasta, Oroville, and Folsom experience a reduction in peak water volume at peak timing of 83.8%. Shasta, Oroville, and Folsom provide more than 20% of California's surface water storage alone. Therefore, a significant reduction in snowmelt would likely undermine the effectiveness of the Central Valley Project given no changes to water management.

By end century, when elevation-dependent warming is most pronounced, snowpack accumulation rates diminish by 77.1% to 80.3% between 0- and 2,000-m elevations. Therefore, snowpack accumulation rates at 1,500–2,000 m by midcentury and 2,000–2,500 m by end century resemble those at 0–500 m historically. Similarly, by end century, snowpack melt rates reduce to 67–73% of historical rates across all elevations, which corroborates other single-model studies of slower snowmelt in a warming world (e.g., Musselman et al., 2017).

Although regional climate model resolution had some impact on the historical representation and projected change in snowpack, regional climate model choice and global forcing data set had more of an impact. This is shown in the broad range of projected snow measures based on the individual model chosen. Although there is spread in the magnitude of decline across models at midcentury, especially in snowpack melt season length and melt rate, by end century most models agree that peak water volume and accumulation and melt rates will diminish substantially.

Without changes to current water management practice based on the assumption of an abundance of mountain snowpack deleterious impacts on water resources could affect the prosperity of California's future (Hanak & Lund, 2012; Tanaka et al., 2006; Wehner et al., 2017). This work provides detailed guidance on the mountain snow conditions faced by policymakers, water managers, and scientists as they build adaptive resiliency and abate the risks related to a future of low-to-no snowpack.

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