



Observed and projected changes in snow accumulation and snowline in California's snowy mountains

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Abstract

The Sierra Nevada and Southern Cascades—California's snowy mountains—are primary freshwater sources and natural reservoirs for the states of California and Nevada. These mountains receive precipitation overwhelmingly from winter-time storms including atmospheric rivers (ARs), much of it falling as snow at the higher elevations. Using a seven-decade record of daily observed temperature and precipitation as well as a snow reanalysis and downscaled climate projections, we documented historical and future changes in snow accumulation and snowlines. In four key subregions of California's snowy mountains, we quantified the progressing contribution of ARs and non-AR storms to the evolving and projected snow accumulation and snowlines (elevation of the snow-to-rain transition), exploring their climatology, variability and trends. Historically, snow makes up roughly a third of the precipitation affecting California's mountains. While ARs make up only a quarter of all precipitating days and, due to their relative warmth, produce snowlines higher than do other storms, they contribute over 40% of the total seasonal snow. Under projected unabated warming, snow accumulation would decline to less than half of historical by the late twenty-first century, with the greatest snow loss at mid elevations (from 1500 to 3300 m by the mountain sub-regions) during fall and spring. Central and Southern Sierra Nevada peaks above 3400 m might see occasionally extreme snow accumulations in January–February resulting entirely from wetter ARs. AR-related snowlines are projected to increase by more than 700 m, compared to about 500 m for other storms. We discuss likely impacts of the changing climate for water resources as well as for winter recreation.

Keywords Atmospheric rivers · Precipitation · Snow accumulation · Snowline elevation · Climate change · Water resources

1 Introduction

Snow-covered mountains are key freshwater reservoirs on which ecosystems and human societies depend for water resources, particularly in precipitation-limited regions (Viviroli et al. 2007; Huss et al. 2017; Immerzeel et al. 2020). In Mediterranean climate regions, where precipitation falls predominantly in the cool season, high mountains retain snow, releasing the much-needed snowmelt gradually to supply often highly populated and traditionally fertile downstream valleys and foothills during the dry summer growing season. Mountain snow reservoirs are highly sensitive to the warming climate, with snowpack being increasingly confined to the colder, higher elevations as warming progresses (e.g. Knowles et al. 2006; Pierce et al. 2008; Siirila-Woodburn et al. 2021), challenging water resource management (Siirila-Woodburn et al. 2021). Much of the precipitation

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that does not fall on the mountain as snow instead produces runoff. Regional warming trends result in increasingly frequent and severe extreme runoff events that elevate flood risk at lower elevations during the warming cool wet season (Das et al. 2013; Musselman et al. 2017; Corringham et al. 2022). In Mediterranean climate settings, the warming of the already hot and dry growing season compounds increasingly frequent and severe water deficits resulting from reduced water availability due to diminished snowpack (Cayan et al. 2010; Polade et al. 2017).

In the southwestern United States (Southwest), the Sierra Nevada and Southern Cascades (hereafter “California’s snowy mountains”) are a primary freshwater source and natural reservoir for the states of California and Nevada, collecting, on average, 18.5 km³ (15 maf),¹ estimated from a 70-year record of reconstructed snow accumulation, see below) by April 1. Given its Mediterranean climate setting, the Sierra Nevada receives precipitation overwhelmingly from wintertime storm systems—frontal cyclones, cut-off lows, and atmospheric rivers arriving from the Pacific Ocean, much of it as snow at the higher elevations (Guan et al. 2013; Huning et al. 2017; Eldardiry et al. 2019; Lynn et al. 2020).

Atmospheric rivers (ARs: AMS 2022; Ralph et al. 2020) are warm, moist low-tropospheric jets transporting on average about 2.6 times the flow of the Amazon river (Ralph et al. 2017), but in the form of water vapor. On average, this transport is southwesterly in the northern hemisphere (Ralph et al. 2017) and mainly impacts the west coasts of mid-latitude continents. The primary mechanism of precipitation production in ARs over land is orographic uplift that occurs when ARs encounter topographic barriers (Ralph et al. 2013). The 640 km-long and 105 km-wide NNW-SSE oriented Sierra Nevada (Fig. 1a), rising up to 4400 m in the southern part of the range and 3400 m in the north, happens to be ideally oriented to maximize precipitation from ARs arriving from the west-southwest. North of the Sierra Nevada but still in California lies the southern end of the Cascade Range, with the volcanic Lassen Peak (3187 m) and Mt. Shasta (4322 m) forming the high points of this range. ARs express spatially in the strongly orographic nature of precipitation accumulation (Fig. 1b; Huning and Margulis 2018) with the Sierra Nevada emerging as the primary water catchment among the network of smaller upwind coastal ranges as well as downwind inland mountain ranges. This topographic complexity creates a wet and dry patchwork marking the Southwest’s landscape of green windward

mountain slopes and dry desert rain-shadows. Atmospheric Rivers, warmer and wetter than other storms, must be responsible for the type of snow skiers refer to as “Sierra cement”—heavy wet snow, as opposed to “champagne powder” that falls from colder and drier winter storms. We suspect that ARs provide the lion’s share of snowpack in California’s snowy mountains and aim to quantify the AR contribution specifically to snow water equivalent (SWE) by month. We also aim to quantify the snowline associated with ARs and non-AR storms as well as observed trends in all these variables, including their seasonality.

Long-term snow-to-rain transition trends have been observed over many mountain regions across the globe (Jennings et al. 2018). Along the North American cordillera, these trends have been especially well-documented (Knowles et al. 2006; Klos et al. 2014; Mote et al. 2018; Lynn et al. 2020). Among the mountains of the North American West, the Sierra Nevada and Cascade Range are highly sensitive to the snow-to-rain transition (Nolin and Daly 2006). Of the snow falling on these ranges (Fig. 1c, d), much falls at temperatures within a few degrees of freezing (Knowles et al. 2006; Nolin and Daly 2006; Dettinger and Culbertson 2008), making Sierra Nevada snow accumulation particularly vulnerable to warming. Nearly all watersheds within California’s snowy mountains historically contained seasonal snow, but warming-induced snowfall declines will decrease water stored in seasonal snow for spring and summer release (Hatchett 2021). Snowpack across many elevations has been declining throughout California: it is accumulating later (Hatchett and Eisen 2018) and peaking earlier (Kapnick and Hall 2010) at a lower volume (Mote et al. 2018). These changes result from warming conditions during and between storms (Knowles et al. 2006; Hu and Nolin 2020) and are accelerated by snow-albedo feedbacks (Walton et al. 2016) or other snowpack energy balance perturbations such as changes in snow albedo from the deposition of light-absorbing particles (Skiles et al. 2018). Here, we aim to diagnose observed and projected warming-related changes in snow accumulation and snowline resolving AR and non-AR storms and as a function of elevation and month. Warming trends can differ on wet and dry days (Abatzoglou et al. 2022); they may also differ for different types of weather patterns and storms. We are interested in resolving such possible differences in snowline trends for ARs and other storms.

Besides the impacts of regional warming on continued snowpack decline (Pierce et al. 2008; Das et al. 2009; Pierce and Cayan 2013; Rhoades et al. 2018), climate change is projected to reduce the number of wet days in the region but increase the precipitation received on wet days (Pierce et al. 2013a). The competing tendencies of fewer, but wetter wet days will boost the natural hydroclimate variability of this region (Polade et al. 2014, 2017; Berg and Hall

¹ Million acre feet (maf)—the units used by water resource managers in the Western United States. Throughout the paper, we provide the results in units used by regional water managers in addition to standard units.

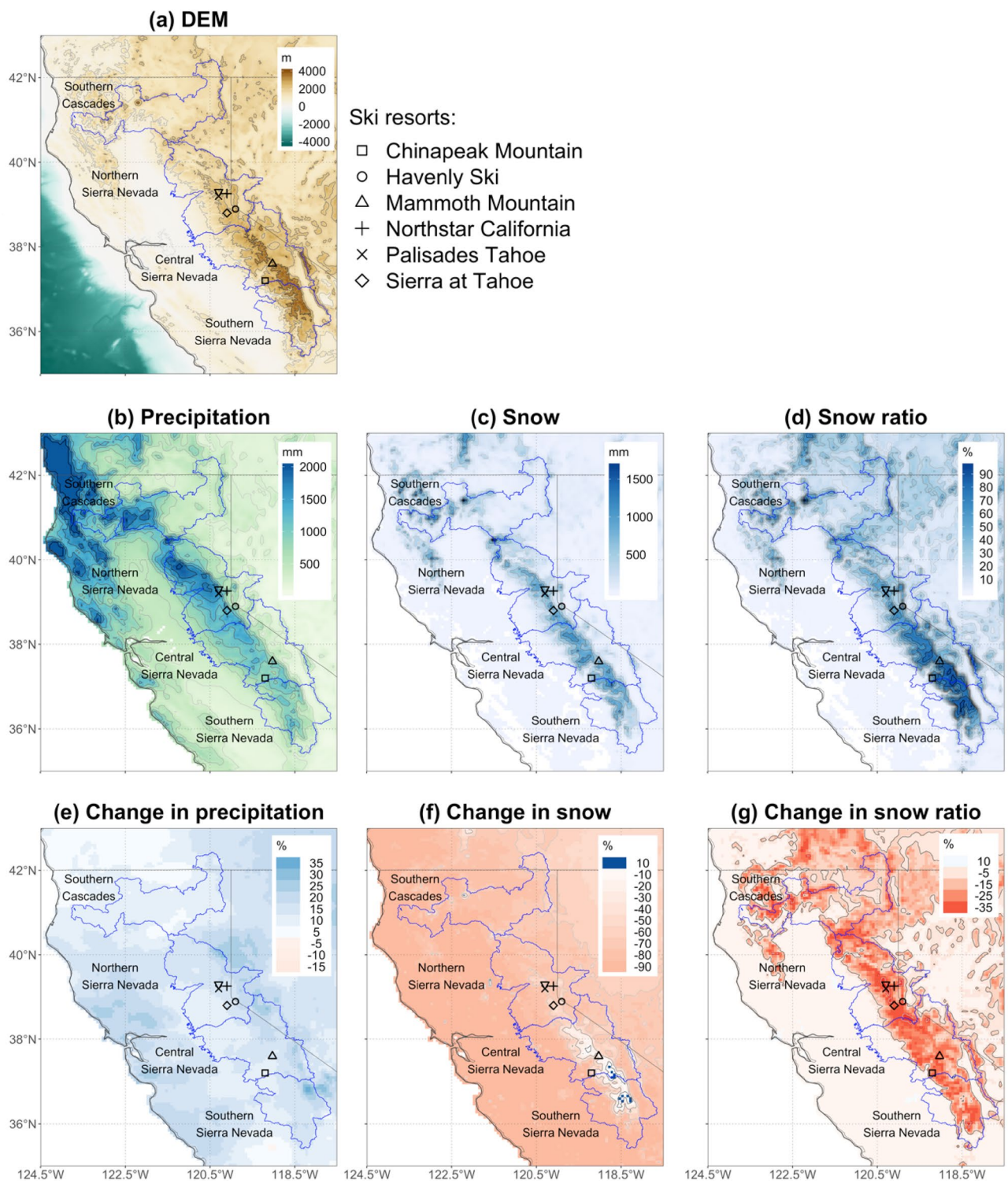


Fig. 1 a Study domain elevations (Digital Elevation Model, DEM, m), b 70-year average of seasonal (October–March) total precipitation accumulation (P, mm), seasonal total snow accumulation (S, mm), and their ratio, expressed as a percent of seasonal snow to total

precipitation (S/P, %). Changes in P, S and S/P (e, f and g, respectively) projected for the second half of the twenty-first century are estimated in percent relative to the second half of the twentieth century using CMIP-5 Global Climate Models RCP8.5 scenario

2015; Swain et al. 2018; Gershunov et al. 2019; Mahoney et al. 2021), where future precipitation and water resources will increasingly disproportionately depend on the warm and warming ARs (Gonzalez et al. 2018; Gershunov et al. 2019). These typically warm storms (Hatchett et al. 2017) are projected to become increasingly intense (Gershunov et al. 2019; Rhoades et al. 2020; Hughes et al. 2022), a process that appears to have already started (Michaelis et al. 2022) while other colder storms are projected to become less frequent (Polade et al. 2014, 2017; Gershunov et al. 2019). Possibly in association with storm-type changes, future projections indicate decreasing snowfall intensities in the lower elevation Cascades and Northern Sierra while increasing snowfall intensities are projected for the higher elevation Southern Sierra Nevada (Marshall et al. 2020). Being mindful of possible differences in warming rates and snowline changes by storm type, we aim to estimate the progressing contribution of ARs to the evolving and projected snowpack in California's snowy mountains.

Impacts of warming on water resources drive our motivation for this work. Winter recreation, however, deserves special attention, as a warming climate implies shorter seasons (Steiger et al. 2017), loss of early season snowpack (Hatchett and Eisen 2019) and more rain instead of snow (Klos et al. 2014). Ski resorts in California provide major sources of income and employment to otherwise often rural communities. Ski resorts are limited to a narrow elevation band due to the relatively high elevation of the seasonal snowline and the relatively low elevation of accessible terrain owing to inherent topographic limitations and/or wilderness designations. We therefore also aim to provide information to the ski industry, which relies on the snowline for lift operation and snowmaking investments as well as business from skier visits following snowfall, which are positively correlated (Hagenstad et al. 2018).

Below, we explore the variability of snow accumulation and snowline, defined as the elevation of the rain-to-snow transition, assessing monthly time scales over the past seven decades from daily 6 km horizontal resolution gridded hydroclimate data, as well as estimating the changes projected by downscaled Global Climate Models (GCMs). Specifically, we assess the role of ARs versus other storms in snow accumulation and snowline at the scale of Sierra Nevada's three regions (high Southern Sierra, Central Sierra and low Northern Sierra) and the southern portion of the neighboring Cascade Range to the north. Elevation, AR frequency and precipitation magnitudes vary among these regions. For each region, we explore the historical and evolving fraction of snowfall accumulation contributed by AR versus non-AR storms by month and elevation bins. The methodology of snowline and snow accumulation identification is presented in Sect. 2. Historical snow accumulation mechanisms and the contribution of ARs to observed trends

in snowline and snow accumulation are explicitly explored in Sect. 3. Last, we provide projected changes in snowline and snow accumulation in Sect. 4, followed by summary and discussion in Sect. 5.

2 Data and methods

2.1 Snowline identification using a precipitation phase temperature threshold

Different snow variables are affected differently by climate change (Pierce et al. 2012). Here we focus on snowline, which is an umbrella term for interpreting the boundary between snow-covered and snow-free areas. The definition of snowline depends on the temporal and process-based contexts in which it is used. In this study we define *snowline* as the land surface elevation at which falling and accumulating precipitation type transitions from rain to snow. We use the Livneh (Livneh et al. 2015; Pierce et al. 2021) dataset of daily surface precipitation and maximum temperature as well as Digital Elevation Model (DEM, NOAA 2009) data to reconstruct a 70-year record (1949–2018) of monthly snowlines and snow accumulations (i.e. accumulation of precipitation that fell as snow) at the west slopes of the Sierra Nevada and Southern Cascades. The study area encompasses the entire Southern Cascades and Sierra Nevada domain along with its four sub-regions: Northern, Central and Southern Sierra Nevada and Southern Cascades based upon California's Department of Water Resources (DWR)'s management of state water resources and topoclimatological characteristics (Fig. 1a).

The higher resolution (1 arc-minute) DEM is aggregated onto the Livneh grid, 1/16 degree (~6 km) using linear interpolation. A spatially-averaged elevation at which temperature reaches the melting level, typically several hundred meters below the atmospheric freezing level, along the west slope of a study area sub-region is detected for every precipitating day. Instantaneous melting level temperatures vary by atmospheric humidity, with low humidity environments leading to higher temperatures due to latent heat exchange (Jennings et al. 2018). To conservatively represent the temperature at which snow turns to rain across varying atmospheric humidities, we set the precipitation phase threshold at 3 °C (3 °C *isotherm*) based on daily maximum temperature (T_{max}). Jennings et al. (2018) found 3 °C to correspond to 25% or less snowfall fractions across a range of saturation vapor pressure values. The use of daily data provides an inherent limitation in defining the snowline because precipitation phase partitioning occurs at timescales much shorter (minutes-hours) than daily. The use of a daily maximum temperature of +3 °C to act as a daily-timescale precipitation phase threshold captures nearly 90% of observed

snowfall at the Central Sierra Snow Laboratory, whereas lowering this threshold to $+1\text{ }^{\circ}\text{C}$ only captures 72% (not shown). The sensitivity of snow and snowline definitions to the choice of melting level and temperature extremity (maximum, minimum or their average) are shown in the Supplementary Methodology section (see the Text and Fig. SM1).

We are also aware, that in their temperature interpolation, Livneh et al. (2015) assumed a fixed lapse rate of $6.5\text{ }^{\circ}\text{C}/1000\text{ m}$, which can introduce elevation-dependent biases in the T_{max} and T_{min} interpolations. We discuss the sensitivity of our results to this bias in the Supplementary Methodology section (Text and Fig. SM2). Based on the supplementary results, we conclude that the detected temperature biases do not impact our research results significantly enough to invalidate our reconstruction and necessitate limiting ourselves to the shorter records of the snow reanalysis and the available less biased daily temperature data sets. Moreover, the statistical downscaling of GCM daily temperature and precipitation (see Sect. 2.3 below) is trained on Livneh data, thus preserving compatibility (along with biases) between the observed and modeled/projected data. For precipitating days with daily maximum temperature above $3\text{ }^{\circ}\text{C}$ at all available elevations, we assume there would be an elevation above existing topography at which the rain-to-snow transition would occur, and we set the melting level at a fixed altitude equal to the highest elevation. The fixed elevation thresholds are 3500 m for the Southern Cascades, 3000 m for Northern Sierra Nevada and 4000 m for central and Southern Sierra Nevada. Monthly snowline elevation is defined as an average of daily snowlines multiplied by the value of daily contribution to monthly precipitation. We weight the daily snowlines by precipitation to capture the outsized contribution of rare heavy widespread snow accumulation days versus the more frequent light snow accumulation days.

In addition to the constructed snowline record, we estimated the monthly total precipitation at each of the four sub-regions as well as its snow and rain components using the $T_{\text{max}} 3\text{ }^{\circ}\text{C}$ isotherm as a threshold for precipitation type. We estimate trends all these variables (Fig. 4, Tables S2 and S3) by linear least squares regression.

2.2 AR snowline identification

To identify the snowline elevations associated with AR events we use an existing AR catalog (the SIO R1 AR catalog; Gershunov et al. 2017) developed from vertically-integrated water vapor (IWV) and vertically-integrated horizontal Vapor Transport (IVT) derived from the NCEP/NCAR reanalysis (Kalnay et al. 1996) moisture and wind data. The methodology for detecting landfalling ARs using criteria of $\text{IVT} > 250\text{ kg m}^{-1}\text{ s}^{-1}$, $\text{IWV} > 15\text{ mm}$, and $\text{length} > 1500\text{ km}$ is described in Gershunov et al. (2017). The AR catalog

provides 6-hourly data on AR landfalls along the West Coast [$20\text{--}60\text{N}$], including the coordinates of AR center landfall locations, their intensity and orientation at landfall, as well as the AR footprints. We use this catalog to detect the daily precipitation patterns associated with ARs that hit the Sierra Nevada and southern Cascades during wet seasons (October–May), 1949–2018. Specifically, daily precipitation ($\geq 0.1\text{ mm}$) at grid cells inside the AR footprint and at grid cells adjacent to this precipitation, even if they were outside the AR footprint are flagged as AR-related precipitation. We do not impose temporal contiguity to AR-related precipitation, however. The $T_{\text{max}} 3\text{ }^{\circ}\text{C}$ -isotherm-based approach described above is applied to the AR-related precipitation to determine *daily AR-related snowlines* as well as their monthly composites.

2.3 CMIP-5 GCM snowlines and projected changes

We also applied the snowline identification approach described above to 5 Global Climate Models (CNRM-CM5, CanESM2, ACCESS1-0, ACCESS1-3 and GFDL-CM3) over the historical period (1951–2000) and projected future (2051–2100) under Representative Concentration Pathway 8.5 (RCP8.5²) from Phase 5 of the Coupled Model Intercomparison Project (CMIP5). These 5 models (hereinafter referred to as “Real-5” GCMs) were identified by Gershunov et al. (2019) as the most realistic in their simulation of AR land-falling activity along the West Coast and AR contribution to the total annual precipitation over the western US. Existing GCM-based AR landfalling catalogs (Gershunov et al. 2019) were used along with Localized Constructed Analog (LOCA)-downscaled daily temperature and precipitation. LOCA (Pierce et al. 2014, 2015) is a statistical downscaling method that includes bias correction; it trains on daily historical observations to add improved fine-scale detail to global climate models using a multi-scale spatial matching scheme to pick appropriate analog days from observations. LOCA downscaling was trained on Livneh (2015) data using the same 6 km grid. Projected changes in the snow accumulation and snowline elevations are quantified as a difference between the second half of twenty-first century (2051–2100, October–May) and the second half of twentieth century (1951–2000, October–May) averaged across the Real-5 GCMs for the entire domain of Southern Cascades and Sierra Nevada as well as for each of the four sub-regions. Details of GCM snow and snowline data

² According to Schwalm et al. (2020), “RCP8.5 is the preferred choice for assessing the climate humans currently live in and is the best tool for assessing the risks to come through midcentury”. For our purposes, it provides an upper-end, near-maximum estimate on snowline rise due to the use of RCP8.5 to ensure managers have a likely upper-bound on snowline to plan around.

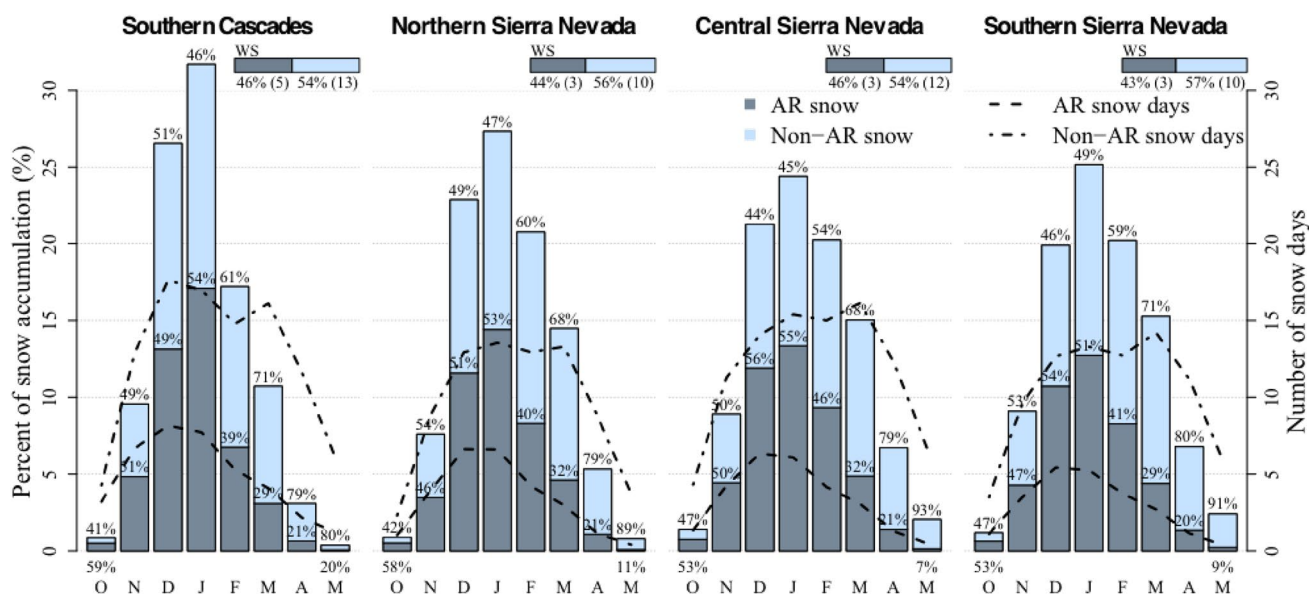


Fig. 2 Percent of seasonal (October–May) total snow accumulation distributed by month (vertical bars are for the months of October through May, O–M) for the four regions. Contributions of AR (dark grey bars) and non-AR (light blue bars) snow accumulations are quantified in percent. Monthly frequencies of AR and other storm days are shown in Table S1. The lines illustrate the monthly frequen-

cies of AR (dashed) and non-AR (dash-dotted) snow days quantified on the right vertical axis. The insets summarize the contribution of AR and non-AR storms to snow accumulation over the wet season (WS, horizontal bar at top), where seasonal frequencies of the AR and non-AR days are shown in parentheses

validations are discussed in the Supplementary section (Fig. SM3).

3 Historical (1949–2018) snow accumulations and snowlines

3.1 Snow accumulations

The total amount of precipitation and SWE accumulated over the study area is reported as seasonal means (October–May, 1949–2018) on Fig. 1b, c. On average, over the entire study area, 30% of total seasonal precipitation fell as snow. Snow accumulation peaks at mid-elevations (1500–2400 m) of the Southern Cascades and Northern Sierra west slopes and the high-elevations (2400–3300 m) of the Central Sierra and Southern Sierra (Fig. S1), due to orographic uplift. ARs, which are generally warmer and wetter, contribute over 43% (Fig. 2) of total seasonal snow even though the occurrence of AR precipitating days is 4 times less frequent than that associated with other wet storms (Table S1, right column). ARs enhance the snow contribution up to 50% at mountain peaks of the Southern Cascades, Northern Sierra and Central Sierra (Fig. S1). Strong orographic uplift during AR conditions is certainly consistent with previous literature (e.g. Ralph et al. 2013). We also know from previous work that AR orientation is sensitive to phases of El Niño Southern Oscillation and is certainly responsible for variability

of precipitation amount relative to California’s topography (Guirguis et al. 2018). Here, we estimated that a third of the seasonal AR-related snow is delivered to the mountain slopes by southwesterly ARs (Fig. S2).

The monthly progression of snow accumulation at each sub-region shows a similar pattern (Fig. 2), indicating the core wet season (December–February; DJF) is key for snow-pack accumulation. On average, 73% ($\pm 16\%$) of the total seasonal snow accumulates over the northern regions and 65% ($\pm 16\%$) over the southern regions during this 3-month period. Almost half of it is delivered by ARs (Fig. 2, grey bars). AR activity declines by March and the end of the snow season is dominated by contributions from non-AR storms (blue bars and dash-dotted lines on Fig. 2). This is consistent with the previously observed seasonality of AR landfalls, which wane in spring (Gershunov et al. 2017). The late season amounts climatologically to roughly 10% of seasonal snow accumulation, with important occasional contributions from so-called “Miracle March” events (Fig. S3 and associated text), which can bring substantial amounts of snow to California’s snowy mountains, as well as across the broader Southwest, during March, offsetting anomalously dry early-middle winter conditions. In a quarter of study years, the March contribution is between 20 and 40% and, in a couple of exceptional years (1991 and 2018), it exceeds 50%, of the seasonal total accumulation (Fig. S3). Spring precipitation can be decisive to California’s water resources and deserves more study.

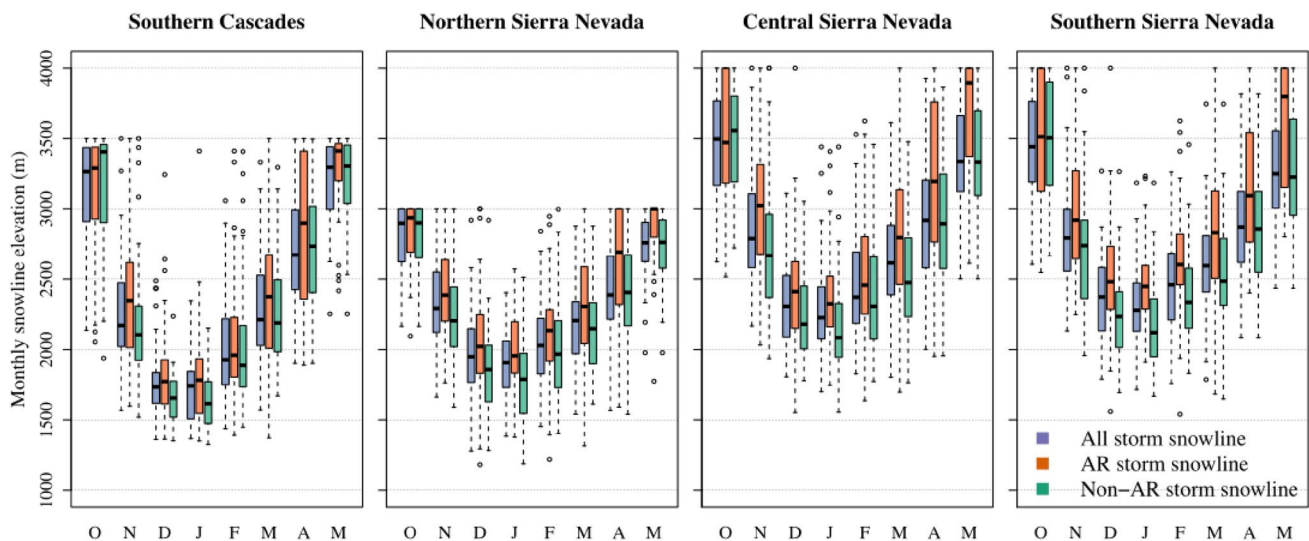


Fig. 3 Monthly total (blue), AR (orange) and non-AR (green) snowline elevations defined using the maximum temperature at 3 °C isotherm during October–May, 1949–2018

3.2 Snowline elevations

Monthly snowline elevations estimated over the 70 wet seasons show that snowlines for both AR and non-AR storms tend to be lowest in December and January and highest in October, April and May in each of the four sub-regions (Fig. 3). During DJF, snowlines are 1750–2000 m in the Southern Cascades and Northern Sierra and 2250–2500 m in the Central Sierra and Southern Sierra. Temperature and storm orientation are in part responsible for these sub-regional differences (~500 m) in snowlines. Warm AR storms typically result in higher snowline elevations by ~120 m in the Southern Cascades and almost 270 m in the Southern Sierra (Fig. 3). Westerly ARs deliver about 20% of seasonal AR-related snow at elevations above 1750 m in the Southern Cascades and Northern Sierra and above 2300 m in the Central Sierra and Southern Sierra (Fig. S2), whereas southwesterly ARs bear the largest amount of snow, approximately 35%, accumulating it at elevations above 2000 m in the two northern areas and above 2600 m in two southern areas. By the end of the wet season (March–April) the AR-related snowlines climb to 2500 m in the Southern Cascades and Northern Sierra and 3000 m in the Southern Sierras. The late season snowlines from non-AR storms are typically above 2350 m in the two northern areas and 2700 m in the two southern areas. The seasonal average snow covered area varies correspondingly (Fig. S4).

3.3 Observed trends

Linear trend analysis shows mostly positive changes in observed monthly snowline elevations during the wet

season (1949–2018) reaching a statistically significant (p value < 0.1) increase in January and March in all sub-regions (Fig. 4 and Table S2a, b). The beginning of the wet season was noted by positive trends in snowline elevations (~100–180 m per 70 years) precessing a significant increase in January. In January all-storm snowlines rose by ~270 m over the 70 years in the Southern Cascades, ~320 m in the Northern Sierra and more than 400 m in the Central Sierra and Southern Sierra. These trends, by construction, reflect wet-day maximum temperature warming observed in January (similar warming trends were reported by Knowles et al. 2006 as well), but also are related to total precipitation decline in January (Table S2a, b, columns 5 and 13, rows 2 and 4). In particular, total January precipitation in the Southern Cascades and Northern Sierra decreased on average by 40% relative to the climatological mean ($1.9 \text{ km}^3/1.6 \text{ maf}$) during our 70-year record (Table S2a, columns 5 and 13, row 2). This is largely explained by a 30% decrease in AR-related precipitation ($1.5 \text{ km}^3/1.2 \text{ maf}$, Tab. S2a, columns 5 and 13, row 6). Since during winter months ARs are the primary source of snow (more than 50%), an AR-related precipitation decrease in January leads to a significant decline of the total snow amount by more than 29% ($1.4 \text{ km}^3/1.14 \text{ maf}$, Tab. S2a, columns 5 and 13, row 3) in the northern regions and by about 14.6% ($0.3 \text{ km}^3/0.3 \text{ maf}$, not statistically significant, Tab. S2b, columns 5 and 13, row 3) in the higher Southern Sierra. Non-AR storms experienced a strong increase of T_{max} , more than 2.5 °C (Table 2Sa, b, columns 5 and 13 row 12) for most regions except for the Southern Sierra. Such warming results in the increase of rain at the expense of snow (Knowles et al. 2006; Lynn et al. 2020), shifting snowlines upward by 300 m on average

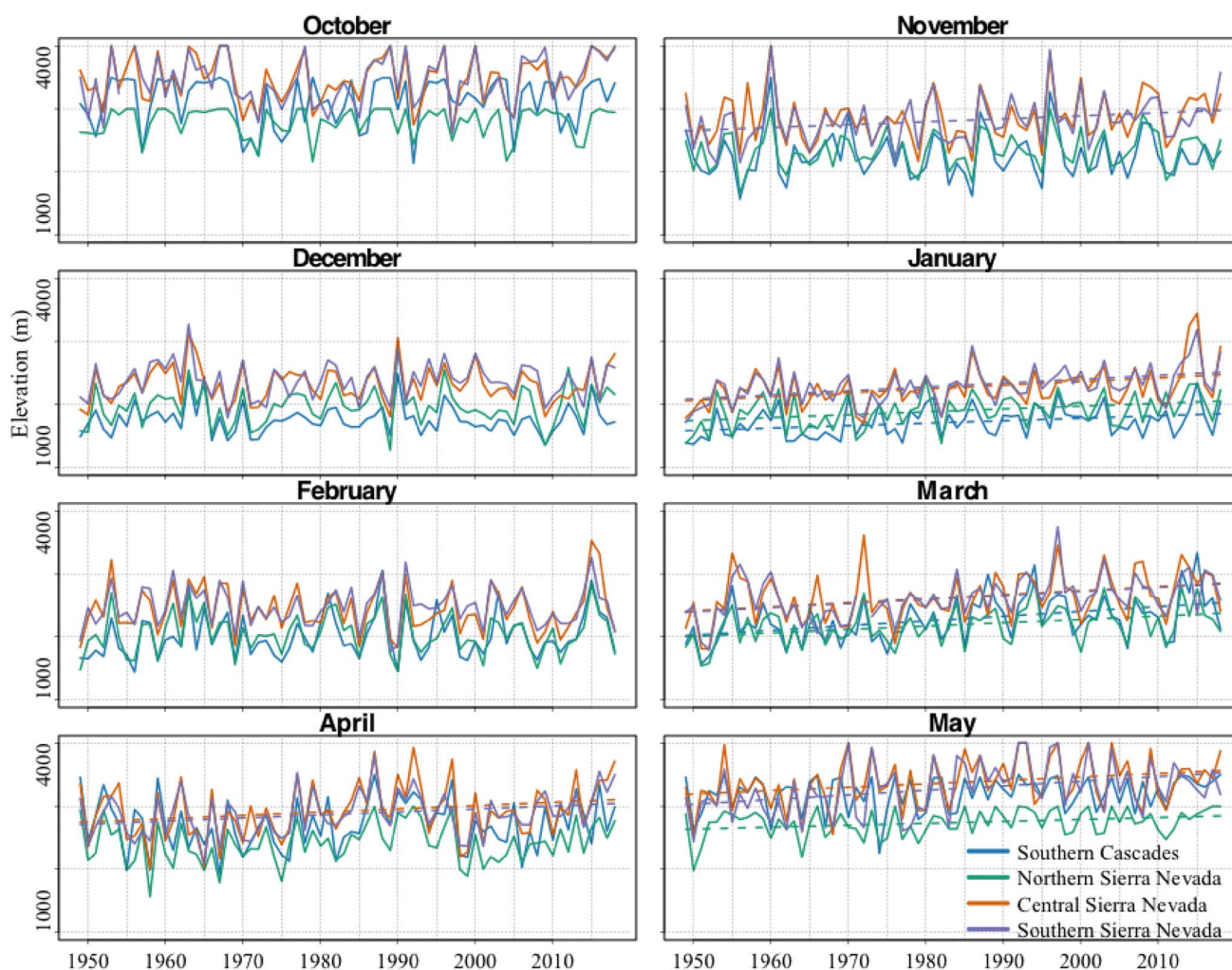


Fig. 4 Monthly mean total Livneh-based snowlines (solid lines) averaged over Southern Cascades (blue), Northern (green), Central (orange) and Southern (purple) Sierra Nevada during 1949–2018

October–May. Significant trends (p value < 0.05) are shown by dashed lines with the color corresponding to the study area sub-region

(Table 2Sa, b, columns 5 and 13, row 9). March is the other month when the wet-day snowlines increase significantly (more than 400 m, Table 2Sa, b, columns 7 and 15). March T_{max} increased strongly (~ 3 °C, Table 2Sa, columns 7 and 15, row 4), but precipitation shows a tendency to increase (about $0.6 \text{ km}^3/0.5 \text{ maf}$, Table 2Sa, columns 5 and 13, row 2) in the Southern Cascades and Sierra Nevada, except for Southern Sierra, where no trend is observed (Table 2Sb, columns 5 and 13, row 2). Precipitation accumulations increased due to ARs, while precipitation from other storms decreased. Since the March T_{max} warmed by almost 3 °C over the past 70 years, the precipitation enhancement disproportionately favored rain, consistent with spring warming shown by Gonzales et al. (2018) and Lynn et al. (2020). A tendency toward snowline increase in April and May was observed as well.

4 Twenty-first century projections of snowlines and snow accumulation

4.1 Projected changes in snow accumulation

In the second half of the twenty-first century, the Real-5 model ensemble, under the RCP8.5 emission pathway, projects a 10% enhancement of total seasonal precipitation (Figs. 5a and 1e) over the entire study area.³ Contribution

³ Polade et al. (2017) reported on precipitation regime projections for California, assessing uncertainty across 30 Global Climate Models (GCMs). Downscaled precipitation projections are variable across models, even across the 5 most realistic GCMs with respect to AR behavior identified by Gershunov et al. (2019) and used here, but this result reflects the general tendency towards more precipitation projected for Northern and less for the Southern California.

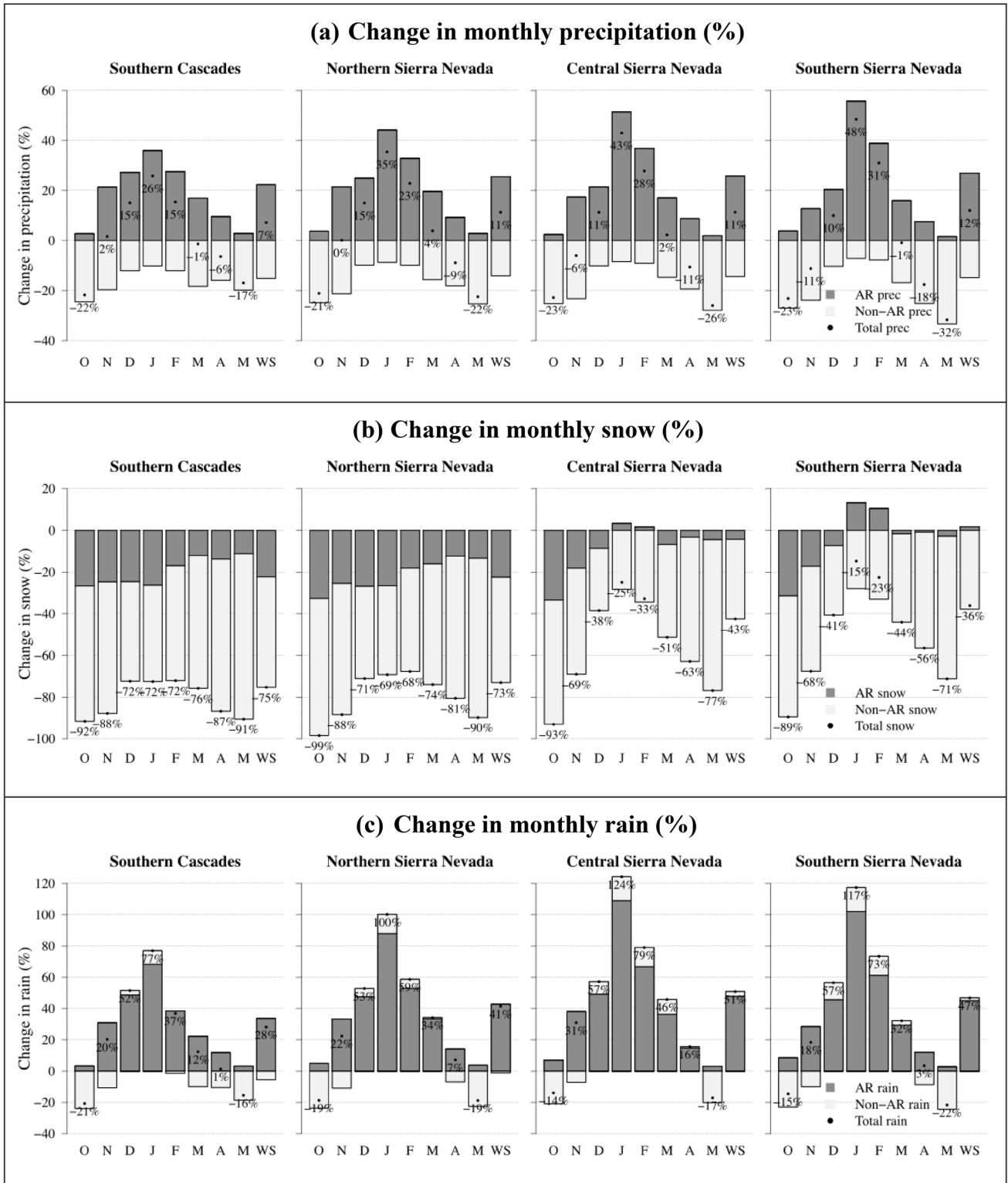


Fig. 5 Changes in monthly precipitation over the Southern Cascades and Sierra Nevada (a), snowpack (b), rain (c) in the projected future (2050–2100) in percent relative to the historical past (1950–2000).

Dots denote changes in all monthly precipitation, while dark and light shading denotes changes due to ARs and other storms, respectively

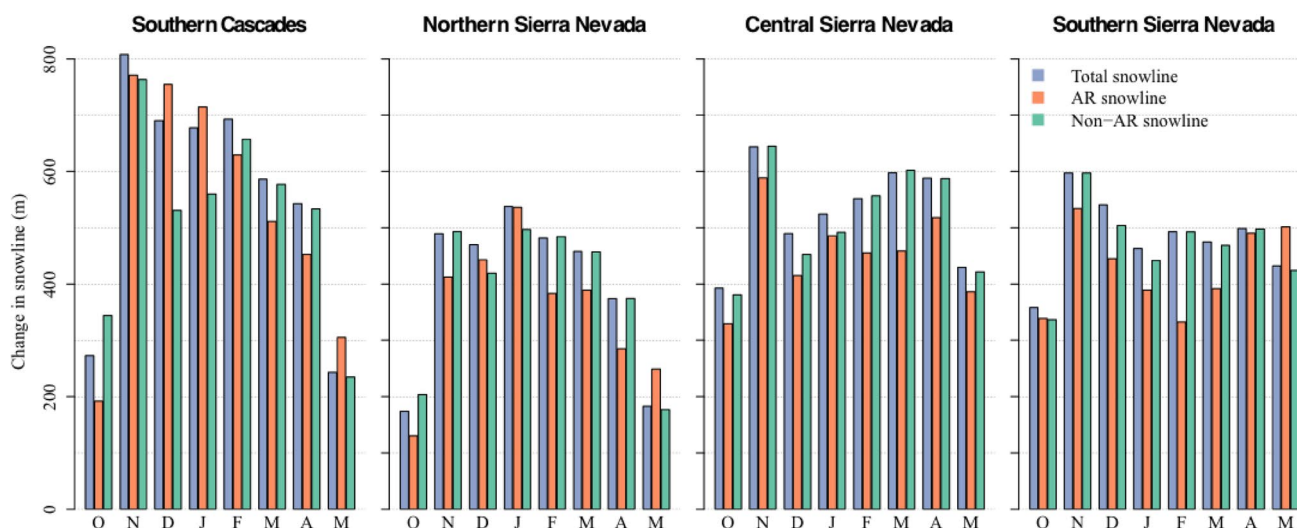


Fig. 6 Monthly snowline elevation (m) changes in all-storm (purple), AR-related (orange) and non-AR-related (green) snow accumulation conditions over the Southern Cascades and regions of the Sierra

Nevada in the projected future (2050–2100) compared to the historical past (1950–2000). The change is defined as the difference between projected and historical average snowlines

from ARs to total seasonal precipitation is projected to increase by 25%, while, in marked contrast, the contribution from other storms is expected to diminish by 15%. Seasonal snow accumulation is projected to decline from the historical 30–12% of the total precipitation during the second half of the century. The average seasonal snow accumulation is projected to decrease by 57% (right bars “WS” on Fig. 5b, also see Fig. 1f), consistent with other projections for the Sierra Nevada and generally for the Western US (Siirila-Woodburn et al. 2021). Across all months, the loss of snow accumulation is decidedly dominated by non-AR-related snowfall decline (Fig. 5b) and some of the non-AR snow loss results from the decline in non-AR precipitation (Fig. 5a), which is seen throughout the October–May season. The northern areas (Southern Cascades and Northern Sierra) are projected to experience more than a 60% loss in seasonal snow accumulation at elevations 1500–2400 m, and up to 50% above 2700 m (Fig. S5a). The snow accumulation depletion in the southern areas (Central Sierra and Southern Sierra) varies from 60 to 18% at elevations 2400–3300 m, respectively, whereas the highest elevations are expected to lose less than 8%. The projected increase in specifically AR precipitation (Fig. 5b and S5a) will contribute more snow to the highest elevations compared to the historical past, although overall snow accumulation from all storms would decrease except above 3600 m. Thus, the higher southern areas are expected to be less affected by the projected warming than the lower northern areas (see Fig. S6 for snow covered area change). The Real-5 GCM ensemble average projects the wet season to narrow (Fig. 5a) due to the non-AR precipitation decrease in fall and spring

months October–November and April–May. Both rain and especially snow accumulation are projected to decrease during these months (Fig. 5b, c).

4.2 Projected change in snowline elevations

Projected changes in the monthly snowlines in the second half of twenty-first century (2051–2100) compared to the historical past (1951–2000) show a clear increase in snowline elevations by 400–500 m (averaged from Fig. 6). The shoulder seasons’ months, October and May, start with higher snowline elevations (Fig. 3) and would experience almost no mountain snow accumulation events by the end of the century under unabated warming (Fig. S6 and Fig. 7), particularly in the elevation-limited Southern Cascades and Northern Sierra. In an average year, snowpack will be increasingly confined to the peak of winter and to the highest elevations (Fig. 7). Specifically, in Southern Cascades the all-storm snowlines in November–March are projected to be up to 560 m higher than that in the historical period with the largest increase of about 690 m during DJF (Fig. 6). During this 3-month winter peak period, AR-related snowlines are projected to increase by ~700 m, compared to almost 600 m associated with non-AR storms. This increase reflects increasing temperatures of approximately 4 °C and is associated with a loss of snow accumulation exceeding 70% (Figs. 5b and 1f). The Northern Sierra would experience about 450 m rise in snowlines during November–March with the largest increase exceeding 500 m in January. This smaller change in projected northern snowlines is associated with the lower elevations of the two northern sub-regions, i.e. the projected future snowlines exceed the available elevations

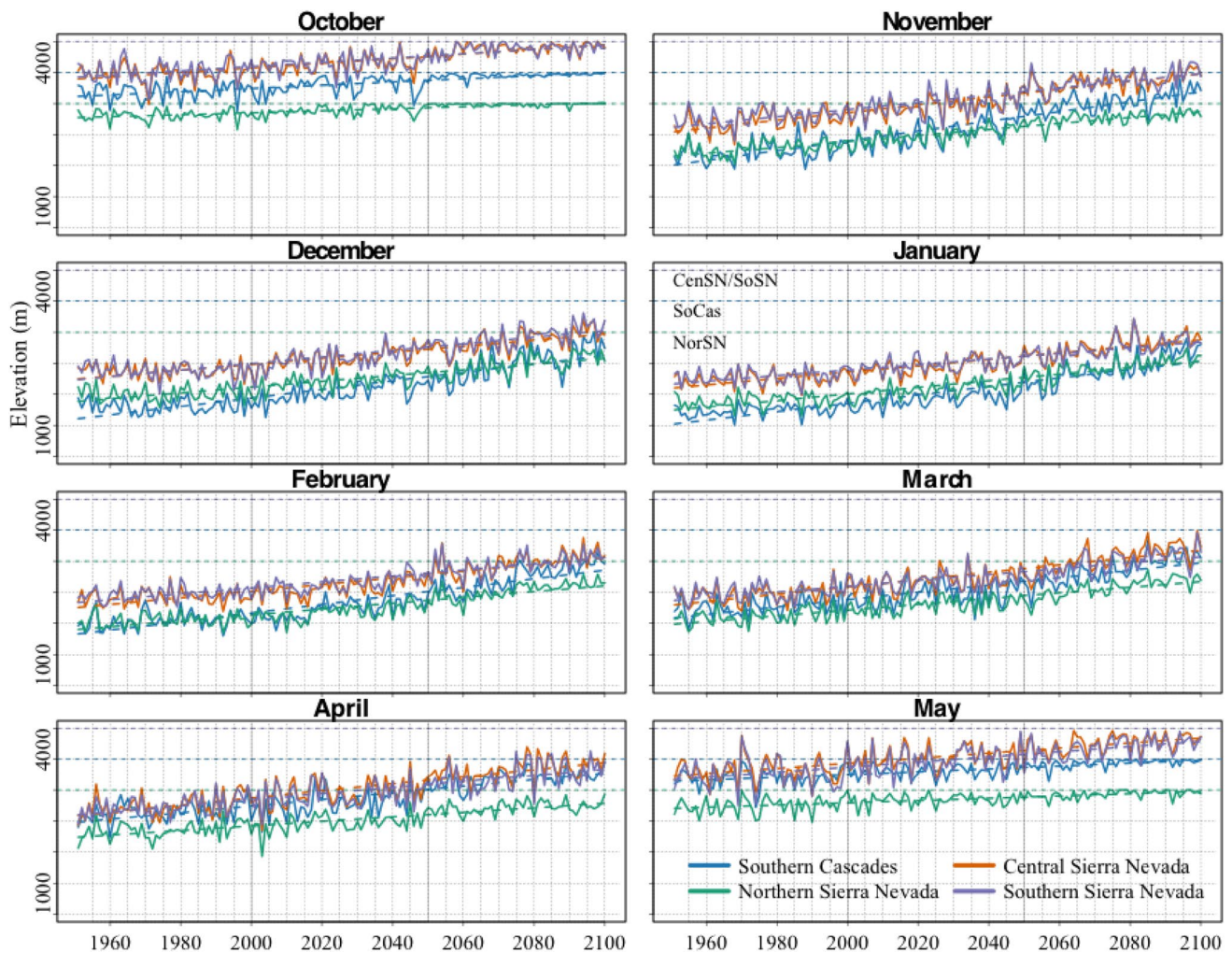


Fig. 7 Historical and future projected (1950–2100) monthly mean snowlines (solid lines) for Southern Cascades (blue), Northern (green), Central (orange) and Southern (purple) Sierra Nevada based on the Real-5 GCM ensemble average. Significant trends (p

value < 0.5) are shown by dashed lines with the color corresponding to the study sub-region. All of the time series shown here display significant trends. Thin horizontal dashed lines mark the peak elevation for each sub-region

(Fig. 7). This explains the more than 70% decline in snow covered area during the winter season in the Northern Sierra (Fig. S6). In the higher central and Southern Sierra Nevada, the November–March snowlines are projected to be roughly 500 m higher than those during the historical period. In DJF, all-storm snowlines are projected to increase by 500 m. Being initially lower, non-AR snowlines (Fig. 3) would increase more (by up to 500 m) than AR-related snowlines (400–450 m).

Analysis of trends over a 150-year historical and future projected GCM record shows a significant increase in monthly snowlines through the October–March season in all four sub-regions (Fig. 7). Trends clearly emerge and accelerate in all months in the early twenty-first century. While most months show trends starting in the late twentieth century, some months (e.g. October, December) do

not yet exhibit such early trends, which is consistent with observations (Fig. 4). Under the RCP8.5 scenario, the wet-day maximum temperature is projected to increase more than 6 °C (Table 3a, b, row 6) over the entire 150-year period. This would drive a substantial shift in precipitation type distribution, resulting in significant increase of snowlines (835 m in Southern Cascades, 583 m in the Northern Sierra and over 700 m in the Central Sierra and Southern Sierra, Table S3a, b, row 3). The monthly total snow accumulations will significantly decline during November–March season by about 1 km³ or 0.8 maf in Southern Cascades, 1.5 km³ or 1.2 maf in the Northern Sierra, 0.8 km³ or 0.7 maf in the Central Sierra and 0.4 km³ or 0.3 maf in the Southern Sierra (Table S3a, b, columns 3–7 and 11–15, row 5). Non-AR snow is projected to decline the most. The largest decrease in total snow accumulation is

registered for the period 2025–2075 over the entire Sierra Nevada and Southern Cascades.

4.3 Projected impacts on selected ski resorts

To show an example of how our approach could further be applied to the ski industry—which relies on the snowline for lift operation and snowmaking investments—we estimated snowline change for seven, including four major, ski resorts, in the central Sierra Nevada. The four major resorts include: Northstar at Tahoe, Heavenly, Mammoth Mountain, and China Peak. Under the RCP8.5 emissions scenario, lower and mid-elevation Sierra Nevada ski resorts are projected to lose more than 60% of seasonal snow accumulation by the second half of the twenty-first century (Fig. 1f and Table S4). High elevation ski resorts (e.g. Mammoth Mountain) would experience smaller average losses (~28% snow depletion at 3400 m) and even increased average snowpack in mid-winter driven by occasional extreme snowfalls.

5 Summary and discussion

We developed an observationally-based 70-year record (1948–2018) of daily snow accumulation and snowline elevations during storms in the Sierra Nevada and the southern portion of the Cascade Mountains of the North American Cordillera—California’s major snowy mountains. We assessed the climate-scale (seasonal and longer-term) variability and trends in historical monthly snow accumulations and snowlines. We quantified the essential role of ARs in the hydrologic regime resolved over four sub-regions of these mountains—the Southern, Central and Northern Sierra Nevada and the Southern Cascades. This involved assessing the contribution of ARs to snow accumulation, rain and snowline variability and trends relative to other storms.

We also developed a similar record of these elements and mechanisms of mountain hydrology, in the historical past and the projected future modeled by five previously validated and downscaled CMIP5 GCMs run under the RCP8.5 emissions scenario. We examined observed and projected trends in all these variables, focusing on snow accumulation and the role of atmospheric rivers in the hydrology of the Sierra Nevada and Southern Cascades.

Our 70-year historical record of daily snow accumulations aggregated by month shows that snow makes up ~30% of the precipitation that falls on California’s major snowy mountains. Much of this snow (over 80%) falls during December–March at the higher elevations. AR events, making up only a quarter of all snow days during October–May, historically contribute 43% of all the snow accumulated over the wet season and more than half of the snow accumulated in the peak months of December and January. AR

contribution to snow and precipitation in general, drops off in the late winter and spring, when the AR season wanes quicker than the overall wet season (Gershunov et al. 2017). The contribution of ARs to snow accumulation seems even more impressive considering that ARs are generally warmer than other snowstorms; so they are typically associated with higher snowline elevations by ~120 m in the Southern Cascades and almost 270 m in the Southern Sierra Nevada.

Under observed ongoing global warming, we see a reduction of seasonal snow accumulation on the mountain slopes highlighted by previous studies (Gleick 1987; Lettenmaier and Gan 1990; Knowles and Cayan 2002; Knowles et al. 2006) that contributes to snowpack decline in concert with later accumulation (Hatchett and Eisen 2018), earlier melt and the earlier coming of spring (Cayan et al. 2001), which are all part of the global warming trend impacting Western North American snow hydrology (Barnett et al. 2008; Mote et al. 2018). The linear trend analysis shows a significant increase of the snowline elevations, particularly in January and March, caused by a wet-day maximum temperature rise observed significantly during these months. A decreasing trend in AR-related precipitation in January also contributed to the observed decline in total snow accumulation. We found that the Southern Sierra Nevada experienced the most changes in snowline elevations due to observed temperature and precipitation trends.

In a rapidly warming future projected under the RCP8.5 emissions scenario by a previously validated set of CMIP5 GCMs, ARs will contribute more to the region’s total seasonal precipitation as ARs grow in potency while precipitation from other storms declines in frequency (Gershunov et al. 2019). In agreement with Musselman et al. (2017), we showed that this increasing contribution from ARs to California’s mountain hydroclimate will manifest most strongly in greater amounts of rainfall on mountain slopes, particularly at the peak of winter. With further warming, snow accumulation is projected to decline to less than half of historical amounts with the greatest snow loss at mid elevations. As snowlines retreat to higher elevations, the snow water volume loss is made more critical because available catchment area declines with increasing elevation. The greatest relative snow loss will be experienced in the shoulder seasons of fall and spring. The Southern Sierra Nevada, however, due to its higher elevation, would be least affected by snow loss at the peak of winter (January–February) due to stronger AR activity. All regions will experience overall snow loss integrated over the warming cool season due to the loss of precipitation from non-AR storms while progressively higher snowlines will not allow increasing AR activity to make up for lost snow except at the highest elevations of the Southern Sierra in the peak of winter. Increasing hydroclimate variability due to decreasing precipitation frequency and increasing intensity (Polade et al. 2014, 2017; Gershunov et al. 2019)

will make snowy winters less and less frequent, but extreme accumulations at high elevations will still be possible in rare winters, even at unprecedented levels leading to increased snow accumulation variability (Lute et al. 2015), which, as our results suggest, is due to increasingly extreme ARs. The current work adds storm-specific snow accumulation detail to previous results projecting diminished snow conditions in space and time across the Western US (Klos et al. 2014; Siirila-Woodburn et al. 2021) and their increasing volatility (Lute et al. 2015).

Impacts of precipitation regime change and temperature warming including the observed and projected changes in snowpack accumulation and depletion will pose challenges to existing water resource management. In particular, our findings support previous results indicating a growing need to accumulate water resources from floodwater during the warming cool season due to increasingly less frequent storms and wetter ARs (Gershunov et al. 2019; Michaelis et al. 2022) as well as expected higher runoff efficiency from warming storms due to progressively higher snowlines, more rain and less snow. The seasonality of the regional hydroclimatic change is consistent with the projected narrowing of the wet season (Pierce et al. 2013b; Swain et al. 2018; Mahoney et al. 2021) due to observed and projected expanding zones of subtropical subsidence, i.e. the descending branches of the Hadley Cells (Johanson and Fu 2009). A narrowing wet season together with increased/decreased contribution from ARs/other storms leads to increasing reliance on extremes as contributors to total annual precipitation and snow accumulation. All this spells greater year-to-year variability or “volatility” of annual precipitation. This increasing volatility of the regional hydroclimate (Polade et al. 2014, 2017; Swain et al. 2018; Gershunov et al. 2019) also creates an increasingly volatile snowpack, especially when assessed relative to its dwindling expected accumulation. On the other hand, if both snow accumulation and depletion processes are accounted for, when seasonal snow becomes more and more of a rarity, peak snowpack variability should decrease (Marshall et al. 2019). These changes go hand-in-hand with a progressively longer dry and warming summer season with impacts on growing season water demand (McEvoy et al. 2020) and wildfires (Williams et al. 2019). The resilience of high-elevation snowpack will further be examined in future work that will focus on snowpack depletion processes.

Besides water resources, California ski resorts and those who depend on snowpack for recreation stand to suffer. Under unabated global warming, lower and mid-elevation ski resorts would experience losses exceeding 60% of seasonal snow accumulation by the second half of this century compared to history. High elevation ski resorts would be less impacted and might even experience unprecedented snowpacks in mid-winter driven by extreme AR-generated

snowfalls. However, the season will shrink at all elevations and snow will be increasingly confined to higher elevations and within a narrowing season. In addition to observed and projected SWE accumulation and snowline, our storm-specific results provide information about the type or flavor of snow important for recreation such as evolving frequencies of heavy wet snow produced by ARs (“Sierra cement”) versus lighter powder accumulations from other, generally colder, winter storms. The value of snow flavor information can be examined locally, e.g. at selected ski resorts. The evolution of avalanche hazard from observed and projected extreme snowfalls at middle to high elevations will also be a focus of future work.

The seasonal cycle of changes in snow accumulation, i.e. a narrowing snow season, would contribute to and exacerbate the drastic changes in the timing of snowmelt already observed (Roos 1991; Cayan et al. 2001; Stewart et al. 2005) and hypothesized for the future (Evan and Eisenman 2021). Testing and implementation of Forecast-Informed Reservoir Operations (FIRO; Jasperse et al. 2020; Delaney et al. 2020) has the potential to enable more flexible reservoir operations to adapt to these changes along with a portfolio of other adaptation strategies (Siirila-Woodburn et al. 2021). Also, if sub-seasonal to seasonal (S2S) forecasts, particularly with respect to AR landfalls and ensuing precipitation and runoff, are developed with adequate accuracy and reliability, they could support improved water resource management. The record of snow accumulation and snowline elevations utilized and extended here will allow for the development of integrated atmospheric and hydrologic S2S prediction models focused on snow accumulation and runoff.

Taken together with results from other studies (e.g. Huss et al. 2017), we expect the main features of regional snow accumulation trends described in this paper to be representative of trends observed and projected on many of the world’s mountain ranges, particularly those near west coasts of continents. Trends over mountains in other Mediterranean climate zones, such as the Chilean Andes (Bambach et al. 2021), would be expected to bear the closest resemblance, including in seasonality, to those observed and projected over the Sierra Nevada and the Southern Cascades. Broader studies connecting the evolution of mountain snowpacks around the world, resolving both accumulation and depletion events, would provide a timely global perspective on expected changes to the mountain water cycle (e.g. Rhoades et al. 2021). Such studies open the door to assessing impacts on regions that depend on seasonal mountain snowpacks for water resources, recreation, and biodiversity.

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Author contributions AG, BH, TS, KG and FMR designed the study. TS carried out the analysis. AG, TS, BH and KG interpreted results

and wrote the manuscript. All authors reviewed the manuscript and provided valuable feedback. AG, BH and KG revised the manuscript based on constructive comments by two anonymous reviewers.

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Data availability Snow accumulation and snowline data produced and used here are available at <https://weclima.ucsd.edu/data-products/>.

Declarations

Conflict of interest The authors have not disclosed any competing interests.

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