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Technical note: Precipitation phase partitioning at landscape-to-regional scales

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Abstract. Water management throughout the western United States largely relies on the partitioning of cool season mountain precipitation into rain and snow that helps determine water storage in spring snowpack. Recent studies indicate a shift towards increased precipitation falling as rain, consistent with a warming climate. An approach is presented to estimate precipitation partitioning across landscapes from 1948-present by combining fine scale gridded precipitation data with coarse scale freezing-level and precipitation data from an atmospheric reanalysis. A marriage of these datasets allows for a new approach to estimate spatial patterns and trends in precipitation partitioning over elevational and latitudinal gradients in major water supply basins. This product can be used in California as a diagnostic indicator of changing precipitation phase across mountain watersheds. Results show the largest increases in precipitation falling as rain during the past seven decades in lower elevation watersheds located within the climatological rain-snow transition regions of northern California during spring. Further development of the indicator can inform adaptive water management strategy development and implementation in the face of a changing climate.

1 Introduction

Mountains are natural reservoirs of water for human and natural consumptive uses in many parts of the world. In snow-dominated mountain environments, substantial quantities of water stored as snow accumulates during the cool season and is released during the warm season as snow melts. The partitioning of precipitation into liquid (rain) and frozen (snow) components was used as a foundation for water management infrastructure in California and other mountain environments in the western United States (US) since the mid-1800s (Milly et al., 2008). Precipitation phase partitioning during the cool season influences the timing and magnitude of surface runoff, evapotranspiration, and groundwater recharge (Berghuijs et al., 2014; Zhang et al., 2015; Musselman et al., 2017; Sturm et al., 2017; Abatzoglou and Ficklin, 2017). The fate of cool season precipitation ultimately drives water management strategies, especially in arid and semi-arid environments characterized by substantial interannual hydroclimate variability (e.g., Sterle et al., 2019).

Many historically snow-dominated mountains, particularly those with mild winter temperatures, are undergoing declines in snow accumulation (Mote et al., 2018). Projections for the 21st century suggest continued warming and snowpack declines (Rhoades et al., 2018). Because of downstream dependence on snow-derived water resources and susceptibility to flooding from snow melt events, California is an ideal location to examine changes in historical precipitation partitioning. Various studies have found evidence for changes in California's cryosphere that are consistent with a warming climate. Some examples include an increase in winter snow levels (Hatchett et al., 2017), delays in early season snowpack accumulation (Hatchett and Eisen, 2019), shifts towards earlier peak snow water equivalent (Kapnick and Hall, 2010), and decreased snowpack water storage efficiency (Das et al., 2009).

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Decreases in snowpack and snow-covered area exacerbates snow loss through the snow-albedo feedback (Walton et al., 2017). This effect is pronounced in lower, warmer parts of watersheds where snow cover tends to be shallower and more ephemeral. The effects of a warming climate on snowpack vary, with the greatest sensitivity found in warm snow climates located near the climatological rain-snow transition elevation (Howat and Tulaczyk, 2005; Mote et al., 2005; Klos et al., 2014), predisposing these regions to warming-induced hydrologic vulnerability (Huning and AghaKouchak, 2018; Mote et al., 2005). Changes in rain-snow partitioning and its manifestation on water storage in spring snowpack are thus of paramount importance to guiding changes in water resource management operations.

The sparse observational network and complex topography of the western US introduces challenges into basin-scale hydrologic monitoring and modelling, necessitating the incorporation of multiple sources of data (Bales et al., 2006) and model output (e.g., Wrzesian et al., 2019). Dataset inadequacies have limited the use of precipitation partitioning for operational purposes as readily-available metrics are provided at scales too coarse for decision making processes or involve observational records that are limited temporally (e.g., < 30-year records) for climatological context. To overcome such limitations, the California Department of Water Resources (DWR) developed a methodology to study historical rain/snow trends at spatial scales relevant to broader management goals and capable of resolving finer scale details across elevational and climatic gradients (DWR, 2014). The purpose of this technical note is to provide an updated approach and detail the methods of this indicator. Importantly, this indicator can be used to inform the development and implementation of adaptation strategies to achieve water resource management goals amidst a changing climate. Because the method uses publicly available gridded data sets, the indicator is scalable to regional-to-continental scales and be an important diagnostic for water resources management in other snowmelt dependent regions. While we focus on California watersheds, an example application to the western United States is provided.

2 Data

2.1 Study Areas

The study areas encompass the Sierra Nevada and Southern Cascades of California (Fig. 1a), with the middle and upper elevations historically receiving the majority of cool season precipitation as snow (Fig. 1c). Runoff originating from melting snow in these regions provides critical water resources for local, state, and federal water projects in California (Kahrl, 1979). Based upon hydroclimate conditions such as the precipitation and the spatial distribution of snow water equivalent (SWE; the amount of liquid water stored in the snowpack), DWR produces monthly forecasts of unimpaired April through July runoff forecasts beginning in early February and published as Bulletin 120 (DWR, 2019). The forecasts in Bulletin 120 are updated weekly until June as conditions evolve. Based upon DWR's management of state water resources, these snowpack-dominated mountain areas are subset into four analysis zones (from north to south: Southern Cascades, Northern, Central, and Southern Sierra Nevada; Figure 1a). The elevation distribution of the analysis zones shifts higher with decreasing latitude and median annual precipitation is the greatest in the Northern Sierra Nevada, followed by the Southern Cascades. In total, 33 United States Geological Survey eight-digit Hydrologic Unit Code (HUC-8) watersheds are included within the four analysis zones. The study period spans water years (WY) 1949-2018; a water year begins on 1 October of the prior calendar year and ends on 30 September.

2.2 Data used in DWR approach to rain/snow partitioning

The DWR approach uses monthly, 800 m horizontal resolution estimates of precipitation from the Parameter Regression Interpolated Slopes Model (PRISM; Daly et al., 2008), a digital elevation model (DEM) corresponding to the PRISM grid, and freezing level elevations from the North American Freezing Level Tracker (described in section 2.3). The method produces

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watershed-aggregated monthly time series of total precipitation and percentage total precipitation estimated as snow ($\%_{SNOW}$). These time series are analysed for the entire water year (October-September), fall (September-November), winter (December-February), and spring (March-May). Because the 800 m PRISM products are not freely available to the public, here we use the 4 km monthly products spanning 1948-present from the PRISM group (http://www.prism.oregonstate.edu/).

2.3 The North American Freezing Level Tracker

The North American Freezing Level Tracker (NAFLT, https://wrcc.dri.edu/cwd/products/) was developed by the Western Regional Climate Center to provide estimates of the height of the freezing level, or elevation of the 0°C isotherm, based upon 6-hourly output from the National Center for Environmental Prediction/National Center for Atmospheric Research Global Reanalysis spanning 1948-present at a 2.5° horizontal resolution (hereafter "NCEP/NCAR reanalysis"; Kalnay et al., 1996). The height of the freezing level is an important parameter for evaluating climate variability and change in mountain environments (Diaz et al., 2003). Freezing level height influences the phase of precipitation at a given elevation, the state of the land surface (frozen or un-frozen), thermodynamic processes occurring in an existing snowpack leading to snowpack ripening and melt, and the duration of the snow-free season.

Beginning in the upper troposphere (200 hPa) and working downward, the NAFLT calculates the freezing level as the elevation above mean sea level where a temperature of 0°C is first achieved in the NCEP/NCAR reanalysis. If the entire atmosphere is at or below freezing on a given 6-hr period, a value of zero meters above mean sea level is provided. The uppermost atmospheric level below which the 0°C isotherm occurs is considered for cases in which the vertical temperature profile includes inversion conditions that has multiple incursions of the 0°C isotherm. In addition to providing estimates of the elevation of the 0°C isotherm, the NAFLT calculates the percent of precipitation that falls at elevations above the 0°C isotherm at 200 m increments from 0-4000 m using coincident 6-hourly precipitation from NCEP/NCAR reanalysis. These calculations are performed during each six-hourly timestep, and accumulated over the month to provide an estimate of the percent of precipitation falling as snow ($\%_{SNOW}$). The freezing level is a very conservative estimate of the snow level as precipitation can often persist as snow below the freezing elevation due to latent heat fluxes (e.g., snow falling in a sub-saturated atmosphere, deep isothermal temperature profiles, or during heavy precipitation episodes that entrains colder air to lower levels in the atmosphere). However, accumulations of snow below the elevation of the 0°C isotherm may be transient due to nominal cold content of snow.

3 Methods

3.1 Description of the DWR approach to rain/snow partitioning

The DWR approach calculates $\%_{RAIN}$ as 100% - $\%_{SNOW}$ over the study area at 200 m increments from 0-4000 m using the freezing level from the NAFLT at the respective PRISM grid point and by linearly interpolating between NAFLT $\%_{SNOW}$ estimates at 200 m increments and the actual elevation of each 4 km DEM grid cell. Horizontal bilinear interpolation is used to estimate the NAFLT freezing level at each grid point. Following the approach of Abatzoglou (2011) who linked free air temperatures from the NCEP/NCAR reanalysis to output from the Variable Infiltration Capacity model (Liang et al., 1994), we multiplied estimates of monthly PRISM precipitation by $\%_{RAIN}$ to partition precipitation between frozen ($\%_{SNOW}$) and liquid ($\%_{RAIN}$) components. The statewide, analysis zone, and watershed average annual precipitation and total average annual $\%_{RAIN}$ (or $\%_{SNOW}$) can be calculated by aggregating data at the native resolution (e.g., 800 m or 4 km) to the spatial unit of analysis, such as a watershed. These metrics are reported annually by DWR in annual hydroclimate reports. As examples, Figure 1 allows comparisons two different water years, a record low snowpack year (2015; Fig. 1d) and a year with much higher partitioning of precipitation as snow (1980; Fig. 1e).

In using the NAFLT for the calculation of $\%_{SNOW}$, we are assuming freezing levels at the chosen analysis points are representative of synoptic scale weather conditions. Despite known mesoscale variability in snow line elevation during individual events (e.g., Minder et al., 2010), reasonably little bias in snow levels (at the interannual timescale) exist between stations located within 200 km of one another along the windward side of the Sierra Nevada (Hatchett et al., 2017). Thus, the 2.5° (~250 km) horizontal resolution of NAFLT appears reasonable for the purpose of interannual tracking of rain/snow partitioning.

3.2 Statistical Analysis

Temporal trends in historical rain/snow partitioning were evaluated spanning water years 1949-2018 using the non-parametric Mann-Kendall test modified to account for temporal autocorrelation (Hamed and Rao, 1998). Significance was determined using an alpha level of 0.05 and when noted, only grid points with statistically significant trends are shown in the resulting figures (Fig. 2 and Fig. 5; all trends are provided in the supplementary information). Trends were calculated by multiplying the Theil-Sen slope by 10 (yielding change in $\%_{SNOW}$ decade^{-1}) at each 4 km grid point for late fall (October-November), meteorological winter (December-February), early spring (March-April), and the cool season (October-April). These calculations were performed over the western United States. To highlight the spatial information provided by the approach, we also calculated trends aggregated by latitude and elevation across the area within the four analysis zones over the cool season and also at HUC-8 watershed scales. In practice, this aggregation can be performed at any scale of interest to the user (i.e., the watershed or sub-watershed scale over any temporal period). For the watershed-level aggregations, average $\%_{SNOW}$ was calculated over the area within a given watershed and the trend calculation was then performed.

4 Results

Trends in estimated changes in $\%_{SNOW}$ (shown as % decade^{-1}) for winter (Fig. 2a), spring (Fig. 2b), and the cool season of the water year (Fig. 2c) range from no change in the highest elevations of the central and southern Sierra Nevada (and Mt. Shasta in the southern Cascades) to decreases of 4% decade^{-1} in lower and middle elevation regions over the 70 year record. Winter season trends were largest in the southern portion of the northern Sierra Nevada region and throughout the central Sierra Nevada region and on the order of -1% to -2% decade^{-1}. Spring trends were of larger magnitude (-2% to -4% decade^{-1}) and concentrated in the middle elevations of all regions. The highest elevations of the southern Sierra Nevada showed no declines as these locations remain above the 0°C elevation during these seasons. Fall trends (not shown) were negative, but magnitudes were smaller than winter trends. No statistically significant positive trends were observed for any season.

Aggregating trends to the HUC-8 watershed scale, as shown in Figure 3, demonstrates how the DWR approach can be used to interpret changes at the watershed scale. The largest negative changes are found in the central Sierra Nevada region on both westward and eastward draining watersheds (i.e., west and east of the Sierra Nevada crest, respectively) and have the greatest magnitudes at middle elevations during the spring (Fig. 3b). Fall and winter trends moderate the magnitudes of the cool season trends (Figure 3c).

Trends in $\%_{SNOW}$ exhibit strong spatial patterns than can further be explored and understood by binning trends by elevation. The largest negative trends in water year partition of precipitation as snow across the four regions were seen at mid-elevations of 1800-

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2500 m (-1.5 to -2% decade^{-1}) and become notably weaker at higher elevations that are climatologically well above the 0°C elevation during winter months (Fig. 4b). Lower elevations (<1800m) occupy a larger portion of the collective watershed area and had significant declines in $\%_{SNOW}$ (-1 to -1.5% decade^{-1}). Further decomposition of trends by elevation and latitude shows the largest declines in $\%_{SNOW}$ at mid-elevations in the southern extent of the region (Fig. 4a), consistent with Figure 3. However, we note that the strongest negative trends south of 38°N occupy a much smaller geographic extent of overall watersheds than those located further north in California.

Long-term trends throughout the western United States (Fig. 5) demonstrate similar magnitudes of change as found in California with decreases on the order of -0.5% to -4% decade^{-1}. Areas east of the Cascade Range (central and northern Washington and central Oregon), the Montana plains, western and northern New Mexico, and much of the non-mountainous terrain in Wyoming and in the Colorado River Basin show the greatest magnitudes of decreases in winter $\%_{SNOW}$ (Fig. 5a). As was found in California, the spring season had the largest magnitudes of decreases in $\%_{SNOW}$ (Fig. 5b) with the greatest magnitudes in central Nevada, southwestern Utah, central Arizona, and along the Front Range of the Colorado Rockies. Averaged over the cool season, the western United States has undergone decreases in $\%_{SNOW}$ by approximately -1% to -2% decade^{-1} over the past ~70 years (Fig. 5c).

5 Discussion

5.1 Is there a transition to "more rain, less snow?"

Combining 4 km PRISM monthly precipitation and using freezing level estimates from a global reanalysis to estimate trends in the percent of precipitation falling as snow confirms widespread declines over California (Fig. 3) and the western United States (Fig. 5). The most notable, or largest magnitude, and widespread changes are occurring in spring at elevations near and below the climatological 0°C height. The method presented here agrees with previous station-based observations showing declines in $\%_{SNOW}$ (e.g., Knowles et al. 2006). The gridded nature of the high-resolution climate products used allows detailed analyses at the regional or watershed level, both spatially (Fig. 3) and across binned elevations and latitudes (Fig. 4) that adds nuance to the analysis. In the case presented, the aggregation techniques highlight the magnitude of change as a function of elevation and latitude (Fig. 4a) to elucidate hydrologic basins that may be most susceptible to changes in precipitation partitioning (Fig. 3).

The spring season signal of increasing precipitation as rain, especially in middle elevation zones and southern upper elevation zones of California and throughout much of the western United States, is consistent with declines in peak snowpack and earlier timing of runoff (Das et al., 2009; Kapnick and Hall, 2010; Mote et al., 2018). The method presented also suggests that the highest elevation regions in the Sierra Nevada, Wasatch Range, and Rocky Mountains have not experienced significant declines in precipitation falling as snow to date, although with continued warming and increased freezing levels these areas are posited to undergo declines in $\%_{SNOW}$.

The transition from snow to rain at lower elevations and middle elevations of the western United States during the primary accumulation seasons (Fig. 4b-c) has reduced the amount of water stored as spring snowpack (Mote et al., 2018) and led to more frequent warm snow drought conditions (Hatchett and McEvoy, 2018). More precipitation falling as rain during storms, especially in regions with large watershed areas in lower elevations, will also increase inflow into reservoirs. Many current reservoir management paradigms require the maintenance of a flood pool during the cool season, meaning this water cannot be stored for later beneficial use and must be managed as a hazard rather than a resource. Work is in progress to develop adaptation strategies such as forecast-informed or dynamic reservoir operations (Steinschneider and Brown, 2012; Talbot et al., 2019) and managed

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aquifer recharge (e.g., Dillon et al., 2010) that can be used to address this water management challenge as continued warming results in additional changes from snow to rain.

5.2 Primary Limitations

This study represents a first step towards a diagnostic indicator to estimate long-term changes in rain/snow partitioning that can be utilized in water resource management decision making. The approach described herein does have several primary limitations in its current form. A major limitation is the assumption that the NAFLT freezing level elevation linearly corresponds to the $\%_{SNOW}$ estimate, which is then multiplied by the PRISM precipitation amount at that grid point at the monthly time scale. One key limitation of PRISM in this application is that it remains an interpolation method based on observational data, which is sparse in mountainous regions (Henn et al., 2018). Indeed, high-resolution model simulations are becoming more skilful at estimating snowpack than observational networks (Lundquist et al., 2020) or gridded products (Wrzesian et al., 2019). Further, our assumption that coarse models (e.g., reanalysis products) accurately represent the freezing level ignores mesoscale effects of snowline variability in complex terrain (Minder et al., 2010) or the effects of near-surface humidity (Harpold et al., 2017). Both sources of uncertainty may result in substantial biases in rain/snow partitioning estimates as a function of individual storms, particularly during frontal passage and when the magnitude and spatial distribution of precipitation is also considered.

6 Concluding Remarks

Changes in the fraction of precipitation falling as snow during the cool season can have significant impacts on the ability of water managers to balance management objectives (e.g., water supply, ecosystem demands, recreation) through reservoir operations. Expectations from climate change projections suggest that dynamic adaptation strategies will have to be employed to maintain the functionality of existing water management infrastructure. A method for estimating snowfall as a fraction of total precipitation at high spatial resolution (800 m or 4 km) and modest temporal resolution (monthly) with readily available output from the North American Freezing Level Tracker (NAFLT) based on a global reanalysis product (NCEP/NCAR), PRISM precipitation, and a digital elevation model was presented. A trend analysis indicates a greater fraction of precipitation across California's historically snow-dominated mountain regions with the spring showing the strongest trends (-2% to -4% decade^{-1}) followed by winter (-1% to -2% decade^{-1}). The largest decreases were found at mid-elevations near the climatological freezing level, which have previously been identified as the most vulnerable to warming (Huning and Aghakouchak, 2018). The developed method uses publicly-available gridded data sets which enable application to areas with similar natural resource or water management paradigms. Ongoing work seeks to address the limitations presented in order to produce more robust estimates of historical change in rain/snow partitioning and enable additional storm or place-based detail that can be utilized in adaptive strategy development and applications. The main advantage of the described approach is that it with the increasing availability of higher resolution gridded data products (e.g., TerraClimate; Abatzoglou et al., 2018), evaluations of rain/snow partitioning can be applied at global scales. It is anticipated that an updated freezing level tracker tool will be developed and used to provide this information to water managers to help inform decision making. California's investment in unique data sets like snow level radar (White et al., 2013) coupled with ongoing efforts to improve *in-situ* weather monitoring in headwater regions (Lundquist et al., 2016) creates an opportunity for further exploration of rain/snow partitioning including storm-based and place-based analyses. These analyses can play important roles in developing and implementing adaptive strategies for water management in a changing climate by providing analog examples of what future cool seasons or storm events in a warming climate may look like (e.g., Hatchett, 2018; Sterle et al., 2019).

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8 Code/Data availability

The MATLAB analysis code, North American Freezing Level Tracker processing code, and processed data (e.g., $\%_{SNOW}$) is available upon request.

9 Author contributions

Elissa Lynn, Aaron Cuthbertson, Minxue He, Jordi P. Vasquez, Michael L. Anderson, and Peter Coombe conceptualized the idea. Elissa Lynn supervised the project. Benjamin J. Hatchett wrote the manuscript with input from all authors and was responsible for analysis and visualization. John T. Abatzoglou developed the North American Freezing Level Tracker, generated the precipitation phase partitions, and performed the analysis and visualization shown in Figure 4. All authors contributed to the interpretation and presentation of data and results as well as the revision and editing of the original manuscript.

10 Competing interests

Authors Elissa Lynn, Aaron Cuthbertson, Minxue He, Jordi P. Vasquez, Michael L. Anderson, and Peter Coombe are employed by the California Department of Water Resources. Authors Benjamin J. Hatchett and John T. Abatzoglou declare that they have no competing interests.

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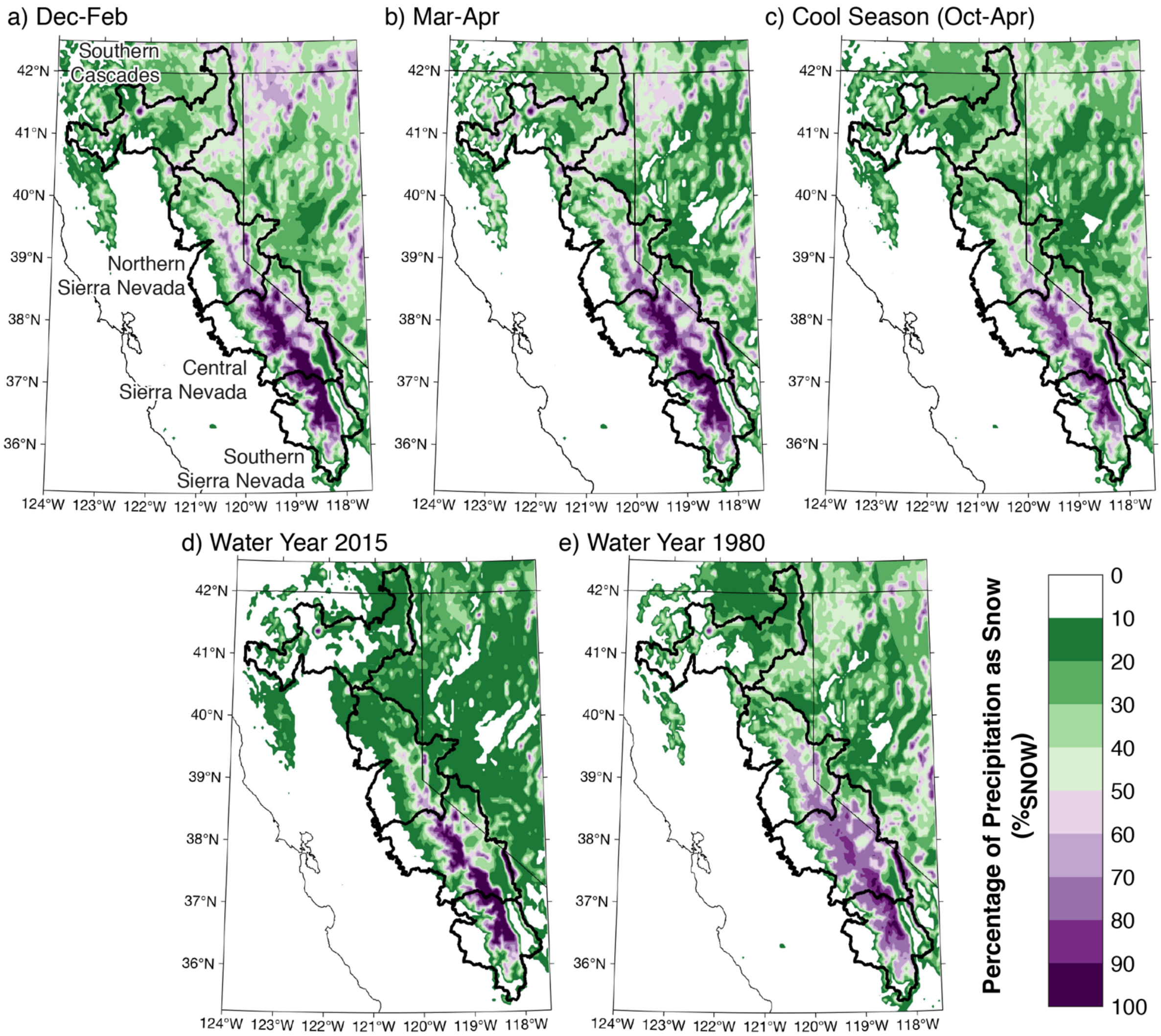
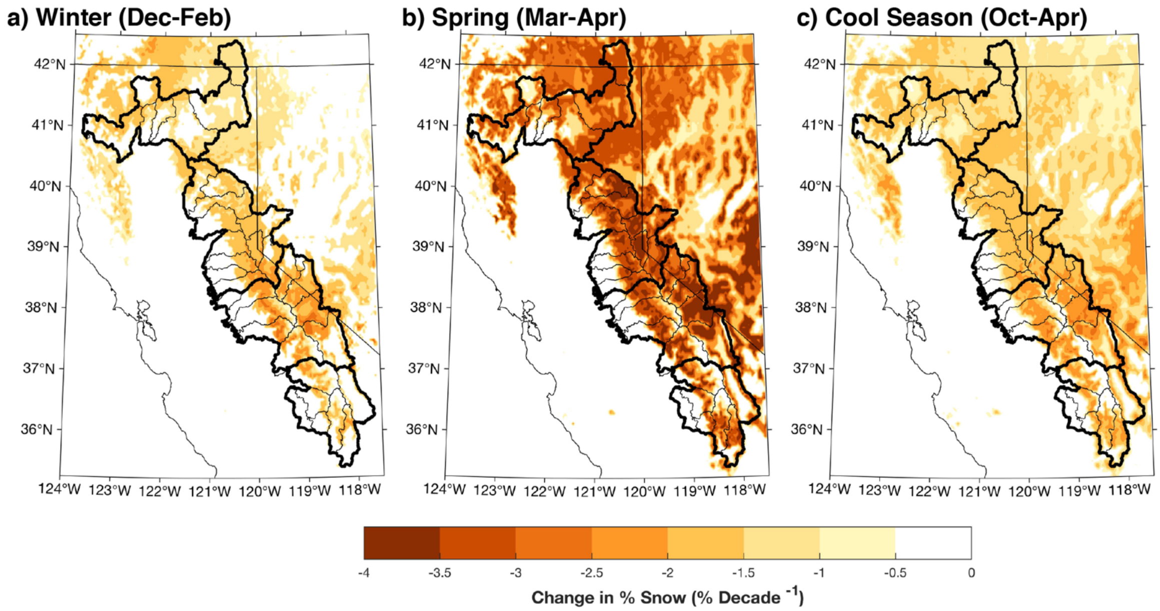


Figure 1: Estimated 4 km horizontal resolution historical (1950-1969) percentages of precipitation as snow for (a) winter (Dec-Feb), (b) spring (Mar-Apr), and (c) for the full cool season (Oct-Apr). Examples of $\%_{SNOW}$ averaged over the cool season (October-April) of water years (d) 2015 and (e) 1980. Thick black contours denote California Department of Water Resources analysis zones.



5 **Figure 2: Estimated changes in $\%_{SNOW}$ (in % decade^{-1}) for (a) winter (Dec-Feb), (b) spring (Mar-Apr), and (c) for the full cool season (Oct-Apr). Thick black contours denote California Department of Water Resources analysis zones. Thin black contours denote United States Geological Survey HUC-8 watersheds. Only gridpoints with statistically significant ($p<0.05$) trends are shown; Supplementary Figure 1 shows trends for all gridpoints.**

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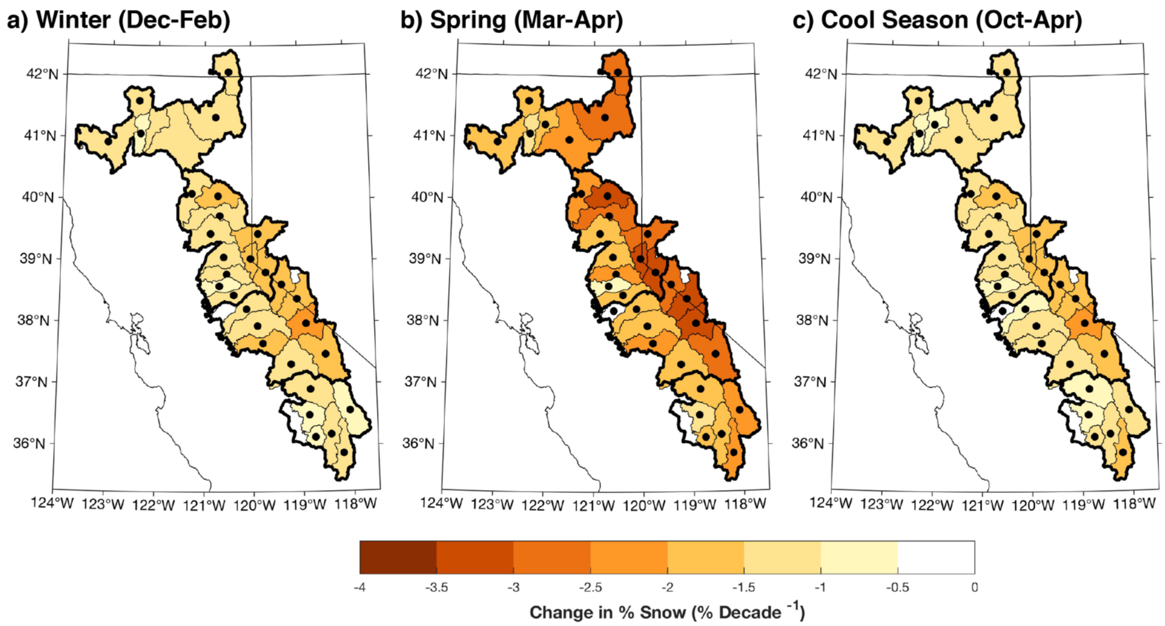

Figure 3: As in Figure 2 but with trends averaged over HUC-8 watersheds. Filled black circles indicate statistically significant (p<0.05) trends.

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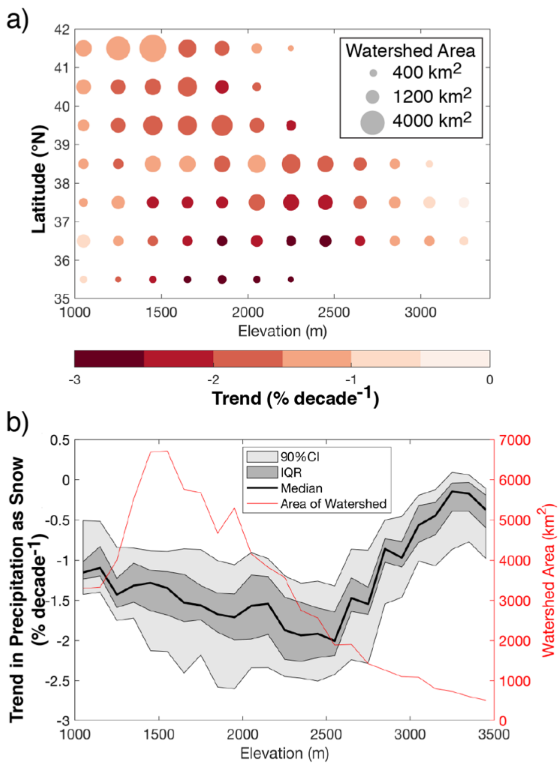

Figure 4: (a) Aggregated trends in $\%_{SNOW}$ (% decade^{-1}) by latitude and elevation. Dot size is scaled by area of watershed occupying each elevation and latitude bin. (b) Elevation-based trends (aggregated over all latitudes) of $\%_{SNOW}$ (% decade^{-1}) showing median (black line), the interquartile range (dark grey shading), and 90% confidence intervals (light grey shading) on the left y-axis. Right y-axis shows the total watershed area occupied by each elevation bin (red line; km^2). Aggregations were performed on gridpoints within the subset of California Department of Water Resources analysis zones (see Figure 1a).

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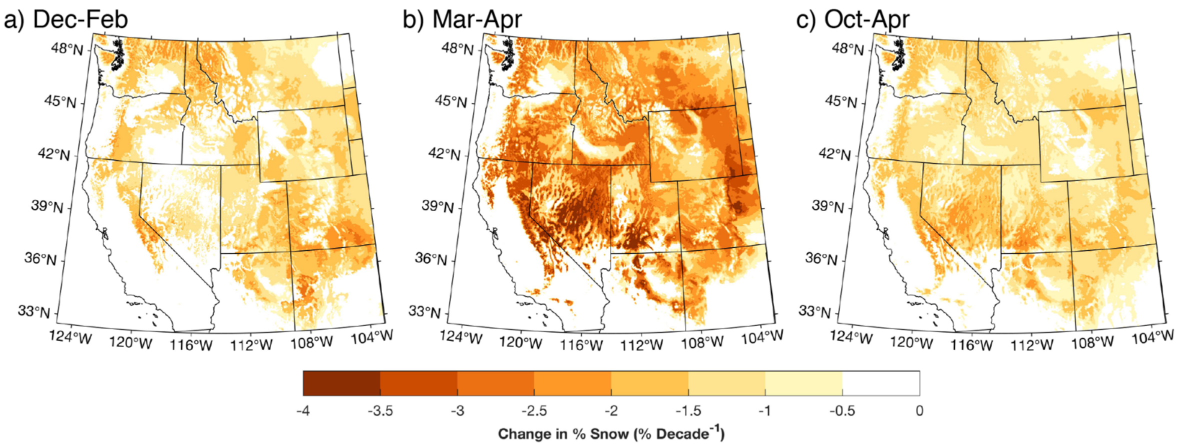

Figure 5: Decadal trends in $\%_{SNOW}$ for the western United States during (a) winter (Dec-Feb), (b) spring (Mar-Apr), and (c) for the cool season of the water year (Oct-Apr). Only gridpoints with statistically significant ($p<0.05$) trends are shown; all gridpoint trends are shown in Supplementary Figure 2.