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Winter melt trends portend widespread declines in snow water resources

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Abstract

In many mountainous regions, winter precipitation accumulates as snow that melts in spring and summer, providing water to one billion people globally. Climate warming and earlier snowmelt compromises this natural water storage. While snowpack trend analyses commonly focus on snow water equivalent (SWE), we propose that trends in accumulation season snowmelt serve as a critical indicator of hydrologic change. Here we compare long-term changes in snowmelt and SWE from snow monitoring stations in western North America and find 34% of stations exhibit increasing winter snowmelt trends ($p < 0.05$), a factor of three larger than the 11% showing SWE declines ($p < 0.05$). Snowmelt trends are highly sensitive to temperature and an underlying warming signal, while SWE trends are more sensitive to precipitation variability. Thus, continental-scale snow water resources are in steeper decline than inferred from SWE trends alone. More winter snowmelt will complicate future water resource planning and management.

Keywords

SNOW TRENDS; MELT; SNOW WATER EQUIVALENT; WARMING; CLIMATE CHANGE

Snow is the primary source of water and streamflow in western North America [1] and supports the water supply for more than one billion people globally [2]. In mountainous

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AUTHOR CONTRIBUTIONS

K.N.M and N.A. designed the study; K.N.M. collected the datasets and conducted the analysis; all authors contributed to the interpretations of the results and wrote the paper.

COMPETING INTERESTS STATEMENT

The authors to declare there are no competing financial or non-financial interests in relation to the work described.

CODE AVAILABILITY

MATLAB code used to conduct the analysis and create figures is publicly available and fully citable with the DOI 10.5281/zenodo.4546596.

regions, accumulated snow extends the downstream delivery of meltwater through the spring and summer when human and ecosystem demands are greatest. For over a century, hydrologists have used mountain snowpack observations to make spring and summer runoff forecasts [3,4], which help farmers plan irrigation, water managers operate reservoirs, communities protect against floods, and energy companies manage hydropower assets and set annual prices [5–8].

It is well established that climate change is expected to shift melt earlier and reduce snow water resources [2,9] with broad impacts on ecosystem productivity [10], winter flood risk [11], groundwater recharge [12], agriculture and food security [13–15], and wildfire hazard [16]. Water resource management in snow-dominated regions rely on distinctly separate snow accumulation and snowmelt seasons such that annual river flows can be predicted based on the quantity of maximum snow accumulation. The occurrence of substantial snowmelt and streamflow prior to maximum SWE reduces streamflow and drought forecast accuracy [17] and complicates the management of dams and reservoirs. How warming has and will continue to impact these diverse socio-environmental systems is a critical research question in light of model projections that snowpack will decline and winter melt will increase this century [18–21]. Ground-based snowpack observation networks offer critical monitoring capacity to assess current conditions and long-term trends in a manner unsurpassed by current remote sensing techniques [22] or models alone [23].

The western U.S. has extensive networks of long-running manual and automated snow observations. Here, manual snow measurement records have facilitated historical trend analyses extending back to the 1950s [24,25], with a recent study reporting declines in early spring SWE at 33% of >600 sites [25], a trend that has stabilized since the 1980s, despite significant global and regional warming [26]. Decadal variability in storm track, precipitation and long-term warming codetermine SWE trends in the western U.S. [24,26,27]. The high sensitivity of SWE to long-term precipitation trends complicates assessments of snowpack response to warming, particularly as future precipitation changes are much less certain than warming [28]. Conversely, winter snowmelt may be more sensitive to warming than to changes in precipitation. While (monthly) manual snow survey SWE data [24,25] do not resolve melt, automated snow station observations of SWE, measured using a weighing device to relate snowpack mass to the equivalent water depth, facilitate long-term melt trend analysis. As a hydrologic flux, snowmelt trends can serve as an insightful indicator of shifts in snow water resources relevant to global water assessments [29].

To date, no study has conducted long-term trend analyses of melt from SWE measurements made at the >1,000 automated stations located across western North America. Only recently has the automated station record become sufficiently long (30 to 40+ years) to permit robust trend analysis. We present an empirical study of daily melt and SWE from 1,065 automated snowpack monitoring stations in the western U.S. and Canada. For each station and year, we compute the cumulative annual daily melt, the date of maximum SWE, and April 1st SWE. The date of April 1st is commonly used in water supply management to divide winter snow accumulation and spring melt and as a proxy for the date of maximum annual SWE [30]. A more conservative definition of ‘winter’ is the snow accumulation period before the date of maximum SWE, observed locally for each station-year. We report the cumulative annual melt as the fraction of total annual melt (fraction of melt; FM) on April 1st (FM_{Apr1}) and the date of maximum SWE (FM_{max}) (see Extended Data Figure 1 and Methods Section). We introduce the FM metric to characterize the mobilization of snow water resources during what is traditionally considered to be the accumulation period before spring melt and use it to assess historical snowpack response to climate variability.

We conduct trend analyses of FM_{Apr1}, FM_{max}, April 1st SWE, and the date and magnitude of annual maximum SWE using a Mann-Kendall test and the Theil-Sen slope estimator on data records ≥30 yrs. and present trends with statistical significance at the 95% confidence level. We relate interannual anomalies in these measured snow metrics to observation-based long-term and interannual variability in temperature and precipitation. Finally, to assess the climatological drivers of observed trends in melt, SWE and date of maximum SWE, we constrain our trend analysis to stations with long (40+ yr.) records coincident with the observation-based Parameter-elevation Regressions on Independent Slopes Model (PRISM) dataset [31]. We used these stations and climate data to conduct a controlled assessment of how decadal variability and long-term trends in temperature and precipitation impact our reported melt and SWE trends. See the Methods Section for details.

Melt and Snowpack Baseline Conditions

To evaluate trends in melt before the date of maximum SWE, we first assess the long-term average date of maximum SWE and the fraction of melt occurring before this date. The average date of maximum SWE computed on all stations for the full period of record is within one day of April 1st (Figure 1a); however, there is much geographic variability (Figure 1b). On average, the snowpack of the Sierra Nevada and inter-continental regions peaks within ~10 days of April 1st, while the snowpack in the U.S. Pacific Northwest and Southwest peaks around the first week of March. In interior Alaska, the date of maximum SWE occurs in mid- to late-April. In cold, continental regions including Colorado, Wyoming, Montana, the Canadian Rockies, and interior British Columbia, maximum SWE occurs closer to May 1st. The variability in the average date of maximum SWE supports a more conservative ‘winter’ melt assessment using FM_{max}.

On average at western North American stations, 78% of annual snow water resources remains available to melt on April 1st as inferred from the average FM_{Apr1} of 0.22 (see vertical line in Figure 1c). Correspondingly, 88% of winter accumulating snow remains available to melt on the station- and year-specific date of maximum SWE (Extended Data Figure 2a). Similar to the date of maximum SWE, both FM metrics (FM_{Apr1} and FM_{max}) exhibit substantial geographic variability (Figures 1d and S2b) with proportionately more winter melt in warmer regions such as the U.S. Pacific Northwest and Southwest, where >20% of annual snow water resources melt during the accumulation season. By comparison, <5% of annual snow water resources mobilizes before spring melt in places like the Rocky Mountains, interior British Columbia, and interior Alaska (Figure 1d). For controlled assessments among sites and over time and for comparison to recent studies, we use April 1st to assess long-term changes in melt and SWE. For completeness, we also report long-term changes in the annual maximum SWE, the date of maximum SWE, and FM_{max}.

Melt and Snowpack Trends

Melt occurring before April 1^{st} has increased at 42% of 634 stations with long records in western North America (Figure 2a; red markers) at an average rate of 3.5% ± 3.3% per decade (Figure 2b; green markers) compared to ~12% of stations with lower April 1^{st} SWE (Figure 2c; red markers). Stations with statistically significant ($p \leq 0.05$) trends toward proportionately more melt before April 1^{st}, shown in Figure 2a, cover all regions of western North America. Very few stations had reductions in FM_{Apr1} (n=7), increases in April 1^{st} SWE (n=8) and/or maximum annual SWE (n=9) (see blue markers in Figures 2a,c,d). Similar to the April 1^{st} metrics, FM_{max} increased at 34% of stations (Extended Data Figure 3a) at an average rate of 2.8% ± 1.7% per decade (not shown) compared to 10% of stations with earlier maximum SWE (Extended Data Figure 3b). Importantly, melt before April 1^{st} has increased at 4.2-times the number of stations with trends toward earlier maximum SWE and 3.5-times the number of stations with less April 1^{st} SWE (Figure 2; compare red markers in panel a to those in panels c and d, respectively). Similarly, melt before annual maximum SWE has increased at 3.1-times the number of stations with declines in annual maximum SWE (Extended Data Figure 3).

Melt is increasing in all snow-dominated months before April 1^{st} (i.e., ONDJFM) with the greatest rate of change in March. Median monthly melt, presented as the fraction of total annual melt occurring in a given month, has increased by ~0.5% per decade in the months of ONDJF and ~1.3% per decade in March (Extended Data Figure 4a). Notably, 9% to 24% of stations with long records (30+ years) have statistically significant ($p \leq 0.05$) melt increases in snow-dominated months before April 1^{st} (Extended Data Figure 4b). The number of stations with monthly trends, shown in Extended Data Figure 5, is greatest in November and March (24% and 22% of stations with long records, respectively) and least in February (9%) followed by October and January (13%) and December (16%). These results indicate that while the number of stations with significant melt increases is most substantial in November and March, melt is increasing in all cold season months (October to March).

Melt and Snowpack Sensitivities to Climate

To evaluate the sensitivities of the snow metrics to interannual variations in air temperature and precipitation during the accumulation season, we assess anomalies in the snow metrics as a function of NDJFM (1979–2019) precipitation and temperature anomalies. The data markers in Figures 3a–c show, for each station-year ($n \approx 29{,}700$), precipitation and temperature anomaly colored by annual anomaly (in percentile units) in the respective snowpack metric. The structure of the data clouds in Figures 3a–c is the same; the shape indicates that drier years tend to be warmer than wetter years, a weak but significant ($p \leq 0.05$) negative correlation ($r = -0.24$), supporting previous work on the topic [32,33]. Importantly, the colors of the data points in Figure 3a–c are stratified uniquely across the precipitation-temperature anomaly space for the three different snow metrics, suggesting different primary drivers of variability.

To characterize the relative influence of precipitation and temperature on the snow indices across the percentile space, the data were divided into six percentile bins (see colors in

Figures 3abc) and a centroid (mean temperature and precipitation anomaly) was computed for each group. The slope of the lines connecting the centroids in Figure 4d indicates the relative influence of temperature and precipitation on the snow metric. The more horizontal the line, the stronger the temperature influence. The centroid line for FM_{Apr1} is more horizontal than for the SWE metrics, showing that FM_{Apr1} is more strongly influenced by temperature. In contrast, for the SWE metrics, the centroid line is steeper, indicating a stronger control of precipitation and a weaker sensitivity to the temperature signal. The curved shapes of the April 1st SWE and date of maximum SWE lines suggest that precipitation plays a dominant role in determining late and high maximum SWE (upper left part of the curve) compared to early and lower maximum SWE (lower right part of the curve), which are more driven by temperature. Simply put, it takes an unusually warm winter to cause very early and/or low maximum SWE, while very late and/or high maximum SWE typically results from unusually wet winters. In contrast, the linear shape of the FM_{Apr1} centroid line indicates that seasonal temperature reliably controls snowmelt. The analysis of FM_{Apr1} anomalies was repeated for different regions with stations partitioned into low, medium and high elevation bands. FM_{Apr1} at lower elevations may be more sensitive to seasonal temperature variations than higher elevations (Extended Data Figure 8).

To connect results from the interannual sensitivity of melt and SWE (Figure 3) to the climatic drivers behind the long-term historical trends shown in Figure 2, we conduct a trend analysis on 173 snow stations that had longer records (1979–2019) (see Methods Section and Extended Data Figure 9). To isolate the effects of trends in temperature and precipitation on the snow indices, we created two subsamples of stations: those with drying trends and those with warming trends. Stations with warming trends were more likely to have melt increases than declines in April 1st SWE (compare red lines in Figure 4a), emphasizing again the greater sensitivity of FM_{APR1} to temperature, but this time at the decadal time scale. Stations with a drying trend have substantial changes in April 1st SWE (Figure 4b).

The number of U.S. stations with significant ($p \leq 0.05$) warming has quadrupled from 21 (12%) in 2009 to 80 (46%) in 2019 (Figure 4a; black line) and cover much of the western U.S. as of 2019 (Extended Data Figure 4a). Conversely, fewer stations exhibited drying trends between 2009 and 2019 and the number has not varied in the recent decade to the same degree as warming (Figure 4; compare the black lines in panels a and b, noting different y-axis scales). A map of stations with precipitation trends as of 2019 indicates that only 14 (8%) have a drying trend (Extended Data Figure 9b). A majority of the stations with warming trends also have melt increases (Figure 4c; see purple line calculated as the ratio of the data shown by the red line in Figure 4a to that of the black line in Figure 4a). The same is not true for April 1st SWE, where most stations with warming have no trends in April 1st SWE (Figure 4a; inferred from the difference between the black and dashed red lines). Generally, stations with long-term precipitation declines (i.e., drying) also have decreasing trends in April 1st SWE (Figure 4d; see orange line calculated as the ratio of the data shown by the dashed red line to that by the black line in Figure 4b). Thus, melt is much more sensitive to long-term warming than April 1st SWE (inferred from the purple line plotting above orange line in Figure 4c), which itself is more sensitive to precipitation variability (Figure 4d).

Summary and Discussion

We assess historical daily melt using automated SWE measurements from 1,065 remote telemetry stations that span mountainous regions of western North America. We show that snowmelt is increasing during the snow accumulation season at 34% to 42% of North American stations using the local and regional average (i.e., April 1) date of maximum SWE, respectively. This is evidence that the seasonal distinction between accumulation and melt is becoming increasingly blurred. The melt increases before peak SWE are 3.1- to 3.5-times more widespread than changes in annual maximum or April 1st SWE, respectively, and are driven by a long-term warming trend whereas commonly reported April 1st SWE declines are less sensitive to temperature than precipitation declines. Precipitation variability is shown to drive trends in the April 1st SWE record, supporting previous results [26,27], whereas melt trends are more temperature-dependent, although mechanistically determined by the snowpack energy balance including net radiation and turbulent transfer [34]; the date of maximum SWE is moderately sensitive to both precipitation and temperature trends. Thus, changes in April 1st SWE are more difficult to detect than winter snowmelt due to the weaker climate change signal in precipitation than in temperature. Widespread melt increases across western North America despite lesser change in commonly used snow metrics indicates that this critical water resource is in steeper decline than is inferred from SWE trends alone. Our results support a recent study suggesting that the recent stability of western U.S. SWE will be followed by a period of accelerated decline once the current mode of natural climate variability subsides [26].

We show that snowpack magnitude has declined at ~12% of 634 stations with long records in western North America. The result appears at odds with recently reported more widespread (33%) declines in April 1st SWE observations since the 1950s from manual snow courses in the western U.S. [25]; however, our results are consistent (33% using 2016 as the end date; see gray line in Figure 4d) when restricted to western U.S. stations with long records. Since manual snow courses are generally conducted at lower elevations than automated stations [35] and snowpack at lower elevations is more sensitive to warming [24,36–39], direct comparisons of trend assessments on manual vs. automated snow observations, particularly over different time periods, should be made with care. Interestingly, trends toward more melt did not predominately occur at lower elevations but were generally more frequent at middle to upper elevations, especially in the Pacific Maritime regions (Extended Data Figure 6). One exception is the Southern Rockies where melt trends tended to occur at lower elevation sites. Similarly, there is limited evidence that April 1st SWE declines have predominately occurred at lower elevations (Extended Data Figure 7). Explaining the elevation-dependent trends and assessing whether the observed dynamics are captured in models are beyond the scope of this paper. More generally, increased understanding of the climatological and physiographical dependencies of snowpack sensitivities to anthropogenic climate warming is needed. To summarize, our results illustrate the benefit of using snow observations from automated stations to monitor melt trends as an insightful indicator of warming-induced changes in snow water resources.

More snowmelt mobilizing earlier in the year has important hydrological and ecological implications. Hydrologically, this melt water readily enters the soil system [40], reducing the buffering capacity of soils and heightening flood risk in response to rain-on-snow [11,41] and spring melt [42]. Increased soil moisture during the snow-covered season sustains microbial activity in soils beneath snow [43], facilitating the production of carbon dioxide (CO_2) and making nutrients readily available for transport [44]. The melt trends we present likely have implications on nutrient cycling and functioning of headwater ecosystems. Hydrologic and streamflow prediction models require accurate characterization of soil moisture [45,46]. Given the challenges of hydrologic models to accurately represent soil moisture [47], snowpack [48] and winter melt fluxes [49], together with the needs to better understand the impacts of climate change on water resources, the carbon cycle, and ecosystem productivity, future studies are needed to address the coupled hydrological and ecological consequences of the shift to more winter melt.

We show that the percentage of annual melt occurring before April 1st is increasing by 3.5% per decade at 42% of available stations. This substantial and widespread rate of change implies a loss of seasonal storage of snow water resources in North American mountain water towers [50]. Over the recent decade, the expansion of stations exhibiting long-term increases in winter melt corresponds with the sharp increase in the number of stations with warming trends (Figure 4a). The magnitude of winter melt increases (Figure 2b), in many regions, remains orders of magnitude less than maximum annual SWE such that a significant increase in melt may not yet yield significant declines in SWE at many sites. Rather, the observed widespread melt trends we report likely serve as a harbinger of snowpack response to global warming, consistent with future model projections of earlier melt [18]. We conclude that long-term melt trends are an overlooked and important indicator of change in western North America’s primary water supply that supports some of the world’s largest agricultural and forest product industries and more than 85 million people.

Methods

Snowpack telemetry station observations

Snowpack telemetry stations measure SWE using a metal, fluid-filled snow “pillow” constructed on the ground and a pressure transducer to relate measurements of the overlying snowpack mass to water depth equivalent. Daily SWE observations for the historical record to September 2019 at 1,065 stations in the western U.S. and western Canada were obtained from the Natural Resources Conservation Service, the California Department of Water Resources, Alberta Environment, the British Columbia Ministry of Environment, and the Yukon Government Water Resources Branch. The earliest record dates to 1963. There were nearly 70 stations operating by 1975 and by 1980 there were 230. The data were visually inspected by individual water year (Oct. 1 – Sep. 30) for erroneous and missing data that would adversely affect the estimation of the timing and magnitude of maximum SWE and accumulation season dynamics. The visual assessment permitted flexibility to include snow-years with substantial missing data after maximum SWE that might otherwise have been excluded with an algorithm [51], as melt data after peak-SWE were not used in this analysis. In the case of missing summer data, a zero SWE value was prescribed on August 1st to best estimate total annual melt (see Calculation of Snow Metrics). The manual inspection procedure identified 1,280 station-years (<4%) in which stations recorded data but were excluded from analysis. An additional 142 station-years were manually corrected to remove erroneous spikes. The quality control procedure left 31,343 station-years for analysis. This data set is publicly available in netCDF format (see Data Availability) including level 1 (raw; formatted) and level 2 (QA/QC) products required for reproducibility.

Calculation of snow metrics

Three snow metrics derived from the historical daily SWE observations provide examples of how those metrics vary between a continental (Extended Data Figure 1a) and maritime (Extended Data Figure 1b) snow regime. First, the date and magnitude of maximum SWE (dashed vertical lines in Extended Data Figure 1) were calculated for each snow season and station. The date of maximum SWE is defined as the day, relative to October 1st, on which the annual maximum SWE value occurred; in cases of multiple maxima, the later date is used [52].

We introduce a metric derived from daily SWE observations that complements the date of maximum SWE and provides additional hydrologic information. The fraction of cumulative annual snow water resources that has melted before a given date i, FM_i, was computed for each station-year. This daily metric was computed in three steps for each of two dates: 1) the date of maximum SWE and 2) April 1st. First, daily melt (Extended Data Figure 1; blue bars) was computed as the daily decrease in SWE, presented as positive values. Second, cumulative daily melt (Extended Data Figure 1; red hashed line) was computed as the cumulative sum of daily melt from October 1st to August 1st. Third, the cumulative sum of daily melt was normalized by the total annual melt (on August 1st) to estimate the (daily) fraction of cumulative annual melt, which was then sampled on the dates of maximum SWE (FM_{max}) and April 1st (FM_{Apr1}). The August 1st end date was chosen to avoid rare cases where early-season (i.e., September) snowfall could impact estimates of the total annual melt and to ensure that any late-lying snow (almost always gone by August at sensor locations) was recorded as annual melt.

The complement '1-FM_i' is the fraction of annual snow water resources that remains to be melted on day of water year, i (the North American water year begins on October 1st). In the idealized case of snowpack as a fully efficient water tower with distinct accumulation and melt seasons delineated by the date of maximum SWE, FM=0.0 on the date of maximum SWE when no snowfall has melted to date and no snowfall will occur after that date. In all cases, FM=1.0 occurs on the last date of snow disappearance. The snow metrics date of maximum SWE, magnitude of maximum SWE, FM_{max}, and FM_{Apr1} were computed for each year of record for all stations.

Historical trend analysis

To assess long-term trends in the snowpack observations, linear trend analysis and a Mann-Kendall test [53] were conducted on each snow metric. The non-parametric Mann-Kendall (MK) [54,55] test was chosen over slope-based alternatives, such as the parametric t-test, as MK performs optimally with non-normally distributed data such as time series [56]. This approach is similar to a recent snowpack trend assessment by Mote, et al. [25]. Only stations with at least 30 years of record were assessed and only trends with statistical significance at the 95% confidence level ($p \leq 0.05$) are reported. Slopes of linear fits to the data were calculated using the Theil-Sen estimator method [57], which is the median of the slopes computed over pair-wise data points, and has been used in the hydrologic [58] and climate trend analyses [59].

Relationships of snowpack trends with precipitation and temperature

We investigate the roles of cold season (i.e., NDJFM) temperature and precipitation in influencing interannual variations in FM_{Apr1} and the date and magnitude of maximum SWE. Monthly air temperature and precipitation were obtained from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) for 1979 – 2019 (PRISM Climate Group, Oregon State University, http://prism.oregonstate.edu, last accessed 10 June 2020). The gridded PRISM data are produced at 800 m resolution and upscaled to and provided at 4 km. Monthly temperature and precipitation data were extracted for all snow telemetry stations in the contiguous U.S. For each station and year, average air temperature and total precipitation were calculated for the months of NDJFM and presented as anomalies relative to the long-term (1979–2019) mean NDJFM values. Similarly, anomalies in the FM_{Apr1} and the date and magnitude of maximum SWE were computed for each station-year. In this way, air temperature and precipitation anomalies were plotted against anomalies in snow metrics for each year and station for which snowpack data were available. The analysis of FM_{Apr1} anomalies was repeated for different regions with stations partitioned into low, medium and high elevation bands based on the 33rd and 66th percentiles of the regional elevation of stations with long (40+ yr.) records.

Controlled snow metric sensitivity and trend assessment

To assess the climatological drivers of observed trends in melt, SWE and the date of maximum SWE, we constrain our trend analysis to stations with long (40+ yr.) records coincident with the observation-based Parameter-elevation Regressions on Independent Slopes Model (PRISM) dataset [31]. We sampled historical monthly temperature and precipitation at the station locations and iteratively modified the end-year of our trend analysis from 2009 (30+ yr. record) to 2019 (40+ yr. record). In this way, we mimic the result of conducting the trend analysis on the record available to date, every year for a decade. We used these stations and climate data to conduct a controlled assessment of how decadal variability and long-term trends in temperature and precipitation impact our reported melt and SWE trends. We evaluated the number of stations with trends in temperature or precipitation and, for these specific station subsets, assessed trends in the snowpack response (melt, SWE and the date of maximum SWE). We thus evaluated how the snowpack trends and drivers have changed over recent decades of this relatively short observation record.

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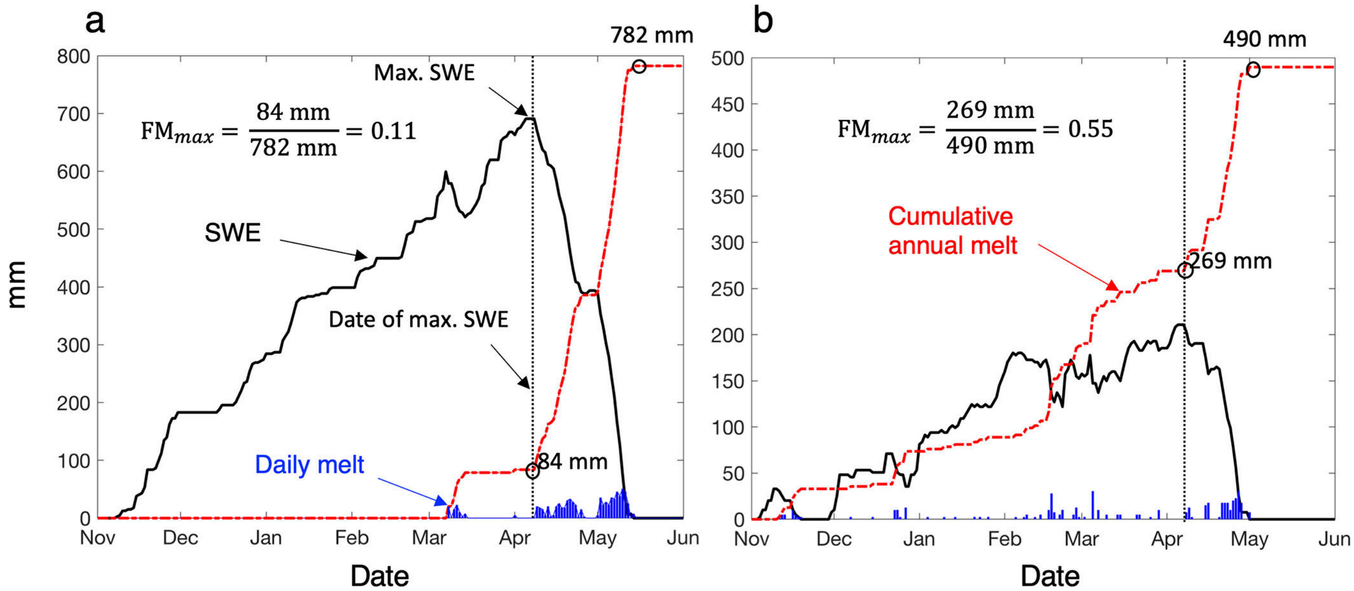
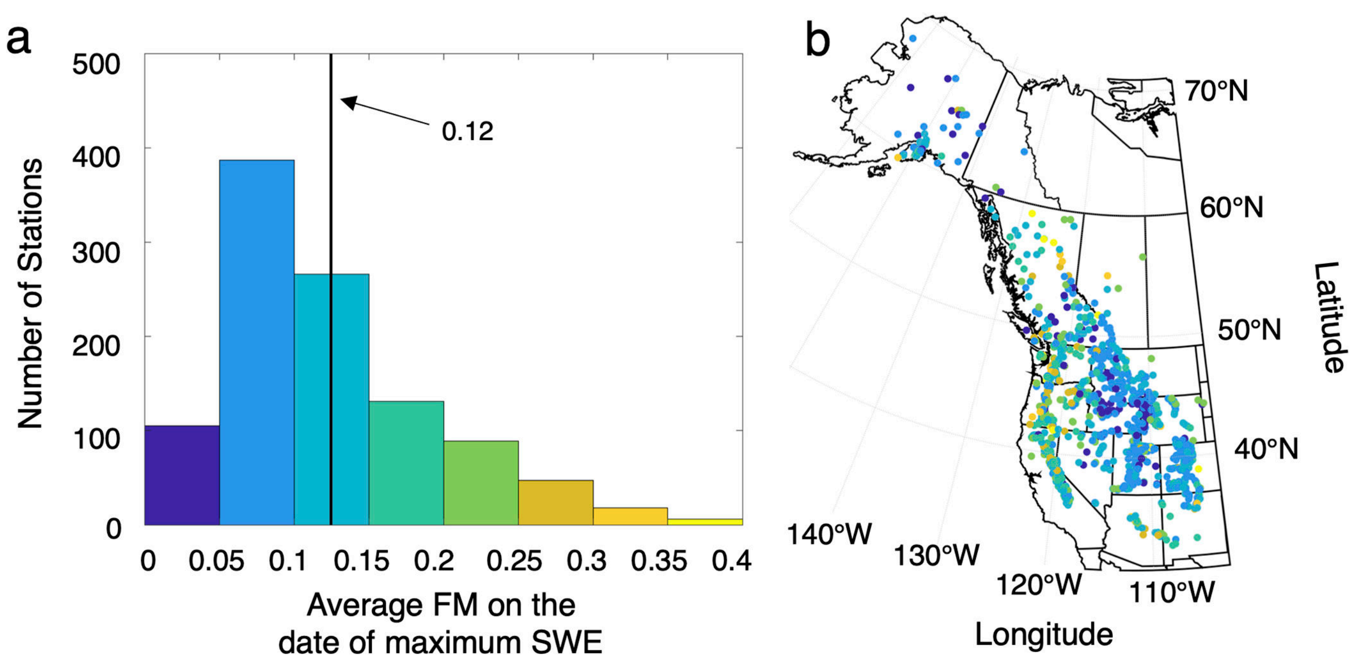
Extended Data



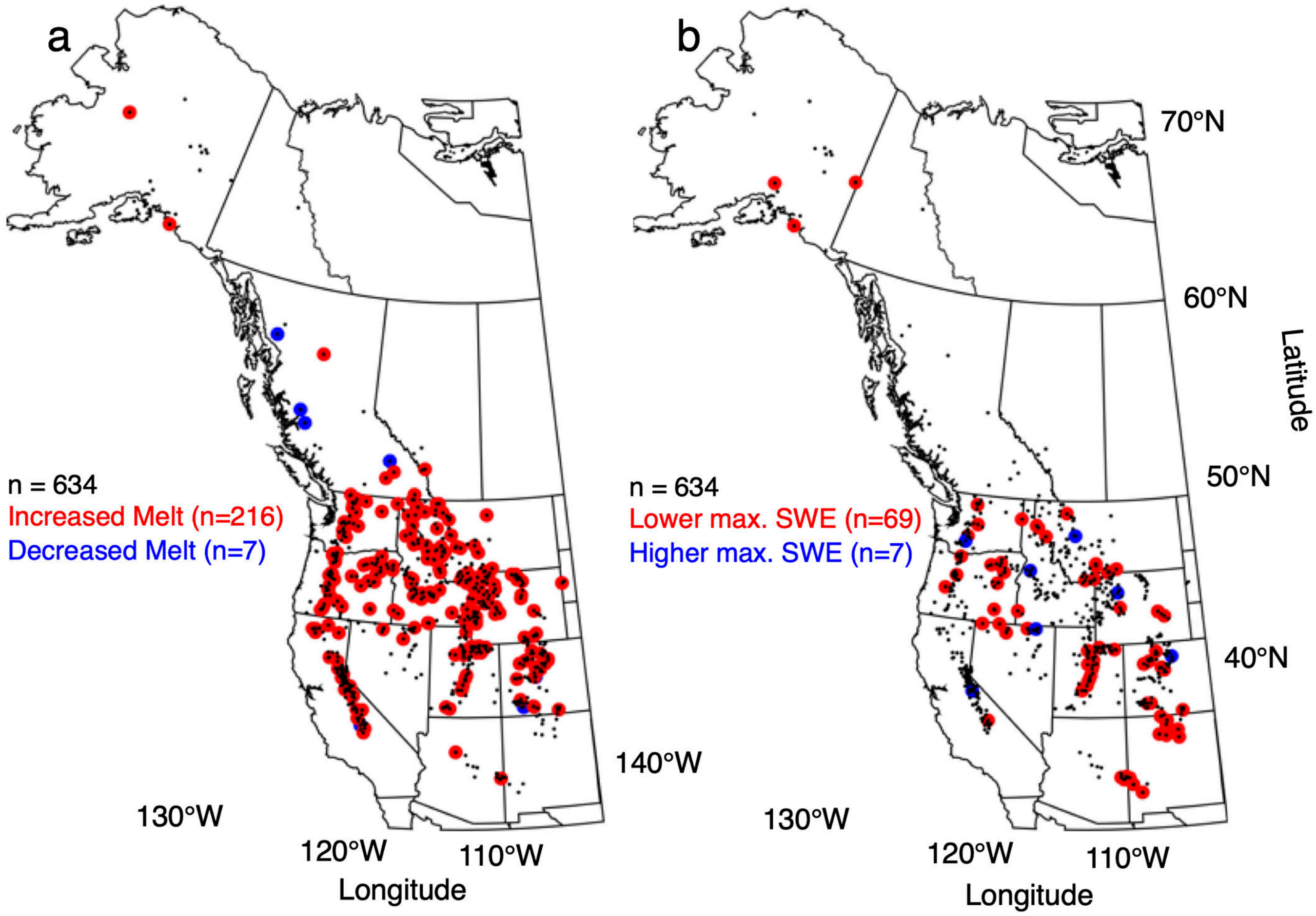
Extended Data Fig. 1. Examples of the snowpack and melt metrics used in this study.

Examples of seasonal SWE time series measured at mountain snowpack telemetry stations in (a) continental and (b) maritime climates showing daily SWE (solid black line) and two metrics derived from the daily decrease in SWE: daily melt (blue bars) and cumulative annual melt (red hashed lines) computed for Oct. 1 – Aug. 1 of each year. The date of maximum SWE is indicated by the vertical dashed line. Calculations of the fraction of cumulative annual melt that has occurred by the date of maximum SWE (FM_{max}) are shown. In these examples, FM_{Apr1} is similar to FM_{max} and is not shown.



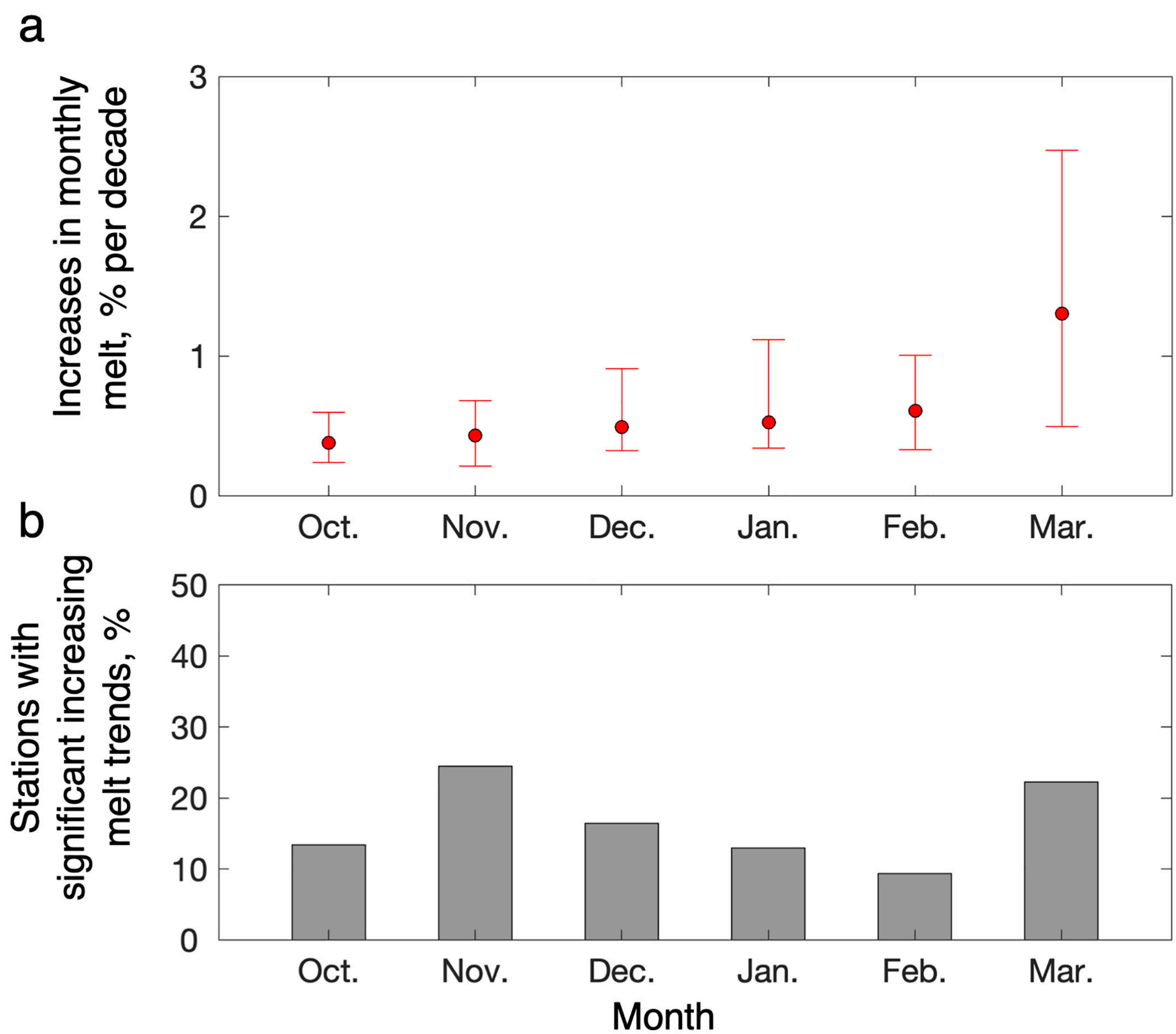
Extended Data Fig. 2. On average across western North American stations, snowpack reaches an annual maximum when 88% of annual snow has yet to melt.

As in Figures 2c and 2d, but showing the average fraction of cumulative annual melt on the date of maximum SWE.



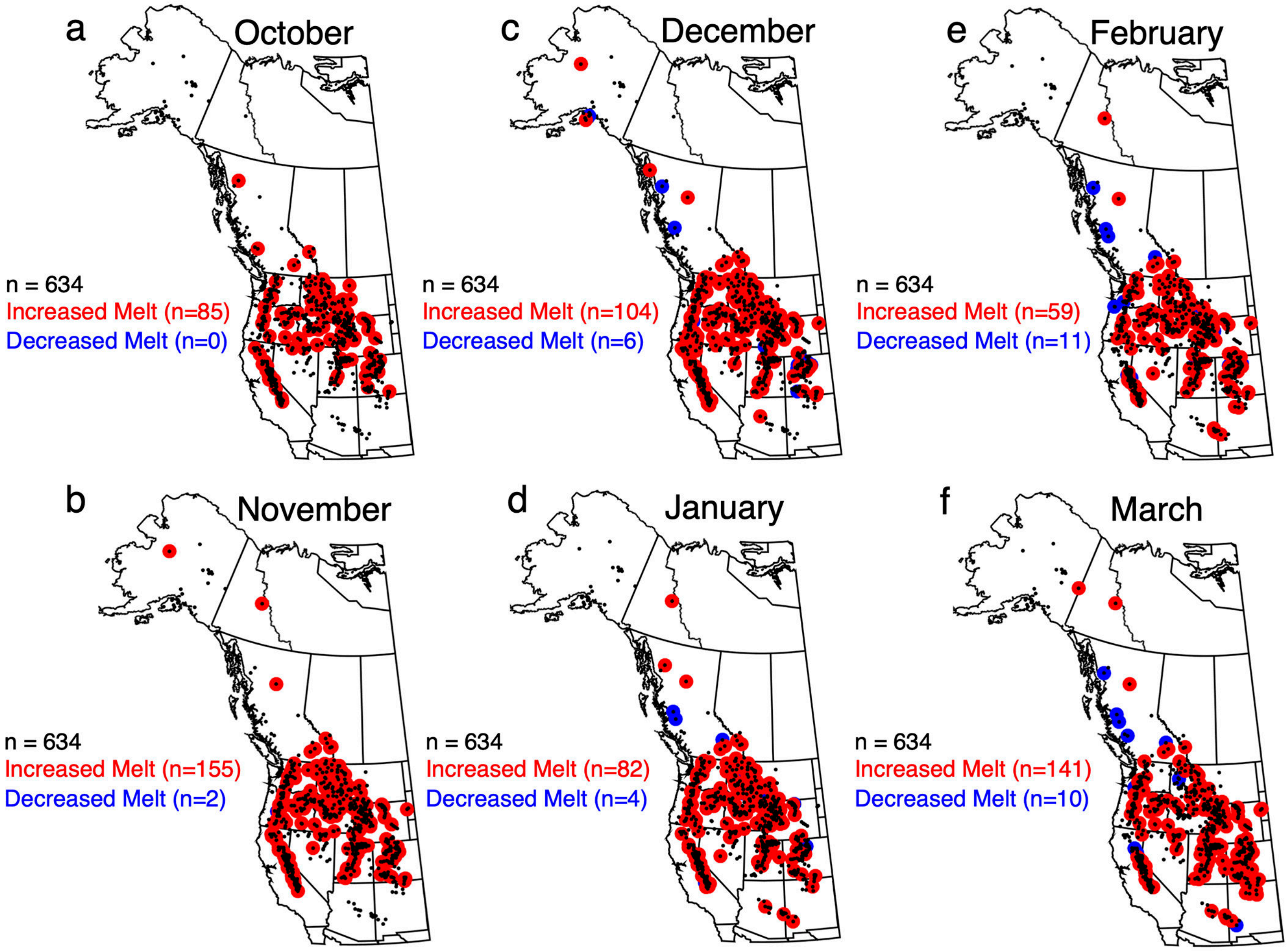
Extended Data Fig. 3. Trends toward more winter melt are three-times more widespread than trends toward lower annual maximum SWE.

As in Figure 2, but showing stations with significant long-term changes in (a) the fraction of cumulative annual melt that has occurred by the date of annual maximum SWE and (b) the magnitude of annual maximum SWE.



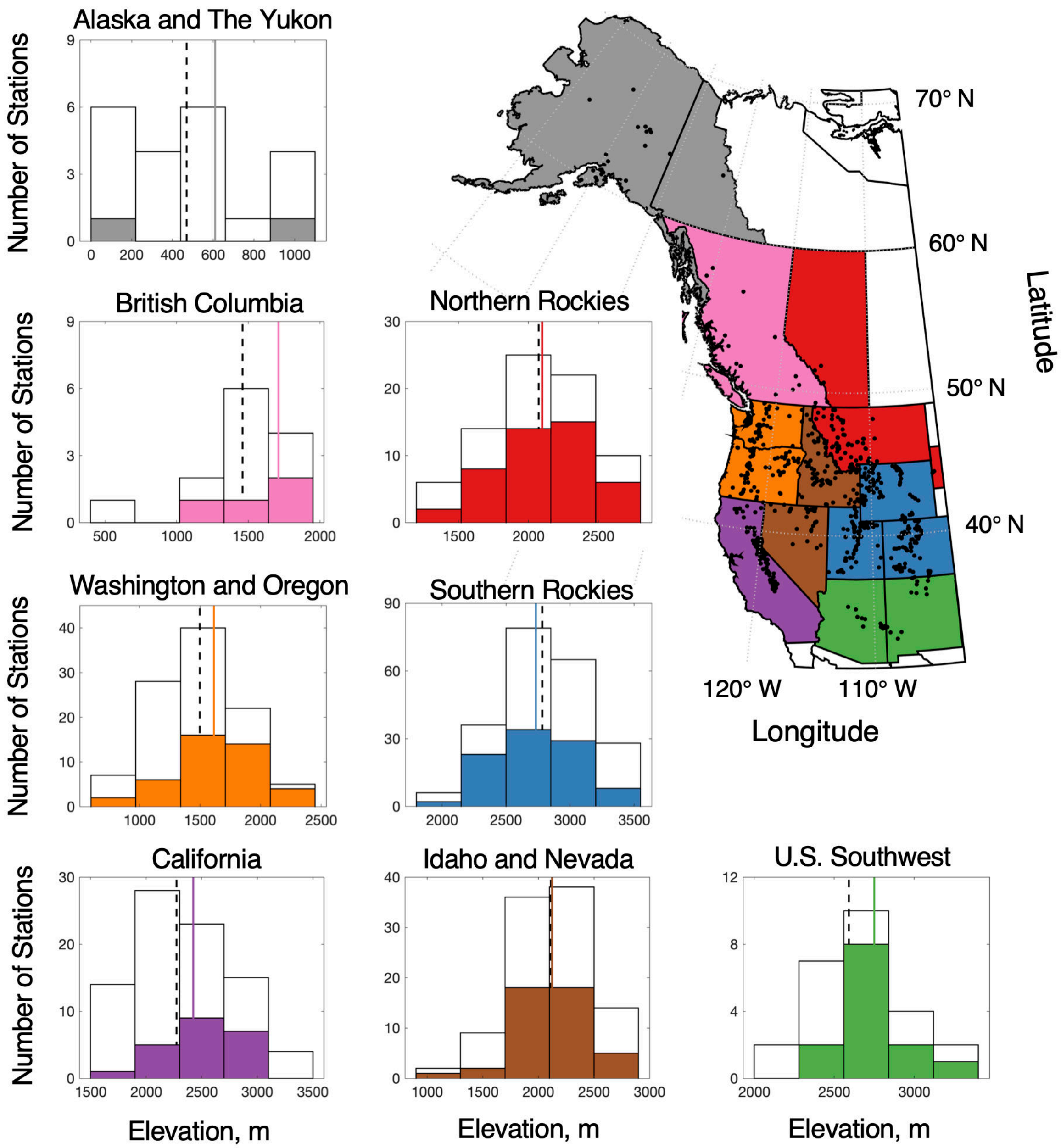
Extended Data Fig. 4. Melt is increasing in all snow-dominated months before April 1st with the greatest rate of change in March.

(a) Increases (% per decade) in monthly melt as a fraction of total annual melt (median shown by red circles, lower and upper quartiles indicated by whiskers) from (b) snowpack telemetry stations with data records ≥ 30 years that have statistically significant ($p \leq 0.05$) positive trends (in percent of n=634 stations). Stations with negative trends not shown: <1% in Oct. and Nov., ~2% in Dec., Jan., Feb. and Mar.



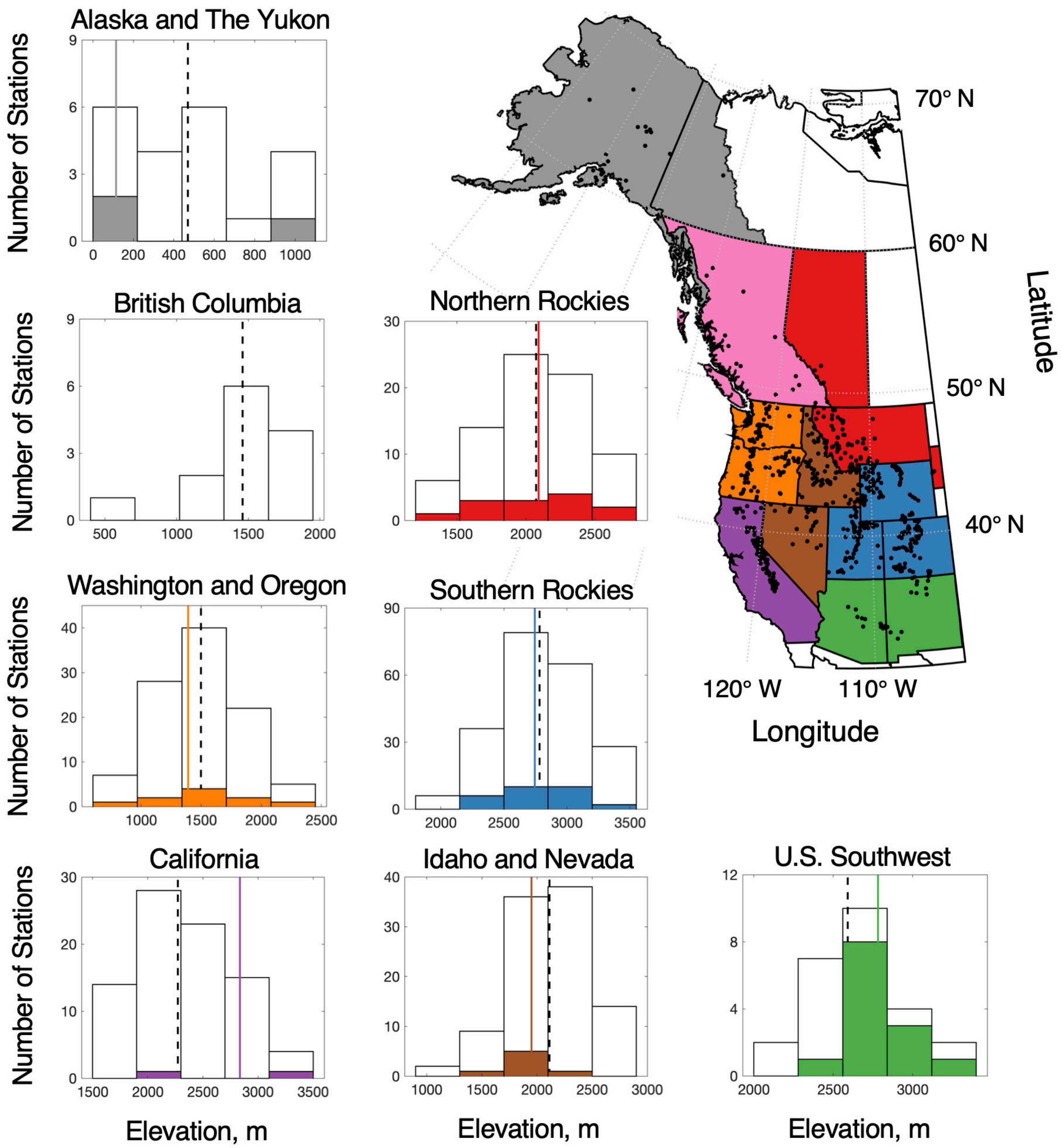
Extended Data Fig. 5. Snowmelt increases during winter months are widespread.

Geographic distribution of the monthly melt trends shown in Extended Data Figure 4 for stations with data records ≥ 30 years (small black markers; n=634) that have statistically significant ($p \leq 0.05$) long-term increases (red markers) and decreases (blue markers) in monthly melt as a fraction of total annual melt for the months of (a) October, (b) November, (c) December, (d) January, (e) February, and (f) March.



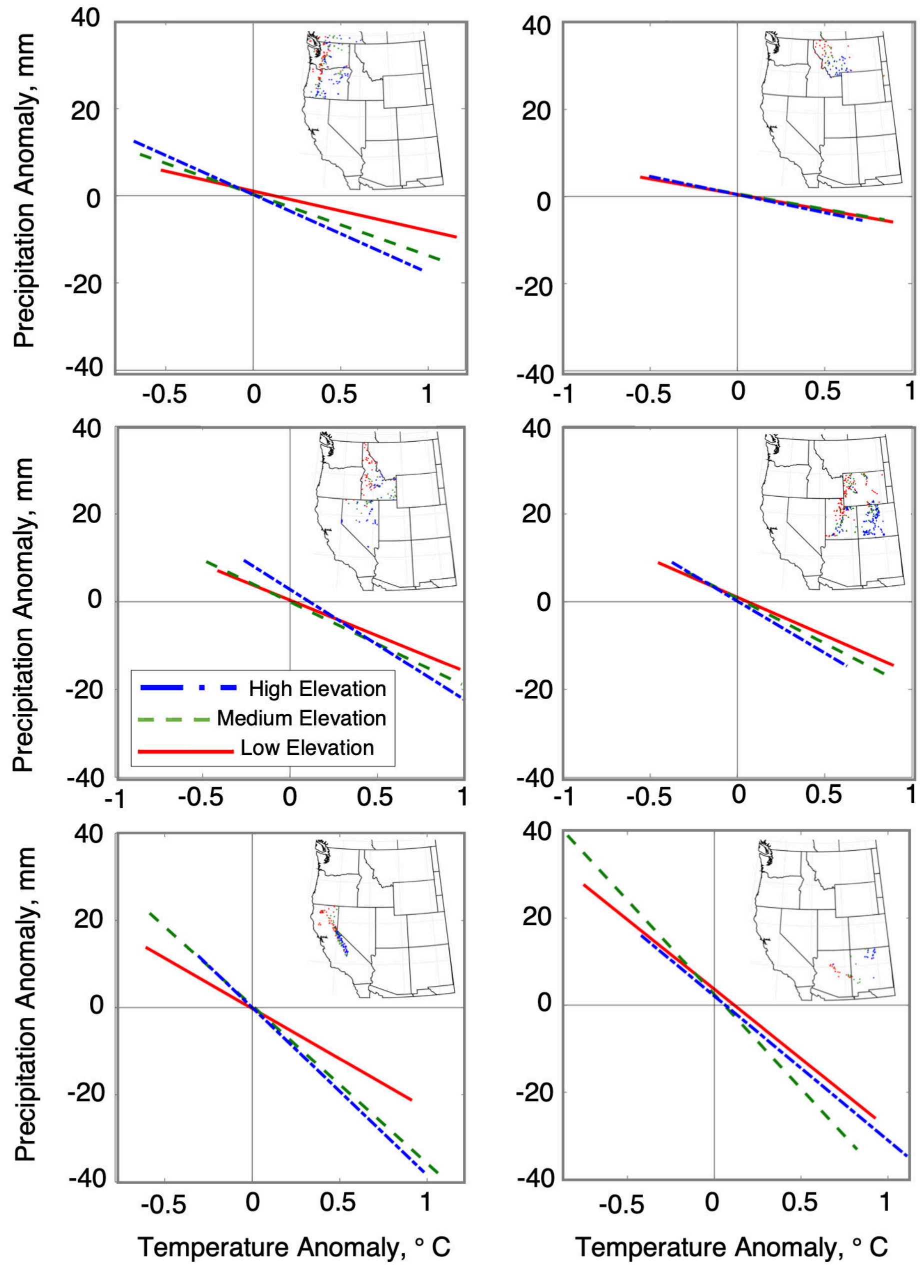
Extended Data Fig. 6. Winter melt increases did not predominately occur at lower elevations but were generally more frequent at middle to upper elevations.

The regional distribution (see colors in inset map) of long-term station (black markers in inset map) elevation (see white histogram bars) and the elevation of stations with long-term increases in the fraction of total annual melt before 1 April (see color histogram bars). The vertical lines in the histogram plots indicate the regional median station elevation (dashed black lines) and the median elevation of station with statistically significant ($p<0.05$) melt increases (solid color lines). When the color line is to the right of the dashed line, it indicates that the melt trend is more prevalent among middle to upper elevation sites.



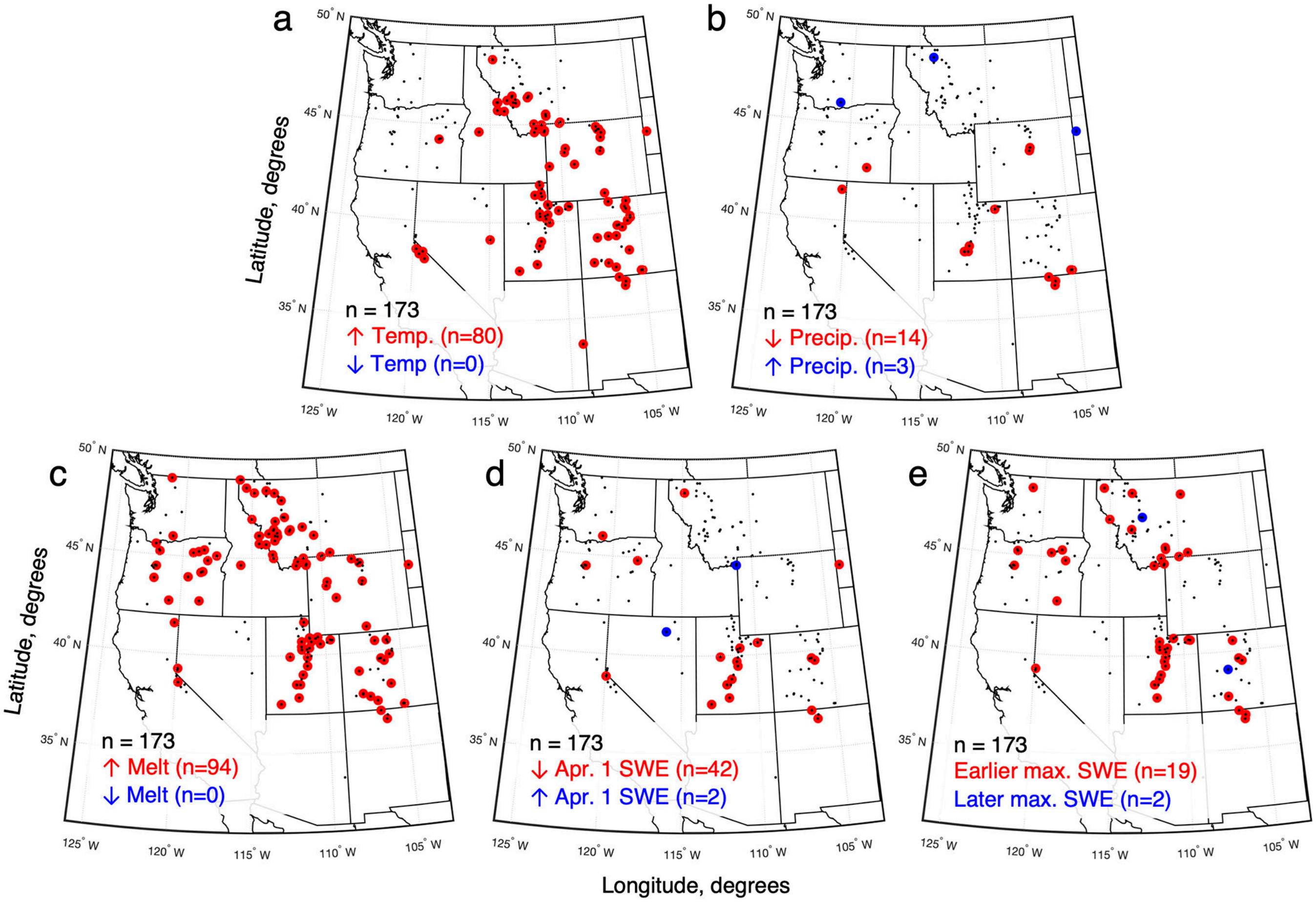
Extended Data Fig. 7. There is limited evidence that April 1st SWE declines have predominately occurred at lower elevations.

As in Extended Data Figure 6, but for trends in the magnitude of SWE on 1 April.



Extended Data Fig. 8. Winter melt at lower elevations may be more sensitive to seasonal temperature variations than higher elevations.

As in Figure 3 but evaluated over six regions with data binned into low, medium and high elevation categories according to the 33rd and 66th percentiles of the regional elevations of stations with long (40+ yr.) records. For visual clarity, shown are linear regressions fit to the centroids of the FM_{Apr1} anomaly (see legend of Figure 3) for each elevation bin. All regression fits are statistically significant.



Extended Data Fig. 9. Snowmelt trends are highly sensitive to temperature and an underlying warming signal, while SWE trends are more sensitive to precipitation variability.

As in Fig. 2 but showing trends (see legends) in a) temperature, b) precipitation, c) FM_{Apr1} (melt), d) April 1 SWE, and e) date of maximum SWE at the 173 U.S. stations with long records (small black markers) coincident with the PRISM climate data (1979–2019).

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DATA AVAILABILITY

Data used in this paper are publicly available and fully citable with the DOI 10.5281/zenodo.4546865.

REFERENCES

1. Li D, Wrzesien ML, Durand M, Adam J & Lettenmaier DP How much runoff originates as snow in the western United States, and how will that change in the future? Geophysical Research Letters (2017).
2. Barnett TP, Adam JC & Lettenmaier DP Potential impacts of a warming climate on water availability in snow-dominated regions. Nature 438, 303–309 (2005). [PubMed: 16292301]
3. Church JE Snow surveying: its principles and possibilities. Geographical Review 23, 529–563 (1933).
4. Garen DC Improved techniques in regression-based streamflow volume forecasting. Journal of Water Resources Planning and Management 118, 654–670 (1992).
5. Pagano T Soils, snow and streamflow. Nature Geoscience 3, 591–592 (2010).
6. Anghileri D et al. Value of long‐term streamflow forecasts to reservoir operations for water supply in snow‐dominated river catchments. Water Resources Research 52, 4209–4225 (2016).
7. Palmer PL in Proc. Western Snow Conf. 43–51.
8. Abramovich R in 75th Western Snow Conference. 103–113.
9. Nijssen B, O'Donnell GM, Hamlet AF & Lettenmaier DP Hydrologic sensitivity of global rivers to climate change. Climatic change 50, 143–175 (2001).
10. Boisvenue C & Running SW Impacts of climate change on natural forest productivity–evidence since the middle of the 20th century. Global Change Biology 12, 862–882 (2006).
11. Musselman KN et al. Projected increases and shifts in rain-on-snow flood risk over western North America. Nature Climate Change 8, 808–812 (2018).
12. Ford CM, Kendall AD & Hyndman DW Effects of Shifting Snowmelt Regimes on the Hydrology of Non-Alpine Temperate Landscapes. Journal of Hydrology, 125517 (2020).
13. Immerzeel WW, Van Beek LP & Bierkens MF Climate change will affect the Asian water towers. Science 328, 1382–1385 (2010). [PubMed: 20538947]
14. Qin Y et al. Agricultural risks from changing snowmelt. Nature Climate Change 10, 459–465 (2020).
15. Shindell D et al. Simultaneously mitigating near-term climate change and improving human health and food security. science 335, 183–189 (2012). [PubMed: 22246768]
16. Westerling AL Increasing western US forest wildfire activity: sensitivity to changes in the timing of spring. Phil. Trans. R. Soc. B 371, 20150178 (2016). [PubMed: 27216510]
17. Livneh B & Badger AM Drought less predictable under declining future snowpack. Nature Climate Change, 1–7 (2020).
18. Musselman KN, Clark MP, Liu C, Ikeda K & Rasmussen R Slower snowmelt in a warmer world. Nature Clim. Change 7, 214–219, doi:10.1038/nclimate3225 (2017).
19. Vano JA et al. Climate change impacts on water management in the Puget Sound region, Washington State, USA. Climatic Change 102, 261–286 (2010).
20. Thackeray CW, Derksen C, Fletcher CG & Hall A Snow and climate: Feedbacks, drivers, and indices of change. Current Climate Change Reports 5, 322–333 (2019).
21. Addor N et al. Robust changes and sources of uncertainty in the projected hydrological regimes of Swiss catchments. Water Resources Research 50, 7541–7562 (2014).
22. Lievens H et al. Snow depth variability in the Northern Hemisphere mountains observed from space. Nature communications 10, 1–12 (2019).
23. Girotto M, Musselman KN & Essery RLH Data Assimilation Improves Estimates of Climate-Sensitive Seasonal Snow. Current Climate Change Reports, doi:10.1007/s40641-020-00159-7 (2020).
24. Mote PW, Hamlet AF, Clark MP & Lettenmaier D Declining mountain snowpack in western North America. Bulletin of the American Meteorological Society 86, 39–49, doi:10.1175/BAMS-86-1-39 (2005).
25. Mote PW, Li S, Lettenmaier DP, Xiao M & Engel R Dramatic declines in snowpack in the western US. npj Climate and Atmospheric Science 1, 2 (2018).

26. Siler N, Proistosescu C & Po-Chedley S Natural variability has slowed the decline in western US snowpack since the 1980s. Geophysical Research Letters 46, 346–355 (2019).
27. Pierce DW et al. Attribution of Declining Western U.S. Snowpack to Human Effects. Journal of Climate 21, 6425–6444, doi:10.1175/2008jcli2405.1 (2008).
28. Pendergrass AG, Knutti R, Lehner F, Deser C & Sanderson BM Precipitation variability increases in a warmer climate. Scientific reports 7, 17966 (2017). [PubMed: 29269737]
29. Oki T & Kanae S Global hydrological cycles and world water resources. Science 313, 1068–1072 (2006). [PubMed: 16931749]
30. Pagano T, Garen D & Sorooshian S Evaluation of official western US seasonal water supply outlooks, 1922–2002. Journal of Hydrometeorology 5, 896–909 (2004).
31. Daly C, Neilson RP & Phillips DL A statistical-topographic model for mapping climatological precipitation over mountainous terrain. Journal of Applied Meteorology 33, 140–158 (1994).
32. Luce CH, Lopez-Burgos V & Holden Z Sensitivity of snowpack storage to precipitation and temperature using spatial and temporal analog models. Water Resources Research 50, 9447–9462 (2014).
33. Lehner F, Wahl ER, Wood AW, Blatchford DB & Llewellyn D Assessing recent declines in Upper Rio Grande runoff efficiency from a paleoclimate perspective. Geophysical Research Letters 44, 4124–4133 (2017).
34. Cline DW, Bales RC & Dozier J Estimating the spatial distribution of snow in mountain basins using remote sensing and energy balance modeling. Water Resources Research 34, 1275–1285 (1998).
35. Dressler K, Fassnacht S & Bales R A comparison of snow telemetry and snow course measurements in the Colorado River basin. Journal of hydrometeorology 7, 705–712 (2006).
36. Musselman KN, Molotch NP & Margulis SA Snowmelt response to simulated warming across a large elevation gradient, southern Sierra Nevada, California. The Cryosphere 11, 2847 (2017).
37. Sun F, Hall A, Schwartz M, Walton B, D. & Berg N Twenty-First-Century Snowfall and Snowpack Changes over the Southern California Mountains. Journal of Climate 29, 91–110, doi:10.1175/jcli-d-15-0199.1 (2016).
38. Howat IM & Tulaczyk S Climate sensitivity of spring snowpack in the Sierra Nevada. Journal of Geophysical Research: Earth Surface 110 (2005).
39. Mote PW Climate-Driven Variability and Trends in Mountain Snowpack in Western North America*. Journal of Climate 19, 6209–6220, doi:10.1175/jcli3971.1 (2006).
40. Harpold AA et al. Soil moisture response to snowmelt timing in mixed-conifer subalpine forests. Hydrological Processes 29, 2782–2798 (2015).
41. Henn B, Musselman KN, Lestak L, Ralph FM & Molotch NP Extreme runoff generation from atmospheric river driven snowmelt during the 2017 Oroville Dam spillways incident. Geophysical Research Letters 47, e2020GL088189 (2020).
42. Berghuijs WR, Woods RA, Hutton CJ & Sivapalan M Dominant flood generating mechanisms across the United States. Geophysical Research Letters 43, 4382–4390 (2016).
43. Brooks PD, Williams MW & Schmidt SK Microbial activity under alpine snowpacks, Niwot Ridge, Colorado. Biogeochemistry 32, 93–113 (1996).
44. Edwards AC, Scalenghe R & Freppaz M Changes in the seasonal snow cover of alpine regions and its effect on soil processes: a review. Quaternary international 162, 172–181 (2007).
45. Shukla S & Lettenmaier D Seasonal hydrologic prediction in the United States: understanding the role of initial hydrologic conditions and seasonal climate forecast skill. Hydrology & Earth System Sciences 15 (2011).
46. Harpold AA, Sutcliffe K, Clayton J, Goodbody A & Vazquez S Does including soil moisture observations improve operational streamflow forecasts in snow-dominated watersheds? JAWRA Journal of the American Water Resources Association 53, 179–196 (2017).
47. Koch J et al. Inter-comparison of three distributed hydrological models with respect to seasonal variability of soil moisture patterns at a small forested catchment. Journal of hydrology 533, 234–249 (2016).

48. Günther D, Marke T, Essery R & Strasser U Uncertainties in snowpack simulations—Assessing the impact of model structure, parameter choice, and forcing data error on point-scale energy balance snow model performance. Water Resources Research 55, 2779–2800 (2019).
49. Pflug J, Liston G, Nijssen B & Lundquist J Testing model representations of snowpack liquid water percolation across multiple climates. Water Resources Research 55, 4820–4838 (2019).
50. Immerzeel WW et al. Importance and vulnerability of the world's water towers. Nature 577, 364–369 (2020). [PubMed: 31816624]

Methods References

51. Serreze MC, Clark MP, Armstrong RL, McGinnis DA & Pulwarty RS Characteristics of the western United States snowpack from snowpack telemetry (SNOTEL) data. Water Resources Research 35, 2145–2160 (1999).
52. Trujillo E & Molotch NP Snowpack regimes of the Western United States. Water Resources Research 50, 5611–5623, doi:10.1002/2013WR014753 (2014).
53. Gilbert RO Statistical methods for environmental pollution monitoring. (John Wiley & Sons, 1987).
54. Mann HB Nonparametric tests against trend. Econometrica: Journal of the Econometric Society, 245–259 (1945).
55. Kendall MG Rank correlation methods. (Charles Griffin & Co. Ltd., London, 1948).
56. Yue S & Pilon P A comparison of the power of the t test, Mann-Kendall and bootstrap tests for trend detection/Une comparaison de la puissance des tests t de Student, de Mann-Kendall et du bootstrap pour la détection de tendance. Hydrological Sciences Journal 49, 21–37 (2004).
57. Sen PK Estimates of the regression coefficient based on Kendall's tau. Journal of the American statistical association 63, 1379–1389 (1968).
58. Lettenmaier DP, Wood EF & Wallis JR Hydro-climatological trends in the continental United States, 1948–88. Journal of Climate 7, 586–607 (1994).
59. Martel J-L, Mailhot A, Brissette F & Caya D Role of natural climate variability in the detection of anthropogenic climate change signal for mean and extreme precipitation at local and regional scales. Journal of Climate 31, 4241–4263 (2018).

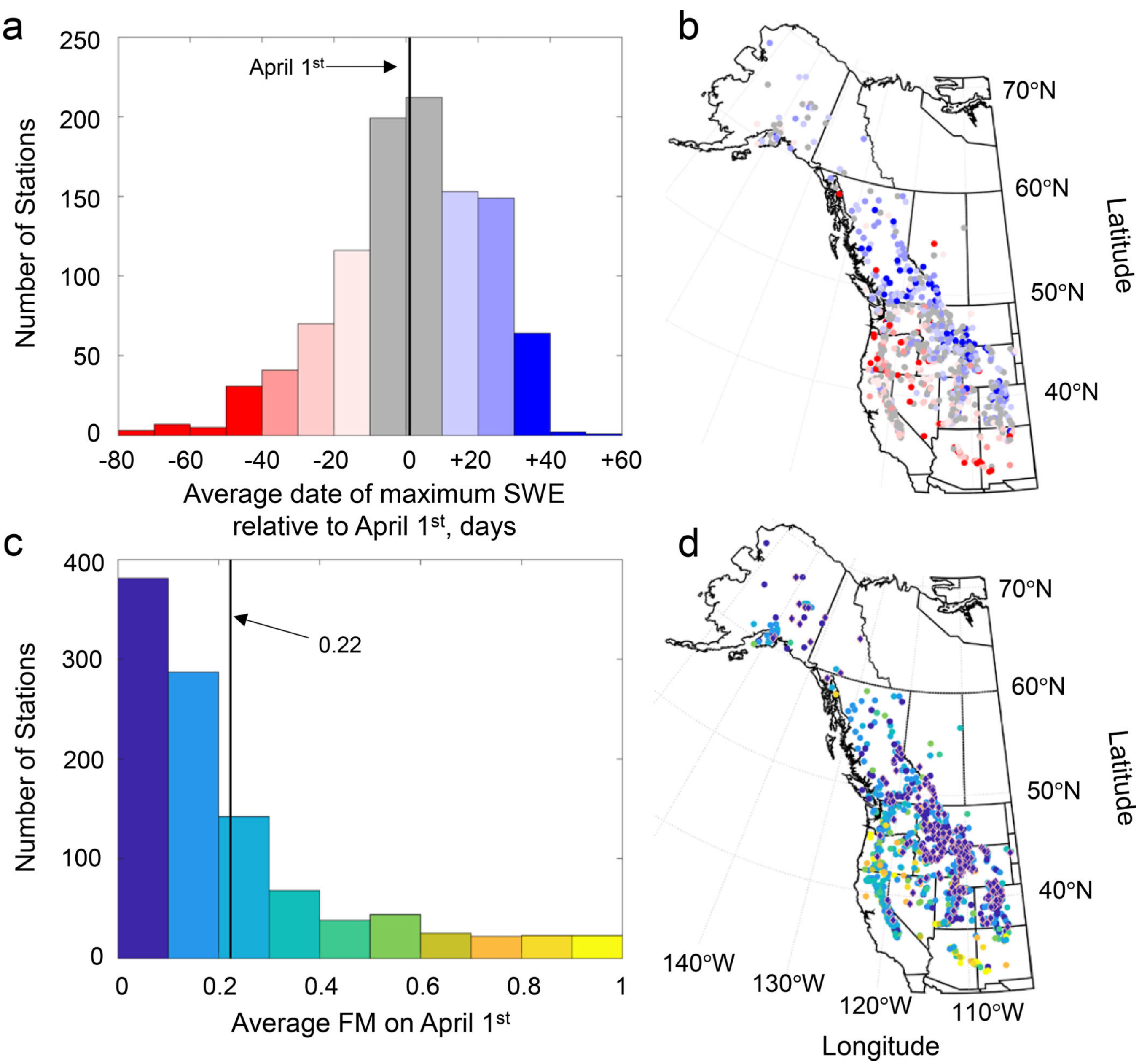

Figure 1 |. On average across western North American stations, snowpack reaches an annual maximum on April 1st when 78% of annual snow has yet to melt.

A (a) histogram and (b) map of the average (Oct. 1960 – Sep. 2019) date of maximum SWE relative to April 1st as measured at 1,065 snowpack telemetry stations (circle symbols) in western North America. The symbol colors in (b) correspond to the values shown in the x-axis of the histogram in (a). (c) and (d) show the average fraction of cumulative annual melt on April 1st as in (a) and (b), respectively. The average values of all sites and station-years are indicated in (a) and (c) by the vertical line. In (d), highlighted diamond-shaped markers indicate stations with FM on April 1st ≤ 0.05.

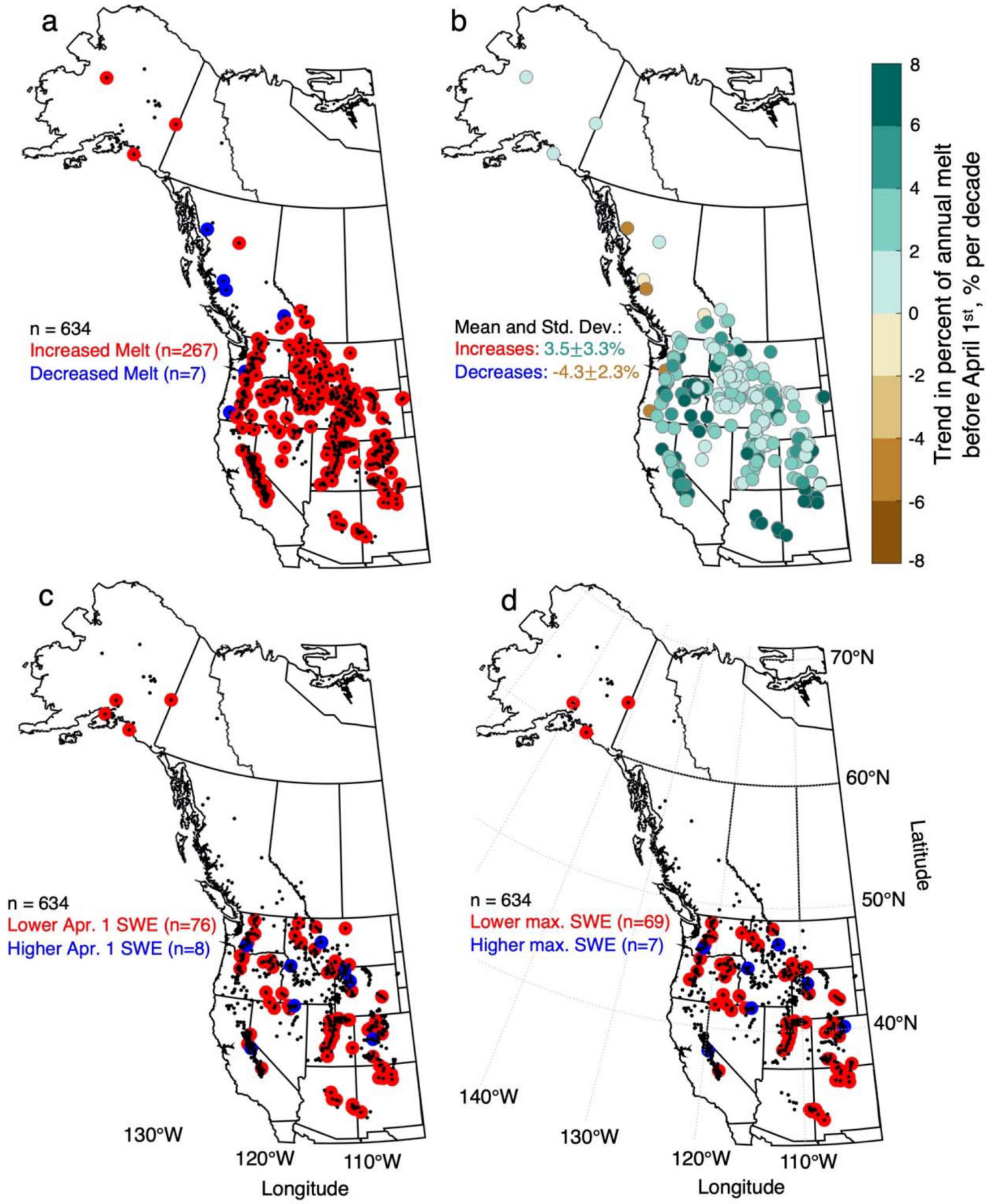

Figure 2 |. Trends toward more melt before April 1st are three-times more widespread than trends toward lower April 1st SWE or maximum annual SWE.

Snowpack telemetry stations with data records ≥ 30 years (small points; n=634) that have statistically significant ($p \leq 0.05$; colored circles) historical trends (see text color in legends) in (a) the fraction of cumulative annual melt that has occurred by April 1st (the corresponding rate of melt change is mapped in (b)), (c) the magnitude of April 1st SWE and (d) the magnitude of annual maximum SWE.

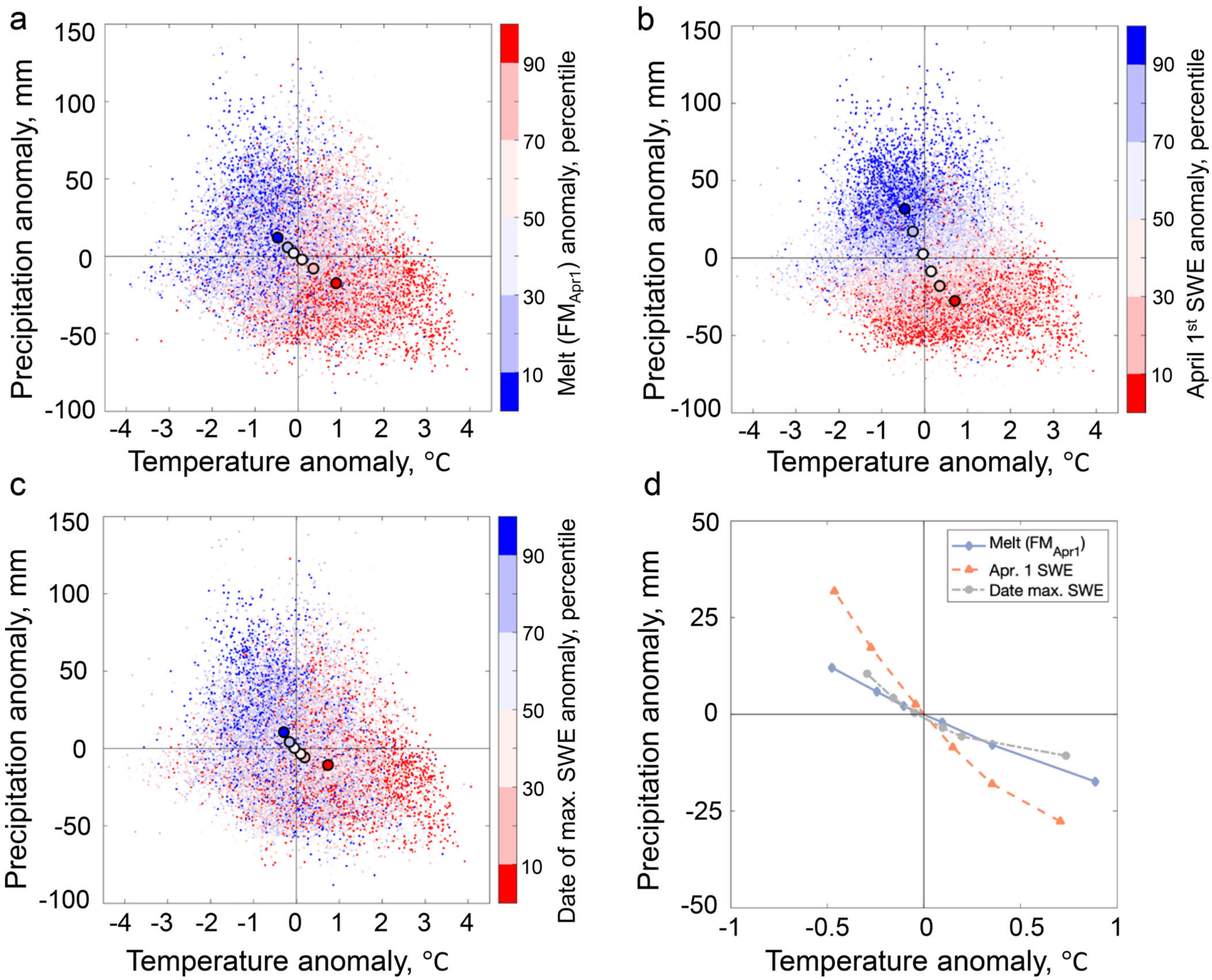

Figure 3 |. Snowmelt is more sensitive to temperature whereas SWE is more influenced by precipitation.

The axes of each panel indicate anomalies in NDJFM precipitation (y-axis) and temperature (x-axis) from PRISM at U.S. snowpack telemetry sites relative to the long-term (1979 to 2019) mean values. The anomalies in (a) FM on April 1st, (b) April 1st SWE, and (c) date of maximum SWE are shown as percentiles using colors. Larger circles indicate the centroid for the percentile classes for each of six color categories (see color bars). (d) Centroids for each snow metric (from a-c; see legend).

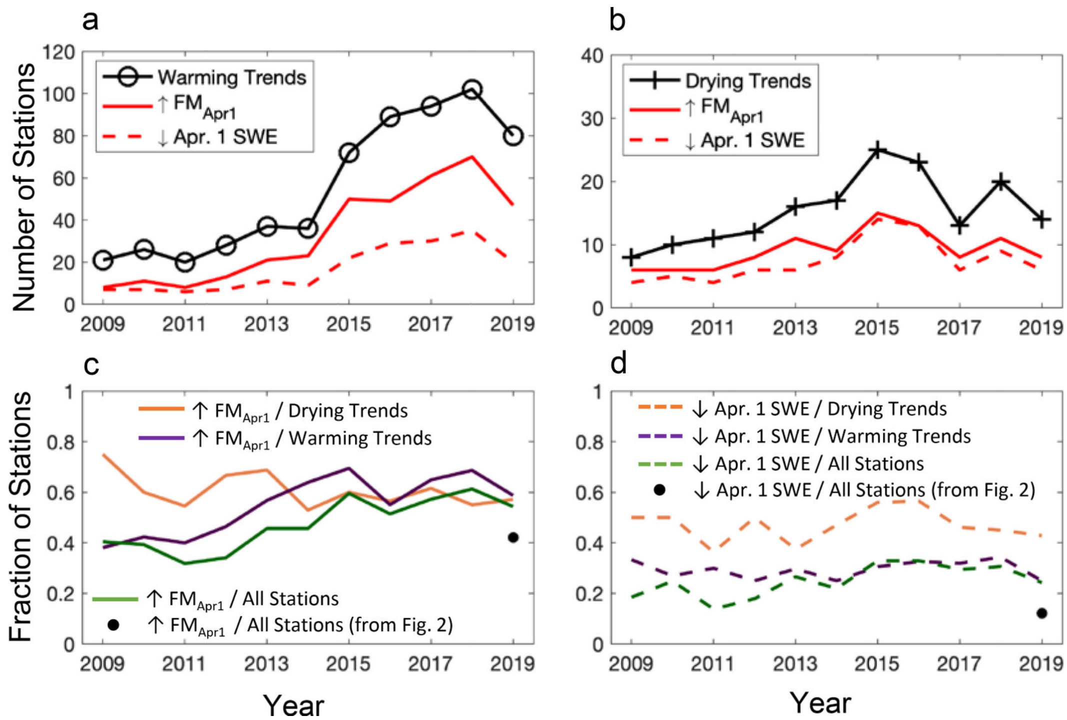

Figure 4 |. The increasing number of stations with melt is explained by widespread, long-term warming while SWE declines are more sensitive to precipitation variability.

Historical trend analyses conducted each year based on information to date showing the number of long-term (40+ yr.) stations with significant ($p \leq 0.05$) a) warming and b) drying trends from PRISM (NDJFM averages) and, of those subset stations, the corresponding number of stations with trends in melt and April 1st SWE (see legends). Note the scale difference between y-axes. The number of stations with decreases in melt or increases in April 1st SWE is negligible; stations with no trends can be inferred from the difference between the black and red lines. The fraction of stations with warming and drying trends that also have trends in c) melt and d) April 1st SWE trends. Also plotted are the fractions of stations with snow trends relative to all subset stations (green lines) and all North American stations as of 2019 shown in Fig. 2 (black circles)