Midwinter dry spells amplify post-fire snowpack decline

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November 16, 2022

Abstract

Increasing wildfire and declining snowpacks in mountain regions threaten water availability. We combine satellite-based fire detection with snow seasonality classifications to examine fire activity in California's seasonal and ephemeral snow areas. We find a nearly tenfold increase in fire activity during 2020 and 2021 compared to 2001-2019 as measured by satellite data. Accumulation season snow albedo declined 17-77% in two burned sites as measured by in-situ data relative to un-burned conditions, with greater declines associated with increased soil burn severity. By enhancing snowpack susceptibility to melt, decreased snow albedo drove mid-winter melt during a multi-week midwinter dry spell in 2022. Despite similar meteorological conditions in 2013 and 2022, which we link to persistent high pressure weather regimes, minimal melt occurred in 2013. Post-fire differences are confirmed with satellite measurements. Our findings suggest larger areas of California's snowpack will be increasingly impacted by the compounding effects of dry spells and wildfire.

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Key Points:

- A factor of 9.8 increase in satellite-based fire detections are observed in California's snow zones in 2020-2021 compared with 2001-2019.
- Measured accumulation season snow albedo declined 25-71% with these reductions driving decreased snow covered days and snow cover fraction.
- Compared with a meteorologically similar 2013 dry spell, snow albedo declines led to rapid midwinter melting in post-fire environments.

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Plain Language Summary

Satellite fire detections indicate substantial increases in wildfire activity in California's snow-covered landscapes during 2020 and 2021, suggesting wildfire is increasingly altering mountain hydrology. During 2022, an multi-week mid-winter drought, or dry spell, occurred. A meteorologically-similar dry spell occurred in 2013, and the 2022 event provides a test case to examine how post-fire changes (canopy loss and deposition of burned dark material on snowpack) alter snowmelt patterns. Using field observations, weather station data, and satellite remote sensing of snow, we find large reductions in snow albedo drove rapid melt during the 2022 dry spell in burned areas whereas during 2013, minimal melt occurred. Our findings motivate additional research into assessing and planning for post-fire hydrologic changes in snow-dominated landscapes as both wildfire and dry spells will increase in frequency with climate warming.

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1 Introduction

Communities and ecosystems worldwide rely on snowpack to meet water demands (Immerzeel et al., 2020). A warming climate changes the spatial patterns and timing of snowpack accumulation and melt via alterations to rain-snow partitioning, decreases in cold content, extended dry spells, and extreme precipitation events (Lynn et al., 2020; Gershunov et al., 2019; Siirila-Woodburn et al., 2021). During the dry season, reduced snowpack combined with warming and drying enhances evaporative demand (Abatzoglou & Williams, 2016; Alizadeh et al., 2021) and lowers fuel moisture (McEvoy et al., 2019).

A warming, drying, and disturbance-prone climate combined with fire suppression promotes severe wildfire at higher elevations in the western U.S. (Millar & Stephenson, 2015; Alizadeh et al., 2021). From 1984-2017, a 9% increase per year in area burned in the seasonal snow zone (Gleason et al., 2019) has been accompanied by a 7.6 myr^{-1} upslope increase in average wildfire elevation (Alizadeh et al., 2021). High burn severity areas also increased during these decades (Parks & Abatzoglou, 2020).

Severe fires alter mountain snowpack processes near and below the treeline in two key ways. First, the burned canopy increases incoming solar radiation and black carbon sourced from burned vegetation reduces snow albedo, which together, accelerate snowmelt rates by up to 57% (Gleason et al., 2013; Kaspari et al., 2015; Gleason & Nolin, 2016; Gleason et al., 2019; Skiles et al., 2018; Aubry-Wake et al., 2022). Second, the decrease in forest canopy reduces interception. Every 20% increase in tree mortality increases below-canopy snow accumulation by 15% (Maxwell & Clair, 2019). In the absence of fire, reduced canopy shifts the timing of peak snowpack later (Cristea et al., 2014).

Additional wildfire impacts on mountain hydrology include changes in soil hydraulic properties (Ebel & Moody, 2017), shifts in surface and subsurface water partitioning and flow pathways that increase water yields (Maina & Siirila-Woodburn, 2020), as well as interactions between forest structure, snow, and fire effects (e.g., Moeser et al., 2020; Wilson et al., 2021). By altering the snow-vegetation-hydrology dynamics, severe fire in montane forests threatens ecosystems and the volume of snowpacks (Stevens, 2017; Gleason et al., 2019; Siirila-Woodburn et al., 2021). While it is well-documented that spring snowmelt rates increase after wildfire (e.g., Gleason et al., 2019; Uecker et al., 2020), the mid-winter impacts remain understudied.

Our work is motivated by two recent phenomena adversely affecting California's snow hydrology: widespread severe wildfires of 2020-2021 reaching into the seasonal snow zone of mountain watersheds (Figure 1) and the multi-week, midwinter dry spell during the winter of 2022. We examine how the post-fire environment during the unusually dry conditions amplified snowmelt rates. We hypothesize fire-impacted regions undergo declines in midwinter snow albedo that drive more rapid and earlier snowmelt compared with pre-fire or unburned conditions.

2 Methods

2.1 Satellite Fire Detection in Seasonal and Ephemeral Snowpacks

In-situ wildfire activity is difficult to quantify. Satellite-based fire detection is a useful proxy for generally assessing wildfire activity by providing consistent overflight return intervals across multiple years (Justice et al., 2002). We acquired daily fire detections at 1 km horizontal resolution from the MODerate resolution Imaging Spectroradiometer (MODIS) via the FIRMS database (`https://firms.modaps.eosdis.nasa.gov/download/`) for the period spanning January 2001 to December 2021. We subset all Californian fire detections into seasonal, ephemeral, and non-snow environments based on the concept of snow seasonality (Petersky & Harpold, 2018; Hatchett, 2021): the duration of time a landscape is continuously snow-covered. To assess seasonality, we applied the snow classifiers to a gridded, 4-km horizontal resolution, daily snow water equivalent (SWE) product (Zeng et al., 2018; Broxton et al., 2019) across California. Seasonal snowpacks are defined as gridcells with an annual median of more than 60 days of continuous snow cover spanning 1982–2018. Ephemeral snowpacks are defined as gridcells with intermittent (i.e., $>$ 60 days of continuous) snow cover.

2.2 Snow Remote Sensing

Daily observations of snow surface properties from the vicinity of the Caldor Fire from Terra MODIS are available from a collaboration between the National Snow and Ice Data Center and the Institute of Arctic and Alpine Research called Snow Today [`https://nsidc.org//snow-today`]. The website provides snow cover percent, snow cover days, snow albedo, as well as the reduction of snow albedo from light absorbing particles (LAP). Initial estimates of snow surface properties are based on the MODIS Snow Covered Area and Grain size model (MODSCAG, (Painter et al., 2009)) and the MODIS Dust Radiative Forcing in Snow model (MODDRFS, (Painter et al., 2012)). Data from the two models are combined to create spatially and temporally complete (STC) daily images that account for forest canopy, off-nadir viewing, and cloud mis-identification (Rittger et al., 2020). Snow cover errors from MODSCAG have been shown to be half the size of standard MODIS products (Rittger et al., 2013) and albedo estimates from STC-MODSCAG/MODDRFS show 5% RMSE with no bias (Bair et al., 2019). STC-MODSCAG/MODDRFS data has been previously used for SWE reconstruction (Rittger et al., 2016; Bair et al., 2016), real-time estimates of SWE (Bair et al., 2018), estimating trends in snow cover at regional scales (Ackroyd et al., 2021), understanding snow darkening related to LAP (Sarangi et al., 2019, 2020; Huang et al., 2022) and improving snow albedo modeling (Hao et al., 2022).

2.3 Albedo Measurements

Our study sites for snow albedo include the 2021 Caldor Fire (measured once in January 2022) and the 2020 Creek Fire (measured once in both February and April 2021; Figure 2a). These are two of the larger fires in California history–the Dixie Fire burned 389,900 ha between July and October 2021, and the Caldor Fire burned 89,800 ha between August and October 2021 [`https://www.fire.ca.gov/media/4jandlhh/top20_acres.pdf`]–and were notable as both crossed the hydrographic crest of the Sierra Nevada. Spectral albedo measurements were made using a Spectral Evolution RS-3500 Portable Spectroradiometer (RS-3500) equipped with a 180° field of view diffuser mounted on an extendable 1.2 m pole (Figure 2b). The RS-3500 has a spectral resolution of 1 nm over the spectral range 350-2500 nm. Measurements were made every 10 m along approximately flat terrain with one 100 m transect for each burn severity class: high, moderate, and unburned. Soil burn severity for each fire was determined using maps produced by the United States Department of Agriculture Forest Service Burned Area Emergency Response [`https://burnseverity.cr.usgs.gov/products/baer`] using field-checked, remotely-sensed pre- and post-fire visible reflectances (Key & Benson, 2006).

2.4 Snowpack and Meteorological Observations

We used station-based observations of SWE, precipitation and solar radiation to examine the impacts of wildfire in burned and unburned areas. Daily SWE observations (1 October 2011–15 April 2022) spanned the two mid-winter dry spells of interest from four stations in the California Cooperative Snow Survey Network (Rattlesnake, Robinson Cow Camp, Greek Store, and Alpha) and two stations from the Snowpack Telemetry Network (SNOTEL; Central Sierra Snow Laboratory and Echo Summit; Figure 2a). Two stations, Rattlesnake and Alpha, were burned in 2021 by the Dixie and Caldor Fires, respectively, but remained functional.

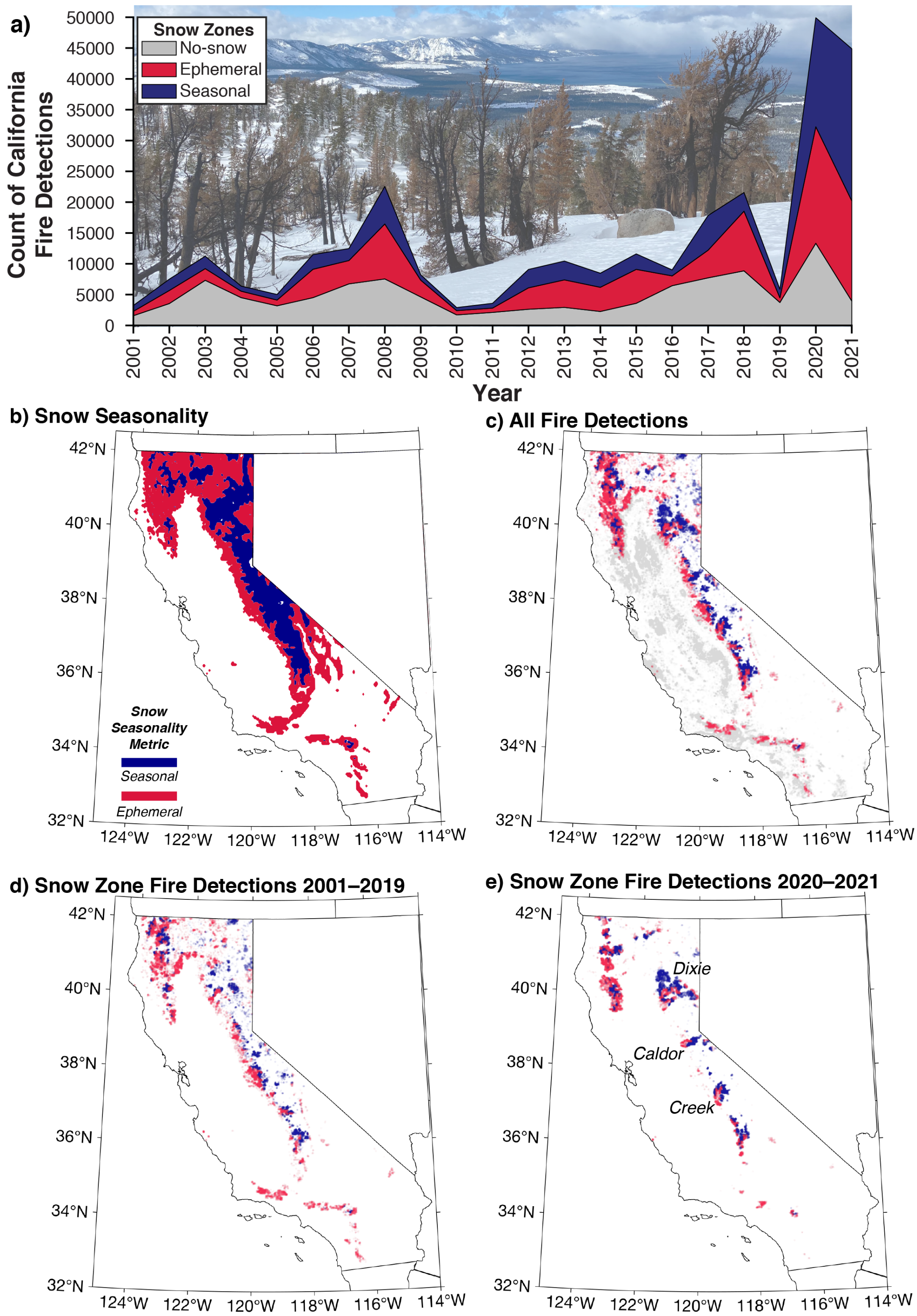

Figure 1. (a) Annual fire detections subset by snow seasonality (snow zone). (b) Snow seasonality classifications for California. (c) All fire detections (2001-2021). Fire detections during (d) 2001-2019 and (e) 2020-2021, noting fires named in the text.

To characterize the frequency of midwinter dry spells and place recent dry spells in a climatological context, we used daily precipitation data spanning 1 October 1917–15 April 2022 from the Tahoe City National Weather Service Cooperative Observation Program. Dry spells were defined as consecutive periods of time with no daily precipitation exceeding 2.54 mm between October and April.

2.5 Weather Regimes

To provide a synoptic-planetary perspective and compare atmospheric circulation patterns during the two dry spell winters, we used the weather regime catalog of Guirguis et al., which evaluates the daily joint phase relationships between four regionally important modes of atmospheric variability (Guirguis et al., 2020). We extended this product to include the winter of 2021–2022. We focus on the days of the dry spell period (30 December to 18 February) shared between the two years.

3 Results

3.1 Fire activity increased in seasonal and ephemeral snow zones

Fire detections show peaks during singular years (2008, 2018) or groups of years (2012–2016, 2020–2021; Figure 1a) across California's seasonal and ephemeral snow zones (Figure 1b). In 2020 and 2021, an abrupt increase in fire detections in the snow zones occurred. ∼50% of total 2001-2021 fire detections in seasonal snow zones and ∼35% in ephemeral snow regions occurred in 2020-2021. A factor of 9.8 increase in mean annual fire detections in the seasonal snow zone occurred in 2020-2021 compared with the 2001-2019 average. Fire activity in snow zones was widespread throughout 2001-2021 (Figure 1c), with a broad distribution of fire occurrence prior to 2020 (Figure 1d). However, very large fires including the Dixie, Caldor, and Creek Fires, as well as fire complexes elsewhere, during 2020 and 2021 clustered fire detections in snow zones (Figure 1e).

3.2 Snow albedo declines following wildfire

Snow albedo measurements in both the accumulation season (January and February) and the ablation season (April) show time-dependent decreases in snow albedo (Figure 2c). Decreases in the visible portion of the spectrum (0.4–0.7 μm) ranged from 17-31% (moderate severity) and 45-49% (high severity) compared to unburned during the accumulation season. In April, high burn severity areas showed a snow albedo decrease of 60% compared to unburned areas. For the NIR (0.7–2.5 μm), accumulation season declines ranged between 31 to 69% (moderate severity) to 47 to 77% (high severity). When comparing moderate to high severity burned areas, April albedo decreased by 34% in the NIR compared to 11% in the visible wavelengths. The opposite occurred in January where NIR decreased by 10% while the visible decreased by 34%. We note that the decreased albedo in the visible wavelengths is mainly due to light absorption by black carbon (Wiscombe & Warren, 1980; Warren, 1982), while decreased albedo in the near-infrared wavelengths is likely due to a combination of increased grain size and light absorption by black carbon (Wiscombe & Warren, 1980; Warren, 1982; Skiles & Painter, 2019). Unlike dust, which has primary absorption in the visible wavelengths (He et al., 2019), black carbon is a "gray" absorber and can absorb throughout the solar spectrum. Translating measured snow albedo changes to net radiation using the Beer-Lambert Law indicates post-fire increases in net radiation from 0.931 Wm^2 (unburned) to 40.3 Wm^2 (high severity) during January and from 27.7Wm^2 (unburned) to 161 Wm^2 (high severity) during April (Koshkin, 2022).

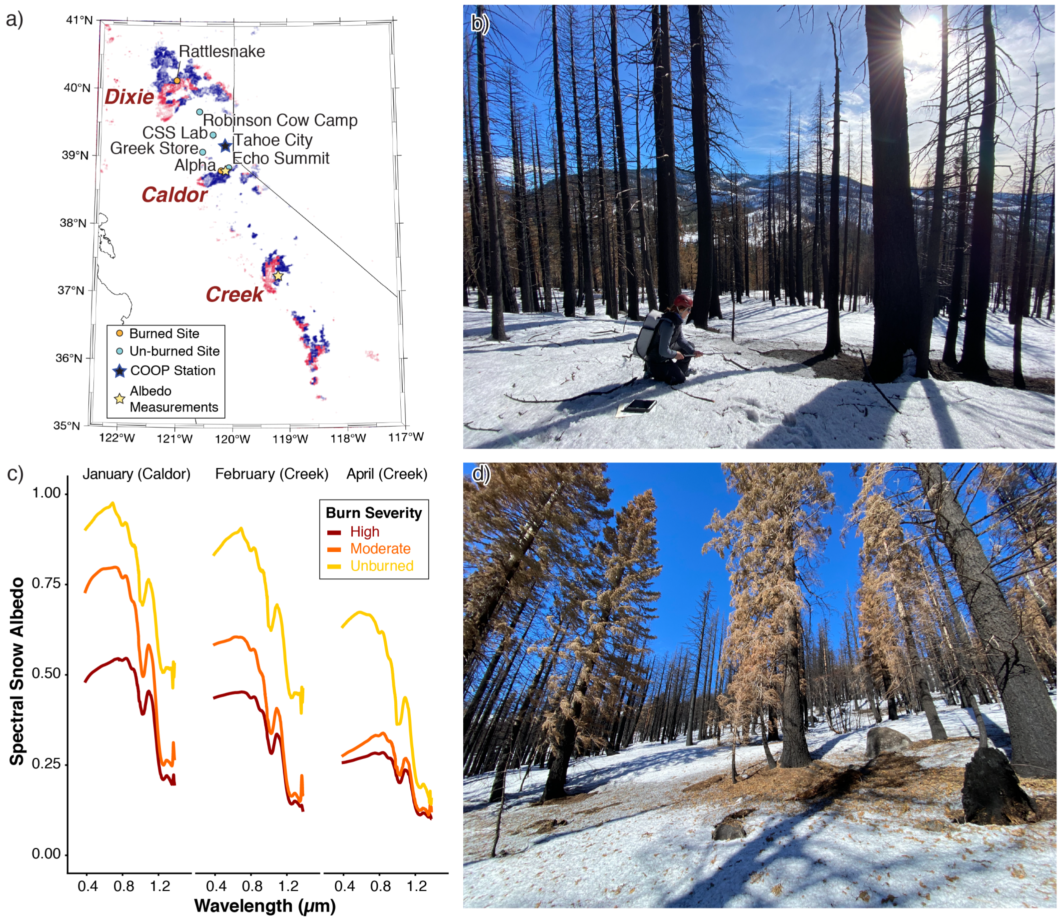

Figure 2. (a) Map of stations and sample locations with fire names. (b) Albedo measurements collection from high burn severity forest during January in the Caldor Fire. (c) Changes in spectral snow albedo for unburned (gold), moderate burn severity (orange) and high burn severity (red) during January (Caldor February (Creek Fire) and April (Creek Fire). (d) Foreground shows burned debris deposited onto the snow surface.

3.3 Rapid snowmelt during a dry spell following wildfire

The long-term median midwinter dry spell at Tahoe City is 22 days. During water year (WY) 2022, Tahoe City experienced its second-longest midwinter dry spell (46 days). With observations beginning in 1917, three of the five longest midwinter dry spells have occurred since WY2011, including WY2015 (third longest with 43 days), WY2022 (second with 46 days), and the record-setting WY2012 (60 days). Although WY2013 (tied for 11th with 36 days) did not experience as prolonged a midwinter dry spell as WY2022, the well-below average precipitation following a wet start to the water year provides an object lesson year for comparison. In both WY2013 and WY2022, heavy precipitation during October-December produced substantial early season snowpacks (338–770 mm SWE), but were followed by persistent well-below average precipitation (Figure 3a) and similar radiation. Compared with WY2013, 5% more accumulated solar radiation occurred during WY2022 between 28 December–18 February period at the Red Baron RAWS (adjacent to the Caldor Fire) but approximately equal radiation between 28 December–1 March (Figure S1).

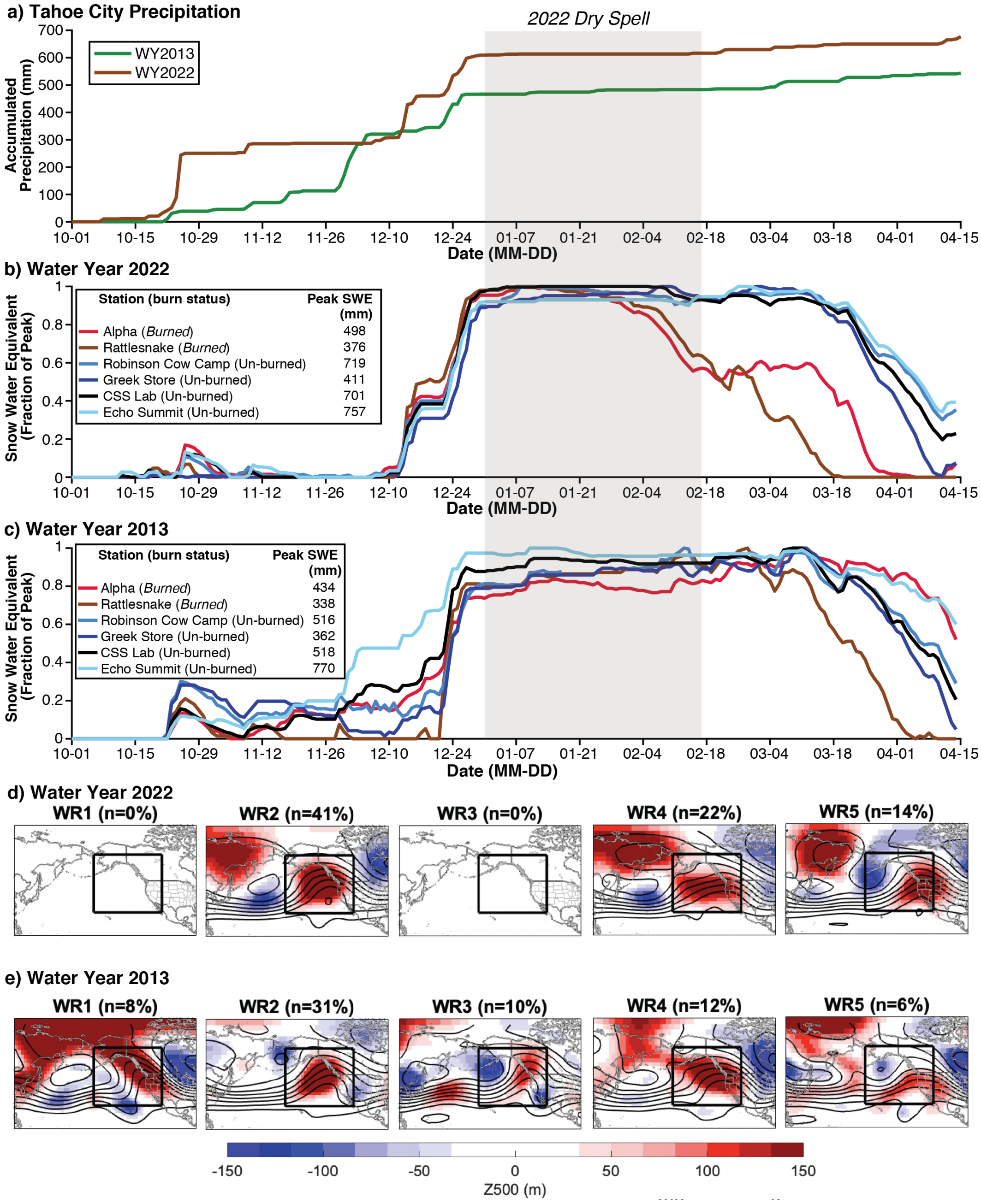

Figure 3. (a) Accumulated precipitation at Tahoe City during WY2013 and WY2022. (b) Snow water equivalent (SWE) as a fraction of peak SWE during water year (WY) 2022. (c) As in (b) but for WY2013. Primary dry weather regimes (WR) and their frequency during the dry spells of December 30-February 18 of (d) WY2022, and (e) WY2013.

SWE declined faster at the two burned sites, Alpha and Rattlesnake, compared to the unburned sites during WY2022's dry spell (Figure 3b). In contrast, all stations behaved similarly during the WY2013 dry spell (Figure 3c), though Rattlesnake began melting in mid-March. Compared to the date of maximum SWE, the SWE at unburned sites declined by 0-4 percentage points in WY2013 and 0-8 percentage points in WY2022 over the course of the dry period. During WY2013, Alpha and Rattlesnake declined by 2-9 percentage points during the dry spell. However, in WY2022 after the wildfire, these stations declined 41-45 percentage points, consistent with enhanced net shortwave radiation loading in burned environments (Figure 2). After a small precipitation event on 18 February 2022, snowpack continued to decline at Rattlesnake but remained consistent at Alpha before declining in late March. Compared to WY2013, snow at both Alpha and Rattlesnake disappeared earlier during WY2022 (Figure 3b-c).

3.4 Midwinter dry spell weather regimes

Analysis of weather regimes (WR; (Guirguis et al., 2022) reveals broad similarities between WY2013 and WY2022 during the midwinter dry spells (Figure 3d-e) but also throughout the accumulation season (Figure S2).The bulk of the snow accumulation in December during both years was associated with wet weather regimes (Figures S2 and S3), which favor anomalously wet conditions over California and anomalous positive snowpack accumulation in the Central Sierra Nevada (Guirguis et al., 2022). Beginning in late December (WY2013) or early January (WY2022) a WR shift occurred bringing atmospheric ridging conditions over/offshore from California (Figure S2).Similar dry-type WRs but with varying frequencies occurred during the respective dry spells (Figure 3d-e). The cessation in SWE accumulation is associated with the onset and persistence of WRs favoring persistent high pressure ridging bringing about mid-winter drought conditions (Figure 3d-e). The ridging patterns were more persistent during WY2022 (Figure 3d). WY2013 was more variable with short-lived weather pattern changes allowing for small snow accumulation events (Figure 4b). These events appear as intermittent breakdowns of the ridging patterns and development of patterns (e.g., WR3) producing weak onshore flow (Figure 3e).

3.5 Snow remote sensing indicates post-fire snowpack decline

Despite similar conditions in snowpack at the beginning of each dry spell (Figure 3b-c) and generally similar meteorological conditions (Figure 3d-e and S2), remote sensing shows widespread rapid post-wildfire snowmelt throughout the accumulation and melt seasons within the Caldor Fire perimeter (Figure 4). Snow covered area declined faster during during January and February WY2022 compared to WY2013 (Figure 4a), with 50% less snow cover at the end of the dry spell in WY2022. Albedo resets following snowfall were more common in WY2013 than WY2022 (Figure 4b), with 2022 demonstrating the lowest basin-average snow albedos on record in early February. Consistent with lower albedo (Figures 2c and 4b), melt occurred faster after storms in WY2022 compared to WY2013 (Figure 4a). Impacts within the fire perimeter are clear with more than 50 days less snow cover days by the end of April (Figure 4c), making WY2022 the year with the lowest snow cover days in the MODIS record. Dry conditions during November (Figure 3a) and melt-out of October snowfall (Figure 3b) contributed to the initially (1 January) low cumulative days of snow cover in WY2022 (Figure 4c). In contrast, WY2013 was near-to-above average in terms of snow cover days until late April (Figure 4c).

Spatial comparisons for February mean snow cover fractions show WY2013 had near-to-slightly below the 2001-2022 mean, whereas WY2022 had well-below mean snow cover fractions within the Caldor Fire perimeter (and Tamarack Fire perimeter; Figure 4d-e). By 1 March, snow cover days were 20-50 days below average only in the lowest elevation (western-most) regions during WY2013 whereas strong correspondence between anomalous below-mean snow cover days and the Caldor fire perimeter occur during WY2022 (Figure 4f-g). These differences increased as the season progressed (Figure S4).

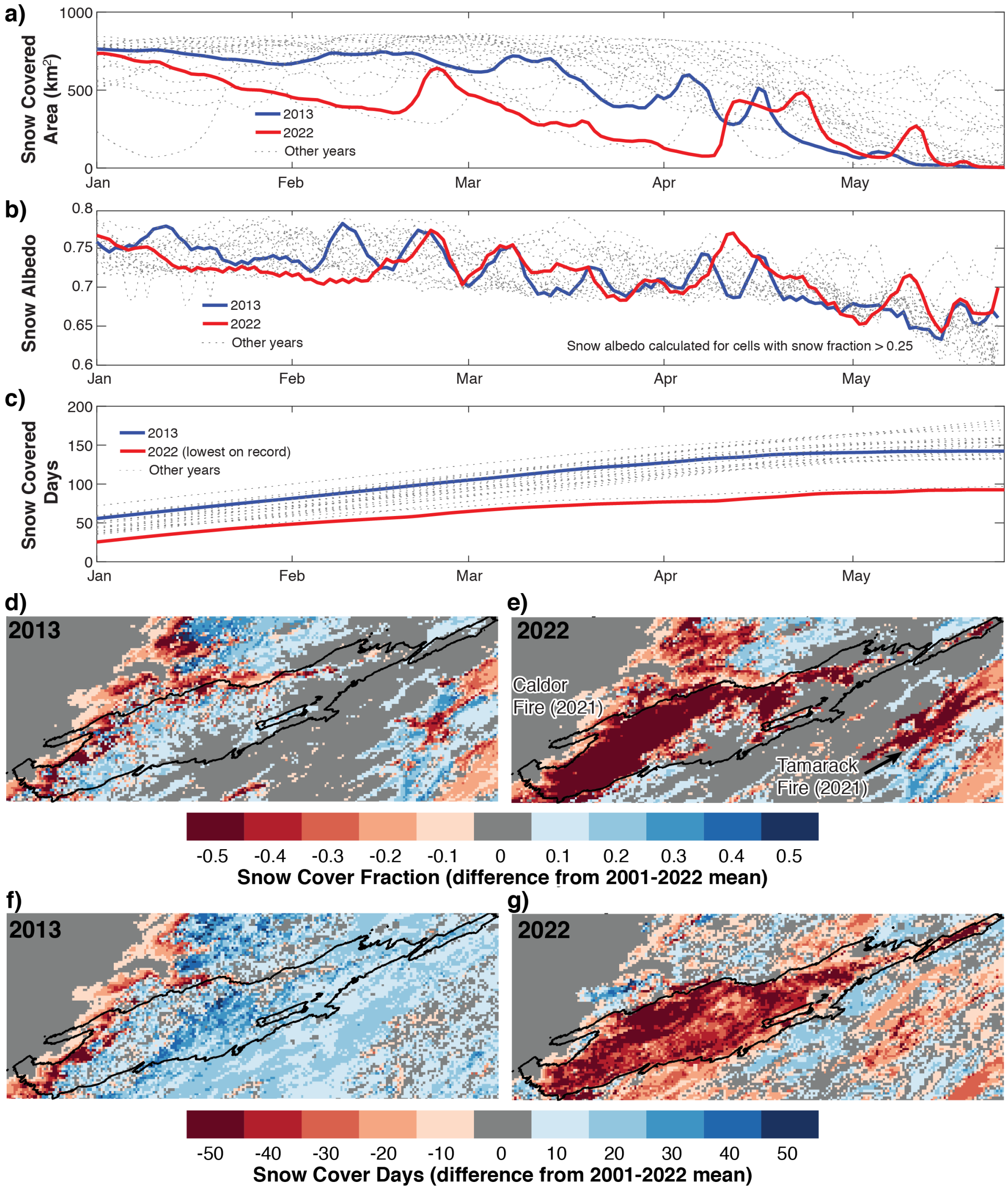

Figure 4. (a) Snow covered area (km^2) for Caldor Fire perimeter between 1 January and 31 May for WYs 2001-2022 (light dashed lines) with WY2013 and WY2022 shown as thick blue and lines respectively. (b) As in (a) but for snow albedo. (c) As in (a) but for snow covered days. February snow cover fractions, as differences from 2001-2022 mean for (d) WY2013 and (e) WY2022. End of February snow cover days (cumulative from 1 October), as differences from 2001-2022 mean for (f) WY2013 and (g) WY2022.

4 Discussion

Wildfires in seasonal and ephemeral snow zones are expected. Our identified abrupt, near-10-fold increase in fire activity during 2020-2021 in California's snow zones relative to the previous 18 years (Figure 1) is embedded in an increasing trend in California wildfire activity (Alizadeh et al., 2021; Gleason et al., 2019).Conditions conducive to large, severe fires will increase as the climate warms (Abatzoglou & Williams, 2016; Gutierrez et al., 2021; Williams et al., 2019) and becomes more volatile (Gershunov et al., 2019). This implies future fire activity in snow zones will more frequently resemble 2020 and 2021.

In moderate to high severity burned areas, the albedo decreases and canopy removal (Figure 2b-d) combined to enhance snowmelt during midwinter dry spells (Figure 3c) leading to reductions in snow covered area (Figure 4c). Similar results associated with local and long-range transport and deposition of fire-generated LAPs occurs in seasonally snow-covered regions (Gleason et al., 2019; Uecker et al., 2020) and glacial environments (Aubry-Wake et al., 2022). However, those studies focused on the ablation season rather than the accumulation season. Our results indicate strong potential for enhanced post-fire midwinter melt under persistent high pressure (Figure 3d).

The wavelength dependence of snow albedo reductions (Figure 2c) suggests impurities are a more dominant control on albedo changes compared to snow grain size during the accumulation season when snowpacks are colder and grain growth is slower (Colbeck, 1982). During the melt season, wet snow causes rapid grain growth (Colbeck, 1982), and these increases in grain size strongly decrease snow albedo in the near-infrared wavelengths (Warren, 1982). Also during the melt season, the concentration of LAPs decreases snow albedo in the visible wavelengths (Warren, 1982; Sterle et al., 2013). The combined effect is a significant overall decrease in snow albedo across the solar spectrum. Similar to dust-on-snow (Skiles & Painter, 2019), in post-fire environments, radiative forcing-induced positive feedbacks likely occur between grain size growth, albedo decline from melt-driven LAP accumulation, and larger-scale land surface albedo decline as the land surface becomes snow-free (Huang et al., 2022; Koshkin et al., 2022).

Guirguis et al. (2022) found increasing frequencies of three midwinter dry patterns that parallel observed declines in California snowpack and water availability (Mote et al., 2018; Siirila-Woodburn et al., 2021). These same atmospheric circulation patterns are associated with the midwinter dry spells in WY2013 and WY2022. While both years demonstrate similar weather patterns to one another, WY2013 had slightly more active weather compared to WY2022 (Figure S2).This implies observed melt resulted predominantly from altered land surface conditions (e.g., burned canopy) rather than meteorological differences. It is also likely that feedbacks between grain size and snow albedo (Koshkin et al., 2022) further accelerated melt, especially at lower elevations (Figure 4j).

Amplified midwinter melt in burned areas during midwinter dry spells raises concern for hydrologic resources and hazards. Enhanced radiation-driven midwinter melt with greater snow accumulation (Maxwell & Clair, 2019) has the potential to elevate soil moisture earlier in the water year and make snowpacks more hydrologically active (Brandt et al., 2022). Additional soil moisture increases runoff efficiency and soil pore water pressures, leading to elevated runoff during rain-on-snow events and higher probabilities for shallow landslides.

Midwinter runoff affects reservoir operations as traditional regulatory frameworks may not allow for additional reservoir storage when flood risk reduction is the primary management concern (Maina & Siirila-Woodburn, 2020; Williams et al., 2022a). Moreover, higher rates of sediment influx from burned areas entering reservoirs (Sankey et al., 2017; Murphy et al., 2018) reduce water quality (Murpyh et al., 2012) and can damage infrastructure (Randle et al., 2021).

The compounding effects of post-fire impacts on snow and midwinter dry spells pose challenges for climate projections and operational forecasts. More frequent fire activity in snow zones and additional dry days are both expectations of a warming climate (Westerling, 2018; Polade et al., 2014; Hatchett et al., 2022). Midwinter snowpack loss may enhance intraseasonal climate variability towards drought by shifting peak SWE earlier and causing earlier snow disappearance (Gleason et al., 2019; Uecker et al., 2020; Smoot & Gleason, 2021) leading to drier late-season soil and vegetation conditions (Harpold & Molotch, 2015). Less efficient spring runoff in exchange for more efficient midwinter runoff (Maina & Siirila-Woodburn, 2020) may offsetting slower melt in unburned areas (Musselman et al., 2017). Skillfully predicting weather regimes associated with high-impact weather (anomalous wet or dry conditions) at subseasonal-to-seasonal scales provides lead-time to implement mitigation measures for altered hydrology (Guirguis et al., 2022). However, mitigation hinges upon skillful hydrologic forecasts. If post-fire effects on snow exacerbates emerging trends towards elevated runoff (Uzun et al., 2021; Williams et al., 2022b), direct updates of snow albedo to operational hydrologic models and improved parameterizations of fire-snow relationships in Earth system models is required (Hao et al., 2022).

5 Conclusions

The societal connection between mountains and humans will be strained as mountains face increasing climate-related stressors (Immerzeel et al., 2020). Midwinter drought, snow loss, and increasing wildfire are expectations of a warming world. Addressing these challenges requires innovative water and forest management paradigms (Millar & Stephenson, 2015; Sterle et al., 2019; Siirila-Woodburn et al., 2021). We identified abrupt increases in wildfire activity in California's snow zones that reduced snow albedo and accelerated melt during extended midwinter drought. To enhance water supply reliability, reduce flood hazards, and inform adaptation strategies–aspects impacted by wildfire's effects on mountain snowpacks–we recommend improving our process-based representation and inclusion of wildfire's impacts in the snow zone in short- and long-term operational hydrologic and Earth system models.

6 Open Research

MODIS fire detections are available from the NASA Fire Information for Resources Management System: `https://firms.modaps.eosdis.nasa.gov/`. Weather regime data (Guirguis et al., 2022) is available from the UCSD library digital collections at: `https://doi.org/10.6075/J089161B`. The University of Arizona Snow Water Equivalent Product is available from the NASA National Snow and Ice Data Center Distributed Active Archive Center at: `https://doi.org/10.5067/0GGPB220EX6A`. Station data is publicly available for SNOTEL stations from the United States Natural Resources Conservation Agency: `https://wcc.sc.egov.usda.gov/reportGenerator/` with RAWS data available from the Desert Research Institute: `https://raws.dri.edu`. The MODIS data is available from the Dryad repository at:

`https://datadryad.org/stash/share/xWCdmAowGgAjlyISPY9jirfiYmvm2bqTYNJz77mG-0E`; upon acceptance this link will be archived as: `https://doi.org/10.5061/dryad.7wm37pvx7`. Spectrometer data is available in the Supporting Materials.

Acknowledgments

BJH and AK were supported by the National Integrated Drought Information System under agreement 1332KP21DNEEN0006. AMR was funded by the Director, Office of Science, Office of Biological and Environmental Research of the U.S. Department of Energy Regional and Global Climate Modeling Program (RGCM) "the Calibrated and Systematic Characterization, Attribution and Detection of Extremes (CASCADE)" Science Focus Area (award no. DE-AC02-05CH11231) and the "An Integrated Evaluation of the

Simulated Hydroclimate System of the Continental US" project (award no. DE-SC0016605). KG and AG were funded by the U.S. Department of the Interior via the Bureau of Reclamation (USBR-R15AC00003, Seasonal to Sub-seasonal Predictability of Heat Waves over the Western US: Impacts on Snowpack) and via the Southwest Climate Adaptation Science Center. KR was funded by NASA grants 80NSSC18K0427 and 80NSSC22K0929. Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. government.

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Supporting Information for "Midwinter dry spells amplify post-fire snowpack decline"

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Additional Supporting Information (Files uploaded separately)

1. Caption for Dataset S1

Introduction The supporting information provides five figures (S1-S5) that utilize the data described in the main text to extend and further support the primary results of the study. The supporting dataset S1 presents the spectral albedo measurements collected from the Creek and Caldor Fires used in Figure 2 and discussed in the main text. Upon accceptance, Dataset S1 will be uploaded to a permanently available FAIR repository for public use.

Figure S1.

Figure S2.

Figure S3.

Figure S4.

Figure S5.

Dataset S1. Comma-separated value (.csv) file of spectral albedo measurements for the three measured transects presented in Figure 2 of the main text. Columns include ”ID”,”wavelength”,”Date”,”Albedo”,”month”,”burn”. The Creek Fire observations were performed in February and April and the Caldor Fire observations were performed in January. Burn severities were estimated using United States Forest Service Burned Area Emergency Response maps.

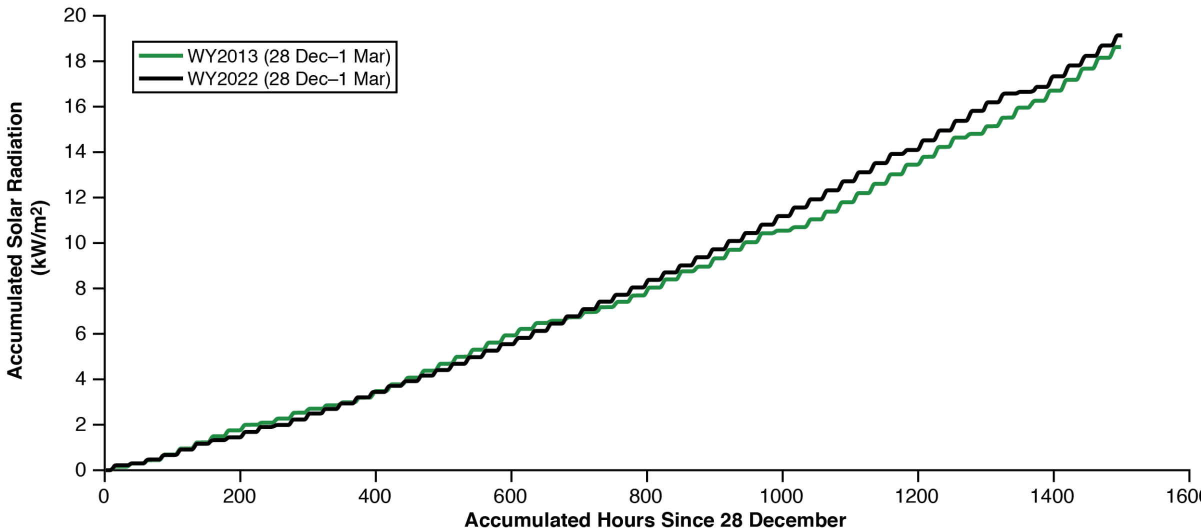

Figure S1. Accumulated hourly solar radiation (kWm^{-2}) from the Red Baron remote automated weather station (RAWS) for 28 December to 1 March period of WY2013 and WY2022. See Figure 2a for the location of the Red Baron RAWS. The total difference in accumulated radiation for the period is 5% higher during WY2022.

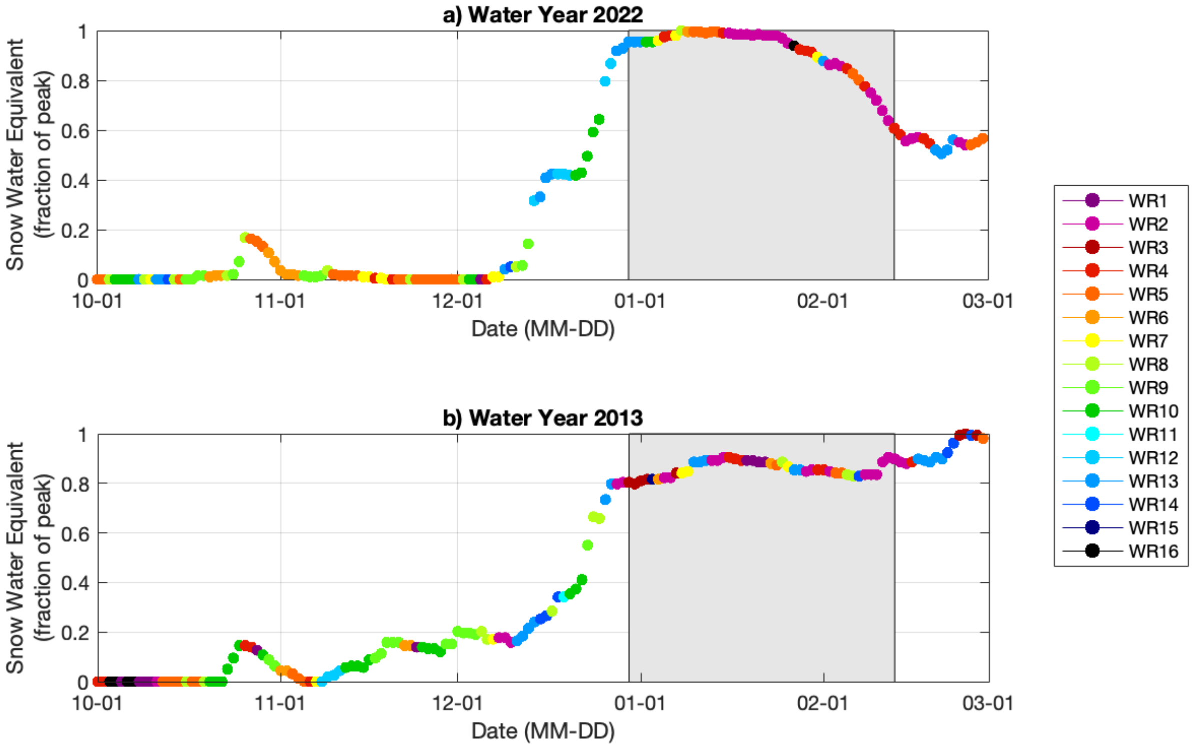

Figure S2. Seasonal evolution of snow water equivalent for the Alpha site, color-coded by the daily observed atmospheric weather regime to indicate the synoptic scale weather patterns driving snow accumulation and depletion. Grey shading highlights the December 30-February 18 dry-spell The mid-winter drought was brought about by a large-scale shift in atmospheric circulation that persisted throughout January and February. The bulk of the snow build-up that occurred in December during both years was associated with weather regimes 8-14 (shown as green or blue), with most accumulation brought by WR9, WR10 or WR12. These weather regimes, all identified by a deep trough positioned offshore from California (Figure S3), have previously been linked to historic atmospheric river landfalls and wet conditions over California, as well as snowpack in the Central Sierra Nevada (Guirguis et al. 2022). Beginning in late December (WY2013) or early January (WY2022) a weather regime shift occurred that brought atmospheric ridging conditions over/offshore from California. This is seen in Figure S3 as a cessation in SWE accumulation associated with the onset and persistence of weather regimes 1-5 (orange-red-pink markers) that brought about the mid-winter drought.

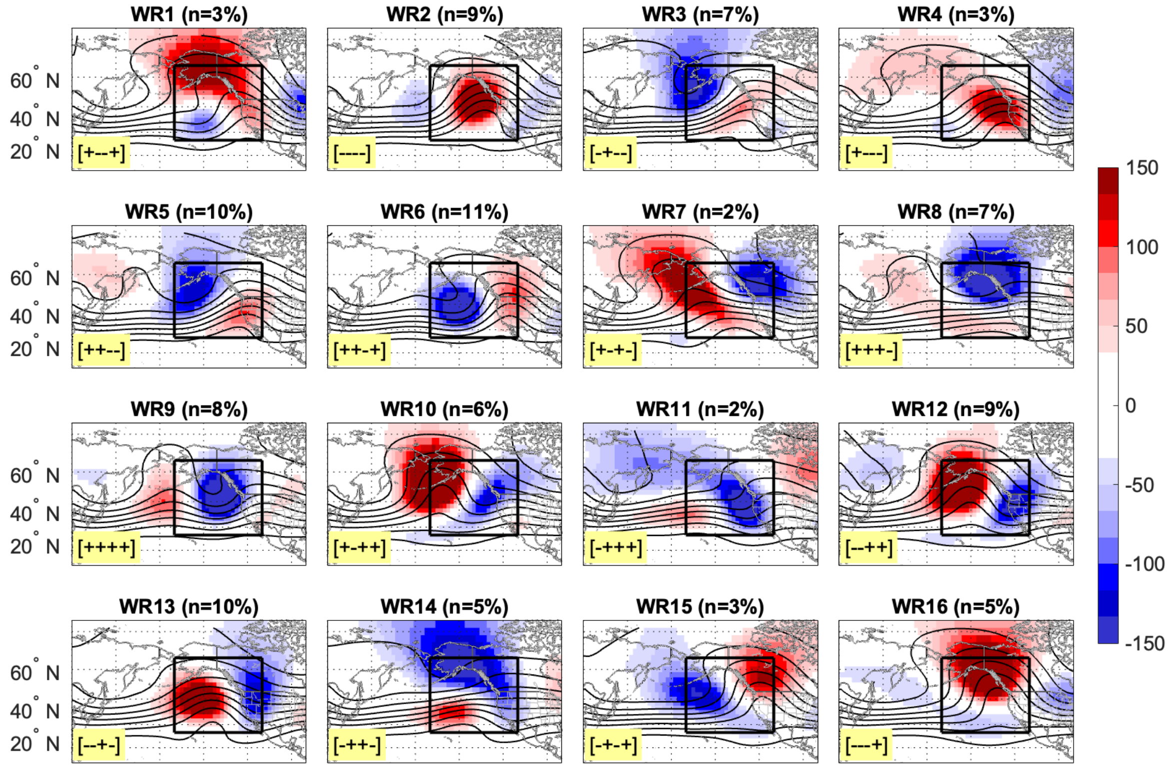

Figure S3. Composites of 500 mb geopotential height anomalies associated with each weather regime based on the methods developed by (Guirguis et al. 2022). The climatological sample size (n) for each weather regime is shown in the title as a percent of days in the historical record.

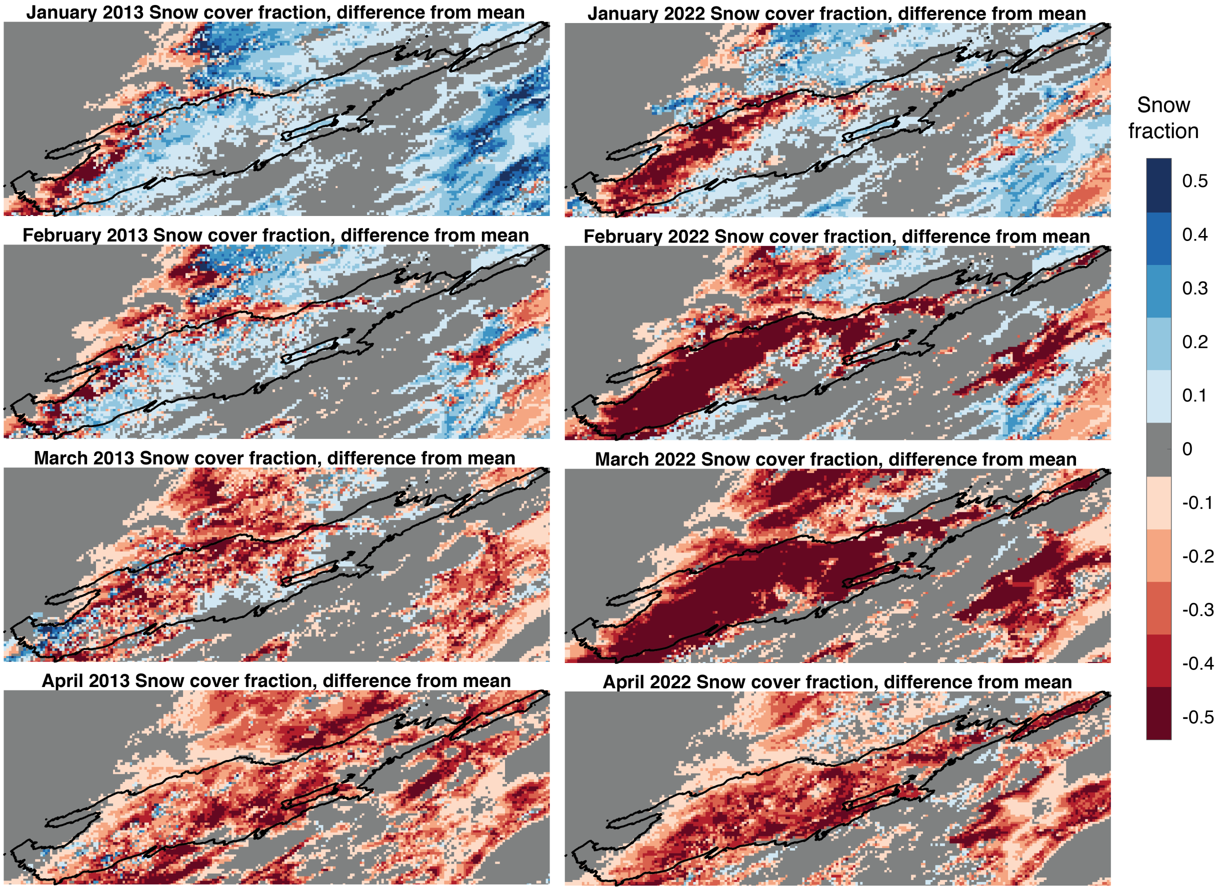

Figure S4. Snow cover days, as differences from WY2001-2022 means, for WY2013 (left column) and WY2022 (right column) for January, February, March, and April.

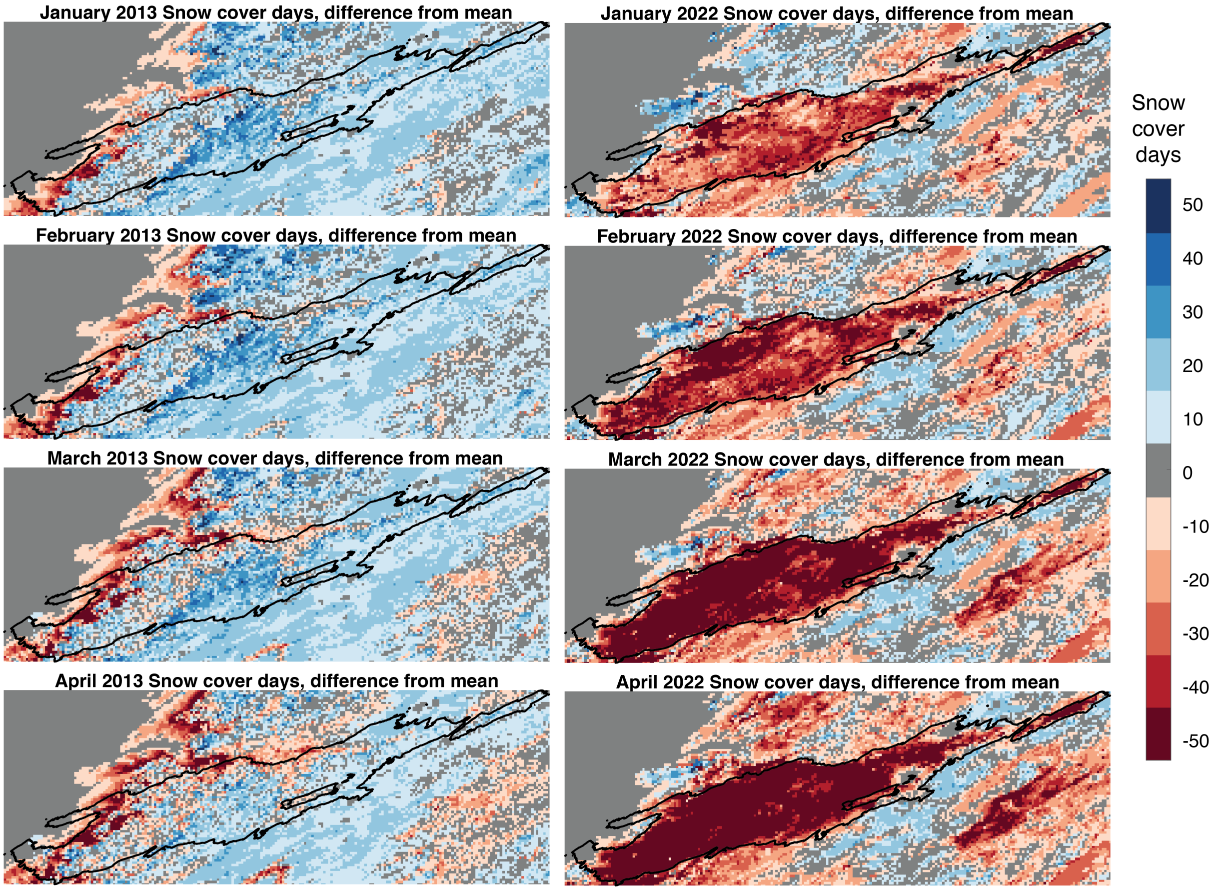

Figure S5. Snow cover fractions, as differences from WY2001-2022 means, for WY2013 (left column) and WY2022 (right column) for January, February, March, and April.