CLIMATE-DRIVEN CHANGES IN SNOWPACK TIMING, MAGNITUDE, AND DOWNSTREAM HYDROLOGY ACROSS WESTERN NORTH AMERICA

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ABSTRACT: Climate warming threatens snow-dependent water resources non-uniformly across western North America, where hydrologic sensitivities to snowpack loss and advanced snowmelt differ between mountain regions and contrasting maritime to continental climates. Communities rely on snowmelt-derived water for ecosystems, agriculture, and downstream supply, yet the physical processes shaping hydrologic sensitivity remain poorly understood, limiting predictions of hydrologic responses to changing snowpack conditions. We use directional statistics, applied to seven decades of daily hydrometeorological data across several mountain watersheds, to quantify annual runoff sensitivity to two components of snow water availability: (1) center-of-mass timing, the seasonal alignment of snowpack-derived water delivery relative to atmospheric demand, and (2) seasonal clustering, the concentration of water availability within a year. Historically, coastal, maritime-influenced regions exhibit greater sensitivity to water availability timing (e.g., Pacific Coastal Mountains, Cascades), whereas interior, continental regions exhibit greater sensitivity to seasonal clustering (e.g., Rocky Mountains), regardless of differences in climatic aridity. Although seasonal clustering has intensified in some regions and weakened in others, producing limited net change across western North America, water availability timing has advanced consistently across the study domain and is the larger contributor to declines in runoff generation, explaining the majority of the runoff ratio trends. Hydrologic vulnerability therefore depends on both regional sensitivity and the magnitude of hydroclimatic change; offering a transferable framework for anticipating where and how snow loss will most affect downstream water availability across global, snow-dependent mountain systems.

KEYWORDS: Snow hydrology, seasonal water availability, hydrologic partitioning, runoff ratio, climate change, western North America

1. INTRODUCTION

Mountain snowpacks act as seasonal water towers, capturing winter precipitation and releasing it gradually through spring and summer melt to sustain downstream ecosystems, agriculture, and community water supply (Immerzeel et al., 2020). Warming erodes this storage capacity through shifts from snowfall to rainfall, declining snowpack, and earlier melt timing (Mote et al., 2018; Musselman et al., 2021), with unknown and consequential effects for snowmelt-derived streamflow (Berghuijs and Hale, 2025). Snowpack vulnerability to a warming climate is well documented (Immerzeel et al., 2020; Musselman et al., 2021; Pepin et al., 2022; Wang et al., 2023), yet hydrologic sensitivities are expected to vary regionally because snow accumulation and melt respond to distinct climate and landscape controls (Aygün et al., 2022).

The hydrologic effects of changing snow seasonality depend on how water availability interacts with atmospheric demand and watershed storage. We distinguish two mechanisms, or processes that explain how and why an outcome occurs, hypothesized to influence annual water partitioning in snow-impacted regions. The first is seasonal timing, defined as the center-of-mass timing of surface water inputs (SWI; rainfall plus snowmelt) relative to potential evapotranspiration (PET). Earlier or later water availability changes the opportunity for evapotranspiration before water reaches the stream network as discharge (Foster et al., 2016; Hale et al., 2023b). The second is seasonal clustering, which represents how concentrated SWI is within a year. Concentrated snowmelt-derived SWI can produce strong seasonal runoff pulses, whereas more uniformly distributed SWI

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provides relatively greater opportunity for subsurface water storage and evapotranspiration (Foster et al., 2016; Hammond et al., 2019).

These mechanisms likely vary in hydrological importance across western North America because mountain climates differ substantially in precipitation seasonality, snow accumulation, and melt dynamics. Coastal ranges experience wetter and warmer winters and greater contributions from rainfall, whereas continental ranges are colder and more strongly snow dominated (Trujillo and Molotch, 2014).

2. METHODS

We analyzed 16 snow-influenced montane eco-regions and 122 HUC-4-equivalent watersheds spanning the western United States and Canada (Figure 1). Daily precipitation, temperature, SWE, runoff, soil moisture, PET, and ET were obtained from the 9-km ERA5-Land reanalysis from 1950 through 2023 (Muñoz-Sabater et al., 2021). SWI was calculated as rainfall plus snowmelt. Model results were independently evaluated at 38 observational locations by combining daily CAMELS-SPAT precipitation and streamflow with co-located SNOTEL and CanSWE snow water equivalent (SWE) records (1980–2018; Addor et al., 2017; Hufkens, 2022; Knoben et al., 2025; USDA NRCS, 2022; Vionnet et al., 2021).

2.1 Directional statistics and hydrologic partitioning

Directional statistics were used to quantify the seasonal timing and clustering of SWI (see Berghuijs et al., 2025). The circular center-of-mass quantified the timing of SWI ($\bar{t}_{SWI}$), while the normalized resultant vector length quantified seasonal clustering (R_{SWI}), with larger values indicating greater concentration within the year. Annual runoff ratio (*RR*) was calculated as annual runoff divided by annual precipitation and used as a measure of hydrologic partitioning.

We used generalized additive models (GAMs) to quantify the relative sensitivity of *RR* to $\bar{t}_{SWI}$ and R_{SWI} (Duchemin et al., 2025; Murphy et al., 2019; Ouarda et al., 2018). Spatial models related long-term mean *RR* to long-term mean SWI characteristics within each eco-region, while temporal models related interannual variability in *RR* to annual changes in $\bar{t}_{SWI}$ and R_{SWI} within individual grid cells. Relative importance was assessed from the partial F-statistics of the two predictors.

3. RESULTS

3.1 Spatial variability

Long-term $\bar{t}_{SWI}$, R_{SWI}, and *RR* all varied substantially across eco-regions (Figure 1). Mean $\bar{t}_{SWI}$ occurred near January 25 (0.32 ± 0.12); R_{SWI} averaged 0.38 ± 0.11, exceeding 0.5 in high-elevation, southern coastal, and northern continental settings; and *RR* averaged 0.28 ± 0.30, exceeding 0.7 along the west coast and falling below 0.3 inland in the southern region of the domain.

3.2 Regional and temporal sensitivity to SWI characteristics

The relative sensitivity of hydrologic partitioning differed systematically between coastal and continental mountain regions. SWI timing ($\bar{t}_{SWI}$) was the more influential predictor of *RR* in six predominantly coastal eco-regions, including the Cascades, North Cascades, Sierra Nevada, and Pacific Coastal Mountains. In these regions, later SWI center-of-mass timing was generally associated with higher runoff ratios. In contrast, SWI seasonal clustering (R_{SWI}) was more influential in ten predominantly continental eco-regions, including the Northern, Middle, and Southern Rockies, where greater seasonal concentration of SWI was generally associated with higher runoff ratios (Figure 1).

In SWI center-of-mass timing-sensitive regions, high-runoff years (years with *RR* in the 75th percentile per eco-region) were characterized primarily by later SWE, snowmelt, and SWI CM timing, relative to low-runoff years, while seasonal clustering differed relatively little. In SWI clustering-sensitive regions, high-runoff years instead exhibited greater seasonal concentration of SWE, snowmelt, and SWI, relative to low-runoff years, while SWI timing remained similar. Across the observational locations, the relative importance of the two mechanisms based on observed precipitation, streamflow, and SWE broadly agreed with the modeled results (r = 0.56; agreement in the dominant mechanism = 68.4%).

3.3 Climate-driven changes in SWI and runoff

SWI timing ($\bar{t}_{SWI}$) significantly advanced across western North America between 1950 and 2023, with a median advance of 11 days, and advances exceeding 39 days in the fastest changing 5% of grid cells. Changes in seasonal clustering (R_{SWI}) were more spatially heterogeneous, with increases and decreases distributed across the domain and little net change overall. Annual *RR* nevertheless declined across nearly the entire region, with a median decline of 0.015.

The contribution of these mechanisms to runoff-ratio trends depended on both sensitivity and rate of change. Advances in $\hat{t}_{SWI}$ produced widespread declines in *RR* and accounted for the largest contributions in coastal regions, where timing sensitivity was also strongest. For example, in the Pacific Coastal Mountains, North Cascades, and Sierra Nevada, changes in SWI timing accounted for 91%, 81%, and 80% of the respective runoff-ratio declines throughout the record period. R_{SWI} contributed more strongly to changes in *RR* in several continental regions, although its contribution varied substantially because changes in clustering were more spatially heterogeneous. Together, sensitivities and changes in SWI center-of-mass timing and SWI seasonal clustering explained approximately 30% of the domain-wide decline in *RR*.

4. DISCUSSION

The contrasting hydrological sensitivities of coastal and continental mountain regions reflect differences in climate seasonality and the role of snowpack as seasonal water storage (Trujillo and Molotch, 2014; Foster et al., 2016; Hammond et al., 2019). In coastal regions, where precipitation is more distributed through fall and winter months, the timing of SWI relative to atmospheric demand provides an important control on whether water is available during periods of high evaporative demand (Foster et al., 2016; Hale et al., 2023b). Consequently, shifts in snowmelt and rainfall timing can substantially and directly alter the timing of SWI and thus the fraction of precipitation partitioned to evapotranspiration versus runoff (Barnhart et al., 2016; Foster et al., 2016; Hale et al., 2024).

In continental regions, colder winters and more concentrated snow accumulation, with limited SWI generated outside of the snowmelt period, produce a more pronounced seasonal water pulse (Trujillo and Molotch, 2014; Hammond et al., 2019). Here, the seasonal clustering of water availability is more important in driving water availability than its timing. Greater seasonal clustering can promote runoff when meltwater inputs exceed the capacity of soils and vegetation for retention and uptake (Foster et al., 2016; Hammond et al., 2019). Conversely, reductions in snow accumulation and increasing rainfall can distribute water availability more broadly across the year, weakening the historical seasonal runoff pulse (Musselman et al., 2021; Kapnick and Hall, 2012).

These regional differences in the controls on hydrologic partitioning have important implications for climate change. Hydrologic vulnerability is greatest where substantial changes in SWI timing or seasonal clustering coincide with strong sensitivity to that characteristic. Coastal regions have experienced strong sensitivity to SWI timing with substantial advances in water availability, making them particularly vulnerable to continued warming (Musselman et al., 2021; Hale et al., 2023a; Hale et al., 2024). Continental regions may instead become increasingly sensitive to changes in seasonal clustering as declining snowfall and increasing rainfall redistribute water through the year (Musselman et al., 2021; Mote et al., 2018; Hale et al., 2023a).

5. CONCLUSIONS

Snow-driven hydrologic partitioning across western North America reflects two complementary characteristics of seasonal water availability: when water becomes available and how concentrated water availability is within a year. The hydrological relative importance of these mechanisms varies systematically across mountainous, western North America, with SWI timing exerting greater influence in coastal regions and seasonal clustering exerting greater influence in continental regions. Because climate change is altering both characteristics, future water-resource impacts will depend on the interaction between regional sensitivity and the magnitude of hydroclimatic change**.** Accounting for these contrasting mechanisms provides a framework for anticipating where changes in snow seasonality are most likely to translate into changes in downstream water availability.

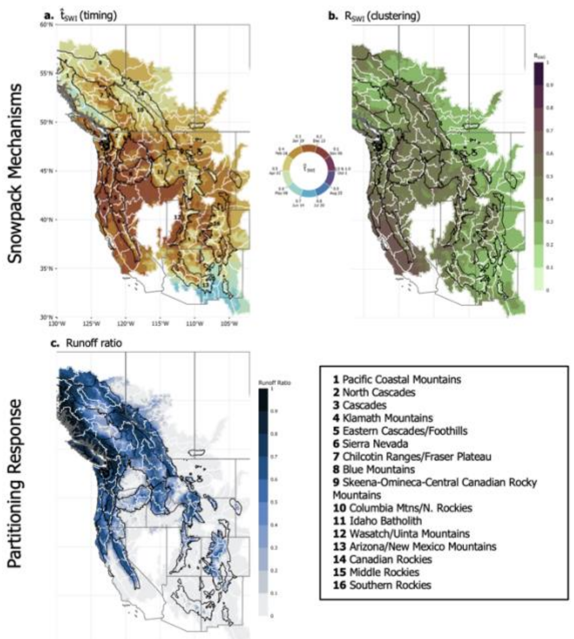

Figure 1. Long-term (1950-2023), grid-cell scale average SWI center-of-mass timing ($\hat{t}_{SWI}$) (a), SWI seasonal clustering (R_{SWI}) (b), and annual runoff ratios (*RR*) (c) across the western cordillera eco-regions, labeled 1–16 in panel (a),

and watersheds nested within them. All panels are overlaid on USA state and Canadian provincial boundaries (gray), EPA Level III eco-regions (black) and North American HUC-4 equivalent watersheds (white). No zero values exist across panels.

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