RECONSIDERING THE UTILITY OF THE APRIL 1ST SNOW WATER EQUIVALENT METRIC FOR WATER RESOURCE APPLICATIONS

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EXTENDED ABSTRACT

Snow is the primary source of water in western North America (Li et al., 2017). In mountainous regions, seasonal snowpack accumulates in the winter and subsequently melts in the spring, effectively delaying the timing of downstream water delivery by as much as a half-year. Because of this capacity to store much of the annual precipitation and extend the delivery of meltwater into the arid spring and summer when demand is highest, snowpack is often referred to as a natural water tower. The date on which the snowpack mass, or snow water equivalent (SWE), reaches an annual maximum at a given location is literally and figuratively a watershed moment – dividing winter accumulation from spring melt and providing useful insight into the expected spring runoff. For these reasons, snowpack is vigilantly monitored across the West to inform reservoir operation and seasonal water supply forecasts that critically support agricultural and resource management decisions.

For the past century, April 1st has been used to approximate the average date of maximum SWE. In fact, seasonal water supply forecasts are largely structured on this date. For example, before the 1950s water supply forecasts in the western U.S. were almost exclusively made for April to September – a period that includes both the snowmelt and agricultural irrigation seasons (Pagano et al., 2004). More recently, forecast target periods have been shortened to April to July to exclude the less-predictable summer rainfall (e.g., the monsoon season) in favor of the more-reliable delivery of meltwater. In warmer regions such as Arizona, New Mexico, and Idaho, forecast periods begin earlier to coincide with earlier snowmelt seasons and/or unique user needs such as earlier agricultural planting schedules. The consistent use of the April 1st metric in water resource applications – and compelling examples of warmer regions where operational forecasts deviate from that target date – begs numerous questions. First, how does the date of maximum SWE vary across western North America? Second, how has this date changed over the past 30+ years of observation in response to reported warming and snowpack declines (e.g., Mote et al., 2018)? Third, what is the hydrologic relevance of the date of maximum SWE? And fourth, how might this change this century?

To address these questions, we present a long-term analysis of SWE data from 969 snowpack monitoring stations in western North America. This includes data from the US SNOTEL network, Alberta Environment and Parks, the Government of British Columbia, and the California Cooperative Snow Survey. The average date of maximum SWE varies geographically (Figure 1). The snowpack of the Sierra Nevada and inter-continental regions such as Idaho peak within a few days of April 1st, while the snowpack in the U.S. Pacific Northwest and Southwest peaks nearly a month earlier. In continental regions including Colorado, Wyoming, Montana and the Canadian Rockies, the timing of maximum SWE occurs closer to May 1st. Despite the large regional variability, the median date of maximum SWE computed on all stations and for the full period of record was within a few days of April 1st.
(KEYWORDS: SWE, April 1st, maximum SWE, snow water equivalent, earlier snowmelt)

A convenient and common conceptualization of the date of maximum SWE is that it distinctly divides the accumulation and melt seasons. We provide two examples of SWE time-series from different sites: a cold continental site (Figure 2a) and a maritime site (Figure 2b). Despite similar dates of maximum SWE (~April 5th), the hydrologic significance of that date is drastically different between the two sites. To communicate this point, the fraction of cumulative annual melt (fCAM) is assessed on the date of maximum SWE ($fCAM_{maxSWE}$). The $fCAM_{maxSWE}$ metric is a measure of the fraction of annual snow water resources that has melted before the date of maximum SWE; the complement '1-$fCAM_{maxSWE}$' is the fraction of annual snow water resources that remains to be

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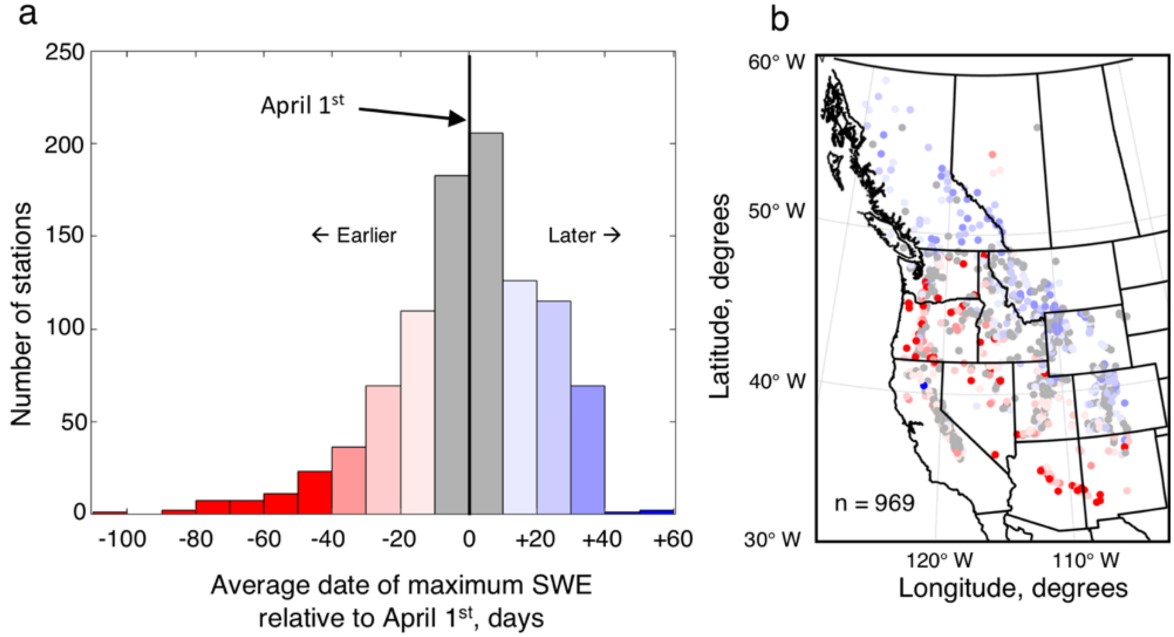

Figure 1. A (a) histogram and (b) map of the average (Oct. 1979 – Sep. 2014) date of maximum SWE relative to April 1st as measured at 969 snowpack telemetry stations (circle symbols) in the conterminous western U.S. and southwestern Canada are shown. The symbol colors in (b) correspond to the values shown in the x-axis of the histogram in (a).

melted on the date of maximum SWE. In the idealized case of snowpack as a fully efficient ‘water tower’, fCAM=0.0 occurs on the date of maximum SWE when no seasonal snowfall has melted to date and no snowfall will occur after that date. In the Figure 2 example, only 0.107, or 10.7%, of the seasonal snowfall had melted at the continental site, while 54.9% had melted at the maritime site on the shared date of maximum SWE. The comparison highlights that: 1) snowpack rarely follows the idealized conception of distinct accumulation and melt seasons, and 2) deviations from the idealized conception are not necessarily reflected in the date of maximum SWE.

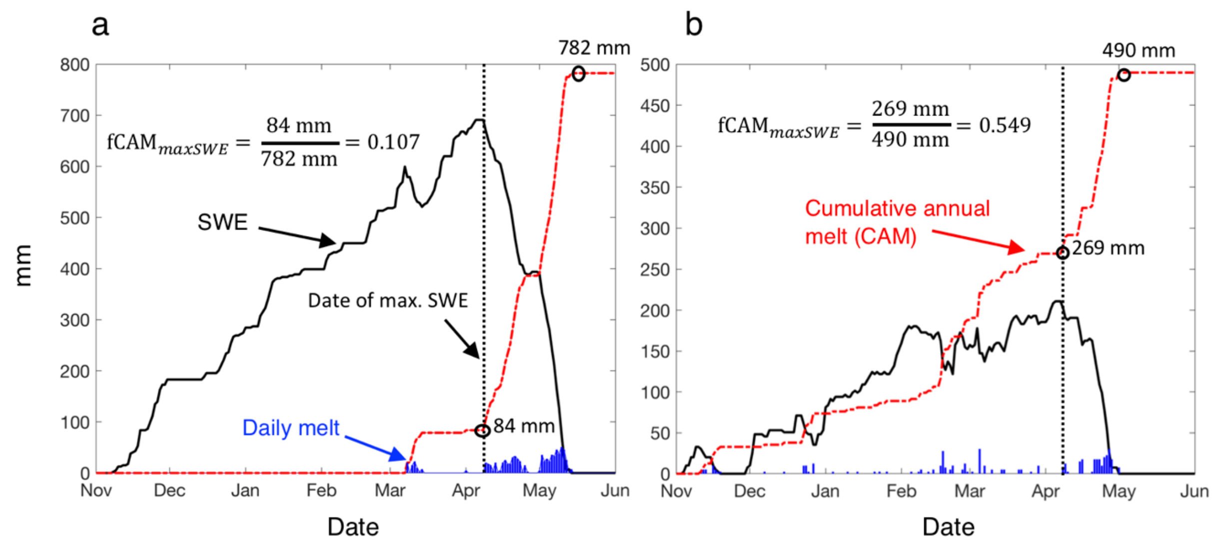

Figure 2. Examples of seasonal snow water equivalent (SWE; solid black line) time series measured at mountain snowpack telemetry stations in a (a) continental and (b) maritime climate. The date of maximum SWE is indicated by the vertical dashed line. Two additional metrics are derived from the daily decrease in SWE: daily melt (blue bars) and cumulative annual (Oct. 1 – Sep. 30) melt (red dash-dot lines). Calculations of the fraction of cumulative annual melt (fCAM) that has occurred by the date of maximum SWE ($fCAM_{maxSWE}$) are shown.

When calculated on all SWE station data, $fCAM_{maxSWE}$ is remarkably consistent (~0.20) for most mountainous regions, suggesting that 80% of annual snow water resources in these regions remains available to melt on the date of maximum SWE. This highlights the reliable utility and hydrologic relevance of snowpack metrics on the date of maximum SWE, as well as the regionally consistent and high storage efficiency of the mountain water towers. Two regional exceptions are the relatively warmer U.S. Pacific Northwest and Southwest, which had average $fCAM_{maxSWE}$ values of ~0.31 and dates of maximum SWE that occurred two to four weeks before April 1st.

Long-term trend analysis at 519 stations with at least 30 years of record indicate little change in the timing of maximum SWE. Figure 3a shows that fewer than 8% of stations have a significant ($p<0.05$) trend toward earlier maximum SWE at an average rate of -7.4 days per decade. There are more significant regional patterns of earlier peak SWE in central Utah, southern Colorado, and northern New Mexico. Conversely, 29% of stations have a significant increasing trend in $fCAM_{maxSWE}$, with an average increase of +4.5% per decade (Figure 2b). The results suggest that the date of maximum SWE may lack sensitivity to climate change compared to other metrics. Importantly, the increasing trend of $fCAM_{maxSWE}$ over the last 30+ years suggests that the hydrologic relevance of the date of maximum SWE is in decline, while the date itself remains largely unchanged. This result has implications on water supply forecast systems that rely on a static date such as April 1st in the estimation of seasonal runoff volumes.

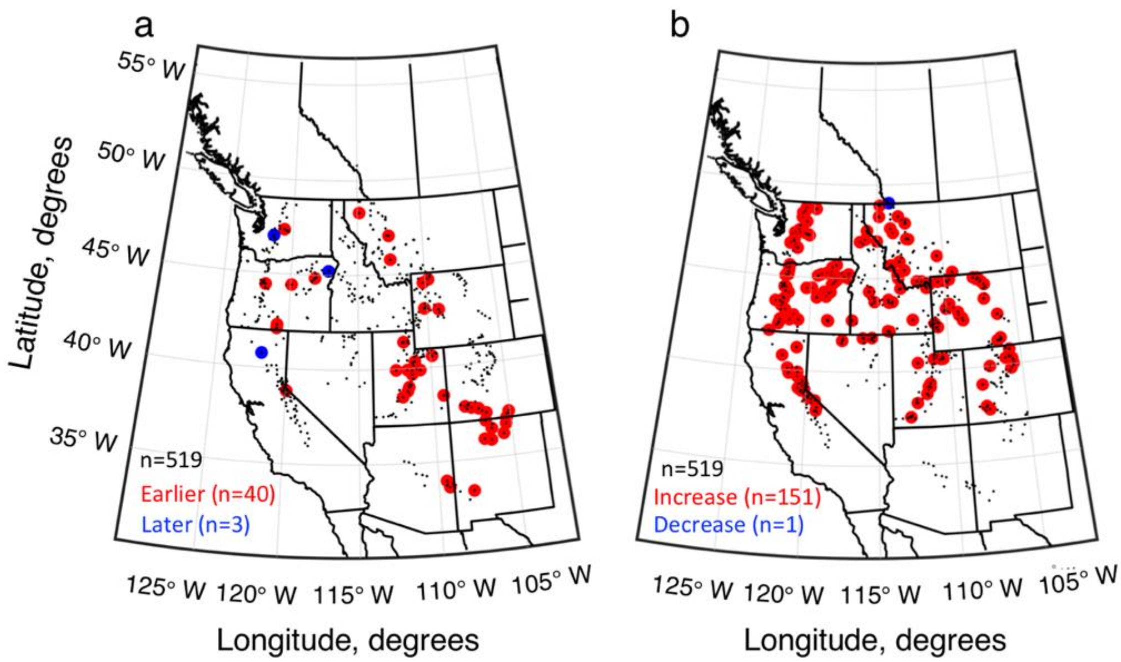

Figure 3. Snowpack telemetry stations with a data record ≥ 30 years (small points; n=519) that have statistically significant ($p \leq 0.05$; large circles) trends in (a) the date of maximum SWE and (b) the fractional cumulative annual melt on the date of maximum SWE.

Finally, we present and discuss implications of model projections of future snow water resources in the context of climate change, the timing of maximum SWE and $fCAM_{maxSWE}$. We analyze output from the physically based Weather Research and Forecasting (WRF) model run for a historic period (2001 – 2013) and a future (end-of-century) climate scenario (Liu et al., 2017). Compared to station measurements, the model simulated the historical date of maximum SWE to within 10 days of the observed values. In the warmer climate, the date of maximum SWE shifted earlier by two to four weeks and the $fCAM_{maxSWE}$ increased by 10% to 22%, with the greatest changes projected for British Columbia and the U.S. Pacific Northwest. We conclude that the date of maximum SWE is projected to shift earlier and the efficiency of our snowpack, or mountain water towers, to store snow water resources until that date of peak SWE will substantially decline. By the end of the 21st century, continental mountain snowpack will melt intermittently during accumulation season similar to the present-day snowpack of the U.S. Pacific Northwest. More work is required to understand the impacts on statistical water supply forecast skill of this ongoing and projected shift away from the typical conceptualization of snowpack as having distinct accumulation and melt seasons. (KEYWORDS: Snow Water Equivalent, maximum SWE, climate change, delayed snowmelt)

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