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The Unusual Nature of Recent Snowpack Declines in the North American Cordillera

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In western North America, snowpack has declined in recent decades, and further losses are projected through the 21st century. Here, we evaluate the uniqueness of recent declines using snowpack reconstructions from 66 tree-ring chronologies in key runoff-generating areas of the Colorado, Columbia, and Missouri River drainages. Over the past millennium, late 20th century snowpack reductions are almost unprecedented in magnitude across the northern Rocky Mountains and in their north-south synchrony across the cordillera. Both the snowpack declines and their synchrony result from unparalleled springtime warming that is due to positive reinforcement of the anthropogenic warming by decadal variability. The increasing role of warming on large-scale snowpack variability and trends foreshadows fundamental impacts on streamflow and water supplies across the western United States.

In the mountains of western North America, snowpack controls the amount of runoff (*1*, *2*), affects temperature through surface albedo feedbacks (*3*, *4*), and influences myriad ecosystem processes (*5*–*8*). In much of this region, snowpack declined since the 1950s (*2*, *9*–*11*), and continued reductions are expected throughout the 21st century and beyond (*2*, *12*). When coupled with increasing demand, additional warming-induced snowpack declines would threaten many current water storage and allocation strategies (*13*) and lead to substantial strain on related infrastructure and overall supplies. Climate model simulations shed light on the relationships between greenhouse gas forcing and observed shifts in regional temperatures and hydrology (*2*), but longer-duration records are needed to characterize the range of natural snowpack variability, particularly at decadal-to-multidecadal time scales (*14*). Did declines similar in duration, magnitude, and extent occur over the past ~1000 years, or are the recent snowpack losses unprecedented? How were previous snowpack declines driven by known mechanisms of temperature and precipitation variability, and to what degree can decadal-to-multidecadal climate variability amplify or dampen future warming-induced trends?

To address these questions, we developed annually resolved, multi-century to millennial-length (500- to >1000-year) snowpack reconstructions for the headwaters of the Columbia, Missouri, and Colorado Rivers. Collectively, these basins serve as the primary water source for >70 million people, and 60 to 80% of their water originates as snowpack (*1*, *2*). Reconstructions are based on an extensive network of tree-ring sites and provide information on patterns and processes across spatial and temporal scales relevant to water- and natural-resource management (Fig. 1).

Tree rings have long been used to reconstruct precipitation, drought (*15*, *16*), streamflow (*17*, *18*), and temperature (*19*, *20*), but to date there has been no systematic effort to produce multi-scale snowpack reconstructions for all three of these river basins. Previous studies in the region show that in certain topographic, edaphic, and climatic settings, the amount of water available to trees during the growing season is largely controlled by the amount of water in the antecedent snowpack (*18*, *21*). We capitalized on these snow-water-growth linkages by using existing tree-ring collections from areas where precipitation is dominated by snowfall and by sampling trees known to be sensitive to snowpack (*18*, *21*). To further isolate the snowpack signal, particularly in the northern portions of the study area, we used recently collected tree-ring records from species whose seasonal biology (timing of tree-ring growth) ties them closely to snow (*22*, *23*).

For calibration of the tree-ring–based reconstructions, continuous annual, sub-watershed (roughly 40,000 ± σ 25,000 km^2) snowpack data sets were constructed by standardizing individual 1 April snow water equivalent (SWE) records to unit deviation then averaging across all records from each watershed (fig. S1 and table S1) (*24*). Snowpack as measured on 1 April is a crucial component of regional runoff forecasting and water supply evaluations, and records of 1 April SWE are generally longer than for any other time of the year. In addition, 1 April measurements often approximate maximum SWE accumulation in our study watersheds (*4*, *11*), although peak accumulation timing can vary substantially at individual measurement sites. Elevations of individual measurement sites in the Upper Colorado subregion (Fig. 1) tend to be higher than those in the Greater Yellowstone (2807 ± σ 311 m versus 2307 ± σ 291 m), and sites in the Greater Yellowstone region are higher on average than those in the Northern Rockies (~1550 ± σ 424 m). Overall, the 27 composite snowpack reconstructions

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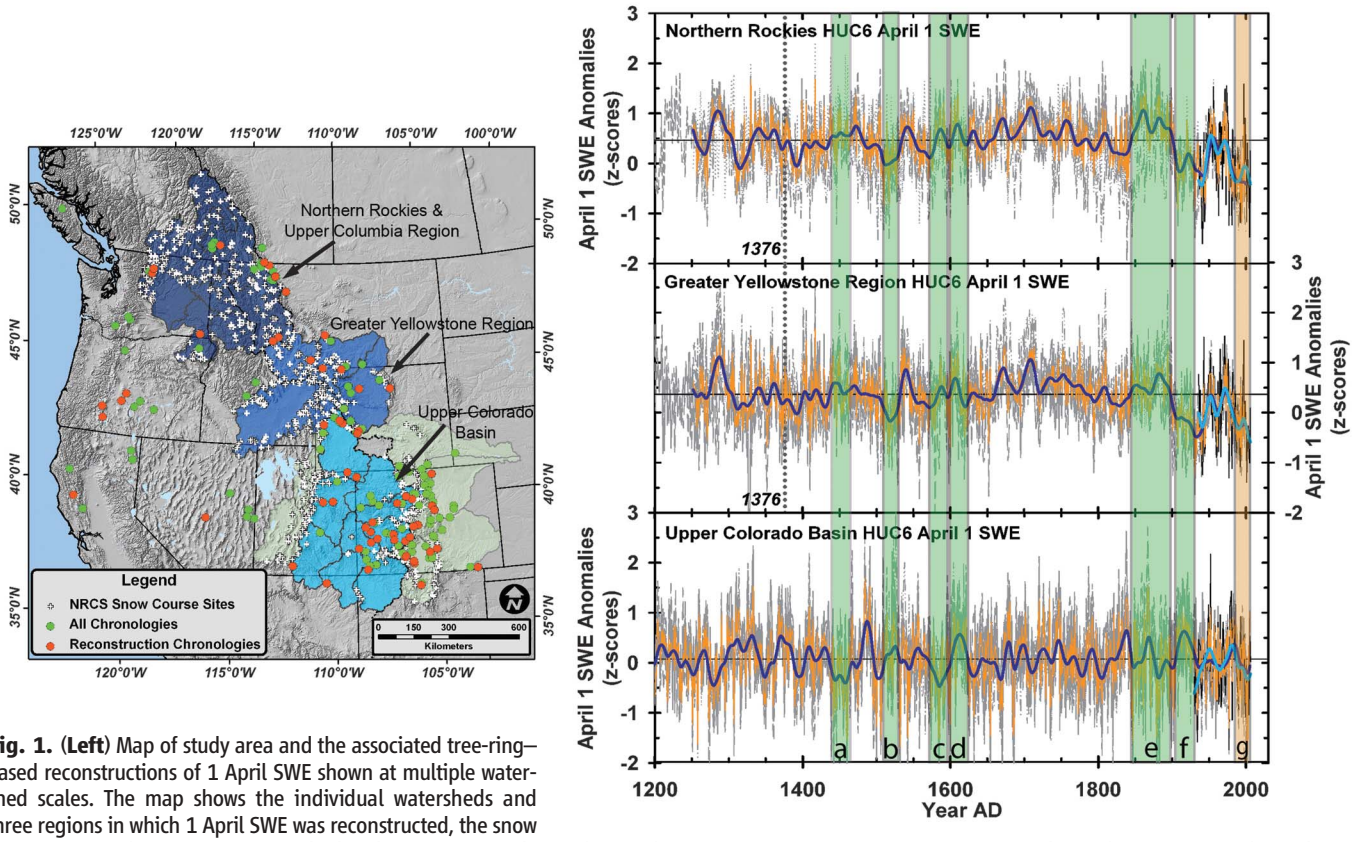

Fig. 1. (**Left**) Map of study area and the associated tree-ring–based reconstructions of 1 April SWE shown at multiple watershed scales. The map shows the individual watersheds and three regions in which 1 April SWE was reconstructed, the snow course sites used to generate watershed-scale averages of observed 1 April SWE, the full set of potential predictor chronologies (green circles), and the final set of chronologies that entered into one or more SWE reconstruction models as a predictor (orange circles). (**Right**) The graphs of the 1 April SWE reconstructions show the individual watershed reconstructions of 1 April SWE (gray lines) by region and latitude, the regional SWE average calculated from each individual reconstruction (orange line), and a 20-year cubic-smoothing spline (50% frequency cutoff) of the regional SWE average (dark blue line). For the Northern Rockies and Greater Yellowstone region, a cut-off date of 1376 is shown (dotted vertical line) because of decreasing sample depth and increasing reconstruction uncertainty. The 20th century records of observed 1 April SWE are plotted for each large region (black lines) and smoothed with a 20-year cubic-smoothing spline to highlight decadal-scale variability (light blue line) coherent with the snowpack reconstructions. Shaded intervals show decadal-scale SWE anomalies mapped in Figs. 2 and 4. Lettering corresponds to the mapped intervals. The observed and reconstructed SWE records are plotted as anomalies from the long-term average, which was calculated by using 1400 to 1950 C.E. as a base period. Other base periods were used to calculate the long-term average SWE conditions, yielding highly similar estimates (table S6).

skillfully capture interannual to multidecadal variability in observed 1 April SWE records (figs. S1 and S2 and tables S2 to S5) and provide detailed estimates of long-term snowpack history (*24*).

The 1 April SWE reconstructions (Fig. 1) show that for the northern cordillera—collectively the Greater Yellowstone and Northern Rocky Mountain subregions that encompass the headwaters of the Columbia and Missouri River drainages—there were only two periods (~1300 to 1330 C.E. and 1511 to 1530 C.E.) of sustained low snowpack in the past 800 years that are comparable with the early and late 20th century (~1900 to 1942 C.E. and ~1980 to present). In contrast, generally high snowpack conditions prevailed across the northern cordillera from the 1650s to the 1890s, coinciding with the maximum Holocene advance of glaciers (*25*) and a period of reduced fire activity across the West (*26*). In particular, two notable, decadal-scale high snowpack anomalies in the northern cordillera (~1695 to 1735 C.E. and 1845 to 1895 C.E.) coincided with cool summer temperatures (*19*) and with major intervals of Little Ice Age (LIA) glacier advance (Figs. 1E and 2E) (*25*). A paucity of positive decadal-scale snowpack anomalies in the southern cordillera—roughly the Upper Colorado headwaters (Figs. 1, 2E, and 3)—in conjunction with warmer summer temperatures (*20*) may explain the lack of a substantial LIA glacial advance over that subregion.

Snowpack reconstructions across the entire latitudinal gradient show pronounced interannual to multidecadal variability (fig. S2), but with distinct regional modes marked by a north-south (N-S) dipole [Figs. 2 and 3 and supporting online material (SOM) text]. The Greater Yellowstone and Northern Rocky Mountain watersheds exhibit decadal-scale and longer-term phasing of snowpack anomalies that are typically opposite those within the Upper Colorado. For example, the periods from roughly 1440 to 1470 C.E. (Figs. 1A and 2A) and 1550 to 1600 C.E. (Figs. 1C and 2C) (*15*, *16*) featured sustained low snowpack conditions centered over the Upper Colorado. During the same intervals, northern cordillera watersheds generally experienced average to above-average snowpack. In contrast, severe low snowpack conditions across the northern cordillera prevailed from 1511 to 1530 C.E., whereas the Upper Colorado experienced average to high snowpack (Figs. 1B and 2B). Comparison of the full multicentury reconstructions for all three regions shows that this antiphasing is generally robust through time (Fig. 3 and SOM text).

The N-S dipole suggests that sustained departures in the average latitudinal position of wintertime stormtracks are responsible for persistent snowpack anomalies. This is consistent with forcing related to interannual [El Niño–Southern Oscillation (ENSO)] and decadal [Pacific Decadal Oscillation (PDO)] sea surface–temperature (SST) variability in the Pacific Ocean, which tends to shift cool season storm tracks north-to-south across western North America (*4*, *27*). Specifically, when the tropical Pacific and northeast Pacific are warm the Pacific Northwest/northern Rockies are dry, southwestern North America is wet, and vice versa (*27*–*29*). Observed early to mid-20th century declines (~1900 to 1942 C.E.) in snowpack

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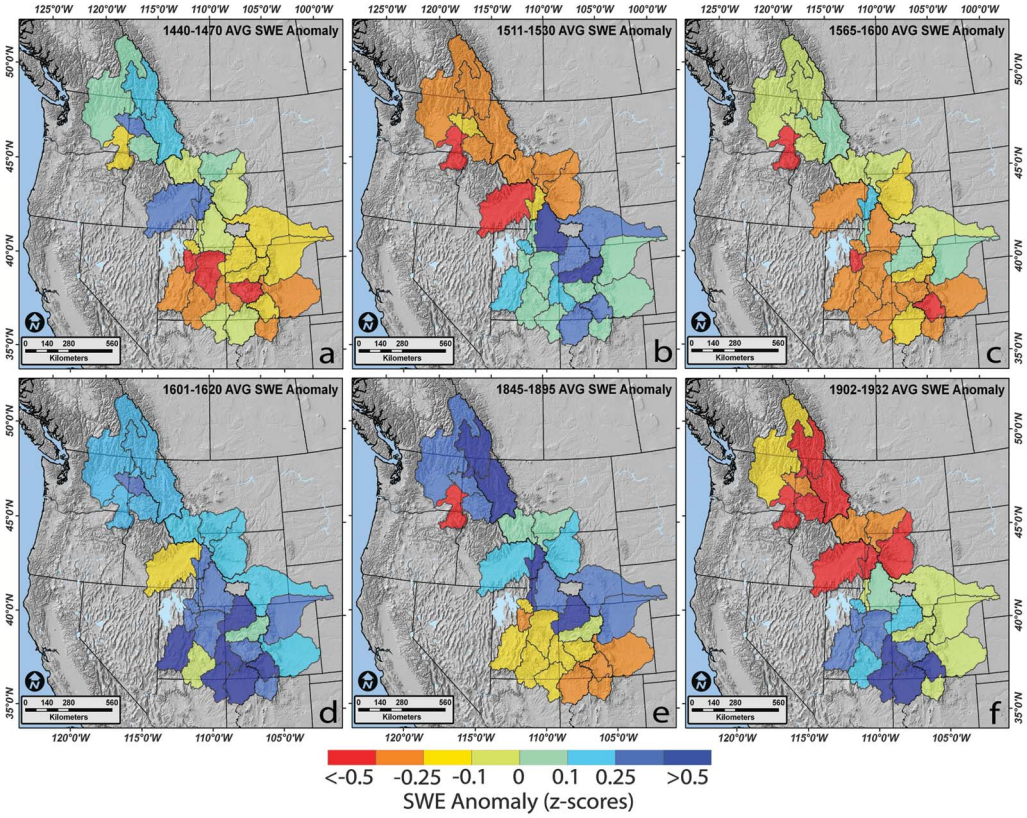

Fig. 2. Decadal departures in reconstructed 1 April SWE for watersheds predominately within the U.S. portion of the North American cordillera. Maps show average SWE conditions over the following intervals previously highlighted in Fig. 1: (**A**) 1440 to 1470, (**B**) 1511 to 1530, (**C**) 1565 to 1600, (**D**) 1601 to 1620, (**E**) 1845 to 1895, and (**F**) 1902 to 1932. The mapped SWE anomalies were calculated by averaging annual conditions for each hydrologic unit code (HUC) 6 watershed over the time interval shown and are plotted as anomalies from the long-term regional mean (1400 to 1950 AD). The final data sets along with the ability to generate user-defined maps of interannual- to interdecadal-scale departures in reconstructed and observed SWE are provided at www.nrmsc.usgs.gov/NorthAmerSnowpack/.

across the northern cordillera (Figs. 1F and 2F) coincided with warm SSTs across the Gulf of Alaska (positive PDO) (*30*), which resulted in pronounced meridional flows and a southerly stormtrack that delivered anomalously high winter precipitation to the Upper Colorado Basin. In the case of the Upper Colorado, this yielded a relative lack of drought and high river flows (*17*, *18*).

Although Pacific Basin forcing of precipitation and the resulting N-S dipole have been defining features of snowpack variability for the past millennium, several notable exceptions do occur. Cordillera-wide periods of low snowpack shown for the 1350s, 1400s, and post-1980s era (Fig. 3) correspond with times of anomalous warmth at regional and hemispheric scales (*19*, *20*, *31*), suggesting that temperature could be a direct or indirect control on snowpack anomalies of the same sign across the entire cordillera (*31*). Likewise, cool temperatures in the early 17th century (~1600 to 1620 C.E.) coincided with high snowpack conditions across the North American cordillera (Figs. 1D and 3). Interannual to decadal modes of ocean-atmosphere variability (related to ENSO and PDO) also may influence subcontinental-scale warming or cooling from February to May, which are the critical months for snow accumulation and melt in western North America (*1*, *2*, *9*, *14*, *32*). West-wide spring warming since ~1976 to 1984, coincident with warming in the tropical and northeast Pacific and anomalously high geopotential heights over western North America, has increased freezing levels, reduced snow accumulation, and

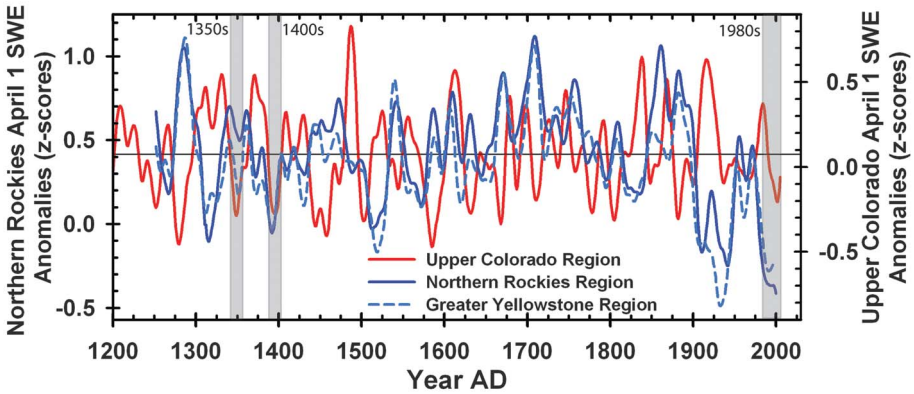

Fig. 3. Decadal-scale antiphasing of the N-S snowpack dipole and periods of synchronous snowpack decline. The 20-year splines of the regional average snowpack anomalies highlight antiphasing and variability at decadal scales. The shaded bars highlight periods of synchronous snowpack decline.

advanced the onset of snowmelt and green-up (*9*, *14*, *32*).

Previous work that used both observations and simulations suggests that temperature is especially important for driving snowpack dynamics in the Northern Rockies (*1*, *2*, *4*, *9*–*11*). The Northern Rockies are relatively low in elevation and snow mass; winters and springs at snow-monitoring sites are ~3°C warmer than in the Upper Colorado River subregion (fig. S3). In the Northern Rockies, the sensitivity to temperature fluctuations is evident in the anomalously high snowpack and glacial advance during the LIA as well as in anomalously low snowpack throughout most of the 20th century. On the other hand, the higher and cooler elevations of the southern cordillera probably buffered the snowpack from substantial temperature-driven losses, at least to date. Taken as a whole, evidence is mounting that projected warming could push mean winter temperatures at most snow-monitoring sites in the Northern Rockies past the 0°C isotherm and the entire snow-accumulation zone past the 0°C isotherm in April (fig. S3).

In the Upper Colorado watersheds, snowpack reconstructions can also be compared against existing long-term records of streamflow variability (*17*, *18*). Periods of high snowpack generally coincide with high flows and vice versa (fig. S4). There are times, however, when regional warming

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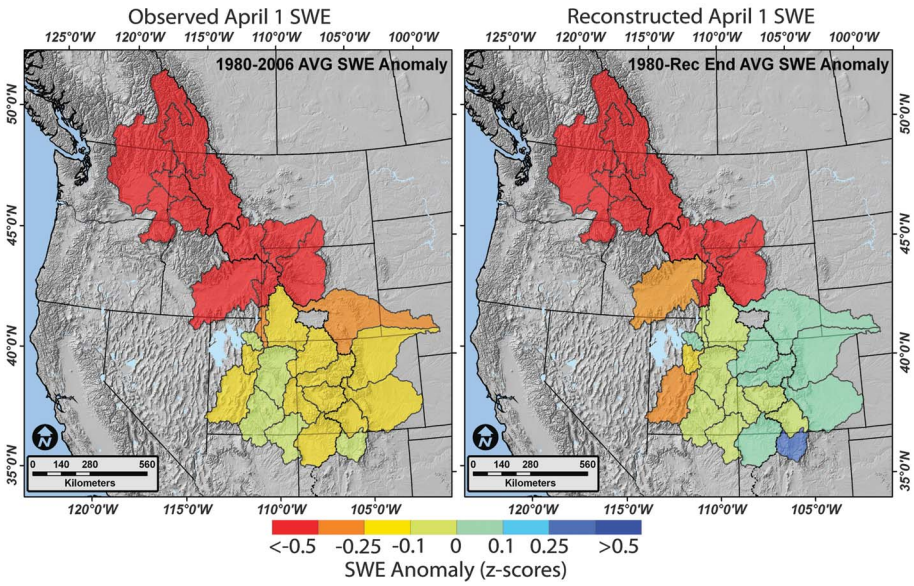

Fig. 4. Post-1980 average 1 April SWE conditions. Maps of post-1980 average SWE conditions (Fig. 1G) are plotted as anomalies from the regional long-term mean (1400 to 1950 C.E.) for the (**left**) observational record and (**right**) tree-ring–based reconstructions. The map showing average reconstructed SWE values is not exactly equivalent to the observational record because many individual watershed SWE reconstructions have different end years, the earliest of which only extend to 1990. This implies that the similarity in patterns of anomalies are notable but that the magnitudes of departure should not be expected to be the same.

may have reduced runoff yield more than would be expected from estimated snowpack amounts alone. For example, average to slightly below-average snowpack prevailed from ~1118 to 1179 C.E. over most of the Upper Colorado basin, yet this was an extreme low-flow period in the streamflow reconstructions (fig. S4). This interval coincides with a period of elevated regional and hemispheric temperatures (*20*, *31*) that may have increased evapotranspiration and sublimation while decreasing soil- and shallow groundwater–recharge and storage. Warmer temperatures and severe decadal-scale snowpack reductions combined to produce an extreme low-flow interval during this period of the Medieval Climate Anomaly (~1143 to 1155 C.E.) (fig. S4). Such interactions between warmer temperatures and cool season precipitation have been documented for the hydrologic (water supply) droughts of the 1950s and early 2000s (*31*), which again raises concerns for the future of snow-temperature-runoff relationships throughout the North American cordillera.

Although the causes of synchronous winter snowpack declines are probably attributable to multiple factors in past centuries, the conspicuous breakdown of the N-S dipole after the 1980s (Figs. 1G, 3, and 4) may now reflect positive reinforcement of anthropogenic warming by decadal variability. Specifically, a decadal-scale shift in Pacific climate ~1976 to 1984 may account for nearly half (~30 to 50%) of the springtime warming in western North America, the trend in decreasing winter precipitation in the north and increasing winter precipitation in the south (*9*, *32*), and the more pronounced snowpack decline in the north. Hence, a decadal shift to cooling in the tropical and Northeast Pacific could temporarily mask the trend in springtime warming and declining snowpack.

Our reconstructions highlight the unusual nature of snowpack declines in northern watersheds and synchronous snowpack losses across the entire cordillera since the 1980s (Figs. 1G, 3, and 4). Together, these events may signal a fundamental shift from precipitation to temperature as the dominant influence on snowpack in the North American cordillera, with major consequences for regional water supplies (*2*, *10*).

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