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California's 2023 snow deluge: Contextualizing an extreme snow year against future climate change

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The increasing prevalence of low snow conditions in a warming climate has attracted substantial attention in recent years, but a focus exclusively on low snow leaves high snow years relatively underexplored. However, these large snow years are hydrologically and economically important in regions where snow is critical for water resources. Here, we introduce the term "snow deluge" and use anomalously high snowpack in California's Sierra Nevada during the 2023 water year as a case study. Snow monitoring sites across the state had a median 41 y return interval for April 1 snow water equivalent (SWE). Similarly, a process-based snow model showed a 54 y return interval for statewide April 1 SWE (90% CI: 38 to 109 y). While snow droughts can result from either warm or dry conditions, snow deluges require both cool and wet conditions. Relative to the last century, cool-season temperature and precipitation during California's 2023 snow deluge were both moderately anomalous, while temperature was highly anomalous relative to recent climatology. Downscaled climate models in the Shared Socioeconomic Pathway-370 scenario indicate that California snow deluges—which we define as the 20 y April 1 SWE event—are projected to decline with climate change (58% decline by late century), although less so than median snow years (73% decline by late century). This pattern occurs across the western United States. Changes to snow deluge, and discrepancies between snow deluge and median snow year changes, could impact water resources and ecosystems. Understanding these changes is therefore critical to appropriate climate adaptation.

climate change | snow hydrology | hydroclimate

Significance

Snow in mountainous regions is critical for water resources and is declining with climate warming. While low snow years have been extensively studied, we know relatively little about large snow years and their potential changes. Here, we introduce the term "snow deluge" to describe extreme snow years and show that the 2023 California snow deluge was roughly a 1-in-54 y event and was a 1-in-320 y event (or greater) at 5% of snow monitoring stations. Snow deluges are projected to decline across the western United States in future climates, although less so than median snow years. Snow deluges can be both destructive and beneficial. Better understanding the phenomenon and its potential changes could improve management of snow-dependent ecosystems and economies.

In recent years, a mounting body of evidence has highlighted the importance of snow drought (1)—a period of anomalous low snowpack—and its consequences for water resources and ecosystem function (2). Snow droughts are becoming more common and will likely continue to do so with continued warming (3–7). However, an exclusive focus on snow drought precludes understanding of the other end of the spectrum: what we term here as "snow deluge"—that is, years in which unusually large quantities of snow water equivalent (SWE) accumulate on the land surface.

The 2023 water year in California presents a promising case study for the concept of snow deluge. California snow surveyors described the year's April 1 SWE as at least the largest since 1952, although they highlighted challenges of comparisons due to changing observational networks (8). The scientific community highlighted the role of atmospheric rivers and uncertainty of potential climate change attribution (9). Immediate impacts of the years' snow deluge included widespread flooding, with subsequent downstream impacts to communities and agriculture; increases in State Water Project deliveries; and rollbacks of emergency drought provisions (8).

Previous work has shown that very large snow accumulations can occur in years with a high frequency of atmospheric rivers in the western United States (10, 11), but most work on extreme snowfall has focused on the event scale rather than seasonal accumulations. Individual extreme snowfall events account for the majority of interannual snowfall variability and have regionally varying correlations with the El Niño–Southern Oscillation (12). Both theory and climate models project that extreme snowfall events will decline less than smaller snowfall events and could even increase in colder regions (13, 14). Other work on large annual precipitation accumulations (pluvials) has focused on total precipitation, rather than snowfall or snow accumulation (15–19). Probabilities of large annual snow accumulations are substantially different from those of precipitation, particularly in the snow-to-rain transition zone that encompasses a large fraction of western watersheds (20). The lack of existing literature on future changes in extreme snowfall years leaves open the question of the probabilities and impacts of extreme snow accumulations on an annual scale.

The term "snow drought" was apparently first used by Wiesnet in 1981 (21), who published a brief (two-paragraph) commentary noting that snow-covered area in January of

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that year was at an all-time low since the inception of the satellite record. Since then, definitions have proliferated, to the extent that Gottlieb and Mankin (2) noted that the term is "amorphous" and ill-defined (*SI Appendix*, Text S1). Snow droughts are commonly defined as "warm" or "dry" snow droughts based on the temperature and precipitation anomalies (1). In defining snow deluge, we consider the extent to which wet or cool conditions produce snow deluges. We hypothesize that snow deluges likely require precipitation anomalies high enough and temperature anomalies cool enough (22) to produce anomalous snowfall or snowpack, while snow droughts may be created by either warm temperatures or low precipitation alone. Individual snow deluge years may nevertheless be primarily driven by relatively large seasonal cold or wet anomalies contingent on the climatological context of the region of interest. As with snow droughts, these climate drivers could affect the spatial distribution and heterogeneity of snow deluge conditions (6).

In this study, we introduce the concept of snow deluge and use the 2023 water year in California as a case study. We ask the following questions: 1) How unusual was the 2023 California snow deluge in the context of the modern observational record? 2) To what extent are snow deluges—including the 2023 water year—driven by relatively cold temperatures or high precipitation? 3) How will snow deluges change in projected future climates? We calculate spatially distributed return intervals of April 1 SWE to ascertain the approximate likelihood of the conditions in the 2023 snow year, using both in situ snowpack observations (*SI Appendix*, Fig. S1) and estimates modeled with the Variable Infiltration Capacity (VIC) model (23), using a Generalized Extreme Value (GEV) theoretical approach. We evaluate the extent to which temperature and precipitation conditions in the masked regions of California were anomalous in 2023 using a long-term climate record (24); we specifically consider the importance of wet-day and dry-day temperature anomalies (25) in addition to average cool-season temperatures. We also evaluate the extent to which the snow deluge of 2023 was rare relative to three previous decades versus the previous century. Finally, we use bias-corrected dynamically downscaled simulations from the Sixth Coupled Model Intercomparison Project (CMIP6) (26) to estimate potential changes in snow deluges relative to median years and to evaluate the change in the probability of the 2023 snow deluge within future climate contexts.

Results

Characterizing the 2023 California Snow Deluge. In situ snow courses and automated snow sensors showed high values of April 1 SWE throughout the mountains of California, with the largest values in the central and southern Sierra (Fig. 1*A*). The statewide median across operational snow monitoring sites was 1.5 m (interquartile range; IQR = 0.8 m), with a maximum value of 2.9 m. Snow conditions were most anomalous in the central and southern Sierra, with return intervals at many sites exceeding 100 y (Fig. 1*B* and see *SI Appendix*, Fig. S2 for study area map). In contrast, snow in the northern part of the state was relatively unexceptional. The median estimated return interval across sites was 41 y (IQR = 50 y); 5% of sites had return intervals exceeding 320 y. While the snow deluge was widespread across the Sierra Nevada, it also extended to other parts of the western United States, with exceptionally high April 1 SWE observed in parts of Utah, southeast Idaho, Nevada, and the western slope of the Colorado Rockies commensurate with the path of numerous atmospheric rivers (*SI Appendix*, Figs. S3–S6).

In situ data also indicate that the 2023 snow deluge was more spatially heterogeneous than previous snow deluges. In 2023, more sites in California (42%) recorded their largest-ever April 1 SWE over their full period of record than any other year (*SI Appendix*, Table S1). The next largest year by this metric was 1983, with 27% of active sites recording their largest April 1 SWE. However, 1983 had a far greater percentage of sites (92%) ranked within the top 5 y on record (*SI Appendix*, Table S2). By this measure, 2023 was only the third largest on record, with 81% of California sites within the top five.

VIC simulations indicated that approximately 56 km^3 of SWE was on the ground in California on April 1, 2023. This is 257% of the 1921-2023 simulated average and the largest April 1 SWE value in the 1921 to 2023 VIC simulations. Sierra Nevada April 1 SWE represented about 93% of total reservoir capacity draining that region (27). VIC simulations approximately reproduced the magnitude and return frequency of in situ April 1 SWE, but spatial distributions were somewhat different. The largest SWE accumulations were simulated around the southern part of the Sacramento River basin and the Central Lahontan, draining to Nevada (Fig. 1*C*). Similarly, the highest estimated return intervals based on the VIC simulations were distributed slightly north of those in the observed data, although with comparable return intervals (Fig. 1*D*). Peak SWE simulations from VIC were not the highest on record, but were otherwise comparably anomalous, with a California-total peak SWE of 59 km^3, which is about 215% of the long-term average (*SI Appendix*, Fig. S7).

Climate Context for the 2023 Snow Deluge. Climate data from the NClimGrid product (23) aggregated over the region of California with at least 50 mm mean peak SWE over the VIC historical record (*Materials and Methods*) indicate that the 2023 snow deluge was driven by relatively cold temperatures—particularly relative to the last several decades—and moderately, though not exceptionally high precipitation (Fig. 2*A*). Six snow deluges with a California-total April 1 SWE return interval greater than 20 y occurred between 1921 and 2023 (similar results are seen using peak SWE; *SI Appendix*, Figs. S8 and S9). Relative to the full period of record, almost all deluge events were within the top 10th percentile of cool season (November to March) precipitation, with the exception of 1922, which had just above median precipitation (*SI Appendix*, Table S3). Cool-season temperatures were within the coldest 10th percentile for four of six deluges, while 1938 and 1983 had temperatures in approximately the 40th percentile. The requirement for relatively cool and wet conditions is also evident in Fig. 2*B*; while there is large interannual variability in cool-season precipitation in California, all snow deluges fall above the mean precipitation and below the mean cool season average temperature. Wet-day and dry-day temperature anomalies were consistently negative in snow deluge years since 1952 when these daily data became available. An exception is the 1983 snow deluge, when wet-day temperature anomalies were in the 71st percentile (*SI Appendix*, Table S3). In 2023, wet-day temperature anomalies had a slightly smaller departure from their average values than did cool-season average temperatures, suggesting that unusually cold storms were not specifically responsible for the deluge (Fig. 2*A*). When aggregated to the large spatial scale of California and temporal scale of a full water year, cool-season temperature and precipitation appear to have a relatively strong influence on April 1 SWE, with about 80% of April 1 SWE variability explained as a linear function of temperature and precipitation (*SI Appendix*, Table S4). Years with precipitation deluge but lacking snow deluge tended to have warmer January-March temperatures than snow deluge years, but did not have major differences in precipitation seasonality (*SI Appendix*, Figs. S10 and S11).

The climate variables contributing to the 2023 snow deluge had spatially heterogeneous anomalies, with colder dry-day temperature anomalies throughout the Sierra Nevada, and colder wet-day temperature anomalies in the northern part of the state where snow

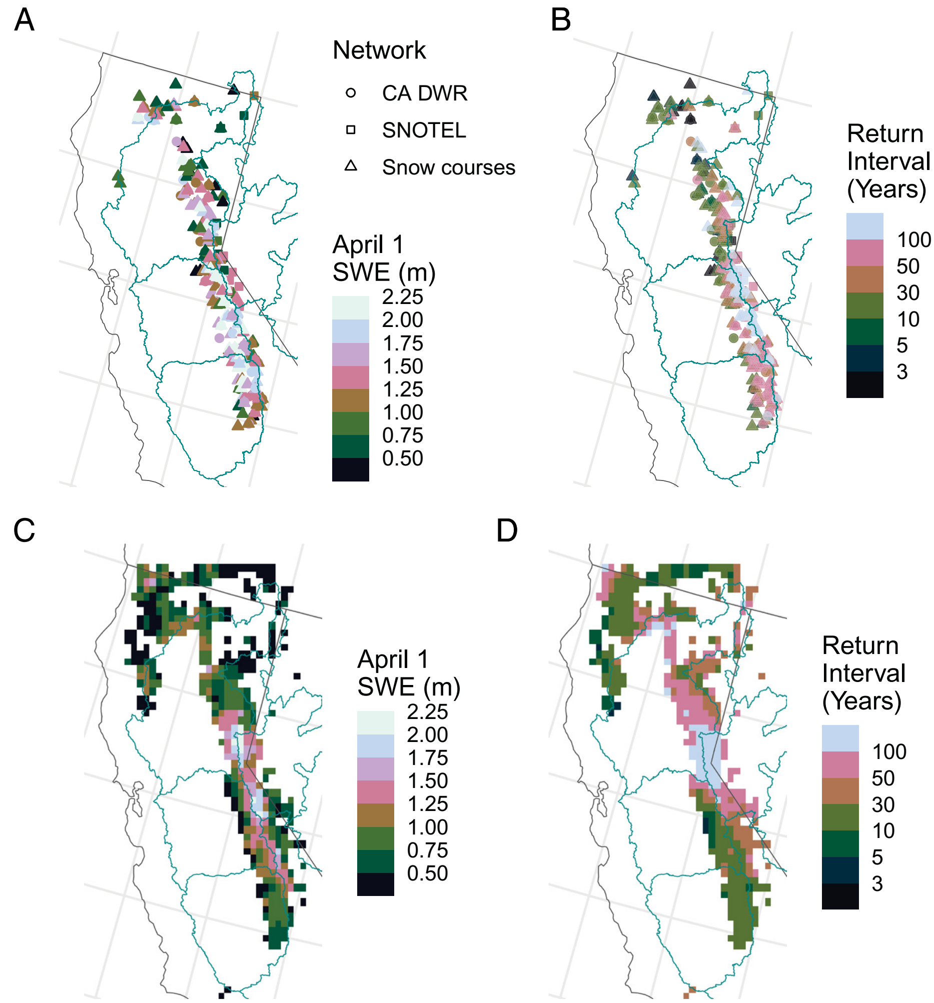

Fig. 1. Observed and modeled April 1 SWE and return intervals. (*A*) Observed 2023 April 1 SWE at SNOTEL and CA DWR snow pillows and snow courses; (*B*) return interval of observed April 1 SWE based on the station period of record; (*C*) VIC-modeled April 1 SWE in 2023; (*D*) 2023 return interval estimated using VIC data, 1921 to 2023.

accumulations were least anomalous (*SI Appendix*, Fig. S12). Anomalies in both precipitation and the number of wet days were greatest at high elevations in the central and southern Sierra Nevada (*SI Appendix*, Fig. S13). Average and dry-day temperature anomalies were colder at high elevations, while wet-day temperature anomalies were colder at lower elevations in the northern parts of the state. While these anomalies showed elevation dependence, the sparseness of observing networks at high elevations and geographic differences in anomalies suggest caution in interpreting these findings.

Return intervals for climate and snow deluge summed across California illustrate the extent to which the 2023 snow deluge was driven by unusually cool temperatures and high precipitation, as well as the importance of sampling uncertainty and hydroclimatic trends (Fig. 3 and *SI Appendix*, Fig. S14). Return intervals for 2023 precipitation were similar regardless of the period of record: Relative to the 103 y period of record, we estimated a 20 y return interval (90% CI: 16 to 30 y); relative to the 1981 to 2010 period [selected to align with historical WRF (WeatherResearch and Forecasting) simulations], we estimated a 15 y return interval (CI: 10 to 29 y; see *SI Appendix*, Table S5 for results relative to a 1991 to 2020 historical period). In contrast, estimates of the infrequency of the cool temperatures of 2023 depended strongly on the period of record: Relative to the 103 y period of record, we estimated a 31 y return interval (CI: 21 to 62 y); relative to the 1980 to 2010 distribution, we estimated a 610 y return interval (CI: 220 to 5.0×10^3 y). These findings reflect nonstationarity in the temperature record over the last century associated with well-documented warming trends. Interestingly, April 1 SWE reflected much less of this discrepancy between the full period and recent decades: Relative to the full period of record, we estimated that April 1 SWE in 2023 was a 54 y event (CI: 38 to 109 y); relative to the 1981 to 2010 period, April 1 SWE was a 59 y event (CI: 40 to 370 y). Peak SWE was about as anomalous as April 1 SWE but with more of a change based on period of record; relative to the 103 y period 2023 peak SWE was a 42 y event (CI: 31 to 77 y) and a 54 y event (CI: 35 to 302 y) based on the 1981 to 2010 period (*SI Appendix*, Fig. S15).

Projected Changes in Snow Deluge Probabilities. We use dynamically downscaled GCM (general circulation model) outputs (*SI Appendix*, Table S6) from the CMIP6 project for the Shared Socioeconomic Pathway (SSP) 3.70 scenario to evaluate potential changes in snow deluge. Note that these are not directly comparable to the VIC simulations due to the use of a different land surface model (Noah-MP) in the WRF simulations used for downscaling (see *SI Appendix*, Figs. S16–S18 for a comparison of the two datasets). We fit the GEV separately on the SWE output from each of the nine dynamically downscaled GCMs, which somewhat circumvents biases inherited from choices of land surface models and parent GCMs. Two-year return interval snow years (approximately

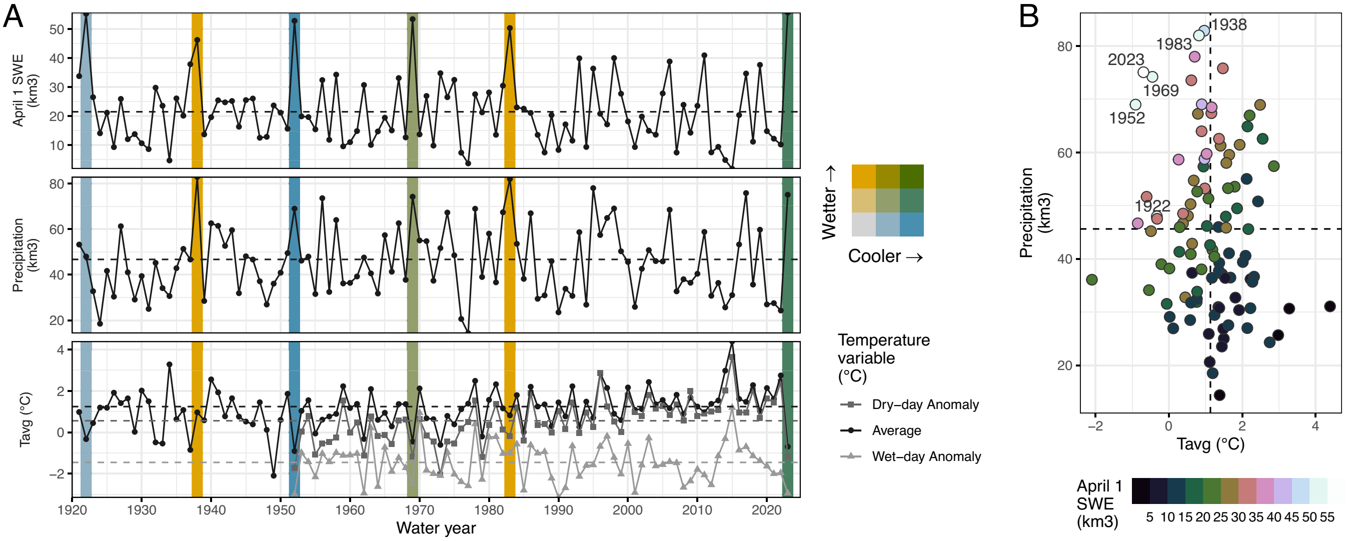

Fig. 2. Historical California snow deluge and associated climate. (*A*) Time series of spatially averaged April 1 SWE; cool-season precipitation; and cool-season average temperature and dry-day and wet-day anomalies Values are spatially averaged over locations with >50 mm mean April 1 SWE over 1920 to 2023. Colors indicate the extent to which highlighted snow deluges are wet or cool relative to other snow deluge years. Dashed lines indicate mean values over the full period of record. (*B*) April 1 SWE as a function of cool-season (November to March) average temperature and total precipitation. The dashed horizontal and vertical lines in (*A* and *B*) denote the November to March mean temperature and cumulative precipitation averaged during 1952 to 2023 (the period of record over which all variables were available), respectively.

equivalent to the median) are projected to decline more on a percentage basis than 20 y snow deluges across California, though there is substantial intermodel variability (*SI Appendix*, Fig. S19). The 2 y event is projected to decline by 36% by mid-century and 73% by late-century (9-GCM median). In contrast, a 20 y event is projected to decline by 22% by mid-century and 58% by late century. For a 60 y event approximately matching the rarity of the 2023 snow deluge, percentage declines are similar to the 20 y event: By mid-century, these events are projected to decline by 21%, with a 59% decline by late century. Results are comparable for peak SWE (*SI Appendix*, Fig. S20). While the multi-GCM median shows a larger percentage decline for median years than deluges, that pattern is not consistent across all individual GCMs (*SI Appendix*, Fig. S21).

The finding that snow deluges will likely decline, but less so than median years, is consistent across the western United States (Fig. 4). The 9-GCM median 2 y peak SWE events have the largest percentage declines in the lower elevation Sierra Nevada, northern Cascades, and lower elevation edges of the Rocky Mountains, with the smallest declines in the higher elevation Rocky Mountains in Colorado and Wyoming (Fig. 4*A*). Spatial patterns are similar for 20 y return interval events. The percent declines in snow deluge years are predominantly smaller than percentage declines for median years: By mid-century, 92% of pixels have a smaller percentage decline in their snow deluge years than median years; by late-century, this rises to 98% of pixels (Fig. 4*B*). Overall, these results suggest that while both median and deluge years will see declines in peak SWE, percentage declines in deluge years will be considerably smaller.

Discussion

April 1 SWE resulting from California's 2023 snow deluge had roughly a 54 y return interval, with considerable spatial variability in the observational record. While unusual, this is substantially

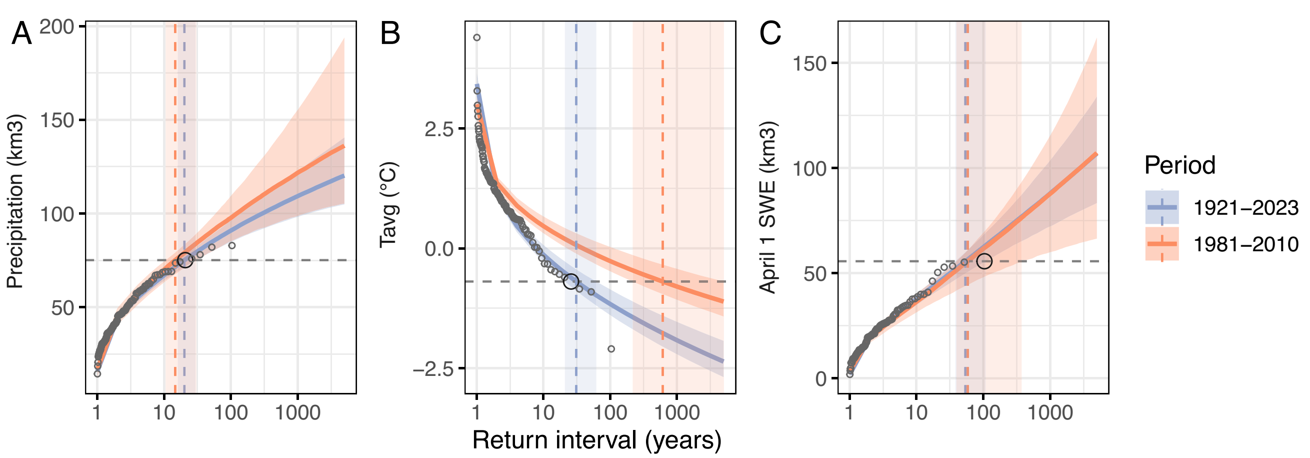

Fig. 3. Precipitation, temperature, and April 1 SWE return intervals. Estimated return intervals for cool-season (*A*) precipitation and (*B*) temperature from NClimGrid; and (*C*) April 1 SWE from VIC. Shading indicates 90% CI for 1,000 bootstrapped samples using ⅔ of the data in each case, and color indicates the period of record from which samples are drawn. Horizontal gray dashed line denotes values for 2023; vertical lines denote associated return intervals. Gray points show observations with empirical return intervals for the 103 y period; the large black point denotes 2023.

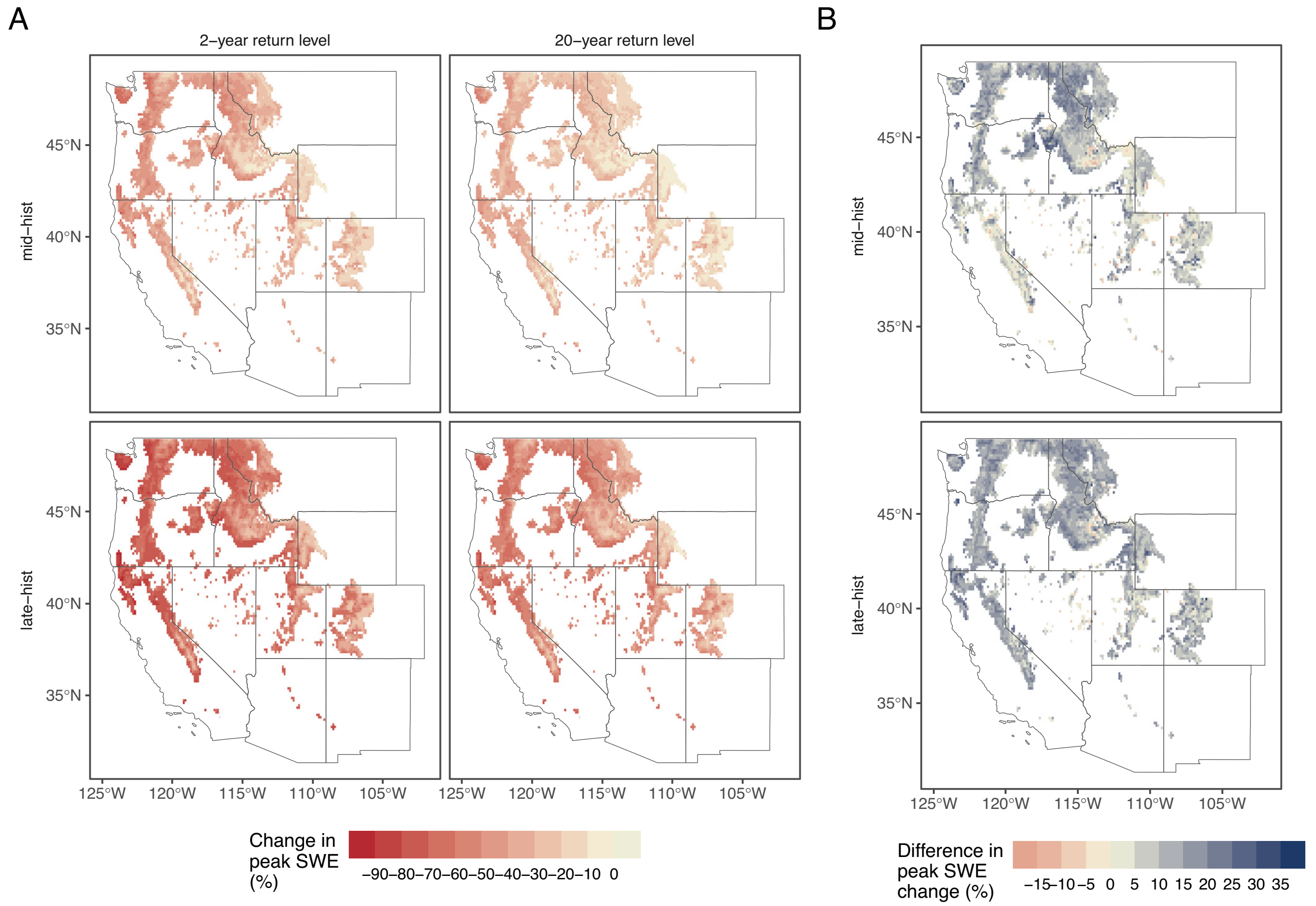

Fig. 4. Projected changes in snow deluge. (*A*) WRF-simulated change in 2 y and 20 y return interval peak SWE values from historical (1981 to 2010) to mid-century (2031 to 2060) (*Top*) and historical to late century (2070 to 2099) (*Bottom*); median across 9 GCMs; (*B*) difference between 20 y and 2 y return interval percentiles for the same periods as in (*A*).

less rare than the 2015 snow drought (28). The anomalous snow conditions were partially explained by spatially averaged cool temperatures and high precipitation, though these climate anomalies might not be collocated with the regions of greatest snow accumulation (*SI Appendix*, Fig. S14). Temporal averaging could also mask important variability: While wet- and dry-day temperature anomalies were similar in 2023, wet- and dry-day temperatures have been warming at different rates (25). Frequencies of compound climate extremes have also been changing (29, 30). These could create a nonstationary relationship between temperature anomalies and April 1 SWE. Future work could also evaluate the extent to which snow deluges are impacted by the frequency and temporal clustering of atmospheric rivers and their synoptic rain-snow elevation relative to the land surface (10). Deluge formation could be impacted by winter melt prior to April 1 (31), which is in turn affected by variability in incoming shortwave radiation (32), snowfall intensity (33), atmospheric humidity (34), rain-on-snow events (35), and changes in snow albedo following disturbance events (36). Despite this range of factors impacting snow accumulation and melt dynamics, spatially aggregated cool-season temperature and precipitation explain at least 80% of variability in statewide April 1 SWE.

The projected smaller percentage decline of snow deluges relative to median years aligns with previous findings that large snowfall events are anticipated to decline less than median events, or even to increase in relatively cold locations (13, 14). This is fundamentally due to competing effects of warming, which decreases the fraction of precipitation falling as snow (20), and Clausius-Clapeyron effects, which increase precipitation intensity (14). Previous studies of these phenomena have been event-based, rather than annual. As the largest events are major contributors to annual snow accumulation (13), the corresponding result at the annual scale aligns with and extends previous findings. Because these changes are calculated relative to historical means, the smaller declines in deluges may or may not lead to an increase in interannual variability. Indeed, while the smaller declines in deluges are consistent across the western United States, interannual variability of peak SWE is projected to increase only in the highest elevations of the maritime regions and in colder interior continental snowpacks (3).

While some likely impacts of snow deluges are evident from existing literature, others are relatively poorly understood. The snow deluge of 2023 resulted in substantial flooding, particularly in the Tulare Lake basin (37); future work could evaluate the conditions under which snow deluges result in large or disruptive flooding. Also important is the extent to which snow deluge years result in high runoff and reservoir storage increases, including potential nonstationarities between snowfall and runoff in a warming climate (38). Indeed, the relative importance of snow deluge versus large total precipitation accumulations for total runoff and associated impacts is not particularly well understood (39). Impacts on reservoir recharge are even more uncertain and could depend on operations and the success of forecast-informed reservoir operations (40).

Snow deluges could also impact snow-dependent terrestrial and aquatic ecosystems. As snow droughts become more frequent yet perhaps remain punctuated by occasional deluges, we might consider two scenarios: In one, a snow-adapted forest ecosystem or river experiences persistent low snow years. In another scenario, these low snow years are occasionally interrupted by a deluge. Differences in ecosystem dynamics—including phenology and mortality rates (41)—between these systems could result in substantially different rates and types of landscape change. Such differences could also depend on underlying geology and capacity for soil profiles to store water throughout the critical zone (42). The relative loss of snow deluge could also be important for wildlife: While declining snowpacks have long motivated concerns for snow-dependent wildlife (43), very large snow events can also increase mortality for some species (44).

Snow deluge impacts on human communities could also be important. For instance, ski area economics could be substantially affected by occasional snow deluge years (45), though recent experience indicates that deluges can enhance winter recreation by extending the season or reduce it due to infrastructure impacts. More widespread impacts to infrastructure (e.g., buildings, transport, utilities) and associated snow hazards during snow deluge events and rapid melt of such events can impact communities (46, 47). Summer recreation is impacted by the magnitude and timing of snow accumulation and melt in a preceding snow year (48, 49), although differences in human and ecological responses can cause phenological mismatches (50). Perhaps even more importantly, historical analysis of Colorado River negotiations finds a risk that high runoff years could breed complacency and delay planned adaptation (51); the impacts of such delays in adaptation response relative to benefits accrued from snow deluge are currently unknown. Snow deluges could also impact hydropower production (52); while many analyses of hydroclimate risks to the power grid have commonly focused on drought impacts (53, 54), potential benefits or unknown drawbacks of snow deluges are relatively undercharacterized (55).

Multiple lines of evidence indicate that 2023 was exceptional in California with respect to April 1 SWE. While it was not alone in the historical record, it had more sites with record-breaking April 1 SWE than any other water year and a 54 y return interval aggregated over the state. Relative to only the last few decades, cool temperatures in winter and spring 2023 appear to be a truly exceptional driver of anomalous snow accumulations in 2023. However, against the backdrop of the last 103 y, both temperature and precipitation were unusual but not extreme, highlighting the importance of spatiotemporal variability, additional energy balance components, and compound extremes for generating snow deluge (56). Climate models indicate that snow deluges comparable to the 2023 California event will become increasingly rare, though will have smaller relative declines than typical years; such changes align with projections of increasing wet snow drought (7). Much as aridification has been posed as a more useful framing than drought (57), increasingly common conditions of snow drought may require that we pay new attention to the other end of the snow spectrum, with future work further exploring snow deluge and its consequences.

Materials and Methods

In Situ April 1 SWE Data. April 1 SWE observations were obtained from snow pillows and courses operated by the California Department of Water Resources (CA DWR) and the United States Department of Agriculture NRCS (Natural Resources Conservation Service) (58). Snow courses in other states operated by other agencies were also obtained from the NRCS website (*SI Appendix*, Figs. S1 and S3). Daily SWE data were gap-filled using linear interpolation when five or fewer days were missing. This resulted in 0.9% (20/2314) of CA DWR site-years and 1 NRCS site-year (out of 23,687) having filled April 1 SWE data. Across the western United States, 840 snow course sites operated by NRCS, 58 cooperator sites (including CA DWR), and 556 NRCS snow pillow sites had an April 1 SWE value in 2023 with at least 30 y of preceding data and were retained for analysis. In California, 215 snow course sites, 30 CA DWR snow pillows, and 23 NRCS snow pillows were retained. Following (59), no adjustment was made for cases when snow courses were obtained slightly before or after April 1. After data cleaning, snow courses had an average of 67 ± 18 (SD) years of data. CA DWR snow pillows had 40 ± 7 y of April 1 SWE observations, and NRCS snow pillow sites had 43 ± 5 y of data.

Modeled April 1 SWE. To provide a spatially complete estimate of the 2023 snow deluge, the VIC model was run using a "drought monitor" instantiation (60) that prioritizes homogeneity of a long record, with limited addition and removal of individual stations (61). Daily output from VIC covers the period 1921 to 2023 and was forced by 1/16th degree meteorological forcings (62) that have been extended through 2023 (63). VIC is a physically based hydrologic model that has shown good comparison with in situ observations as well as with trends (64) and has comparable spatial patterns and SWE totals to other well-validated data products, though it slightly underestimates April 1 SWE relative to a higher-resolution product derived from satellite remote-sensing observations (65, 66); *SI Appendix*, Figs. S22–S24 and Text S3). VIC pixels were subset to locations with at least 50 mm average peak SWE simulated over the period of record (1921 to 2023). April 1 SWE values were extracted for each pixel, and statewide April 1 SWE values were summed across this region for each year.

Historical Climate Data. Monthly precipitation and average temperatures from the NClimGrid dataset (67) were used to evaluate the extent to which snow deluges were driven by relatively cool or wet conditions (24). NClimGrid extends from 1895 to the present across the contiguous United States at a 1/24th degree resolution. NClimGrid is derived from Global Historical Climate Network-Daily stations, using substantial quality correction procedures and climatologically aided interpolation to develop the gridded product. Errors exist due to interpolation and sampling uncertainty but are well quantified (24). For each water year from 1921-present, average monthly temperature over November to March and total monthly precipitation over the same period were calculated for the masked area of California derived from the VIC product. Throughout the manuscript, references to "temperature" or "precipitation" refer to November to March average and total, respectively. We interpret these values as estimates appropriate for relative comparisons and historical contextualization, rather than perfectly accurate values.

The daily NClimGrid product, available from water years 1952 to 2023, was used to evaluate the contributions of wet- and dry-day temperature anomalies and total wet days. Following (25), the daily average temperature anomalies on wet and dry days were calculated and averaged over November to March. Daily NClimGrid was also used to obtain the number of wet days for each year.

Projected Changes in Snow Deluge. Dynamically downscaled GCM outputs from the CMIP6 project (68) were used to contextualize the 2023 snow deluge against simulated historical and future climates, and to evaluate the expected change in snow deluges relative to median snow years using the methods of (69, 70). Nine GCMs (*SI Appendix*, Table S6) were bias corrected to the ERA5 (71) historical period for 1980 to 2010 prior to downscaling following the methods of ref. 72. These bias-corrected GCMs were then used as forcing to the WRF model (73), run at a 9-km grid length across the western United States. WRF was coupled with the Noah-MP land surface model. Simulations were run for the historical period (1980 to 2013) and the SSP 3.70 period (2015 to 2099). A single scenario was used based on initial analyses indicating that intermodel variation was greater than interscenario variability, indicating that a suite of GCMs for a single scenario could adequately capture an appropriate range of uncertainty (74). The mid-century period was defined as 2031 to 2060, with a late-century period defined as 2070 to 2099. To evaluate projected changes in snow deluge, April 1 SWE and peak SWE were calculated for each year and GCM in the WRF dataset. As with VIC, statewide April 1 SWE was calculated by summing SWE over the masked area of California, defined as grid cells that had at least 50 mm average peak SWE across 9 GCMs in the WRF record during model years 1980 to 2010.

Statistical Analysis. Return intervals for in situ and VIC-modeled April 1 SWE for both individual pixels and statewide aggregated data were estimated using a GEV distribution fit in the R programming language (75) using the extRemes package (76). Sampling uncertainty in the VIC record was calculated by bootstrapping 1,000 samples, each with ⅔ of the relevant period of record, and identifying snow deluges as years with at least a 20 y return interval relative to the full period of record (see *SI Appendix*, Text S2 for full details). For each of the three defined periods in the WRF dataset (historical, mid-century, and late-century), California-total April 1 and peak SWE values were calculated for 2 y, 20 y, and 60 y return intervals for each GCM, and median percentage changes in these return values are reported and mapped.

Data, Materials, and Software Availability. In situ April 1 SWE data are available from the NRCS: https://wcc.sc.egov.usda.gov/reportGenerator/ (58). VIC-modeled April 1 and peak SWE are available at https://zenodo.org/records/10602557 (61). NClimGrid data are available from the National Oceanic and Atmospheric Administration: https://www.ncei.noaa.gov/access/metadata/landing-page/bin/iso?id=gov.noaa.ncdc:C00332 (67). WRF simulations are available at https://aws.amazon.com/marketplace/pp/prodview-g4wqgpy2pa5dk#resources (70).

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