Characteristics and Causes of Extreme Snowmelt over the Conterminous United States

Josh Welty and Xubin Zeng

ABSTRACT: Snowmelt is an essential process for the health and sustenance of numerous communities and ecosystems across the globe, though it also presents potential hazards when ablation processes are exceedingly rapid. Using 4-km daily snow water equivalent, temperature, and precipitation data for three decades (1988–2017), here we provide a broad characterization of extreme snowmelt episodes over the conterminous United States in terms of magnitude, timing, and coincident synoptic weather patterns. Larger-magnitude extreme snowmelt events usually coincide with minimal precipitation and elevated temperatures. However, certain regions, particularly mountainous regions and the northeastern United States, exhibit greater likelihood of extreme snowmelt events during pronounced rain-on-snow events. During snowmelt extremes, snowmelt rate often exceeds precipitation in many regions. Meteorological patterns and associated water vapor transport most directly connected to extreme events over different regions are classified via a machine-learning technique. Over the 30-yr study period, there is a weakly increasing trend in the frequency of extremes, though this does not necessarily signify an increase in snowmelt magnitudes.

KEYWORDS: Extreme events; Flood events; Precipitation; Snow; Snowmelt/icemelt; Temperature

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Corresponding author: Josh Welty, welty@email.arizona.edu

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AFFILIATIONS: Welty and Zeng—Department of Hydrology and Atmospheric Sciences, The University of Arizona, Tucson, Arizona

Snowmelt is an inherently complicated phenomenon, both in origin and implications. It is a vital resource in that large segments of society and the global economy depend upon seasonal snowmelt to bolster water availability for direct consumption, agriculture, and support for ecosystems (Li et al. 2017; Qin et al. 2020). Conversely, it can pose a great threat to life and property when the melt process is exceedingly rapid and/or when it is exacerbated by concurrent precipitation and preconditioned soils from antecedent wet periods. Extreme snowmelt episodes, coupled with other meteorological processes such as rain-on-snow (RoS) events, can generate catastrophes such as landslides, dam failure, and widespread flooding damage (Freudiger et al. 2014; Jennings and Jones 2015; Li et al. 2019). Extreme snow ablation, which includes snowmelt, has also been shown to exceed extreme precipitation events at 2-day intervals for regions such as the western United States (Harpold and Kohler 2017).

Deeper understanding of the processes that drive extreme snow ablation events is essential, particularly in the context of a changing climate wherein the phase and magnitude of snowmelt and, consequently, extreme snowmelt will depart from climatological norms (Adam et al. 2009; Jeong and Sushama 2018). For example, previous studies using water balance models identified changing climate as a catalyst for transition to earlier peak river flow during late winter and early spring due to increasing surface temperatures, accelerated snowmelt rates, and a larger proportion of winter precipitation falling as rain, creating a temporal gap between peak flow earlier in the water year and peak water demand in summer (Middelkoop et al. 2001; Barnett et al. 2005). In addition to the complexity generated by nonstationarity in temperature and precipitation, analysis of snow ablation is convoluted by an array of ablation processes such as sublimation and evaporation, which are profoundly connected to atmospheric state variables such as humidity (Harpold and Brooks 2018). Furthermore, ablation rate is closely tied to snowpack depth, as deeper snowpack regions (e.g., high elevation) are likely to retain snow later in the water year when temperatures are warmer and shortwave radiation is amplified (Wu et al. 2018). Though sublimation, evaporation, and wind effects/advection are not explicitly addressed in this study, we will use the term “snowmelt” in lieu of “ablation” because snowmelt is the predominant contributor for extreme snow ablation analysis. For example, even in a sublimation-favored region like a Himalayan glacier, sublimation rates on the order of $\sim 1 \text{ mm day}^{-1}$ are much smaller than the extreme losses [e.g., $50 \text{ mm (2 days)}^{-1}$] we consider here (Stigter et al. 2018).

By identifying past extreme snowmelt events and attributing to certain meteorological patterns, there will be a greater understanding of the potential future change in characteristics of snowmelt associated with projected changes in meteorology. For example, Musselman et al. (2017a) utilized control and perturbed WRF simulations to posit that snowmelt will generally be slower in a warming climate, owing to the reduction of the snow-covered season to periods of lower available energy. The phase shift and magnitude reduction of seasonal snowmelt carries direct consequences for vegetation stress, seasonal cycles of soil moisture, and streamflow (e.g., Davenport et al. 2020). In addition to the direct effect of increasing temperatures, Harpold and Brooks (2018) demonstrated that a warming climate translates to greater ablation rate sensitivity to temperature in regions with greater humidity (e.g., Pacific Northwest).

Furthermore, both the causes and characteristics of extreme snowmelt events can vary region to region due to disparities in the governing meteorological processes. Atmospheric rivers (ARs) are a prominent example of short- to medium-duration, high-impact meteorological events that govern and modulate snowpack over many regions such as the western United States (Guan et al. 2010; Chen et al. 2019a,b; Ralph et al. 2019). Differences in the nature of precipitation, snowfall, and temperature over high- versus low-elevation locations, or humid versus dry climate regions, can affect the actual snowpack storage at a given time (López-Moreno et al. 2013), and therefore affect the catastrophic flooding potential.

Additionally, the frequency and magnitude of RoS events has been shown to vary regionally, and this too could suggest large disparities in the meteorological processes associated with extreme snowmelt over different parts of the conterminous United States (CONUS; Cohen et al. 2015).

Using our recently developed snowpack data, this study seeks to address some basic questions about the nature of extreme snowmelt episodes over the CONUS. Most fundamentally, what are the characteristics of extreme snowmelt episodes over the entire CONUS and across its different regions in terms of magnitude, timing, and corresponding temperature and precipitation conditions? Second, what meteorological patterns are responsible for snowmelt episodes in different regions of the CONUS? Is temperature or precipitation more strongly associated with extreme episodes, and does this vary from region to region? Are there regions where RoS episodes are more prevalent than others?

First, we will provide a comprehensive characterization of 2-day extreme snowmelt events over the CONUS for a 30-yr period, including the magnitudes, timing, and corresponding meteorological conditions. On a smaller scale, for case studies of extreme snowmelt events over different regions, we will identify the weather patterns that were associated with these extremes. Last, we will apply a machine-learning technique to cluster 500-hPa height maps associated with extreme 2-day snowmelt events over different regions (see regions in Fig. ES1). We will also test this methodology with other melt periods, namely, 1 and 3 days, as previous studies focus on either 1-day periods (e.g., Yan et al. 2018) or multiple periods due to the inherent differences in each (e.g., Harpold and Kohler 2017; Cho and Jacobs 2020).

The primary dataset used for this study is The University of Arizona (UA) 4-km daily snow water equivalent (SWE), or snow mass, dataset for the 30-yr period 1988–2017 over the CONUS (Broxton et al. 2016; Dawson et al. 2018; Zeng et al. 2018). The UA dataset has been constructed using Snowpack Telemetry (SNOTEL) and Cooperative Observer Program (COOP) data and has been validated by point-to-point interpolation, point-to-pixel interpolation, evaluation against snow-cover extent data, and evaluation against airborne lidar measurements (Broxton et al. 2016; Zeng et al. 2018). It has also been validated by independent research groups against gamma-ray SWE (Cho et al. 2020).

To quantify the magnitude of extreme snowmelt, we compute 2-day changes of SWE values $\{dSWE = -[SWE(t) - SWE(t - 2)]$, i.e., snowmelt magnitude $\}$ at each pixel. Here we only consider 2-day dSWE values exceeding 50 mm (~ 2 in.) in magnitude, as smaller events are of less societal impact in regard to flooding and threat to life and property. The maximum dSWE value at each pixel over the whole study period serves as the extreme event. Thus, for all the events analyzed in this study, there is one value corresponding to each pixel. While the timing of many pixels is not unique (extreme events often extend beyond the spatial scale of one 4 km $\times$ 4 km pixel, thus multiple pixels may experience extreme occurrence on the same day), there is marked variation in the spatial extent of melt events. As an extension of this analysis, we will also analyze the top 10 snowmelt events by magnitude at each pixel to test the robustness of the results and perform trend analysis.

To perform initial characterization of extreme snowmelt events, we use the 4-km daily Parameter-Elevation Regressions on Independent Slopes Model (PRISM) temperature (T) and precipitation (P) data (Daly et al. 2008) that are utilized in the production of the UA SWE dataset. PRISM mean T and accumulated P are calculated for the 2-day time periods corresponding to 2-day snowmelt events.

To characterize the meteorological patterns coinciding with extreme snowmelt events, the Modern-Era Retrospective Reanalysis, version 2 (MERRA-2) 500-hPa heights (Gelaro et al. 2017) are analyzed using the self-organizing map (SOM), and corresponding composites of water vapor transport are generated [which utilize MERRA-2 U , V , and specific humidity (Q_v)]. Prior studies have successfully implemented SOMs for clustering into the

most frequent patterns associated with certain phenomena (Cavazos 2000; Liu et al. 2006; Fassnacht and Derry 2010; Ford et al. 2015; Gibson et al. 2017). SOMs constitute an unsupervised, topology-conserving machine-learning technique. This technique utilizes inputs (in this case, 500-hPa maps corresponding to extreme snowmelt events) that, via weights/synapses, update an output layer of predetermined neuron number based on which neuron is the best-matching unit (minimum Euclidean distance from the input). For this study, a 3×3 SOM grid structure is utilized, resulting in nine neurons that constitute the output layer (i.e., nine 500-hPa maps). Simple 500-hPa maps corresponding to the middle of a 2-day snowmelt event are used.

Additionally, while 500-hPa heights are vital for characterizing synoptic conditions, it is also essential to provide some visual quantification of atmospheric moisture transport, which is a proxy for precipitation as well as humidification. This can have significant implications for the type of melt event occurring, such as RoS-driven snowmelt (e.g., Henn et al. 2020). Thus, MERRA-2 profiles of horizontal wind (U , V) and specific humidity (Q_v) are utilized to calculate integrated vapor transport (IVT) from the surface to a prescribed pressure level; for this study, we use 500 hPa as the top pressure level. IVT is one of the most common metrics for quantifying moisture advection/divergence that directly affects rainfall. For this study, IVT composite maps corresponding to the SOMs (which are trained only with 500-hPa heights) will be used to supplement discussion of the meteorological patterns.

Characteristics of extreme snowmelt events

Figure 1 provides, for the first time, basic characterization of 2-day extreme snowmelt events at 4-km resolution over the CONUS for an extended period (30 years). As expected, the largest magnitude events occur primarily over the Cascade range, as well as the Sierra Nevada and Rocky Mountains (Fig. 1a). Corresponding temperatures are mostly above the freezing point (Fig. 1b), with many locations experiencing $+10^\circ\text{C}$ of warmth during extreme snowmelt events. Additionally, many of these events coincide with relatively limited P (Fig. 1c), the exception being some of the higher-elevation regions. Last, the timing of these events with respect to water year is important, as this carries implications for water availability, evaporative stress, and potential meteorological patterns that vary seasonally and can potentially accelerate/exacerbate ablation processes (see regional climatologies in Fig. ES2). Many of the higher-elevation regions experience snowmelt extremes at later times during the water year (into spring, even into June and July), whereas many of the lower-elevation regions, including much of the eastern United States, experience extremes much earlier in the water year, typically during mid- to late winter (Fig. 1d). The highest elevations and most poleward regions experience $>50 \text{ mm (2 days)}^{-1}$ ablation most often, with sharp gradients in frequency over the complex topography of the western United States (Fig. 1e).

To ensure robustness of these results, a similar visualization is presented using the top 10 snowmelt episodes at each pixel. Previous studies have demonstrated the value of looking at top 10 events, such as RoS (e.g., Musselman et al. 2018). The threshold is adjusted so as to not exclude a superfluous amount of pixels. Pixels with less than 10 events exceeding 10 mm day^{-1} of mean snowmelt are excluded [i.e., $20 \text{ mm (2 days)}^{-1}$]. The average of the top 10 snowmelt magnitudes, corresponding temperatures, accumulated precipitations, and day of water year are presented in Fig. 2. We see that the results are consistent with Fig. 1, with most of the largest snowmelt magnitudes over the mountainous regions like the Cascades, the Sierra Nevada, and the Rockies (Fig. ES3). Small pockets of the Northeast exhibit moderately large values. The vast majority of average temperatures indicates that extreme snowmelt events often occur during above-freezing conditions, which is an intuitive result. Many of the snowmelt episodes coincide with minimal accumulated precipitation, the exceptions being the Northeast, parts of the Great Lakes, and the windward side of the Cascades and Coast

Fig. 1. (a) Distribution of extreme snowmelt events as characterized by 2-day SWE loss (greater than 50 mm), (b) 2-day average temperature, (c) 2-day precipitation accumulation, (d) timing with respect to month, and (e) number of extreme occurrences per year exceeding 50 mm. The largest-magnitude 2-day SWE change value is selected at each pixel for the period 1988–2017.

Range in the Pacific Northwest, where precipitation tends to be markedly larger. In regard to average timing, snowmelt episodes occur later in the water year (mid- to late spring) over the high elevations of the West, particularly the Rockies, and earlier in the water year (late winter to early spring) over much of the eastern half of the United States. Overall, the mean conditions for the top 10 events at each pixel are in strong agreement with findings from Fig. 1. Findings are similar for 1- and 3-day periods (Figs. ES4 and ES5).

An important question regarding snowmelt is, if/how does the contribution of precipitation to runoff potential (RP) vary region by region? We define RP following previous studies through simple mass balance: $RP = P + dSWE$, with the dSWE convention positive here (e.g., Yan et al. 2019). For this analysis, the average precipitation contribution to RP [$P/(P + dSWE)$] is displayed for the top 10 snowmelt episodes at each pixel (Fig. 3, top). Overall, it is clear that the contribution of precipitation to RP is relatively small over much

Fig. 2. As in Fig. 1, but for the top 10 snowmelt events at each pixel (exceeding 10 mm day⁻¹ average).

of the CONUS, particularly the Rockies and the northern Great Plains. However, regions such as the Northeast and the windward side of the Pacific Northwest ranges, as well as portions of the Great Lakes, exhibit larger P contributions to RP on average for the top 10 dSWE episodes. The average P contribution to RP over the northern Great Plains and much of the Rockies is surprisingly small, indicating that snowmelt is the primary driver of RP in these regions during extreme snowmelt periods. Similarly, Fig. 3 (bottom) displays the fraction of top 10 events at each pixel exhibiting RoS ($T > 0^{\circ}\text{C}$, $p > 5$ mm). Extreme snowmelt episodes are much more frequently associated with RoS over the Pacific Northwest, Northeast, and Great Lakes regions. These results suggest that many of the dSWE events over less RoS-prone regions, such as the Rockies and northern Great Plains, are more strongly influenced by air temperature/energy.

Using the corresponding precipitation and temperature values at each pixel, we can easily compute the correlation of dSWE relative to precipitation and temperature over the CONUS and regionally. Though the overall T -dSWE and P -dSWE correlations are weak, there are some indications that T and P may wield more influence over certain regions. Over regions like the Rockies, where SWE is usually much deeper and temperatures are consistently colder at higher elevations (energy-limited), there is an indication that P is more strongly associated with extreme snowmelt magnitude [$r = 0.38$ (0.31) for topmost (top 10) extremes, $p = 0.001$] with much smaller T -dSWE correlation. Over the eastern United States, where snowmelt is more SWE limited and enhanced temperatures are more common due to lower elevations and southerly advection from the Gulf of Mexico, T is more strongly associated [$r = 0.27$ (0.24) for topmost (top 10) extremes, $p = 0.001$] with much smaller P -dSWE correlation. The meridional gradients in average snowmelt magnitude, temperature, and timing over the eastern United States are consistent with the fact that events tend to occur earlier (later) at lower (higher) latitudes when temperatures are climatologically cooler (warmer). It is also important to note that humidity may at least partially explain regional differences in T -dSWE correlations in

Fig. 3. (top) Average precipitation contribution to runoff potential ($P + dSWE$) for top 10 two-day snowmelt events at each pixel. **(bottom)** Fraction of top 10 events that are characterized as RoS at each pixel.

particular, as Harpold and Brooks (2018) found steeper (flatter) ablation slopes with respect to temperature over more (less) humid regions.

Events over time

One interesting question regarding extreme snowmelt over the CONUS is, if/how is the frequency/timing of extreme events changing through time across different regions? Additionally, if/how is the frequency of extreme snowmelt episodes associated with RoS changing? Thirty years of data enable us to draw preliminary conclusions on the changing nature of snowmelt over the CONUS.

First, the occurrence of extreme snowmelt, as represented by the number of pixels per month experiencing the topmost extreme event, is shown as a time series for the whole study period (Fig. ES6). For the 4-yr period of 1996–99, there are consecutive winters with frequent and/or widespread extreme snowmelt events. This period also includes three of the four

case studies to be discussed later. Figure 4 displays the annual cycle of extreme snowmelt pixel numbers by decade and region. It also shows the annual cycle of dSWE magnitudes which, as expected, indicates that the largest magnitude episodes occur later in the water year (mid- to late spring). Over the different focus regions, snowmelt event occurrence has generally become more amplified during the most recent decade. For example, the top panel indicates that, across all CONUS pixels, the number of extreme event pixels is greater for both April and May during the most recent decade relative to the first two decades. On a regional scale, with the exception of the Northeast, all regions exhibit greater numbers of event occurrence for April and May during the most recent decade; the Northeast only shows amplification during April. Results are comparable if the minimum SWE loss threshold of 50 mm is increased to 75, 100, and 150 mm (figures not shown).

Musselman et al. (2017a) identified the potential for earlier (and hence slower due to less available energy) snowmelt in a warming world. However, Musselman et al. (2017b) indicated that, though annual average melt rates are expected to decline in a warming climate, an increase in the spatial extent and intensity of daily melt extremes over regions like the Sierra Nevada may occur. The question in the context of this study is, do we then expect to see a change in the frequency of dSWE extremes throughout the 30-year period using the enhanced sample size

Fig. 4. Average annual cycle (from December to July) of extreme snowmelt event pixel numbers for (top) the whole domain and (left) five regions and (right) the average dSWE values corresponding to these events. The green, gold, and brown lines correspond to the decades 2008–17, 1998–2007, and 1988–97, respectively.

of top 10 dSWE episodes at each pixel? Results using top 10 dSWE episodes are consistent with Fig. 4, including the amplification of the frequency of extreme occurrence during the most recent decade over the CONUS, particularly during April (and May over the Rockies) (Fig. ES7). As in Fig. 4, all of the regions indicate, as expected, that the average magnitude of dSWE extremes is largest later in the water year (right column). A simple trend analysis using the Theil–Sen estimator shows that the number of events is increasing over the CONUS by 861.6 pixels per year ($p = 0.25$), and the number of RoS episodes is increasing by 99.7 pixels per year ($p = 0.19$). It is important to note that, while not significant, these trends could suggest that the frequency of extremes is increasing. The overall trend is primarily driven by changes in frequency during the month of May. The frequency of occurrence is increasing by 155.9 pixels per year ($p = 0.03$) over the CONUS for May, and the region with the strongest increasing trend for May is the Rockies (56.8 pixels per year, $p = 0.08$). When examining the trend of average dSWE magnitude, there are no notable patterns. Thus, while the frequency of these extremes appears to increase during the period, this does not necessitate a change in the overall magnitude of these extremes.

An additional question is, are the trends in frequency of dSWE extremes different based on the snowmelt period of interest? To address this question, 1- and 3-day dSWE extreme frequency trends are also analyzed using the top 10 episodes at each pixel (Figs. ES8 and ES9). The frequency of 1-day dSWE extremes increased by 1594.4 pixels per year ($p = 0.12$), and RoS events increased by 175.0 pixels per year ($p = 0.07$). The frequency of 3-day dSWE extremes and 3-day RoS dSWE extremes also increased, but less strongly than the 1- and 2-day counterparts [479.0 pixels per year ($p = 0.39$) and 66.5 pixels per year ($p = 0.48$), respectively]. These preliminary results do indicate that, though slower snowmelt is expected in a warming world, there is the possibility for increasing frequency of extreme snowmelt events. Further study with a longer period of data will be necessary to more fully elucidate these results and find statistically significant relationships, and to provide greater detail regarding how trends may vary between SWE- and energy-limited locales.

Connecting ablation to historic flood occurrences and societal impacts

The general characteristics of extreme snowmelt, as previously delineated, provide a framework for broad understanding of the history, yet this approach lacks the proximity of singular snowmelt extremes associated with larger events that have made a profound impact on humanity and society. For a deeper understanding of extreme snowmelt episodes and the potential hazards to life and property, four case studies, as microcosms of larger snowmelt events, are described in the sidebar over very different regions, terrains, and climate regimes, as summarized in Fig. 5. As a caveat, these 2-day episodes are not singularly responsible for these events; many of these events occurred as the cumulative effect of persistent antecedent temperature or precipitation patterns over the course of multiple days to months. To provide spatial context, a map of the total pixels experiencing their top extreme for the 2-day snowmelt period ending on the indicated day for each case study, in addition to the previous six 2-day snowmelt periods, is provided (Fig. ES10). For the Pacific Northwest event, 18 of the 19 pixels experiencing their top extreme over the 7 total days occur on the last period ending with the case study on 31 December 1996. For Northern California, 16 of the 25 pixels occur during the case study 2-day period (10 February 2017). For the Red River Valley case, which was much more spatially expansive, 116 of the 560 pixels occur during the case study (3 April 1997). Last, for the Northeast event, 694 of the 1358 pixels occur during the case study (20 January 1996). From this analysis, there is a dichotomy between the spatial extent of the western U.S. and eastern U.S. case studies, with pixel extremes much more pervasive for the eastern U.S. cases even when including the previous six 2-day snowmelt periods.

Four Historic Ablation Episodes

Pacific Northwest flooding on 30–31 December 1996

The sequence of weather patterns from November through December of 1996 primed the Pacific Northwest for potential flooding by augmenting moisture stored in both soil and snowpack. A wetter period with anomalously low 500-hPa heights over southwestern Canada and the Pacific Northwest dominated the latter half of November and early portions of December, after which flow amplified over the Pacific from mid- to late December, with ridging over eastern reaches and downstream troughing over the CONUS. Though this period was drier, 50–100 mm of P (mostly snow) fell over portions of the western United States. Subsequently, ridging over the central and eastern Pacific and the associated subtropical jet stream advected warmth and moisture to the Pacific Northwest from 23 December through early January (Halpert and Bell 1997). The synoptic map (Fig. 5a) indicates strong subtropical moisture advection from south-southwest between the upstream east Pacific trough and ridge over the CONUS. Total event runoff (roughly estimated as SWE loss + P) is calculated by summing the product of pixel areas and 2-day values of SWE loss and P at all pixels (green circles in Fig. 5a) for the event. Average temperature is calculated by averaging the 2-day mean temperature over the event pixels. Total SWE (P) contribution to runoff was $1.7 \times 10^7 \text{ m}^3$ ($2.1 \times 10^7 \text{ m}^3$), which translates to an average of $67.4 \text{ mm (2 days)}^{-1}$ [$81.4 \text{ mm (2 days)}^{-1}$], and 2-day mean temperature was 1.9°C . Economic losses exceeded 100 million U.S. dollars in Washington, where mudslides were one of the primary hazards (Lott et al. 1997). This event was notable due to its timing, when climatological available energy was near its annual minimum.

Northern California flooding on 9–10 February 2017

The winter of 2016/17 was a record-breaking El Niño winter for California regarding both snowpack and precipitation (California Nevada River Forecast Center 2017). Initially, a wet autumn saturated soils and preconditioned northern California for major flood potential. In early February 2017, high pressure hovering over southeastern Alaska weakened, allowing low pressure to the south to act as a subtropical moisture conveyor to portions of northern and central California. As moisture advected over California on 7 February, $>30 \text{ mm}$ vertically integrated water vapor was observed (White et al. 2019), more than adequate to qualify as a noteworthy atmospheric river event. The 500-hPa map (Fig. 5b) indicates that the geostrophic wind was perpendicular to the California coast on 9–10 February, which is known to increase precipitation when an atmospheric river is present. As a cool front entered the northern reaches of California, an atmospheric river advected a plume of moisture into central California. The boundary between anomalous low pressure and high pressure bisected California. The eight-station average (that represents northern Sierra precipitation) recorded accumulations of 34.5, 56.9, and 84.3 mm on 8, 9, and 10 February. Oroville Dam structural compromise occurred in February 2017 in response to an enhanced number of storms during WY2017, an anomalously warm October–December 2016 period favoring rain instead of snow, and compromised spillways (Vano et al. 2019). The largest area of ablation in Fig. 5b, due to enhanced precipitation and moderate temperatures, corresponds to the regions surrounding Shasta Dam, which released water from gates at the top of the spillway in February 2017 for the first time in almost 20 years (Serna 2017). SWE contribution to runoff was $4.8 \times 10^7 \text{ m}^3$ ($2.4 \times 10^7 \text{ m}^3$ from precipitation), which translates to an average of $183.3 \text{ mm (2 days)}^{-1}$ [$90.1 \text{ mm (2 days)}^{-1}$], and 2-day mean temperature was 4.2°C .

Red River Flood over the upper Great Plains on 2–3 April 1997

An abnormally snowy few months occupied much of the winter of 1996/97 over large portions of North Dakota and western Minnesota. Over many parts of the region, September 1996–April 1997 witnessed roughly 2 times the normal snowfall, resulting in large snowpacks and an abnormally icy Red River. Intrusions of Arctic air associated with these snowy systems resulted in prolonged cold and limited snowmelt. Subsequently, during the period 21 March–5 April, warmer temperatures invaded the region due to advection of a mild Pacific air mass, with some locations reaching 15°C on multiple occasions, as well as some overnight lows remaining above freezing (Halpert and Bell 1998). Additionally, snowstorm Hannah swung through on 5 April, preceded by robust southerly advection. Moisture stored in snowpack from previous precipitation episodes was released, resulting in a notable snowmelt event known as the Red River Flood. Figure 5 (top panel) shows that the highlighted region over Minnesota experienced warm temperatures and limited precipitation. The 500-hPa height map (Fig. 5c) indicates the presence of snowstorm Hannah as it amplified over the western United States, generating pronounced low-level warm-air advection and strong moisture transport downstream over the central United States from both Pacific and Atlantic Oceans. Runoff from SWE was $9.8 \times 10^7 \text{ m}^3$ (with P contributions to runoff merely $1.3 \times 10^5 \text{ m}^3$), or on average, $56.0 \text{ mm (2 days)}^{-1}$ [$0.1 \text{ mm (2 days)}^{-1}$], and 2-day mean temperature was 7.3°C .

Northeast Flood on 19–20 January 1996

The Northeast Flood of January 1996 was a significant RoS event and inundated large swaths of the mid-Atlantic region. On 16 January, observations of SWE on the order of 76.2–139.7 mm across the region confirmed that indeed, previous snowfall episodes had charged the region with large amounts of stored water (Marosi and Hagner 2021). As a burgeoning low pressure system began to depart the northern Rockies on 17 and 18 January, strong southerly flow advected increasing temperatures and dewpoints across the region, with some daily high temperatures and dewpoints reaching $>10^\circ\text{C}$. Subsequently, ascent ahead of the cold front produced widespread, mostly liquid, precipitation. The 500-hPa map (Fig. 5d) clearly indicates the progression of a low pressure system over the central United States, with southerly flow downstream associated with the warm sector. Strong southerly flow over the eastern seaboard advected Gulf/Atlantic moisture over the eastern United States. The 2-day mean temperature for the event was 4.0°C . Runoff from SWE was $7.2 \times 10^8 \text{ m}^3$ ($4.6 \times 10^8 \text{ m}^3$ from precipitation), which is much larger than the other three case studies. This is due to the large horizontal extent of the episode which extended from Pennsylvania to Maine. On average, SWE loss flux was $64.7 \text{ mm (2 days)}^{-1}$ and precipitation flux was $40.1 \text{ mm (2 days)}^{-1}$. Though this is an individual event, perhaps it signifies a broader message in regard to the widespread snowmelt extreme potential over the eastern United States vs other regions, as the abundance of Gulf heat/moisture can rapidly degrade snowpack across a large area relatively uninhibited by topography (as opposed to the western United States).

a) Northwest

b) California

→ 250 $\frac{\text{kg}}{\text{m s}}$

c) Red River

d) Northeast

Fig. 5. (top) Temperature vs precipitation lattice corresponding to pixels from four snowmelt events, and (bottom) MERRA-2 500-hPa heights (contours and colors; m) and integrated vapor transport (vectors; $\text{kg m}^{-1} \text{s}^{-1}$) corresponding to 2-day melt events that contributed to flooding in the surrounding regions with dots in each region corresponding to pixel extremes. The pixels in the four regions (Northwest, California, Red River, and Northeast) are indicated by different colors in the bottom four panels.

Causes of extreme snowmelt

To further characterize extreme snowmelt events, we use SOMs to elucidate the most closely associated synoptic weather patterns. SOMs constitute an unsupervised machine-learning technique that performs clustering of input data into a number of predetermined neurons, and these neurons then serve as two-dimensional classifications of the dataset (Liu and Weisberg 2011). SOMs have proven to be effective tools for capturing patterns within input data (Liu et al. 2006). In this study, SOMs are used to provide basic characterization

of the meteorological patterns associated with extreme snowmelt events over the previously mentioned five prescribed regions: Pacific Northwest, Sierra Nevada, Rocky Mountains, Great Lakes, and Northeast.

Here, we use 1,497 maps of 500-hPa geopotential height to train a 3×3 SOM grid (i.e., nine output nodes), with each map corresponding to at least one snowmelt “episode.” If an episode ends on day t (i.e., snowmelt period occurring during days $t - 1$ and t), we utilize the 500-hPa height map at the end of day $t - 1$. We define an episode endpoint on any day during the period 1988–2017 when at least five pixels exhibit their extreme 2-day dSWE (only considering magnitudes ≥ 50 mm loss over 2 days). In other words, each one of the 1,497 maps corresponds to a specific day when at least five pixels over the CONUS domain experience their extreme snowmelt event, recalling that currently we are concerned with only the most extreme snowmelt event at each pixel (i.e., each pixel has one date corresponding to the most extreme snowmelt event at that pixel). The configuration of the 3×3 SOM grid is chosen to strike a balance between the potential effects of “washing out” some of the finer details using fewer maps and superfluous complexity using more maps, as well as provide sufficient nuance to analyze RoS versus non-RoS events over each region.

Next, we use the trained map network to classify maps corresponding to snowmelt episodes over the whole CONUS domain, then events specifically over the Northwest ($n = 272$ maps), Sierra Nevada ($n = 214$ maps), Rockies ($n = 492$ maps), Great Lakes ($n = 181$ maps), or Northeast ($n = 262$ maps) regions. Similarly, each of the episode maps for the discrete regions are defined under the same criteria, with at least five pixels exhibiting their extreme on a given day within each domain. We can then calculate the fraction of maps corresponding to snowmelt episodes over each region that match each of the nine trained maps (e.g., the number of Rocky Mountains episode maps classified as one of maps in Figs. 6a–i, divided by 492, i.e., total number of Rocky Mountains snowmelt episode maps). We repeat this analysis for RoS and non-RoS events over each region to identify how synoptic configurations can vary between the two types of events, even when focusing on the same region. RoS (non-RoS) events for each domain are identified on days when the average of precipitation accumulations are >5 (≤ 5) mm. For all analyses, the actual 500-hPa height maps, rather than the 500-hPa height anomaly (with seasonal cycle removed) maps, are utilized because snowmelt extremes are associated with seasonality. Thus, seasonal influence is retained.

The highest fraction of maps corresponding to episodes over each region, or in other words, the “most representative map” for each region, are as follows in Figs. 6 and 7: map “g” for the Northwest, map “d” for the Sierra Nevada, map “a” for northern Rockies, map “c” for the Great Lakes, and map “e” for the Northeast. For the Northwest and Sierra Nevada, the match with maps “g” and “d” is consistent with expectations, as we see a pattern indicative of a subtropical jet and an atmospheric river positioning over the West Coast, with a ridge squarely over the western United States for map “g” and the inflection point of the upstream flank of the ridge near the coastline for map “d.” The Rocky Mountains episode preference for map “a” also makes sense with Fig. 1 in mind, as much of the timing is later in the spring when temperatures/heights have grown markedly since late winter/early spring. Additionally, there is ridge amplification over the Rocky Mountains. The majority of snowmelt episodes over the Great Lakes and Northeast corresponding to maps “c” and “e” indicates a preference for melt to occur when the ridge is positioned over central and eastern portions of the United States, indicative of warm southerly advection and frontal passage between the downstream ridge and upstream trough over the western United States. For the Northeast/map “e,” IVT is shifted to the east and exhibits a greater zonal component compared to the Great Lakes/map “c” configuration.

As mentioned earlier, the IVT composites are helpful in that they provide an immediate sense for the moisture transport associated with each of the synoptic configurations. For the

Fig. 6. Self-organizing maps of 500-hPa heights associated with snowmelt events over different regions defined in Fig. ES1. Vectors are integrated vapor transport composites corresponding to the 500-hPa maps. Circles indicate which map is the most representative for each region.

Pacific Northwest and Sierra Nevada snowmelt configuration (maps “d” and “g”), the IVT pattern is distinct from the other setups in regard to IVT orientation over the Pacific. On the upstream flanks of the ridge axis over the western United States, there is an enhanced IVT region oriented southwest–northeast with contours intersecting the coastline, suggesting that moisture intrusion into the western portions of the United States is generally associated with this synoptic pattern. Overall, for the Pacific Northwest and Sierra Nevada snowmelt configurations, the IVT composites are much more characteristic of West Coast atmospheric river orientation than most of the other configurations (Payne et al. 2020).

For the Great Lakes and Northeast snowmelt configurations (maps “c” and “e”), IVT influence reaches the central and eastern portions of the United States, extending prominently to near the northern border and driving meridional moisture advection from the Gulf of Mexico associated with frontal passage ahead of the upstream low. The Northeast IVT structure is slightly stronger, slightly more zonal, and shifted to the east compared to the Great Lakes setup. Last, for the Rockies configuration (map “a”), the pattern is less defined, with no clear IVT structure. This indicates that moisture transport may be less responsible for extreme snowmelt events over the Rockies, and that timing (seasonality) of these events may be a stronger driver of snowmelt. The analysis is repeated for 1- and 3-day snowmelt periods as well, using the singular top extreme event at each pixel and adjusting the minimum threshold to 25 and 75 mm for 1- and 3-day snowmelt to be congruous with the 50 mm for 2-day (Figs. ES11 and ES12).

To further elucidate the synoptic patterns associated with regional snowmelt events, we use the same trained nine-map network to classify RoS and non-RoS events over each domain (Figs. 6 and 7). The fraction of each regional map set corresponding to RoS events is 35% for Northwest, 18% for Sierra Nevada, 19% for Rockies, 24% for Great Lakes, and 28% for Northeast. For the Northwest and Sierra Nevada, map “i” indicates the presence of a trough near the coast. For the Rockies, map “e” shows a trough propagating through the central United

Fig. 7. (top) Bar plots displaying the fraction of event maps for the CONUS (all) and five regions corresponding to each of the nine maps in Figs. 6a–i. **(bottom)** As in the top panel, but for (left) RoS and (right) non-RoS events.

States. For the Great Lakes (Northeast), maps “c” (“e”) also implicate frontal passage and deep moisture transport, with more (less) meridional orientation, respectively. Thus, overall, RoS events are expectedly tied to frontal structures within the vicinity of the regions of interest. For non-RoS events, the synoptic setups are more similar to the overall analysis that neglects the RoS/non-RoS partitioning. The representative maps are as follows: map “d” is the Northwest, Sierra Nevada, and Rockies and map “c” is the Great Lakes and Northeast. As described before, map “d” is characterized by amplified ridging over the western United States, with deeper heights indicative of warmer temperatures, and map “c” is characterized by enhanced moisture transport from the Gulf of Mexico over the eastern United States on the upstream flank of a ridge over southeastern portions of the country.

Summary

The results presented here constitute a first-of-its-kind study providing a broad picture of the nature of extreme snowmelt over the CONUS. Extreme snowmelt events here are characterized by magnitude, associated meteorological conditions, and timing, and are classified based on near-surface temperature and precipitation conditions. Additionally, a number of case studies over different regions with large societal impacts are explored with the purpose of delineating

snowmelt mechanisms associated with distinct meteorological patterns. Furthermore, a machine-learning technique is utilized to classify meteorological patterns most directly connected to extreme snowmelt events over the different predetermined regions. Last, time series over the 30-yr period are employed to analyze any potential long-term changes in the occurrence of snowmelt with regard to timing and magnitude.

Overall, there is large variation in magnitude, timing, and coincident temperature and precipitation conditions for the top extreme snowmelt events. The largest-magnitude events occur over the mountains of the western United States, particularly the Cascades and Sierra Nevada (average dSWE of 137.5, 141.8, 112.4, 62.1, and 83.2 mm for five regions: Northwest, Sierra Nevada, Rockies, Great Lakes, and Northeast domains, respectively), and the latest events tend to occur during late spring and early summer over the Rockies. More events are associated with higher temperatures over the Northeast and Great Lakes compared to the western United States. Average temperature corresponding to melt events are higher for the eastern United States (10.5° and 8.9°C for Great Lakes and Northeast, respectively) compared to the western United States (8.8°, 8.0°, and 8.2°C for Northwest, Sierra Nevada, and Rockies, respectively).

Many events over the western United States are associated with anomalous high pressure and enhanced atmospheric river vapor transport on the upstream flank, whereas many events over the Northeast occur during frontal passage with large precipitation accumulations. Average precipitation accumulations are greatest for the Northwest and Northeast (5.1 and 5.8 mm, respectively), with slightly smaller amounts over the Sierra Nevada (3.4 mm) and the lowest over the Rockies and Great Lakes (1.9 and 2.7 mm, respectively). However, during snowmelt extremes, snowmelt rate exceeds precipitation rate in many instances, particularly over the Rockies, leeward side of the Sierra Nevada, and over the northern Great Plains. Events over the Rockies are driven more so by seasonality, with many occurring during the late spring when available energy is greater.

For the three decades from 1988 to 2017, there is a weakly increasing trend of extreme snowmelt occurrence, as well as RoS-related extreme snowmelt occurrence, though there is no clear trend for average extreme snowmelt magnitude. Regardless, as the climate system continues to evolve with global warming, extreme snowmelt will become increasingly more relevant, with implications for water availability, ecosystem stability, and potential hazards to life and property.

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Data availability statement. UA SWE data are available from the National Snow and Ice Data Center (<https://nsidc.org/data/nsidc-0719/versions/1>). PRISM data can be downloaded from the PRISM Climate Group (<https://prism.oregonstate.edu/>). MERRA-2 data are available from the Goddard Earth Sciences Data and Information Services Center (<https://disc.gsfc.nasa.gov/>).

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