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Seasonal and Ephemeral Snowpacks of the Conterminous United States

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Abstract: Snowpack seasonality in the conterminous United States (U.S.) is examined using a recently-released daily, 4 km spatial resolution gridded snow water equivalent and snow depth product developed by assimilating station-based observations and gridded temperature and precipitation estimates from PRISM. Seasonal snowpacks for the period spanning water years 1982–2017 were calculated using two established methods: (1) the classic Sturm approach that requires 60 days of snow cover with a peak depth >50 cm and (2) the snow seasonality metric (SSM) that only requires 60 days of continuous snow cover to define seasonal snow. The latter approach yields continuous values from −1 to +1, where −1 (+1) indicates an ephemeral (seasonal) snowpack. The SSM approach is novel in its ability to identify both seasonal and ephemeral snowpacks. Both approaches identify seasonal snowpacks in western U.S. mountains and the northern central and eastern U.S. The SSM approach identifies greater areas of seasonal snowpacks compared to the Sturm method, particularly in the Upper Midwest, New England, and the Intermountain West. This is a result of the relaxed depth constraint compared to the Sturm approach. Ephemeral snowpacks exist throughout lower elevation regions of the western U.S. and across a broad longitudinal swath centered near 35° N spanning the lee of the Rocky Mountains to the Atlantic coast. Because it lacks a depth constraint, the SSM approach may inform the location of shallow but long-duration snowpacks at risk of transitioning to ephemeral snowpacks with climatic change. A case study in Oregon during an extreme snow drought year (2014/2015) highlights seasonal to ephemeral snowpack transitions. Aggregating seasonal and ephemeral snowpacks to the HUC-8 watershed level in the western U.S. demonstrates the majority of watersheds are at risk of losing seasonal snow.

Keywords: ephemeral snow; snow; snowpack; seasonal snow; United States

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1. Introduction

Snowfall occurs over a wide range of landscapes worldwide [1–3], providing essential services to ecosystems and human society [4–6]. Environmental drivers, notably precipitation, radiation, and wind, govern the temporal persistence and spatial extent of snow cover as well as the amount of water stored in the snowpack by driving patterns of snow accumulation and its ablation [7–9]. For seasonal (i.e., non-perennial) snowpacks, these processes vary across time scales ranging from minutes to seasons and space scales from meters to thousands of kilometers [7]. Vegetation and topographic characteristics, such as canopy cover, slope, aspect, and elevation also determine the behavior of snow cover [10–12]. Ultimately, interactions between the topoclimate, meteorology, and land surface conditions determine the physical character of snow cover during and following snow deposition [7,8,13,14].

Classifying snow cover in terms of its seasonal and physical characteristics has long been a focus of cryospheric and hydrologic science [13] with the earliest classification systems developed in the early 1900s [15,16]. Prior to the advent of remote sensing and numerical modeling, snow classifications were primarily qualitative [16] and based upon field observations, though more quantitative characteristics were later incorporated [17]. Sturm et al. [13] introduced a physically-based classification system based upon multiple physical

snowpack parameters with the goal of global applicability. The approach developed by [13] has since become a widely-used standard.

Delineating regions of seasonal and ephemeral snow at scales relevant to decision making (i.e., typically less than 10 km) aids identification of regions where climate change poses the greatest risks for snow and the systems that depend on snowpack [18–21]. Shifts from seasonal to ephemeral snowpacks will disrupt upstream and downstream environments by altering terrestrial hydrological processes and states and their predictability [5,9,22]. Vegetation adapted to seasonal snow cover and its associated hydrologic regime may be less resilient under a shift towards an ephemeral snow regime characterized by a longer and drier growing season [21]. Increased watershed contributing area with a growing transient snow zone area enhances flood risk [23], especially as the snowline rises [24] and the fraction of precipitation falling as snow declines [25]. A compounding impact results as these changes can also increase the price of water [5].

Because of their importance as natural freshwater reservoirs [5], especially in mountains [4,6,26], seasonal snowpacks persisting for longer than two months [13] receive the bulk of scientific attention [4,9,27]. Seasonal snowpacks tend to experience distinct accumulation and ablation seasons that are sequential in time [7]. Higher elevation (i.e., colder and typically wetter) watersheds with seasonal snowpacks produce peak streamflows in summer, recharging reservoirs at the time of peak downstream demand, and are important sources of warm season baseflows for aquatic ecosystems [4]. Changes in seasonal snowpack accumulation and melting patterns have the potential to alter both peak streamflow and late warm season low flows [18,20] as well as vegetation dynamics [21], disturbance regimes [28], soil water availability [29], and water and solute transport in upland watersheds [27]. Seasonal snowpacks also provide economic benefits to rural economies from recreation [30–34] and agriculture [5,35].

Ephemeral snowpacks form the transition region between seasonal snow regions (if one exists) and non-nival (i.e., snow-free) regions. These shallow and warm snowpacks often result from a single snowfall event [13]. Ephemeral snowpacks differ from seasonal snowpacks by experiencing accumulation and melting processes nearly simultaneously [7]. This aspect makes them challenging to observe and model [9,14]. Ephemeral snowpacks occur in the transient snow zone, defined by Harr [36] as the location of where snow falls and melts more than once per year. This transient zone is an important region from erosion and flooding perspectives [23,36], as rapid melting of shallow, low cold content snowpacks can produce higher rates of water input to soil than direct precipitation. Regions with ephemeral snow also demonstrate different soil moisture and other hydrologic responses compared with seasonal snowpacks [9] as well as markedly different surface energy budgets [7].

The increasing availability of spatially distributed (i.e., gridded) and temporally continuous snow products increases our ability to classify and evaluate change in snowy but often sparsely instrumented regions [37] thereby improving our ability to identify regions most sensitive to potential shifts towards increased ephemerality and associated impacts. These products are typically developed using observational data derived from satellite measurements [2,38–43], station observations [44,45], or numerical models using station-based or remotely sensed observations as input [46–49]. As noted by [13], difficulty in producing generic snow classifications that can be measured and applied across landscapes limits the applicability of many approaches. Applying snow seasonality classification schemes to readily available parameters (e.g., snow water equivalent; SWE) from spatially distributed products at daily temporal resolution allows for easy calculation and comparison of seasonality definitions.

My aim here is to demonstrate the application of both classic [13] and recently-developed [9] snow seasonality classification schemes to a newly-available spatially distributed snowpack reanalysis product [45] in order to highlight similarities and differences between these classification regimes across the varied landscapes of the United States (U.S.). The classification schemes used herein rely on indicators of snow presence (e.g., non-zero

SWE) and do not require field-based measurements of snowpack stratigraphy or grain size [13]. However, they do require continuous daily values, which can be difficult to obtain from remotely-sensed platforms resulting from cloud cover or satellite overpass frequency. A central goal, beyond providing a reference for the seasonality classification of a given regions snowpack, is to motivate continued analysis of spatially distributed snowpack products, especially projections, in order to identify regions sensitive to transitions from seasonal to ephemeral snowpacks in both lowland and montane environments. Identification of such locations will aid assessments of impacts of snow seasonality change to human and natural systems. The analyses performed herein represent an initial effort to broadly classify and identify sensitive (or "at-risk" [19]) seasonal snowpacks across the U.S. at the native 4 km scale and aggregated to the scale of small watersheds. By identifying vulnerable regions and assessing impacts for a range of past and projected scenarios, adaptation strategies can be identified, prioritized, and implemented to minimize negative outcomes on the environment and economy.

The manuscript is organized as follows: Section 2 describes the University of Arizona Snow product, how the snow seasonality classifications used are defined, and the digital elevation and hydrologic datasets used to evaluate snow seasonality across topography and at the small watershed scale. In Section 3, the key results are highlighted from each seasonality classification and are compared against one another, showing that seasonal snowpacks have greater snow water equivalent and snow depth and are confined to the higher elevations in the mountainous western U.S. and lower elevation regions of the high latitude regions of the eastern U.S. Section 3 also provides results from a case study of an extreme snow drought year in Oregon and the identification of 'at-risk' small watersheds throughout the western U.S. The discussion in Section 4 explores possible reasons for differences between the snow seasonality classification schemes, highlights possible conditions leading to loss or retention of seasonal snowpacks in low-snow or shorter-duration snowpack years and the implications of these losses. It provides suggestions for future research, which largely focus on incorporating additional datasets and products to better constrain average snowpack seasonality and its variability. A brief summary of the paper and its primary conclusions and suggestions for future work are provided in Section 5.

2. Materials and Methods

2.1. The University of Arizona Snow Product (UAswe)

I used the daily gridded 4 km snow product developed by the University of Arizona [45]; hereafter UAswe). The UAswe product provides continuous spatial coverage through assimilation of in situ measurements of snow water equivalent (SWE) and snow depth (SD) from the Natural Resources Conservation Survey's Snow Telemetry Network (SNOTEL) and National Weather Service Cooperative Observer Network and gridded 4 km temperature and precipitation from the Parameter-elevation Regressions on Independent Slopes Model (PRISM; [50]). Specific details about the methodology used to develop UAswe and various tests of its robustness can be found in [44,51,52].

UAswe spans water years 1982–2017. In the western United States, a water year begins on October 1 and ends on September 30 of the following year, with the ending year corresponding to the named year (e.g., water year 2017 spans 1 October 2016–30 September 2017). Water year definitions vary by location in terms of their start and end times, but generally correspond to the period covering a full cycle of accumulation from zero to peak snowpack and then complete melting back to zero SWE. This may span 2 calendar years (e.g., northern hemisphere) or could plausibly fit within a single calendar year (e.g., southern hemisphere), but ultimately depends on regional snow accumulation and melting cycles. Glaciated and permanently snow-covered (firn) regions, which cover a very small total area in the conterminous U.S., are exempt from the UAswe dataset. As such, the vast majority of water resources derived from frozen water in the conterminous U.S. originate from seasonal and ephemeral snowmelt and not runoff from glacial or firn regions. For example, the Colorado River Basin has no ice cover and the Columbia River in

the northwestern U.S. has only 0.31% ice cover [4]. Elevation analyses were performed by re-gridding the 800 m PRISM elevation digital elevation model to the 4 km resolution of the UAswe product using two-dimensional bilinear interpolation. For reference, a topographic map of the conterminous U.S. is provided in Figure 1 with key regions and mountain ranges discussed in the text labeled.

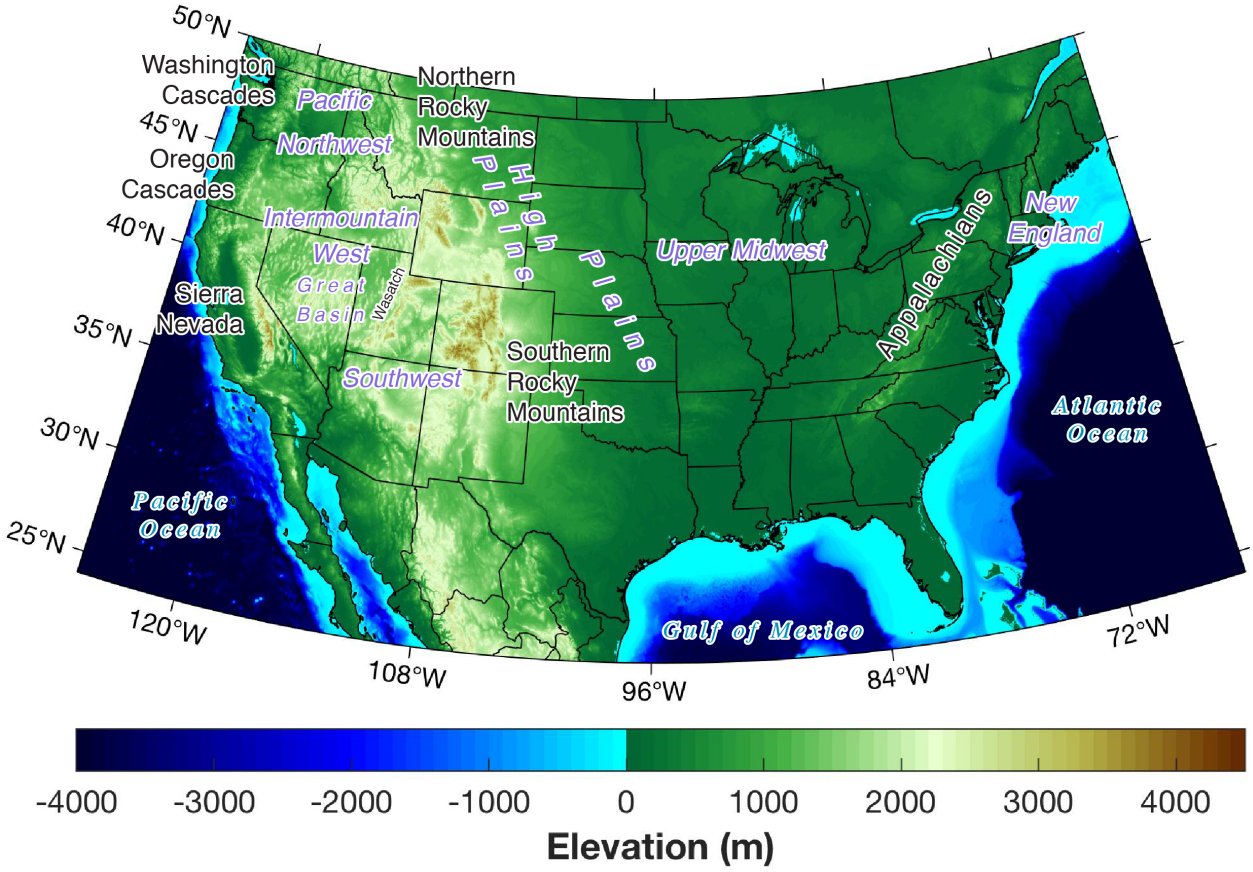


Figure 1. Topography of the conterminous U.S. and surrounding ocean bathymetry from the 1 arc-minute ETOPO digital elevation map [53]. Regions (light purple italicized text) and mountain ranges (black standard text) discussed in the main text are highlighted.

2.2. Snow Seasonality Definitions

Snow seasonality can be categorized utilizing snowpack variables including snow cover duration, snow depth, and snow density (e.g., [13]). I defined snow climates in two ways, both of which can be readily calculated using daily SWE and snow depth. First, I used the Sturm et al. [13] method (hereafter "Sturm") where 60 days of continuous SWE are required with a peak depth of at least 50 cm. This approach lumps the tundra, taiga, alpine, and maritime snowpack classifications based upon the duration of snow cover [13]. By providing both SWE and snow depth, the UAswe product allows the calculation of Sturm seasonal snowpacks without requiring assumptions about snowpack density to calculate depth from SWE (or vice-versa). Second, I calculated the snow seasonality metric (SSM) introduced by Petersky and Harpold [9], which did not include a depth criteria and only required an indicator of snow presence at the daily timescale. The SSM was previously applied over the Great Basin region of the Intermountain West by Petersky and Harpold [9] using gridded output from the Snow Data Assimilation System model [47]. The SSM is defined as follows:

$$SSM = \frac{Days_{Seasonal\ Snow} - Days_{Ephemeral\ Snow}}{Days\ with\ Snow} \quad (1)$$

where days with seasonal snow are defined as the number of days with at least 60 days of continuous non-zero SWE. The SSM is calculated over a water year and thus represents an annual measure of snow seasonality. Completely ephemeral snowpacks receive a value of -1 whereas completely seasonal snowpacks receive a value of +1. The SSM is an ideal approach to use with spatially distributed snow estimates because most *in situ* snow observations are located in regions characterized by historically seasonal snow, only becoming ephemeral in extreme years [9]. In practice, because early or late season snowfall events led to additional days with snow that were classified as ephemeral, fewer 'perfectly' seasonal snowpacks (i.e., $SSM = 1$) were identified than otherwise might be expected. In a few cases, I identified double seasonal peaks. In these cases a seasonal snowpack was established, melted to zero SWE, then a second seasonal snowpack formed. In this situation I considered the longest-running continuous snowpack as the value for the seasonal snow days term in Equation (1).

Snowpack classifications from the 4 km UAswe product were further evaluated in two ways. First, I grouped classifications into 1° latitudinal bins to provide a distribution of snowpack seasonality classification across elevations for each latitudinal bin. Second, I used the eight digit U.S. Geological Survey Hydrologic Unit Codes (HUC-8) watersheds [54] to aggregate cells categorized as seasonal or ephemeral. I report the percentage declines between "expected" (more than 28 of 36 years classified as seasonal) and minimum (or "worst in record") seasonal cells to highlight 'at-risk' watersheds where losses of seasonal snowpacks may impact water resource management or ecosystem processes. For transitioning cells, the volume of water no longer stored in seasonal snow for each HUC-8 and percentage decrease in seasonal snow proportion is reported. For the Oregon case study, I selected water year (WY) 2015. Characterized by above-average precipitation but below-normal snowpack, WY2015 motivated development of the concept of warm snow droughts in maritime mountain regions [55–57]. In addition to examining how a warm snow drought influences snow seasonality, I explored the use of percentiles to help identify grid-cell level snow drought conditions with the goal to test whether a percentile-based approach can identify anomalies associated with transitions from seasonal to ephemeral snowpacks.

3. Results

3.1. Snow Seasonality

The SSM approach categorized large regions of the conterminous U.S. as a seasonal snowpack, particularly in the coastal Cascades and Sierra Nevada, Intermountain West, Northern Plains, Upper Midwest, and New England (Figure 2a). The total area of median seasonal snowpack (SSM > 0) equaled 2,651,936 km^2. A slope from the highest SSM values (SSM > 0.9) towards lower SSM values was observed along the periphery of mountain regions or elevated terrain in the western U.S. and along the southern margin of the seasonal snowpacks of the High (northern) Plains, Upper Midwest, and New England. The larger the median value of SSM, the greater the seasonality of the snowpack (i.e., more days of seasonal snowpacks and/or more frequent years of seasonal snowpacks). The Sturm method generally identified similar regions but with roughly two-thirds less areal extent (Figure 2b); a total of 736,864 km^2 of Sturm snowpacks are classified. Seasonal snowpacks identified by the SSM but absent from the Sturm approach included the High Plains, much of the Upper Midwest, and areas of New York and Pennsylvania. Overlapping areas of median values satisfying the Sturm and SSM approach are shown in (Figure 3). The majority of overlap was found in major western U.S. mountain ranges, the Great Lakes region of the Upper Midwest, the Appalachians of the Virginias and New England. The vast majority of overlap fractions exceeded 0.9; lower values were found sporadically in the Upper Midwest and New England with the overlapping areas following the Sturm-classified seasonal snowpacks (cf. Figure 2b).

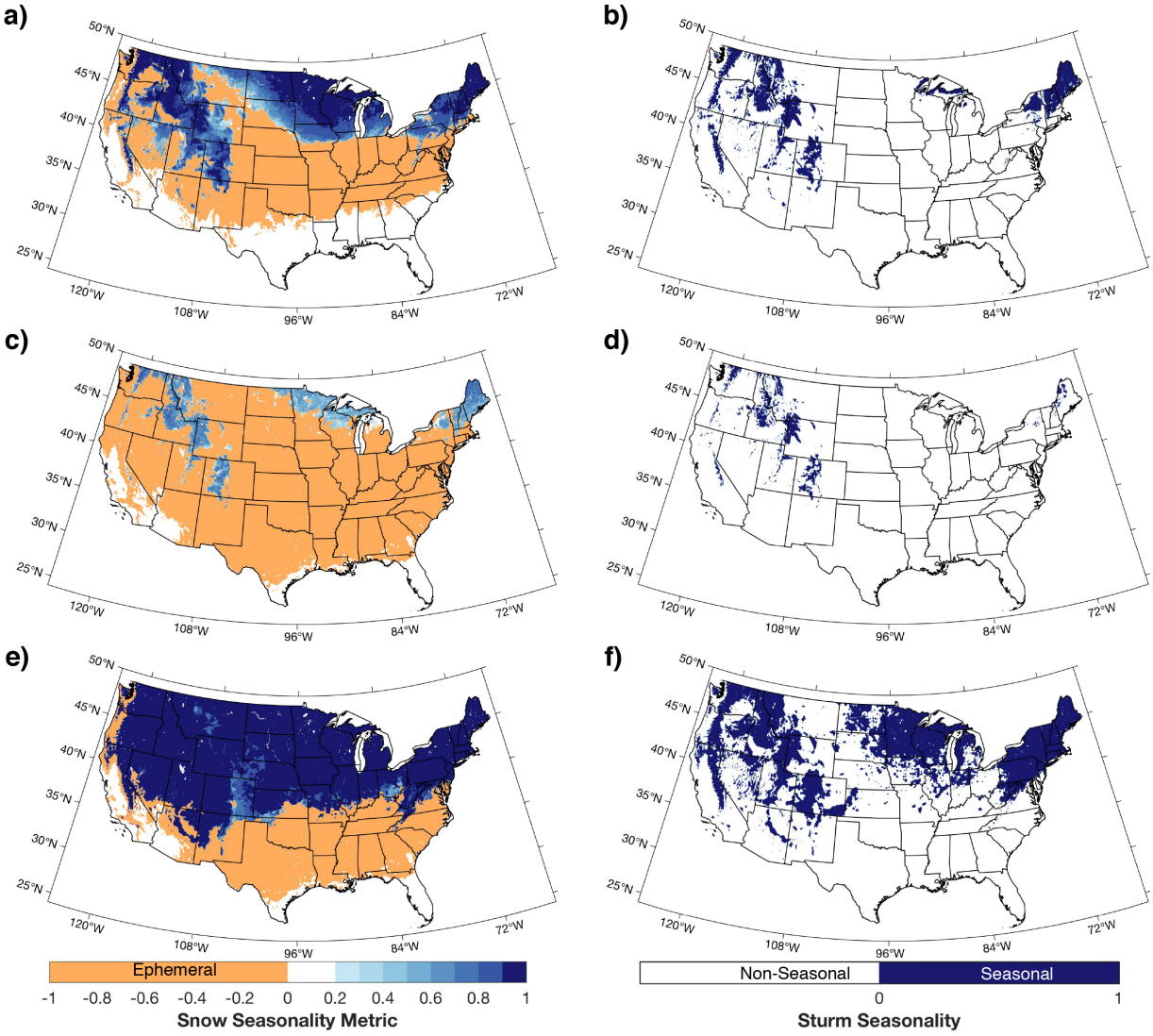


Figure 2. (**a**) Median snow seasonality metric (SSM). (**b**) Median Sturm seasonality. (**c**) Minimum snow seasonality metric. (**d**) Minimum Sturm seasonality. (**e**) Maximum extent of seasonal snow based on the snow seasonality metric. (**f**) Maximum extent of seasonal snow based on the Sturm approach.

Minimum values of the SSM indicated a large fraction of the conterminous U.S. can experience an ephemeral snowpack (Figure 2c). The UAswe method never created any type of snowpack in the low elevation and coastal regions of California, Arizona, and near the Gulf of Mexico coast. Areal coverage of seasonal snowpacks can contract, as shown by smaller values of SSM and the reduced spatial extents of values greater than 0. The transitions from seasonal to ephemeral snowpacks were most prominent in the maritime ranges of the Cascades and Sierra Nevada of the western U.S. and the Intermountain ranges of eastern Oregon, eastern Nevada, southern Utah, as well as northern Arizona and New Mexico. The northern Cascades of Washington and the Rocky Mountains and Wasatch Range (northern central Utah) maintained seasonal snowpacks, though the lower values of SSM indicated additional days that are classified as ephemeral, during these 'worst in record' years. Reductions in seasonal snowpacks were also possible during poor snow years with the Sturm approach (Figure 2d). The largest reductions agreed with the SSM approach in the western U.S., however the Sierra Nevada remained classified as a seasonal snowpack. The Upper Midwest and New England regions underwent extensive losses of seasonal snowpack in minimal years. Note that both the minimum and maximum values (discussed next) corresponded to 'all time' minimum/maximum values for each

individual gridpoint and two adjacent points may experience minimum or maximum values in different years.

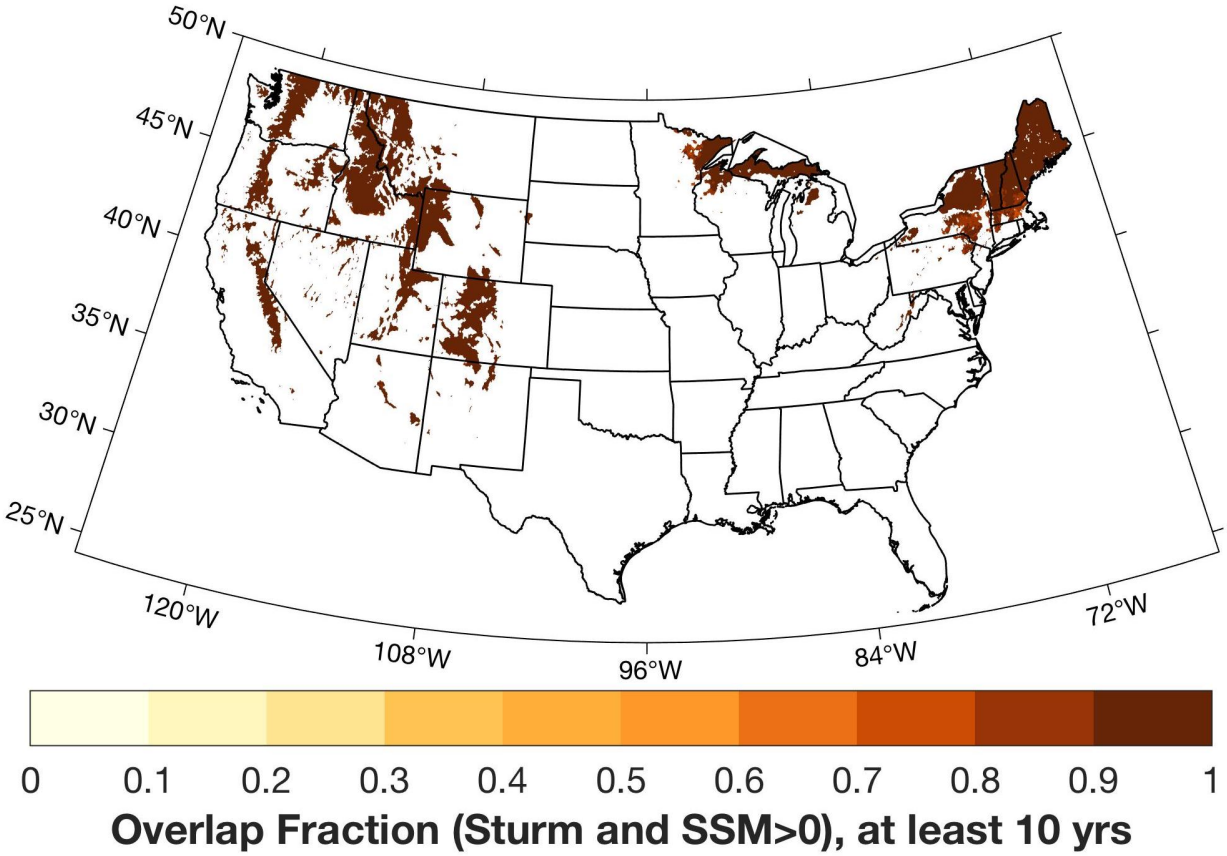


Figure 3. Agreement (overlap fraction) between seasonal snowpacks identified via the snow seasonality metric and Sturm seasonality classification schemes. Only grid cells with at least 10 years of snow observations were considered.

Maximum SSM values highlighted that over half the conterminous U.S. could potentially experience a seasonal snowpack (Figure 2e). East of the Rocky Mountains, the seasonal snowpack formation occurred north of 37° N. Because of the 50 cm depth requirement in the Sturm method, less spatial expansion of seasonal snowpacks was evident (Figure 2f) compared to the SSM maximum values (Figure 2e). Seasonal Sturm snowpacks could expand in western mountains and in the Upper Midwest, High Plains, and New England.

Counts of years satisfying either seasonal or ephemeral snowpacks are shown in Figure 4. These counts can be interpreted as the frequency of which a given type of year occurred; different methods identified varying numbers of years satisfying the given classification scheme. In the case of the SSM, this can help identify locations that experienced some number of seasonal and ephemeral years rather than all seasonal or all ephemeral. Comparing counts of seasonal years defined by the SSM approach (Figure 4a) with counts of Sturm seasonal years (Figure 4b) further demonstrated the impact of the 50 cm depth criteria in the Sturm approach. This criteria led to nearly all years satisfying the criteria or none of the years. In contrast, seasonal snowpacks identified via the SSM approach were most common in the regions described previously, but the gradation in frequency (a decrease in counts of years) of seasonal years highlighted the transition from locations that nearly always achieved a persistent snowpack towards those that did not achieve one. Prime examples occurred along the southern periphery of the High Plains, Upper Midwest, and New England as well as throughout the Intermountain West. The lower elevation coastal regions of the western U.S., as well as the Southwestern U.S. rarely achieved seasonal snowpacks. Seasonal snowpacks

occurred with decreasing frequency east of the Rocky Mountains from 40° N southwards. Seasonal snowpacks abruptly declined in frequency immediately in the lee of the Rocky Mountains in central Montana southeastwards across Wyoming and then southwards across the Front Range of Colorado into northern New Mexico.

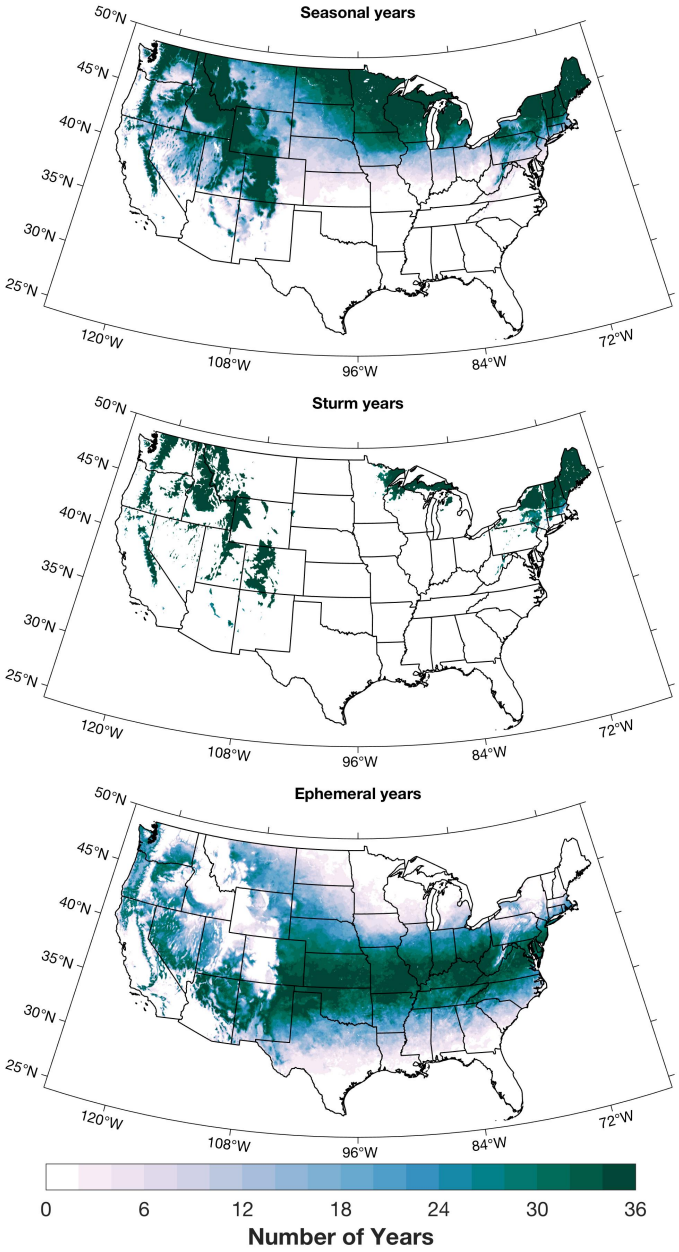


Figure 4. Counts of years (maximum of 36) that each classification was satisfied: (**top**) Seasonal snowpacks defined by the snow seasonality metric (SSM); (**middle**) Seasonal snowpacks defined by the Sturm method; (**bottom**) Ephemeral snowpacks defined by the snow seasonality metric (SSM).

A peak in ephemeral snowpack frequency was found across the eastern half of the U.S. (east of the Rocky Mountains; Figure 4c), increasing in frequency (i.e., counts) consistent with the decrease in frequency of seasonal snowpacks. In the mountainous western U.S., ephemeral snowpacks were found along the flanks of major mountain ranges (e.g., the Sierra Nevada of California and the Cascades of Washington and Oregon) or in elevated basins of the Intermountain West (eastern Oregon and Washington and northern Nevada). The southeast-trending band from central Montana to eastern Wyoming demonstrates a

balance between seasonal and ephemeral years. Further south along the lee of the Rocky Mountains, ephemeral years became more common, extending into the Texas Panhandle, much of New Mexico, and northern Arizona. The peak in ephemeral snowpack frequency was found along a zonal (east-west) band spanning 35–39° N before declining southwards into the climatologically warmer and more humid Gulf of Mexico coastal region of the southeastern U.S.

3.2. Peak Snow Water Equivalent and Snow Depth

Figure 5a provides a map of the median annual maximum (or peak) SWE across the conterminous U.S. for reference. The "natural reservoirs" of the high mountains of the western U.S. were highlighted by maximum SWE values greater than 300 mm. Consistent with these regions were areas of median annual maximum snow depths exceeding 500 mm (in the highest areas exceeding 1500 mm; Figure 5c). Cumulative distribution function plots showed how in all but the most extreme cases, ephemeral snowpacks exhibited lower values of SWE compared to seasonal snowpacks (Figure 5b) and demonstrated shallower snow depths (Figure 5d). Outside of the uppermost percentiles, ephemeral snowpacks did not exhibit a wide range in peak SWE or snow depth. This is to be expected by definition because these snowpacks accumulated and quickly melted, rarely accumulating more than 100 mm SWE (Figure 5b) or 250 mm of depth (Figure 5d). The differences between snowpack types diverges das one moved upwards from the lower quintile into the upper quintile of the distributions. This is reflective of both the upper bound of ephemeral snowpack accumulation and the ability for high elevation western U.S. mountains to develop deep snowpacks storing substantial water.

3.3. Snow Seasonality Relations to Elevation and Latitude

The distribution of seasonal and ephemeral snowpacks as a function of elevation indicated the role of elevation and latitude in defining snowpack seasonality (Figure 6). In all cases, only grid points with at least 10 years of either a seasonal or ephemeral snowpack were considered. Both the SSM (Figure 6a) and Sturm (Figure 6b) approaches agreed on lower (i.e., south of 35° N) and middle (e.g., between 35° N and 40° N) latitude regions necessitating elevation to achieve seasonal snowpacks. The consistencies between the two approaches declined with increasing latitude: the rightwards shift in Sturm seasonality compared with the SSM highlighted the 50 cm depth criteria that relegated Sturm-defined seasonal snowpacks to mountainous or otherwise elevated regions in lower latitudes. In contrast, by not having this constraint, the SSM had a greater frequency of seasonal snowpacks at lower-to-middle elevations ranging between 500 and 1500 m. Ephemeral snowpacks were largely absent from upper elevations except in the lowest latitude regions (i.e., south of 37° N) and were confined to elevations below 2000 m in higher latitudes (i.e., north of 37° N; Figure 6c).

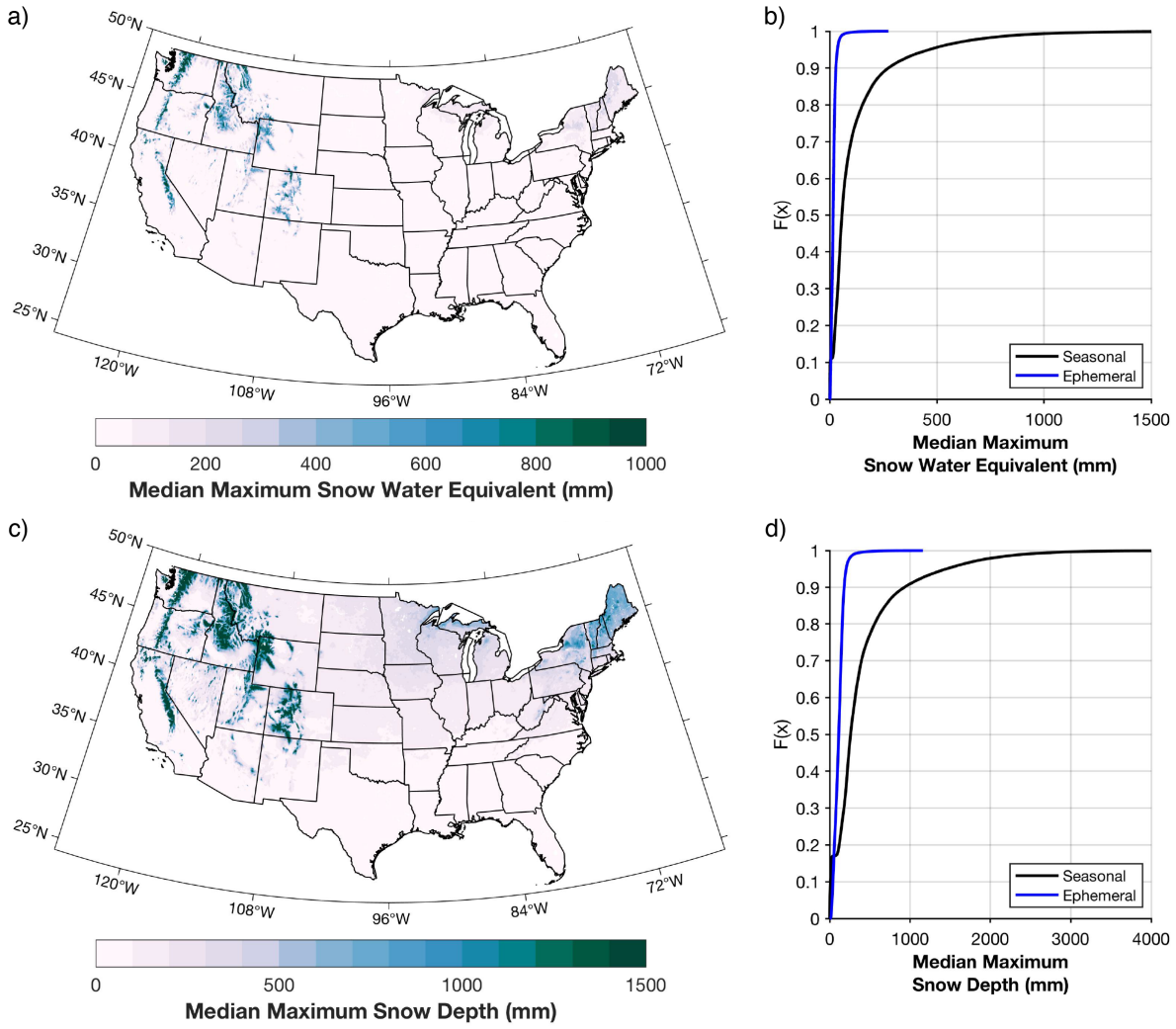


Figure 5. (**a**) Median annual maximum snow water equivalent and (**b**) the cumulative distribution functions of median maximum snow water equivalent for seasonal (black line) and ephemeral (blue line) snowpacks. (**c**,**d**) As in (**a**,**b**) but for median annual maximum snow depth.

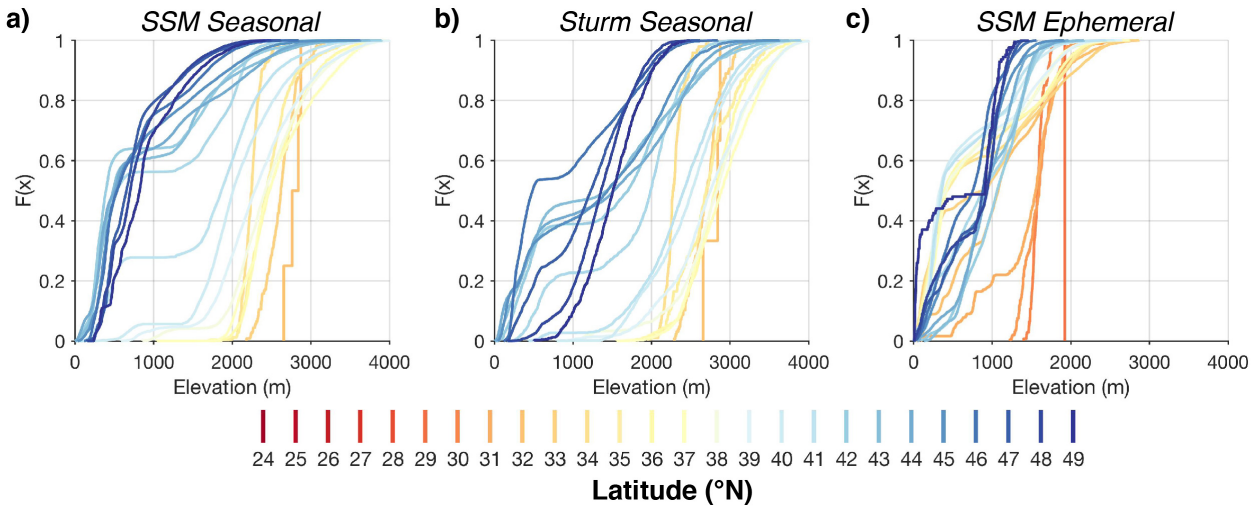


Figure 6. Cumulative distribution functions of snowpack classifications (requiring 10 years of snow observations) distributed by 1° latitude bins for: (**a**) Seasonal snowpacks defined by the snow seasonality metric (SSM); (**b**) Seasonal snowpacks defined by the Sturm method; (**c**) Ephemeral snowpacks defined by the snow seasonality metric (SSM).

3.4. "Expected" and "Worst In Record" Snow Seasonality at the HUC-8 Scale

To provide a perspective on a potential impact of changing snow seasonality for water resource management, percent seasonal snow (using cells with SSM > 0 and SSM < 0, for seasonal and ephemeral snow, respectively) was aggregated to HUC-8 watersheds. Percentage decreases in seasonal snow proportion and decreases in water stored in seasonal snow were calculated for "Expected" conditions compared to "Worst In Record" conditions, and are interpreted as the contraction of seasonal snowpacks due to various hydrometeorological conditions (e.g., increases in rain versus snow proportion, dry spells, or mid-winter melt events). The HUC-8 maps shown in Figure 7a,b mirror the differences shown Figure 2a,c. The watersheds of the maritime ranges in the far-western U.S. (Oregon Cascades and California Sierra Nevada) demonstrated the transitional nature of having both ephemeral and seasonal snow with 30–70% percent seasonal snow. Mountains in the Intermountain West and Rocky Mountains, as well as the cold, higher latitude High Plains, showed the dominance of seasonal snowpacks. During the "Worst In Record" years (Figure 7b), substantial reductions in seasonal snow proportions occurred throughout the western U.S. (Figure 7c). Only the mountains in central Idaho, western Wyoming, far-northern Washington, and central Colorado did not show more than 20% decreases in seasonal snow proportion. By calculating the volume of water stored in snow that was no longer seasonal, Figure 7d shows where the impacts of the seasonal snow reductions may have been most notable. Though many areas lost all seasonal snow in the "Worst In Record" conditions (Figure 7c), the decreases in volumes of water tended to be less than 50,000 ac/ft in many basins. However, Oregon, California, Nevada, Washington, North Dakota, northern New Mexico, southern Idaho, and the northern Utah/southern Wyoming/northwestern Colorado regions showed small watersheds with decreases in water stored in seasonal snow on the order of more than 200,000 ac/ft).

3.5. WY2015 Oregon Cascades Case Study

Water year (WY) 2015 in the Pacific Northwest was characterized by above-normal accumulated precipitation but below-normal snowpack. These conditions came to be recognized as a warm snow drought [55] and were often characterized by an anomalous frequency of warmer-than-normal storms that produced rain instead of snow [56,58], which is a concern for a warming future [57] in lower elevation regions known to be at risk for the impacts of climatic change [19]. The mountains of Oregon, particularly the Cascades, are susceptible to a warming climate as a result of their low elevation. During WY2015, seasonal snow climates retreated considerably compared to median seasonality (Figure 8a,b) in the Cascades but also in interior ranges such as the Blue (central eastern Oregon), Wallowa (northeastern Oregon), and Steens (southeastern Oregon) Mountains. These changes are exemplified in Figure 8c, which shows the upslope contraction of seasonal snowpacks as lower elevations transitioned to ephemeral snowpacks along the flanks of the Cascades and throughout the eastern half of the state. Ephemeral snowpacks were also lost in the Coastal Ranges (not shown, but can be identified by comparing (Figure 8a,b). Peak SWE anomalies were greatest in the Cascades, with reductions on the order of 500–800 mm compared to the median peak value (Figure 8d). Drier, colder interior ranges (e.g., the Blue and the Wallowa Mountains) underwent changes of smaller magnitude, with reductions on the order of 300—500 mm.

The sensitivity to a transition from a seasonal snowpack to an ephemeral snowpack is highlighted in Figure 8e. Only SWE anomalies for cells defined as ephemeral in WY2015 are shown; the magnitudes of negative SWE anomalies range from 25–400 mm with lower values observed in interior parts of the state and the largest anomalies being observed along the windward (western) side of the Cascades and along the leeside of the southern Cascades. Several thresholds of SWE anomalies, both percentile-based and based upon the arbitrary threshold of 80% of 1981–2010 average used by [56] are shown in Figure 8f–i. Each criteria only shows anomalies for cells with less than a given threshold of peak SWE. In the most strict case (Figure 8f), changes are confined to higher topography and mountainous

regions and generally reflect regions of remaining seasonal snowpack (cf. Figure 8b). Little difference appears between the 25^{th} and 33^{rd} percentiles (Figure 8g,h). All but the smallest negative anomalies appear when using the 80% of average threshold (Figure 8i).

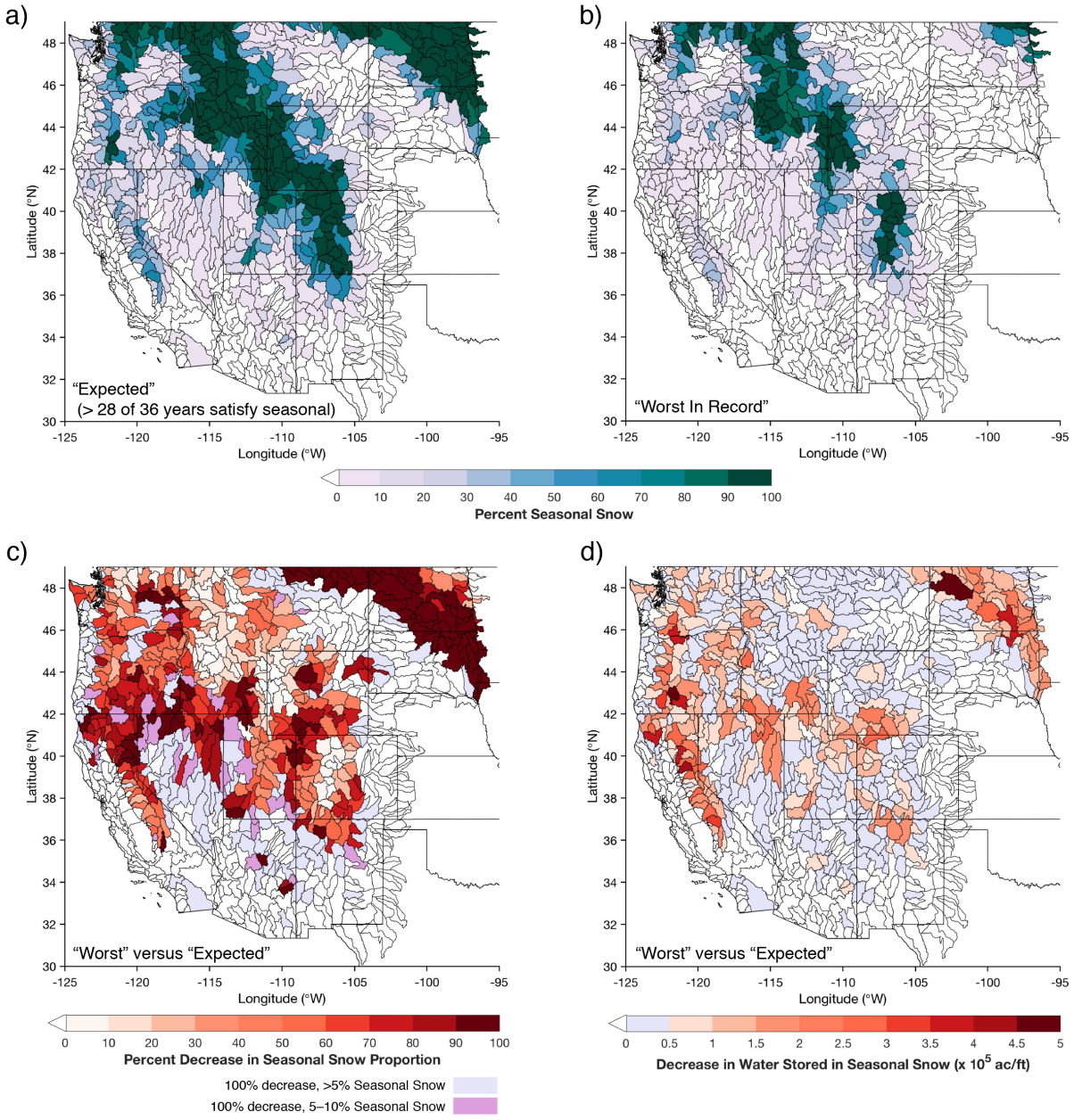


Figure 7. Percent seasonal snow aggregated to HUC-8 watersheds across the western U.S., defined using the snow seasonality metric, for: (**a**) "Expected" seasonal snowpacks (defined as more than 28 of 36 years (78%) satisfying a seasonal snowpack) and (**b**) "Worst In Record", or the fewest seasonal snowpack cells in a watershed (cf. Figure 2c). Only grid cells receiving snow (seasonal or ephemeral) were considered. (**c**) Percent decrease in seasonal snow proportion for the "Worst In Record" years versus the "Expected" conditions. Watersheds with less than 5% (5–10%) seasonal snow experienced 100% losses in the worst years and are shown as light purple (purple) to reduce visual impact. (**d**) Decrease in water stored in seasonal snow (units of 100,000 ac/ft) in "Worst In Record" years versus "Expected" conditions.

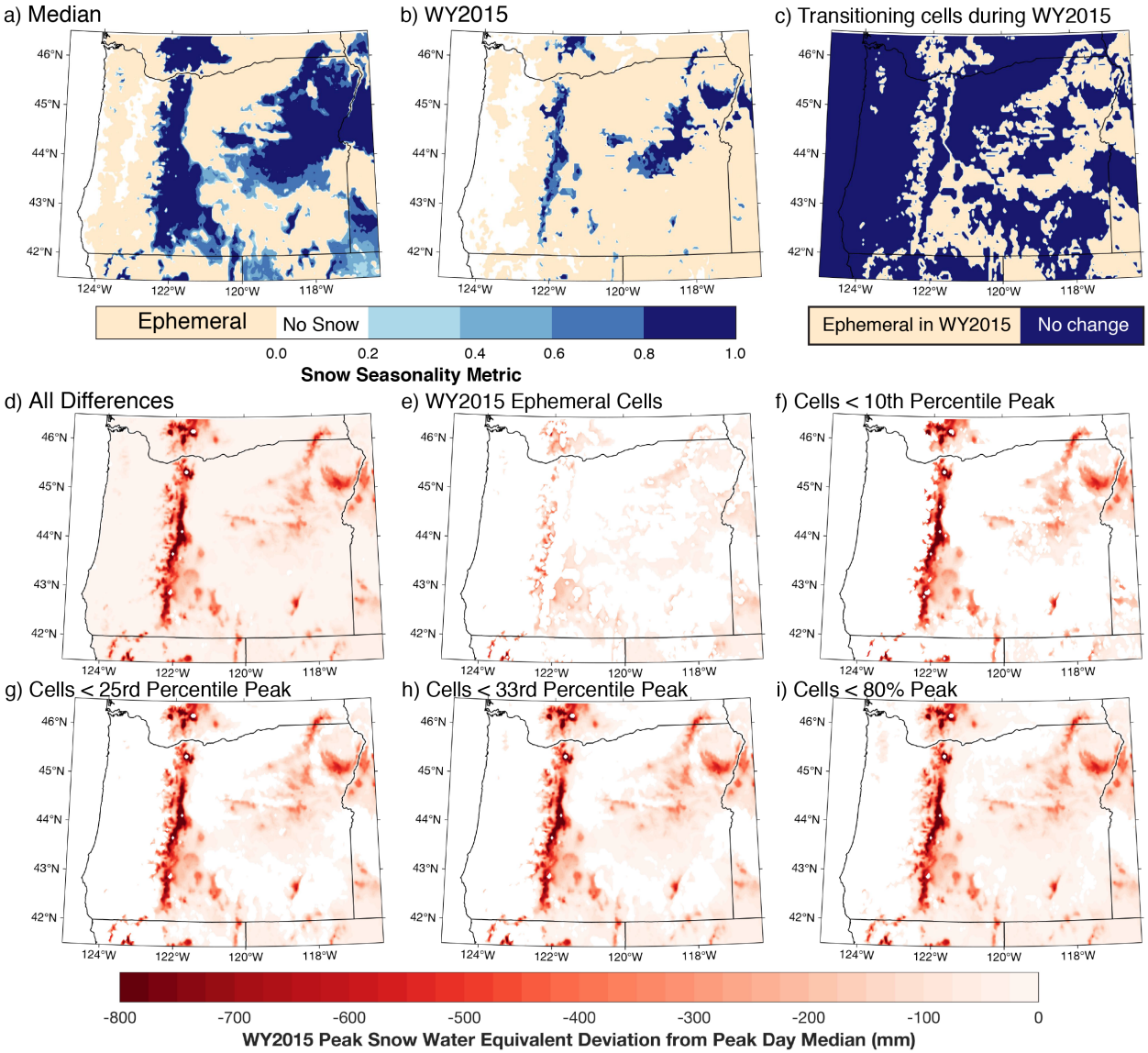


Figure 8. Example application of snow seasonality metric (SSM) to a snow drought year in Oregon. (**a**) Median SSM across all years; (**b**) SSM during water year (WY) 2015); (**c**) Cells that transitioned from seasonal to ephemeral in WY2015 are colored in tan; all other cells that remained seasonal or did not change are colored in blue. Deviations in peak WY2015 snow water equivalent (SWE; in *mm*) from all year median values for (**d**) All cell differences; (**e**) Only ephemeral cells; (**f**) Cells with less than 10th percentile of peak SWE; (**g**) Cells with less than 25th percentile of peak SWE; (**h**) Cells with less than 33rd percentile of peak SWE; (**i**) Cells with less than 80% of average peak SWE (subjective criteria used to define snow drought by [56]).

4. Discussion

The comparison of two methods to identify seasonal snowpacks highlights how the 50 cm depth criteria in the Sturm approach creates substantial differences in regions achieving a seasonal snowpack (2,651,936 km^2 for the SSM versus 736,864 km^2 for Sturm). The continuously valued nature of the SSM approach compared to the binary classification of the Sturm method yields a gradation of areas that display the potential to experience a seasonal snowpack (Figure 2a) and demonstrates sensitivity to a wider range of expansions and contractions of seasonal snowpacks (Figure 2c,e). The more restrictive Sturm approach leads to the overlap fraction mirroring the Sturm distribution (Figure 3) in all but a few locations. In the case of the SSM, relaxation of the depth criteria implies that the seasonal term only refers to the duration of snow cover. The lack of a snow depth requirement poses a limitation for applications where depth is important for ecosystem processes or is critical to recreation. Snow of sufficient depth provides insulation from cold atmo-

spheric temperatures, allowing sub-nival animals and vegetation to live at the snow/soil interface [59,60]. Sufficient snow depth also allows safe over-snow vehicle operation and human-powered recreation [32], which are important revenue-generating components of many rural economies [30,31] throughout the U.S. and other snowy regions worldwide [33,34]. Further, shallow but persistent snowpacks are prone to temperature-gradient metamorphism that promotes weakening of snowpack structure and increases avalanche hazard upon further loading from additional snowfall [61]. Therefore, consideration of the depth of snow, and how it varies across landscapes in time, is an important facet of many regions to include when also considering the duration of snow cover (i.e., its seasonality). A simple improvement to the SSM allowing it to capture the importance of snow depth would be the development of locally-relevant depth (or density) thresholds, such as the 30 cm depth used to determine sufficient depth for safe over-snow vehicle travel [32], and require this value to be met just as is required by the Sturm method. Threshold depth values should be based on the application of interest, reflect local climate and adaptations of plants and animals to historic snow depth, and include characteristic snow density for each region. In the case of snowpack stability pertaining to avalanche hazard, variables such as snow depth, snow density, and other factors pertaining to mass and energy fluxes would need to be considered, and likely would require the integration of more complex, physically-based snowpack modeling (e.g., [62].

Minimum values (Figure 2c,d and Figure 7b) highlight seasonal snowpack "refugia" in years experiencing low snowfall or frequent melt events due to anomalous weather conditions such as rain-on-snow, high humidity and wind conditions, or radiation excesses (e.g., downwelling longwave radiation from persistent cloud cover; [63]) that reduce areal coverage of seasonal snowpacks. The HUC-8 results highlight how this reduction has the potential to decrease the amount water stored in seasonal snowpacks (Figure 7b,c). While the precise magnitudes of water volumes no longer stored in seasonal snowpacks reported in Figure 7d should be interpreted with caution, this analysis suggests a non-negligible volume of water is being discharged [18] and may not be captured for downstream use (depending on factors such as infrastructure or reservoir operations). This previously seasonal snow becomes available for evapotranspiration as it melts and contributes to soil water [29]. The latter outcome reduces watershed runoff efficiency leading to lower streamflow [64] and alters patterns of vegetation water use [21].

The Oregon case study demonstrates how warm snow drought produces an upslope retraction of seasonal snowpacks in both maritime and intermountain mountains (Figure 8b,c). In both seasonal classification schemes, high mountains in the western U.S. (with the exception of Nevada and Arizona) appear more resilient to seasonal snowpack losses. Regions like the Sierra Nevada of California may transition towards a less seasonal and more ephemeral classification because a greater number of days may be classified as ephemeral due to snowpack formation and subsequent melting, especially at lower elevations. This offers a possible explanation for the greater contraction of seasonal snowpacks using the SSM approach versus the Sturm approach (Figure 2b,c), as certain areas become more dominated by ephemeral snow characteristics.

Seasonal snowpacks are notably absent along the lee (eastern side) of the Rocky Mountains in the High Plains along a northwest-southeast transect from central Montana to western Nebraska (Figure 4a). One explanation for this may be mid-winter snow ablation events caused by dry downslope Chinook ('snow-eater') winds that warm adiabatically and favor snowpack reduction via melting and sublimation [65,66], which may further be accelerated by snow-albedo and other feedback mechanisms [67,68]. The leeside of the Rocky Mountains frequently experience winter and spring downslope Chinook winds [69]. The results from the snow seasonality calculations suggest the eastward extent of their influence spans beyond the immediate lee of the Rockies into the Dakotas and northern Nebraska (Figure 4a). This indicates a widespread climatological influence of Chinook winds on snow seasonality in this region.

Intercomparisons of snow seasonality with additional snow reanalysis [41,46] or model products [46,47,49], and/or remotely-sensed data [14,70] are reasonable next steps. A comparison using both satellite data and ground-based observations could also be used to further validate the UAswe snow depth product in forested or topographically complex terrain, where measurements of snow cover are challenging [10,71]. To further this validation across a range of snow-covered environments, citizen science observations of snow depth, such as the Community Snow Observations effort [72] could be leveraged. Comparisons against global monthly snow products such as TerraClimate [69] may be applicable if assumptions are made such as increasing the duration requirement to three months and including a depth requirement during the peak month. Further disentangling changes in snow cover duration and depth during transitional years will provide insight into the role of various dynamic physical processes such as wind redistribution and scour, ablation through energy fluxes such as sublimation and melting, and changes in accumulation (e.g., rain-on-snow), and static controls including topography and elevation [9]. Physically-based models, such as the Snow Data Assimilation System [47] or SnowModel [7] offer valuable tools to estimate the relative roles of these mechanisms in ephemeral snowpacks or weakly seasonal snowpacks (e.g., [9]) to further identify and prioritize areas of interest for further study. The continuous and daily data availability of UAswe facilitates anomalous accumulation or ablation events to be identified in data sparse regions for further modeling or meteorological analysis of synoptic mechanisms [14].

Loss of seasonal snowpacks, whether achieved through permanent disappearance or reduced frequency of occurrence will have implications for all aspects of their local and downstream environment. These losses may not require substantial changes in SWE (Figure 8e). Overall, the implied increase in ephemerality, which corresponds to a decrease in water stored in seasonal snow (Figure 7d), reduces the predictability of snowmelt, runoff, and soil moisture and groundwater recharge [9]. Improved evaluation of the physical processes at work and their roles in driving change will add clarity to the ecohydrological and economic impacts in regions undergoing shifts towards more ephemeral snow. Overall, these changes will decrease water availability [73] and reduce drought predictability [22]. In watersheds with a transitional climate where both rain and snow occur, this shift leads to water being managed as a hazard rather than a resource to reduce flood risks [23]. As snowpacks shift towards more ephemeral and seasonal snow cover duration declines [70], later warm season ecosystem stress increases as less soil water is available to plants [9] and aquatic systems [20]. Throughout the warm season, this contributes to earlier drying of finer fuels like grasses or shrubs [74] that influence wildfire connectivity across landscapes [75] and long-term drying and drought stress of timber, increasing wildfire potential [28]. Finally, winter recreation opportunities will decline in areas currently near the periphery of historically seasonal snowpacks [30] as these areas have less reliable snow upon which to recreate.

All of these outcomes will require local and regional management shifts to ensure negative economic and ecosystem impacts are minimized while still aiming to achieve long-term management goals. Possible adaptations might include broadening the portfolio of recreation opportunities (e.g., expanding trail networks), utilizing available, but often costly adaptive capacities (e.g., snow-making; [34]), implementing restoration projects with techniques to induce drought-tolerance in native plants [76], exploration of alternative water management strategies [77], and changes in reservoir operations [78]. This analysis demonstrated a substantial fraction of the western U.S., Upper Midwest, and Northeastern U.S. is susceptible to shifting from a seasonal to an ephemeral snowpack (cf. Figure 2a,c and Figure 7a,b). The western and southern portions of the Oregon Cascades (Figure 8e) provide one example during a warm snow drought season [57]. Identifying the most vulnerable of these regions, i.e., those with at-risk socioeconomic assets or ecosystems, at the regional or watershed level (e.g., Figure 7d) to further examine drivers of snowpack seasonality change is recommended.

5. Conclusions

A spatially distributed snowpack reanalysis product was used to classify seasonal and ephemeral snowpacks throughout the conterminous U.S. Two methods, one developed by Sturm et al. [13] and one introduced by Petersky and Harpold [9] were utilized to identify seasonal snowpacks. The second method estimates snow seasonality using the calculation of a snow seasonality metric (SSM). The SSM is continuously valued, sensitive to interannual variability in snow cover, and is able to identify ephemeral snowpack presence. The sensitivity of the SSM results from a lack of a depth constraint and its ability to quantify seasonal and ephemeral snow cover duration. By including a locally-relevant depth constraint, the SSM could offer a metric to identify and assess transitions from seasonal snow to ephemeral snow that builds on the well-established Sturm method.

Both techniques showed seasonal snowpacks being most common in the mountainous western U.S. and in the high latitudes of the Midwestern and Northeastern U.S. Seasonal snowpacks are increasingly limited to higher elevations with decreasing latitude. Many locations with normally occurring seasonal snowpacks can also have years characterized by ephemeral snow. During these minimal snowpack years, seasonal snowpack retention occurs largely in the highest elevations of the Cascades and Rocky Mountains or in scattered high latitude areas in the Upper Midwest and Northeastern U.S. The retraction of seasonal snowpack area corresponds to non-negligible decreases in water stored in seasonal snow that is made available for earlier runoff or evapotranspiration. A key benefit of the SSM method is its ability to identify ephemeral snowpacks and variability in the frequency of seasonal snowpacks. Ephemeral snowpacks can form throughout much of the U.S. north of approximately 31° N. In the western U.S., ephemeral snowpacks bounded seasonal snowpacks in lower elevation terrain, whereas east of the Rocky Mountains ephemeral snowpacks increased in frequency with increasing latitude until approximately 37° N before declining in frequency as seasonal snowpacks became more common. The transition from seasonal to ephemeral snowpacks was highlighted by a case study during the warm snow drought of water year 2015 in Oregon. This case study indicated negative snowpack anomalies on the order of 50–100 mm of snow water equivalent were present in transitioning regions.

I recommend that future efforts compare climatological snow seasonality across varied snowpack reanalyses, examine sensitivities based upon varied depth thresholds (e.g., 30 cm depth for over-snow vehicle travel), and assess future transitions from seasonal to ephemeral snow using climate projections from regional models. I also recommend the development of locally-relevant depth thresholds to increase the ability of the SSM approach to identify locations of meaningful seasonal snowpacks. Depending on data availability, regional weather or climate model output and/or physically-based snowpack models should be used to assess the roles of various physical processes in driving transitions and to identify thresholds where shifts in snowpack classifications occur.

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Abbreviations

The following abbreviations are used in this manuscript:

UAswe	University of Arizona Snow Product
SNOTEL	Snow Telemetry Network
SSM	Snowpack Seasonality Metric
SWE	Snow Water Equivalent
U.S.	United States

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