Article

Seasonal and Ephemeral Snowpacks of the Conterminous United States

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Abstract: Snowpack seasonality in the conterminous United States (U.S.) is explored using a daily, 4 km horizontal resolution gridded snow water equivalent and snow depth reanalysis product. I calculated seasonal snowpacks 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. The latter approach yields continuous values from -1 to +1, where -1 (+1) indicates an ephemeral (seasonal) snowpack. Both approaches identify seasonal snowpacks in western mountains and the northernmost central and eastern U.S. By relaxing the depth constraint and providing continuous values, the SSM identifies greater areas of seasonal snowpacks compared to the Sturm method, particularly in the upper Midwest, New England, and the Intermountain West. Ephemeral snowpacks are identified throughout lower elevation regions of the western U.S. and across a broad swath centered near 35N spanning the lee of the Rocky Mountains to the Atlantic coast. Because it lacks a depth constraint, the SSM approach is sensitive to interannual variability, indicating it may inform the location of shallow but long-duration snowpacks at risk of transitioning to becoming ephemeral with climatic change. A case study in Oregon during an extreme snow drought year highlights seasonal to ephemeral snowpack transitions.

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

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1. Introduction

Snowfall occurs over a wide range of landscapes worldwide [1–3] and with a seasonal volume of snow of approximately 9,000 Gt [4], snow provides essential services to ecosystems and human society [5]. Myriad environmental forcings 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 [6,7]. 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 [6]. Vegetation and topographic characteristics, such as slope, aspect, and elevation also determine the behavior of snow cover. Ultimately, interactions between the topoclimate, meteorology, and land surface conditions determine the physical character of snow cover during and following deposition [6,8,9].

Classifying snow cover in terms of its seasonal and physical characteristics has long been a focus of cryospheric and hydrologic science [8] with the earliest classification systems developed in the early 1900s [10,11]. Prior to the advent of remote sensing or numerical modeling, snow classifications were primarily qualitative [11] and based upon field observations, though more quantitative characteristics were later incorporated [12]. Sturm *et al.* [8] introduced a physically-based classification system based upon multiple physical snowpack parameters with the goal of global applicability. The approach developed by [8] has since become a widely-used standard.

Because of their importance as natural freshwater reservoirs [5], especially in mountains [4,13,14], seasonal snowpacks persisting for longer than two months [8], receive the bulk of scientific attention

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[4,7,15]. Seasonal snowpacks tend to experience distinct accumulation and ablation seasons that follow one another in time [6]. 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 [16,17] as well as vegetation dynamics [18], disturbance regimes [19], soil water availability [20], and water and solute transport in upland watersheds [15]. Seasonal snowpacks also provide economic benefits to rural economies from recreation [21–23] and agriculture [5].

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 [8]. Ephemeral snowpacks differ from seasonal snowpacks by experiencing accumulation and melting processes nearly simultaneously [6]. This aspect makes them challenging to observe and model [7,9]. Ephemeral snowpacks occur in the transient snow zone, defined by Harr [24] 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 [24,25], 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 [7] as well as markedly different surface energy budgets [6].

Delineating regions of seasonal and ephemeral snow at scales relevant to decision making aids identification of regions where climate change poses the greatest risks for snow [16–18,26]. Shifts from seasonal to ephemeral snowpacks will disrupt upstream and downstream environments by altering terrestrial hydrological processes and states and their predictability [5,7]. Vegetation adapted to seasonal snow cover and its associated hydrologic regime may be less resilient to a shift towards an ephemeral snow regime characterized by a longer and drier growing season [18]. Increased watershed contributing area with growing transient snow zone area enhances flood risk [25], especially as the fraction of precipitation falling as snow declines [27], which may also increase the price of water [5]. 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 [28] 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 [29], station observations [30,31], or models [32–34].

My aim is to demonstrate the application of classic [8] and recently-developed [7] snow seasonality classification schemes to a newly-available spatially distributed snowpack reanalysis product [31] to highlight similarities and differences between classification regimes across the varied landscapes of the United States (U.S.). 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. By identifying vulnerable regions and assessing impacts for a range of scenarios, adaptation strategies can be identified, prioritized, and implemented to minimize negative outcomes on the environment and economy.

2. Materials and Methods

2.1. The University of Arizona Snow Reanalysis (UAswe)

I used the gridded 4 km snow reanalysis product developed by the University of Arizona [31]; hereafter UAswe). The UAswe product provides continuous spatial coverage through assimilation of *in situ* measurements of snow water equivalent (SWE) and snow depth (SD) and gridded 4 km temperature and precipitation from the Parameter-elevation Regressions on Independent Slopes Model (PRISM; [35]). Specific details about the methodology used to develop UAswe and various tests of its robustness can be found in [30,36,37].

UAswe spans water years 1982–2017. 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 October 1, 2016–September 30, 2017). Glaciated and permanently snow-covered (firn) regions are exempt from the UAswe dataset. 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.

2.2. Snow Seasonality Definitions

Snow seasonality can be categorized utilizing snowpack variables including snow cover duration, snow depth, and snow density (e.g., [8]). I defined snow climates in two ways. First, I used the Sturm *et al.* [8] 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 [8]. Second, I calculated the snow seasonality metric (SSM) introduced by Petersky and Harpold [7], which does not include a depth criteria. 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. 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 [7]. In practice, because early or late season snowfall events led to additional days with snow that were classified as ephemeral, few 'perfectly' seasonal snowpacks were identified. 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 were calculated across continuous elevations and 1° latitudinal bins. 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 [38–40]. In addition to examining how a warm snow drought influences snow seasonality, I explore the use of percentiles to help identify grid-cell level snow drought conditions with the goal to test whether a percentile-based approach can inform anomalies associated with transitions from seasonal to ephemeral snowpacks.

3. Results

The SSM approach categorizes large regions of the northern U.S. as a seasonal snowpack, particularly in the Intermountain West, northern Plains, upper Midwest, and New England (Figure 1a). A gradient is observed from the highest SSM values (SSM > 0.9) 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 Plains, Midwest, and New England. The Sturm method broadly identifies similar regions but with less extent (Figure 1b). Seasonal snowpacks identified by the SSM but absent from the Sturm approach include the northern 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 2). The majority of overlap is found in major western U.S. mountain ranges, the Great Lakes

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region of the upper Midwest, West Virginia and New England. The vast majority of overlap fractions exceed 0.9; lower values are found sporadically in the upper Midwest and New England.

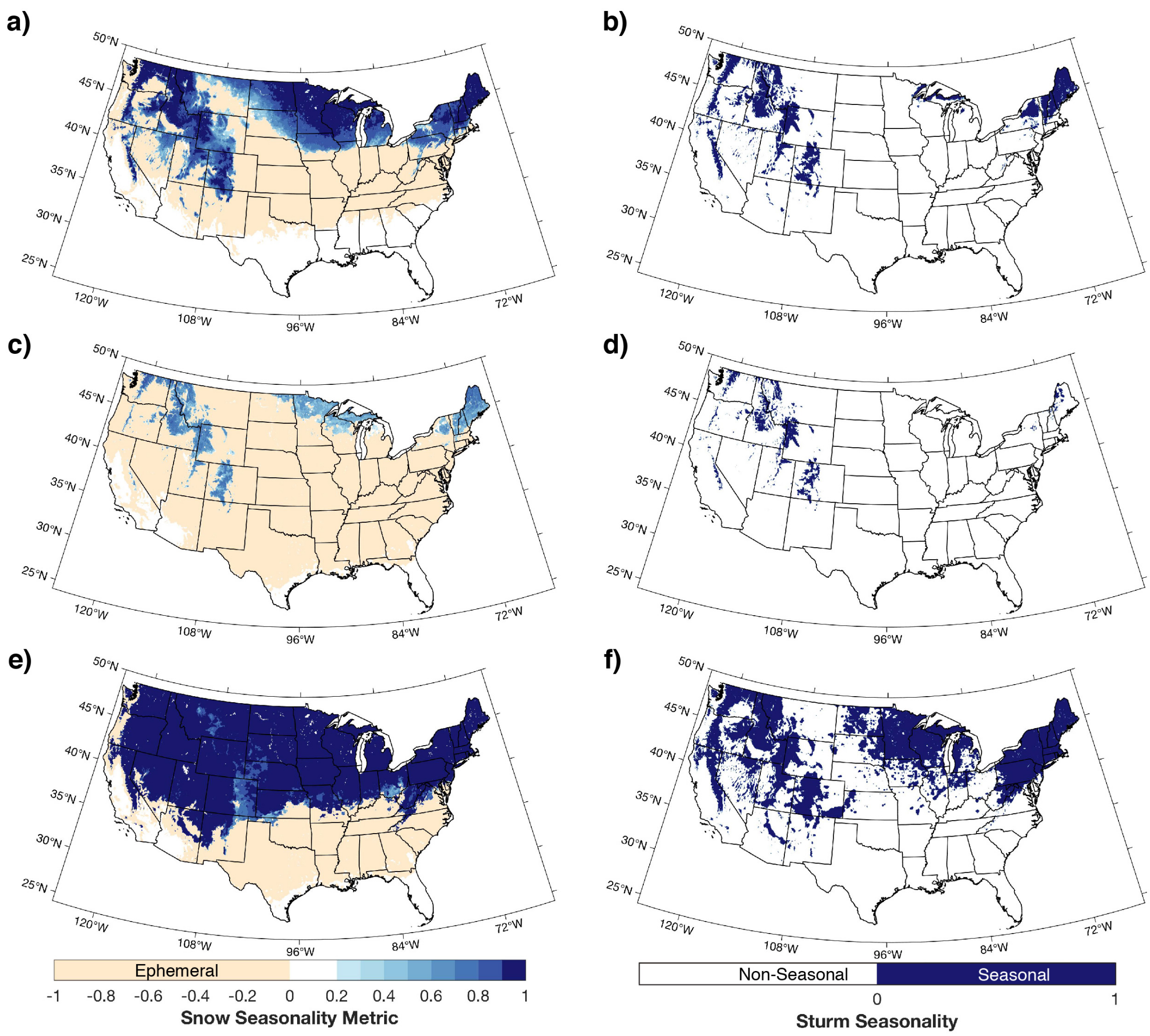

Figure 1. (**a**) Median snow seasonality metric. (**b**) Median Sturm seasonality. (**c**) Minimum snow seasonality metric. (**d**) Minimum Sturm seasonality. (**e**) Maximum snow seasonality metric. (**f**) Maximum Sturm seasonality.

Minimum values of SSM indicate a large fraction of the conterminous U.S. can experience an ephemeral snowpack (Figure 1c). The UAswe method never creates any type of snowpack in the lowest elevation and coastal regions of California, Arizona, and near the Gulf Coast. Areal coverage of seasonal snowpacks can contract, as shown by smaller values SSM and the reduced spatial extents of values greater than 0. The transitions from seasonal to ephemeral snowpacks are most prominent in the maritime ranges of the Cascades and Sierra Nevada of the western U.S., 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 (Utah) appear to maintain a seasonal snowpack, though the lower values of SSM indicate additional days that are classified as ephemeral in 'minimal years'. Reductions in seasonal snowpacks are also found with the Sturm approach (Figure 1d). The largest reductions agree with the SSM approach in the western U.S., however the Sierra Nevada remains classified as a seasonal snowpack. The upper Midwest and New England regions undergo extensive losses of seasonal snowpack in minimal years. It should be noted that both the minimum and maximum values (discussed next) correspond to 'all time' minimum/maximum values

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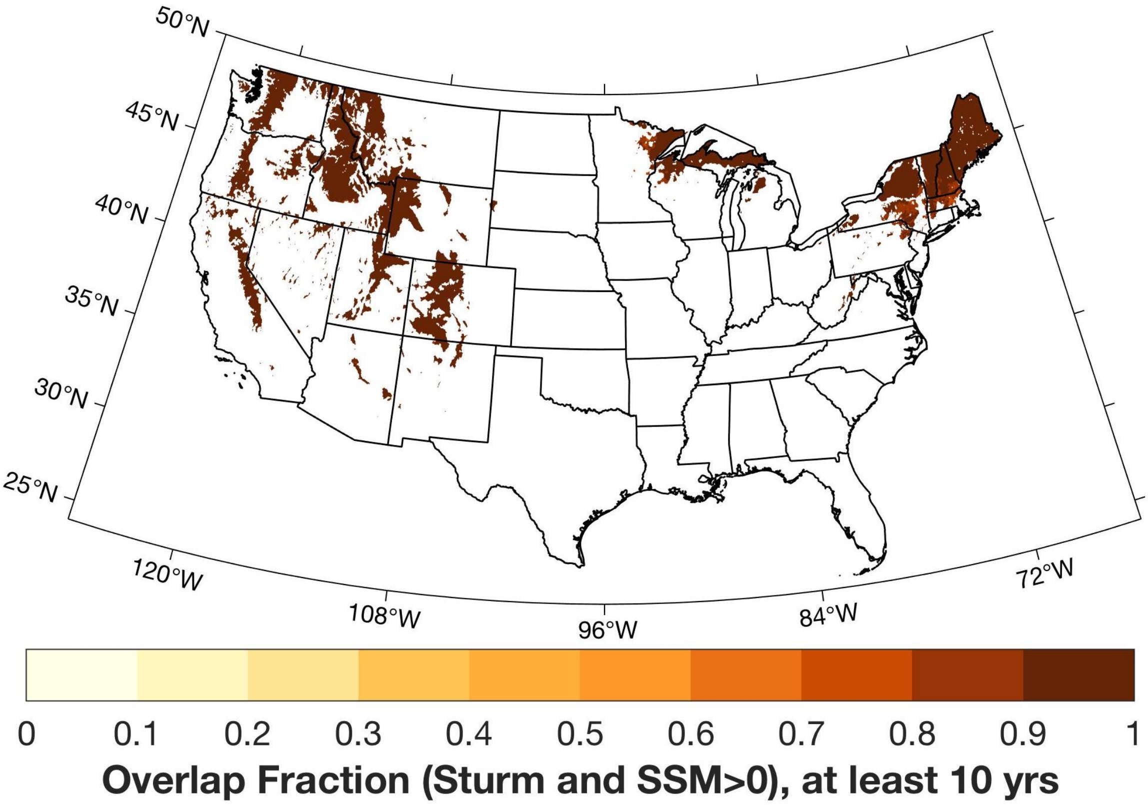

Figure 2. Agreement (overlap fraction) between seasonal snowpacks identified via the snow seasonality metric and Sturm seasonality classification schemes. Only grid cells with at least 10 years of data were considered.

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

Maximum SSM values highlight that nearly half the conterminous U.S. have the potential to experience a seasonal snowpack (Figure 1e). East of the Rocky Mountains, the seasonal snowpack formation occurs north of 37°N. Because of the 50 cm depth requirement in the Sturm method, less spatial expansion of seasonal snowpacks are evident (Figure 1f) compared to the SSM maximum values (Figure 1e). Seasonal Sturm snowpacks can expand in western mountains and in the upper Midwest, northern Plains, and New England.

Counts of years satisfying either seasonal or ephemeral snowpacks are shown in Figure 3. Comparing counts of seasonal years defined by the SSM approach (Figure 3a) with counts of Sturm seasonal years (Figure 3b) further highlights the impact of the 50 cm depth criteria in the Sturm approach, which leads to nearly all years satisfying the criteria or none of the years. In contrast, seasonal snowpacks identified via the SSM approach are most common in the regions described previously, but the gradation in frequency of seasonal years highlights the transition from locations that nearly always achieve a persistent snowpack towards those that do not achieve one. The lower elevation coastal regions of the western U.S., as well as the Southwestern U.S. rarely achieve seasonal snowpacks. Seasonal snowpacks occur with decreasing frequency east of the Rocky Mountains from 40°N southwards. Seasonal snowpacks abruptly decline 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 and into northern New Mexico.

A peak in ephemeral snowpack frequency is found across the eastern half of the U.S. (east of the Rocky Mountains; Figure 3c), increasing in frequency consistent with the decrease in frequency of seasonal snowpacks. In the mountainous western U.S., ephemeral snowpacks are 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 (eastern Oregon and Washington, northern Nevada, southern Intermountain West). The southeast-trending band from central Montana to eastern Wyoming demonstrates a balance between seasonal and ephemeral years. Further south along the leeside of the Rocky Mountains, ephemeral years become much more common, even into the Texas Panhandle, much of New Mexico, and northern Arizona. The peak in ephemeral snowpack frequency is found along a zonal (east-west) band spanning 35-39°N before declining southwards into the climatologically warmer and more humid Gulf Coast region of the southeastern U.S.

The distribution of seasonal and ephemeral snowpacks as a function of elevation indicate the role of topography and latitude in defining snowpack seasonality (Figure 4). In all cases, only distributions with at least 10 years of either a seasonal or epehermal snowpack was considered. Both the SSM (Figure 4a) and Sturm (Figure 4b) approaches agree on lower (i.e., south of 35°N) and middle (e.g., between 35°N and 40°N) latitude regions necessitating topography to achieve seasonal snowpacks. The consistencies between the two approaches declines with increasing latitude: the rightwards shift in Sturm seasonality compared with the SSM highlights the 50 cm depth criteria that relegates Sturm-defined seasonal snowpacks to mountainous or otherwise elevated regions. In contrast, by not having this constraint, the SSM has a greater frequency of seasonal snowpacks at lower-to-middle elevations ranging between 500 and 1500 m. Ephemeral snowpacks are largely absent from upper elevations except in the lowest latitude regions (i.e., south of 37°N) and are confined to elevations below 2000 m in higher latitudes (i.e., north of 37°N; Figure 4c).

Water year (WY) 2015 in the Pacific Northwest was characterized by its above-normal accumulated precipitation but below-normal snowpack. These conditions came to be recognized as a warm snow drought [38] and are often characterized by an anomalous frequency of warmer-than-normal storms that produce rain instead of snow [39,41], which is a concern for a warming future [40] in lower elevation regions known to be at high risk for impacts of climatic change [26]. The mountains of Oregon, particularly the Cascade Range, are highly susceptible to a warming climate as a result of their low elevation. During WY2015, seasonal snow climates retreated considerably compared to median values (Figure 5a–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 5c, which shows the upslope contraction of seasonal snowpacks as lower elevations transitioned to ephemeral snowpacks along the flanks of the Cascades and throughout much much of the eastern half of the state. Ephemeral snowpacks were also lost in the Coastal Ranges (not shown, but can be identified by comparing (Figures 5a and 5b). Peak snow water equivalent (SWE) anomalies were greatest in the Cascades, with reductions on the order of 500–800 mm compared to the median peak value (Figure 5d). Drier, colder interior ranges (e.g., the Blue and the Wallowa Mountains) underwent changes of lower 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 5e. 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% used by [39] are shown in Figures 5f–i. Each criteria only shows anomalies for cells with less than a given threshold of peak SWE. In the most strict case (Figures 5f), changes are confined to higher topography and mountainous regions and generally reflect regions of remaining seasonal snowpack (cf. Figure 5b). Little difference appears between the 25^{th} and 33^{rd} percentiles (Figures 5g–h). All but the smallest negative anomalies appear when using the 80% threshold (Figure 5i).

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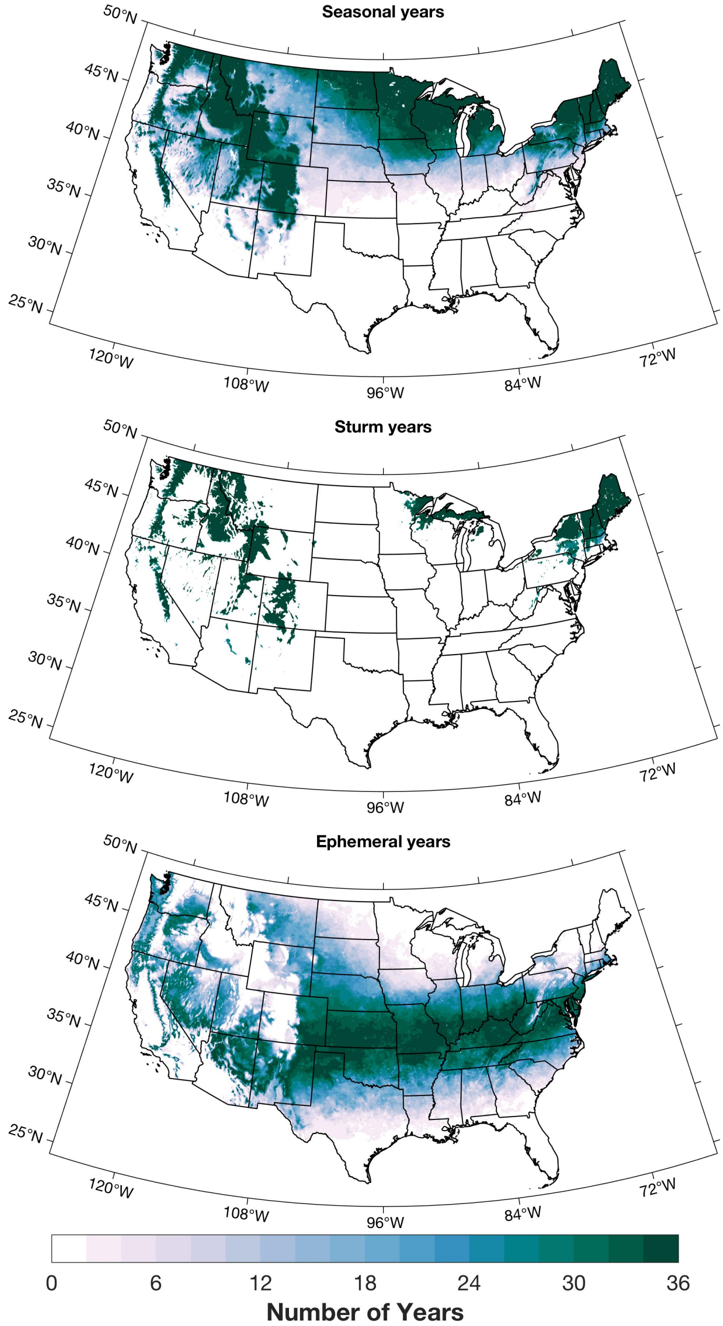

Figure 3. Counts of years (maximum of 36) that each classification was satisfied: (**top**) Seasonal snowpacks defined by the snow seasonality metric (SSM); (**middle**) Seasonal snowpacks defined by the Sturm method; (**bottom**) Ephemeral snowpacks defined by the snow seasonality metric (SSM).

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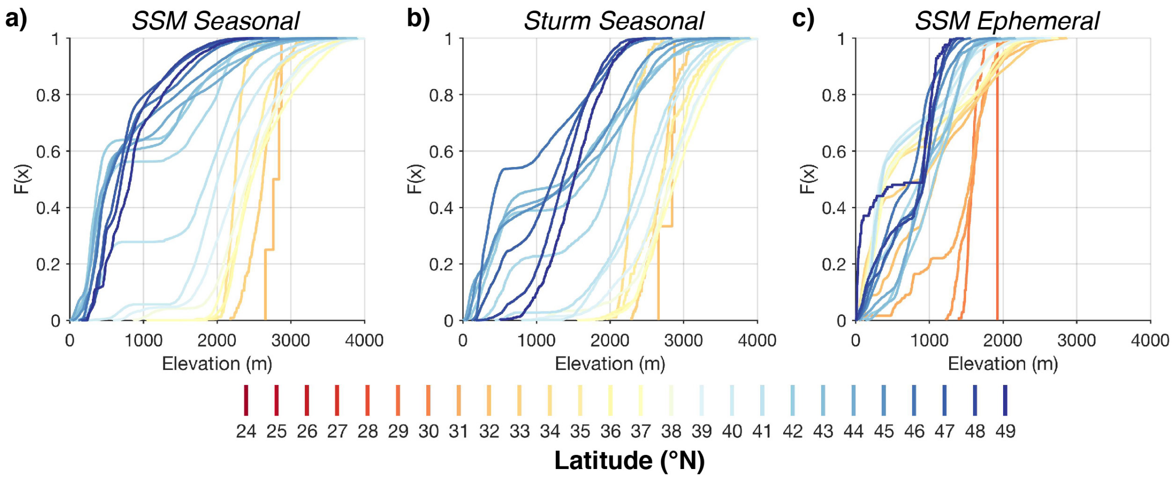

Figure 4. Cumulative distribution functions of snowpack classifications distributed by 1° latitude bins for: (**a**) Seasonal snowpacks defined by the snow seasonality metric (SSM); (**b**) Seasonal snowpacks defined by the Sturm method; (**c**) Ephemeral snowpacks defined by the snow seasonality metric (SSM).

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 identified as achieving a seasonal snowpack. The continuously valued nature of the SSM approach compared to the binary classification of the Sturm approach yields a gradation of areas that display the potential to experience a seasonal snowpack (Figure 1a) and demonstrates sensitivity to a wider range of expansions and contractions of seasonal snowpacks (Figure 1c,e). The more restrictive Sturm approach leads to the overlap fraction mirroring the Sturm distribution (Figure 2). In the case of the SSM, the relaxation of the depth criteria implies that the term seasonal refers only 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 critical to recreation. By providing insulation from cold atmospheric temperatures for sub-nival animals and vegetation [42,43] as well as providing sufficient snow cover for over-snow vehicle and human-powered recreation [22], the depth of snow is an important facet of many regions. 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 [44]. 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 [22], 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.

Minimum values (Figure 2c–d) 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). The Oregon case study further demonstrates how warm, wet conditions caused an upslope retraction of seasonal snowpacks in maritime and intermountain regions (Figure 5b–c). In both seasonal classification schemes, high mountains in the western U.S. (with the exception of Nevada and Arizona) are most resilient to seasonal snowpack losses. Regions like the Sierra Nevada of California may transition to an ephemeral classification not because they do not satisfy seasonal snowpack constraints but 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

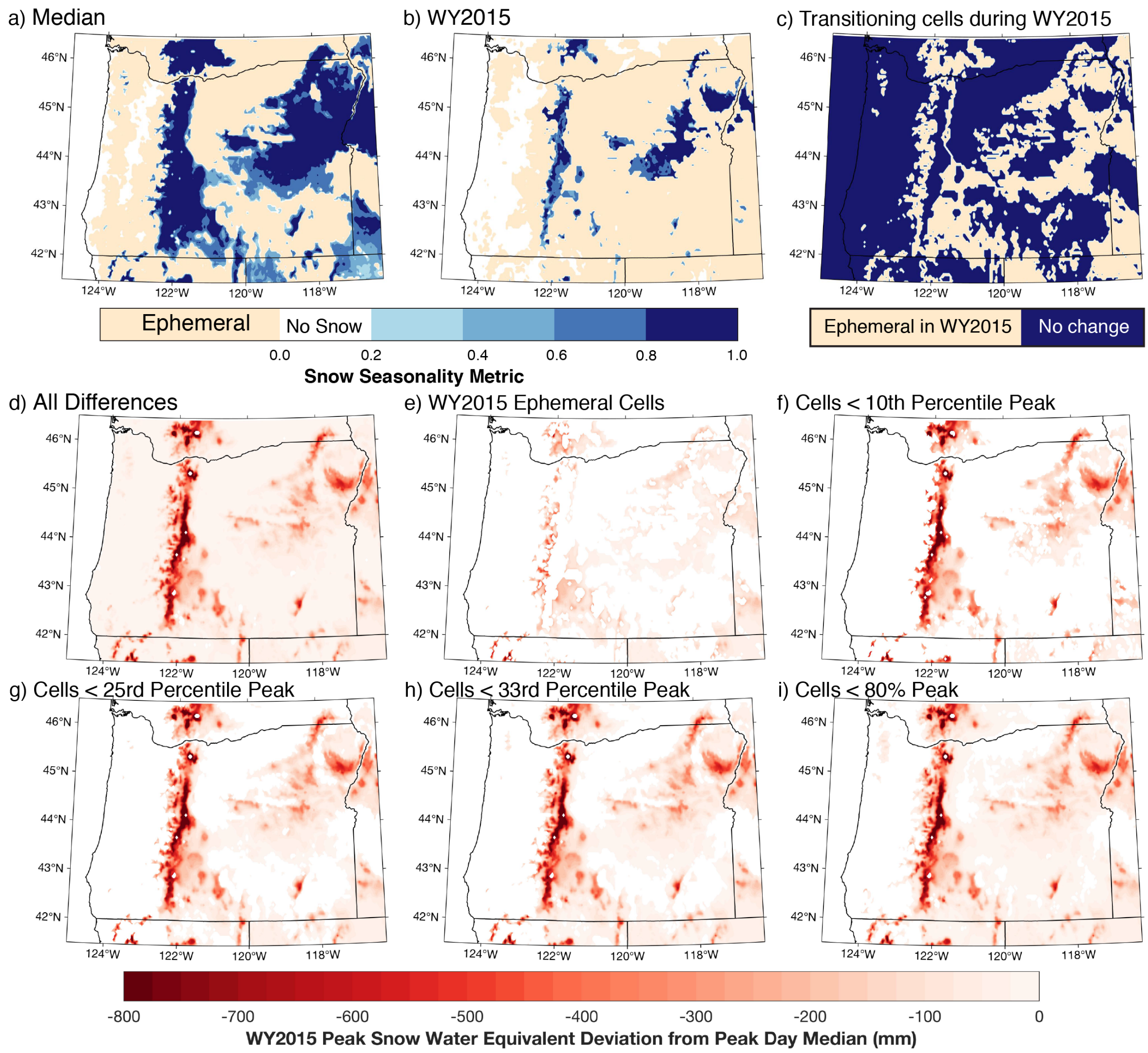

Figure 5. Example application of snow seasonality metric (SSM) to a snow drought year in Oregon. (**a**) Median SSM across all years; (**b**) SSM during water year (WY) 2015); (**c**) Cells that transitioned from seasonal to ephemeral in WY2015 are colored in tan; all other cells that remained seasonal 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 differences; (**e**) Only ephemeral cells; (**f**) Cells with less than 10^{th} percentile of peak SWE; (**g**) Cells with less than 25^{th} percentile of peak SWE; (**h**) Cells with less than 33^{rd} percentile of peak SWE; (**i**) Cells with less than 80% peak SWE (criteria used to define snow drought by [39]).

explanation for the greater contraction of seasonal snowpacks using the SSM approach versus the Sturm approach (Figure 1b–c).

A curious finding pertains to the lack of seasonal snowpacks along the lee (eastern side) of the Rocky Mountains in the western High Plains along a northwest-southeast transect from central Montana to western Nebraska (Figure 3a). 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 [45]. The leeside of the Rocky Mountains frequently experience winter and spring downslope Chinook winds [46], but the eastward extent of their influence spans beyond the immediate lee of the Rockies into the Dakotas and northern Nebraska (Figure 3a) suggests a widespread climatological influence of Chinook winds on snow duration.

Intercomparisons of snow seasonality with additional snow reanalysis [29,32], model products [32,33], and/or remotely-sensed data [9,47] are reasonable next steps. Comparisons against global monthly snow products such as TerraClimate [46] 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 [7]. Physically-based models, such as the Snow Data Assimilation System [33] or SnowModel [6] offer valuable tools to estimate the relative roles of these mechanisms in ephemeral snowpacks or weakly seasonal snowpacks (e.g., [7]) 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 [9].

Loss of seasonal snowpacks, whether achieved through permanent disappearance or reduced frequency of occurrence will have implications for all facets of their local and downstream environment. These losses may not require substantial changes in SWE (Figure 5e). Both kinds of seasonal snowpack loss imply increased ephemerality and thus reduced predictability of snowmelt, runoff, and soil moisture and groundwater recharge [7]. 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 [48] and reduce drought predictability [49]. 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 [25]. As snowpacks shift towards more ephemeral and seasonal snow cover duration declines [47], later warm season ecosystem stress increases as less soil water is available to plants [7] and aquatic systems [17]. Throughout the warm season, this contributes to earlier drying of fine fuels and long-term drying and drought stress of timber, increasing wildfire potential [19]. Winter recreation opportunities will decline in areas currently on the periphery of long-duration snowpacks [21].

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 manangement 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; [23]), implementing restoration projects with techniques to induce drought-tolerance in native plants [50], exploration of alternative water management strategies [51], and changes in reservoir operations [52]. 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. Figures 1a,c). The western and southern Cascades of Oregon (Figure 5e) provide one example during a warm snow drought season [40]. Identifying the most vulnerable of these regions, i.e., those with at-risk assets or ecosystems, at the regional or watershed level to further examine drivers of snowpack classification change is recommended.

 doi:10.20944/preprints202011.0545.v1

5. Concluding Remarks

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.* [8] and one introduced by Petersky and Harpold [7] 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. Especially with the inclusion of a locally-relevant depth constraint, the SSM offers a helpful 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 limited to higher elevations with decreasing latitude. Seasonal snowpack refugia occurs largely in the highest elevations of the Cascades and Rocky Mountains, with scattered areas in the upper Midwest and Northeastern U.S. A key benefit of the SSM is its ability to identify ephemeral snowpacks and gradients 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 decreasing 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 future efforts to compare climatological snow seasonality across varied snowpack reanalyses, to examine sensitivities based upon varied depth thresholds (e.g., 30 cm depth for over-snow vehicle travel), and to assess future transitions from seasonal to ephemeral snow using climate projections from regional models. Last, I recommend the development of locally-relevant depth thresholds to increase the ability of the SSM approach to identify meaningful seasonal snowpacks.

Funding: This research was funded by faculty start-up funds at the Desert Research Institute.

Acknowledgments: I thank Alan Rhoades and Ty Brandt for helpful conversations. All errors and omissions are my own.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

Abbreviations

The following abbreviations are used in this manuscript:

UAswe	University of Arizona Snow Reanalysis
SSM	Snowpack Seasonality Metric
SWE	Snow Water Equivalent
U.S.	United States

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