Associate Editor and Reviewers,

We greatly appreciate the thoughtful reviews from the two anonymous reviewers of our paper "Now You See It Now You Don't: A Case Study of Ephemeral Snowpacks and Soil Moisture Response in the Great Basin U.S.A" for publication in Hydrology and Earth System Science. Both reviewers' comments have substantially improved the paper's story and clarity. We have completed all additional analysis and new figures, with the exception of a seasonal analysis of the SNODAS data for reasons we explain in our responses below in blue text. Given the changes recommended by the reviewers and our own internal revisions, we believe the revised manuscript has substantial improvements in readability.

We thank the reviewers for recognizing the importance of this under researched topic and its inclusion in to the special edition. We believe strongly that the submitted manuscript will be of wide interest to HESS readership.

Best regards,

Adrian Harpold

Dr. Sean Carey,

We, the authors of *Now You See It Now You Don't: A Case Study of Ephemeral Snowpacks and Soil Moisture Response in the Great Basin U.S.A.* appreciate your involvement in the process of publication and your suggestions about improving our final draft.

On Figure 1, we have added state boundaries per your suggestion. We have also shrunk the labeling and legend sizes in Figures 1, 5, 10 and 11.

The sentence about GRIDMET now reads: "In that six-year period, the year with the lowest average winter (Dec 1st to Apr 1st) temperature using gridded meterological (GRIDMET) 4 km resolution surface temperature estimates was 2013 at -0.9 °C while the year with the highest average winter temperature was 2014 at 1.0 °C (Abatzoglou 2012; Table 1)" (P16L12). which adds information about the resolution of GRIDMET along with clarifying that it is used to estimate surface temperature.

The grammatical mistake that you pointed out when discussing the absence of blowing snow in our results was omitted, and we have revised the sentence at P16L22 to read: "Blowing snow sublimation was not the dominant cause of snow ephemerality in the Great Basin for any year; SNODAS struggles to represent wind redistribution of snow (Clow et al., 2012; Hedrick et al., 2015)." This is very similar to your suggestion with the one difference being that we used a semicolon in the place of a comma in order to avoid a comma splice.

We have removed the submeter resolution on elevation in Table 1.

Lastly, we appreciate your comment on the use of "we" in our manuscript and have reduced their number to 29.

Thank you for recognizing the importance of ephemeral snow in the field of snow hydrology, and for selecting our paper for the *Hydrology and Earth Systems Science* special edition.

Sincerely yours,

Rose Petersky

Adrian Harpold

Anonymous Referee #1

Received and published: 14 March 2018

General comments:

This study focuses on mapping ephemeral snow over the Great Basin in the US and diagnosing the mechanisms for ephemeral snow behavior to better understand the impacts of ephemeral snow on soil moisture. To do so, the authors use station based SNOTEL and SCAN observations of snow and soil moisture, remotely sensed snow-cover from MODIS, and modeled snow data from the SNODAS product. A snow seasonality metric is developed using MODIS snowcover imagery and SNODAS data to map ephemeral and seasonal snowcover. Then a decision tree is developed using SNODAS modeled data to diagnose the mechanism of ephemeral snow. Finally, the landscape characteristics of estimated snow duration are explored. The study's results are that topography and climate are strong controls on the distribution of ephemeral snowpack. This paper extends previous work on ephemeral snow by attempting to classify the processes driving snow loss (no snowfall, melt, sublimation/blowing snow).

This paper addresses a previous unaddressed question of identifying and mapping the dominate process causing ephemeral snow cover. Further, connecting snowmelt from ephemeral snow to soil moisture and this link's sensitivity to inter-annual variability (or climate change), is an interesting scientific issue fully within the scope of HESS. I believe this paper will provide a valuable contribution after some of the issues below are addressed.

Specific comments:

- Title: The title should be more descriptive of what the paper is about: diagnosing ephemeral snow mechanisms and impacts on soil moisture.

We agree, although we like the visual nature of the previous title and combine to: "Now You See It Now You Don't: A Case Study of Ephemeral Snowpacks and Soil Moisture Response in the Great Basin, USA"

- The abstract provides some descriptive comments on the seasonality of the observed and modeled results, but only hints at "recommendations to bolster physics based modeling". These recommendations (and results supporting them) should be clearly articulated in the abstract.

We have majorly rewritten the abstract. The final two sentences address this specific point.

- Lack of discussion of how uncertainty in the SNODAS model affect the results of this study, namely the classification of ephemeral snow. Over high-elevation terrain where we could expect blowing snow redistribution and sublimation losses to be greatest,

SNODAS at 1km by 1km, likely does not capture these processes well. This may be supported by Figure 7, showing SNODAS diverging from MODIS at highest elevations (This is an interesting finding that could be discussed more as well).

We agree that the finding of mismatches between the SNODAS and MODIS are interesting and worth highlighting. To that end, we have incorporated another figure directly comparable (Fig. 7). The results snow clear biases in the SNODAS estimates of snow duration that we discuss. With regard to the specific point about wind-blown snow effects in SNODAS, we agree and add the following statement at the end of the discussion: "Although SNODAS assimilates MODIS imagery into the model, it does not appear to capture the finer elevation patterns we found using the MOD10A product (Fig. 5 and 6), and in particular, seemed to overestimate consecutive days of snow cover. Part of the challenges at higher elevations is modeling blowing snow patterns over 1-km grid cells, which is consistent lower accuracy of SNODAS above tree line and in more windy areas (Clow et al., 2012; Hedrick et al., 2015). The Great Basin shows tremendous variability in snow ephemerality caused by interactions of topography, elevation, and prevailing wind (Fig. 10-11) and thus, represents an area where improvements in the physically-based modeling will be critical to predicting snow water resources under a variable and changing climate."

It should be noted this statement was already in the text: "Blowing snow sublimation was not the dominant cause of snow ephemerality in the Great Basin for any year, but its known that SNODAS struggles to represent wind redistribution of snow (Clow et al., 2012; Hedrick et al., 2015)."

- Because ephemeral snow occurs during short events, the driver of snow loss for a given 1km SNODAS cell could be variable with time. How does your ephemeral snow mechanism modeled results change if you look at smaller time slices than a year?

This is an important suggestion, given that the temporal dynamics of ephemeral snow are extreme and seasonal. However, two important methodological concerns kept us from completing this. First is the fidelity of the SNODAS model, which is going to be weaker using a shorter duration window. Second, and more importantly, our maximum consecutive snow duration was developed for an annual time step and is not easily computed (or contextualized) at shorter time steps. The combination of these two concerns makes the execution of this recommendation implausible. However, given the importance of this concern, we add the following sentence: "Our approach to classify proximate causes of snow ephemerality has some limitations. Namely, it assigns only a single mechanism to each grid cell when there could be multiple mechanisms. Moreover, the method cannot consider changes in the mechanisms with time (e.g. melt tends to occur more in spring) because we applied annualized estimates of snow cover duration and concerns about the fidelity of the SNODAS model at short time scales."

- Snowpillows modify the ground heat flux to snow and the calculated snow presence/absence. Please address how this observational uncertainty impacts your results.

This is a reasonable point and we add the following caveat to the methods: “It should be noted that ablation on the snow pillow may be impacted by differences in ground heat flux and co-location issues with the soil moisture sensors.”

- Using the peak of (I assume hourly?) soil moisture data for your calculations for Figure 6, may bias this metric toward high intensity rainfall events (i.e. Feb 2015 in Figure 5e), that may be slightly higher than later snowmelt driven soil moisture increases. Try using a longer averaging time or at least address the sensitivity of your results to this metric choice.

This analysis was done with daily maximum values. We have added a third panel to this figure to help show differences in the absolute (day of year) timing.

- Making your final mapped snow regions publicly available will greatly improve the usefulness of this study.

Yes we agree, we should have this finalized before resubmission.

Technical corrections:

- Page 2, 5 – Missing citation of Kormos et al., 2014

Added

- Page 2, 14 – Inputs “to soil”

Added

- Page 2, 16 – Comparable to? To previous studies using the 60 day threshold?

This sentence was changed to read: “While it is arbitrary, using the 60-day threshold allows for comparisons between the extent of ephemeral snow to previous studies and among different areas.”

- Page 2, 34 – Currently sentinel-2 provides 5-10 day repeat times. Coupled with Landsat, this can provide far more cloud free images of ephemeral snow.’

This is worth mentioning and was added to the following sentence: “Given the intermittent nature of ephemeral snow, observations must be daily or finer to capture its dynamics (Wang et al., 2014). Consequently, products like Landsat that has a 16-day overpass and Sentinel that has 5-10 day overpass do poorly at estimating snow seasonality compared to products like the MODIS that have twice daily overpass, but offer untapped potential for merged products with higher spatial and temporal resolution.”

We also add this sentence to the recommendations: “While very fine resolution climate datasets are beginning to be produced, there is a large need to merge existing remote sensing snow observations into a data product that maximizes the current space and time resolutions across different platforms (.e.g. spatial resolution of Sentinel 2 but the temporal resolution of MODIS).”

- Page 6, Citation for earth engine

- Noel Gorelick, Matt Hancher, Mike Dixon, Simon Ilyushchenko, David Thau, Rebecca Moore, Google Earth Engine: Planetary-scale geospatial analysis for everyone, Re- mote Sensing of Environment, Volume 202,

This was added

- Figure 1b is not needed, it can be stated in the text.

We removed this figure.

- Figure 7 - Date ranges for MODIS and SNODAS should be consistent for comparison.

This was redone for all figures making direct comparisons.

- Figure 8 – Need consistent color bar ranges to aid comparison (or note in caption if you make them different).

Noted in caption that low elevations have a larger area and require a different caption. But, we took this suggestion to heart and removed the consistent color bars from a later figure.

- Figure 11. 2012 and 2013 “No Snow” look green instead of black.

We experimented with this and were not happy with the results and do not see a downside of using black.

Anonymous Referee #2

Received and published: 16 March 2018

General Comments: This paper addresses an important topic in the hydrology of snow dominated regions. Ephemeral snowpacks are a significant, yet understudied, component of the mountain water balance. This paper identifies key unknowns related to ephemeral snowpacks, presents clear thorough analyses designed to address those unknowns, and concludes recommendations that other investigators can use in future studies. I think the paper falls within the scope of HESS, and is worthy of publication after some moderate revision.

Specific Comments 1. In section 5.1 there is a lot of attention given to lag between date of snow disappearance and date of peak soil moisture in ephemeral vs seasonal snowpacks. In ephemeral snowpacks the lag times are 79 and 48 days for shallow and deep soil moisture, while in seasonal snowpacks the lag times are about 5 days. However, the actual dates of peak soil moisture are not very different. From figure 5 it appears that the dates of peak soil moisture tends to occur in mid-late may regardless of when the snow disappeared. Does this imply that the timing of snow disappearance in ephemeral snowpacks doesn't really matter to soil moisture? Late winter rain keeps the soil wet in the absence of snow, and peak soil moisture is more a function of the timing of evapotranspiration?

The consistent timing of deep soil moisture response between ephemeral and seasonal snow zones is a bit of an anomaly due to the lack of deep soil moisture response. We have added a third panel to that figure that shows the absolute timing of peak soil moisture for clarification. The deep soil moisture response in ephemeral areas is strongly biased by the wet years with late snow packs, which are the only years to have sizable deep soil moisture effects (see time series). Given the challenges of interpreting this by the reviewer, we have clarified the text in addition to modifying the figure: "Using similar records to those illustrate at these two sites we use 328 site years (50 ephemeral and 278 seasonal site years) from all SNOTEL and SCAN sites in the Great Basin (Fig. 1) over water year 2014, 2015, and 2016 to illustrate the broader patterns of soil moisture response to ephemeral and seasonal snowmelt. We found that soil moisture following seasonal snowmelt reached a maximum 5 and 7 days prior to snow disappearance for shallow and deep soil moisture, respectively. This confirms previous findings that seasonal snowmelt drives coincident wetting and deeper water percolation (Harpold and Molotch, 2015; McNamara et al., 2005). In contrast, the median soil moisture peaked 79 and 48 days after of snow disappearance from ephemeral snowmelt for shallow and deep soil moisture, respectively (Fig. 4a). This is consistent with the peak shallow soil moisture occurring much earlier in the water year in shallow ephemeral snowmelt areas (Figure 4b). The later deep soil moisture response in ephemeral areas reflects the lack of response, or low coefficient of variation (CV), as compared to seasonal snowmelt (Fig. 4c). The lower CV for deep ephemeral snowmelt (0.2) compared to deep seasonal snowmelt (0.4-0.5) is indicative of reduced deep percolation and less water becoming available to groundwater and streamflow."

2. The introduction should be modified to better introduce the actual topics in the paper. Specifically, the relationship between ephemeral snowpacks and soil moisture is a dominant theme in the paper, but receives little attention in the introduction. Except for a brief mention in the opening paragraph, the term soil moisture doesn't appear again until the research questions in the final paragraph.

This is a great point and was addressed in the revisions. We made several additions and moved information from the discussion to help with clarity.

The second paragraph of the introduction now focuses on soil moisture response: "Snowmelt influences a variety of terrestrial hydrological processes and states,

particularly soil moisture dynamics in areas with low summer precipitation (Harpold and Molotch, 2015; Seyfried et al., 2009). Snowmelt-derived soil moisture is a primary control on streamflow generation and timing and ecosystem productivity in many semi-arid systems (Jefferson, 2011; McNamara et al., 2005; Schwinning and Sala, 2004; Stielstra et al., 2015; Trujillo et al., 2012). Although few studies have isolated their hydrological importance, ephemeral snowpacks modify the intensity and duration of precipitation inputs to soil by storing and releasing water in a less predictable way than seasonal snow. For example, (McNamara et al., 2005) described five predictable phases of soil moisture evolution in semi-arid watersheds with seasonally dominant snowmelt: (1) a summer dry period, (2) a transitional fall wetting period, (3) a winter wet, low-flux period, (4) a spring wet, high-flux period, and (5) a transitional late-spring drying period. Soil moisture response to ephemeral snow melt is likely to sit between the predictable timing and rates of seasonal snow and the stochastic nature of rainfall, but few observations across this gradient exist. Despite the hydrological and ecological importance of ephemeral snow (McNamara et al., 2018), we lack widely accepted methodologies to classify, map, and model snow ephemerality."

3. The writing in some sections needs to be tightened up. Although well organized and generally well-written, it has a feeling of having been written by multiple authors. Section 5.3, for example, has quite a few awkward and complex sentences while other sections are more clear. I suggest a thorough edit of the entire manuscript by a single author.

- Yes, the senior author has spent time to improve readability.

4. I am not a fan of combined Results and Discussion sections, although I understand the appeal. It is sometimes difficult to decipher what is a result of this study from what is an interpretation of others. Consider separating the sections. This is not a publication deal-breaker, but just something to consider.

I am usually the reviewer making this comment! I agree that combined results/discussion is often not the ideal format for a results heavy article, however, in our case this format allows us to link three generally disparate ideas (soil moisture, MODIS patterns, and SNODAS mechanisms) into a comprehensive story. Because this is the first broad paper about ephemeral snow hydrology, the broader story is more conducive to a combined results and discussion. We hope you find the new version easy to digest.

Technical Corrections (Page, line) 1,13 Cold content should be defined

1, 32 Is "in- termittent" and "ephemeral" the same thing?

Yes and this was clarified in the text.

4, 8 Goal should be about research questions. . .

We agree and have modified this sentence to: "The goal of this paper is to use the Great Basin as a case study to estimate the distribution and mechanisms causing ephemeral snow to better constrain their impact on soil moisture and hydrological response."

4,15 The soil moisture problem has not been adequately introduced

This has been changed. See previous comments.

Fig. 2 I don't see the value of this figure. I could be deleted with any impact on the paper if space is a concern

We moved Figure 2 and 3 to the supplemental.

9,11 I don't think these are proper sentences

12,19 Awkward sentence reen

Changed to read.

Fig 8. Panel c has alignment issues

This has been fixed

16,2 I don't think the first sentence is necessary. This idea was already introducted. Just start the section with "We propose a. . ."

Agree this change was made.

16, 5-10 These sentences are redundant with the introduction. They seem out of place in a Results and Discussion section.

Agreed. This was removed and some text moved to other sections.

6,11 Awkward, complex sentence. I'm not sure what the "based on. . ." phrase means.

This was changed.

Table 1 Average winter temperature estimates should cite the source and method. What duration was used? Probably should round elevations to integer values. Degree symbol is used in caption, but text is used in column heading.

This was clarified to be December 1 to April 1 in all locations. We have added the degree symbol in all instances.

17,6 LaMontagne 2009 is an MS thesis. Better to cite Tyler et al (2008) Tyler, S.W., Burak, S.A., McNamara, J.P., Lamontagne, A., Selker, J.S, and Dozier, J. 2008. Spatially

distributed temperatures at the base of two mountain snow- packs measured with fiber optic sensors. Journal of Glaciology, 54(187): 673-679.

Thank you for this. We also added the reference: Slater, A. G., D. M. Lawrence, and C. D. Koven (2017), Process-level model evaluation: a snow and heat transfer metric, *The Cryosphere*, *11*(2), 989–996, doi:10.5194/tc-11-989-2017.

Fig 12 Consider putting the years within the figure boxes rather than above them. At first glance, it looks like years should be the x-axis titles.

This was changed.

20, 27 I don't think the problem of defining the length of snow covered periods is an algorithm problem. It's a conceptual understanding, or community definition problem.

We agree it's a definition problem, but it is also an algorithm problem. We have clarified this to read: "Improving and standardizing snow ephemerality metrics: Our research suggests there is a snow duration threshold where snowpack and soil moisture patterns begin to resemble seasonal instead of ephemeral snowmelt, and perhaps a second threshold when they begin to resemble rain (Fig. 3). Yet evidence that this threshold is near the 60 days used in the (Sturm et al., 1995), or consistent across space, is lacking. Instead of using this arbitrary 60 day threshold, we recommend that future research use the snow properties and soil moisture response of ephemeral snowpacks combined with a sensitivity analysis to create a snow duration threshold capable of differentiating seasonal and ephemeral soil moisture response (e.g. McNamara et al. (2005)."

Now You See It Now You Don't: A Case Study of Ephemeral Snowpacks and Soil Moisture in the Great Basin U.S.A.

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Abstract Ephemeral snowpacks, or those that ~~routinely experience accumulation and ablation at the same time and~~ persist for <60 continuous days, are challenging to observe and model~~.~~ because snow accumulation and ablation occur during the same season. This has left ephemeral snow understudied, despite its widespread extent. Using 328 site years from the Great Basin, we show that ephemeral snowmelt ~~delivers water~~ causes a 70 day earlier soil moisture response than seasonal snowmelt. ~~For example, we found that day of peak soil moisture preceded day of last snowmelt in the Great Basin by 79 days for shallow~~In addition, deep soil moisture ~~in ephemeral snowmelt compared to 5 days for~~response was more variable in areas with seasonal snowmelt. To understand Great Basin snow distribution, we used ~~moderate resolution imaging spectroradiometer (~~MODIS~~)~~ and Snow Data Assimilation System (SNODAS) data ~~from water years 2005–2014~~ to map snow extent. Estimates of maximum continuous snow cover duration from SNODAS consistently overestimated MODIS observations by >25 days in the lowest (<1500 m) and highest (>2500 m) elevations. During this time period snowpack was highly variable. The maximum seasonal snow cover during water years 2005-2014 was 64~~%~~ % in 2010 and ~~the~~at a minimum ~~was~~of 24~~%~~ % in 2014. We found that elevation had a strong control on snow ephemerality, and nearly all snowpacks over 2500- m were seasonal~~. Snowpacks were more likely to be ephemeral~~ except those on south facing slopes ~~than north facing slopes at elevations above 2500 m~~. Additionally, we used SNODAS-derived estimates of solid and liquid precipitation, melt, sublimation, and blowing snow sublimation to define snow ephemerality mechanisms. In warm years, the Great Basin shifts to ephemerally dominant as the rain-snow transition increases in elevation. Given that snow ephemerality is expected to increase as a consequence of climate change, ~~we put forward several challenges and recommendations to bolster physics based modeling of ephemeral snow such as better metrics for snow ephemerality and more ground based observations~~physics-based modeling is needed that can account for the complex energetics of shallow snowpacks in complex terrain. These modeling efforts will need to be supported by field observations of mass and energy and linked to finer remote sensing snow products in order to track ephemeral snow dynamics.

1 Introduction

Seasonal snowmelt supplies water to ~~1/6~~one-sixth of the world's population, which supports ~~1/4~~one-fourth of the global economy (Barnett et al., 2005; Sturm et al., 2017). Seasonal snowpack provides predictable melt timing and volumes in the spring, which influences streamflow timing, surface water and groundwater availability (Berghuijs et al., 2014;~~-~~ Jasechko et al., 2014; Stewart et al., 2005). Reliable spring snowmelt also provides a strong control on vegetation phenology and productivity in many ecosystems (Parida and Buermann, 2014; Trujillo et al., 2012). Despite the importance of seasonal snow to water supplies, much of the world's snow is ephemeral~~,~~ (or intermittent), which means it melts and sublimates throughout the snow cover season instead of having one consistent period of snowmelt. Even small shifts from seasonal to ephemeral ~~snowpack~~snowpacks due to regional warming could disrupt snowmelt rates and timing~~. in ways that could alter summer~~

~~productivity, soil temperature, and soil moisture regimes (Hamlet et al., 2005; Harpold and Molotch, 2015; Jefferson, 2011; Parida and Buermann, 2014; Regonda et al., 2005; Stielstra et al., .2015; Trujillo et al., 2012).~~ A shift from seasonal to ephemeral snowpacks will also have negative implications for the winter tourism~~,~~ that requires continuous snow cover, as well as water management~~,~~ and hydropower~~, and forest management sectors in particular~~

that relies on the predictability of snowmelt from mountain 'reservoirs' (Schmucki et al., ~~2014~~2017; Sturm et al., 2017). ~~Despite the~~The hydrological ~~and ecological importance~~impacts of ephemeral ~~snow, we lack widely accepted methodologies to classify, map, and model snow ephemerality~~snowpacks have received little study.

Snowmelt influences a variety of terrestrial hydrological processes and states, particularly soil moisture dynamics in areas with low summer precipitation (Harpold and Molotch, 2015; Seyfried et al., 2009). Snowmelt-derived soil moisture is a primary control on streamflow generation and timing and ecosystem productivity in many semi-arid systems (Jefferson, 2011; McNamara et al., 2005; Schwinning and Sala, 2004; Stielstra et al., 2015; Trujillo et al., 2012).~~One~~ Although few studies have isolated their hydrological importance, ephemeral snowpacks modify the intensity and duration of precipitation inputs to soil by storing and releasing water in a less predictable way than seasonal snow. For example, (McNamara et al., 2005) described five predictable phases of soil moisture evolution in semi-arid watersheds with seasonally dominant snowmelt: (1) a summer dry period, (2) a transitional fall wetting period, (3) a winter wet, low-flux period, (4) a spring wet, high-flux period, and (5) a transitional late-spring drying period. Soil moisture response to ephemeral snow melt is likely to sit between the predictable timing and rates of seasonal snow and the stochastic nature of rainfall, but few observations across this gradient exist. ~~Despite the hydrological and ecological importance of ephemeral snow, we lack methodologies to classify, map, and model snow ephemerality.~~

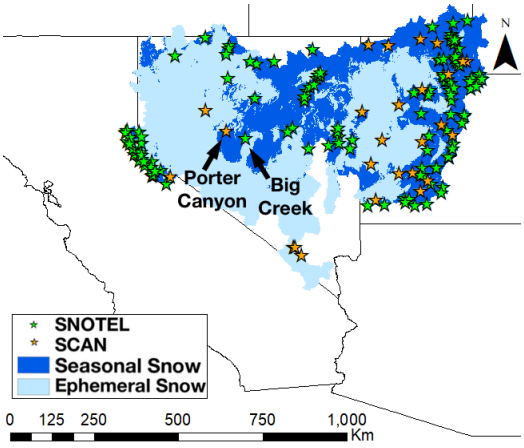
Despite the hydrological and ecological importance of ephemeral snow, there are no widely accepted methodologies to classify, map, and model snow ephemerality.

One commonly used snowpack classification system ~~in snow hydrology~~ by Sturm et al (1995) divides snowpack into six categories~~: Tundra, Taiga, Alpine, Maritime, Ephemeral,~~ and ~~Prairie. In that system,~~ defines ephemeral ~~-~~snowpacks ~~are defined~~ as ~~all snowpacks that persist~~those persisting for less than 60 consecutive days, are less than 50 cm depth, and have less than three different snow layers (Sturm et al., 1995). ~~The~~ While it is arbitrary, using the 60-day threshold allows for comparisons between the extent of ephemeral snow to previous studies and among different areas. The Sturm et al. (1995) classification system is also incorporated into physical snowpack models, such as SnowModel (Liston and Elder, 2006), to separate seasonal and ephemeral snowpacks~~.~~ into different modeling domains. Models often ~~separate the calculation of seasonal and ephemeral snowpack~~ make this separation because the energetics ~~because~~of ephemeral snowpacks are much more sensitive to basal melt from ground heat flux. Additionally, cold content varies more rapidly through time in shallow ephemeral snowpacks. Most physics based models (e.g. Liston and Elder (2006)), are optimized for seasonal snow, and produce less accurate results over ephemeral snow (Kelleners et al., 2010; Kormos et al., 2014).~~Although not much is known about their hydrological impacts, ephemeral snowpacks modify the intensity and duration of precipitation inputs by storing and releasing water in a less predictable way than seasonal snow. While it is arbitrary, using the 60-day threshold allows for comparable estimates of the extent of ephemeral snow and resulting implications of increased snow ephemerality.~~

Ground-based and remote sensing observations have their own strengths and weaknesses for observing ephemeral snowpacks~~.~~ and soil moisture response. Most ground-based snow measurement stations (e.g. the National Resource Conservation Snow Telemetry ~~Snow Telemetry~~, NRCS SNOTEL) in the Great Basin, ~~–~~, and ~~the rest of the~~ Western United States, ~~–~~, are built to observe seasonal snow (Fig. 1). This is because sites are typically placed in topographically sheltered forest gaps that retain snow longer than nearby terrain. This improves the skill ~~in~~of streamflow forecasting, the primary goal of the SNOTEL network, but means that most SNOTEL sites only have ephemeral snow cover in exceptionally dry or warm years (Serreze et al., 1999). Only two of the 131 SNOTEL stations in the Great Basin experience an ephemeral snow season on average (Fig. 1) each water year from 2005-2014. The scarcity of ground-based ephemeral snow and soil moisture data has changed slightly in recent years with additional measurements at NRCS Soil Climate Analysis Network (SCAN) (Fig. 1) and ~~within~~increased deployment in research watersheds (Anderton et al., 2002; Jost et al., 2007). On average, 26 out of 39 SCAN stations in the Great Basin experienced ephemeral snow cover each year (Fig. 1). However, the lack of field observations from ephemeral snowpacks with co-located soil moisture has limited previous investigations (e.g. Sturm et al. 2010).

Spectral remote sensing collects observations over all cloud-free ~~area, including both seasonal and ephemeral snow zones~~areas, but has its own sets of advantages and challenges~~. There~~ for observing ephemeral snow. One issue is that there are multiple methods to define the start and end of the observed snow covered period. Often, it is defined as the date of the first and last remotely sensed observations of snow cover (e.g. Choi et al. 2010; Kimball et al., 2004; Nitta et al., 2014). Because this approach does not account for intermittent snow free periods, it tends to

overestimate snow duration and miss important ephemeral dynamics (Thompson and Lees, 2014). Snow persistence thresholds can be used to define snow ephemerality, but no standard persistence threshold exists (e.g. Gao et al. (2011; Karlsen et al., 2007). Given the intermittent nature of ephemeral snow, observations must be daily or finer to capture its dynamics (Wang et al., 2014). Consequently, products like Landsat that ~~have~~has a 16-day overpass and Sentinel that has 5-10 day overpass do poorly at estimating snow seasonality compared to products like the ~~moderate~~ MODIS that have twice daily overpass, but they offer untapped potential for merged products with higher spatial and temporal resolution. ~~imaging spectroradiometer (MODIS).~~ Moreover, high cloud cover reduces observation frequency, and limits the ability to observe ephemeral snow events. Like with ground-based snow research, some remote-sensing based studies exclude ephemeral events altogether (e.g. Sugg et al. (2014)). ~~The~~ Only a limited number of algorithms have been developed to handle ephemeral snow specifically. For example, the algorithm developed by Thompson and Lees (2014) ~~removed most of the methodological flaws mentioned above by using~~uses daily MOD10A1 data and ~~accounting~~accounts for snow absences in the middle of the snow season, but their study was challenging to verify and applied only in a small area of Australia. Given the current lack of ground-based observations (Fig. ~~1), remote sensing is one path forward for observing~~1), there is great potential to use finer-scale satellite products and employ more refined methods targeted at areas with ephemeral snow.



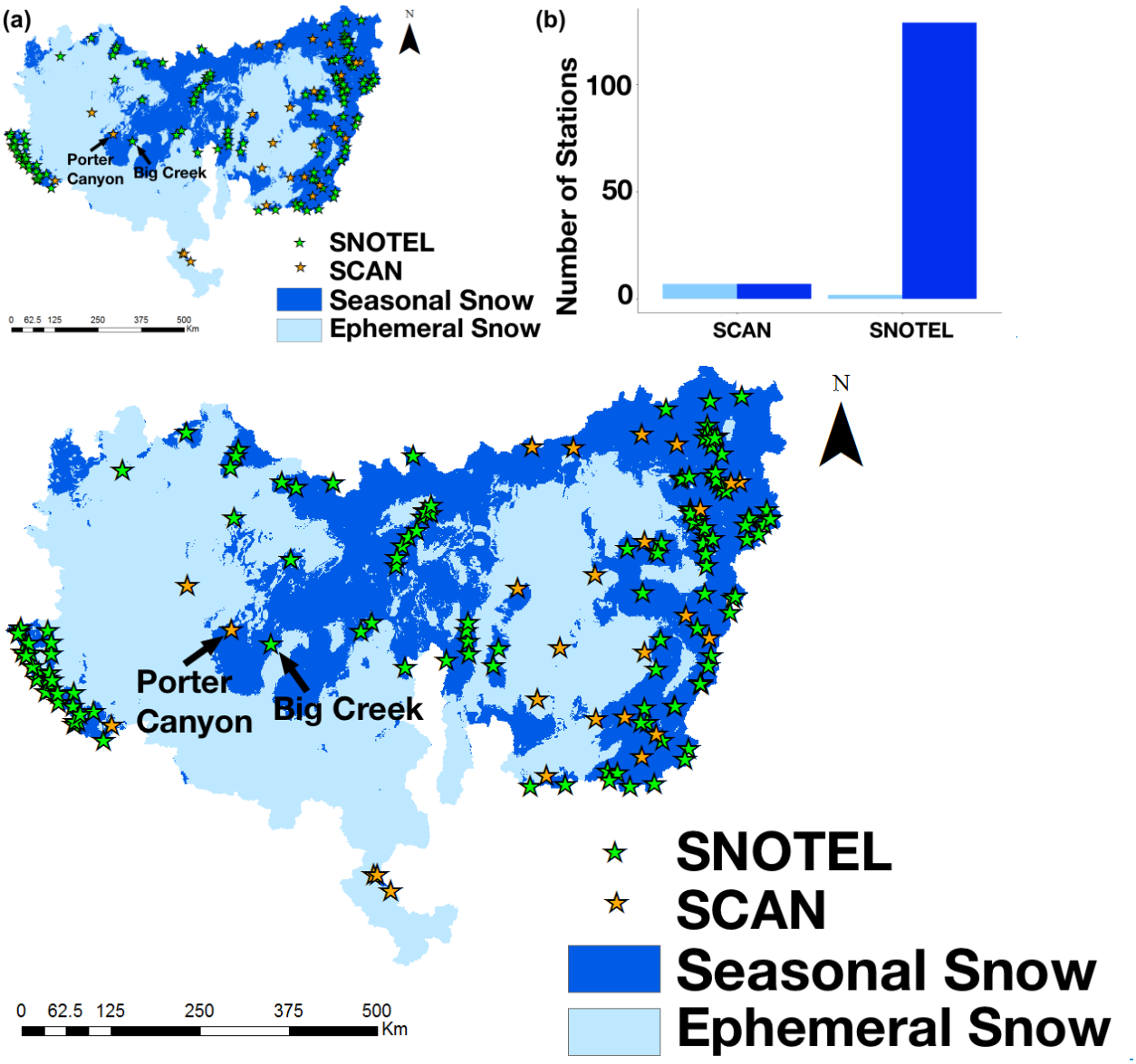


Figure 1: (a) Locations of ~~and (b) Number of Snow Telemetery (~~SNOTEL~~)~~ and ~~Soil Climate Analysis Network (~~SCAN~~)~~ stations in the Great Basin, USA ~~that are located~~ in ephemeral and seasonal snow as defined by <60 or ≥~~>=~~60 days of maximum consecutive snow duration, respectively. ~~Snow duration data collected using the Snow Data Assimilation System model.~~

~~Modeling ephemeral snowpacks is challenging and has not received the same attention as modeling more persistent, seasonal snowpacks. Most physics based models (e.g. Liston and Elder 2006), are optimized for seasonal snow, and produce less accurate results over ephemeral snow (Kelleners et al., 2010; Kormos et al., 2014). As stated previously, however, there is a lack of field observations to interrogate and verify these models against (Sturm et al., 1995; Toure et al., 2016).~~

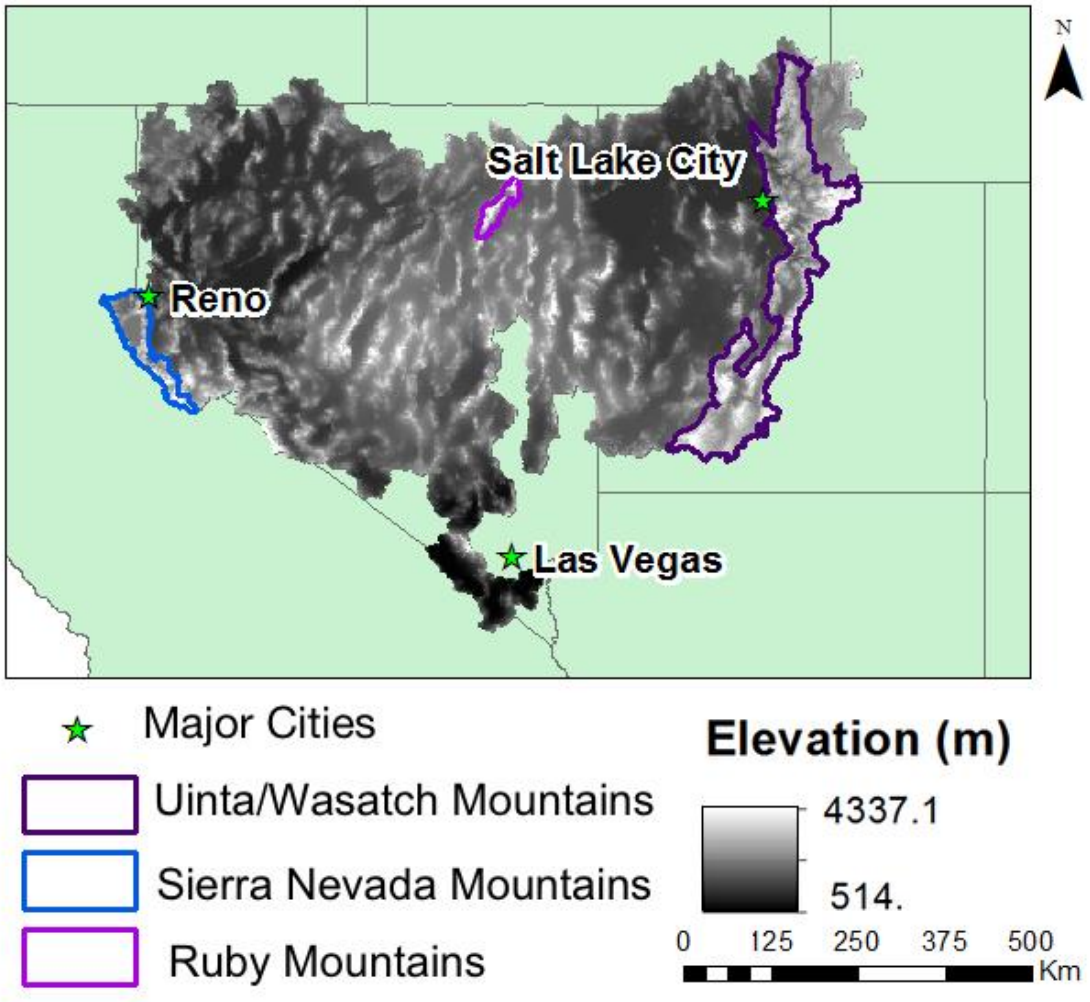
There are a variety of underlying processes that cause ephemeral ~~snowpacks~~snowpack and challenge snow models. Based on previous classification systems, we define three mechanisms causing ephemeral snowpacks: 1) Rainfall limiting the accumulation of snowpack, 2) Snowpack ablation from melt or sublimation, and 3) Wind scour

removing snowpacks. All of these mechanisms have a variety of underlying atmospheric and snowpack processes that challenge prediction with snow models. At rain-snow transition elevations, even small temperature variations and other atmospheric variables can alter the mixture of rainfall and snowfall (~~Henderson and Leathers, 2010~~Harpold et al., 2017b; Jefferson, 2011; Klos et al., 2014~~; Regonda et al., 2005~~). Complete snow water equivalent (SWE) removal from melt or sublimation is also another common cause of snow ephemerality (Clow, 2010; Leathers et al., 2004; Mote et al., 2005; Sospedra-Alfonso and Merryfield, 2017). Typically, physics- based models overestimate modeled SWE in ephemeral snowpack, due to neglect or underestimation of ground heat flux and the challenges of tracking cold content in shallow snowpacks (Cline, 1997; Hawkins and Ellis, 2007; Kelleners et al., 2010; Kormos et al., 2014; ~~LaMontagne, 2009~~Slater et al., 2017; Şensoy et al., 2006; Tyler et al., 2008). Models parameterize energy fluxes differently, which can lead to differences in model estimates of sublimation and melt (Essery et al., 2009; Schmucki et al., 2014; Sospedra-Alfonso et al., 2016). Removal of snowpack from wind scour is ~~a very~~an important ~~factor~~control on snow accumulation in alpine regions, but is often neglected in models altogether (e.g. Mernild et al. 2017; Pomeroy, 1991; Winstral et al., 2013). Widespread evidence exists that wind redistribution of snow can cause ephemeral snowpacks that are consistent from year to year because of topography and dominant wind directions (Hood et al., 1999). The three mechanisms causing ephemeral snow (i.e. rain-snow transition, ablation by sublimation and melt, and wind scour) have fundamentally different underlying causes, with ~~different~~variable and poorly quantified ~~sensitivity~~sensitivities to climate and land cover variability.

The goal of this paper is to use the Great Basin as a case study to estimate the distribution~~, hydrological consequences,~~ and mechanisms ~~of~~causing ephemeral ~~snowpacks using both ground-based~~snow to better constrain their impact on soil moisture and ~~remote sensing observations.~~hydrological response. We adapt ~~a~~the classification from (Sturm et al., 1995) to map snow and soil moisture response across the Great Basin, compare remotely sensed and modeled estimates of ephemeral snow, and develop our own ~~metric~~metrics to further classify snow seasonality. The Great Basin is ideal for this investigation because it spans dramatic gradients of elevation and hydroclimatology~~.~~ with large areas of both seasonal and ephemeral snow. This prototypical area depends disproportionately on mountain snowpack for water supplies, contains few ground-based observations, and there is relatively little winter cloud cover to limit spectral remote sensing techniques. Three research questions guide our analyses of ephemeral snowpacks in the Great Basin: 1) What are the implications for soil moisture from seasonal to ephemeral ~~snow melt~~snowmelt~~?~~ 2) How does topography affect snow seasonality~~,~~? and 3) What mechanisms cause ephemeral snowpacks and how does that vary with climate? We find that ephemeral ~~snowmelt leads to fundamentally different water availability than seasonal~~ snow ~~that results when~~originates from melt and ~~rain-snow transition shift~~ shifts to lower ~~in~~ elevation rain-snow transitions during warm winters, which leads to fundamentally different soil moisture response than from seasonal snowmelt.

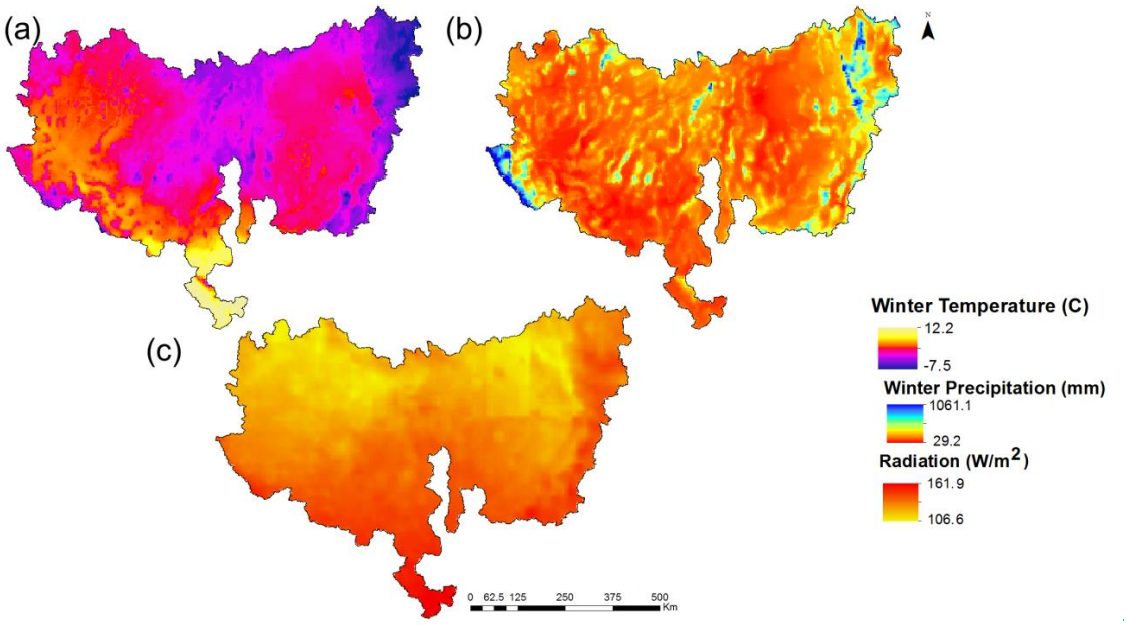
2 Study Area

The Great Basin is the closed basin between the Wasatch and southern mountain ranges in Utah and the eastern slope of the Sierra Nevada mountain range in California. The region is known for having ~~"~~internal drainage~~,"~~ which means that none of the waterways travel to the ocean (Svejcar, 2015). The climate is semi-arid and the ecosystem is shrub-dominated (Svejcar, 2015; West, 1983~~).; Wigand et al., 1995).~~ We defined the Great Basin region based on the Hydrologic Unit Code (HUC) Region 16 adapted from Seaber et al., (1987) by the United States Geological Survey (USGS) (Fig. ~~2). Overall,~~A1). Precipitation in the Great Basin ~~has a mean winter precipitation of 12 cm and a mean winter temperature of 0.4 degrees C (Fig. 3) (Abatzoglou, 2012). Precipitation~~ varies widely between <10 cm in many of the lower elevations to >100 cm on many of the high elevation mountains (Fig. ~~3~~A2). Overall, the Great Basin has a mean winter (defined as Dec 1st to Apr 1st) precipitation of 12 cm and a mean winter temperature of 0.4 ºC (Fig. A2; Abatzoglou 2012).



~~Figure 2: Map of the Great Basin region, USA as defined by the United States Geological Survey (USGS) Hydrologic Unit Code (HUC) Region 16 along with major cities and mountain ranges. The Sierra Nevada and Wasatch/Uinta mountain ranges defined using the US EPA L4 ecoregion classifications of "Sierra Nevada" and "Wasatch Uinta" respectively. Ruby Mountains were defined using a combination of "Mid-Elevation~~

~~Ruby Mountains" and "High Elevation Ruby Mountains" in the US EPA L3 classification (Omernik, 1987). Elevation contours at 1000 m intervals.~~



~~Figure 3: (a) Average winter temperature,(b) average winter precipitation, and (c) average winter radiation across water years 2001-2015 along with elevation in the Great Basin.~~

3 Methods

In order to compare the effect of snow ephemerality on soil moisture patterns, we first investigated snow and soil moisture response ~~at all~~for SNOTEL and SCAN stations within the Great Basin. To evaluate how soil moisture varies based on snowpack parameters during a drought year (water year 2015) and a non-drought year (water year 2016), we chose two SNOTEL stations: Porter Canyon (ID: 2170, Elevation ~~2191m~~2191 m) and Big Creek Summit (ID: 337, Elevation ~~2647m~~2647 m) that differ in elevation but are in close proximity. We ~~then~~ used average snow water equivalent (SWE) data ~~across water years 2005-2014~~ from ~~the~~ snow ~~data assimilation (SNODAS) model~~pillows to ~~categorize each SNOTEL and SCAN station year as being in ephemeral or seasonal snow if the duration of~~ determine snow cover. We categorized each day as snow covered if continuous ~~snow cover~~SWE was ~~less or more~~greater than 0.1 cm. We then designated site years as seasonal or ephemeral depending on if continuous snow cover was greater or less than 60 days~~,~~ respectively. For these stations, we compared percent soil moisture, ~~soil temperature~~ at 5 and 50 cm soil depth along with snow depth, and SWE. We then also acquired soil moisture and SWE data at 5 and 50 cm for all the SNOTEL and SCAN stations in the Great Basin in water years 2014-2016~~.~~ and categorized site years from those stations as ephemeral or seasonal. We discarded years and stations containing more than ~~7~~seven days of continuous missing data or soil moisture values that were 0 %. To compare the timing of snow and peak soil moisture, we then took the difference between the day of last snow and the day with peak ~~average~~median 10 day soil moisture for each year at each site. It should be noted that ablation on the snow pillow may be impacted by differences in ground heat flux and co-location issues with the soil moisture sensors. We also calculated the coefficient of variation (one standard deviation divided by the mean) of soil moisture for each year at each station. ~~We used the maximum length of continuous SWE that was greater than 0.1 cm to categorize years as containing ephemeral or seasonal snow.~~

We mapped ephemeral snow across the Great Basin using two methods: spectral remote sensing with MODIS data and modeled SNODAS data. We used Google Earth Engine to analyze the data, which is a cloud-based computing platform optimized for mapping large datasets~~.~~ (Gorelick et al., 2017). The MODIS dataset ~~we~~ used was the 2010 MODIS/Terra Snow Cover Daily L3 Global 500 m Grid (MOD10A) and we used the Normalized Difference Snow

Index (NDSI) with parameters outlined in (Hall et al., 2006) to find fractional snow covered data. The equation for calculating NDSI in MOD10 is:

$$NDSI = \frac{Band4 - Band6}{Band4 + Band6} \quad (1)$$

A pixel is then mapped as containing fractional snow ~~based on~~using the NDSI value ~~and~~, as long as the ~~percent~~ reflectance ~~value~~ in Band 2~~. If the reflectance~~ is ~~less than~~ ≥10~~%, the pixel won't be mapped as containing snow regardless of the NDSI value~~ % (Hall et al., 2001). We classified all pixels with a snow fraction of 30-100 as Snow, pixels with snow fractions between 0 and 30 as No Snow, and pixels that had all other designations as Other. We also used an algorithm derived from (~~Sturm et al., 1995~~Thompson and Lees, 2014) to minimize the impact of cloud cover in our MODIS data. The algorithm 'grows' the boundaries of all areas containing snow and reclassifies pixels that were classified as Other to Snow if the corresponding pixels in the previous image were classified as Snow. It also reclassifies pixels that were classified as Other to No Snow if the corresponding pixels in the previous image were No Snow.

To determine the number of ephemeral and seasonal snow events, we used a Google Earth Engine function to note the day of the ~~Water Year~~water year when snow appeared (when a pixel went from classified as No Snow in the previous day to classified as Snow in the current day) and when snow disappeared (a pixel went from classified as Snow in the previous day to being classified as No Snow in the current day), and determined the length of snow cover by subtracting the day of snow appearance from the day of snow disappearance. If the length of snow cover was <60 days, then the snow event was classified as ephemeral. Otherwise, if the length of snow cover was ≥60 days, the snow event was categorized as seasonal. In addition to these metrics, we derived a snow seasonality metric (SSM) to quantify a MODIS pixel's tendency to have ephemeral or seasonal snow, rather than a binary metric like <60 days. The SSM is depicted in Eq. (2) and it works by classifying every day where there was seasonal snow present as 1 and every day where there was ephemeral snow present as -1, and then averaging all -1 and +1 values. This created a -1 to 1 scale, where -1 signifies that all the snow covered days in a given pixel within one water year were ephemeral and +1 signifies that they were all seasonal.

$$SSM = \frac{Days_{Seasonal} - Days_{Ephemeral}}{Days_{Total}} \quad (2)$$

Additionally, we discarded all instances where snow was absent for one day only from the overall record of snow disappearance and appearance because there were~~we found~~ numerous artifacts from the MOD10A NDSI processing that lead to single day snow disappearance during long stretches of snow cover. One day snow events were also removed from the SNODAS algorithm to make both algorithms more consistent. For each water year from ~~2001~~2005 to ~~2015~~2014, we recorded the maximum total number of days where snow was present (to be referred to as the maximum snow duration).

To determine the relationship between elevation and snow seasonality, we took the average maximum snow duration across water years ~~2001-2015~~2005-2014 and used elevation, and aspect as measured by a digital elevation model (DEM) obtained from the Shuttle Topography Mission resampled to the same resolution with bilinear sampling (Farr et al., 2007). To calculate northness, we used the equation:

$$Northness = cos(\frac{aspect * \pi}{180}) \quad (3)$$

We then categorized each MODIS pixel based on five 500 m elevation bins from a range of 1000 to >3000 m. Then, to remove bias based on the size of each bin, we used random sampling to make each bin contain the same number of points as the least full bin (13548 points that were >3000 m). Then we combined each resampled bin into one dataset and created heatmaps to compare the elevation vs. the average maximum snow duration. We also use the same method to compare aspect to average maximum snow duration with aspect using eight 45 degree bins from a

range of 0 to 360 degrees. We randomly sampled 195163 points from each bin (the size of the bin from 315 to 360 degrees). After resampling, we combined all the bins together and split them into three elevation categories: Low Elevation (Elevation <1500 m), Medium Elevation (1500 ≥ Elevation <2500), and High Elevation (Elevation ≥ ~~2500m~~2500 m). Then, we resampled again to 82823 points per bin (the size of the High Elevation bin).

We used SNODAS data to ~~simply~~ differentiate the mechanisms that cause snow to become ephemeral. The four mechanisms were assigned if the net ablation (or rain) exceeded 50 % of the total winter precipitation (Fig. ~~4~~2): 1) A mixture of rain and snow limiting snow accumulation (the rain-snow transition), 2) snowpack loss due to sublimation, 3) snowpack loss due to melt, and 4) snowpack loss due to wind scour. We determined the prevailing mechanism in each 1000 m SNODAS pixel in each year. ~~-~~We used Earth Engine to execute the modeled algorithm on each 1000 m SNODAS pixel in the Great Basin. We then chose six years (2009-2014) and created histograms of each mechanism by elevation for each year.

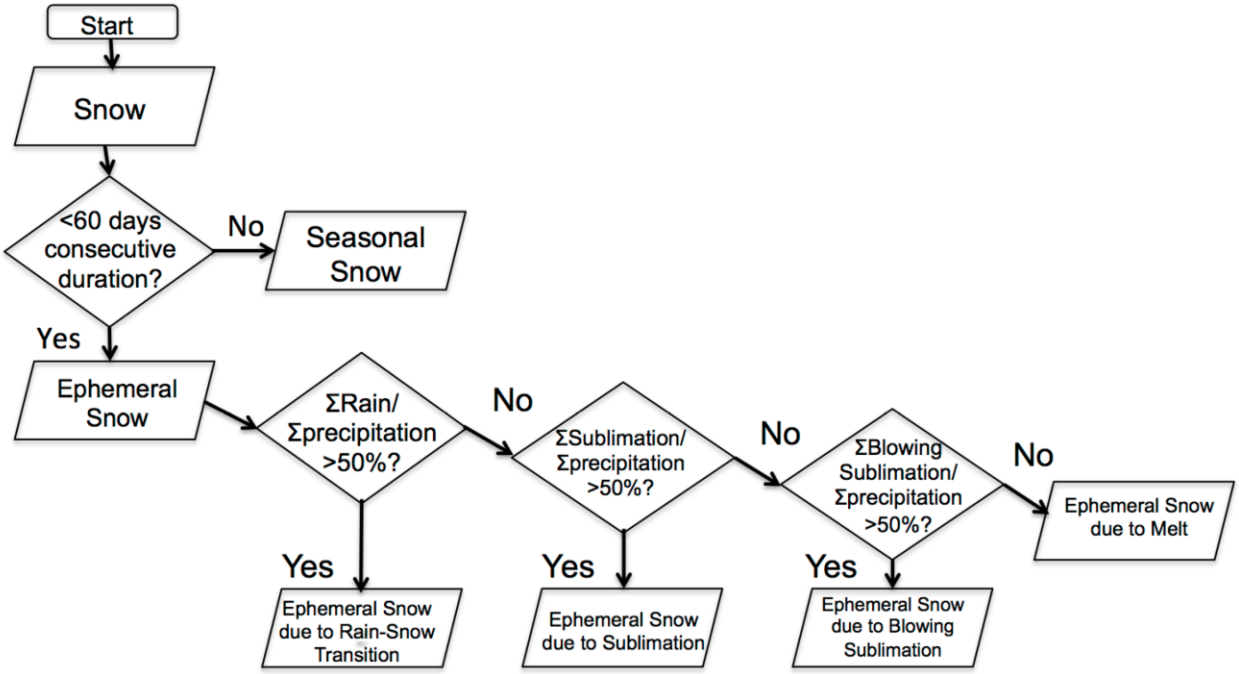


Figure ~~4~~2: Diagram of the process for the ephemeral snow mechanism model. Seasonal snow outputs were rejected, all other outputs were categorized.

4 Results and Discussion

4.1 Ephemeral Snow and Soil Water Inputs

~~Snowmelt influences a variety of terrestrial hydrological processes and states, but it has a dominant influence on infiltration and~~ In order to quantify differing soil moisture ~~dynamics in areas with low summer precipitation (Harpold and Molotch, 2015). Soil moisture is a primary control on rainfall-runoff response and water availability for vegetation (McNamara et al., 2005; Schwinning and Sala, 2004).~~

~~We quantified differing response of soil moisture~~ between seasonal and ephemeral snowpacks that have important ecohydrological implications~~. (McNamara et al., 2005) described~~ for the Great Basin, we use the five phases ~~of soil moisture evolution in semi-arid watersheds with seasonally-dominant snowmelt: (1) a summer dry period, (2) a transitional fall wetting period, (3) a winter wet, low-flux period, (4) a spring wet, high-flux period, and (5) a~~

~~transitional late-spring drying period. We use the (McNamara et al., 2005~~in the (McNamara et al., 2005) framework for soil moisture response to seasonal snowmelt. ~~to illustrate differences with soil moisture response to ephemeral snow melt.~~ First, we qualitatively ~~using~~compare two nearby sites with differing snow regimes. ~~Then second quantitatively,~~Second, we make quantitative analyses using all of the soil moisture records available in snow covered places of the Great Basin (Fig. ~~5~~3).

We contrast soil moisture response at two adjacent SNOTEL stations that differ in elevation by >500 m (Fig. 1) to illustrate differences between ephemeral and seasonal snowmelt. Soil moisture at 5 and 50 cm ~~were~~depth was used to represent ~~a~~ shallow and deep ~~response~~responses during a drought year (water year 2015) and a typical year (water year 2016). Porter Canyon had ephemeral snow (28 days maximum duration) in 2015 and seasonal snow (116 days) in 2016 (Fig. ~~5a~~3a). Big Creek had seasonal snowpack both years, although much shallower snowpack in 2015 (Fig. ~~5b). Soil~~3b). When seasonal snowpack is present at both sites in 2016, soil moisture follows the phases outlined by (McNamara et al., 2005) for a semi-arid, snowmelt driven environment. ~~durings seasonal snowpack in 2016.~~ Shallow and deep soil moisture was in a low-flux state during ~~December February~~Dec-Feb (DJF) at Big Creek in 2016 (Fig. ~~5f~~3f). During ~~March~~Mar-May (MAM), soil moisture increased substantially and was in a high-flux state. Average shallow soil moisture in 2015 and 2016 was similar in the MAM period (24.4 % and 24.8 %, respectively) and DJF period (11.3 % and 19.8~~%) between 2015 and 2016, %),~~ suggesting that snow storage and melt negates differences in early season soil moisture between years with very different winter precipitation. Porter Canyon also showed a similar soil moisture increase in the MAM period after a stable low-flux pattern in the DJF period during water year 2016. Both sites also reach their near maximum annual soil moisture coincident with snow disappearance in 2016 (Harpold and Molotch, 2015~~) in 2016,~~), but Porter Canyon has snow disappearance in both years that preceded peak soil moisture by several months. The deeper 50 cm soil moisture had a smaller and shorter peak during 2015 at Porter Canyon as compared to 2016 and Big Creek response.

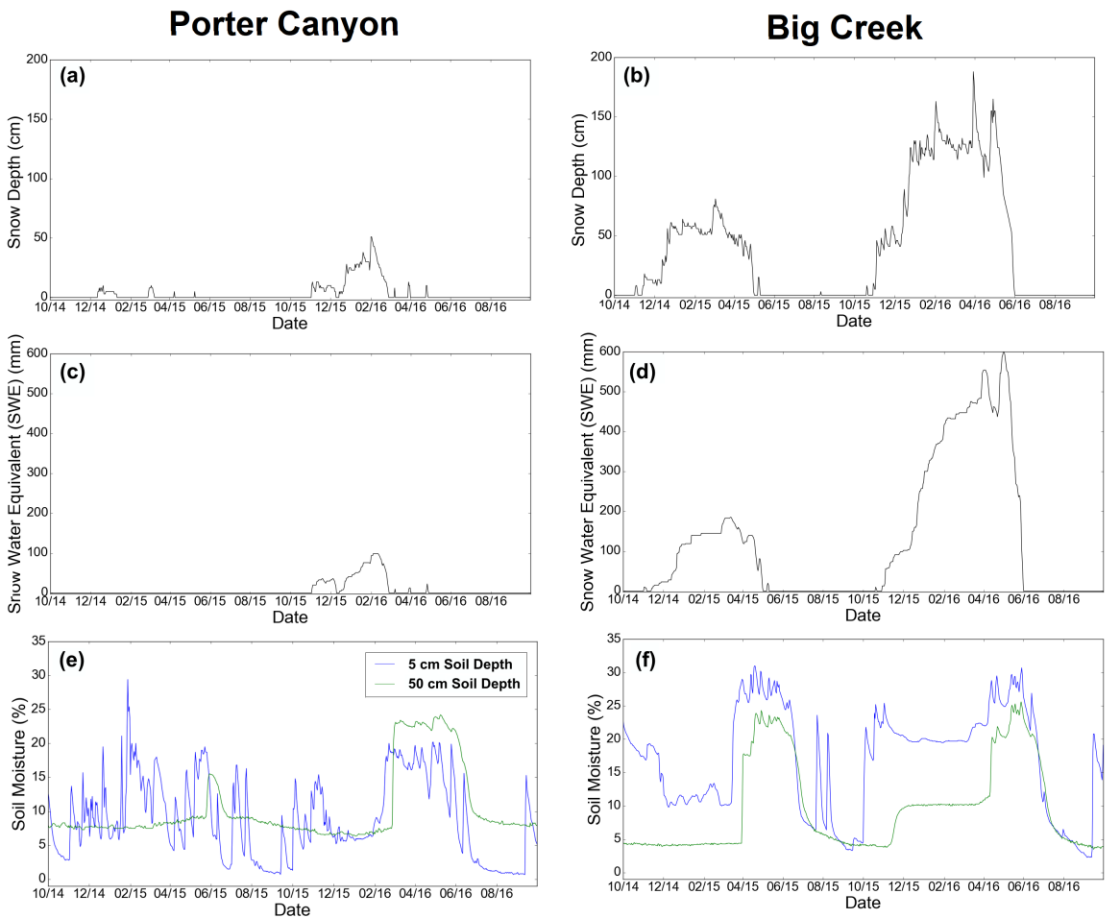


Figure ~~5~~3: (a,b) Snow depth, (c,d) Snow Water Equivalent and (e,f) Soil Moisture measured at Porter Canyon and Big Creek Snow Telemetry (SNOTEL) stations for water years 2015-2016, which were a drought year and a typical year respectively.

~~In addition~~Using similar records to ~~comparing soil moisture responses for~~those illustrated at these two sites~~,~~ we ~~also analyzed~~use 328 site years (50 ephemeral and 278 seasonal site years) from all SNOTEL and SCAN sites in the Great Basin (Fig. 1) over water ~~year~~years 2014, 2015, and 2016 ~~in order~~ to illustrate the broader patterns of soil moisture ~~between~~response to ephemeral and seasonal ~~snow melt~~snowmelt. We found that soil moisture following seasonal ~~snow melt peaked on average~~snowmelt reached a maximum 5 and 7 days prior to snow disappearance for shallow and deep soil moisture, respectively. This confirms previous findings that seasonal ~~snow melt~~snowmelt drives coincident wetting and deeper water percolation (Harpold and Molotch, 2015; McNamara et al., 2005). In contrast, the median soil moisture peaked 79 and 48 days after of snow disappearance from ephemeral ~~snow melt~~snowmelt for shallow and deep soil moisture, respectively (Fig. ~~6a). Deep~~4a). This is consistent with the peak shallow soil moisture occurring much earlier in the water year in shallow ephemeral snowmelt ~~had a~~areas (Fig. 4b). The later deep soil moisture response in ephemeral areas reflects the lack of response, or low coefficient of variation (CV~~) of 0.2~~), as compared to ~~0.4 0.5 for~~ seasonal snowmelt (Fig. ~~6~~4c). The lower CV for deep ephemeral snowmelt (0.2) compared to deep seasonal ~~snow melt likely reflects~~ snowmelt (0.4-0.5) is indicative of reduced deep percolation and less water becoming available to groundwater and streamflow.

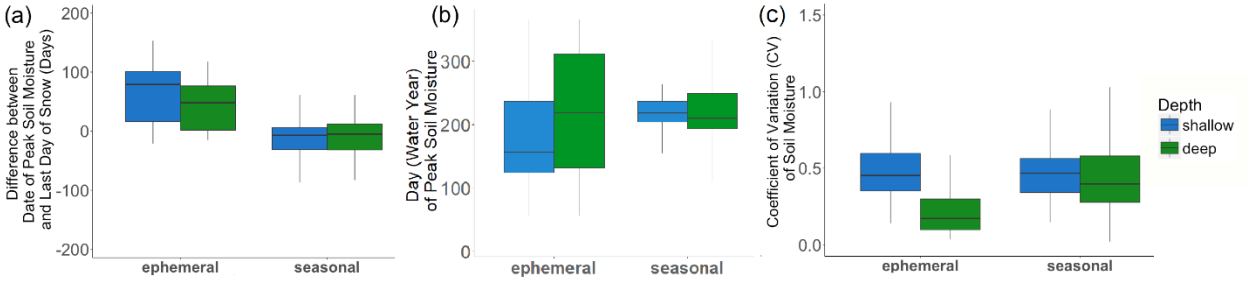


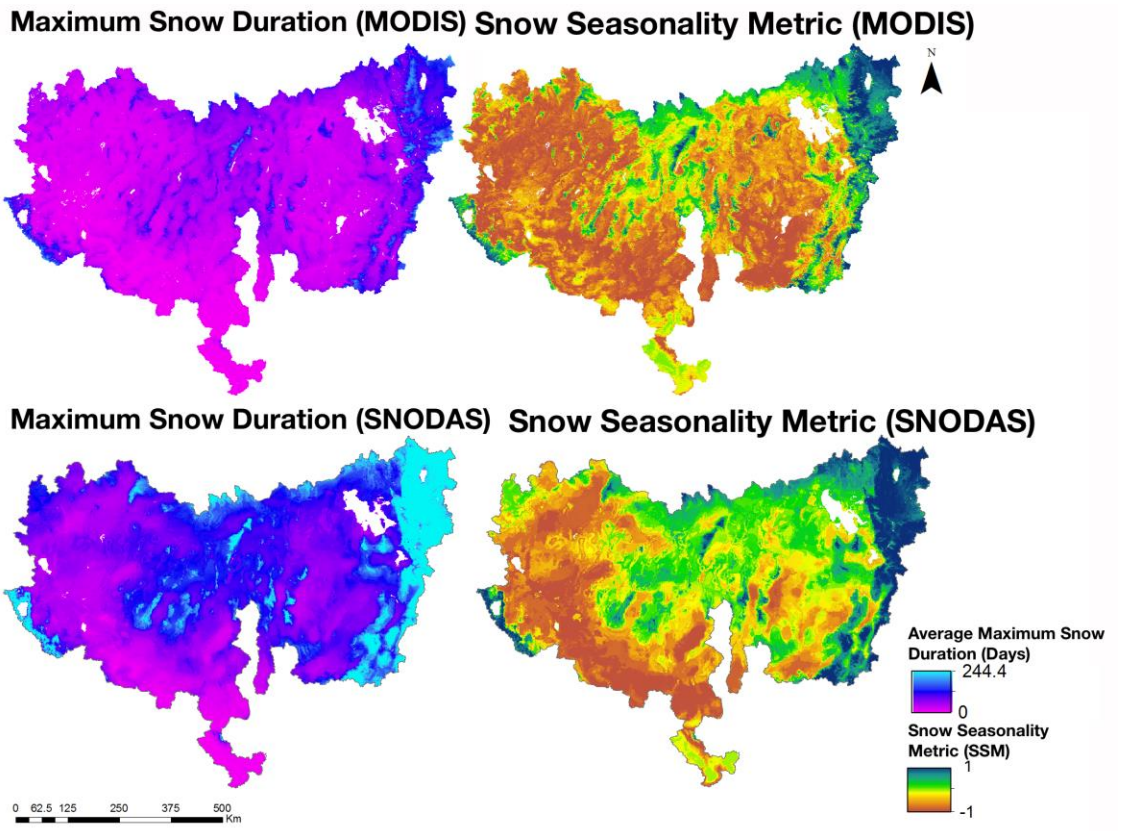
Figure 4: (a) The difference between date of peak soil moisture and last day of snow (Days) for shallow (5 cm) and deep (50 cm) soil moisture during water years 2014-2016 in Great Basin SNOTEL stations with ephemeral snow (50 site years) and seasonal snow (278 site years). (b) Day of peak soil moisture for SNOTEL and SCAN stations for shallow (5 cm) and deep (50 cm) soil moisture during water years 2014-2016 (c) The coefficient of variation (CV) for shallow (5 cm) and deep (50 cm) soil moisture during water years 2014-2016 ~~in Great Basin SNOTEL and SCAN stations is also shown.~~

The differences in soil moisture response between seasonal and ephemeral snowpacks across the Great Basin could have important consequences for vegetation phenology and runoff generation. For example, the timing of soil moisture is a strong control on the timing and amount of net ecosystem productivity (Inouye, 2008), with earlier snowmelt causing an earlier and longer growing season with reduced carbon uptake (Hu et al., 2010; Winchell et al., 2016). (Harpold, 2016) also showed that earlier snow disappearance generally led to more days of soil moisture below wilting point at SNOTEL sites. ~~across the Western U.S.~~. Our finding that soil moisture peaked earlier in ephemeral ~~snow melt~~snowmelt than seasonal snowmelt is thus likely to be correlated with reduced vegetation productivity and ~~increase~~increased late season water stress in many areas. In addition to stressing local vegetation, ephemeral snowmelt may reduce groundwater recharge and streamflow. For example, baseflow contributions to streamflow and overall water yield declined when snowmelt rates were smaller (Barnhart et al., 2016; Earman et al., 2006; Trujillo and Molotch, 2014) and overall water yields were lower in basins receiving more rain and less snow (Berghuijs et al., 2014). Changes in percolation patterns also affect the distribution of more shallow rooting plants versus deeper rooting plants that need long duration soil moisture pulses to grow and reproduce (Schwinning and Sala, 2004). These differences in how ephemeral versus seasonal snowmelt ~~-~~affects ~~on~~ soil moisture provide a strong motivation to understand the distribution and causes of ephemeral snowpacks across the Great Basin.

4.2 Topographic Controls on Snow Seasonality

In a typical year, much the Great Basin experiences ephemeral snow (Fig. ~~7~~5) that can only be comprehensively observed with remote sensing platforms because of the lack of standard ground stations (Fig. 1) . Using MODIS imagery, there are ~~and an object-based approach, we employ~~ two new metrics to estimate snow ephemerality with daily snow cover products: 1) The maximum consecutive snow duration and 2) The snow seasonality metric ~~or~~ (SSM~~.~~). The SSM describes both the consecutive snow season length and shoulder-season ephemerality. A SSM value <1 means an area experiences at least one ephemeral snow event. The average SSM was -0.4 ~~in~~(Fig. 5), suggesting that on average the Great Basin ~~(Fig. 7).~~was dominated by ephemeral snow extent. Maximum consecutive snow duration can be compared to the (Sturm et al., 1995) 60-day threshold for ephemeral snow, as done in this case, but it is flexible enough to include a threshold of any day length. The average maximum consecutive snow duration in the Great Basin from MODIS data was 42.1 days (Fig. ~~7~~5). We found ~~slightly different~~higher estimates of the average maximum consecutive snow duration measured using SNODAS of 62.9 days ~~and the~~ , but a similar average ~~snow seasonality metric (~~SSM~~) was~~ of -0.4 (Fig. ~~7). Although~~5). While the maps of the two products tend to produce similar results (Fig. 5), the SNODAS ~~ephemerality~~ spatial patterns often miss finer scale topographic controls (e.g. Wasatch mountains in the far eastern Great Basin) and over estimates ~~were very similar to MODIS,~~ snow durations in the colder, lower elevations (e.g. basins below the Ruby Mountains in the central Great Basin). In general, SNODAS over ~~estimated~~estimates snow duration in areas with the longest and shortest~~does not capture the elevation caused patterns (Fig. 7). The results of both metrics and both~~ snow ~~datasets are consistent an area that experiences mostly ephemeral snowpacks but contains areas of persistent seasonal snow at higher~~durations, i.e. highest and lowest elevations (Fig. ~~7).~~6). In these critical water supply areas >2500 m, where

snow would persist for >150 days according to MODIS, the SNODAS estimate were often biased by >50 days (Fig. 6). We explore the challenges of coarse, physically based models, such as SNODAS, later in this paper.


Maximum Snow Duration (MODIS)
Snow Seasonality Metric (MODIS)
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Maximum Snow Duration (SNODAS)
Snow Seasonality Metric (SNODAS)
Average Maximum Snow Duration (Days)
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0
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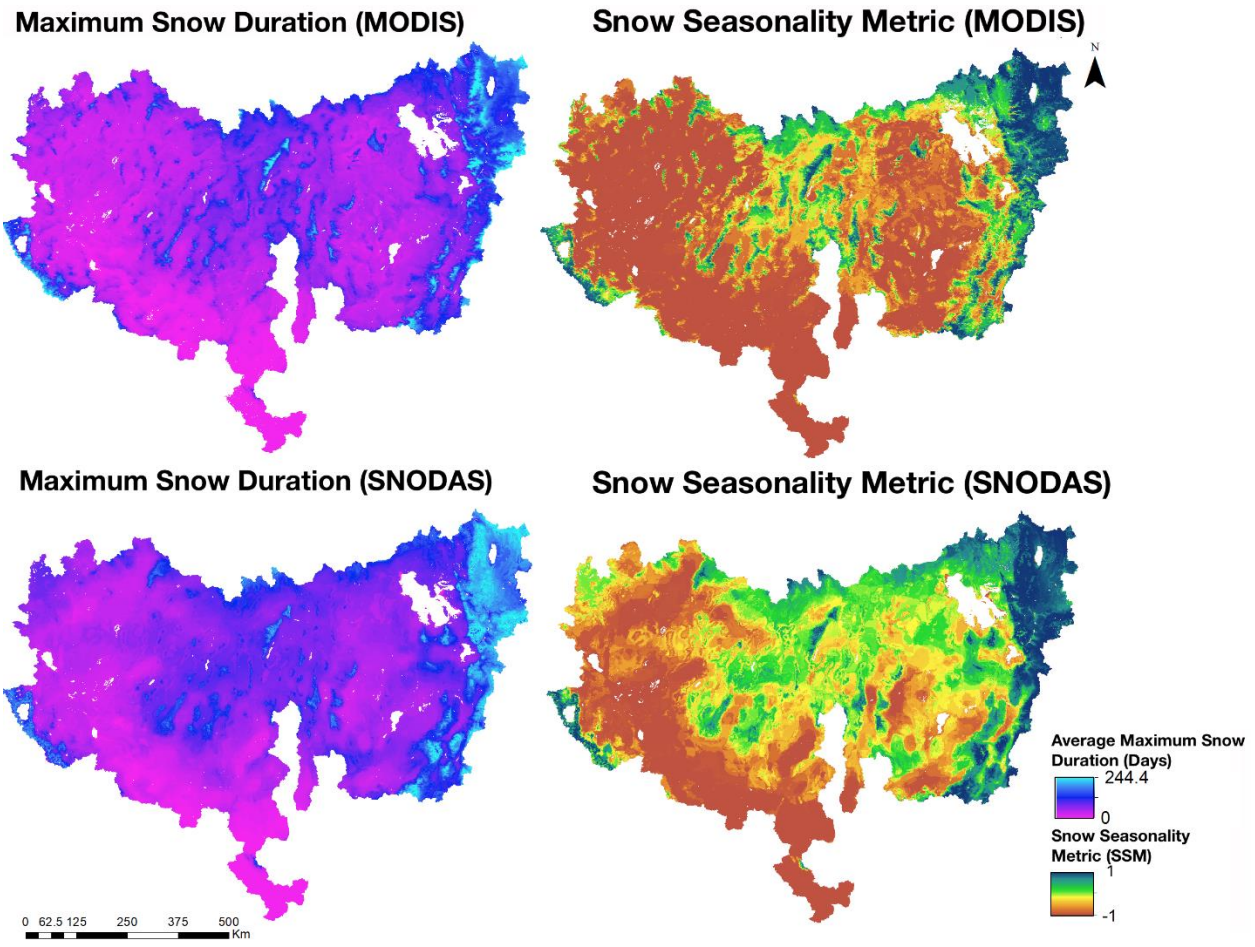
1
-1
0 62.5 125 250 375 500
Km


Maximum Snow Duration (MODIS)
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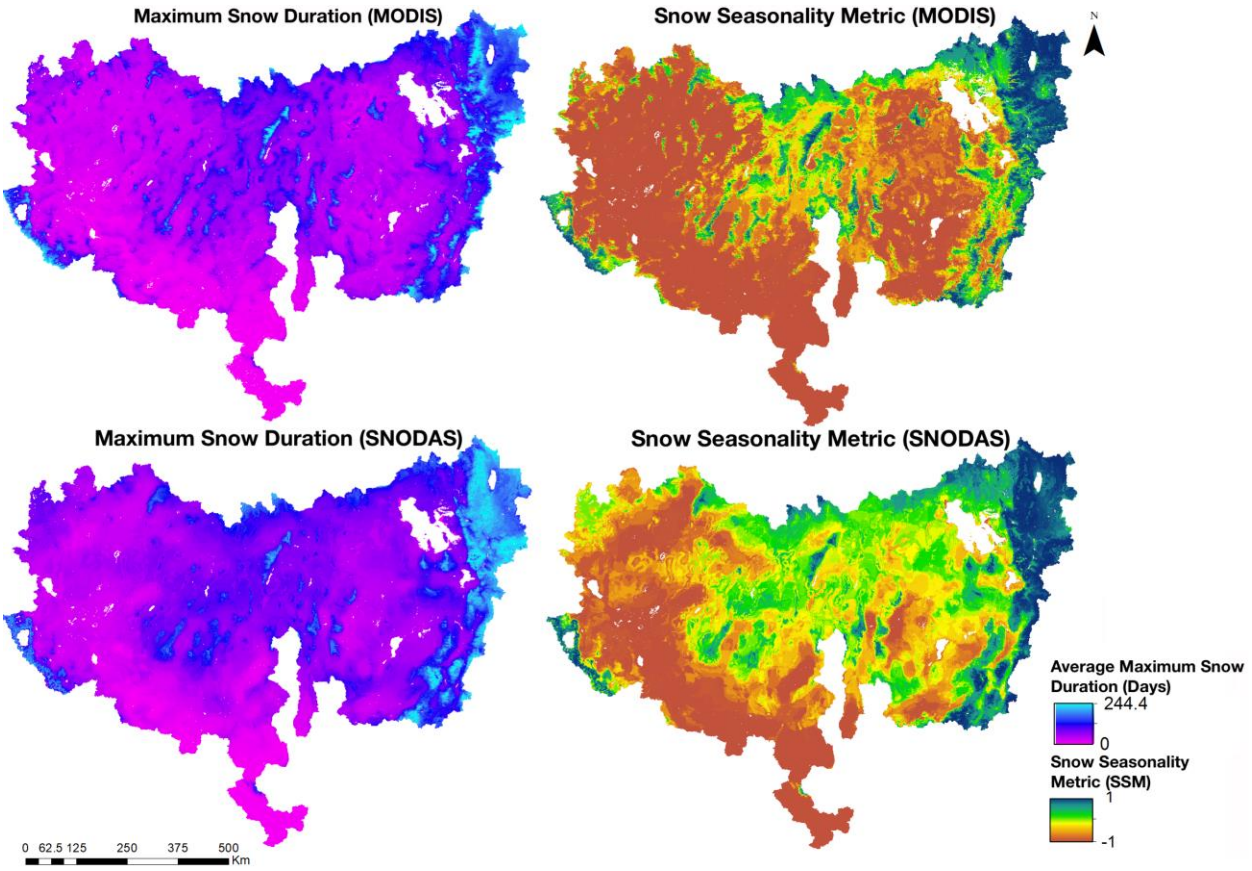


Figure ~~7~~5~~:~~ Average maximum consecutive snow duration (~~**Maximum**~~**maximum** snow duration) and snow seasonality metric (SSM) for the Great Basin measured using ~~**moderate resolution imaging spectroradiometer (**~~MODIS~~)** and snow data assimilation system (SNODAS) data in the Great Basin, USA~~**. MODIS data is from water years 2001-2015 and SNODAS data is from**~~ for water years 2005-2014.

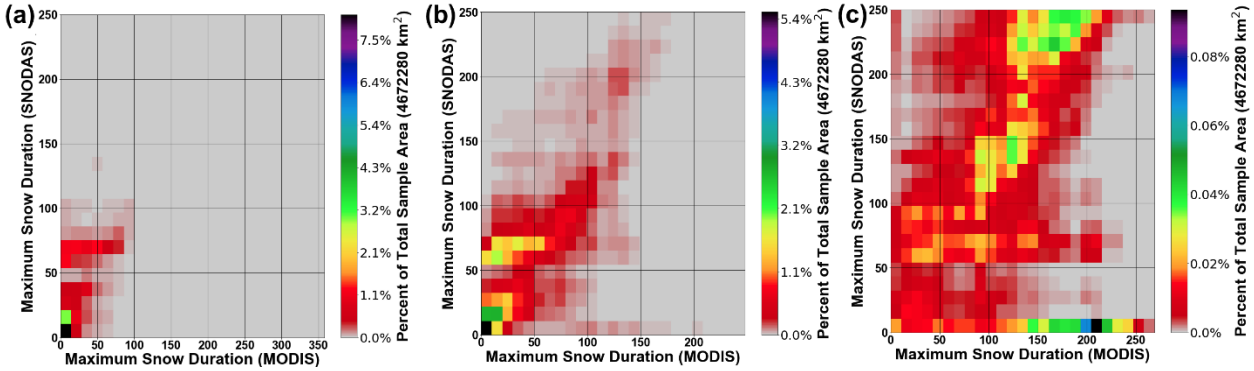


Figure 6: Maximum consecutive snow duration (maximum snow duration) measured using MODIS and snow data assimilation system (SNODAS) data and snow seasonality metric (SSM) for the Great Basin measured using MODIS.

We investigate elevation and aspect as proxies for snowpack mass and energy dynamics in order to expand our understanding of snow ephemerality~~ beyond mapping.~~. Elevation is a primary control on near surface air temperature due to the adiabatic lapse rate (Bishop et al., 2011; Greuell and Smeets, 2001; Nolin and Daly, 2006). Prior research has found that there is a strong elevation dependence on snowmelt timing, runoff generation, snow water equivalent (SWE), and snow season length (Hunsaker et al., 2012; Jefferson, 2011; Jost et al., 2007; Molotch and Meromy, 2014). Elevation effects ~~are the summation of~~likely due to a variety of factors, including temperature

controls on the rain-snow transition, longwave radiation in cloudy areas, and sensible heat flux. Aspect is often a secondary control on snow distributions because it influences incoming shortwave radiation (Jost et al., 2007; Pomeroy et al., 2003) and wind patterns (Knowles et al., 2015; Leathers et al., 2004; Winstral et al., 2013). Shortwave radiation is the primary driver of ablation via melt and sublimation (Cline, 1997; Marks and Dozier, 1992).

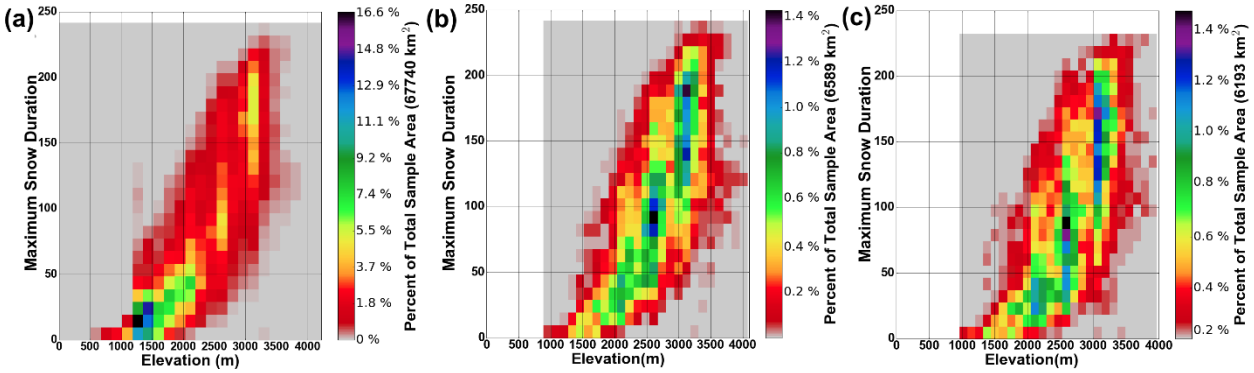


Figure ~~8: Heat maps showing~~7: Heatmaps of the relationship between elevation and average maximum consecutive snow duration from MODIS at (a) all slopes,(b) north-facing slopes only, and (c) south facing slopes only in the Great Basin, USA. North facing was defined as Northness >0.25 and south facing was defined as Northness<-0.25. ~~The colors correspond to~~Color bar scale is different in panel (a) reflecting the much larger area ~~within each~~at low elevation ~~and maximum snow duration.~~ .

~~Splitting~~Dividing the Great Basin into low elevations (<1500 m), mid elevations (1500-2500 m), and high elevations (>2500 m) illustrated ~~the~~elevation's dominant role ~~that elevation has~~ on snow cover duration (Fig. 7~~8). In our area normalized sample~~7). Across the Great Basin, 96.2 % of low elevation area and 75.2 % of mid elevation area had a maximum consecutive snow duration of ~~less than~~ <60 days. ~~Only~~Conversely, only 10.5 % of high elevations had a maximum consecutive snow duration of ~~less than~~ <60 days (Fig. ~~8~~7). The results suggest that mid and low elevations of the Great Basin are more likely to be ephemerally~~-~~ dominant. The heat maps also illustrate that elevation alone is not a strong predictor of maximum consecutive snow cover days (Fig. ~~8~~7). We use three smaller mountain ecoregions ~~that are focused on three distinct mountain ranges (see~~ (Fig. ~~2~~A1) to illustrate variability in elevation effects (Fig. ~~9~~8). There were similar average maximum snow duration values in the Ruby Mountains (Fig. 9a8a), eastern Sierra Nevada (Fig. ~~9b~~8b), and western Wasatch/Uinta ecoregion (Fig. ~~9c~~8c) (107, 100, and 95 days, respectively). However, snow in the Ruby Mountains ~~tended to have~~persisted longer ~~persisting snow~~ than the Sierra Nevada and Wasatch/Uinta ecoregions. The Sierra Nevada ecoregion had a weaker relationship between snow persistence and elevation above 2500 m, while the Wasatch/Uinta ecoregion had a weaker relationship with elevation below 2500 m (Fig. ~~9~~8). These differing relationships between maximum snow duration ~~with~~and elevation ~~point to~~suggest other factors are affecting snow ephemerality.

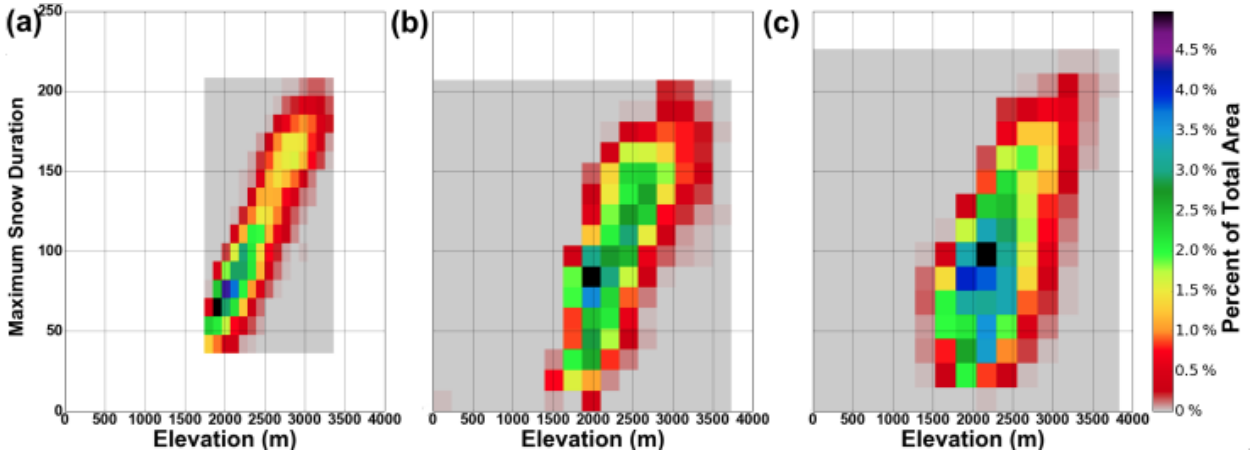


Figure ~~9~~8: ~~.~~ Heat maps showing the relationship between elevation and average maximum snow duration for three seasonally-dominant ecoregions in the Great Basin: (a) The Ruby mountains, (b) the Sierra Nevada mountains, and (c) the Wasatch/Uinta mountains.

Aspect is also an important control on snow seasonality in the Great Basin, but its importance is limited to mid and high elevations. We find that there are shorter maximum snow durations in south-facing aspects at elevations >1500 m (Fig. ~~10~~9). At low elevations, the difference in average maximum snow duration between north and south facing slopes was 0.4 days, while for mid and high elevations, it was 2 and 5 days, respectively (Fig. ~~10~~9). This is consistent with aspect ~~being a control of~~strongly controlling solar radiation, which is the main energy input to the snowpack. This suggests that deeper, high elevation snowpacks ablate in response to greater solar radiation and corresponding warmer temperature on south facing ~~hillslope~~hillslopes (Hinckley et al., 2014; Kormos et al., 2014). In contrast, lower elevation areas appear to have maximum snow duration caused by factors other than aspect. This is consistent with the outsized importance of other energy fluxes and factors, like ground heat flux and rain-snow transition elevation, that are not captured ~~with simple topographic relationships~~by aspect and elevation (Fig. 7, 8~~,~~ and 9 ~~and 10~~).

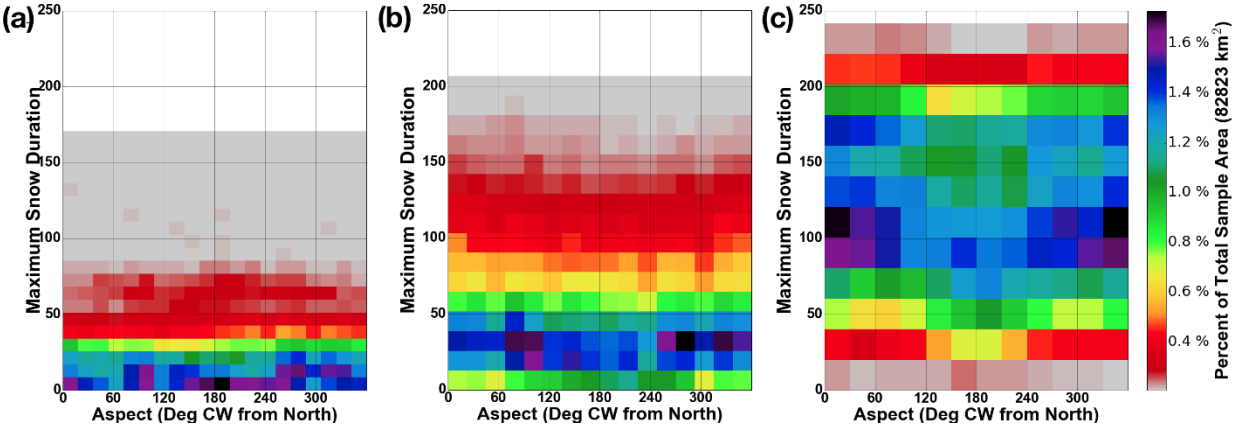


Figure ~~10: Heat maps~~9: Heatmaps of the relationship between aspect and average maximum consecutive snow duration at (a) low elevations (0-1500 m), (b) medium elevations (1500-2500 m) and (c) high elevations **(**>2500 m**).**

4.3 Proximate Mechanisms Controlling Snow Ephemerality

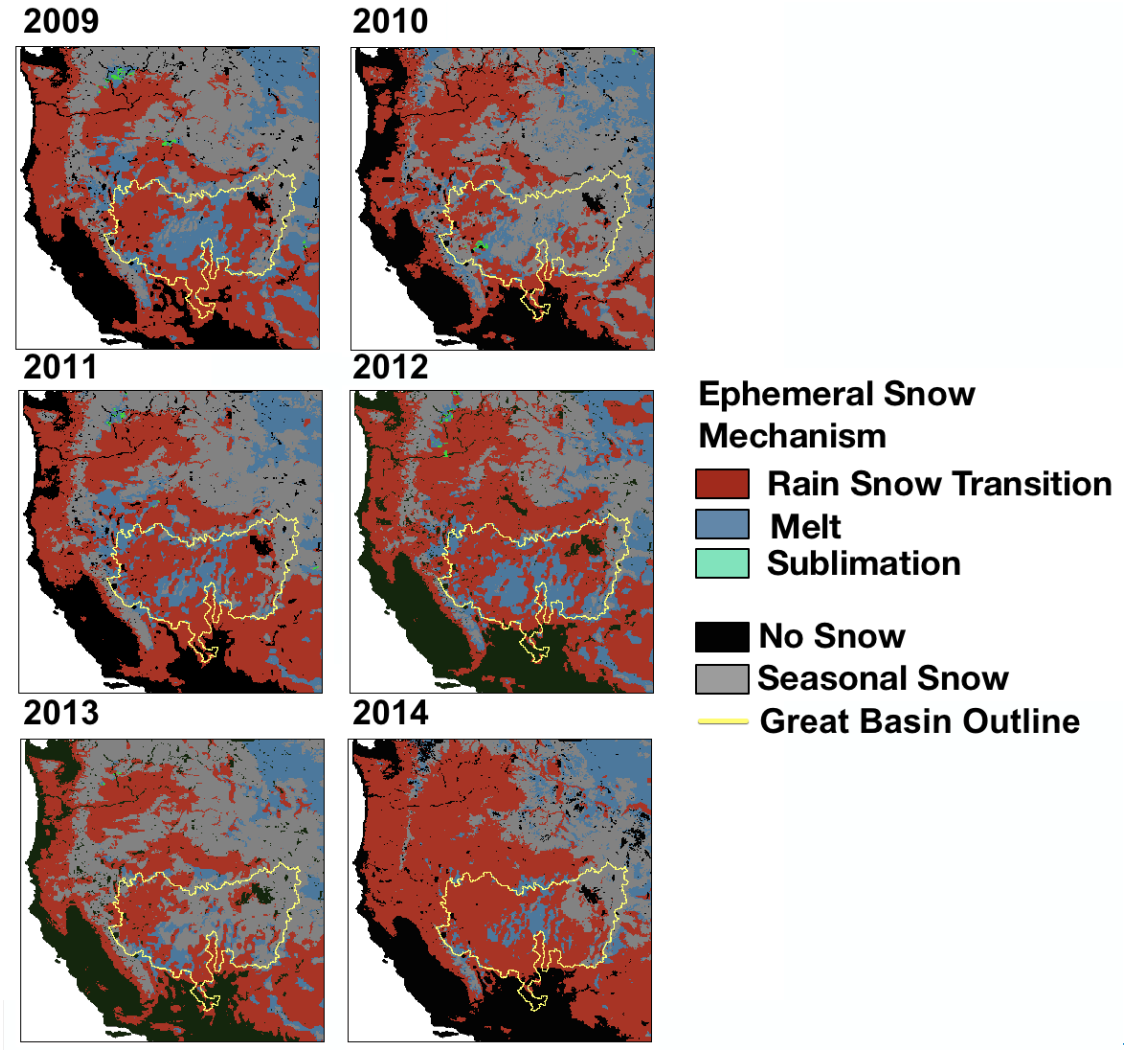
~~Deciphering the mechanisms controlling ephemeral snowpacks and their sensitivity to climate is challenged by a lack of models and observations. However, we~~We propose a three-mechanism classification scheme to help frame

our understanding of snow ephemerality: 1) rain-snow transitions limit snow accumulation, 2) snowpack ablation from melt and sublimation, and 3) wind scour or redistribution. Probably the most explored and observed mechanism is the potential for rising rain-snow transition elevations to limit snow accumulation and duration (Bales et al., 2006; Klos et al., 2014; Knowles ~~et al., 2006~~and Cayan, 2004; Mote, 2006). Reduction in snow duration can also be caused by the melt of snowpack (Mote, 2006) and losses from sublimation (Harpold et al., 2012; Hood et al., 1999); however, much less is known about the role and distribution of these processes outside of the seasonal snowpack zone. Finally, wind scour can reduce snowpacks by redistributing it to other areas or by increasing blowing wind sublimation (Knowles et al., 2015; Leathers et al., 2004).

We chose six years to evaluate the dominant mechanisms causing snowpack ephemerality using a new classification system (Fig. ~~3~~2) based on SNODAS data that compared favorably to estimates from MODIS (Fig. ~~7~~5 and 6). In that six year period, the year with the lowest average winter (Dec 1st to Apr 1st) temperature using gridded meterological (GRIDMET) 4 km resolution surface temperature estimates was 2013 at -0.9~~°C~~ °C while the year with the highest average winter temperature was 2014 at 1.0~~°C~~ °C (Abatzoglou 2012~~;~~) Table 1). In water year 2013 and water year 2010, the two coldest years, seasonal snowpacks were dominant in most of the Great Basin and Western United States (Fig. 10-11~~-12~~). In the coldest years of 2010 and 2013, the rain-snow transition and melt caused ephemerality to shift lower in elevation (Fig. ~~12~~11). In the warmest year ~~(~~of 2014~~.),~~ seasonal snowpack was lowest at lower elevations ~~in all~~ throughout the Western US mountain ranges (Fig. ~~11).,~~10), including the Great Basin where the increase in ephemeral snowpacks ~~increased in middle and~~ at higher elevations was due primarily to a~~the~~a rain-snow mechanism (Fig. 10 and 11~~ and 12~~). Melt caused snow ephemerality also increased in the warm 2014, but ~~ephemerality~~ ephemeral snow remained ~~low~~ sparse above 2500 m in all years. Overall, our findings are consistent with the importance of variability in rain-snow transition elevations limiting snow accumulation and duration (Bales et al., 2006; Klos et al., 2014; Knowles and Cayan, 2004; Mote, 2006). Sublimation was only present as a limiting mechanism in 2010 and only for a small area (Fig. 10~~11~~10). Blowing snow sublimation was not the dominant cause of snow ephemerality in the Great Basin for any year~~;, but its known that~~ SNODAS struggles to represent wind redistribution of snow (Clow et al~~. 2012 Hedrick et al. 2015).~~., 2012; Hedrick et al., 2015). Our approach to classify proximate causes of snow ephemerality has some limitations. Namely, it assigns only a single mechanism to each grid cell when there could be multiple mechanisms. Moreover, the method cannot consider changes in the mechanisms with time (e.g. melt tends to occur more in spring) because we applied annualized estimates of snow cover duration and concerns about the fidelity of the SNODAS model at short time scales.

Table 1: Average winter (Dec 1st-Apr 1st) temperature **(**°C) and average elevation (m) for both dominant mechanisms of snow ephemerality and seasonal snow from 2009-2014 in the Great Basin.

Water Year	Average Winter Temp (deg C)	Mean Elev for Rain Snow Transition (m)	Mean Elev for Melt (m)	Mean Elev for Seasonal Snow (m)
2009	0.1	1806~~.3~~	1751~~1750.8~~	1728~~.4~~
2010	-0.6	1811~~.3~~	1747~~.1~~	1761~~.3~~
2011	-0.2	1803~~.7~~	1766~~1765.6~~	1700~~1699.6~~
2012	0.4	1803~~.7~~	1745~~.2~~	1710~~1709.8~~
2013	-0.9	1816~~1815.6~~	1710~~1709.8~~	1754~~.1~~
2014	1.0	1790~~1789.9~~	1749~~1748.9~~	1732~~1731.5~~


2009
2010
2011
2012
2013
2014
Ephemeral Snow Mechanism
Rain Snow Transition
Melt
Sublimation
No Snow
Seasonal Snow
Great Basin Outline

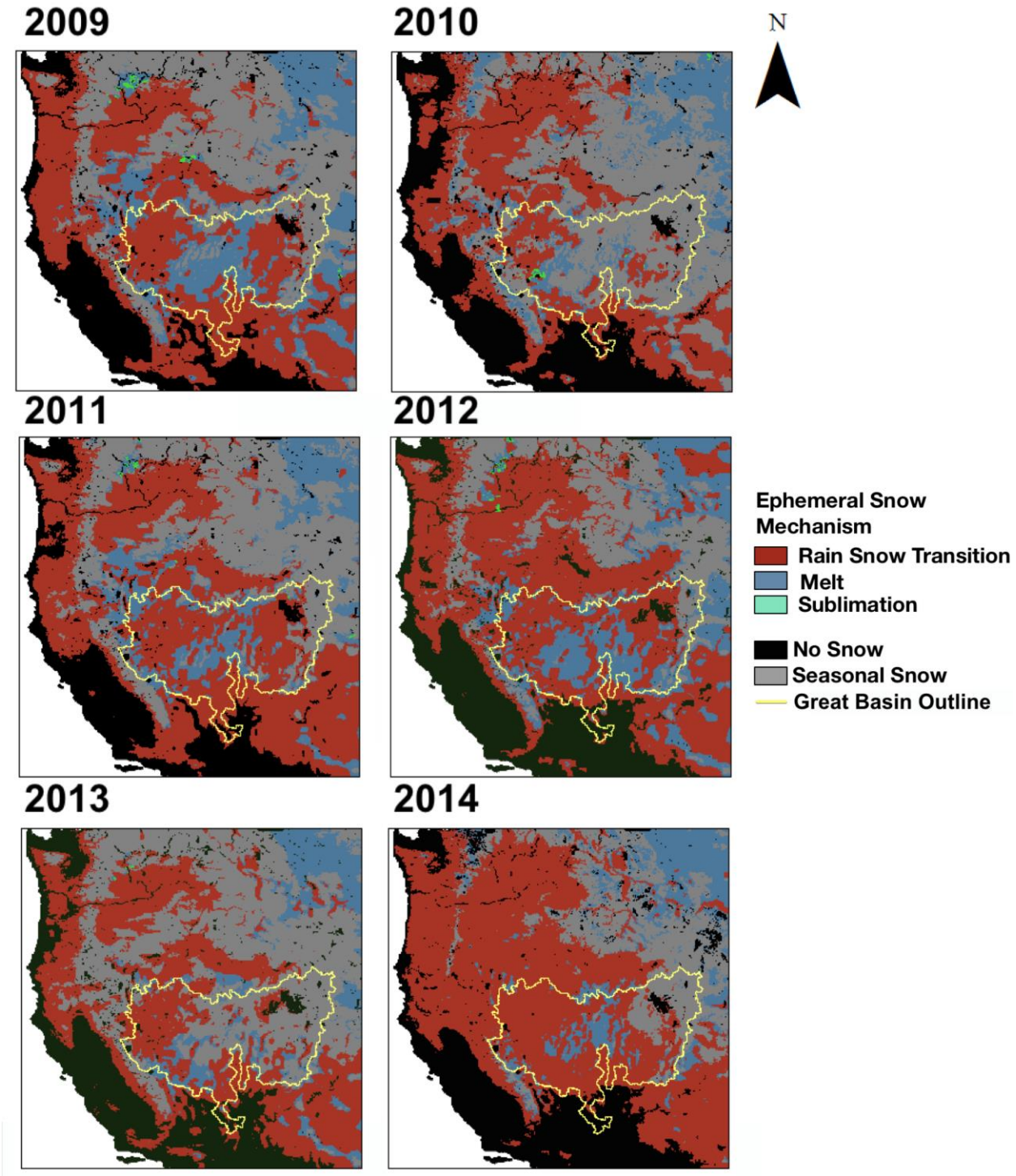
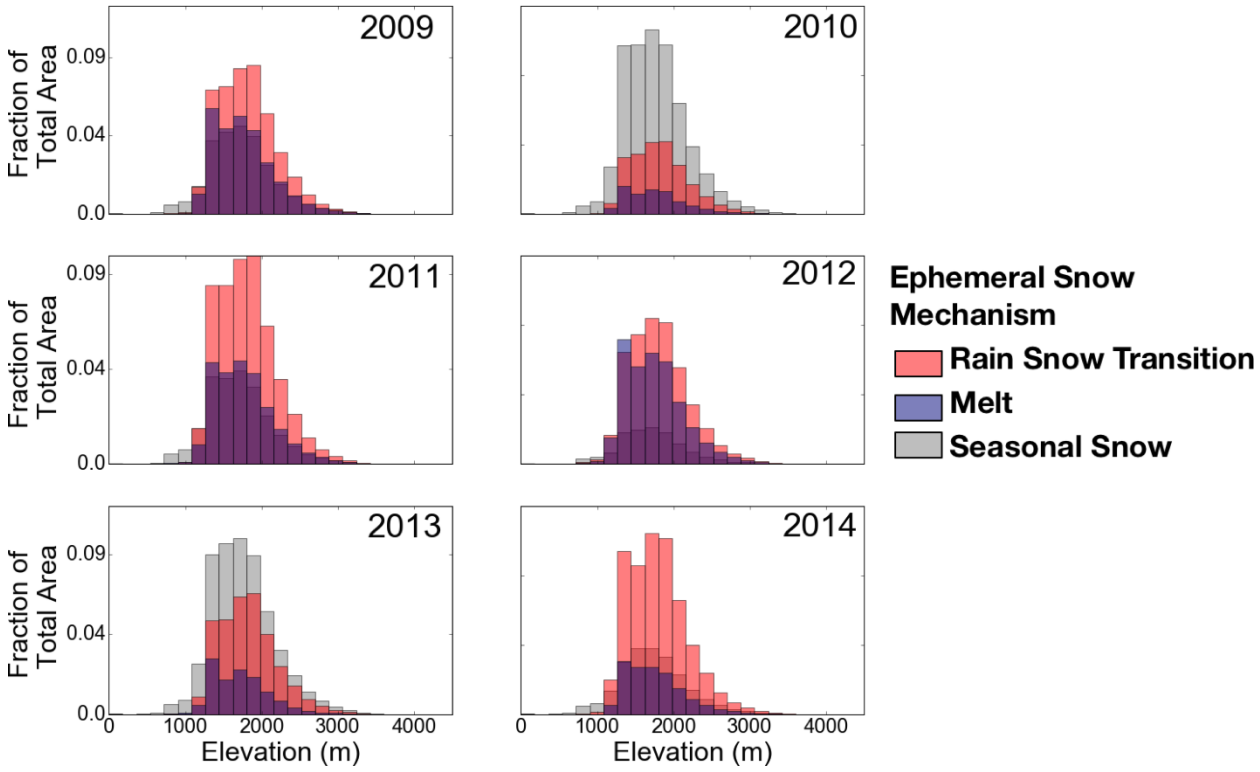


Figure ~~11~~10~~:~~ ~~-~~Dominant mechanisms for~~causingfor~~ snow ephemerality from water years 2009-2014 in the Western United States. ~~**Data obtained from SNODAS.**~~ Areas with seasonal snow~~,~~ (grey), no snow~~,~~ (black), and water bodies (black) are also depicted ~~**as black**~~. The Great Basin region is outlined in yellow.


2009
2010
2011
2012
2013
2014
Fraction of Total Area
0.09
0.04
0.0
0
1000
2000
3000
4000
Elevation (m)
Ephemeral Snow Mechanism
Rain Snow Transition
Melt
Seasonal Snow

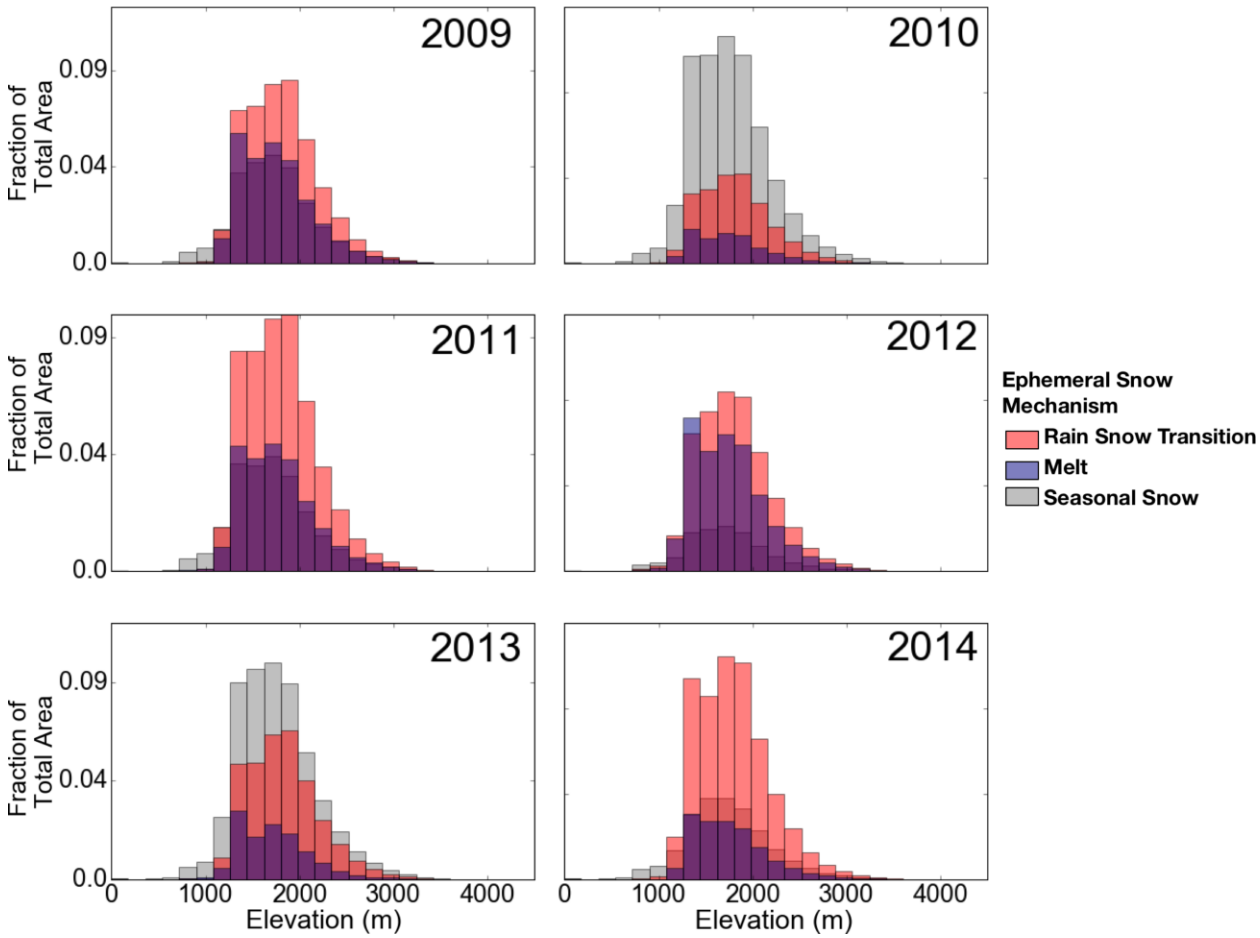


Figure ~~12~~11~~:~~ ~~-~~Histograms of the ~~fractional area of different ephemerality~~relationship between elevation and the dominant mechanisms ~~versus elevation~~ in the Great Basin from water years 2009-2014.

The mechanisms causing snow ephemerality that can be inferred from the SNODAS model have important implications for water availability in the Great Basin, but there is less~~we lack~~ confidence in the model fidelity in these shallow snowpacks~~.~~ given their differences with the MODIS observations (Fig. 6). These limitations are present in all snowpack energy models because the models were developed for deeper snowpacks where terms like ground heat flux and albedo~~-~~ depth relationships can be ignored or are insensitive (Cline, 1997; Harstveit, 1984; ~~LaMontagne, 2009;~~ Liang et al., 1994~~;~~)~~.~~; Slater et al., 2017; Tyler et al., 2008). In shallow snowpacks, these terms are more critical (Hawkins and Ellis, 2007; ~~LaMontagne, 2009~~Slater et al., 2017; Şensoy et al., 2006; Tyler et al., 2008), and the lack of SWE means the internal energy state of the snowpack (i.e. cold content) is more easily varied by short term climate forcing (e.g. warm, sunny days) (Liston, 1995~~) and thus, more critical to accurately track.~~). Ephemeral snowpacks also exist at lower elevations with warmer soils and increased ground heat flux (~~LaMontagne, 2009).~~Slater et al., 2017; Tyler et al., 2008). Uncertainty in the rain-snow transition principally arises from predicting climate forcing and in particular temperature~~.~~ and humidity in places like the Great Basin (Harpold et al., 2017a). However, the underlying phase prediction method and related model decisions and climate forcing data can also be important for the quality of precipitation phase prediction (Harpold et al., ~~2017~~2017b). Further complicating rain-snow transition mechanisms is storage or drainage of liquid water on~~in the~~on existing snowpacks (Lundquist et al., 2008; Marks et al., 2001). Although SNODAS assimilates MODIS imagery into the model, it does not appear to capture the finer elevation patterns we found using the MOD10A product (Fig. ~~7),~~5 and 6), and in particular, seemed to overestimate consecutive days of snow cover. Part of the challenges at higher elevations is modeling blowing snow patterns over 1-km grid cells, which ~~is~~gives consistent ~~with challenges reported by other~~lower accuracy of SNODAS ~~verification efforts in complex terrain~~above tree line and in more windy areas (Clow et al., 2012; Hedrick et al., 2015). The Great Basin shows tremendous ~~sensitivity to~~ variability in snow ephemerality ~~from~~caused by

interactions of topography ~~and,~~ elevation, and prevailing wind (Fig. 10-11 ~~12~~) and thus, represents an area where improvements in the physically-based modeling ~~of shallow snow and rain-snow transition elevations~~ will be critical to predicting snow water resources under a variable and changing climate.

5 Conclusions ~~and Recommendations~~

Mapping, measuring, and modeling ephemeral snow is challenging with current techniques, but ~~will be~~it is vital for understanding ~~how~~future water resources and vegetation ~~will respond to future climate~~water use. Ephemeral snowpacks do not have distinct accumulation and ablation periods, which means the timing of soil moisture input varies and is more challenging to predict~~.~~ than seasonal snowmelt (e.g. McNamara et al. (2005)). Consequently, as snowpacks shift from seasonal to ephemeral, there are potential ecohydrological consequences such as changes to vegetation response, vegetation distribution, drainage, lateral water flow, and solute transport.

Our work shows that while topography and climate variability have strong controls on the distribution of ephemeral snowpacks (Fig. ~~8~~7 and ~~11~~10), those factors will not be sufficient for predicting snow ephemerality under varying climate. Instead, there is a~~we will~~ need for physics-based models capable of capturing the three broad mechanisms identified by this study: 1) rain-snow transitions limit snow accumulation, 2) snowpack ablation from melt and sublimation, and 3) wind scour and redistribution. These classifications could help better identify local and regional sensitivity to increased snow ephemerality (Fig. ~~11~~10 and ~~12~~11). This work has also highlighted major weaknesses in the observational infrastructure, data analysis, and modeling techniques needed to support the growing importance of ephemeral snowpacks~~.~~ in the Great Basin. In light of these diverse needs, we conclude with a short summary of recommendations meant to guide future research directions ~~into this important research topic~~:

• ~~Better~~Improving and ~~standard~~standardizing snow ephemerality metrics: Our research suggests there is a snow duration threshold where snowpack and soil moisture patterns begin to resemble seasonal instead of ephemeral snowmelt, and perhaps a second threshold when they begin to resemble rain~~.~~ (Fig. 3). Yet evidence that this threshold is near the 60 days used in the (Sturm et al., 1995~~) paper~~), or consistent across space, is lacking. Instead of using this arbitrary 60 day threshold, it is recommended ~~we recommend~~ that future research use the snow properties and soil moisture response of ephemeral snowpacks combined with a sensitivity analysis to create a snow duration threshold capable of differentiating seasonal ~~snow melt caused~~ and ephemeral soil moisture response (e.g. McNamara et al. (2005~~)) from ephemeral effects and rain.~~).

• ~~More~~Increasing snow and soil moisture observations in ephemeral areas: In the Great Basin, only two snow telemetry (SNOTEL) stations and 26 soil climate analysis network (SCAN) stations observe ephemeral snowpacks (Fig. 1). The lack of observations makes it more difficult to ~~leverage the clear differences in SWE,~~develop relationship betweeen snow ~~depth, and shallow~~melt soil moisture ~~between ephemeral and seasonal snow~~. To help develop better criteria for categorizing snowpack as ephemeral, we need more snow and soil moisture observations in ephemeral areas. Also, we show that observing both shallow and deep soil moisture can add significant hydrological inferences. We can then also use these observations to verify results derived from remote sensing and physically-based models.

• Improved remote sensing algorithms: There is ~~currently~~ no consistent standard for defining the length of snow covered ~~periods~~period. It is still common for papers to define the length of a snow covered period by the first and last days of snow cover. This ~~standard~~approach does not account for ~~ephemeral events~~short-term snow disappearance between those days. Approaches that report the total number of snow covered days miss information contained during show snow-free periods. Additionally, there is no consistent algorithm for accounting for cloud cover~~.~~ and that may make these types of methods infeasible for some regions. More widespread use of the object-oriented techniques, like the one used in this study, is needed to evaluate ~~its~~their efficacy and accuracy across ~~multiple~~differing regions and snow regimes. ~~.~~

• Improved spatial resolution and fidelity of snow and climate data: The MOD10A data product has a spatial resolution of 500 m. The coarse resolution made it difficult to verify our ephemeral snow results with SNOTEL observations that use ~~~~ 3 m wide snow pillows. Topographic complexity leads to variations in climate on much finer resolutions than the 4000 m gridded meteorology data used for this analysis. Gridded snow and climate data should have a spatial resolution more consistent with the variability in snowpacks on the order of 10-100 m~~meters~~. While very fine resolution climate datasets are beginning to be produced, there is a large need to merge existing remote

sensing snow observations into a data product that maximizes the current space and time resolutions across different remote sensing platforms (e.g. spatial resolution of Sentinel 2 but the temporal resolution of MODIS).

• Improved physics-based modeling: Identifying weaknesses in physically-based models was not the objective of this study; however, it is clear this is a need for better prediction of snow ephemerality. Improving model parameterization of ground heat flux and ensuring the temporal model resolution is sufficient to capture rapid changes in cold content are two ways to improve these models. These improvements are contingent on new and better observations of mass and energy fluxes to support greater model fidelity in ephemeral snow.

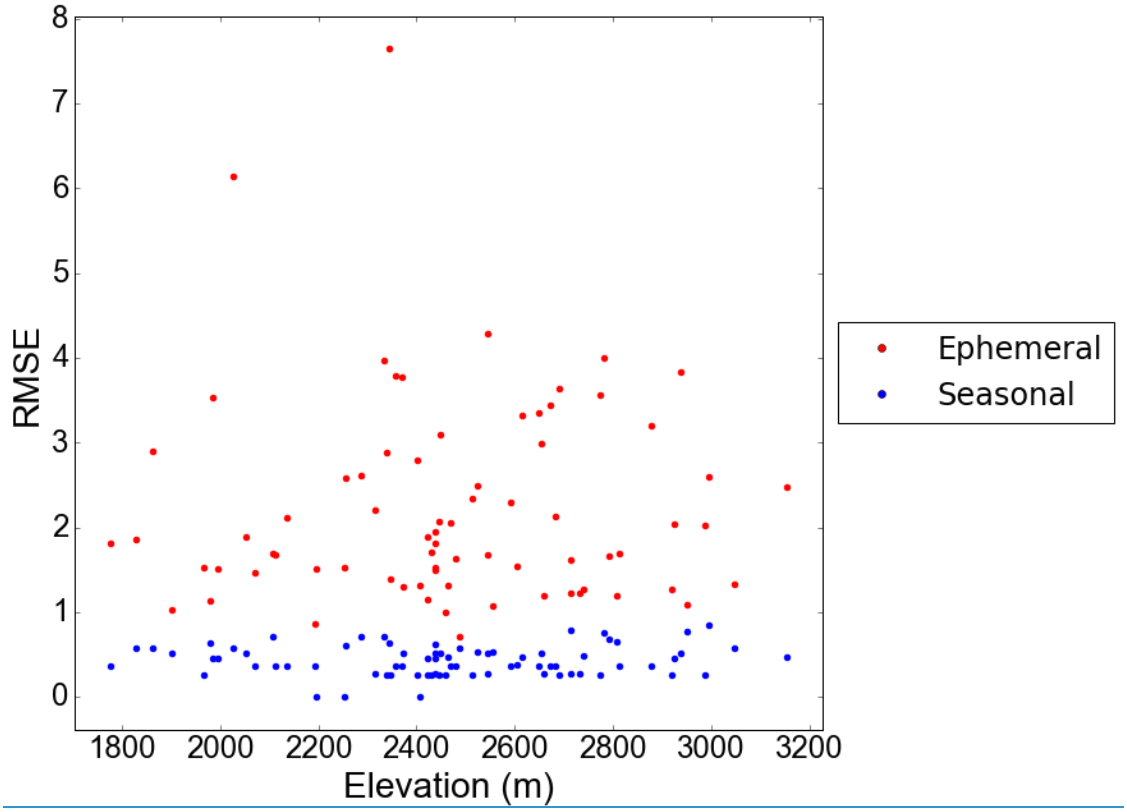
Data Availability: Petersky, R., and Harpold, A.: Now You See It Now You Don't: A Case Study of Ephemeral Snowpacks in the Great Basin U.S.A. ScholarWorks, *https://scholarworks.unr.edu/handle/11714/2952* 2018.

Appendix A: ~~Supplemental Information~~

Contents of this file: Figures A1-~~A3~~A4

Introduction:

The following figures provide additional information about the ephemeral snow algorithm. Figure A1 is an elevation map of the Great Basin, USA showing key ecoregions and ~~modeled Random Forest (RF) ephemeral snow results~~major cities. Figure A2 is a map of average winter (Dec 1st-Apr 1st) temperature, precipitation, and radiation across ~~vegetation types.~~water years 2001-2015. Figure ~~S1~~A3 shows how the measured number of ephemeral and seasonal snow events at SNOTEL sites corresponded to the number derived from the ephemeral snow algorithm. Figure ~~S2~~A4 shows how the 30 % snow fraction was chosen using a sensitivity analysis~~. Figure S3 shows histograms of residuals of measured and RF modeled ephemeral snow for all vegetation species~~.


RMSE
Elevation (m)
Ephemeral
Seasonal
0
1
2
3
4
5
6
7
8
1800
2000
2200
2400
2600
2800
3000
3200

~~Figure A1~~

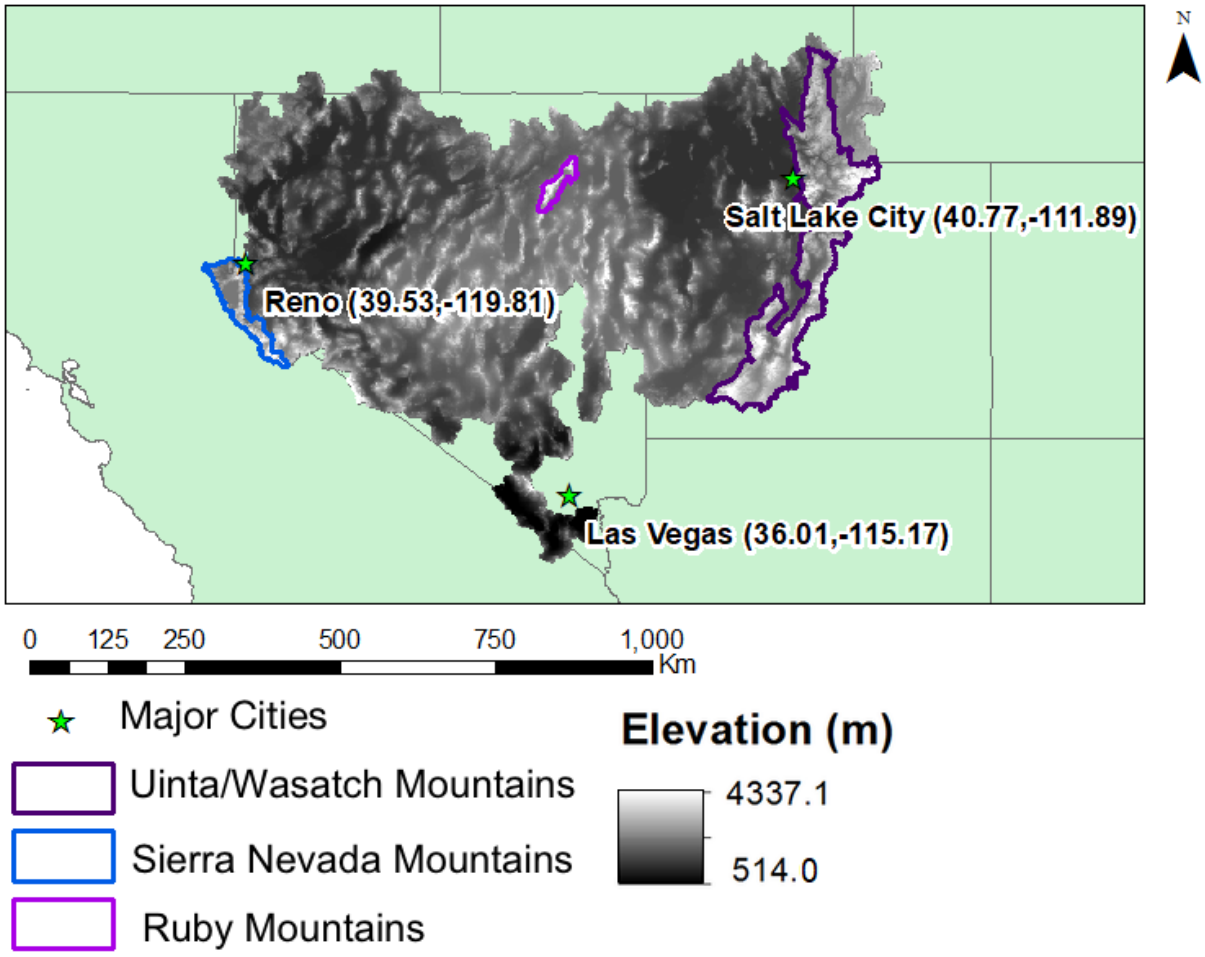


Figure A1: ~~Map~~ Map of the Great Basin region, USA as defined by the ~~United States Geological Survey (~~USGS~~)~~ ~~Hydrologic Unit Code (~~HUC~~)~~ Region 16 along with major cities and mountain ranges. The Sierra Nevada, Ruby, and Wasatch/Uinta mountain ranges are highlighted.~~defined using the US EPA L4 ecoregion classifications of "Sierra Nevada" and "Wasatch Uinta" respectively. Ruby Mountains were defined using a combination of "Mid-Elevation Ruby Mountains" and "High Elevation Ruby Mountains" in the US EPA L3 classification~~.

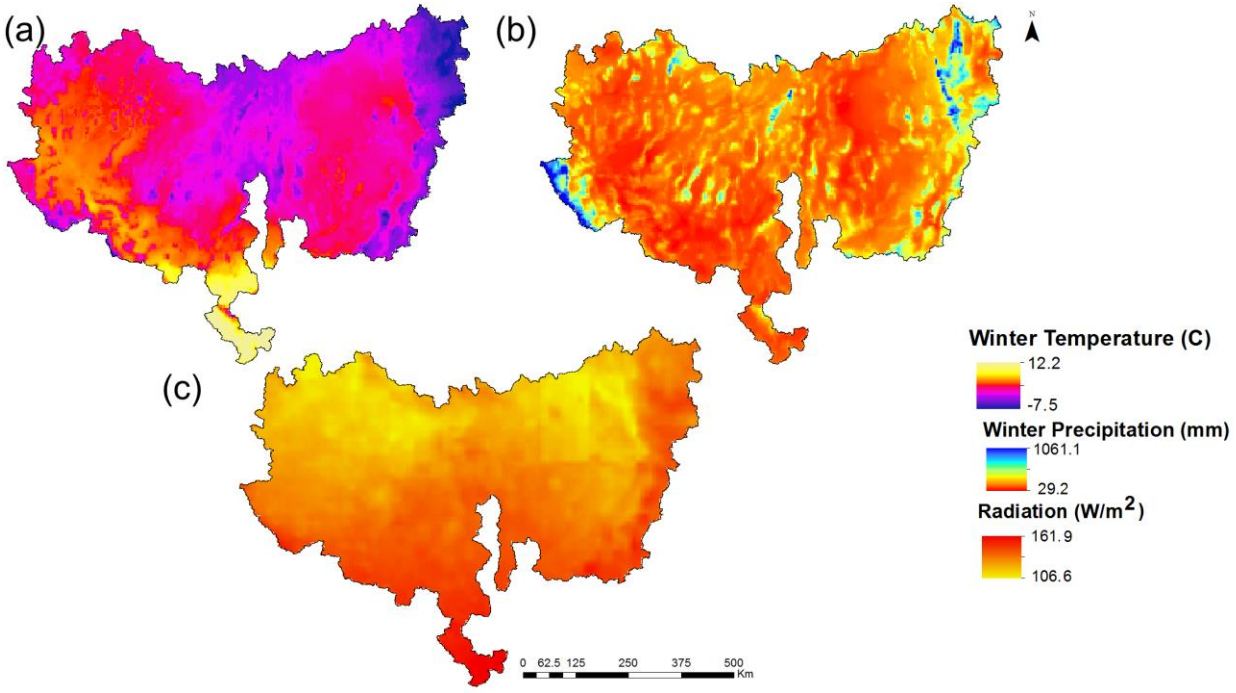


Figure A2: (a) Average winter temperature, (b) average winter precipitation, and (c) average winter radiation across water years 2001-2015 in the Great Basin.

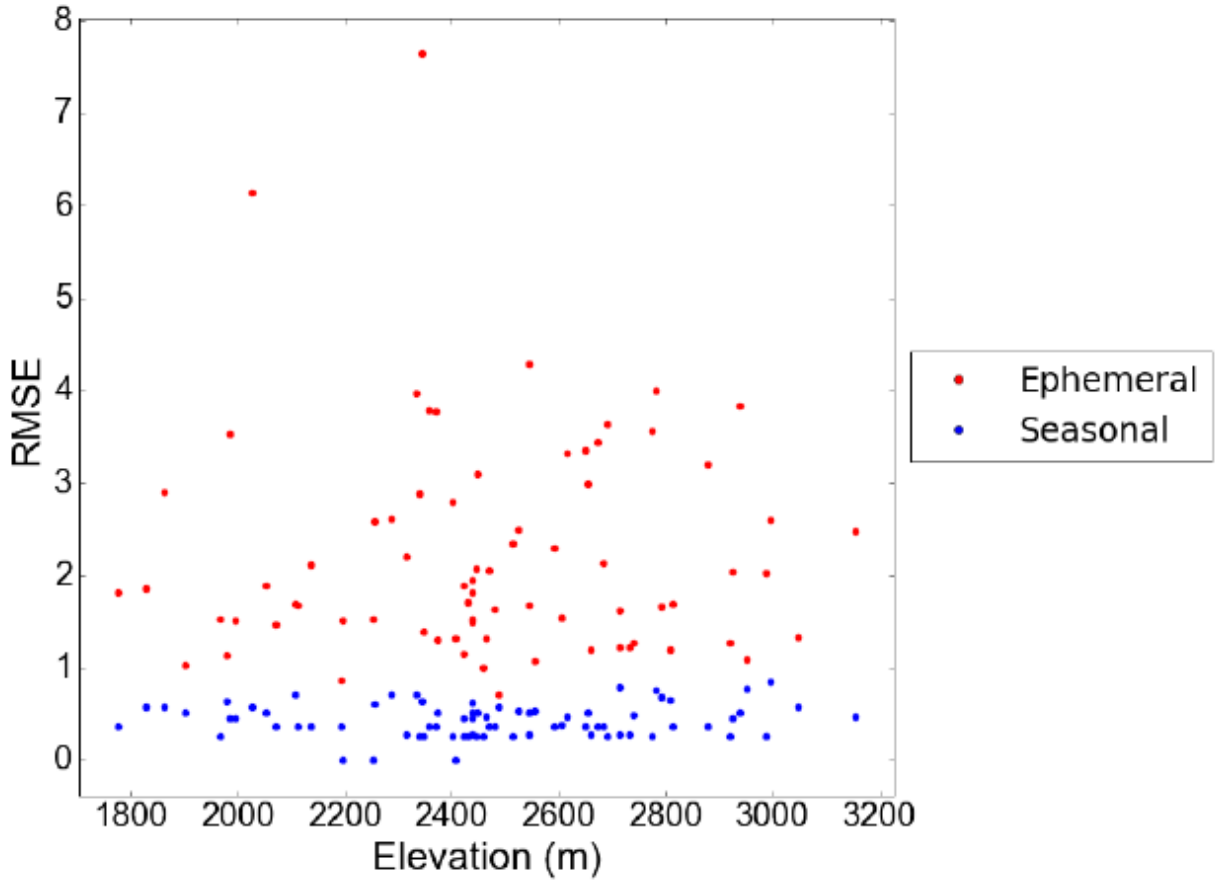


Figure A3: Root Mean Square Errors between the number of observed ephemeral and seasonal snow events at Snow Telemetry (SNOTEL) stations and the number of ephemeral and seasonal snow events derived from the algorithm in Google Earth Engine in each ~~500m Moderate resolution imaging spectroradiometer (~~500 m MODIS~~)~~ pixel corresponding to that station. Measured SWE (Snow Water Equivalent) of 0.3~~3in~~3 cm. or greater was used to determine snow presence for SNOTEL sites.

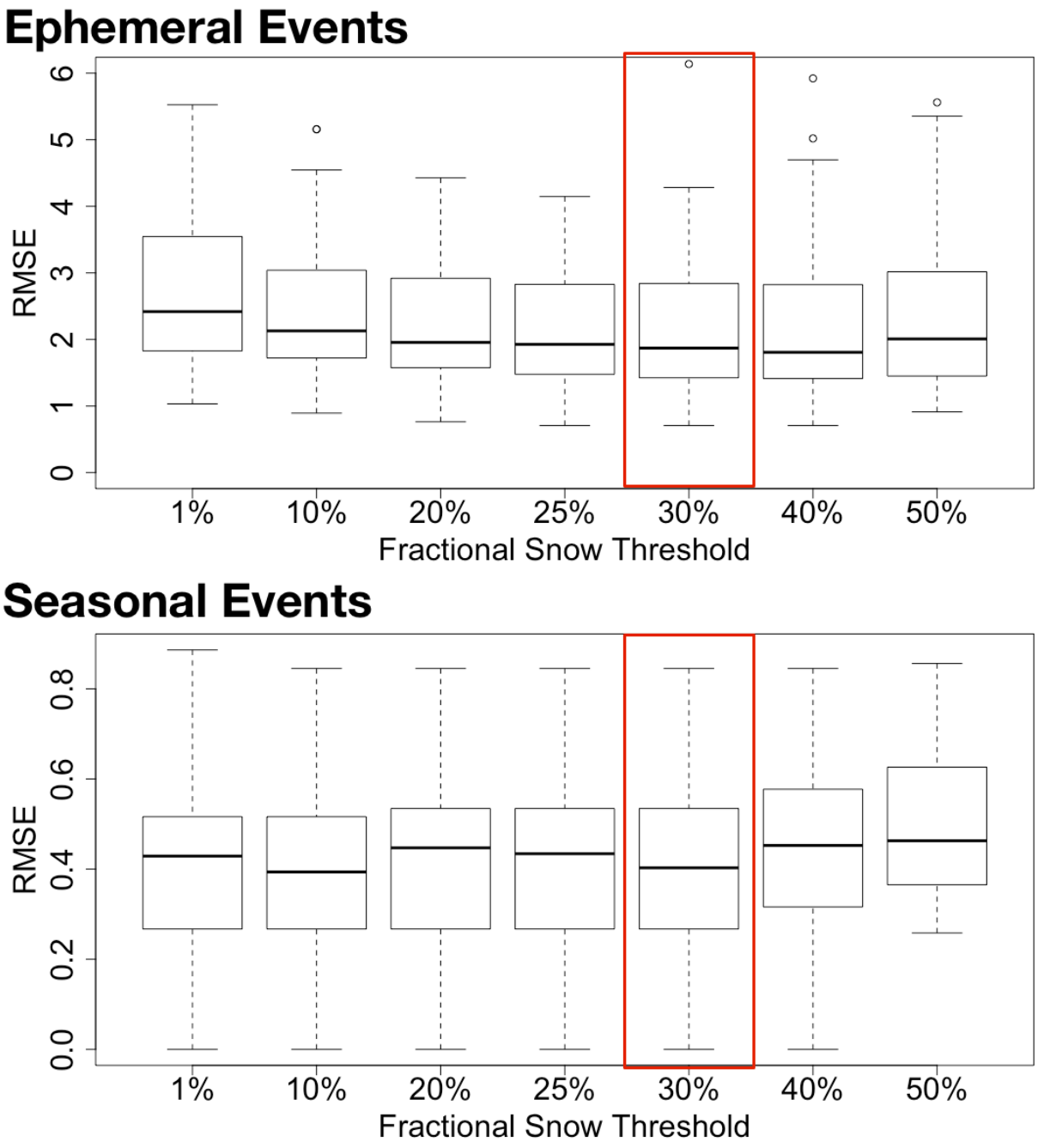


Figure ~~A2~~A4: Boxplots depicting the Root Mean Square Errors between the number of observed ephemeral and seasonal snow events at Snow Telemetry (SNOTEL) stations and the number of ephemeral and seasonal snow events derived from the algorithm in Google Earth Engine in each ~~**500m Moderate resolution imaging spectroradiometer (**~~500 m MODIS~~)~~ pixel corresponding to that station at snow fractions of 1-50 %. 30 % (highlighted in red) was the chosen snow fraction.

Acknowledgements: The NASA Space Grant Consortium and USDA NIFA NEV05293 for providing funding. Patrick Longley helped in creating the snow ephemerality metric. Charles Morton of the Desert Research Institute and the members of the Google Groups Earth Engine Forum helped with Google Earth Engine. We also thank Dr. Scott Tyler for his support.

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