Review: Changing Snow Water Storage in Natural Snow Reservoirs

Summary
The authors of "Changing Snow Water Storage in Natural Snow Reservoirs" (Aragon and Hill) present a new metric, Snow Water Storage (SwS) to evaluate the snowpack in the mountainous United States (U.S.) throughout the length of the snow season in meter-days. Unlike traditional metrics used to quantify and characterize the snowpack at a single point in time (e.g., April 1 or peak SWE), the SwS captures the area under the SWE curve to illustrate differences and changes in snowpack accumulation and ablation seasons as well, better illustrating the nature of the complete snow season (in a given area). While the metric has great and complementary utility in quantifying the snowpack (on a monthly, annual, or by elevation bin scale), the manuscript would benefit from further depicting the SwS using actual examples across the U.S. in raw units (meter-days as opposed to predominantly reported % changes). Hypothetical examples of the SwS and changes in the SwS are presented in Figure 1 of the manuscript, yet observed and modeled changes in SwS are reported as only % changes. In order to contextualize these changes and further emphasize the added utility of this metric, the readership needs to learn how the SWE curve has changed in various parts of the U.S. to understand why the SwS has increased or decreased, and how the SwS thus provides more/added information compared to other metrics. Translating what is presented in Figure 1 to the real/raw observed and modeled data which are used in the presented work is a critical missing component to this work and would add more intuition around the new metric. Toward the tail end of the discussion, readers learn that "the conceptual SWE curve has been flattening over the 39-year period of record," which is the first mention of how the SWE curve has changed (not just monthly or annual SwS % changes), by way of the SwS evaluation, and thus provides valuable, new information (but also leaves the reader questioning, for example, how is this different from a lower April 1 SWE value? What more does this tell us about the changing snow season?). These questions need to be directly addressed (and seemingly can be, by way of the information gained from SwS). Since the metric leans on the important of temporal changes in the snow season – in addition to changes in magnitude, and thus a novel combination of snowpack characteristics – the changes in SWE curve shape need to be reported throughout the manuscript when % changes are stated (with complementary figures, ideally). This will greatly assist the readership reach the intended conclusions made in the manuscript. The manuscript would benefit from further elaborating on other, recent metrics aimed at quantifying snow water storage (e.g., Hale et al., 2023; Immerzeel et al., 2020) and being more specific in naming changes seen within individual ER3s (instead of "only one" or "four" ER3s, the authors should state the specific areas of reference), such that comparisons can be further made between the SwS and observed changes in other metrics.

Line-by-line
Line 7: "An average of 72% of the annual SwS_A" – This is a challenging number to capture as a reader. Perhaps defining/clarifying the SwS in terms of units (in the abstract) would help.

Line 20: Suggest eliminating "at river headwaters," since snow functions as a reservoir to some degree anywhere in a watershed/landscape.

Line 10: "The greatest SwSM loss occurs early in the snow snow season, particularly in November" – suggest stating the % loss or magnitude of loss, similarly with the next statement regarding "more spatially widespread significant decreases… than increases" – adding numerical statistics (as either a percent or raw value) would help contextualize the results here.
- Also, delete "snow" where used twice in a row
- Was the p-value for determining significance 0.05? If so (or if not), please clarify here.

Line 19: "Keystone," since there are many definitions to this term (including political and ecological perspectives, both of which the authors speak to later in this paragraph), suggest using a more precise term that is more synonymous with what is intended – or further defining this term.

Line 30: Suggest elaborating on why snow water storage may be changing, further shedding light on the importance of this work (e.g., climate change, interannual extremes).

Line 31: "the findings," unclear what this is referring to.

Line 32: This paragraph and the next two seem to be organized by snow characteristics and measurement metrics which lead to a statement around line 56 suggesting improvements for snowpack monitoring. It seems that these

three paragraphs could be shortened/combined, while the importance of looking at snow across the entire snow season could be elaborated upon and related back to climate change (or the various drivers of SWE changes, etc.; but with respect to why SwS would shed light on changes in the snowpack moreso than April 1 SWE, for example).

Line 34: Suggest a citation in reference to "and more."

Line 34-35: "the depth of water one would get upon melting a column of snow," "it allows you to quantify the amount of water being stored" – suggest removing "one" and "you" as primary subjects in these sentences, as they read somewhat colloquially and are not necessary for conveying the intended message in each sentence.

Line 35: "reservoir elevation,"… is this meant to say "reservoir at elevation"?

Line 45: Similar comment to above, suggest a citation with "among others" – unclear which metrics are being referred to here.

Line 56: "full time-history," suggest rephrasing (e.g., "a complete evaluation of volumetric and temporal changes in SWE across the entire water year, as opposed to one occurrence in time").

Line 58: "SWE starts the accumulation phase of the snow season up to a peak," suggest rephrasing such that SWE is not "starting" something, but rather (something along the lines of), "SWE accumulation begins and continues until peak SWE occurs, marking the onset of the SWE ablation season."

Additional citations that will need to be included and referenced within the author's introduction of metrics used to evaluate the snowpack (magnitude and timing):
- Hale, K. E., Jennings, K. S., Musselman, K. N., Livneh, B., & Molotch, N. P. (2023). Recent decreases in snow water storage in western North America. *Communications Earth & Environment*, *4*(1).
- Immerzeel, W. W., Lutz, A. F., Andrade, M., Bahl, A., Biemans, H., Bolch, T., ... & Baillie, J. E. M. (2020). Importance and vulnerability of the world's water towers. *Nature*, *577*(7790), 364-369.

Line 94: "(say a SNOTEL site)" another example of somewhat colloquial language, suggest rephrasing or deleting.

Line 94: Units here are very helpful – reiterating the suggestion to include this in the abstract when talking about changes in SwS.

Line 105: "Datasets used for this paper are summarized in Table 1, and briefly reviewed here." Suggest starting this paragraph with the review and ending the paragraph with "a full, comprehensive list of the datasets used in this work are listed in Table 1."

Line 114: "While we recognize the potential limitations of using a modeled SWE product" – this might be addressed later (edit: I do not believe this was addressed later in the discussion), but currently suggest at least listing some of the potential limitations to which the authors refer to here, in addition to citations.

Line 133: "locations that have a mean of at least 30 snow covered days per year based on a 39-year climatology (1982-2021)" – this is determined using the UASWE dataset? If so, please state here.

Line 140: "To answer the first research question, are there significant trends in SwS$_A$ and SwS$_M$ across the US" suggest brevity here (and all similar sentences throughout) by deleting the first clause, "to evaluate significant trends in SwS$_A$ and SwS$_M$ across the US"…

Line 148: "This study used the Hamed and Rao Modified MK test fron the pyMannKendall python package to compute trends in SwS (Hussain and Mahmud, 2019)." Suggest starting this paragraph with this sentence. The paragraph currently leads with describing the MannKendall test and leading the reader to believe that unmodified MannKendall tests were performed. In general, suggest starting the paragraph with the major takeaway/subject and clarifying after the fact.
- Also spelling: "fron"

Header "2.4.2 SwS Trends in Mountain Ecoregions": This paragraph seems to focus primarily on how hypsometry was calculated and how the data in each ecoregion was binned accordingly. Thus, suggest changing this title accordingly.

Line 171: "figure1" add space.

Line 173: "1b", does "figure" need to be added here?

Line 178: "One hundred twenty-three of the stations of the 367 stations with decreasing SwS$_A$ trends, had significant decreases." Suggest being consistent with when numbers are spelled out or not (e.g., 33.5% of the stations with decreasing trends in SwS showed significant decreases (123 of the 367 stations).
- Further, could the authors add the range of significant declines in meter-days? That will further help contextualize the listed percent changes presented in the text and the figures.

Line 179: "The is a mean" grammar.

Line 188: "Remember that the station network only includes the western portion of the US." Suggest deleting.

Line 189: "Only 5% of US grid cells have significant increasing trends, and have a mean percent increase of 84.4%." Delete "," – but also, depicting this 84.4% increase with raw units would again be helpful here. Further, perhaps this is coming, but can the authors share **how** the SwS is increasing (or decreasing)? There are a few sentences that following regarding increases in precipitation but also increased winter temperatures – how has the SWE curve changed in response that has led to such large SwS increases?

Line 199-202: Suggest stating which ER3s the authors are referring to when they point out "only one" or "while four" and the "only one" mountainous ecoregion which shows insignificant increases in SwS.

Line 202: When aggregating the UASWE data to the ER3 scale, is the average annual SwS value an average of its constituents (e.g., is one SWE curve generated per eco-region per year?) or an average of the grid-cell SwS values per year? These values would likely be different and mean different things. I understand that the 93.8% is the division of 15 / 16 ecoregions.

Line 206: Please list number of stations experience a loss in monthly SwS in November where stated.

Paragraph 204-215: Here is another location in the text where it would be fruitful to learn more about how the SWE curve and thus SwS (in raw units) have changed in various locations. In general, the annual and monthly % changes are important to state, however understanding how these changes show up in the SWE curve seems complementary and particularly helpful for the readership in grasping this new metric. Figure 1 does a great job in illustrating why the SwS is important and novel. However, giving examples of annual and monthly SwS values next to actual data and SWE curves used in this analysis seems imperative in communicating these otherwise somewhat abstract % changes.

Line 221: "An average of 72% of the annual SwS$_A$ in the US is held in the 16 mountain ER3s, despite these ER3s only covering 16% of the US land area." Please refer back to Figure where this is shown.

Line 223: "Across all mountain ER3s, there has been a 22% decline in SwS$_A$ over the 39 year period of study" – Same question as above, how are these data averaged across the 16 ER3s?

Line 228-229: These sentences read as though they belong in the introduction or discussion section.

Line 232: How exactly has the SwS$_A$ decreased in most ecoregions and increased in the North Cascades? Generally, how do these changes relate to the examples shown in Figure 1?

Line 238: "highest" – please clarify, highest in elevation?

Line 243: "Looking across all mountain ER3s, there are only significant declining SwS_A trends and no significant increasing trends." It is not clear what led to this statement, which is different from the paragraph above stating that SwS_A increased in the North Cascades – is it related to significance? I'm sure it is so important to continually state trends that are not significant throughout this document – or rather, they should be listed as having no change.

Line 245: "we are able to get an idea"… suggest rephrasing.

Line 247: "This could be a result of increasing snow variability as freezing levels move to higher elevations, resulting in increased irregularity in precipitation form." It would be helpful here again to understand how the SWE curve and thus SwS is changing in these areas – in general, there is a need to couple the stated % changes to the actual data and examples of calculating actual SwS values.

Line 250: "Rige and Valley" spelling.

Paragraph 245-251: Still not quite clear what SwS_D is (not entirely defined at its introduction in line 162) – it might be helpful to reclarify here, however, since this is a section regarding SwS_A trends on the landscape.
- What exactly does "on the landscape" refer to? Is this referring to the binning of SwS values per elevation band? If so, suggest rephrasing title/header.

Line 255: "The percent of stations with negative trends was greater than the percent of stations with positive and positive significant trends in all metrics considered." What exactly does this mean? So, this is a comparison of the # of stations with positive and negative trends per metric?

Line 260: "percent chance" spelling/grammar.

Paragraph 260-269 & Figure 11: This is helpful in beginning to shed light on the utility of the SwS over other metrics. However, without shedding light on the mechanism behind SwS change (how is the SWE curve changing which is causing for changes in the SwS), the changes in SwS relative to other metrics is challenging to contextual and compare/contrast.

Line 271-273: Suggest several citations here regarding the snowpack change literature.

First discussion paragraph: Suggest emphasizing the uniqueness of the SwS compared to other metrics here, in addition to the changes revealed in this work.

General discussion comment: I am less familiar with the required format of this paper, but the equations provided toward the end of the discussion seem out of place – more appropriate in the methods or results section.

Line 293: I believe "outsized" is one word without the hyphen.

Line 295-297: Suggest making the direct connection to SwS and the 13 water basins – e.g., why would SwS be more appropriate here than SWE metrics/other metrics?

Line 315: "Assuming there have not been systematic changes in synoptic weather patterns" – is this a fair assumption? At the very least, a citation should be added here.

Line 320: "Comparison of the various snow metrics provides insight as to how the SWE curve is changing." – From the readership standpoint, I'm not actually sure this is true/has been completed, depending on how one defines "change" here. Added insight has been provided on the magnitude of SwS change compared to other metrics – but changes around the actual shape of the SWE curve and how that relates to changes in SwS have not wholly been described, and I believe that is a critical need in this manuscript.

Line 337: This description or visual explanation of the changing SWE curve is what is desired much earlier in the manuscript – a coupled figure would also be appropriate (ideally showing example changes in SWE curves in the different areas mentioned in this text).

Figure 2: I see that the ER code and name are located in Table 2 – suggest adding that information with this figure if Table 2 will not be in close proximity as in the current manuscript draft.

Figure 10: Units are m^{3}days – this seems inconsistent or at least confusing to the meter-days units explained in the text.