Response to AR1

We thank the Anonymous Reviewer 1 (AR1) for taking the time to review our manuscript for a second time and provide helpful comments. In this document, the blue text is ours, the black text is that of AR1.

Review: Changing Snow Water Storage in Natural Snow Reservoirs

Summary: I thank the authors for addressing my comments made during the first round of reviews. My overall summary of the work remains consistent, with additional suggestions made below as line-by-line comments. In general, the additions made to the text and figures greatly enhance the work and the introduction of the Snow Water Storage metric (SwS). My remaining comments are with respect to needed clarification in the text and further representation of SwS in the figures (beyond represented *changes* in SwS). My hope is that addressing this round of feedback will further highlight the importance and applicability of the SwS metric. I look forward to seeing an updated version of the manuscript ready for publication soon.

The above paragraph summarizes remaining feedback from AR1. Our understanding is that the largest outstanding request from reviewer 1 is to see further representation of SwS. In response to this comment, we have updated figures 5 and 6 to include raw SwS change values. We have also included mean SWE curves (the area under which is the SwS) from the initial and final 20 years of the study period to Figure 11. We feel these changes have improved the manuscript and hope AR1 agrees.

Line-by-line

Line 6: Suggest more specific synonym for “special” (particular?).

We changed from special to particular.

Lines 9: Suggest stating the *direction* of change when possible. Annual SwS is stated to have decreased across almost all mountainous ecoregions in line 12-14. Also suggest reporting annual trends separately from monthly trends, as opposed to switching back and forth between sentences. For example, the sentence at lines 12-14 could replace the sentence at line 9. Monthly SwS averages and trends could be reported after annual results. Stating results as non- mountainous ecoregions and mountainous ecoregions (since there is a special focus on these regions) might also increase readability, as that distinction is not clear.

Thank you for this recommendation, the language in the abstract has been modified so that it is more concise and direct. Sentences have also been reordered to talk about SwS_A before talking about SwS_M.

Line 10-11: It is unclear if “in mountainous regions” is (or is not) referring to the 16 mountainous ecoregions here.

This sentence was changed to “... in the 16 mountainous ER3s” to clarify.

Line 15 and Line 19: Is there a mechanism that has been explored to explain why monthly SwS has increased and decreased across the area/across elevation bands? If so, it is suggested these results (or potential mechanisms) be added to the abstract to exemplify how the SwS may become more "valuable." With respect to the use of "valuable," what type of applications are the authors referring to when "valuable" is mentioned? Valuable for predicting snow water resources (referring to "provide information on the natural reservoir function of snowpacks" at lines 16 and 17)? Similarly, is "more valuable" in reference to a comparison to other snowpack metrics or a comparison to its value in the past?

Regarding line 15 - the mechanism for differences in SwSM change was not explored in this study. Line 19 was changed to "As we move into a future of increased climate variability and increased variability in mountain snowpacks, spatially and temporally flexible snow metrics such as SwS may become more valuable for monitoring and predicting snow water resources."

Lines 21-24: Suggest citations.

Done.

Lines 29-33: Suggest moving these sentences to the end of the introduction or methods.

These sentences have been moved to the methods section.

Line 34: Suggest a citation.

We feel that this is a well-enough accepted fact that a citation is not required. In order to soften our point, we changed the sentence to "Snow water equivalent (SWE) is a relevant snowpack characteristic for many water resources applications."

Line 42: It is unclear what "composite" in quotation marks means (could the quotes be removed?).

Good point, we removed the quotes.

Line 48-54: While the figure is extremely helpful in demonstrating the SwS concept, it is unclear what the purpose of this figure is in the context of the introduction. Suggest starting this paragraph with the potential research gap that has been identified by the authors after reviewing the metrics in the previous two paragraphs.

With no intention of disrespect, the purpose of this figure is to frame the introduction in a way that demonstrates the SwS concept so that readers can contextualize the idea of SwS in relation to the annual SWE curve and other snow metrics. We did restructure the final introduction paragraph to better frame the research gap in response to this comment.

Line 75-76: The reference to Greenland and Antarctica seems irrelevant to this study

The point of this sentence is to contribute to the discussion of diversity in snowpack regimes by providing an example of a snowpack regime that is different from a mountain snowpack regime.

Line 77: Similar comment to “more valuable” in Line 19, it is unclear what “less useful” is referring to here – less useful for what exactly?

We recognize the reviewer’s point and have modified this sentence for clarity: “While metrics such as April 1 SWE, SWE_{max} and SCD do a good job of characterizing mountain snowpacks, they are not as useful at capturing the transient nature of ephemeral snowpacks or the lack of an ablation season on ice sheets.”

Suggest including a half or full paragraph in introduction on “future of increased climate variability” (taken from abstract).

Thanks for this recommendation. A brief discussion of climate variability was added to the first introductory paragraph.

Line 78-79: Great set up for this final introductory paragraph. The following sentences before the research questions, however, read as though they belong in the methods section. Instead, the authors could emphasize why and where there is a need for quantifying changes in snow water storage in a new, integrated way.

Thank you, we have reworked the final introductory paragraph to better frame the research gap and purpose of this paper.

Line 111: Suggest remaining consistent between “we used” vs. “This study also uses” (e.g., “In this study, we also used...”?).

Thank you for this suggestion, “we” statements have been removed from our methodology to add consistency.

Line 179: “Typical mountain snowpack” is what was used earlier with respect to “mountain snowpack” here (add “average” or “historical” or “typical”?). A definition of “typical mountain snowpack” vs. “permanent or persistent snowpack” vs. “intermittent or ephemeral snowpack” would be helpful to set the readership up for items in the discussion section.

This is a great point. We checked the full text to consolidate our terminology so now we only reference mountain snowpacks, and ephemeral snowpacks. We added wording to the 6th introductory paragraph to clarify what is meant by a mountain snowpack and an ephemeral snowpack in response to this feedback.

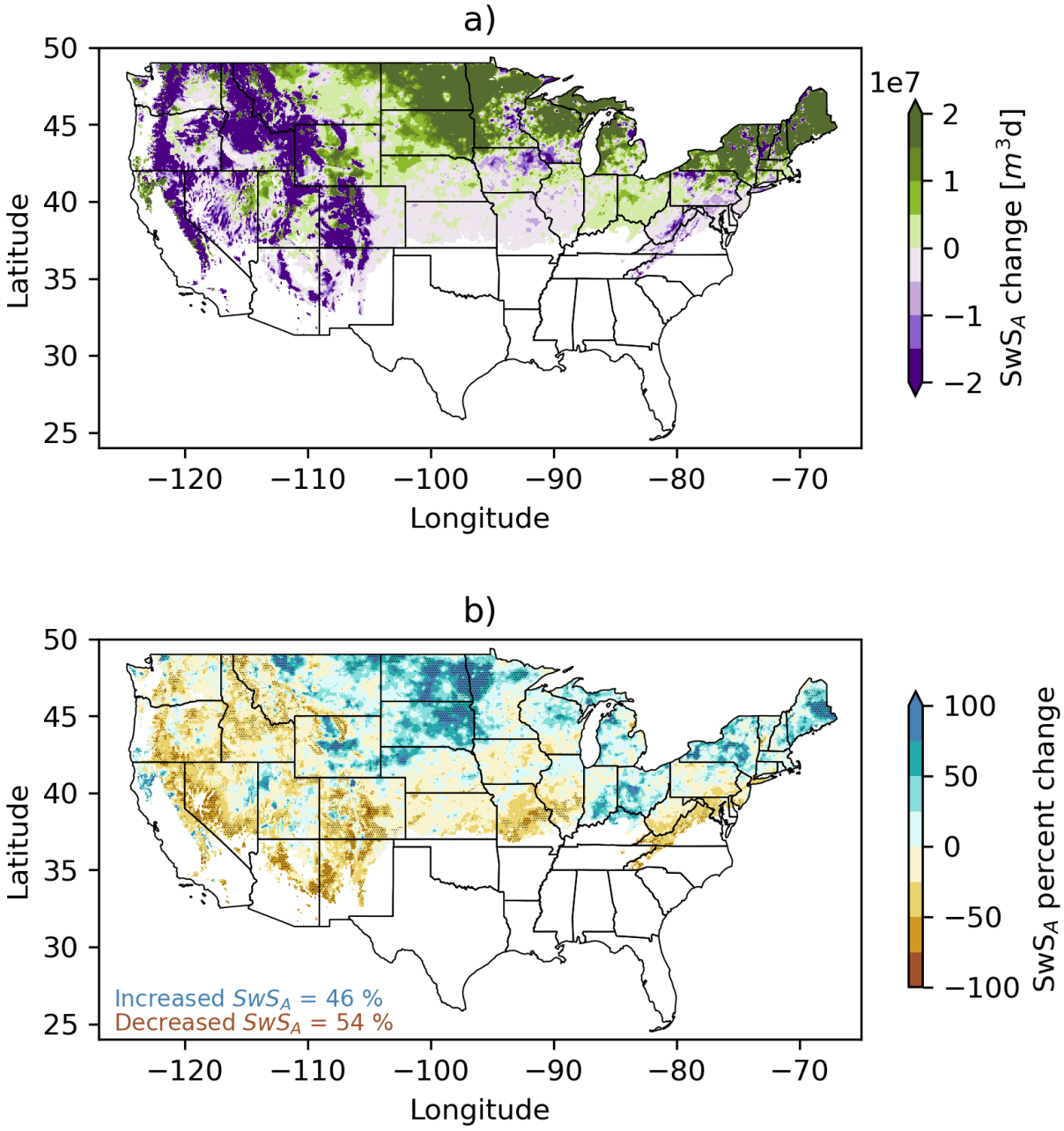
Section 3.1: My outstanding comment here and from my previous review is with respect to reporting how the SwS has changed in these areas (i.e., the physical changes in SWE curve and SwS representation). Figure 11 is an excellent addition to this manuscript – however readership is still left wondering what SwS actually looks like, numerically, across the region and each individual ecoregion. For now, suggest mentioning that the specific ways in which annual

SwS has changed will be shown in section 3.3. This is in addition to the way in which Figure 11 exemplifies the SwS' uniqueness to other snow metrics. See further comments below.

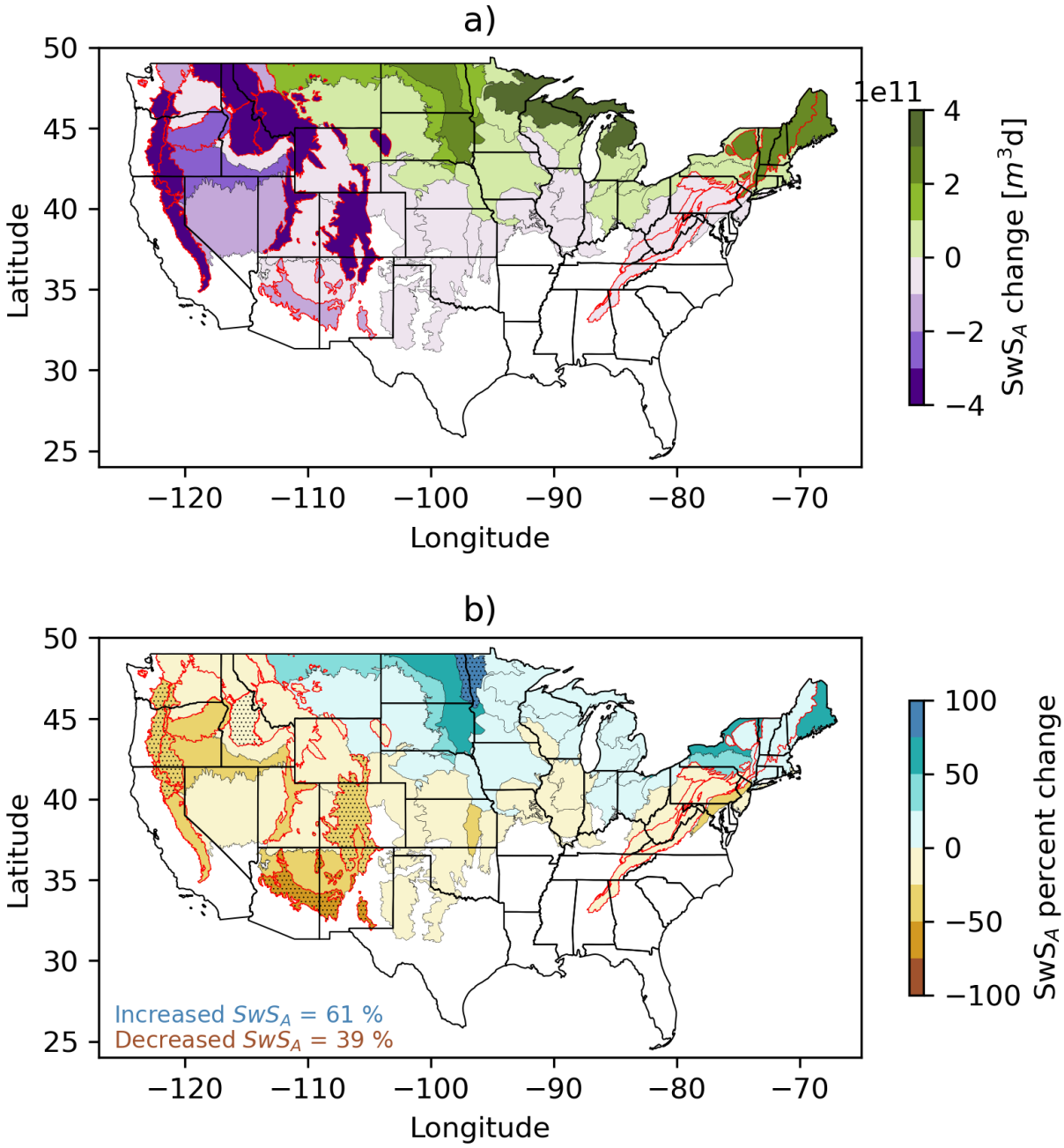
Good recommendation, a sentence was added at the end of section 3.1 saying: "The specific ways in which SwS_A has changed across ER3s and how these changes relate to other snow metrics will be discussed in section 3.3." We also added a response to your Figure 11 comments below (page 8).

Figure 6: The use of actual/raw SwS values in the text helps contextualize the metric – however this figure only shows percent change. Suggest making this a two-panel plot with average annual SwS across the region and then change through time (current figure).

We added a subplot to figures 5 and 6 to show the raw SwS values in addition to the percent changes.



Updated Figure 5.



Updated Figure 6.

Section 3.2: Perhaps the ecoregions which are considered mountainous vs. non-mountainous could be listed in the text (as shown in Figure 2) and used as a distinction between Section 3.1 and 3.2 (listed first in Section 2.3). In averaging annual SwS across stations – how many of those stations are in and outside of mountainous ecoregions? It would be very beneficial to include those points in Figure 2 (I see they are shown in Figure 4 but without the ecoregion

boundaries). Many of the non-mountainous eco-regions would not be represented by those station results (albeit they are represented via the modeling results). As such, the spatial average results from the station data and the results from the model are very different, and I'm not sure those differences are obviously noted in the text. In general, it is challenging to follow which areas in Figure 2 are represented across sections 3.1 and 3.2. And differences in station results between sections 3.1 and 3.2 are challenging to distinguish, given the areas of interest (i.e., entire CONUS above SCD threshold vs. mountainous ecoregions).

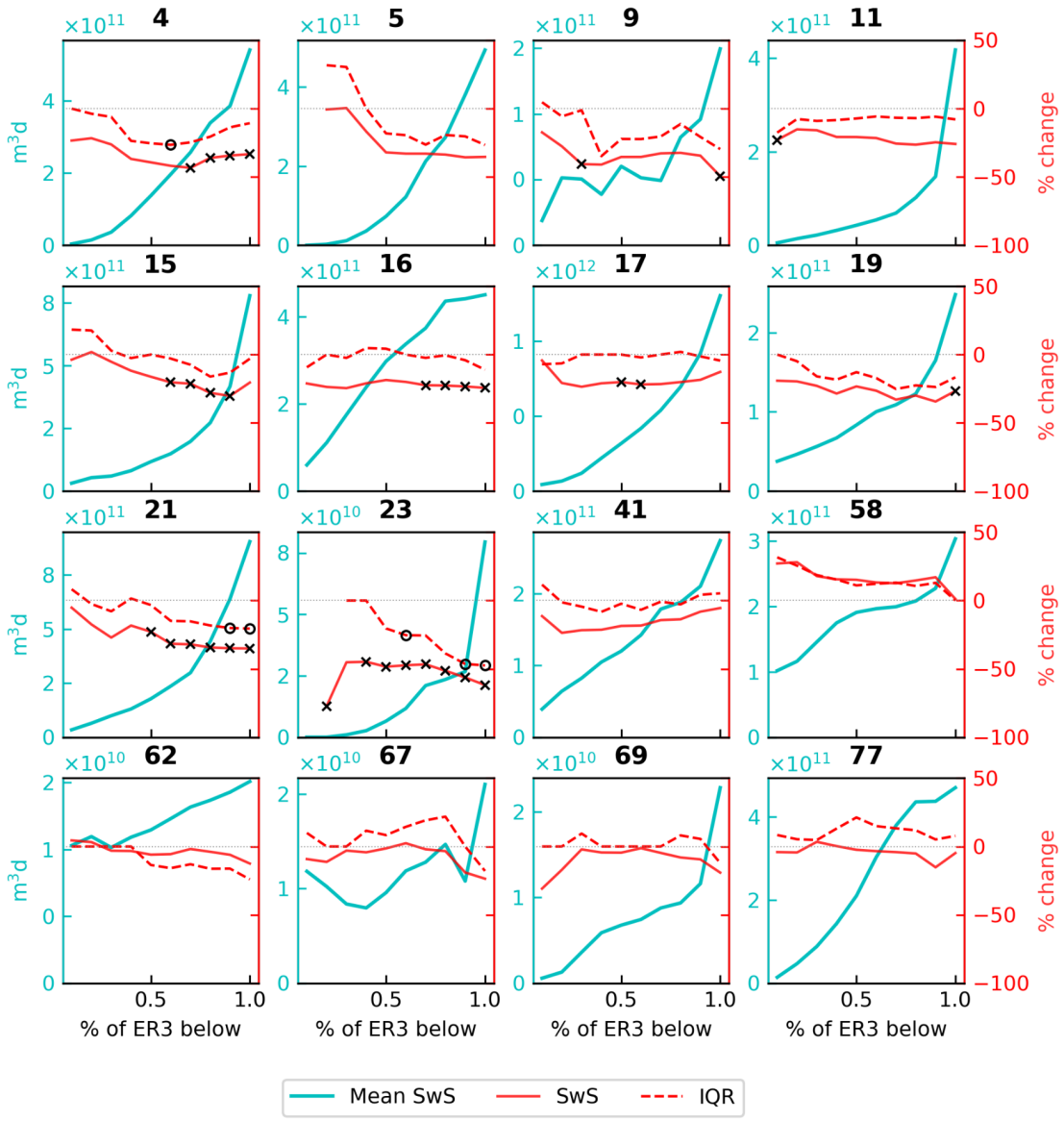
Since there are so many non-mountainous ER3s and they are not the focus of our results, we do not think it is necessary to list them by name in the text. We agree that the distinction between sections 3.1 and 3.3 should be improved. Section 3.1 now covers the non-mountainous ER3s and the discussion about SwS_A changes in mountainous ER3s was moved to Section 3.3.

Annual SwS was not averaged across stations, instead it was calculated at each station individually in the station analysis. In the ER3 analysis, annual SwS was computed at each grid-cell of the UA SWE product and then aggregated to the ER3 scale (see methods section 2.4.1). Because of this, we do not feel we would glean any additional information by evaluating which stations fall into ER3s.

Figure 10: Suggest labeling these panels with the name of each ecoregion.

The figure was crowded with the full ecoregion names, but we did add a legend to facilitate figure interpretation and added "Refer to Table 2 for ER3 names" to the figure caption

to let readers know where they can find ER3 names.



Updated Figure 10.

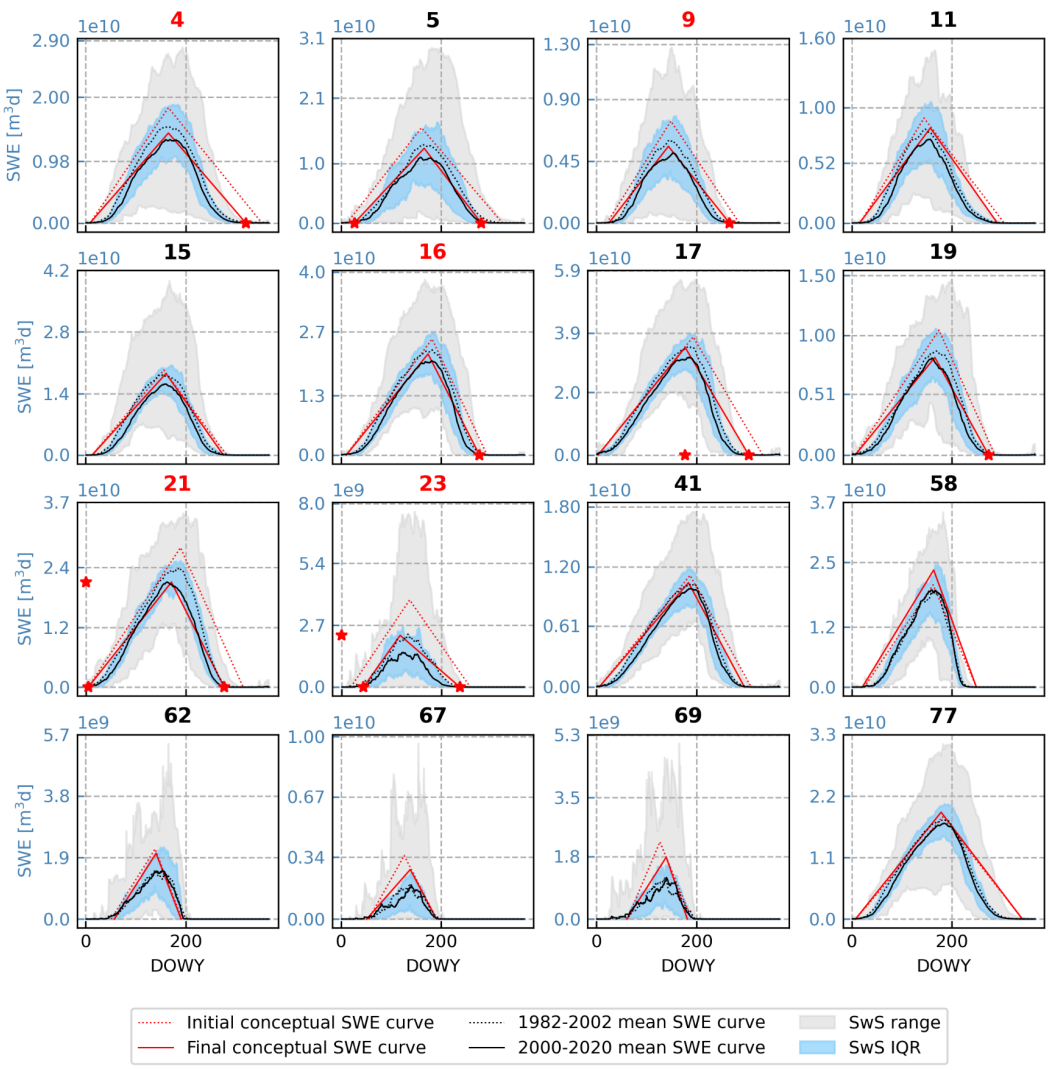
Figure 11: This is a very helpful addition to the manuscript and is the figure that truly highlights the utility of this metric. Again, suggest labeling these panels with the name of each ecoregion, especially since they are most easily referenced by name in the text. Also suggest letting the y-axis change such that readers can see the changes in SWE curves for all ecoregions (especially 23, 62, 67, 69). Suggest labeling each colored line on one panel – it is challenging to decipher what each line indicates from the figure caption. Does the red labeling indicate a significant decrease or increase in annual SwS (currently says “change”)? Those differences in

direction should be noted. Finally, it is unclear what “conceptual SWE curve” represents from the actual SWE curve or SwS as represented by the datasets. Is the SwS represented here at all? That is unclear but would be the final, most important piece – to see what SwS actually looks like through time (start of study period vs. end of study period). Perhaps even noting the final numerical SwS calculation for the red dotted line triangle and the red solid line triangle would provide context for this metric.

We are pleased that the reviewer found Figure 11 to be a useful addition to the paper and we appreciate the additional feedback. Similar to our comment for Figure 10, we found the figure to be overly crowded with the full ecoregion names, so we left their number code instead and added “Refer to Table 2 for ER3 names” to the figure caption to let readers know where they can find ER3 names. We did allow the y-axis to scale with each ER3 as the reviewer suggested and added a legend to facilitate figure interpretation. The reviewer has a good point about indicating the direction of change and the language has been adjusted to specify the direction of change. The language in the introduction was adjusted to provide a description of the conceptual SWE curve as follows:

“ The conceptual SWE curve for mountain snowpacks is defined by three points; a DSO the peak SWE (SWE_{max}) and the DSD. SWE accumulation begins at the DSO and continues up to a SWE_{max}, which may or may not occur on Apr 1 (northern hemisphere). After SWE_{max}, the ablation phase of the snow season begins and the SWE depth declines until it reaches zero at the DSD.”

We hope this description of the conceptual SWE curve adds clarity for the reviewer. Since SwS is the integrated area under the SWE curve, it is reflected in this figure as the shape below the SWE curve. In response to the reviewer comment, we replaced the mean SWE curve for the full time period with two mean SWE curves, one from the 20 years of the study period and one from the final 20 years of the study period. In this way, one can get a general idea of how the actual SWE curve and associated SwS has changed over time.



Updated Figure 11.

Line 284: Suggest elaborating on or rephrasing “paint the full picture.”

This sentence has been rephased and now reads: “The inability of common one-dimensional snow metrics to reflect snow storage change is particularly apparent when snowpacks transition from one snow regime to another, such as a permanent snowpack transitioning to a mountain snowpack or a mountain snowpack transitioning to an ephemeral snowpack.”

Line 287-288: Citation or figure?

This statement is based on an analysis that we performed. The sentence was updated to say “This study found the number of annual snow-free periods…” to clarify that this was a result we

found. The figure associated with this result can be found below, though we do not feel this figure needs to be added to the paper.

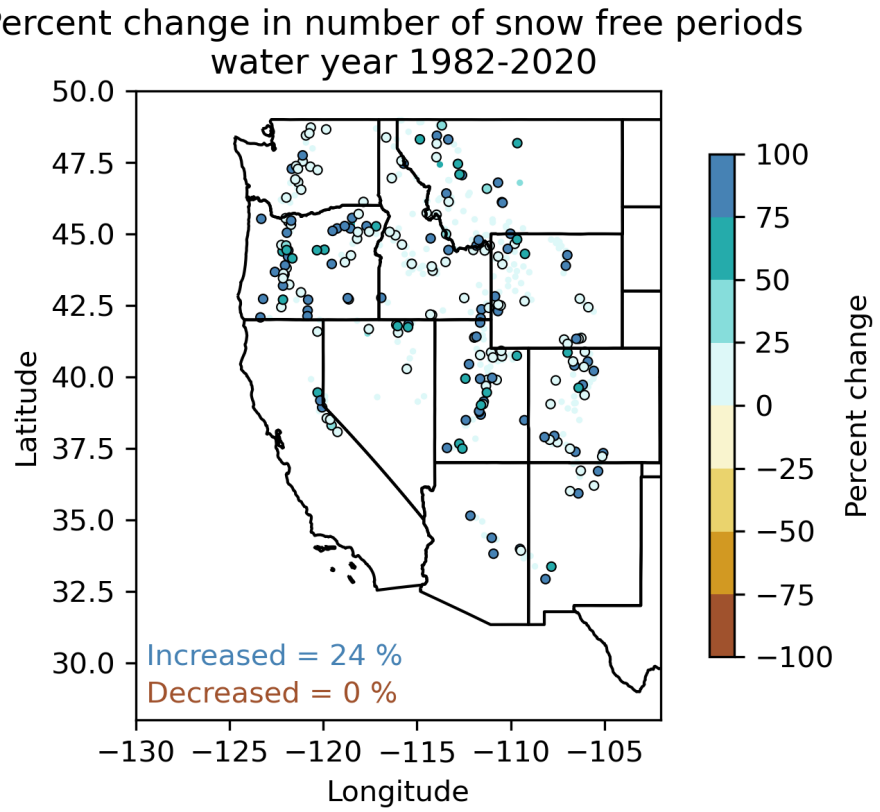
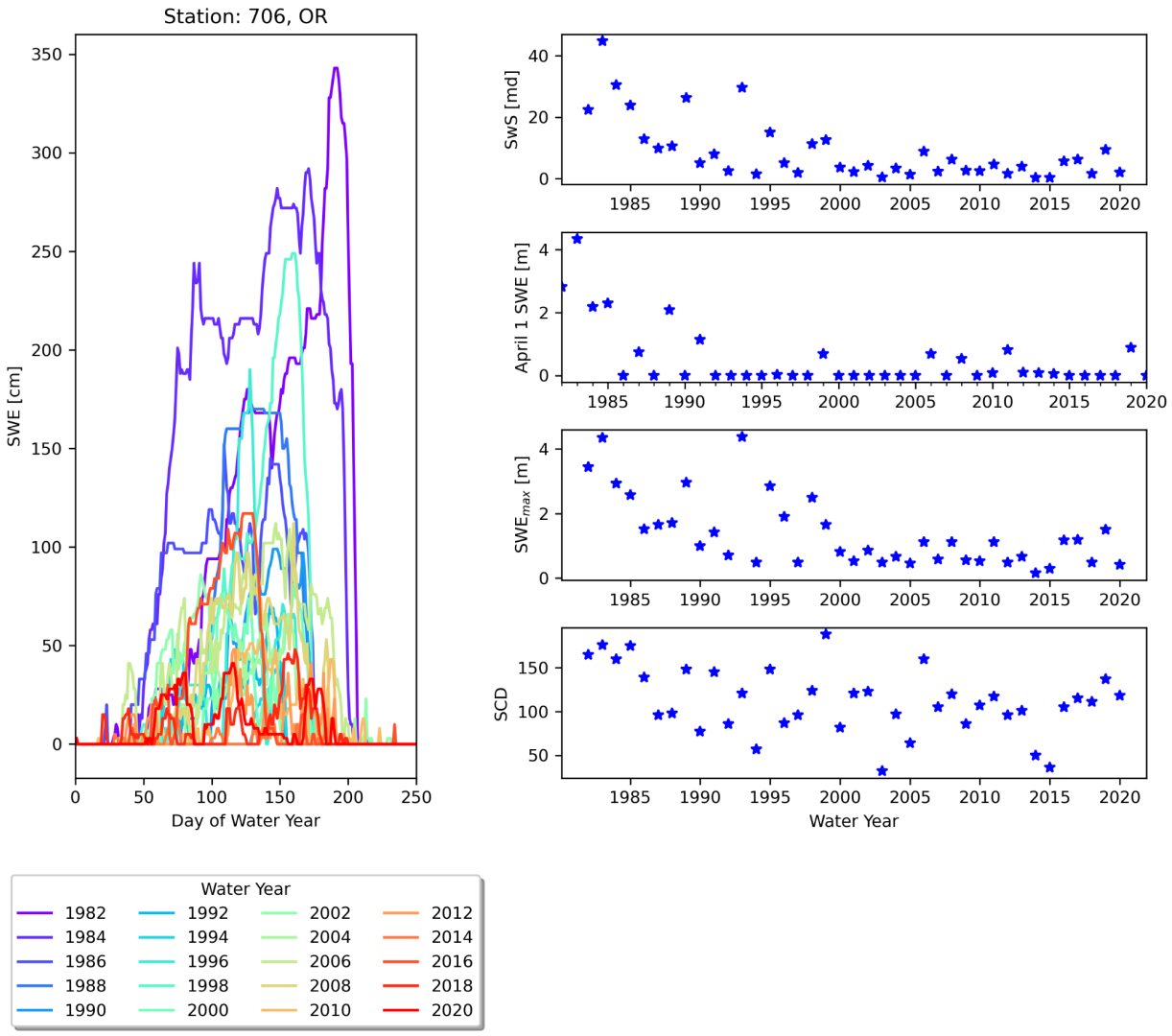


Figure 13: In the text, it is suggested that this figure is a side-by-side comparison of annual SwS, April 1 SWE, max SWE, and snow-covered days – however that is not teased apart in the actual figure. This case study would be extremely valuable if the readership could observe how – perhaps – April 1 SWE have not changed (e.g., it is mentioned that April 1 SWE is often 0 here), SCD has increased, but SwS has decreased. In addition to SWE curves, suggest plotting a subpanel of SCD through time, maximum SWE through time, and then SwS through time with example curves (e.g., first year on record SWE curve + annual SwS value, final year on record SWE curve + annual SwS value).

Thank you for suggesting this. In our analysis we created plots to explore the trends in snow metrics over time and we agree that the addition of subplots would improve this figure. See the updated Figure 13 below.



Line 308-310: As mentioned above and from the first review, *showing* the SWE curve flattening through time, on average, would be very informative to see and complement the results written in Section 3.1 and shown by ecoregion in Figure 11.

The result of the SWE curve flattening was based on station data, and the relative percent changes were not evaluated at ER3 scales. Additionally, this result is based on a regression analysis that shows that the percent change in SWEmax is greater than would be expected relative to the percent change in SwSA and the percent change in SCD is less than would be expected relative to the percent change in SwS_A. We found this result by doing a regression analysis on the 465 available stations, so there is notable variability across stations. If we understand your comment correctly, you are interested in seeing an example of a SWE curve flattening over time for a specific location. We do not feel there is utility in showing SWE curves from a single station because of the variability that exists across stations. Instead, we think that the current regression plots are the most effective means of showing this result.

Line 311: “More informative” for what? I ask these repetitive questions because it seems a half sentence is often missing in emphasizing the utility of this metrics over others with respect for water resources. These results seem to hint at incorporating the SwS in a water management scenario.

Thank you. The sentence was updated to “So, relying on a single metric like April 1st SWE gives an incomplete assessment of the storage of snow throughout a full season, and a more holistic metric like SwS may be more informative when considering a full snow season.”

Line 368: This is a comment likely intended for the methods or results, but the elevation bands (low vs. higher) could generally be defined for each region, since Figure 10 (referencing hypsometry) shows results relative to elevation in each ecoregion.

Figure 10 includes elevation, but in a normalized sense. We chose this normalized approach purposefully. If we interpret your comment above correctly, you seem interested in knowing dimensional information (actual elevations) about the ER3s. As noted in the manuscript, 10 elevation bands are defined for each ER3. To accommodate your interest in the raw elevations, we have added a column to Table 2 that provides (min, max) the minimum and maximum elevation for each ER3. With this information, it is straightforward for the reader to understand what the dimensional elevation bands are for each ER3. We retain the normalized presentation in Figure 10, however, so that the reader can easily see what is going on at ‘relative’ elevations across the different ER3s. Thank you for your comment and we hope that we have read it correctly.

Discussion: Suggest somewhere in this section to interpret and discuss the implications of the changes seen in Figure 11 and the average “flattening of the SWE curve.” Does this indicate that melt is occurring earlier in the year and/or more intermittently throughout the winter? Or is less snow falling throughout the year? Or both? How do these results compare to the metrics mentioned in the introduction? (A good example of this is at line 380 – but this is specific to SWE variability at higher elevations).

The second paragraph of the discussion addresses why the findings in Figure 11 are important, but we realized that we did not explicitly reference Figure 11 in our previous submission. We have added a reference to Figure 11 in this second paragraph. As far as the flattening of the SWE curve, this paper is not focused on the mechanism of cause, it is focused on presenting a new snow metric and calculating the history of snow water storage. We added the following to paragraph 3 of the discussion to further interpret our results as they relate to plausible mechanistic drivers of change:

“While future work could explore the exact mechanistic drivers of predominantly decreasing SwS trends, these findings are reasonable in the context of mechanistic drivers explored in other snow change literature. From an energy budget standpoint, snow falling at warmer temperatures (as a result of climate warming) and overall shallower snowpacks (due to reduced snowfall fractions) contribute to reduced cold content and more readily ripening snowpacks

(Jennings and Molotoch, 2020) . Additionally, shallower snowpacks are susceptible to enhanced snowmelt from the albedo feedback as vegetation and soil are exposed (Kapnick and Hall, 2010).”