REVIEWER 2:

Overall, this is an interesting and novel study that investigates the impact of snowpack dynamics on liquid water buffering using a physics based model.

Overall, I had some major concerns with the written manuscript, as a lot of information seems to be missing that rendered it difficult for the reader to easily understand the results. I am recommending a major revision.

My main concerns are: Some additional justification and background is needed in the introduction, there needs to be a data section in the methods, model evaluation/accuracy using RMSE, MAE, and/or bias needs included and the process explained in a new section,

See my overall comments below:

Abstract:

Comment:

Line 12 – I recommend including the model name instead of a "a snowpack model"

Proposed Action:

We will add the name of the model to the sentence

Comment:

Line 16: There needs to be a brief explanation why there is a long-term decline in LWbc.

Response:

The long-term decline in Liquid Water buffering capacity in the region is likely linked to changes in synoptic scale meteorology under a changing climate, which is a topic beyond the scope of this project. A discussion of why the changes in LWbc occurred would need to be based on an analysis linking the variations in LWbc to climate dynamics. To our

knowledge, no such study exists. Hopefully, future work will elucidate the cause of the long-term decline in LWbc.

Proposed Action:

We will add text to indicate that the decline in LW_{bc} is largely due to reduced SWE and cold content in late November through late January.

"The LWbc of the snowpack exhibited robust long-term declines, that is driven by reduced SWE along with reduced cold content in late November through late January across all elevation bands, despite high intra- and interannual variability."

Comment:

Introduction

Line 61: I am recommending a paragraph introducing and justifying the model used in this research. It should include literature supporting that it is the most appropriate model for this research question and justify the choice.

Response:

Methods section 2.2 ("Snowpack Simulations") of this paper briefly describes the model used for this study. The authors believe that the methods section is the appropriate section for discussing the model used in the study. However, more information on the model and identification of aspects of the model that make it an appropriate choice for this study would be beneficial to the reader. Further, considering all the comments from this reviewer, we believe that restructuring the methods section will help make the text clearer.

Proposed Action:

We will add information to the "Snowpack Simulations" section, including a discussion of why the model works well for the study goals. We will also move the sentences describing Alpine3D outputs used in this study (Cold Content and SWE) and how Alpine3D calculates Cold Content to the "Snowpack Simulations" section.

We will add information on SNOTEL sites to the first methods section ("Study Basin"), where SNOTEL sites are first mentioned within the text. Added information on SNOTEL sites will include the measurements that these sites provide which were used to parametrize ERA5-Land precipitation values.

We will move information pertaining to ERA5-Land from the "Snowpack Simulation" section to a new section within the methods section (ERA5-Land Derived Forcing Parameters"), this new section will discuss the forcing parameters derived from ERA5-

Land and will discuss how data from SNOTEL locations were used to help parametrize the precipitation input value from ERA5-Land. This section will also include examples of where ERA5-Land has been used to force other snow and hydrology models.

Comment:

~Line 61- Another paragraph needs added that provides background on SNOTEL including an explanation of SNOTEL and the data that are extracted from it and justifies with literature ERA5 as input to the model.

Response:

SNOTEL is an observational snowpack network in the US which is cited in peer-reviewed literature many thousands of times. However, as the reviewer points out, some readers may not be familiar with SNOTEL as it is a US-based program.

Proposed Action:

We will add two sentences to Section 2.1 ("Study Basin") describing SNOTEL sites and the relevant measurements that they provide.

Proposed addition:

"SNOTEL sites are automated snowpack and climate monitoring stations operated by the Natural Resources Conservation Service which is part of the US Department of Agriculture. They provide hourly measurements of SWE, precipitation, temperature, and sometimes snow depth at remote locations in mountainous regions of the Western United States."

We will move information pertaining to ERA5-Land from the "Snowpack Simulation" section to a new section within the methods section (ERA5-Land Derived Forcing Parameters"), this new section will discuss the forcing parameters derived from ERA5-Land and will discuss how data from SNOTEL locations were used to help parametrize the precipitation input value from ERA5-Land. This section will also include examples of where ERA5-Land has been used to force other snow and hydrology models.

Information on how SNOTEL sites were compared to model results will be added to the Appendix. See our response to the comment about Line 126

Comment:

Line 65 (e.g. final paragraph of introduction): The objections paragraph here should also include that model – perhaps after/with this sentence? "72-year model simulation of the seasonal evolution of internal snowpack conditions"

Response:

We believe that the reviewer is suggesting that we add the name of the model that we use to model snowpack in this sentence.

Proposed Action:
We will specify that we use Alpine3D in this sentence.

"… we utilize Alpine3D to conduct a 72-year model simulation of the seasonal evolution of the snowpack conditions."

Methods:

Comment:

Line 94: something seems to be missing here: "a spatially distributed snow allocation and surface hydrology …. Model?"

Response:

Good catch. Thank you.

Proposed Action:

We will add 'model' to this sentence

Comment:

Line 90 New Section 2.2: Data - There needs to be a data section where you explain the SNOTEL and ERA5 data. You also need to include an explanation of "beginning of Early Accumulation to through the end of Melt Onset". Also an explanation of early, core, and late accumulation – what specifically was used to define these?

We will restructure the methods section as stated above. Please refer to responses to previous comments referring to line 61 addressing adding information about SNOTEL and ERA5-Land data for more information about adding a new section.

Although the dates associated with each period defined in this text are described in section 2.4 ("Trend analysis") of the document, the reviewer has highlighted that this information is buried in the text whereas it should be easily accessible.

Proposed Action:

Please refer to proposed actions to previous comments referring to line 61 for a description of how we propose to improve the text with respect to SNOTEL and ERA5-Land data.

We will add a table giving the dates for the four periods defined in the text (Early Accumulation, Core Accumulation, Late Accumulation, and Melt Onset). The caption for this table will state that we define the periods based on inflection points in our results.

Comment:

Line 98: ERA5 needs its own paragraph

Response:

We agree with the reviewer.

Proposed Action:

We will move information pertaining to ERA5-Land from the "Snowpack Simulation" section to a new section within the methods section (ERA5-Land Derived Forcing Parameters"), this new section will discuss the forcing parameters derived from ERA5-Land and will discuss how data from SNOTEL locations were used to help parametrize the precipitation input value from ERA5-Land. This section will also include examples of where ERA5-Land has been used to force other snow and hydrology models.

Comment:

Section 2.2: Snowpack Simulations – I'm a little unclear here – in the trends, you mention that you have modelled SWE, cold content, and LWbc – however, this is not described in this section. Therefore, I am requesting the following:

1. You need to include an explanation of the input parameters, the input data, and an explanation of the variables that were modelled, and an explanation of the outputs.

Response:

We agree with the reviewer that this section is confusing. It should focus on snowpack simulations only.

Proposed Action:

We will add information to the "Snowpack Simulations" section, including a discussion of why the model works well for the study goals. We will also move the sentences describing Alpine3D outputs used in this study (Cold Content and SWE) and how Alpine3D calculates Cold Content to the "Snowpack Simulations" section.

How we calculate LW_{bc} will be presented in a methods section of its own (LW_{bc} from model outputs). This section includes our method for using output Alpine3D outputs (Cold Content, SWE, liquid water content, and runoff) to calculate LW_{bc} (with the equation) as well as how we calculate S_w from the Alpine3D output.

Comment:

Line 126: A new Section 2.3: A new section needs added here for model error. I am requesting the following:

1. Please add an RMSE, MAE, and bias between your simulated data and the SNOTEL data to quantify model accuracy. You need to ensure that you simulate a variable that is also available within the SNOTEL data so that you can quantify model accuracy

Response:

Comparison of modeled SWE to SNOTEL derived SWE is given in Figure A1. This figure includes a comparison of absolute max annual SWE as well as the day of snow year where the peak in SWE occurs.

It should be noted that comparisons between the distributed Alpine3D model outputs and measurements from the SNOTEL sites are not directly relatable. This is due to well-known problems with comparing gridded model outputs to point measurements. As an example,

our model grid points include areas that have varying elevations, slopes, and aspects in the real world, thus there are real-world, natural variations in snowpack properties within the area covered by any single grid cell.

Understanding that all SNOTEL vs model output comparison methods are equally invalid; we chose to compare SNOTEL data against model pixels with the closest elevation to the SNOTEL site while still having centroids within approximately 1 km of the SNOTEL location.

Because this study is not comparing model data to point data, and instead focuses on long-term trends, we believe this information is appropriate for the Appendix.

<u>Proposed Action:</u>

We will add the r^2 (0.94 for max SWE, 0.64 for date of max SWE), RMSE (16.8 cm, 15.7 days), MAE (13.6 cm, 10.3 days), and bias (-1.7 cm, 3.5 days) to the caption of Figure A1.

<u>Comment:</u>

2. Add a new section before trend analysis that describes your process for model accuracy

<u>Response:</u>

Model accuracy is not well defined when comparing model output to ground measurements. Also, we do not presume that the model outputs are accurate. In fact, if the model was accurate to point measurements, it would be a sign that the model is over-tuned to the point measurements.

<u>Proposed Action:</u>

We will add a section discussing the comparison of model output data to point measurements from SNOTEL sites to the appendix.

The proposed section is:

"A.1 SWE Comparison to SNOTEL point observations

Within the model area there are two SNOTEL stations: Emery Creek and Noisy Basin. Emery Creek SNOTEL is located near the northernmost part of the SFF basin at 1326 m, the DEM derived elevation for the output model grid point that includes Emery Creek SNOTEL is 1488 m. The Noisy Basin SNOTEL is located approximately 30 km south of Emery Creek station in the Flathead Basin at 1841 m elevation, the model grid point that contains the Noisy Basin SNOTEL has an elevation of 1805 m. Understanding that all SNOTEL vs model output comparison methods are equally invalid; we chose to compare SNOTEL data against model pixels with the closest elevation to the SNOTEL site while still having centroids within approximately 1 km of the SNOTEL location. Recall that the model pixels are 800 m by 800 m. By taking this approach, we recognize that elevation has a considerable influence, both with total amplitude and timing, on snow accumulation and melt without completely neglecting regional or watershed scale variations. The modeled pixel that we use as a comparison to Emery Creek SNOTEL data is at an elevation of 1325 m and is located two pixels (approximately 1.1 km) south of the true SNOTEL location. The pixel used for comparison with Noisy Basin SNOTEL has an elevation of 1836 m and is in the pixel directly south of the true SNOTEL location (less than 1 km). All comparisons are for both SNOTEL stations for the years 1981 through 2022 modeled data which results in 84 unique points for each model to SNOTEL comparison presented herein."

Comment:

Results:

Line 165: "beginning of Early Accumulation to through the end of Melt Onset" were not defined in the methods. Are these specific days that you chose for the analysis?

Response:

Although the dates associated with each period defined in this text are described in section 2.4 ("Trend analysis") of the document, the reviewer has highlighted that this information is buried in the text whereas it should be easily accessible.

Proposed Action:

We will add a table giving the dates for the four periods defined in the text (Early Accumulation, Core Accumulation, Late Accumulation, and Melt Onset). The caption for this table will state that we define the periods based on inflection points in our results.

Comment:

Line173: Need to include figure reference – I recommend including individual figure references (e.g. 3a, 3b, 3c) because its hard to cross reference currently.

Response:

We will add individual figure references, where appropriate, within the text.

Example:

"Across the Early Accumulation Period, the magnitudes of SWE trends are negative, indicating diminishing snowpack over the 72 years (Fig. 3b)."

Comment:

Line 201: I like how you reference figure 4a, 4b, 4c, etc. all separately in this section and I am recommending a similar format in section 3.1

Response:

We will add individual figure references to the text of Section 3.1, where appropriate.

Example:

"The SWE loss is accompanied by a small reduction in CC of 175 up to 0.050 ± 0.02 mm WE yr^{-1} (Fig. 3d), and small but significant trends of decreasing LWbc (Fig. 3f)."

Comment:

Section 3.4: This seems like it could use a figure.

Response:

This section references Figure 5d (Line 239); however, we will add further references to figures in this section, where appropriate.

Proposed Action:

We will add further references to figures in this section, where appropriate.

Discussion:

I thought this was written rather well.