Leone et al. The 2022-2023 snow drought in the Italian Alps doubled glacier contribution to summer streamflow

Reviewer 2 response to author corrections

I thank the authors for a very thorough approach to the corrections. The paper was revised substantially in response to comments. It reads much more succinctly and the model limitations are better quantified (especially in relation to the glacier area change). I have a few remaining comments in relation to the changes which I document below. I copy here only the comments where there are remaining things to change, those which were satisfactorily dealt with I have not mentioned again. My comments are in blue and line numbers refer to the revised manuscript without track changes. Since overall the remaining changes are rather minor I would hope the authors could deal with them without another round of revisions.

Reviewer 2

Main comments

a) Description of results. In some places I find the description of results to be a little too detailed, in terms of including many statistics in the main text which could be easily summarized more succinctly or the reader could be referred to a figure. Sometimes just shortening the text is enough, whereas in other cases improving the current figures or adding new ones would be beneficial. I think this would help keep the story clear for readers.

We agree with the reviewer and will revise the Results section to improve clarity, in particular by reducing the amount of detailed numerical information in the main text, referring more explicitly to figures, and summarizing key patterns more succinctly.

Changes: In the revised manuscript, we reduced the number of detailed numerical values reported in the main text and instead summarized the key patterns while referring readers to the figures and tables for detailed statistics (see Section 4).

The results section has been much approved and is more succinct which is great. A minor thing is the somewhat confusing % changes, e.g. line 230 and 232, e.g. (around -60-30 %). Maybe instead '(around -30 to -60%)' is better?

b) Clearer description of (some) of the study limitations as well as model uncertainty. I think there could be an improvement in the description and illustration of the comparison of the model results against glacier mass balance (see detailed comments), and potentially remote sensing datasets could be used for comparison too. It would also be useful (if possible) to quantify the effect of not evolving the glacier outlines. The authors are clear about how they estimate the glacier contribution to discharge and already mention that it is a simplification, but I think it likely leads to an overestimation of glacier contribution to discharge since many of the not included elements (groundwater and ET) result in losses and therefore would increase the calculated glacier contribution. Potentially the glacier melt as a proportion of inputs (rain, snowmelt and ice melt within the catchment) could be used as an alternative and/or other studies could be used to compare against the magnitude of the results (even if they are in a slightly different region of the Alps). This could go in the discussion and would allow your results to be seen better in context.

We thank the reviewer for this comprehensive and constructive comment. We agree that a clearer discussion of model uncertainty and study limitations would strengthen the manuscript, and we will revise the Discussion accordingly. Validation of glacier melt estimates at the catchment scale remains challenging, particularly in the Italian Alps, where many glaciers are partially or extensively debris covered. While satellite based geodetic mass balance datasets are increasingly available, their applicability in this region is often limited by debris cover and by the difficulty of separating snow, ice, and debris signals. For this reason, we consider the ablation stake dataset used here - collected by regional glaciological services - to be the most reliable source for evaluating glacier melt in our study area. We will clarify this point more explicitly in the revised manuscript and improve the description and illustration of the comparison between modelled melt and stake measurements. We also agree that the use of static glacier outlines is an important source of uncertainty. As suggested, we will therefore quantify glacier melt contributions using updated glacier outlines from the most recent regional inventories. This sensitivity analysis allows us to explicitly assess the impact of glacier area uncertainty on meltwater contribution and streamflow ratios. With respect to the estimation of glacier contribution to discharge, we acknowledge that our simplified approach likely overestimates absolute contributions, since groundwater losses and evapotranspiration are not explicitly accounted for. We will emphasize this limitation more clearly where we already introduce our definition of contribution as glacier melt over streamflow. Finally, to better place our findings in context, we expand the Discussion by comparing the magnitude of glacier contributions observed here with those reported in other Alpine and mountain-region studies.

Changes: In the revised manuscript we expanded the Discussion and Limitations sections to better describe model uncertainty and study limitations. Specifically, we improved the description and illustration of the comparison between modeled glacier melt and ablation stake measurements. We also quantified the effect of static glacier outlines by performing a sensitivity analysis using updated regional glacier inventories (Aosta Valley 2019 and Lombardy 2021) and recalculating glacier contributions to streamflow. In addition, we clarified that our simplified estimate of glacier contribution to discharge (ratio of glacier melt to observed streamflow) does not account for evapotranspiration and groundwater losses, which may lead to a modest overestimation of absolute contributions (see section 5.1).

Nice to see an improvement in Figure 2 and the additional statistics. However, the text does not yet mention that the model has a tendency to overestimate ablation and underestimate accumulation. The differences per elevation band are not so small and so I think its important to recognise this, at least in the results and potentially in the discussion. What might be the impact of this bias in mass balance profile on the results?

It is also great to see the new calculations of contributions with the more recent glacier outlines, and it is clear that the main messages of the paper still stand, which is super. It would be nice though to have a sentence in the discussion which compares the glacier contributions between the RGI and more recent outlines directly, so that the impact in terms of the actual contributions (not just relative changes) is known.

Also line 467: 'regions are likely to be energy limited and thus evapotranspiration is small.' Only since your modelling is not calculating the energy balance, so you are just inferring from another study here.

c) Treatment of snowmelt. It seems like the SWE (at least over glaciers) is calculated for the catchments and that the glacier melt contribution is a combination of the snow and ice melt over the glaciers, which

is pretty reasonable. However, it is less clear to me how off-glacier snow is dealt with. In section 3.1 it is mentioned that SWE is calculated by S3M nationally (so I presume also off-glacier), and yet the snow contribution to discharge is not discussed later in the paper, only the on-glacier SWE variations. Maybe for this study off-glacier snow melt was not calculated? I respect that the authors may have chosen to concentrate specifically on the glacier melt contribution, but I think it either needs to be said clearly why the off-glacier snow melt component was not calculated/analysed or for it to be included alongside the glacier melt contribution.

We thank the reviewer for highlighting this lack of clarity and we apologize for the confusion in the original manuscript. In this study, we do not quantify snowmelt contributions to discharge. Our analysis focuses exclusively on ice melt water originating from glacierized areas, which is used to estimate the glacier contribution to streamflow. While S3M Italy simulates snow water equivalent both on and off glaciers at the national scale, offglacier snowmelt is not analysed here because attributing its contribution to discharge would again require a fully coupled hydrological model accounting for groundwater storage, evapotranspiration, and routing processes, which is beyond the scope of this work. We agree that this was not sufficiently clear in the original text. In the revised manuscript, we will therefore clarify (i) that the glacier contribution analysed here refers to meltwater generated over glaciers only, and (ii) why off-glacier snowmelt was not included in the analysis. This clarification will be explicitly stated in the Methods and reiterated in the Discussion.

Changes: We have clarified this point in the revised manuscript. Specifically, we now state in Section 3.1 that although S3M simulates SWE across the entire domain, SWE and meteorological variables are analysed only over glacierized areas and off-glacier snowmelt contributions are not quantified in this study. We also explain at lines 103-106 that isolating the contribution of off-glacier snowmelt would require a fully coupled hydrological model including runoff routing, groundwater storage, and evapotranspiration processes, which is beyond the scope of this work.

This is now much clearer thanks. Just watch line 108: 'on and off glacier, off-glacier…'

Minor comments

Figure 1 Can you include the modelled catchment areas as well? Maybe make the hydrometric station stars larger so they are more distinguishable from stakes. In the caption, 'various inset maps' rather than 'various zooms'.

We agree with the reviewer and we will revise Figure 1 accordingly. The modelled catchment boundaries will be included in the figure, the hydrometric station symbols will be enlarged to improve their distinction from ablation stakes, and the figure caption will be revised to use "various insert maps" instead of "various zooms".

Changes: We revised Figure 1. The modelled catchment boundaries are now included in the figure, the hydrometric station symbols are larger, and the figure caption has been changed.

Great, much improved. In the caption 'The yellow outlines are the modelled catchments.'

L172-173: This text on the temperature differences is not so efficient, these values would be better as a graph of anomalies v elevation, you could have a line per month.

We agree with the reviewer and will revise the manuscript by synthesizing the description of temperature differences and adding a new figure showing air temperature anomalies vs elevation.

Changes: We simplified the text and added a table with mean seasonal air temperatures in order for this paragraph to be more efficient (see lines 209-216 and table 1).

This text is now much improved, but maybe there is a bit of repetition between lines 208 and 232 and the text in lines 233 to 241? I also see now that the temperature differences with elevation are in Figure 4, so perhaps the new Table is not so necessary? I am just not completely sure what differences are between the description of the temperature/precipitation differences against elevation mentioned in the first part of this section and the temperature anomalies mentioned later. Maybe you can better integrate the text still, so in other words mention the detailed anomalies of temperature (Figure 3) and the seasonal anomalies with elevation (Figure 4) together for each year/place?

L186: Write out 2023 if you want to start a sentence with it.

This change will be implemented in the text.
Changes: This change has been implemented in the text (see line 218).

Still to do.

L286: 'growing to 63 m3s-1'

We will correct the unit measures in the revised manuscript.
Changes: Unit measures have been changed throughout the manuscript (see line 310).

My apologies but the '-1' also needs to be superscript. So use 'm^3 s^{-1}'.

Also see line 400: 'measured streamflow. As for Aosta Valley…' [add space]