Replies to the review comments by the anonymous reviewer on 'Reconstructed glacier area and volume changes in the European Alps since the Little Ice Age'.
by Johannes Reinthaler and Frank Paul

The manuscript by Reinthaler and Paul describes a glacier surface and extent reconstruction for the Little Ice Age maximum (assumed to be in 1850) and calculates area, thickness and volume changes from the LIA maximum to 2000 and 2015. The study makes use of numerous existing datasets and newly determines LIA outlines and surface topography for 19% of all glaciers in the Alps (>0.1 km^2) for which outlines were missing in previous inventories. I find that the study uses generally robust methods to generate novel and significant findings. The manuscript is well-structured and well-written, the presentation is clear, and the results, analysis and discussion provide useful perspectives on acceleration of changes as well as uncertainties. I suggest the manuscript can be published after minor revisions. My comments are detailed below. I have some doubts about the method that is used to calculate the total volume error estimate, which I would like to see addressed. Other (minor) comments are mostly suggestions for textual revisions, added discussion, clarification and additional references.

Dear reviewer, thank you very much for taking the time to carefully read our manuscript. We are happy to read that the study has a robust method and that the analysis was done well. Below, we go through your comments and address each of them.

Comments:

Volume uncertainty: The current error estimate of the volume does not seem correctly calculated. Summing squared relative errors and taking the square root is normally applied to calculate the total error of a variable that is the product (or division) of other variables with known errors (see e.g. https://www.statisticshowto.com/statistics-basics/error-propagation/). The total volume is however not the product of glacier outlines, surface reconstruction, and bed topography, but rather the product of the related ice thickness and area. Therefore, a better way to calculate volume errors is to apply error propagation on the product of area and thickness where relative errors of glacier area and thickness are individually defined. I think this formula could be used; eps_V = V*sqrt((eps_H/H)^2 + (eps_A/A)^2) where eps_V, eps_A and eps_H are volume (V), area (A) and thickness (H) errors, respectively.

Thank you for the suggestion! You are right that the volume uncertainty is in the end related to uncertainties in glacier area and ice thickness, but in our study ice thickness is already a derived variable resulting from the independently derived glacier beds (which we are just using) and the glacier surface (which we have reconstructed). So, in our case we have to consider the uncertainties of glacier outlines (i.e. area) reconstructed by us, the uncertainty in elevation of the reconstructed glacier surfaces (which we also have calculated) and the uncertainty in the elevation of modelled bed topography (which we take from the related publications). As these are the three independent sources of uncertainty to be considered, we think our way of calculating volume uncertainty is correct.

L19-20: "Many glaciers have now only remnants of their former coverage left, which led to deglaciation of entire catchments.". Please specify how many glaciers this applies to and which catchments are affected, because now it is a rather hollow statement.

We agree that the statement is not quantitative, but think this is sufficient for the abstract as a detailed specification would be rather lengthy and is presented in the main text. It touches upon the difficult question when a glacier is gone. This might be defined by size or when there is no flow. For size, the widely used threshold is 0.01 km2; but what if three or more pieces smaller than this but forming a remaining ice body larger than 0.01 km2, are left? We would prefer to not enter into this discussion in the abstract and prefer to stay with the more generalized statement.

L20: "The new datasets should support a wide range of studies related to the effects of climate change in the Alps.". This is also rather vague. It could be good to specify types of studies / study fields that would benefit from the dataset.

We agree, but think this is a rather long list. We have now written: The new datasets should support a wide range of studies related to the determination of climate change impacts in the Alps, e.g. future glacier evolution, model validation, hydrology, surface albedo and land cover change, plant succession and emerging hazards.

L36-37: References and links to GLIMS and RGI should be included here and/or in the Data Availability section.

We have added the references for GLIMS and RGI.

L40-41: "However, in contrast to other regions in the world, extent differences (e.g. between 1850, 1820 or 1600) are small in the Alps.". Is there a reference for this?

We have listed references for example in the following sentences. We do not cite any general study since this is our conclusion reviewing relevant literature.

L51-54: "Whereas reconstructions ... European Alps.". This could be merged with / moved to the paragraph ending at L38.

We have moved the paragraph to the desired location.

L76-77: "Due to differences in interpretation of glacier extents by different analysts for the two datasets, we will only present glacier changes at a regional scale rather than per glacier.". This helps in case the observer errors are random, but not when they are systematic. Are there any indications for potential systematic errors between the two outline inventories?

Only regionally. For example, some regions in Austria had less good snow conditions in 2016 than in 2003 and included many of the perennial ice and snow fields, leading to additional 'glaciers' being mapped for the 2016 inventory. There is also a random difference in interpretation due to the different sensor resolutions. The 10 m Sentinel-2 images show details that are not visible at 30 m resolution and might have been digitized larger or smaller in 2003.

L82: "As a starting point for the LIA outline digitizing, we used outlines from 1967-1971 (for France) and the RGI v7.0 from 2003 for the other regions.". What is meant by "as a starting point" here? Is it just to get a rough idea where the glacier is? Or is more information extracted than that?

"As a starting point" means that they were used as a base before modifying them to fit the LIA moraines. We have rephrased the sentence.

L95-96: "A few glaciers that melted away before 2003 would lower this number by a few decimals.". What data is this statement based on? Is it possible to give an estimate of the number of glaciers that may have melted entirely since the LIA maximum?

The statement is not based on specific datasets, but the general observation that glaciers also decreased in size between the LIA and 2003. Hence, without outlines in 2003 (or 1967-1971 for France), we cannot reconstruct former glacier extents and thus also not determine the number of glaciers that completely melted away. This would require having a 'perfect glacier map' from the LIA that is consistent with today's interpretation. Nevertheless, we have rephrased the sentence to make it clearer.

L102-103: "The method calculates a scaling factor by dividing the gradient by the LIA elevation change (from interpolating outline points only)." This is not very clear. Please give a short summary of this method (as described in Reinthaler and Paul, in review) and how it compares to other methods.

We agree and have added a few more details about the method, but to keep the text short we would prefer to refer to the Reinthaler and Paul (2024) publication for a full description (which is now published).

L105: Please add a reference for the Topo to Raster toolbox.

We have added this reference: Hutchinson, M. F.: A new procedure for gridding elevation and stream line data with automatic removal of spurious pits, J. Hydrol., 106, 211–232, https://doi.org/10.1016/0022-1694(89)90073-5, 1989.

L118-119: "Similarly, we have used the year 1850 as the date of maximum LIA extent.". This is a (justifiable) assumption of the timing of LIA maximum extent. It would be good to add this information already in the abstract or introduction.

In the abstract we write "around 1850" to indicate that this date has a bit of variability. We hope this is sufficient here.

L128: "This probably resulted in positive elevation changes in several accumulation areas (Figure S6).". Does this also explain differences with Sommer et al. (2020)?

Yes, this could be one of the reasons. However, we have not performed a more detailed analysis on this as it is beyond the scope of this study.

L144-145: See my previous comment about possibly incorrect quantification of the volume error.

See above, we think our assessment is correct. We have, however, exchanged 'glacier outlines' with 'glacier area' to be clearer.

L170: "15%". Is it coincidence that this is exactly the same value as the volume loss or is it inherent to the method that was used to reconstuct the surface shape back in time which preserves much of the modern glacier shape (i.e. area - thickness distribution)?

As both values were determined completely independent and also the input datasets were (slightly) different, we would say the coincidence is by chance. Please note, the changes reported here for the period P2 are not related to our surface reconstruction, but are based on area change rates calculated from subtracting the 2015/16 from the 2003 area and volume change rates from Hugonnet et al. (2021).

L171-172: "This is caused by differences in interpretation from different analysts, sensor resolutions (Landsat vs. Sentinel-2) and mapping conditions (snow, clouds and shadow) rather than by growing glaciers.". Is there any reference for this? I also wonder whether a similar overestimation in 2015 likely also applies to the other (larger) glaciers?

We have described the problem in Sections 4.4 and 6 as well as Fig. 10 of Paul et al (2020) which has been added. It is mostly related to smaller glaciers located at higher elevations (and being impacted by remaining seasonal snow and topographic shadow).

L179-180: "Generally, elevation changes were largest at an elevation of around 1600 m (dominated by Region 6) and decreasing towards higher elevations (Figure 4).". Can this elevation also be calculated for P2 (2000-2015)? With glaciers retreating I would expect this elevation to migrate upwards as well with time.

Yes, this is possible. For P2 the elevation with the highest elevation change is at 1750 m. We have added this value to the manuscript.

L181-182: "The largest elevation changes (-105 m) were found at 1650 m in the western (Figure 4a) and at 2250 m (-65 m) in the eastern Alps (Figure 4b)". This does not seem consistent with the 1600 m for the entire Alps (?).

The reason why the value for the entire Alps is very similar to the one for the western Alps, is because no glacier in the eastern Alps reaches down to the elevation of 1600 m. So the 'signal' is dominated by the western Alps.

Figure 3: In the caption please indicate which period it applies to (P1 or P3).

The values correspond to P3. We have edited the figure caption accordingly.

L191: "238 km^3". Why is the 5% for the missing glaciers only added to the upper bound and not to this lower bound?

This is because missing glaciers could only correspond to an underestimation rather than overestimation, i.e. they introduce a bias.

Figure 4: This figure could be improved. The resolution is currently rather poor, reducing readability. Furthermore, the right axis is missing in both panels.

This is indeed a very busy figure. We now added the missing right border. The resolution of the image will be improved for the final version.

L210-212: "Overall, ... (Figure 3c).". Since these glaciers are not experiencing frontal ablation, elevation change rates, and trends of those, could be compared with longterm surface mass balance trends. I am not well up to date regarding available long-term SMB datasets for the Alps, but when available it would be interesting to compare long-term SMB trends with the surface height change trends presented here.

Yes, fully agreed but it comes along with several caveats as study periods and glacier extents used will differ (e.g. extents are adjusted each year for field-based SMB measurements). We have, however, presented some comparisons in the discussion section.

L216-217: "the regional variability ... Hugonnet et al. (2021).". It could be good to indicate the average relative changes compared to P1 for these as well.

Yes, this can be done. We have added the related mean elevation change rates for the DEM differencing and Sommer et al. (2020) as well as Hugonnet et al. (2021) datasets.

L217-218: "Further research is necessary to investigate what causes the differences among the available datasets". It could be considered to include a comparison with surface mass balance studies, e.g. Davaze et al. (2020; https://doi.org/10.3389/feart.2020.00149), in order to have some independent source to compare to. I would also like to see some more discussion on potential causes of the discrepancies between the available datasets.

Yes, this would be great but doing this carefully would require a separate study resulting in a long additional paper (one of the many studies we mention now at the end of the abstract). A related analysis is thus beyond the scope of this study where we focus on glacier changes since the LIA.

L220: "The absolute volume change rates...". I suppose this is based on the use of Hugonnet et al. (2021) for P2? It could be good to clarify since in the previous paragraph different surface height change datasets were considered.

Yes, the volume change rates are here calculated from the Hugonnet et al. (2021) dataset. We have now added this information.

L265: "which is certainly not the case in 2015". I may be missing the point here. Why are 2015 conditions relevant for the Haeberli and Hoelze estimate (published in 1995)?

We only refer here to the method of Haeberli and Hoelze (1995), not the estimate. Their method works best when glaciers are close to a dynamic equilibrium state, which is not the case for glaciers in the European Alps in 2015.

L277: "depending on the specific characteristics of a glacier". It could be interesting to discuss these characteristics a bit further (as it might give some directions for future work).

Yes, this would be one of the mentioned further interesting studies that can now be performed. As a related investigation is beyond the scope of this study. we now cite Reinthaler and Paul (2024) who look at such characteristics a bit closer. Apart from this, we think that the scientific community will have a large number of further ideas for follow-up studies.

L300: "an approximate regional average of 1850 has been used.". Larger response times of large (thick) glaciers will likely cause many of those glaciers to have a later LIA maximum extent date than small glaciers. Although this may be hard to account for in the approach, at least some discussion on the size dependence would be good.

We agree, but would again enter here into uncharted territory, i.e. requiring another study that can now be performed. Regarding response times, we think that slope is more important than size and the considerable overlap of slope classes for differently sized glaciers would result in an unclear relation with glacier size. We also note that the response of smaller glaciers might be increasingly impacted by non-climatic controls, e.g. due to shading their evolution can be largely decoupled from climatic changes. Despite their small size, their response times might get very long. Some discussion of the impact of the maximum extent timing and calculated area change rates can be found in Reinthaler and Paul (2023) which we have now also cited.

L310-313: "The observed change in median elevation of 143 m would translate to a temperature increase of 0.84 to 1.43 °C, depending on the atmospheric lapse rate applied (Haeberli et al., 2019; Kuhn, 1989; Rolland, 2003; Zemp et al., 2007). This is lower than the 1.5° and 1.6° temperature increase determined by Begert and Frei (2018) and Auer et al. (2007) for Switzerland and the Alps, respectively.". This needs some clarification. I assume the temperature increase in the first sentence is purely due to the elevation drop. But what is the 1.5-1.6 deg C change in the second sentence referring to? Does it include both anthropogenic warming and elevation-drop induced warming?

Yes, the first 4 studies are cited for the range of possible atmospheric lapse rates. These are required to transform the change of median elevation into a change of temperature. The other two studies only refer to the observed atmospheric warming rather than vertical lapse rates, providing an independent dataset for comparison not related to glacier changes.

L317-327: Interesting discussion on peak runoff!

Thank you.

Conclusions: The conclusions section gives a good summary of the work. However, I do miss some recommendations for future work. Would there for example be room for inverse (ice flow) modelling methods to generate physically more robust LIA surface topography?

Thank you. As mentioned in the abstract and being the reason for the vague statement of possible future applications, there is a near endless number of possibilities for future work and we think the community will have their own ideas. We would thus prefer to not enforce specific applications here.

Textual revisions:

All text errors have been corrected

L10 (and elsewhere): digitising --> digitization
L17: In the mean --> On average
L18: 1600 m --> 1600 m above sea level (m a.s.l.)
L55: "first" --> "first complete"
L60: "Regional subdivision" --> "Study regions"
L99: "DEM" --> "Digital Elevation Model (DEM)"
L112: "the total glacier volume" --> "the contemporary total glacier volume"
L141: "Uncertainties of the bed topography impact" --> The impact of bed topography uncertainty"
L143: Add "volume" between "overall" and "uncertainty".
L160: "reconstructed to" --> "estimated at"
L170: "shrunk" --> "shrank"
L196: "altitude" --> "altitude range"
L201: "are" --> "is"
L203: "Increase in change rates". Please change to something more specific (indicating the variables it refers to).
L252: "if considering" --> "when including"
L261: "would" --> "could"
L269: "estimated" --> "estimate"
Figure 6b: Please mention that changes are negative.
L330: "coverage by area" --> "areal coverage"
L331: "these glaciers" --> "all glaciers" (otherwise it refers to the missing glaciers)
L356: "GILIMS" --> "GLIMS"