Anonymous Reviewer #1

We thank the reviewer for the constructive comments. In our letter, we highlight the comments from the reviewer in orange. Our responses are in black font, and our planned corrections are highlighted in bold font.

General comments:

R1C1: This research proposes to estimate glacier surface elevation change by using the length of shadows cast by surrounding topography. Specifically, it relies on a reference DEM from which shadows are modelled at times corresponding to several Landsat acquisitions over the 1990-2020 period. From the imagery, a binary thresholding on the green band is used to map the actual shaded area. The proposed method then derives the change in glacier surface elevation along the boundary of cast shadows. This is done using the difference in length between the modelled and mapped shadows in the direction of illumination, and under the assumption of unchanged topographic gradient in that direction.

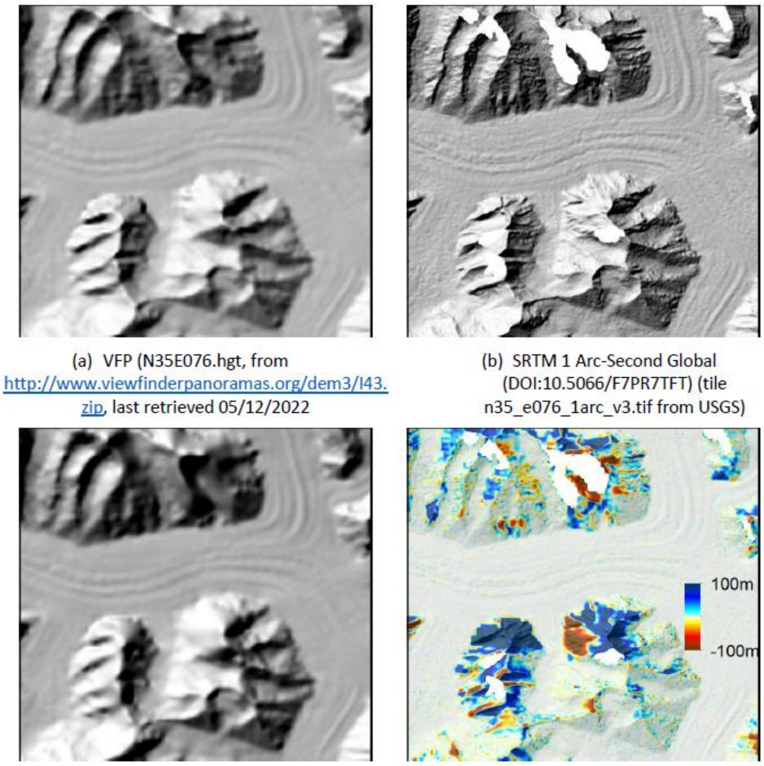
The method is tested on 5 glaciers that exhibit a prominent surrounding topography casting extensive shadows over parts of the glaciers. The SRTM 1'' DEM (acquisition Feb 2000) is used as reference DEM for 3 glaciers (Sperry, Aletsch, South Cascade); a variation of SRTM 3'' potentially mixed with other unknown data source (Viewfinder Panoramas DEM, VFP) is used for Baltoro, and ArcticDEM for Gulkana. For each glacier and each Landsat image, differences in shadow length are converted to height variations and analysed statistically with a Bayesian multi-level linear regression model to estimate linear trends of thickness change for each glacier. This suggests significant downwasting trends for Aletsch, Cascade and Sperry, while the author conclude thickening for Baltoro and no significant trend for Gulkana. A comparison of results with repeated DEMs is completed on all but Baltoro glacier. The effect of DEM source and resolution is assessed on Aletsch Glacier.

Overall, I find this contribution original and interesting but not overly convincing. It is clear and well written. The methodology is well and sufficiently explained, and the results can be reproduced. However, although limitations of the approach appear correctly identified, I find several shortcomings that require attention and significant revisions before this work can be considered for publication.

R1A1: We thank the reviewer for this positive feedback on our work. In our responses below, we address any of their concerns and detail how we will solve the issues in a revised manuscript. In summary, we will emphasize that our trends in glacier elevation change are valid only for areas on glaciers covered with shadows from adjacent mountains. We will further assess the impact of different DEMs on the simulated shadows and associated trends of glacier elevation change. Finally, our revised manuscript will also consider the data on glacier elevation change from Hugonnet et al. (2021) and thus offer a stringent comparison to one of the most elaborate datasets of its kind to date.

Specific comments:

R1C2: I find the use of Viewfinder Panoramas DEM for Baltoro Glacier arguable. This DEM is of uncertain quality. The authors themselves state that “date of the map basis of VFP is not known”. It also appears incorrectly referenced as 30m resolution in Table A2 although it is specified that VFP DEM in Asia is only at 3’’ (http://viewfinderpanoramas.org/dem3.html). **Figure R1C1** in this review compares the VFP DEM with the SRTM 1’’ (30m) and CGIARSRTM v4.1 (90m) over Baltoro Glacier. It confirms the 3’’ resolution of VFP. **Figure R1C1b** also shows that SRTM 1’’ exhibits no hole that would compromise the shadow algorithm. **Figure R1C1d**, however, demonstrates how different VFP is from SRTM 1’’, in particular over areas of significance to render proper shadows. In view of this, I don’t understand the choice made by the authors to mix VFP and SRTM. I believe the analysis of Baltoro should be redone on the basis of SRTM 1’’ alone.



(a) VFP (N35E076.hgt, from http://www.viewfinderpanoramas.org/dem3/I43.zip, last retrieved 05/12/2022

(b) SRTM 1 Arc-Second Global (DOI:10.5066/F7PR7TFT) (tile n35_e076_1arc_v3.tif from USGS)

(c) CGIAR SRTM v4.1 (https://srtm.csi.cgiar.org/wp-content/uploads/files/srtm_5x5/TIFF/srtm_52_05.zip)

(d) VFP minus SRTM 1’’

Figure R1C1: Various DEMs of Baltoro glacier and difference between VFP and SRTM 1".

R1A2: The reviewer is right that the VFP-DEM has a resolution of 3’’. **We will change this statement to “90 m (3 arc seconds)” in Table A2 accordingly.**

We initially used SRTM 1’’ data (doi: 10.5066/F7PR7TFT; shown by the reviewer in **Figure R1C1b**) to cast shadows from Mitre Peak on the surface of Baltoro Glacier. Yet the accuracy of SRTM DEM decreases in the Higher Himalayas as elevation and steepness increase. In addition, the SRTM features regions with missing data (voids) (Mukul et al. 2017, Liu et al., 2019). In **Figure R1C1b**, the reviewer used a void-filled derivate of the original SRTM data according to the online documentation: "SRTM 1 Arc-Second Global (Digital Object Identifier (DOI) number: /10.5066/F7PR7TFT) elevation data offer worldwide coverage of void filled data at a resolution of 1 arc-second (30 meters)". **Figure R1A1** confirms that Mitre Peak is void-filled according to the non-void filled original product (doi: 10.5066/F7K072R7). These voids have been filled "*using interpolation algorithms in conjunction with other sources of elevation data"* (https://www.usgs.gov/centers/eros/science/usgs-eros-archive-digital-elevation-shuttle-radar-topography-mission-srtm-non). It remains unknown which method or data USGS EROS used to approximate the elevation of Mitre Peak in SRTM 1''.

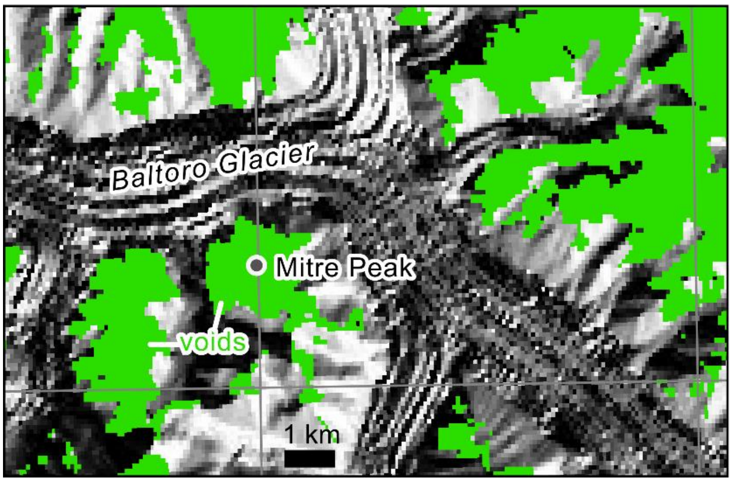


Figure R1A1: Voids (green) in SRTM 3" data on mountains adjacent to Baltoro glacier. Mitre Peak is within a void, suggesting that its elevation in SRTM 1'' data was estimated using either interpolation or unspecified data by USGS EROS.

This uncertainty motivated us to fill the void in Mitre Peak in SRTM 3'' with data from View Finder Panoramas (VFP). VFP has higher accuracy in steep terrain than SRTM 3'' (see Fig. 6 in Liu et al. 2019). We recall that we left the SRTM 3'' data for the flat surface of Baltoro Glacier unchanged. Thus, we provide a seamless DEM of VPF for Mitre Peak and SRTM 3'' for Baltoro Glacier. It is the choice of the interpolation algorithm or ancillary data that explains the difference of ~100 m between VPF and SRTM 1'' in **Figure R1C1d** provided by the reviewer.

In any case, the underlying data source for Mitre Peak remains unknown in either data set. The reviewer thus raised the important question as to which the choice of the DEM will change the shape and area of shadows casted from steep mountain peaks. Decreasing the grid resolution of DEMs (i.e. increasing the cell size) acts as a low-pass filter on the topography, degrading features such as sharp ridgelines, narrow valley bottoms, and local topographic roughness generated by bedrock outcrops (Gao 1997, Grieve et al. 2016). DEMs of higher resolution (i.e. smaller cell size) might better preserve the distinct shape of mountains.

To assess the impact of DEM resolution on cast shadows, we compared the elevation in the VFP DEM with reported values in the literature and other globally available DEMs (**Figure R1A2**). Accordingly, the elevation of Mitre Peak from VFP (6066 m) is most consistent with reported values of its elevation ranging between 6010 m (https://en.wikipedia.org/wiki/Mitre_Peak,_Pakistan) and 6030 m (https://www.himalaya-info.org/Map%20karakorum_baltoro.htm). The vertical datum of the reported elevations remains unknown, but differences of ~23 m in elevation between the WGS 84 ellipsoid and the

EGM96 geoid (the vertical datum of the SRTM and VFP) can largely account for this offset. The other DEMs feature consistently lower elevations for Mitre Peak and, generally, DEMs with 90 m resolution have lower peak elevations than their 30-m counterparts due to smoothing of high frequency signals. In comparing mapped to simulated shadows on Baltoro Glacier, we find that SRTM+VFP (lower left panel in **Figure R1A2)** closely approximated, and all other DEMs underestimated, the maximum elevation of Mitre Peak. We did not find any evidence for major rockfalls in high-resolution images, and thus assume that Mitre Peak in the VFP DEM is representative for its form in the year 2000, the acquisition date of the SRTM.

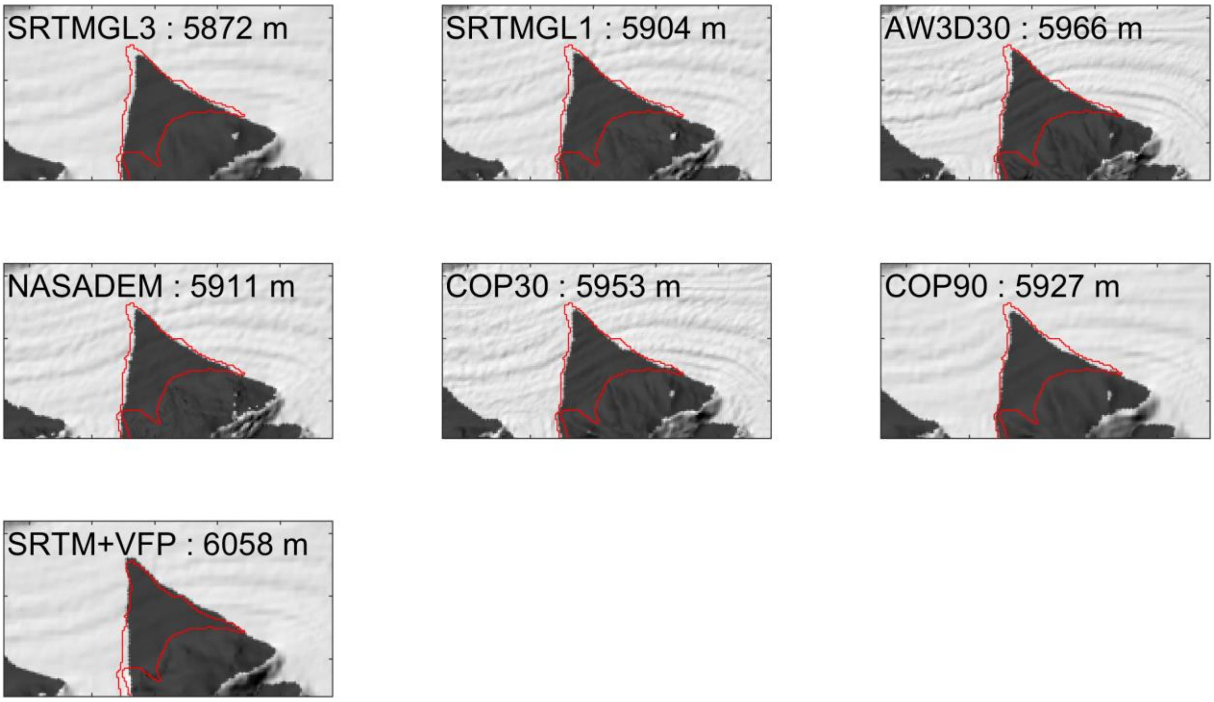


Figure R1A2: Shadows of the Mitre Peak derived from different DEMs. Elevations provided for each panel refer to the elevation of Mitre Peak obtained from the different DEMs. The red outline shows the shadow for year 2000 with an azimuth angle of 151.94° and a sun elevation of 29.48°.

R1C3: For Baltoro Glacier, the authors also state in P9L192 that no data are available for comparison. I would recommend that the authors give more consideration to Hugonnet et al. (2021) as data are readily available from https://www.theia-land.fr/en/monitoring-700000-km%C2%B2-of-the-worlds-glaciers/.

R1A3: We thank the reviewer for bringing this study to our attention. Hugonnet et al. (2021) produced time series of automatically generated DEMs from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) satellite mission between 2000 and 2019. Similar to our assessment, Hugonnet et al. (2021) estimated cumulative and mean rates of glacier elevation change in this period from a number of DEMs per glacier using stereo-photogrammetry. Data on mean rate of glacier elevation change are available either as rasters at a cell resolution of 100 m × 100 m, or as tables showing trends for the entire glacier area between 2000 and 2019 (https://doi.org/10.6096/13). Neither of the products can therefore be used directly to quantify the change in glacier elevation in the shaded areas at the same time points as in our analysis. Yet, we are pleased that the lead author Romain Hugonnet has kindly agreed to extract the entire time series of glacier elevation changes for the shaded areas of the glaciers only. **In our revised manuscript, we will therefore include a new figure that**

compares the rates of glacier elevation change within shadows between this study and ours, and discuss any related inconsistencies.

R1C4: By curiosity, I plotted the 2000-2019 rate of surface elevation change from Hugonnet et al. (2021) for Baltoro Glacier (**Figure R1C4a**). The spatial variability in surface elevation change illustrates one major limitation of the proposed approach. It reveals how trends along a path that is limited to cast shadow can fail to resolve significant signal and trends for the rest of the glacier. The unambiguous negative trend visible from Hugonnet et al. (2021) also potentially contradicts results from this study (e.g., figure 4 and statement P10L218 "*Baltoro Glacier shows slight gains in glacier thickness*") which cast concerns over the methodology and/or statistical testing. It may suggest that the inference derived from the statistical model are ill-informed or that the selective coverage of cast shadow is deceiving as it conceals the overall behaviour to the extent of drawing wrong conclusions. It appears necessary to revisit findings and conclusions with this in mind. Again, I am curious to see what would come from using the SRTM 1'' data as it may exemplify further the sensitivity of the method to the DEM.

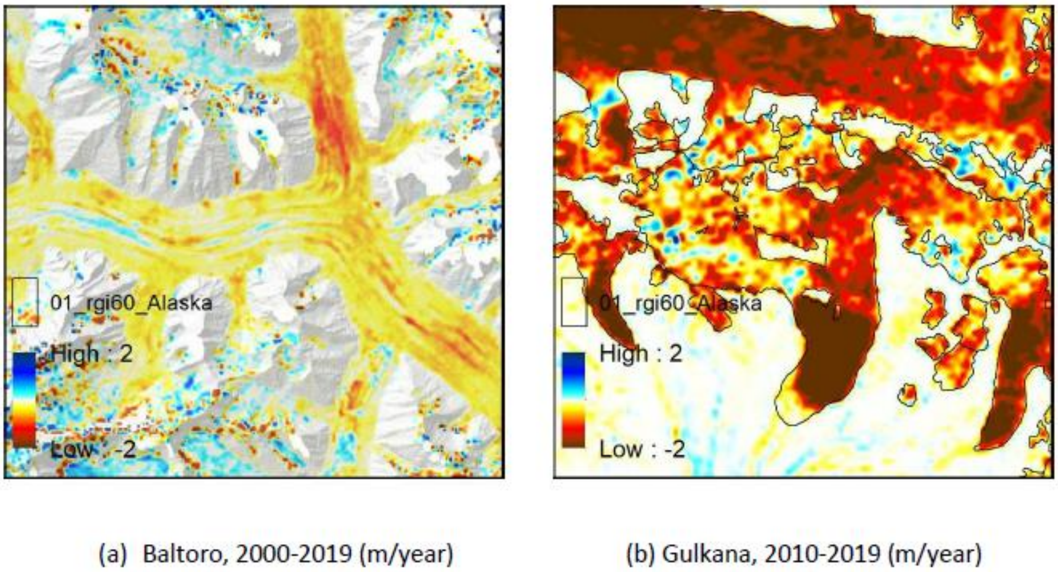


Figure R1C4: Surface elevation change form Hugonnet et al. 2021 (https://www.theia-land.fr/en/product/rate-of-glacierelevation-changes-from-2000-to-2019/)

R1A4: We agree that our approach only informs about the changes in glacier surface elevation within the area of covered by shadows. We had repeatedly addressed this premise in our earlier manuscript (L18, L58, L60-61, L77, L144-145, L238, L275-276, 327-329,), and will further strengthen this concept in our revised version of the abstract: **"Accordingly, a shadow on Baltoro Glacier (Karakoram, Pakistan) suggests slight local increases in elevation between 1987 and 2020, while shadows on Great Aletsch Glacier (Switzerland) point to the most negative thinning rates of about 1 m per year. Our estimates of glacier elevation change are tied to the occurrence of mountain shadows, and may help complement field campaigns in regions that are difficult to access."** In the revised discussion, we will add: **"We stress that our results are tied to local changes of shadows casted from adjacent mountains. Thus, we caution against comparing our results with glacier-wide mass balances because these integrate over entire glaciers or elevation bands within glaciers, and may refer to different study periods. For example, Hugonnet**

et al. (2021) estimate that the entire areas of Great Aletsch and South Cascade Glacier had elevation changes of -1.42 ± 0.1 and -0.66 ± 0.15 m yr^{-1} (mean and 1σ error), respectively, in 2000-2019. Our estimates are lower ($-1.08^{+0.06}/_{-0.05}$ and $-0.42^{+0.11}/_{-0.11}$ m yr^{-1}, respectively) in the longer Landsat period, either because we measure elevation changes at higher parts of the glacier with possibly lower melt rates, or because glacier melt has accelerated in recent decades (Hugonnet et al. 2021).” We will conclude our manuscript with: **“We demonstrate for four glaciers that our method provides quantitative information about local changes in glacier elevation over time that are consistent with independent DEMs of difference in shadow-covered areas.”**

In our revised manuscript, we will compare our trends in local glacier elevation change with those obtained by Hugonnet et al. (2021), see our reply **R1A3**. Yet we disagree that the trend at Baltoro is “unambiguously negative” at Baltoro. In **Figure R1C4**, the reviewer shows a map of mean annual rate of glacier elevation change in 2000-2019 provided by Hugonnet et al. (2021). We obtained the same data (**Figure R1A4a**), and also the error in elevation change (one standard deviation, **Figure R1A4b**). From both maps, we extracted all raster cells of the glacier area covered by the shadow from Mitre Peak in the period 2000-2019. In **Figure R1A4c**, we show both the mean and the error in glacier elevation change. We find that in each grid cell, the error is higher than the mean glacier elevation change, embracing both positive and negative trends. Thus, our findings are well within the uncertainties provided by Hugonnet et al. (2021) for the entire glacier, and possibly more accurate on a local scale.

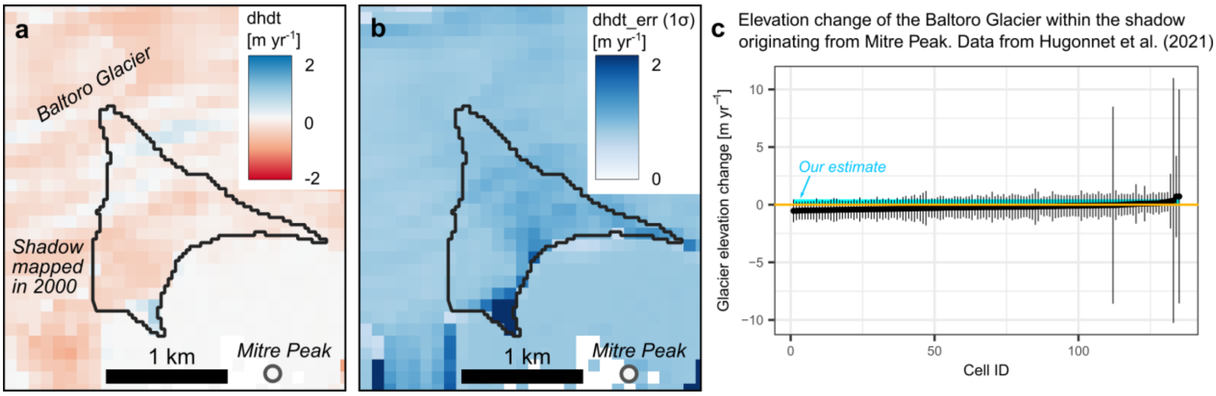


Figure R1A4: Glacier elevation changes at Baltoro Glacier using gridded data (100 × 100 m) from Hugonnet et al. (2021). **a,** Mean glacier elevation change (dhdt) and **b,** Uncertainty in glacier elevation change (err_dhdt) in the period 2000-2019. We extracted value pairs of dhdt and err_dhdt from the shadow (black outline) cast on Baltoro glacier. **c,** dhdt and err_dhdt for each pixel in the shadow. While trends are largely negative, the errors allow for positive values within the shaded area, consistent with our results.

R1C5: Another useful comparison can be made for Gulkana Glacier. Hugonnet et al. (2021) map rates of change over the 2010-2019 period that are directly comparable with the trends and conclusion inferred by the authors from cast shadows. **Figure R1C4 (b)** shows the contrasts in trends from the accumulation area with shadow cast by Ogive Mountain and those cast by Icefall Peak. In this context, the authors state P10L217 that “*Annual rates of glacier elevation change at Gulkana Glacier are not credibly different from zero*”, and strengthen their conclusion P11L237 by stating “*At Gulkana, both our method and high-resolution DEM suggest the highest uncertainties in the estimated trends, leaving little room for a credible trend in glacier elevation change*”.

While I could conceive that the author's method finds not trend from shadow cast by Ogive Mountain as it would correspond to marginal rate of change in **Figure R1C4b**, it would be expected that shadows cast by Icefall Peak yield a significantly negative signal. While revisiting the results in view of these data, it would be useful to separate signals from each mountain and compare critically with the rates assessed by Hugonnet et al. (2021). The conclusion that annual rate is not credibly different from zero must be reassessed as it either echoes again a significant limitation of the method, or it compromises findings from Hugonnet et al. (2021). At this stage and with the evidence provided by the authors, I believe the former remains more credible.

R1A5: We agree that these shadows need to be treated separately because they are cast at different elevations on Gulkana glacier, i.e., at ~1750m m for the shadow from Icefall Peak and at ~1800m m for the shadow from Ogive Mountain. **In our revised manuscript, we will calculate the trends in glacier elevation changes for both shadows separately and revise all figures and statements accordingly. This revision will also allow us to discuss how robustly our method can detect glacier elevation changes at different elevation bands along a glacier. The discussion of this analysis will also refer to the data trimmed to the shadow area, which we will receive soon from Romain Hugonnet.**

R1A6: By contrast, rate inferred for Sperry, South Cascade, and Aletsch seem to compare better with Hugonnet et al. (2021) although the trends derived over the 1990-2020 period may subdue that assessed by Hugonnet et al. (2021) over the 2000-2020 period. Such detail assessment with a consistent dataset would be desirable and will provide more perspective on the validity and limitations of the proposed approach, while also shedding light on the contrasted and generally unconvincing agreements found by the authors with trends derived from repeated DEMs and historical maps.

R1A6: In our revised manuscript, we will calculate trends in glacier elevation change constrained to the same period (2000-2019) as in Hugonnet et al. (2021). We will add a table that compares our trends with data from Hugonnet et al. (2021) both for the entire glacier and the area trimmed to the shadow.

R1A7: Finally, the authors assess the variability of shadow predicted over Aletsch Glacier from various DEMs. This is a useful and well-thought comparison that does inform about uncertainties associated with resolving shadows. Nonetheless, I find the assessment falls short of considering the effect of using these different DEMs on determining a trend of elevation change. It would be necessary that the authors repeat the full analysis on Aletsch with each DEMs to fully determine how DEM propagate uncertainties into the linear model.

R1A7: We agree that a comparison of different DEMs will help quantifying the impact of the underlying DEM in our workflow. **To this end, we will select three input DEMs, swissALTI3D, SRTM, and COP90 DEM, to cover the entire range of available raster resolutions, i.e. 5, 30, and 90 m, in our analysis. We will then repeat the steps to calculate the difference between modelled and Landsat-derived shadows to see how the trends in glacier elevation change vary based on the underlying DEM.**

Technical corrections

R1C8: P6L127: “manually mapped shadow” should better be called “shadow derived from Landsat images” as it is not mapped manually but rather derived via thresholding on the Green band.

R1A8: We will correct this statement accordingly.

R1C9: P6L129: A *geodetic line* is defined as the shortest distance between two points on the surface of the ellipsoid. I don’t think this is a relevant name for what is used here, namely a set of regularly spaced line in the direction of the sun at the time of image acquisition.

R1A9: We will replace “geodetic line” with “bearing line” throughout the manuscript.

R1C10: P19&20: Notes in both Tables A3 and A4 should read “at a lower” instead of “at an lower”.

R1A10: We will change our wording accordingly.

R1C11: P19TableA2: ViewFinder Panoramas DEM of Baltoro is ~90m (3’’ for ASIA, see http://viewfinderpanoramas.org/dem3.html).

R1A11: We will correct the resolution of VFP in Table A2 accordingly.

R1C12: P19TableA2: There is no SRTM 1’’ for Gulkana glacier

R1A12: We will delete “Gulkana” in this cell accordingly.

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