

Response to Reviewer 1

Review of: 'Brief Communication: Mass Balance of Glaciers in the Eastern Hindu Kush from 1979 to 2002 using KH-9 Panoramic and SPOT-5 stereo imagery' The study of Ramzan and Ghuffar presents a set of geodetic mass balance estimates for glaciers in a sub-region of the Hindu-Kush in High Mountain Asia, over the period 1979-2002. They use declassified American spy satellite imagery (acquired by the Hexagon KH-9 panoramic camera) and more contemporary SPOT-5 images to generate a pair of DEMs, from which they derive surface elevation change estimates and subsequent mass balance data. The methods they have followed to undertake these analyses are robust and follow best practice established by previous studies. Consequently, I trust that their results are robust and have captured the mass change rate of the studied glaciers accurately. Their findings are highly relevant to the journal and the field and extend our view of the multi-decadal evolution of glacier mass balance in a part of High Mountain Asia where data coverage is currently sparse.

I believe the analyses and presentation of the results could be improved. At the moment, the paper presents mass balance estimates for a subset of the local glacier population, which is considerably larger than indicated by the figures in the paper. The paper doesn't describe how or why the subset was chosen or what portion of the local glacier population it represents. The size of individual glaciers covered by the sample of mass balance data is only briefly mentioned at the end of the discussion (2-89 km²). The characteristics of the glacier sample are important because the reader needs to know whether they can make a fair comparison between the results of this study and other studies which likely have generated results for glaciers of a diverse size. I would therefore encourage the authors to update their manuscript to include this information, along with a justification of why they have selected the glaciers they present results for.

Aside from this main point, there are several other areas of the manuscript where I think more clarity is needed. These are mainly related to the more concise description of the results, and I have made some suggestions about how this could be achieved below.

We thank the reviewer for their thorough and constructive review. Below are our detailed responses to each comment, with corresponding manuscript modifications indicated.

Abstract: I'm missing a clear statement within the abstract which describes how these findings advance our knowledge of glacier behaviour in the region. If these are the first observations prior to the more contemporary period, I think it's worth stating so.

Response: We have revised the abstract to explicitly state the novelty and

significance of our findings.

We have added the following lines: "These observations represent the first geodetic mass balance estimates for the Eastern Hindu Kush prior to 2000, extending the temporal record of glacier change by two decades and revealing that moderate mass loss (-0.13 ± 0.10 m w.e. a⁻¹) has been sustained since the late 1970s, similar to the post-2000 observations."

Introduction:

L13: I'd suggest adding a brief description of where these studies based on historical images apply to. The previous sentence cites global studies, but I believe those cited on L13 apply to HMA.

We have added a few more references and slightly changed the line to: Historical images reveal in different regions that glaciers have been losing mass since the 1960s (Bhattacharya et al., 2021; Zhao et al., 2020; McDonnell et al., 2022; Wytiahlowkyet al., 2023).

L16: Again, if this discussion is focussed on HMA, this should be emphasised.

We have specified in the sentence.

L25: Would suggest rewording 'the melting period' to 'ablation primarily occurs'.

We have applied this change. Now shown in L30

L26: (Scher et al., 2021) in brackets.

We have applied this.

L33: I think ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) needs defining on first use. Same for Digital Elevation Model (DEM).

We have applied this change.

Fig. 1: I think all RGI7 outlines should be shown on this Figure. I think I would probably also suggest the use of true colour optical imagery as the background for the figure, which would provide more information about the different glacier types present in the study region.

We have updated the figure as suggested.

L36: I think it would be useful to state the ranges of elevation change values Wang et al. (2017) measured if they are markedly more variable over shorter timeframes than the other studies cited in this section.

We have added more detail and changed this to: Wang et al. (2017) observed that precipitation shows high annual variability in the Hindu Kush where 1 m precipitation anomaly relates with 5.5 ± 1.6 mwe change. We have also added the elevation change as observed by Wang et al. (2017) in the revised version. For a more detailed discussion of the interannual variability reported in that study, the reader is referred to the original publication.

Data and methods:

L50: Suggest stating clearly at the beginning of this section that the KH-9 panoramic camera imagery is of significantly higher resolution than either the alternative declassified images (KH9 mapping camera) used in previous studies mentioned above – this is an improvement on previous work. The post-processing approach applied to the derived elevation change data is consistent with previous studies and applies robust techniques to remove potential biases and anomalies stemming from area of lower image quality.

We have incorporated these suggestion. Please see L55-63 in the revised version.

L50: A clear omission from this method section is information about the subset of glaciers that the elevation change data (and therefore mass balance) covers following post-processing. RGI7 contains many more glaciers over the study region than the authors present mass balance data for (~1500 in RGI7 over the extent of Fig.2? see below) so I feel the authors should present information on the portion and number of the local glacier population their data covers. It would also be useful for the authors to provide information and/or an illustration of the range of glacier areas that their mass balance estimates cover. If the sample of mass balance data is biased towards larger/smaller glaciers, the calculated regional mass balance signal may not reflect the mass loss rate of all glaciers. This should be made clear to the reader.

We have reanalysed our results to include a greater number of glaciers by reducing the area threshold to 0.5 km². We have also added the total number of glaciers and the total glacier area for which the mass balance is computed. We have also further explained the exclusion of glaciers, which is also illustrated in fig 1. We computed mass balance of 265 glaciers covering an area of approx. 1050 sq. km.

Fig.1. Subset of RGI7 approximating the extent of Fig.2 in Ramzan and Ghuffar, including 1468 glaciers.

I'd also suggest showing the full coverage of RGI7 on Figures 1 and 2, which currently suggest that glacier over in the region is fairly sparse compared to my Fig.1 above. The

RGI7 outlines could be shown as thinner outlines and the glaciers for which the authors have mb data could have thicker outlines?

We have changed the figure as suggested.

Fig.2: I'd really like to see elevation change data over the full extent of the figure, rather than over glacier surfaces from which the authors have derived mass balance estimates. The absence of elevation change data over stable areas (off-glacier) would illustrate the success of the methods applied, which is common practice in most geodetic studies. This is shown in the supplement (over a very large range of values) but would be useful here.

We have added the stable terrain in the supplement, which is now more illustrative in the revised version.

I'd also suggest tweaking the colour ramp slightly to have a broader range of values illustrating no/little change as white (+/- 0.5 m/yr perhaps?). This would help separate and illustrate the opposing signals of thinning/thickening associated with surging slightly better.

We tried to apply this change, but the figure became harder to interpret as a greater range of numbers was shown in white.

In the 4x4 grid at the bottom (b and c), I think panels III and IV could be combined to show the outlines from different time periods over the dHdT data. The two IV panels should use the same colour bar and range of values as the main panel A in my opinion, also showing off-glacier data.

We have changed the panels III and IV as suggested, whereas the off-glacier data is attached in the supplement of the revised version.

Results:

L97: Would suggest just shortening this first sentence to 'During the period 1979-2002, the mean mass balance of glaciers we studied was -0.13....'

We have applied this change

L99: More detail required here. Which post-2000 dataset did the authors use and what was the mean mass balance (with uncertainty)?

We computed mass balance using the elevation change datasets of Brun et al., 2018, Shean et al., 2020, and Hugonnet et al., 2021 for comparison with post-2000 results. Here, we have also referred to Figure S4, so the reader has more clarity.

L101: Are the highest thinning and retreat rates associated with surging glaciers? If so, I'd signpost this at the start of this paragraph to clarify the point and then present your observations.

We do not intend to imply here that high melting at the terminus of glaciers in the study area is related to surging glaciers. In this paragraph, we highlight that Noroghikun is a surging glacier (a possible surging glacier according to Guo et al., 2023), as it is an important characteristic of the glacier. We observed high retreat and thinning on both surging and non-surging glaciers, which we attribute to the debris-free ice.

L111: I'd suggest removing this last sentence citing Sarikaya et al. (2012), I'm not sure it adds a great deal.

We have removed this

L112: Do they really influence the mean mass balance significantly as it is only two out of the full glacier sample (the total size of which remains unknown without discussion in the methods section). I can see how their mass balance would influence the total mass loss budget, but would only impact the mean mass balance if the sample size was very small.

We have changed this statement and made changes relevant to this in the revised manuscript. The two glaciers have a comparatively larger size compared to the sample, with respective sizes of 82 km² and 90 km², which occupy around 19 % the total glacier area in the study region.

L111: The paragraph from L111-L127 contains a lot of information but it's hard to place these in the context of the wider. The paragraph begins by mentioning two of the larger glaciers in the sample – are the rest of the glaciers in this paragraph also of a larger size? A sentence signposting the characteristics of the glaciers discussed in this paragraph in particular would help better understand these results (as the next paragraph does about surging glaciers).

The paragraph generally explains the behaviour of glaciers in the southern part of the study area. The two glaciers mentioned at the start have relatively larger sizes than the rest, but this is not an indication that the mass balance results are presented here with reference to the glacier area. We have added here an additional line at the start and arranged the first 3 lines of this paragraph as follows:

“The elevation of the Hindu Kush peaks at the Tirich Mir which surrounds glaciers showing a variable and complex melting pattern. Atrak and Tirich (also known as Upper Tirich glacier), which are the largest glaciers in the study area, are losing mass at $-0.23 \pm 0.37 \text{ m w.e a}^{-1}$ and $-0.26 \pm 0.09 \text{ m w.e a}^{-1}$ during the study period, respectively.

”

L144: I think it's unlikely that the lower parts of Noroghikun Glacier would experience heightened ice loss in response to surge activity, when ice mass gain normally occurs over the lower parts of the glacier. I'd agree that the glacier would experience higher ice losses at low elevation after a surge, simply due to a large volume of ice sitting in higher temperatures

We understand that surge activity initially reveals thickening, which is eventually followed by thinning at the glacier terminus. Here, we expect this because we generally observe that retreat has occurred below the elevation of 3900 m in the study area.

L149: I think this sentence needs some clarification. I don't really follow 'Most of the retreating glaciers in the region are debris-free and range from slight to above 1 km² of the retreated area.'

Here, we highlight that the retreating debris-free glaciers are higher in number compared to debris-covered retreating glaciers. We further explain that the retreated area of debris-free glaciers ranges from slight to above 1 km². We have also updated the revised manuscript with more clarity and have changed this to “Individually, the mass balance of debris-covered and debris-free glaciers shows high variability, while the mass balance when differentiated between debris-covered and debris-free glaciers is nearly the same.”

Fig. 3: This is a nice figure. I think it could be presented as one row with three sub-panels. This would suite the journal format better and avoid so much white space. Alternatively, you could add a fourth panel showing the mass balance contrast between debris covered and debris-free glaciers?

As per your suggestion, we have included a fourth panel here so that the x-axis of panels a and b remains aligned.

Discussion L165-169: I think this paragraph could be reworded to state the overarching results with more clarity. As I see it, the main points are that the results capture glacier mass loss rates over a period where observations are scarce. The results suggest that glacier mass loss rates have remained steady over at least the last 50 years in this part of the Hindu Kush, with this study results being very similar to those of the Brun/Shean/Hugonnet studies.

We have modified the lines to as follows:

In this study, we present our results on mass balance for the glaciers of Hindu Kush which contribute to extending the existing knowledge regarding the state of these glaciers to nearly two decades in the pre-2000 period. We employ state of the art sensors available during the study period and report the mass balance of glaciers which, to our knowledge, has not been documented before. Our estimated mass loss is slightly negative which is in agreement with Brun et al. (2017), Shean et al. (2020), and Hugonnet et al. (2021) within their respective uncertainties. Our results suggest that glaciers in Hindu Kush have maintained a nearly stable rate of mass loss for at least four decades which is in contrast with the accelerated mass loss generally observed in parts of High Mountain Asia such as the Nyainqentanglha and the Tien Shan (Bhattacharya, 2019). We further re-assessed the retreating glaciers in the region and estimate a higher retreat compared to previously documented (Sarikaya).

As the discussion is currently rather short, the authors could tie these main points to supporting information that might show a record of climatic variability over a similar period, which could indicate why mass balance has remained relatively stable?

Hindu Kush mainly receives its precipitation during winter due to the westerly system. We have analysed the temperature and precipitation patterns acquired from the meteorological station in Chitral, which show an increase in temperature at 0.33 °C per decade, whereas precipitation has remained variable over time without any significant long-term trend. Despite rising temperatures in Upper Chitral, the glaciers have maintained a moderate rate of mass loss. Generally, the lower part of debris-covered glaciers is relatively stable compared to clean ice, whereas the higher elevation parts of debris-covered and debris-free glaciers show almost similar behaviour. The effect of rising temperature on glacier melting is either moderated by precipitation or due to the debris cover of glaciers.

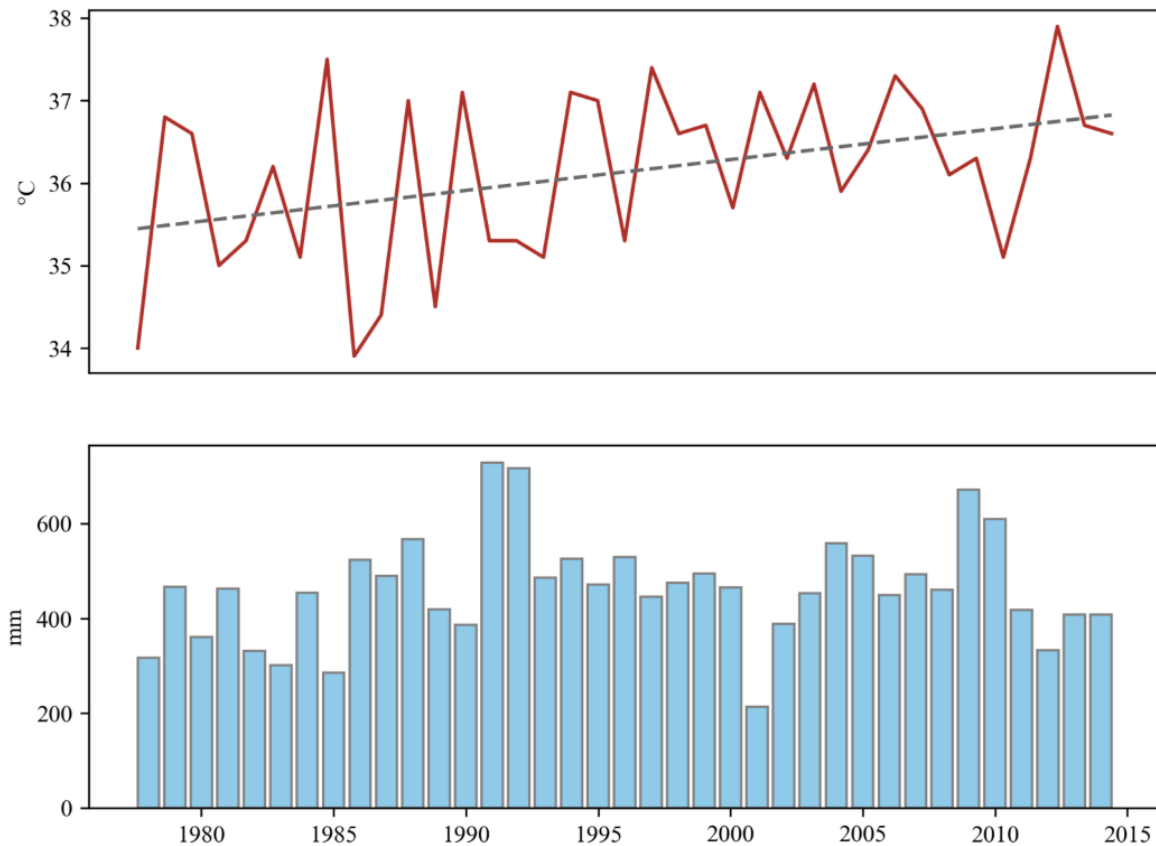


Figure: Temperature (top) and Precipitation (bottom) acquired from Pakistan Meteorological Station (PMD) ground station.

L171: It's not clear what 'overall moderate conditions' are to me.

We have rephrased to this : 'overall moderate mass balance conditions'

L171: This is the only information I can see on the size of glaciers examined in the study. Was 2 km² a minimum area threshold set at the beginning of the work or is it an arbitrary number which happens to be the size of the smallest glacier with suitable data coverage?

We have updated the data and methods section to include this detail

L177: Discrepancies in glacier outlines from different sources were mentioned at the beginning of the discussion and they are again highlighted here, but I don't think I've seen a clear comparison between area change rates calculated as part of this study against those from the literature. I think the paper could be strengthened by calculating area changes rates for this earlier study period and comparing them specifically against any more contemporary results that area available. This would support the statements

that are made about improving the record of glacier area change here which are currently not substantiated.

As we have already indicated in the data and methods section, the glaciers which have undergone retreat were modified for the pre and post retreat period. Our obtained outlines for the pre-retreat period are mostly similar with the sampled glaciers of Sarikaya et al, 2012, whereas our retreat rates are generally higher compared to Sarikaya et al., 2012. A major difference between the studies is that Sarikaya primarily used Landsat and ASTER optical datasets to identify glacier terminus positions whereas the current study involves the elevation change and orthoimages from 1979 and 2002.

Response to Reviewer 2

In this paper, Ramzan and Ghuffar report geodetic mass balance of glaciers located in the eastern Hindu Kush for the period 1979-2002. They find a moderate glacier mass change of -0.13 ± 0.12 m w.e. a⁻¹, which is similar to post 2000 mass changes documented in the literature.

Overall, the authors use state of the art methods to differentiate KH-9 Panoramic and SPOT-5 stereo imagery. It is very nice to see the use of KH-9 Panoramic imagery as described in Ghuffar et al. (2023). It is also great to see a SPOT-5 instead of SRTM reference for circa. 2000 dates. To my knowledge, the study area is on the edge of previous studies, but not covered for the pre 2000 period. Still the glacier area covered is relatively modest (< 1000 km²), and thus the results are not expected to have a major impact.

I recommend publication of the paper after minor corrections.

Main comments

A- I am surprised to see so few glaciers on figures 1 and 2. I quickly looked at the RGI and there are indeed many missing glaciers (see figure below)! It is not an issue not to calculate the mass balance for each and every glacier, but the criteria for glacier exclusion should be clearly stated, and glaciers without mass balance data should still be plotted on the maps. The authors need to better quantify the total area, the area with valid pixels and the sum of the glacier area with mass balance values. On figure 2, I would like to see the off-glacier elevation changes as well. The figure S3 is clearly not enough to see the quality of the elevation difference map because the color scale is not adapted, I recommend using the same as for figure 2.

The fewer number of glaciers was due to the area threshold of 2 sq. km which we have used in the first version. In the revised version, we have increased the number of glaciers by lowering the glacier area threshold to 0.5 sq. km. We have added details regarding the glacier sample for which the mass balance is computed, and have also updated Figure 1 to show all the glaciers in the region so the reader can have a better idea. We have further mentioned the glacier exclusion criteria in the data and methods section. In total we have calculated mass balance of 265 glaciers covering an area of approx. 1050 sq. km

We have also updated Figure S3 so it is now easier to interpret by adjusting the colorbar.

B- I am missing a short paragraph about the climate context of the region. The stability of the glacier mass balance from 1979 to 2020 should be discussed further.

We have added this in discussion: Hindu Kush mainly receives its precipitation during winter due to the westerly system. We have analysed the temperature and precipitation patterns acquired from the meteorological station in Chitral, which show an increase in temperature at 0.33 °C per decade, whereas precipitation has remained variable over time without any significant long-term trend. Despite rising temperatures in Upper Chitral, the glaciers have maintained a moderate rate of mass loss. Generally, the lower part of debris-covered glaciers is relatively stable compared to clean ice, whereas the higher elevation parts of debris-covered and debris-free glaciers show almost similar behaviour. The effect of rising temperature on glacier melting is either moderated by precipitation or due to the debris cover of glaciers. The graph of temperature and precipitation is available in supplement (Figure S5)

L11-12: more references are needed, and the description should be a bit more precise at the scale of the High Mountain of Asia. Additional references should include: King et al., 2019; Maurer et al., 2019; Zhou et al., 2017, 2018

We have changed the sentence to make it more relevant to High Mountain Asia and have also further added additional references as suggested. L16: However, in the High Mountain Asia (HMA), historical images reveal that glaciers have been losing mass since the 1960s (Bhattacharya et al., 2021; Zhao et al., 2020; King et al., 2019; Maurer et al., 2019; Zhou et al., 2017).

L12-13: this statement is too strong, see for instance Gascoin (2024)

We have changed this line to: Mountain glaciers are an important freshwater resource which contribute in agriculture, power generation, domestic use and drinking water for the downstream communities.

L29: Additional references should include: Zhou et al., 2017, 2018

We have added these references in the revised manuscript

L62: contradiction with the line above. Why not co-registering KH9 and SPOT5?

Both the KH-9 and SPOT-5 DEMs were co-registered to the SRTM DEM, rather than to each other, because the reference DEM should ideally provide continuous spatial coverage across the entire study area. The KH-9 and SPOT-5 DEMs contain data gaps caused by low image texture, shadows and occlusions. Co-registering these DEMs directly to each other could therefore, propagate local biases into areas lacking valid data in either DEM. Using SRTM as a common reference surface allows systematic errors in both DEMs to be corrected consistently over the entire region.

Equation 1: what is the link with Rolstad? (L84-85)

I think that the whole error propagation calculation is not very clear.

We do not assert here that Equation 1 is linked with Rolstad. We cite Rolstad et al in line L84 for its association with the equation in line 83 where Rolstad investigated the role of spatial correlation and its scale in calculating the uncertainty for geodetic glacier elevation changes. We have revised the uncertainty estimation description to make it more understandable. We also now use the area based elevation uncertainty as given in Eq:1 for regional mass balance but using the 50m hypsometric bins.

For instance, on L84-85, the mean off glacier elevation difference is used as a systematic error, but it should be zero by construction?

Practically, the mean off glacier elevation difference is not exactly zero which may arise due to imperfect coregistration and bias effects, therefore it is being incorporated here as systematic error.

I simply don't understand the link between the calculations L83 and equation 2

Line 83-84 refers to calculation of uncertainty in glacier elevation change for individual glaciers combining both random and systematic error. L91 shows the relation between volume uncertainty is related with uncertainty in elevation change, which is further used in equation 2.

Eq. 2: definition of f ??

Here ρ refers to density, we have indicated this in the text.

Fig. 2: colorbar not centered on zero + glacier names should be shown somewhere on figure 1 or 2

We have centered the colorbar to zero in our revised version. We already tried displaying the glacier names but the figures looked too crowded. Here, most glaciers have names but some are referred to by their RGI IDs. We will add an additional line with figure 1 which refers the reader to fig S1 in the revised manuscript.

L104-105: -0.23 m w.e. is not a large thinning...

Here we mentioned high because in this study area this was a relatively higher mass loss. We will modify this sentence. The -0.23 mwe was the mass balance of the glacier, and we will also add here the thinning experienced by the Kotgaz glacier which is 3.5 m a⁻¹ at its terminus site.

L101-105: give the dates of known surges

Here, we have highlighted that Noroghikun glacier, which has undergone the highest retreat, is a surging glacier. Noroghikun is currently classified as a possible surging glacier.

L111: give the area of the glacier

Here, Tirich and Atrak glaciers have a respective area of 85 sq. km and 90 sq. km.

L161-162: I don't understand this sentence

We mention here that the group of debris-covered and debris-free glaciers both show variability in mass balance among individual glaciers but the total mass balance of debris-covered and debris-free glaciers is nearly the same. We have further elaborated this line in the revised text.

L168-169: different periods so not meaningful

We understand that the studies being compared are of different time periods. Our intention here, was to compare/relate out pre-2000 results with the post-2000 studies.

L170-171: this needs to be better quantified!! Warning, errors are larger for small glaciers than for big ones -> this could explain the discrepancies

We appreciate the reviewer's comment. We understand that inclusion of small glaciers adds greater uncertainty. We have discussed the variability and discrepancies in the discussion section of the revised text.

L184: “high variability” compared to what??

We refer here to the variability of mass balance among individual glaciers.

L190-191: again there is no reason to agree because periods are different

We will clarify here, that our main point was to compare the pre-2000 and post-2000 periods.

Data availability: only DEMs and orthos available -> add the per glacier mass balance data?

We will also publish the data per glacier data.