

Reviewer 1:

Basal Sliding and Hydrological Drainage at Baltoro Glacier

Wendleder et al. have addressed most of my major concerns and those of the other reviewer. I appreciate their detailed and thorough responses, and I am satisfied by their explanation of why they have not followed two of my suggestions. The Results section in particular has been reorganized and I find it much easier to follow and to identify the key findings. I have just a few remaining minor and technical corrections to suggest.

Dear Reviewer,

thank you very much for the helpful corrections and also for the great glaciological discussion. We really appreciate it. All the corrections and comments have been included.

All the best,

Anna Wendleder with co-authors

Line 6: I'm sorry, I acknowledge that I asked for more precision about the use of "runoff index", but I wonder if maybe the abstract is not the best place to add this much detail, however I do think it's important to highlight this is specifically proglacial runoff. Maybe the sentence about glacier variables could read, "For the glacier variables, we used surface velocity, supraglacial lake extent, snow and ice melt extent, and proglacial runoff index derived from Earth Observation data", and then you do not need the following sentence defining the runoff index.

Thank you for the suggestion. We changed it accordingly.

Line 25: I'm sorry for being particular about the wording, but I think the wording that "sliding is initiated [...]" could be clarified further, since the authors responded to my original comment by agreeing that there is likely to be sliding in winter. Maybe it is more accurate to say that "sliding increases as the ice decouples from the bed"?

You are right. We corrected it.

Line 31: I appreciate citing Weertman (1957) for regelation, but this explanation is still not clear to me. It is possible that you mean to explain enhanced ice-roof closure rates around obstacles (e.g., Creyts & Schoof, 2009). In that case, please provide correct and precise citations, including the listed paper and some of the references within. Otherwise, for the canonical description of channel opening and closing mechanisms, see e.g. Section 6.3 of Cuffey & Paterson (2010).

Thanks for the detailed explanation. We meant the canonical description and therefore referred to Cuffey and Paterson.

Line 32: The transition from hydrology to dynamics is quite abrupt. Given the change in topics and that this is already a long paragraph, maybe this should be split into two paragraphs to separate hydrology and dynamics.

Done.

Line 47: Reading this line, about how supraglacial lake drainage into an efficient drainage system can reduce ice velocities, has made me think: you have attributed fall speed-ups to supraglacial lake drainage. Does this explanation for fall speed-ups fit with your conceptual model of subglacial drainage

development in Section 5.1? If not, could you explain this in Section 5.1 and provide some possible reasons why?

You are right. In our case, the supraglacial lake drainage does not lead to the transition from inefficient to efficient subglacial drainage, but only to a speed-up in fall. We changed the sentence in Line 47: "A few studies have observed that supraglacial lake drainage could lead to a transition from an inefficient to an efficient subglacial drainage system and hence lead to a slowdown of the glacier velocity (Vincent and Moreau, 2016; Stevens et al., 2022)". The possible reasons are discussed in section 5.2.

Figure 1: Please indicate in the caption what the white crosshairs represent. It would also be nice to add the flowline distance along with each place name. E.g., Urdukas / 3900 m / XX km.

The white crosshairs represent the coordinate grids which help to better estimate the distances. The distances along the centerline for the four locations were added in the figure.

Table 1: Could you explain more precisely the difference between "maximum" and "summarized" lake area in the text? My interpretation is that the "maximum" lake area refers to the maximum area that is instantaneously covered by supraglacial lakes, and that the "summarized" lake area refers to the total area that is ever covered by lakes, but the text was not completely clear on this.

To avoid misunderstandings, we are now using the terms "maximum area" and "total annual area" and added additionally the explanation: "The maximum area refers to the area at a specific point in time and the total summer area to the summarized area during summer."

Line 308-309: The sentence "In 2018, 2020, and 2022, air temperature..." there is a comma or adjoining word missing somewhere here.

For a better understanding, we changed the sentence to "In 2018, 2020, and 2022, air temperature and melt as well as air temperature and supraglacial lakes have a high R^2 (0.65-0.83), but the dependency is low (0-7 °C/km²)."

Section 5.1 and Line 359: The authors had nice and detailed responses to my earlier comments about these two sections. Could you add one to two sentences summarizing your responses to these sections? I think this would add value for the reader.

Done.

For section 5.1, maybe it would help to explicitly say that this is a hypothesis or a conceptual model. Maybe change the first sentence to something similar to, "Although each year is different, here we present a general conceptual model that explains the observed seasonal patterns".

Thank you for the hint. We changed the first sentence of this section.

Line 392: My apologies, I think my earlier comment was not clear. Sundal et al. (2011) show that, in a year with high surface melt rates, the peak surface velocity might be higher, but the development of efficient subglacial drainage leads to slower late-summer velocities (Figure 3). The net effect is that the overall annual ice displacement (in meters) is similar for years with low and high surface melt rates. Can you comment on whether or not you find something similar? Or does annual total displacement (or annual average velocity if you prefer to think of it that way) also increase strongly with surface melt for this glacier?

Thank you for the detailed explanation. We apologize that we misunderstood your question. The glacier surface velocity from 1992 to 2017 was analyzed in detail in Wendleder et al. (2018). The long time series shows that some years (2008-2010, 2015) are affected by higher averaged annual (Figure

2) and summer velocities (Figure 3), respectively. As this was a topic in the last publication, we will refrain from discussing it in more detail here.

Reference:

Wendleder, A., Friedl, P. and Mayer, C. (2018) Impacts of Climate and Supraglacial Lakes on the Surface Velocity of Baltoro Glacier from 1992 to 2017. *Remote Sensing*, 10 (1681), pp. 1-25. MDPI. DOI: 10.3390/rs10111681 ISSN 2072-4292.

Figure 5: I like this addition to further support the discussion about changes in the time lag between peak melt and the summer velocity peak. Could the authors add just a few sentences explaining more specifically what physical processes they think could explain this dramatic change in lag time? I am concerned that the conclusions in line 404-409 are too strong. There are only six years of data, and for processes with such a large variability, the trends are not robust. It is an interesting finding that you are correct to highlight, but I think the conclusions need to be more careful. Perhaps this could be highlighted as an interesting feature that emerged from your dense, multi-method and multi-sensor observational record that warrants further investigation. As a technical note, the dotted lines (especially the yellow line for Urdukas) are thin and hard to see.

You are fully right; the time series only covers six years and therefore no robust or significant linear trend can be derived given the high variability. However, on purpose we never use the word “trend” in the text. In the lines of the conclusion you mention (L. 406-410) we refer to this tendency as “indication” that requires a “careful interpretation”. To further clarify, we added the following sentence (Line 327): “As the calculation bases only on six years, this observation requires a careful interpretation and needs further investigation.” Additionally, we added an explanation for possible physical processes (Line 326): “Thus the amount of meltwater causing glacier velocity variations is reached in a shorter which will be more supported by warmer climates in the future.” The lines in Figure 5 were changed and are now better recognizable. Furthermore, we have amended the figure 5 caption by emphasizing the “linear trend - to indicate the tendency only - is displayed in dotted lines.

References

Creyts, T. T., and C. G. Schoof (2009), Drainage through subglacial water sheets, *J. Geophys. Res.*, 114, F04008, doi:10.1029/2008JF001215

Reviewer 2:

Basal Sliding and Hydrological Drainage at Baltoro Glacier

This paper provides an interesting and useful overview of the factors controlling velocities at Baltoro Glacier. Overall, the manuscript is much improved from the original version, and I appreciate the substantial work that the authors have made in updating it and constructively responding to the original reviewers comments. My remaining comments are all generally minor, and many reflect small technical corrections. A common issue is that 'snowmelt' is often still used in the paper, when I think that 'snow and ice melt' or 'melt' is the more accurate term to use – this is highlighted several times in my comments below.

Dear Reviewer,

thank you very much for the helpful corrections and also for finding the spelling errors. We really appreciate it. All the corrections and comments have been included.

All the best,

Anna Wendleder with co-authors

Title: the title is improved by including Pakistan in it, but it doesn't properly reflect the focus of the paper as basal sliding isn't being directly measured or quantified. Instead a title such as 'Velocity variations and hydrological drainage at Baltoro Glacier, Pakistan' would better reflect the actual content.

Thank you for your suggestion. The title was modified accordingly.

L10: here and elsewhere in the abstract you refer to 'snowmelt', but I assume that you really mean 'snow and ice melt', since there is little snow left in the summer?

Corrected in Line 10 and 12.

L18: when you refer to 'the future', do you mean in 'a future warming climate'? If so, then specify this.

Corrected.

L20: delete 'the' from 'over the glacier dynamics'

Deleted.

L22: here you refer to 'melt water', but in the next line you use 'meltwater' (no space between words). These should be consistent throughout the paper.

Thank you for the hint! We changed it to 'meltwater' and have ensured consistent spelling.

L29: change 'a efficient' to 'an efficient'

Corrected.

L32: This first para is long, so I suggest adding a para break before 'Glacier movement'

We separated it into two paragraphs.

L46: change 'inefficient drainage system' to 'inefficient subglacial drainage system' (assuming that's what you're referring to here?)

Yes, we are referring here to the subglacial drainage system. We changed it accordingly.

L58: add 'of' before 'whether'

Added.

Fig. 1 caption: add ', respectively' after 'yellow, blue, and orange'

Added.

L103: would be useful if you can include the resolution of the DEM here in m, instead of just stating 1 arc second, since the resolution of your other datasets is given in m

You are right. We have specified now the spatial resolution in meters (30 m).

L106-107: add reference to Fig. 1 here since it shows the location of these points

Thank you for the suggestion. We added the reference: "For the analysis, we extracted the surface velocity values along the glacier centerline at four different locations (Figure 1), namely at Urdukas (11 km), at the confluence with Yermanendu Glacier (16 km), Gore (23 km), and Concordia (33 km distance from terminus). The four different points were selected to best reflect the spatial variation along the glacier."

L130: change 'by 2021 and 2022' to 'to 2021 and 2022'

Changed.

L131: change to 'their aggregated area' (assuming that's what you're referring to here?)

Yes, we are referring to their aggregated area. We changed it.

L133: it would be useful to add a sentence at the start of this para to make it clear that you're referring to the proglacial stream after it exits the glacier terminus

Thank you for the suggestion. We have included the term twice to make this clearer.

L146-147: I'm unclear as to what 'assigned geographically' refers to here, and it's unclear which delta or confluence you're referring to

Apologies for the imprecise explanation. We changed the sentence to "The class "runoff" was assigned by a fixed, manually selected point on the western border of the mapping area that was always covered with water."

L173: specify that 12 pm refers to local time (e.g., rather than UTC)

We specified the time in adding the wording 'local time'.

Fig. 2a: change legend and secondary y-axis label from 'Snowmelt' to 'Snow and ice melt' (assuming that's what you mean here?).

Fig. 2: I find it difficult to distinguish between the lines plotted for Snowmelt (E), (C) and (W) in the second part of each plot since they're similar shades of grey. Can you use different colours for these lines instead?

We changed 'Snowmelt' just to 'Melt' to be consistent with Figure 4 and that the label still fits along the plot. To better distinguish the lines of the melt, we have changed the colors.

L271-272: I assume that you're referring to the transition in subglacial drainage here? If so, then specify this.

Yes, you are right. We changed it to “transition from inefficient to efficient subglacial drainage”.

L275: change ‘begin’ to ‘beginning’

Changed.

L285: I assume that you mean both snow and ice melt here, rather than just snowmelt?

Yes, we changed it to “snow and ice melt”.

L290: I don’t understand the units of m². Do you mean km²?

Thanks for spotting this error! Of course, it is km²!

L293-306: for the values provided in this para specify what they refer to: e.g., write ‘(r=0.58-0.89)’, rather than just ‘(0.58-0.89)’. This is because I’m a bit unclear what some of the numbers refer to. For example, on L295 you state ‘high relationship (>0.6)’, but is this referring to r or significance value? If it’s referring to r the statement is incorrect since you say that r values ranged as low as 0.58 earlier in the sentence.

We would like to apologize for the misunderstanding. We have corrected the mistake and changed the sentence as follows: “In the two periods, the correlation of the variables temperature and melt (0.7-0.95) as well as temperature and supraglacial lake (0.58-0.89) showed a similar pattern with a correlation above 0.58 though with negligible minor changes in the Pearson correlation during both periods (0.1-0.2);”

L303-304: Pearson correlation values can vary between 0 and 1, but on these lines you say that they decreased by a value of more than 1 (e.g., <1.5). I think that you mean to say that they varied from a positive to a negative correlation (or vice versa), so this should be made clear

You are right, the sentence is misleading. We corrected it to: “Particularly noticeable was the variation between positive and negative correlation within the observation period for Urdukas in both parameters.”

Fig. 3: in the legends, provide units for the velocity (presumably m d⁻¹). I assume that the labels should also be ‘snow and ice melt’, rather than snowmelt?

Thank you for spotting this! We added the unit of the glacier velocity (m/d) and changed ‘snowmelt’ to ‘melt’.

L346: change ‘snowmelt’ to ‘melt’

Corrected.

L370: this calculation ignores any contribution from melt of glacier ice, but in summer I expect that this is the dominant source of water on Baltoro Glacier, rather than snow melt. This would be even more true if the glacier is experiencing a negative surface mass balance. I think that these factors should at least be mentioned, and their importance briefly evaluated.

It is true that in summer the ice melt is greater than the snow melt. The crucial point is that the snowmelt starts first and thus plays the most important role in changing the dynamics. The ice melt only begins when large areas of the glacier are free of snow. At this point, however, the change in glacier velocity is already ongoing. The melt could be quantified with a degree day model. Therefore, we need the snow depth or the snow water equivalent which are not available for the region or for this study area.

L370: change 'millions' to 'million'

Corrected.

L379: I'm unclear what 'increase in lake rise' refers to. E.g., do you mean the depth of supraglacial lakes? Or perhaps the highest elevation at which they're found? Clarification is needed.

We are very sorry for the confusion. We meant the increase of the lake area. The sentence was corrected.

L387: presumably you mean 'snow and ice melt', rather than 'snowmelt'? Also elsewhere, such as L404, L406.

Corrected.

L403: make it clear here and elsewhere that you're referring to efficiency of the subglacial drainage system (i.e., as opposed to the supraglacial system)

Thank you for the suggestion. We changed it to 'subglacial drainage' throughout the manuscript.

L409: it's problematic to state that there's a higher risk of flood hazards with a faster transition to efficient subglacial drainage when you present no data to back this up. For example, it could be argued that flood hazards are actually higher when subglacial drainage is inefficient, as in this case ice-marginal lakes could build up in size if they're unable to drain all the water flowing into them – and then release catastrophically when they become overfilled. So I suggest deleting or modifying this final sentence.

We deleted the last sentence.

Tables A1 and A2: indicate in the table caption that these are r values (i.e., as opposed to r²). In the tables, I assume that you mean 'snow and ice melt' or 'melt', rather than 'snowmelt' (to match wording in Tables 2 and 3).

Thank you for spotting this. We changed both.