Review of Wendleder et al.: Basal Sliding and Hydrological Drainage at Baltoro Glacier

Wendleder et al. investigate the climate-hydrology interactions of the debris-covered Baltoro Glacier using a broad suite of remote sensing data products to further understand the debris-covered glacier cycle generally and gain insight into this glacier system more specifically. The authors combine meteorological (air temperature, precipitation) and glaciological (surface velocity, supraglacial lake area, snowmelt area, and proglacial runoff) data for six complete hydrological years (2016-2022). This wide variety of data is used to interpret hydrological changes responsible for the observed surface velocity patterns. Snowmelt and supraglacial lake drainage are found to be the most influential factors for explaining surface velocity patterns. The patterns themselves significantly vary year-to-year, with the warmest year (2022) displaying behaviour that is distinct from the other cooler years.

The authors have done a good job at integrating an impressive breadth of high temporal resolution (and some spatially resolved) data to answer their primary questions and have clearly presented the data in a few very useful figures. My main comment is that, while the data used in the study have been appropriately summarized and presented, the results and discussion do not synthesize and summarize the data to the same level. I feel that the manuscript will be a valuable contribution to the debris-covered glacier literature, as well as the broader literature investigating melt-hydrology-dynamics feedbacks more generally, after some work to more effectively summarize the results and extract interpretable patterns.

I have listed these and other general comments below along with a number of specific comments. The authors should interpret the number of specific comments as an indicator of my interest in the work. I hope that the authors find most of the comments are reasonable, and I understand that not all the open-ended comments may be addressed.

General Comments

1. Clarity and conciseness in Results. I feel that with some work the Results can be brought up to the standard set by the comprehensive data set developed in the methods section. In the current form, there is a large quantity of information presented with little structure to help with understanding. My general comment would be to develop a concise list of the few most important points from each type of analysis and to focus the results and discussion on these.

   I would also encourage the authors to further divide each large section (e.g., 4.1 Temporal Relationship) into sub-sub-sections, with one sub-sub-section for each data product/relationship. I think this would help readers find relevant information they are looking for. Each of these sections could further be structured to begin with the most broad patterns, and progressively focus down towards the most specific.

2. I think the scope of the work could be expanded by including a stronger link to the impact of debris cover on the inferred hydrology and velocity patterns, and how this may be transferable to other debris-covered systems. This goal is hinted at in the introduction by pointing out some differences between debris-free and debris-covered glacier behaviour, and it would be nice to see this continued through the manuscript.

3. I have some questions about the conclusion that the time lag between snowmelt and velocity is decreasing, and whether this is fully supported by the data and results. I'm not clear on what results in particular support this statement. I would have thought this time lag would be quite sensitive to the particular pattern of surface melt each year, and so it would be difficult to conclude there is a persistent, large-scale climate-driven cause given the six years of data presented here. If you can support this statement with your results, it would be important to discuss some mechanisms that could explain such a trend in the Discussion, and how interannual snowmelt variability might make this challenging.

Specific Comments

May be nice to highlight in the abstract which of the identified behaviours are different due to debris cover. Perhaps the lakes?

Line 140-157: Do the authors have any assessment of the snowmelt mapping method, from this or other studies? It could be helpful to comment on the performance of the method over a variety of surface types, since the snowmelt data form a core part of the results and conclusions of this paper.

Line 165: You explain that you use a weather station located at Urdukas to derive a monthly mean lapse rate. Could you elaborate on the instrumentation and methods used for this? Do you have multiple temperature sensors at different elevations to derive the lapse rate, or are you comparing the point AWS measurement to the reanalysis data? Finally, can you comment on the quality of the HAR precipitation and temperature data compared based on the AWS data?

Figure 2 and related text: I generally find this figure an excellent visualization for the large quantity of data that it presents. I have two questions about the relationship between lake surface area and velocity.

- Do the lakes mostly drain into the subglacial drainage system through moulins and crevasses, so that we should interpret changes in lake area directly as a proxy for inputs into the subglacial system, or does much of the meltwater drain laterally without accessing the bed?
- There is clearly a temporal relationship between decreasing lake area and the timing of the fall velocity peak (especially in 2017, 2018, and 2021). In 2022, it looks like lake area is consistently decreasing from 1 June until 30 September, while velocity has complex patterns. For example at Gore, velocity increases until about July, decreases until about

September, then increases until the end of September. What factors might be influencing this complex behaviour, especially considering the consistent high temperatures you show in 2022? And how do you think this impacts your linear statistics?

Figure 3: This has the potential to be a great figure. I find it difficult to see the difference in the shade of blue between (a) and (b) to interpret the difference in glacier velocity. It is also difficult to see the supraglacial lake boundaries, at first the lake outlines look like noise in the velocity field since they are plotted in the same colour. Maybe it would be easier to interpret if the velocity field and lakes were shown in different colours.

- I am also curious why it looks like the snowmelt begins in the mid-glacier, in the Concordia zone. Has all the snow melted below this point already by 13 April, but then why would we see snowmelt on the glacier tongue starting between 7 May and 18 July?
- What is the detectability of wet snow over debris, where perhaps the snowpack can drain better through the debris layer, compared to bare ice where the snowpack may become saturated or swampy?

Figure 4: This is another great figure to display a lot of information. I think it might be nice to include a broader discussion of the patterns that you can see here (i.e., the difference in the shape between (a) and (b)) in the results section corresponding to this figure. For example, I see that there are generally lower velocity–snowmelt and velocity–runoff R^2 values in the second time period, but I found the results instead focussed on many specific years as examples. Even more broadly, most correlations are "shrunken" in (b), i.e. closer to the R^2=0 contour, showing that internal dynamics are more important later in the melt season.

Despite the title including "...and hydrological drainage", the hydrology piece is mostly not introduced until the Discussion. Perhaps there could be some more that you can introduce in the results to emphasize this piece of the study.

I think the content that is in the Discussion is mostly good, however I feel readers may be curious about some other features that you could add:

- What are some drivers of variability in the relationships that you observe? For example, there are quite large year-to-year changes in the R^2 values between velocity and runoff in Fig. 4(b), and statistically significant trends that switch sign year-to-year in Table 2. Is this just a response to the specific temperature, precipitation, etc. patterns, or is there more going on?
- Revisit the trends from the results and highlight what is (un)expected, novel, and specific to debris-covered glaciers. How do the patterns seen here depend on the debris cover?

Section 5.1 goes through an overview of the inferred hydrology of Baltoro Glacier. The presented distributed/channelized switch conceptual model is well understood, but I wonder if in this case there might be more going on. For example, might changes in bed connectivity (e.g., Andrews et al., 2014; Hoffman et al., 2016) or a more nuanced understanding of basal hydrology and sliding (e.g., Gilbert et al., 2022) also explain some of the inferred patterns? What is the basal environment (hard bed, soft bed?), and might storage/drainage through till be important here? A similar comment could be made about the description near line 30.

I think it would help to add one or two sentences about how you infer sliding from surface velocities (perhaps in Section 5.1, to support some of the conclusions). I imagine you are assuming the deformational component does not change significantly through the year, and so the only remaining mechanism to explain the seasonal velocity variations is a change in basal velocity. Making this explicit would support the later conclusions nicely.

What controls the timing of lake drainage? Do lakes reach a threshold size and then drain, or is it more complex? See also line 327 comment.

Line 324: I am curious if it's possible to use the difference between snowmelt and the runoff index to try to quantify, or at least observe, a release of stored water when the drainage system connects and channels can evacuate the system. This is hinted at here, but it would be interesting to look into this in a little more detail.

Line 327: The idea that high summer velocities enable crevasse development and lake drainage has some nuance and subtlety (e.g., Poinar & Andrews, 2021). Have you looked at this hypothesis by estimating strain rates (as best as possible with the limited resolution from remote sensing data) to see if this is at least reasonable? Further, wouldn't this mechanism predict lakes to drain mostly during acceleration, whereas Figure 2 shows lake area sometimes decreasing while velocities also decrease? I do think this is a reasonable mechanism to propose, but some more care should be taken here.

Line 368: It would be interesting to see the difference between peak surface velocities and net surface displacement over the melt season and over the calendar year (especially as the authors have elsewhere cited Sundal et al., 2011). This would be a nice addition to the discussion, then could be referenced here.

Technical corrections

Line 28: Does Baltoro Glacier have basal motion in winter? I would tend to think of basal motion as a continuum, and not that basal sliding initiates from zero over winter, but rather that basal motion accelerates as effective pressure decreases. For example, this helps to explain why there are winter variations in velocity, otherwise the deformational component would have to be changing rapidly.

Line 30: I do acknowledge that there are different ways to explain subglacial drainage evolution. However, to some readers (especially modellers), "inefficient channels" is an unusual phrase. If the authors agree, consider changing to describe these channels as small, incipient, etc.

Line 33-35: "In the absence of meltwater the *ice- overburden* pressure is larger and ...". Would this be more clear to say that the *effective pressure* is larger (because water pressure decreases, not because ice overburden changes)?

Line 35: Is there evidence that regelation contributes to channel closure?

Line 35-39: I prefer to think that glaciers respond to the balance between driving and resistive stresses. Driving stress should vary slowly, since this is controlled by geometry. The resistive stress (especially basal traction in response to effective-pressure variations) instead can vary over short timescales.

Line 37: I wonder if maybe the 50% contribution of sliding to total glacier surface velocity has been taken out of context. For Greenland outlet glaciers, or surge type glaciers, basal motion can contribute well over 50% to velocity.

Line 48: Would it also be conceptually possible for supraglacial lake discharge to contribute to enhanced subglacial channel development, eventually reducing ice surface velocities?

Line 49: This is a long (but nicely detailed) paragraph. It might be easier for the reader to split into two paragraphs, separating background theory from details specific to Baltoro Glacier.

Line 74: What proportion of the debris covered area is enhancing vs. inhibiting surface melt?

Figure 1: Adding elevation labels, at least for the boundary between regions, and perhaps distance markers (as long as the figure does not become too busy) would help readers who are not familiar with this glacier.

Section 3.2: I understand that this method is detailed in a previous paper, and the description here is in appropriate detail. Can you very briefly comment on the sensitivity/performance of the different sensors used here?

Section 3.3: The term ‘runoff-index’ used on line 123 is a great way to acknowledge the simplified metric used here (as compared to runoff in units $m^3 s^{-1}$). I was confused about the type of runoff being measured until this section. Could identify that you are measuring *proglacial* runoff (i.e., as opposed to runoff through supraglacial streams) and briefly acknowledge the area index the first time you say ‘runoff’ (including abstract)?

Section 3.5: Since I am not familiar with the HAR data specifically, I found the hierarchy between the different levels of meteorological data confusing here.

Line 179: What proportion of lakes did not drain or fill during the observation period?

Line 185: Is the end of the ablation season defined as 30 September based on the water year starting on 1 October, or was 30 September determined to be the usual end of summer melt?

Section 3.8: Do you see lakes drain fully within the 2–4 day observation frequency? If so, does the interpolation artificially smooth this lake area signal, i.e. turn a discrete drainage event that happened at some time in the 2-4 day window into smooth linear decrease at daily resolution?

Table 1: I appreciate the level of detail in this table. What is the difference between "aggregate" and "cumulative" lake area? And are these areas presented just for active lakes?

Line 211: What factors do you think cause the hardly discernible time delay from lower to upper sectors here?

Figure 2 is an excellent comparison of so many fields of data. Is there a way to also label each year with its total positive degree days without making the figure too busy?

L321: Should this be "Schoof, 2010"?

L328: "The drained lake which is only disposable after the slowdown" is unclear.

References

Andrews, L. C., Catania, G. A., Hoffman, M. J., Gulley, J. D., Lüthi, M. P., Ryser, C., ... & Neumann, T. A. (2014). Direct observations of evolving subglacial drainage beneath the Greenland Ice Sheet. *Nature*, *514*(7520), 80-83.

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