Will landscape responses reduce glacier sensitivity to climate change in High Mountain Asia?

We thank the reviewer 2 for their detailed comments and suggestions on our paper. These have been extremely useful in helping us rewrite the text and have made the paper much clearer. Our replies are in red below.

Response to Reviewer 2

Summary

The authors present a perspective on an alternative pathway (called the 'Paraglacial Transition' view) of how Himalayan glacier systems may respond to climate change in the future, different to the common view that future climate warming will result in sustained glacier retreat and ice loss ('Major ice loss' view). They describe how rising rock and moraine instabilities release inscreasing amounts of debris material on glacier surfaces, with impacts on their melt, dynamics, and morphologies. A preliminary analysis of past long-term glacier retreat rates shows distinct differences across HMA. The authors suggest a potential transition into stagnant debris covered glacier tongues and eventually into rock glaciers for some glaciers, causing a prolonged life cycle for glacier ice.

General comments

The manuscript is well written and structured, and the balance of theoretical background, motivation and new insights based on a preliminary analysis is tempting and adequate. The study gives a fresh view on alternative ways how glaciers in the Himalays can develop in the future, complementary to the conventional view based on global and regional-scale simulations of sustained ice loss in the Himalayas expected by the end of the century. I like the authors' view on future glacier response as mirroring that of the past. In my opinion the manuscript fits well into the scope of The Cryosphere and as a perspective paper. However, I suggest addressig two major points and clarify few minor points specified below, to make the study more robust.

We thank the reviewer for these supportive words.

Main points

- Debris thickness

I miss a discussion of the fact that the major part of debris supply for debris-covered tongues comes from headwalls and is transported englacially, i.e. its rate is controled by headwall erosion rates, but also the glacier's ice dynamics and surface ablation. Therefore, I don't see clearly how e.g. typically downwasted (concave) near-stagnant debris-covered tongues can become drastically more debris-covered and eventually transition into a rock glacier in the near or far future. Unless the authors are talking in general about very small

tongues of debris-covered glaciers without lateral moraines, which might be directly connected gravitationally to nearby rock walls. But in general, I think lateral debris supply from headwall erosion, rock falls and moraines can not efficiently increase the debris thickness of debris-coverered tongues of 'normal' valley glaciers. I suggest addressing this point more clearly in the manuscript, since the increase in debris supply and increase in supraglacial debris covered area and debris thickness are a major part of the proposed Paraglacial Transition pathway and also play a crucial role for point 2 above (glacier-rock glacier continuum).

This is an important debate. Our view is that as glaciers retreat to form ice remnants in high cirque basins as the climate warms, a couple things happen. The glacier slows down dynamically; it thins, shrinks in area, slows its movement, and slows its erosion of the bed. In addition, the area of cirque headwalls adjacent to the glacier increases (at least increases relative to the perimeter length and area of the glacier) and this increases the area of the backwall that is capable of failure, driving the accumulation of debris to the glacier surface.

As a result, debris delivery increases to the remnant glacier by mass wasting (rock topples and small landslides), and new rock glaciers (periglacial) will develop. So, basal erosion decreases, periglacial and paraglacial rock delivery increases. The upper part of the cirque glacier generally will not have lateral moraines, because it is in the accumulation zone, and it may well be convex, and debris can reach it. But snow and ice avalanches onto the glacier can add rock debris (as well as ice/snow) to the glacier.

We argue that with sustained glacier retreat, the paraglacial and periglacial component of rock debris to the waning glacier system will increase in relative terms; and as glaciers waste, they erode less, and with mass wasting from rock walls increasing, there should be an increasing paraglacial/periglacial component to the glacier sediment production and transport and to the internal constitution of the glacier. So in terms of debris and ice accumulation, we argue that there is a transition from a clear glacial system to what looks increasingly like a paraglacial and periglacial system.

- Transition into rock glaciers

Many studies have disussed the presence or absence of a transition of glaciers into rock glaciers and divided the community in either the continuum- or the permafrost creep school (e.g. Berthling, 2011), a difference that comes mainly from focusing on either the genesis or morphogoly of rock glaciers. To my understanding a transition of a glacier into a rock glacier is a rather rare case, and I can not see the continuum of a typical downwasted, concave Himalayan debris-cover tongue into a rock glacier to be a common transition. Also, the presence of underlying permafrost, a requirement for the presence of rock glaciers, might also not be valid in many landscapes where currently debris-covered glacier tongues are present. Since debris-covered glaciers are rather downwasting than retreating as stated by the authors, I see the possibility of a glacier-rock glacier transition as rather small in most

places in the Himalayas, unless maybe in cases where the debris-coverd tongue ends up in a small cirque located at high altitude in permafrost conditions. The authors state the uncertainty associated to this transition (e.g. 417-418) and very long time scales needed for this to happen (e.g. l. 311), but the very low probability of this transition should be stated more clearly in the text and should therefore not be menitioned in the abstract, as it might concern only a very small subsample of Himalayan glaciers, in my opinion. Instead of explicitly mentioning rock glaciers in this manuscript I strongly suggest stating e.g. 'ice-debris landforms' instead, when talking about stagnating dead ice bodies buried under a large amount of debris, what the PT view is essentially suggesting.

Thank you for this discussion. We argue that the glacier-rock-glacier transition has now been studied quite widely (see references below) and we think that a similar large-scale transition is likely in many parts of HMA. We have added these to the text

Johnson, P.G., 1980. Glacier-rock glacier transition in the southwest Yukon Territory, Canada. *Arctic and Alpine Research*, *12*(2), pp.195-204.

Anderson, R.S., Anderson, L.S., Armstrong, W.H., Rossi, M.W. and Crump, S.E., 2018. Glaciation of alpine valleys: The glacier–debris-covered glacier–rock glacier continuum. *Geomorphology*, *311*, pp.127-142.

Monnier, S. and Kinnard, C., 2017. Pluri-decadal (1955–2014) evolution of glacier–rock glacier transitional landforms in the central Andes of Chile (30–33 S). *Earth Surface Dynamics*, *5*(3), pp.493-509.

Knight, J., Harrison, S. and Jones, D.B., 2019. Rock glaciers and the geomorphological evolution of deglacierizing mountains. *Geomorphology*, *324*, pp.14-24.

Monnier, S. and Kinnard, C., 2015. Reconsidering the glacier to rock glacier transformation problem: New insights from the central Andes of Chile. *Geomorphology*, *238*, pp.47-55.

We agree with your suggestion re 'ice-debris landforms' and have explicitly referred to this in the discussion sections (lines 407, 419, 465).

We have added reference to Jarman, D., Wilson, P. and Harrison, S., 2013. Are there any relict rock glaciers in the British mountains?. *Journal of Quaternary Science*, *28*(2), pp.131-143, which specifically discusses ice-debris landforms.

Minor points

-Thoughout the manuscript I was not sure if the authors talk about the Himalayas as a specific region of HMA or about HMA in general, targeting the entire arc. Please specify more clearly in the text. We have done this by making it clear we are talking about HMA.

-l. 135: “high glacier volume loss” - this contradicts partly your previous sentence (l. 132-134), in which relatively small ice volume losses were stated. We have addressed this.

-l. 140-141: This sentence is thematically disconnected to the previous one and I suggest to add some more content here to clarify.We have done this by deleting ‘For instance’.

Fig. 1: It would be helpful for understanding and discussion to have also ice mass loss as an additional line in subfigures b, d and e, if possible. We have added this.

-l. 178: “unlike the approach taken by climate models” – what do you mean here? Please clearify. We agree that this phrase is ambiguous and have deleted it.

-l. 218-219: “and the slow melting of clean ice and debris-covered glaciers” – what do you mean here? This is somehow disconnected to the rest of the sentence. We have clarified this statement.

-l. 230-236: Although you mention later that a combination of both responses (MIL and PT) might exist (l. 415-417), I suggest stating the likely coexistence of both views more prominently and step back partly form the impression that either one or the other is the only view (e.g. in the abstract, discussion, conclusion). Agree

-l. 261: “ice glaciers” – do you mean “clean ice glaciers”? Done

-l; 269-270: supraglacial ice cliffs should be mentioned in line with supraglacial ponds here as melt hot spots, and appropriate literature cited. We have done this and cited Sakai, A., Nakawo, M. and Fujita, K., 1998. Melt rate of ice cliffs on the Lirung Glacier, Nepal Himalayas, 1996. *Bull. Glacier Res*, *16*(57-66) as an example.

-l. 367: compiled Done.

-l. 382, 389: please clearify the meaning of “MIS 2” and “MIS 3”, as the explanation in brackets (l. 383) is not clear to me. Done.

-l. 419: “above” – do you mean “below” instead? Yes! Done.

-l. 471: “increase snowfall” – is this predicted? Yes, at high elevations. Given our understanding of increased atmospheric water vapour and climate warming.

-l. 493-494: Point 4 is unclear to me, please clearify. Agree. We have reworded this.

References:

Berthling, I. (2011). Beyond confusion: Rock glaciers as cryo-conditioned landforms. Geomorphology, 131(3-4), 98-106. We have added this reference.