Harry Zekollari,

Thank you for all the good publication suggestions, thoughtful questions, and thorough review of the text. Incorporating the suggested changes has made the paper much stronger.

- Nicole Schaffer and Shelley MacDonell

Editor

General comments

First, I would like to apologize for the delay in finalizing the editing of this manuscript. I would like to thank both authors for having addressed the comments by the reviewers and for having updated the manuscript accordingly. The brief communication is now in a good shape to almost be accepted for publication. I have formulated a series of, mostly minor, comments that I invite the authors to address before we can advance to a full acceptance of this manuscript.

Specific comments

- l.8: “However, these laws are limited…” i.e. suggest adding ‘laws’ to clarify.

RESPONSE: We have modified the text as requested.

- l.9: “…monitor water resources…”, i.e. suggest removing ‘these’.

RESPONSE: We have modified the text as requested.

- last sentence of abstract: found this to be a bit surprising as a kind of statement and a bit disconnected with respect to the rest of the abstract. Maybe connect with: “Finally, we also review both national…”?

RESPONSE: We have modified the text as requested.

- l. 19: “specifically designed for glaciated regions”, i.e. suggest adding ‘designed’.

RESPONSE: We have modified the text as requested.

- l. 27: Andean glaciers and their importance as national heritage. Suggest also adding a reference to Bosson et al. (2019) here, which also includes glaciers over your study area

RESPONSE: The reference has been added.

- l.34-35: “Here, we define the hydrological role of the glacier as including contributions…”: suggest making this more specific.

RESPONSE: We have removed this sentence in response to the comment for l.36.

- l.36: "glaciers that are more sensitive to changes in climate (e.g. debris-free glaciers)": this is a central statement in your story. But is this really the case? Are debris-free glaciers changing more than debris-covered glaciers? Suggest adding references to back this up. For instance, the recent changes for all glaciers in South America are known: is it clear that debris covered glaciers change less than debris free ones? For this, refer to two important studies by Braun et al. (2019) and Dussaillant et al. (2019), which are complete and allow you to quantify this statement. Or rely on the recent global product by Hugonnet et al. (2021).

RESPONSE: Thank you for your questions regarding debris-free versus debris-covered glaciers. We have reviewed the literature on this topic and find that elevation change data does support the theory of debris-free glaciers changing more than debris-covered glaciers for the La Laguna catchment (Robson et al. 2022) and this agrees with a global study by Rounce et al. (2019) who conclude that the net effect of accounting for debris in all regions is a reduction in sub-debris glacier melt, by 37% on average. However, this does not hold true everywhere in the semiarid Andes nor in the world. For example, Ayala et al. (2016) report similar mass losses for Pirámide glacier (classified as intermediate) and two nearby debris-free glaciers, mainly because Pirámide is at a lower elevation. Similar mass losses have also been observed in the Himalaya (Gardelle et al. 2013; Kääb et al., 2012). We suggest a conservative approach when assigning a level of sensitivity for protection to intermediate glaciers (previously called semi-sensitive glaciers in the text) by initially assuming they will have the same mass balance rate as sensitive glaciers, with the option to downgrade this if there is data available to justify the change. For a more complete discussion please see the modifications made to the text starting at line 149.

We have added a table with some examples of intermediate glaciers that were compared to sensitive and/or insulated glaciers using elevation change data and assigned a (revised) category for protection using the method described after line 142 (third paragraph; see Table 2). For these examples we use the data sets from Ayala et al., (2016), Robson et al. (2022) and Braun et al. (2019). The study area is also covered by Hugonnet et al. (2021) and Dussaillant et al. (2019), but these data sets are only available for download as tiles with a resolution of 1 degree, which is too coarse for this comparison.

Through this literature review we have understood that glacier type does not necessarily correspond to the hydrological role (e.g. sensitive and intermediate glaciers may have the same mass balance rate). We have therefore removed the association between sensitivity and the hydrological role in the paper. The sentence on line 35 and the rest of this paragraph has been modified to reflect that and better define sensitivity. We have also made changes throughout the text.

- l. 40: "…reflects their sensitivity, which is closely related to their hydrological role": again, need statement to back this up. Also refer to previous comment for this.

We have modified this sentence to only refer to the sensitivity (please see our comment for l.36)

- l.44 and throughout the manuscript (e.g. l.260, l.288, l.292,…): “black carbon” is mentioned many times. But does this really play a big role for glaciers here? Is this from local sources/roads? And how can this influence the mass balance of debris-covered and rock glaciers? Would suggest mentioning this less explicitly/often, as expect it is of (very) minor importance for glacier mass balance. Or would need references to back this up.

RESPONSE: We agree that black carbon is over-emphasized in the text. The impact on mass balance in the study region is largely unknown as there are no peer-reviewed published papers on this specific topic in the area. We have added a recently published paper that came out on tracing particulate matter sources for Tapado Glacier and removed most instances of black carbon mentioned in the text. Black carbon is only mentioned once in the introduction and in the discussion.

According to Rowe et al. (2019) the main source of black carbon north of Santiago is emissions for diesel engines that power the mining industry and major astronomical observatories. Near Santiago, sources include transportation (e.g. diesel), industrial pollution, and residential heating. The regional average vertically-integrated loading of black carbon is much lower in the north compared to further south, but albedo reductions measured in snow due to light absorbing impurities is higher in the north (Rowe et al., 2019). We do not expect that black carbon has an important influence on debris-covered glaciers that are fully covered or rock glaciers.

- l.47-49: “Interpretations range from…”: not entirely clear what refers to what in this sentence. “a glacier that has a very thin debris cover” refers to debris covered glacier and “thick enough debris cover to insulate the ice below” to rock glacier?

RESPONSE: We have modified this sentence to clarify as follows:

“In some instances glaciers that have a very thin debris cover and some ice exposed are considered rock glaciers (e.g. Chilean national inventory), while in other cases a thick enough debris cover to insulate the ice below is required (~> 3 m; Janke et al., 2015).”

- l.50-51: sensitive and insensitive to environmental changes: if this is the case, would need to see this in observed glacier changes (which should correlate to degree of debris cover and thickness), is this the case from e.g. Braun et al. (2019) and Dussaillant et al. (2019) for glaciers in the Andes?

RESPONSE: We have modified this sentence to refer specifically to debris cover and not to sensitivity in general and it now reads: “The difference between these interpretations is an important consideration since the former option potentially encompasses glaciers that have a debris cover thin enough to allow sufficient heat transfer to melt the ice surface below (e.g. < 0.2 m; Nicholson and Benn, 2006), while the latter option only includes glaciers that have a thick enough debris cover to, in theory, insulate them from heat at the surface (Bonnaventure and Lamoureux, 2013; Janke et al., 2015).”

We were able to compare the glacier Las Tetas to both Tapado and an insulated glacier nearby using the output from Robson et al. (2022) and this shows Tapado (debris-free part) with the greatest mass loss rate, followed by Las Tetas (intermediate glacier), followed by the insulated glacier. This is included in the examples in Table 2 and in the .kmz file. We were also able to do a comparison with one glacier in the Braun et al. (2019) data set and found the same pattern. However, this dataset generally excludes rock glaciers so only a small portion of the insulated glacier could be compared.

- l.57-60: found sentence hard to understand. Suggest splitting in two sentences and being more specific [adding “these inventories”]: “… with the proposed groups. Based on this, suggestions are provided to modify these inventories to facilitate…”

RESPONSE: We have modified the text as requested.

- l. 64: “which identifies four distinct zones”: not entirely clear which these zones are. Below you mention three zones (which partly overlap by the way). I may be missing the point / misunderstanding, but suggest making this more consistent: e.g. by mentioning the 4 zones, and then mentioning on which you decide to focus.

RESPONSE: We have modified the text to clarify this by mentioning all four zones then specifying the region we are focusing on.

- l.71: water availability. Suggest to possibly make link here with the Water Tower Index (or more specifically the ‘Supply Index’) by Immerzeel et al. (2020)

RESPONSE: We have added a sentence to describe the Water Tower Supply Index on line 67.

- l.110: definition of the threshold at 0.3 m. Is this based on the single study mentioned in the line before? Would be good to clarify.

RESPONSE: The 0.3 m threshold is primarily based on the Ferrando (2012) and Ayala et al. (2016). Direct measurements in Ferrando (2012) show that persistent surface melt occurs at 0.3 m debris thickness which indicates the threshold should be > 0.3 m. The modelled debris cover thickness and mass balance in Ayala et al. (2016) for Piramide roughly agree with this threshold. Mass balance becomes more negative as elevation decreases as would be expected, until ~3800 m.a.s.l, below which debris cover thickens, and the mass balance suddenly becomes less negative and remains constant down-glacier (~-1 m w.e. a-1). The debris thickness at 3800 m a.s.l. is heterogeneous with a range of approximately 0.1-0.5 m thick (modelled debris thickness).

Your review comment prompted me to contact the author A. Ayala to ask if he could provide additional data that would help to identify an appropriate threshold. He sent me some plots of modelled debris thickness versus mass balance plus an interpretation of these. These plots of modelled debris thickness versus mass balance show that on Pirámide ablation is reduced by 80% when debris thickness is 30 cm and 90% when it is 60 cm (A. Ayala, personal communication, March 7 2022). He also mentioned that modelled debris thicknesses > 0.2 m in this study under-estimate compared to in situ measurements and are prone to error so these results should be interpreted with caution. This agrees with Rounce et al. (2021) who provide globally distributed debris thicknesses and sub-debris melt outputs and conclude that thin debris cover (typically 0.03 m – 0.05 m) enhances sub-debris melt while thick debris cover can result in a >90% reduction in sub-debris melt. Based on these results we feel it is reasonable to be more specific with the threshold and place it at ~0.5m debris thickness (as opposed to > ~0.3m). We have updated the text to reflect this change and have added additional information from the study by Ayala et al. (2016) and personal communication with A. Ayala.

A threshold of > 0.3 m and ~0.5m roughly agrees with modelled debris cover thickness and mass balance results on Bello and Yeso Glaciers that are adjacent to Piramide as well (Ayala et al. 2016). On Bello the vast majority of the debris cover is < 0.2 m (modelled thickness). For this glacier mass balance has a linear relationship with altitude and the debris cover near the terminus has a minimal effect on the mass balance pattern. On Yeso glacier there is a thick debris patch at the terminus (0.2-0.6 m) and this is a associated with a very obvious decrease in mass balance at the terminus.

- l.113: "about 95% of the surface", or more, right?

RESPONSE: Yes, we have modified the sentence adding "or more."

- l.114-115: using the surface cover as a proxy for debris cover thickness seems to be relatively rough / qualitative.. Especially given that this seems to rely on a single study. Possibility to make this statement sounder / adding additional studies to support this? Here, without knowing a lot about debris, would think of e.g. work by Scherler et al. (2018), Herreid and Pellicciotti (2020) and Rounce et al. (2021). Especially the latter seems important and would be very relevant in your story in general, as it estimates the debris thickness for all glaciers. I see that you briefly refer to this study later on, but it would be good to have this more prominently featured. From my understanding, despite some of the limitations (you mention the debris thickness is derived from relationship from glacier in High-Mountain Asia), it would be a great tool that could maybe directly / or in complement with what you suggest here, be used to categorize glaciers in terms of debris presence/thickness (and related sensitivity to climate change, which you mention)

RESPONSE: In response to this comment, we have added the following sentence:

"Global products of glacier debris cover could be used to quantify the percentage of debris cover to remove subjectivity (e.g. Herreid and Pellicciotti, 2020; Scherler et al., 2018), however outputs have not been validated for the Andes and coverage is limited to glaciers included in the RGI. We proposed that this initial classification could be refined or used in combination with modelled debris thicknesses (e.g. Rounce et al., 2021) but not replaced by these model outputs since these have not been validated for the Andes and coverage is limited (see Sect. 5)."

We have also added the following sentence on L141:

"Differentiation between intermediate and insulated glaciers could be made more robust by combining the qualitative classification with modelled debris thicknesses, but not be replaced given that methods for modelling thick debris cover (e.g. > 2 m) have not been validated (see Sect. 5)."

- l.132: permafrost in the glacier. Again, probably related to my relatively limited knowledge about the subject: but can there be permafrost in a glacier? Or is this specifically for rock glaciers (which you seem to target under the next category, nr.3)

RESPONSE: We have removed the word permafrost.

- l.140-169: quite long and found this to be disturbing the flow of your manuscript a bit. Could you consider slightly shortening this?

RESPONSE: We have made this section more concise.

- l.193: “These glaciers are more responsive to climatic changes”. See also previous remark on this (l.36): this is quite central in your story, but is this also clear from large datasets that cover your glaciers of interest (Braun et al., 2019; Dussaillant et al., 2019; Hugonnet et al., 2021)? Moreover, also the study by Rounce et al. (2021) could help answer this, as the title of that study suggests: “Distributed global debris thickness estimates reveal debris significantly impacts glacier mass balance”

RESPONSE: Please see our answer to the review comment for l.36. We have also modified this paragraph significantly.

- l.201: “such as contructions of roads”: could you explain how this affects the glaciers?

RESPONSE: The construction of a road on top of a rock glacier could require the removal or disturbance of ice. Indirect impacts might include the deposition of dust from road construction which can impact glacier mass balance (Rowe et.al. 2019) or the use of heavy machinery (e.g. vibration compactor) which may destabilize the slope and create heat. All of these impacts could lead to permafrost degradation.

- l.209: what are “cryospheric glaciers”?

RESPONSE: We have removed “cryospheric” as this was an error.

- l.224-225: the sentence is not entirely clear. Maybe split in two sentences? e.g. “…(RGI). Insulated glaciers are excluded,…”

RESPONSE: We have divided this in to two sentences.

- l.235: “is completed but not yet publicly available”: just checking, is this still the case?

RESPONSE: Yes, this is still the case. The inventory is not yet publicly available.

- l.256-257: “…during a thorough review of the Argentinian inventory”. Can this be quantified, is the data possibly available somewhere to show this? Maybe possible to add as supplement to the publication?

RESPONSE: We have included a .kmz file as supplementary material which includes a layer outlining the geographical area reviewed in both the Chilean and Argentinian inventories (a rectangle) as well as all of the examples listed in Table 1. The Chilean and Argentinian inventories are publicly available and the links to access them are provided in the text (we have added the web page where the Chilean inventory can be downloaded). We have also added a reference to the supplementary material at the end of this sentence (supplementary material S1).

- l.270: "not sensitive to environmental changes": ok, way less sensitive than a debris-covered glacier or a debris-free glacier, but in the end also sensitive to environmental changes (although much slower reaction), right?

RESPONSE: Correct. We have modified the sentence to say "…not very sensitive …"

- l.277: automatic detection methods: suggest mentioning some examples for this here (e.g. Khan et al., 2020; Lu et al., 2021)

RESPONSE: The reference Lu et al. (2021) was added on line 287.

- l.282-283: you suggest this is not a reliable tool. I agree that there are indeed quite some considerable uncertainties, but not sure if it is better to work with relatively qualitative relationship between few measurements debris thickness measurements and link with debris cover..

RESPONSE: The errors with estimating thick debris cover are large (e.g. ~0.2 m according to Ayala et al., 2016), however the error from the qualitative relationship could definitely be large as well. We have modified this sentence in light of this comment.

"At present, methods for modelling thick debris cover (e.g. > 2 m) have not been validated so their effectiveness at differentiating between intermediate and insulated glaciers is unknown."

Given the uncertainty in both methods, perhaps a convergent approach would work where both methods are used. If they agree a high degree of confidence is assigned to the classification. If they disagree, a low degree of confidence is assigned to the classification. We have modified the sentence starting on L275 to reflect this

"We therefore propose that this be used as an initial classification which is later refined or used in combination with a more sophisticated…"

- l.298-314, l.317-324, l. 348-356: quite long and not very specific. In some cases, also quite repetitive. It would be good to shorten these passages.

RESPONSE: We have modified these sections to remove repetitive and unnecessary text.

- l.317-318: not sure if I understood this correctly. Are there many categories in Janke et al.? From this, various categories were removed to have 2 categories, after which 'additionally' debris-free glaciers were added to have 3 categories in the end?

RESPONSE: Yes, that is correct. We have modified these sentences to clarify as follows:

"These categories are aligned with Janke et al. (2015) who propose six categories for debris-covered and rock glaciers. The categories in this paper additionally include debris-free glaciers and the number of categories has been reduced to three."

- l.365-368: as there is a need for time and expertise to apply this, would it not make sense to work with automated products, which are in some cases directly available? (e.g. Rounce et al., 2021)

RESPONSE: The distinction between sensitive and intermediate glaciers could be completed with an automatically generated product (e.g. Rounce et al., 2021), but these outputs should be compared to measured debris thicknesses on glaciers in the semiarid Andes to evaluate their accuracy since the model was calibrated on a debris-covered glacier in Nepal. Furthermore, this study uses the Randolph Glacier Inventory. This inventory does not include insulated glaciers and for the vast majority of hybrid glaciers (e.g. sensitive and semi-sensitive) only a small portion of the glacier is included if ice is exposed otherwise these glacier types are excluded as well so the automatic product by Rounce et al. (2021) would be missing a large number of glaciers/parts of glaciers. Despite these limitations we agree that it would be beneficial to incorporate automated products and we have therefore modified the text on L114 as follows:

"…Therefore, having > 95 % of the surface or more covered by debris could be used as a criterion to approximately identify this threshold using satellite imagery. Global products of glacier debris cover could be used to quantify the percentage of debris cover to remove subjectivity (e.g. Herreid and Pellicciotti, 2020; Scherler et al., 2018), however outputs have not been validated for the Andes and coverage is limited to glaciers included in the RGI. We proposed that this initial classification could be refined or used in combination with modelled debris thicknesses (e.g. Rounce et al., 2021) but not replaced by these model outputs since validation in the Andes is needed and coverage is limited (see Sect. 5)."

At present, methods for modelling thick debris cover (e.g. > 2 m) have not been validated so their effectiveness at differentiating between intermediate and insulated glaciers is unknown. However, we do agree that incorporating modelled debris cover would be beneficial. We have added the following sentence at L 141:

"Differentiation between intermediate and insulated glaciers could be improved by using both the qualitative classification proposed and modelled debris thicknesses, although these model outputs have large uncertainties (see Sect. 5)."

References

All references mentioned above are now included in the reference section of the manuscript.