Authors' reply to Referee 2 comments on the TCD manuscript "Assessment of permafrost distribution maps in the Hindu Kush Himalayan region using rock glaciers mapped in Google Earth" by M. O. Schmid et al.

We would like to thank the referee for his constructive comments, which helped to improve this paper.

Referee comments are in bold, author reply's without formatting and *changes to the manuscript in italic.* The feedback of the Referees had two important points in common that we address here:

A) The relation between rock glaciers and permafrost

The initial manuscript may have been misleading in a way that Referees questioned whether rock glaciers really delineated the lower limits of permafrost existence, when in fact, we purposefully avoided the term and concept of permafrost limits. Our understanding is that rock glaciers are not suitable to delineate the boundaries of permafrost, as ground thermal conditions are spatially too heterogeneous to justify the concept of limits. Extensive research has shown, however, that rock glaciers frequently occur near the lowermost regional occurrence of permafrost in mountains. The manuscript reads now as follows:

The occurrence of rock glaciers is governed by the ground thermal regime and by the availability of subsurface ice derived from snow avalanches, glaciers, or ice formation within the ground. Furthermore, sufficient supply of debris as well as topography steep enough to promote significant movement is required. As intact rock glaciers contain ice (latent heat) and move downslope, their termini can be surrounded by permafrost-free ground. The frequently occurring cover of coarse clasts promotes relatively low ground temperatures and thereby further retards the melting of the ice within the rock glacier. This makes termini of rock glaciers local-scale indications for the presence of permafrost, frequently occurring at an elevation indicative of the lowermost regional occurrence of permafrost in mountains (Haeberli et al., 2006). This tendency of begin among the lowermost occurrences of permafrost in an area is exploited in this mapping exercise. The spatially heterogeneous ground thermal regime and the frequent existence of permafrost-free areas directly adjacent to rock glaciers makes the concept of "permafrost limits" impractical as these limits are neither measureable nor clearly defined and consequently we avoid this concept despite its prevalence in the literature. In more gentle terrain, such as parts of the Tibetan Plateau, not the ground thermal conditions (i.e. the presence of permafrost), but the slope angle is the

limiting factor. Therefore, the presence of rock glaciers can be used as an indicator of permafrost occurrence, but the absence of rock glaciers does not indicate the absence of permafrost. Mapped rock glaciers will thus result in a conservative estimate of the actual permafrost distribution, as over large areas of permafrost no rock glaciers can be present due to the lack of debris, low slope angles, lack of avalanche snow or the elevation of the valley floor.

B) Difficulties to understand to concept of a mapped candidate area (Fig. 6, 7 and 8)

The rock glacier mapping in our study is only meaningful for areas where rock glaciers can potentially exist. There are most likely vast regions in the HKH region, mainly on the Tibetan Plateau, where rock glaciers are absent due to the lack of topography and debris. For those we cannot perform an assessment of the available permafrost distribution maps. To exclude such areas we created the concept of the mapped candidate area, which includes only the area where we can potentially expect the presence of rock glaciers. This reduced investigation area does not include all mapped samples anymore, but only the sample areas which fulfil certain criteria concerning topography, satellite image quality and glacier coverage. This mapped candidate area is then the basis for the assessment of the available permafrost distribution maps. The manuscript reads now as follows:

Rock glaciers outside the signatures for permafrost provided by the evaluated maps indicate false negatives, as the map indicates the likely absence of permafrost, but the existence of permafrost was inferred based on mapped rock glaciers. A comparison of mapped rock glaciers with predicted permafrost extent, however, is only informative in situations where the formation and observation of rock glaciers can be expected. *In the further analysis we excluded all parts of the initial samples where no rock glaciers can be expected. This subset of our mapping was named potential candidate area and includes only sample areas, which fulfil the following three criteria*: (a) Topography: Only sample polygons where the vertical standard deviation of the SRTM 90m DEM is larger than 85 m. This threshold was chosen so as to be smaller than the lowest observed value where rock glaciers were mapped, which is 89.5 m. (b) Image quality: Only samples with sufficient image quality in Google Earth were taken into account. (c) Absence of glaciers: Glacier covered areas were excluded based on the glacier inventory published by Bajracharya and Shrestha (2011), which largely covers the HKH region with the exception of parts of China.

However, the authors seem to ignore the importance of geology, topography and source of snow in the discussion of why rock glaciers are present in certain areas and

absent in others. Even though the reviewer agrees that rock glaciers can be extremely helpful in determining the permafrost distribution in mountainous areas, their absence or the altitude distribution of the front may not directly reflect the lower elevation limit for permafrost to exist. Non-climate related parameters may also play a role in that distribution. As a reviewer I'm missing this critical discussion in the manuscript.

It is important that the authors are precise in their formulations. Permafrost is a thermal conditions and rock glaciers are indirect indicators for the presence of permafrost.

p. 5295 - l. 3: Use a reference that supports the statement in the first sentence

The reference for this is Gruber (2012), connected via two sentences "*Examples include*…" and "*This list is not exhaustive*…"

p. 5295 - l. 3: Permafrost isn't thawing, but degrading and aggrading. Only ground ice can thaw.

AC: We disagree: Ground ice melts (i.e., complete phase change). While this process is underway, often taking a long time, the permafrost thaws (i.e., only a part of the constituents undergo melt, others, such as mineral particles remain solid). In this regard, the English Language Glossary of Permafrost and Related Ground-Ice Terms lists: "thawing (of frozen ground): Melting of the ice in *frozen ground*, usually as a result of a rise in temperature." Similarly with degradation: Strictly speaking, the degradation of permafrost refers to a rise of ground temperatures to above 0ºC, as otherwise, permafrost will remain to be permafrost. Here, the concept and expression of thaw (or thawing) as describing the process of ice loss, often accompanied by important changes to physical characteristics, offers a good way of describing frozen material undergoing significant change. The English Language Glossary of Permafrost and Related Ground-Ice Terms is not very explicit in describing permafrost degradation as "A naturally or artificially caused decrease in the thickness and/or areal extent of permafrost." But appears to conform with our interpretation.

p. 5295 - l. 4: What is meant by changes in societal conditions

AC: It refers to differences such as those between a mountain community relying on Yak herding (Himalaya) or on winter tourism and cable cars (Switzerland).

p. 5295 - l. 5: stick to either singular or plural in the example list

AC: Done

p. 5295 - l. 8: what is a "permafrost phenomena"

AC: “permafrost phenomena” (singular phenomenon) refers to observable entities related to permafrost, including landforms (rock glaciers, drunken forest), events (rock fall, landslide, lake drainage). The term phenomenon is convenient in including both processes and landforms.

p. 5295 - l. 8: Gruber 2012 does not discuss societal impacts, but simply makes the same statement that is in your manuscript in the introduction. Please be careful how you make cross-references..

AC: In fact, Gruber (2012) lists a number of permafrost-related phenomena that clearly impact society: “Examples include ground subsidence (Nelson et al., 2001), vegetation changes on pastures (Wang et al., 2006), slope instability (Gruber and Haeberli, 2007; Lewkowicz and Harris, 2005), hydrological changes (Woo et al., 2008), damage to infrastructure (Larsen et al., 2008), and special requirements for construction (Peng et al., 2007; Bommer et al., 2010).”. While that publication does not have the aim to investigate societal impact as such, this list should be sufficient, to show that “permafrost interacts with human systems” and to support the argument that further changes to permafrost may alter these interactions. In the present manuscript, this statement is part of the introduction, outlining the motivation for the work conducted and setting the stage. We believe that this justifies a statement that is backed up in this way by simply referring to another publication.

p. 5296 - l. 7: use "extent" instead of "proportion"

AC: Done

p. 5296 - l. 11: Do not use "cf." so often. Including a reference should be sufficient, no need to explicitly indicate "see".

AC: We prefer to keep this because the use of “cf.” provides a distinction in referring to more in-depth or other material, as opposed to referencing a particular statement to be based on the findings of another publication. Wikipedia: “The abbreviation cf. derives from Latin word confer. In spoken English it is commonly read aloud as "compare". In context the abbreviation advises readers to consult other material, drawing attention to related ideas that provide additional arguments or information.”

p. 5296 - l. 26: Use "such as …" instead of "(e.g., …"

AC: Done

p. 5296 - l. 29: remote, high-elevation …

AC: Done

p. 5297 - l. 7: Add reference for the statement

AC: Done, (Haeberli et al., 2006)

p. 5297 - l. 14: delete "cf"

AC: we prefer to keep this.

p. 5297 - l. 22: Add Capps, 2010 who coined the term.

AC: Done

p. 5297 - l. 24: "… of buried glacier ice and segregated ice formed …"

AC: Done

p. 5298 - l. 9: delete "cf."

AC: Done

p. 5298 - l. 15: What about availability of debris / sediments? Topography is not the only limiting factor, but also geology

AC: We agree with the referee, that availability of debris / sediments does influence the presence of rock glaciers, as it is written shortly before the questioned sentence (p.5298 l. 11). We have reformulated to make this argument broader: "*The occurrence of rock glaciers is governed by the ground thermal regime and by the availability of subsurface ice derived from snow avalanches, glaciers, or ice formation within the ground. Furthermore sufficient supply of debris, controlled by geology, weathering regime, and topography, as well as topography steep enough to promote significant movement is required.*" (New Manuscript l. 122)

p. 5298 - l. 18: It is unclear why these results are conservative, can you provide a rational for this.

AC: Done, the manuscript now reads: *"Therefore, the presence of rock glaciers can be used as an indicator of permafrost occurrence, but the absence of rock glaciers does not indicate the absence of permafrost. Mapped rock glaciers will thus result in a conservative estimate of the actual permafrost distribution, as over large areas of permafrost rock glaciers may be absent due to a lack of debris, low slope angles, lack of avalanche snow or the elevation of the valley floor*." (New Manuscript l. 138)

p. 5299 – l. 2: it would be better if the authors use "indicator for the presence of permafrost" instead of "permafrost indicator".

AC: Done

p. 5299 – l. 21ff: It is likely correct that the spatial accuracy of imagery available in Google Earth, in particular when also considering the historic images available, has not been the focus of research, the reviewer disagrees with the statement that Google Earth is not a commonly used tool. Several geoscientists in industry as well as academia rely heavily on Google Earth for various purposes.

AC: Agreed, this statement is removed

p. 5300 – l. 13: Use italic, for example, to differentiate the R-function name from the rest of the text.

AC: Done

p. 5300 – l. 16ff: What scale was used for mapping? In order to compare the results of the mappers it is important that they work on the same scale, otherwise there would be a bias and a comparison cannot be made. Also, when mapping, did the mapper reduce the vertical exaggeration? And to what rate?

AC: Both scale and vertical exaggeration were independently chosen by the mapping person based on what made most sense for a specific scene. To our knowledge and based on our experience this did not bias the results in any way. Also this is in agreement with the procedure used for manual delineation of glaciers in the study of Paul et al. (2013).

p. 5301 – l. 1: Please define "poor image quality", what parameter was used to do this?

AC: We changed this to: "If the visual detection of rock glaciers was not possible due to *an insufficient resolution of the satellite image."* (New Manuscript l. 203)

p. 5301 – l. 11: How was the activity of the rock glacier assessed? There is no rational given for the criteria used. Considering that this is extremely subjective, it is recommended to not include the activity unless a proper criteria has been established that is supported by actual measurements which indicate current rock glacier movements. Unless relict, it also doesn't matter too much if a rock glacier is active or inactive.

AC: The mapping person surmised the activity based on the flow structures (longitudinal flow structures and transversal flow structures) and the frontal appearance of the individual rock glacier. Active rock glaciers were characterized by well pronounced ridges and furrows, steep gradient frontal slope, absence of vegetation and presence of fresh, unweathered material. We agree, that this is a subjective criterion. Still, when setting up the mapping process, we considered it to be eligible to collect as much information as possible. Nevertheless, in any further analysis this was not included and none of our results are

related to how the activity of a rock glacier has been judged by a mapping person. We agree with the last statement and for that reason did only distinguish activity into intact (i.e., active and inactive in common terminology) from relict forms.

p. 5301 – l. 13: "description"

AC: This refers to a name in Google Earth. For a better understanding we write it now in italic.

p. 5301 – l. 15: "Manually mapped …"

AC: Done

p. 5301 – l. 23ff: The degree of the two individuals is less important than their experience, ie. for how long have they been doing such mapping?

AC: We agree that a degree itself is of minor importance, but equally the specialization they have does say something. We added to the manuscript that there was a two month training phase and that only one of the three had previous experience in mapping rock glaciers. It reads now as the following: *". After two month of specific training in rock glacier mapping*, the mapping was done during six months by three people with expertise in this field (two holding a MSc in Glaciology and one holding a MSc in Environmental Science with a focus on periglacial processes). *One of them already had previous experience of mapping rock glaciers."* (New Manuscript l. 224)

p. 5302 – l. 14: What "difficulties" were resolved during these meetings and doesn't such discussions affect the independency between the mappers?

AC: Most difficulties were related to Google Earth and the structure in which the mapped rock glaciers had to be in. Occasionally a specific scene or feature was discussed. As the mapping persons were on different time schedules and there were so many scenes to map, we are confident, that the independency of the individual mappings is still intact.

p. 5303 – l. 7ff: It is unclear how the steepness of the front derived from the data uses could be used as an indicator for the rock glacier activity. Considering the raster point resolution of the DEM and the imagery, the error in the orthorectification of the images, the vertical and horizontal resolution and error of the DEM as well as the orthorectification of the DEM there are significant doubts how the slope at the rock glacier front could be accurately measured.

AC: Apparently our manuscript was not as clear as intended on this. The steepness of the rock glacier front was solely based on visual inspections in Google Earth. A steeper front results in constant movement of the surface debris and thus less weathering of the surface

material, which was often visible on the satellite images. The manuscript reads: *"It was possible to assess visually the steepness or activity of the rock glacier front and the characteristic of transversal and longitudinal flow structures, providing a subjectively acceptable, but here not objectively testable, level of confidence in interpreting landforms as indicators for the presence of permafrost."* (New Manuscript l. 256)

p. 5303– l. 10: In the HKH, vegetation is not a good indicator

AC: We agree and have now formulated this more clearly: "*Vegetation coverage on a rock glacier was only identified in two sample polygons in the whole HKH region and is either absent in the investigation area, or not visible based on the imagery available. In European mountains, vegetation cover has often been taken as an indication of relict rock glaciers (Cannone and Gerdol, 2003) but this concept is difficult to generalize to other mountain ranges. The two cases mapped here have been disregarded for further analysis*." (New Manuscript l. 260)

p. 5303 – l. 14: How do you explain the difference in the rock glacier mapping. There seems to be a significant discrepancy in the level of details and attention made by the two individuals that did the mapping. It would be good if the paper discusses the guidelines and instructions that were given to the two mappers.

AC: As described in Paul et al. (2013) manual delineation of debris covered glacier outlines varies significantly even when conducted by experts (p. 5301 l. 14). Therefore similar variations in the delineated outlines of rock glacier can be expected and thus we think that the variations in our study are on a tolerable level. To further increase the reliability of the mapped rock glaciers for the final analysis we used only the areas delineated as rock glaciers in both mappings (p. 5302 l. 10).

p. 5304 – l. 5: delete "e.g."

AC: Done

p. 5304 – l. 10ff: Could that be caused by local climate conditions (microclimates)?

AC: This sudden shift is most likely linked to local climate, but probably not to local microclimates as the observations on both sides of the mountain range remain similar for up to multiple hundreds of kilometres. Investigations on the climate rock glacier interaction may be very interesting but go beyond the scope of this manuscript.

p. 5305 – l. 8ff: more details on basis of the two permafrost maps that were used and compared must be provided.

AC: More detail about the two permafrost maps can be found in the Introduction part of the manuscript (p.5296 l. 6.ff). We have added to the description of the PZI in the introduction: *"PZI is an index representing broad spatial patterns but it does not provide actual permafrost extent or probability of permafrost at a location.*" And some more for the IPA map: "*The map has been digitized and is available digitally from the Frozen Ground Data Center at the National Snow and Ice Data Center, Boulder, Colorado, USA."* (New Manuscript l. 72).

p. 5305 – l. 10: capitalize "Permafrost" when used in conjunction with a name, e.g. Sporadic Permafrost.

AC: Done

p. 5306 – l.7: specify what you mean by "relatively small difference" as this is a subjective description.

AC: This is related to a number of things and needs detailed explanations, which can be found Results chapter (p. 5302 l. 16ff). The manuscript reads now as the following: "Comparison of the two rock glacier mappings showed relatively small differences, *as described in section* ***Error! Reference source not found.***, indicating that the proposed mapping procedure works consistently." (New Manuscript l. 345)

p. 5306 – l.15: You need to discuss the potential errors associated with the minimum elevations determined using Google Earth. The resolution of the DEM together with the uncertainties related to the mapping (also caused by the differences between the two mappers) impacts the elevation. Als, one has to keep in mind that the presence of rock glaciers is not only related to the permafrost, but also controlled by local geology and general topography. If the whole area is located at elevations with a high probability for permafrost to exist rock glaciers fronts will be high and cannot be compared with areas where the topography allows rock glaciers to be present in areas of low probability. In other words, minimum elevation is not the only factor and it is suggested that the authors include a discussion on topography and geology.

AC: This comment appears to refer to the sentence "Minimum elevations reached by rock glaciers are a few hundred meters lower than what previous more local studies have reported for Nepal (Jakob, 1992, Ishikawa et al., 2001) and match well with previous reports from Pakistan (Owen and England, 1998).". For the first part of the reviewer comment we point to the potential errors and uncertainties related to Google Earth and the DEM are discussed in section 5.1 (p. 5303 l.26). If more rock glaciers are mapped, then a wider elevation range than in limited local studies is to be expected. For the relation between the presence of permafrost and rock glacier please see our general answer.

p. 5307 – l.6: "5 rock glaciers mapped …"

AC: Done

p. 5307 – l.6: The fact that only 5 rock glaciers are outside the PZI is not necessarily an indicator for a good agreement. It could also be a sign that the PZI is too conservative.

AC: Absolutely, this is a key issue, but not clear cut: The PZI is defined as an index in Gruber (2012) precisely because the measurements and methods for testing real permafrost extent are currently lacking: "Because the accuracy of estimated PE cannot be demonstrated and many relevant fine-scale processes have to be neglected at the global scale, model results are interpreted as a permafrost zonation index (PZI) that serves to represent spatial patterns but that does not provide actual extent or probability of permafrost at a location." As such, any evaluation of this map (and similar other ones) is inherently very difficult. Correspondingly, the legend is given in a transition of colours and without quantitative statements. Demonstrating this was one of the aims/outcomes of Gruber (2012). For this reason we formulated the aims in the present paper rather carefully: "In the present study, the purpose of using a permafrost map in the HKH region is to (a) exclude areas without permafrost from further analysis, (b) to provide an indication of permafrost extent within the area likely to contain permafrost, and (c) to provide regionally aggregated estimates of permafrost extent.". Also, as the index is not claimed to correspond to actual extent, stating the map to be biased conservatively/anti-conservatively is conceptually difficult. Following your comment, we changed the sentence in the conclusion to: "*Based on the information available, PZI excludes areas where no permafrost can be expected quite successfully and is currently the best estimation of the permafrost distribution in the HKH region."* (New Manuscript l. 370) Furthermore, we have added to the description of the PZI in the introduction*: "PZI is an index representing broad spatial patterns but it does not provide actual permafrost extent or probability of permafrost at a location".* (New Manuscript l. 75)

p. 5307 – l.10ff: Here the impact of geology and general topography should be discussed. In general, the discussion should be extended and based on the experience the authors made in the HKH region the limitations of using rock glaciers for mapping the presence of permafrost should be discussed.

AC: Beyond what we have covered in the Background chapter plus the discussion about the used methodology (p. 5306 l. 6ff.) and the limitations of rock glaciers used as permafrost indicators (p. 5307 l. 13.) in the last chapter, more statements cannot be confidently made based on our study. To really discuss the limitations of rock glaciers as an indicator for the presence of permafrost one would need a data set comprising many other surface types and

topographic situations to compare too. This would be a very important addition to the topic, but likely would have to come from a better investigated part of the world.

Figure 1: Coordinate system?

AC: Done. We added the following sentence to the caption: "*SRTM DEM version 4.1 from CGIAR at a spatial resolution of 90 m (Jarvis et al., 2008) projected with the WGS84 coordinate system.*" (New Manuscript l. 510)

Figure 1: Lowest elevation <0m?

AC: This is what the SRTM DEM shows for some pixels at shore lines. Depending on the geoid used and possible measurement error this is plausible.

Figure 1: Source of the DEM?

AC: Done, see comment above.

Figure 2: Add north arrows. Scale is extremely difficult to read. Add locations for each picture (coordinates) in the figure caption

AC: Added north arrows, locations coordinates and increased the size of the scale.

Figure 3: Add north arrow, scale, coordinate system

AC: Added north arrow and scale. The same projection as in Fig. 1 is used, where also coordinates of the shown region can be seen. As the figures with our results and analysis are already heavily loaded with content and not very easy to understand, we decided to not add this information.

Figure 4: North arrows. scale is extremely difficult to read.

AC: Added north arrow and increased the size of the scale.

Figure 5: Add north arrow, scale, coordinate system

AC: See comment to Fig. 3.

Figure 6: Do not use any bold font

AC: This was done during the editing process of the TCD.

Figure 6 and 7: y-axis: Use "Total rock glacier area per mapped …"

AC: Done

Figure 8: Add north arrow, scale, coordinate system

AC: See comment to Fig. 3.

References

Bajracharya, S. and Shrestha, B.: The status of glaciers in the Hindu Kush-Himalayan region., ICIMOD, Kathmandu., 2011.

Cannone, N. and Gerdol, R.: Vegetation as an Ecological Indicator of Surface Instability in Rock Glaciers, Arctic, Antarct. Alp. Res., 35(3), 384–390, doi:10.1657/1523-0430(2003)035[0384:VAAEIO]2.0.CO;2, 2003.

Haeberli, W., Hallet, B., Arenson, L., Elconin, R., Humlum, O. and Ka, A.: Permafrost Creep and Rock Glacier Dynamics, Permafr. Periglac. Process., 17, 189–214, doi:10.1002/ppp, 2006.

Ishikawa, M., Watanabe, T. and Nakamura, N.: Genetic differences of rock glaciers and the discontinuous mountain permafrost zone in Kanchanjunga Himal, Eastern Nepal, Permafr. Periglac. Process., 12(3), 243–253, doi:10.1002/ppp.394, 2001.

Jakob, M.: Active rock glaciers and the lower limit of discontinuous alpine permafrost, Khumbu Himalaya, Nepal, Permafr. Periglac. Process., 3(April), 253–256, 1992.

Jarvis, A., Reuter, H. I., Nelson, A. and Guevara, E.: Hole-filled SRTM for the globe Version 4, [online] Available from: http://srtm.csi.cgiar.org, 2008.

Owen, L. a and England, J.: Observations on rock glaciers in the Himalayas and Karakoram Mountains of northern Pakistan and India, Geomorphology, 26(1-3), 199–213, doi:10.1016/S0169-555X(98)00059-2, 1998.

Paul, F., Barrand, N. E., Baumann, S., Berthier, E., Bolch, T., Casey, K., Frey, H., Joshi, S. P., Konovalov, V., Bris, R. Le, Mölg, N., Nosenko, G., Nuth, C., Pope, A., Racoviteanu, A., Rastner, P., Raup, B., Scharrer, K., Steffen, S. and Winsvold, S.: On the accuracy of glacier outlines derived from remote-sensing data, Ann. Glaciol., 54(63), 171–182, doi:10.3189/2013AoG63A296, 2013.