Authors' reply to Referee 3 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.

This manuscript provided a new vision or possible method to map the modern permafrost based on rock glacier distribution in such a large mountainous region with very few available dataset.

AC: We assess permafrost distribution maps in the HKH region (p.5294 l. 9). We do not show a new method or vision on how to map modern permafrost.

As the authors described, the terminus of some rock glaciers frequently occurs at an elevation similar to the lowermost regional occurrence of permafrost in mountains, but of course, they are not exactly located at the boundary of mountain permafrost distribution. So more detailed dataset and pronounced analysis, and even validation from field data are needed.

AC: See our general comment, we have modified the text to: "*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."* (New Manuscript l. 125)

1. Generally, the terminus of some active rock glaciers, but not all, might be one of the indicators of the lower limit of mountain permafrost in many regions. So, it is very important not only to map the rock glaciers, but also to identify the active ones from all the mapped rock glaciers. So field investigations are needed to validate rock glaciers or not, and active ones or just relics. Furthermore, not all active rock glaciers (here after as RGs) are distributed in the boundary areas of permafrost occurrence. So it should be recognized for which kinds of RGs are distributed near the lower limits of permafrost.

AC: Please see our response to the previous comment regarding limits. The text now reads: "The high resolution of Google Earth images and the rigorous exclusion of samples with minor image quality made it possible to discriminate rock glaciers from other (similar) landforms. 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*. *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. 258)

2. Characteristics of rock glaciers are great different in regions with different periglacial environment, and in debris deposits with different origins. Of which, climate, and climate factors are most important. Even though there are a few weather stations in this vast study-region. But the regional climatic background could be found not only in literatures, but many climate dataset products. So I strongly suggest the authors to validate the reliability of the results of this manuscript through comparing the lower boundary for active RGs with investigated or modelled lower limit of permafrost.

AC: Which factors are most important is scale-dependent, and our manuscript (and the other two referees) argue that locally, also topography, geology and avalanche supply are important. The concept of permafrost limits (see above) is inherently ill defined and the limits are not measurable. Therefore, the relationships between rock glaciers and permafrost limits and between climate and permafrost limits are only useful for very approximate work. For quantitative investigations, this is not a useful concept. Concerning climate datasets, Gruber (2012) shows (Figure 3 of that paper) that commonly accepted data sets differ by +/- 4ºC even in their long-term mean annual air temperature in the HKH region. For these reasons, the mapping of rock glaciers, even with the shortcomings and uncertainties described, provides a valuable "foot on the ground" for testing if and where permafrost can be inferred.

3. RGs in regions under different climatic conditions should be different. It was said that the lower boundary of RGs under some climate conditions are exactly coincided with the lower limit of permafrost, but are lower or higher in other regions. So it is necessary to discuss the relationship between the lower boundary of RGs and the lower limit of permafrost in different climatic conditions.

AC: See our statement above on limits.

4. The title of this manuscript is "Assessment of permafrost distribution maps", but no permafrost map was showed in this manuscript. It must be better if the authors can give a map which was compiled based on the method of this manuscript, even just for a very small region and validate it through investigation or modelling.

AC: As we only assess maps, we only provide results on their evaluation and not the maps themselves. The maps are referenced in the introduction and are both available online for free.

References

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