Authors' reply to the Referee 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.

Referee 1

I endorse the arguments for getting a better handle on the distribution of permafrost in High Asia, and much more attention to the largely neglected topic of rock glaciers there, for this and other purposes. Great concentrations do occur in certain mountain ranges, and offer a way to appreciate the occurrence and complexities of cryosphere conditions and a basis for tracking changes.

I also agree that this task is severely constrained both by the sheer extent, diversity and logistical difficulties of the terrain and environments of interest, and the near total lack of any concerted research in most of the high mountains, least of all into rock glaciers. As such there is an urgent need to exploit the high resolution satellite imagery that has become available, and I agree that it now shows good diagnostic detail for identifying RGs, their dimensions and diversity of forms, and sub-regional differences.

As a contribution to Cryosphere Discussion, important questions arise as to:

i) how far and how well prevailing notions of rock glaciers and permafrost, largely developed elsewhere, apply in poorly or un-researched areas of High Asia;

ii) how far rock glaciers relate to permafrost, are sensitive or effective indicators of its extent or boundaries; and

iii) the promise and reliability of emerging GIS methods in a vast, complex, and data-poor region.

Regrettably I find the paper as developed so far, hard to follow. The methodology and statement of results seem unconvincing. A much better appreciation of the nature of rock glaciers is required, their relations to permafrost, and implications of what is seen in the HKH.

MAJOR CONCERNS

The basic hypothesis or purposes of the study seems to be: use of rock glaciers (RGs) as indicative of permafrost, especially its lower elevation limits in the HKH region, and as a test and extension of two existing permafrost maps. In principle this seems fine, but:

1. First, the results cast doubt on the purpose and conclusions. It is stated that "Comparison of the two rock glacier mappings showed relatively small differences indicating that the proposed mapping procedure works consistently."(p.5306 l.7-8)

However, apparently the “mappings” only identify or are reliable *in 4%* of the 4.5 million km2 region of interest! They exhibit a larger area (26%) with uncertainty, and exclude over 70% of the region. Does this not suggest that either the hypothesis, or the method used to test it, are, at best, inefficient or marginal to the problem?

AC: In total we mapped 4000 sample polygons, each with an area of approximately 30km^2. In 4% of all samples both mappings contained rock glaciers and in 93% of all samples neither mapping contained rock glaciers. To us this shows, that rock glaciers are relatively rare in the investigation area, but does not say anything about the reliance or the efficiency of the chosen method. In fact this is what could be expected because of the definition of the HKH region by ICIMOD which contains large parts outside the high mountains. We believe this comment to be based on a misunderstanding of our strategy and findings and have reformulated the corresponding results section: “*Of the 4,000 samples 3,432 (86%) received the same classification by both mapping persons: 70% did not have any rock glaciers, 12% had insufficient quality and 4% contained rock glaciers (Fig 3). In 3% of all samples only one mapping contained rock glaciers but the other did not.*” (New Manuscript l. 243)

For similar reasons the results say very little about the two region-wide permafrost maps. The “first order” (?) differences or agreements seem sketchy for IPA, and very local and marginal for PZI (?)

AC: See comment above.

The results in Fig. 6 and 8, give an impression of complex and fine-tuned findings, but it is not clear to this reviewer what they mean. How does Fig 6. reveal RGs “…in relation to Permafrost Zonation Index summarized *over the entire HKH region*” -- <u>if only established for 4% of it???</u>

AC: Regarding a mapping of only 4%, this is due to rock glaciers being relatively rare when looking at the entire region. The legend now reads: “….. *over the mapped HKH region*” to be more conservative in our claims. (New Manuscript l. 533)

And in areas I know I cannot make sense of Fig. 8. It shows yellow squares in the core of the NW Himalaya/Karakoram/Hindu Raj area suggesting “ there is only permafrost in favorable conditions”. Surely, there is only ever permafrost under favorable conditions! However, in these sub-regions there are not only large areas of permafrost, but also hundreds if not thousands of RGs.

AC: This figure is indeed conceptually difficult and we have improved our explanation of this analysis in several parts. The legend here, however, clearly states what the colours refer to “Spatial patterns of agreement between mapped rock glaciers and PZI. Colour indicates the lowest PZI value in the mapped rock glaciers within each 1° x 1° square. Green and yellow are signalling an apparent good agreement between lowest elevations reached by rock glaciers and predicted lowest possible elevations for permafrost by the PZI." To make this point even more clear, we have now also modified the figure and its legend.

Meanwhile:

2. A more critical assessment is needed of why the authors are convinced that RGs in these high mountain environments are, or can be, used delineate the limits of permafrost. My work suggests considerable caution on this. Even in the Alps and subpolar regions there has been a progressive retreat from the early view that permafrost is a prime factor in the origin of RGs, let alone definitive of them. Certainly, in the Hindu Kush, Hindu Raj, Karakoram, and NW Himalayan Ranges, with which I have some familiarity:

i) a majority of RGs depend primarily on avalanched snow and rockfall or talus deposits, on glaciers up above or transitional to RGs, typically some combination of all these. They drive the development, scope, downslope reach and fluctuations in RGs, but relations to permafrost are unkown. At least, an explanation is needed for assuming that lowest or 'mean minimum lowest' reach would depend upon, or reflect the presence of, permafrost, rather than the scale and strength of avalanching, rockfall, glacier and wind driven processes.

ii) Experience suggests that, in addition to RGs "… which do not reach the regional lowermost occurrence of permafrost.,,(p, 5307, l.12) there are many others that reach below it.

iii) A key determinant of the lowest reach in any given valley and, presumably, mean minimum elevation of RGs (not permafrost), *is the elevation of valley floors*. This is determined by landscape and stream system evolution, in which permafrost is a dependent variable too. Thus, the RGs you reference in England and Owen (1998), descend as low as 4,300 m (there are many others in the same valleys terminating higher and up to 4,900 m). However, within 50 km to the west and north, many RGs descend below 3,900 m and some down to 3,400 m. There is no reason to think RG-generative conditions are much different, but valley floors are incised lower.

AC: Please see our general answer for the relation rock glaciers and permafrost

3. I have trouble with various aspects of the statistical procedures and results.

Is 'random sampling' as used here, an appropriate method? It is one thing to select at random to prevent bias in sampling for characteristics distributed within a known population. But thousands of random spatial samples in order to find some particular item in this vast region seems like searching for needles in haystacks? Moreover, it must provide randomized outcomes based not on your concerns, but on probability distributions of regional terrain. It seems unlikely to be good at discriminating the comparatively rare RGs.

AC: We decided to use a random sampling strategy because we do know so little about the rock glacier distribution in the HKH. This implied that we would have many samples without rock glaciers (needle in the haystack), but still we ended up with 155 samples containing more than 700 rock glaciers (p. 5305 l. 5). Therefore random sampling seems to be a feasible approach to map rock glaciers in the HKH region. We agree with this reviewer that there may have been a more effective way to generate this data, but had we chosen that route, then we might have to justify later why we made certain assumptions during our sampling. Our results as they are presented are not affected by this choice.

Incidentally, we *know* there are tens of thousands of individual RGs clustered across the whole region! In this sense I am surprised that all your results involve only 'one, two, or occasionally 'more than three" RGs. In hundreds of valleys in the NW Himalayan ranges and, no doubt, other parts, there are concentrations of dozens of RGs within radii of 10-30 km.

AC: In Figure 5 we made those three classes because if there are only one or two rock glaciers in the sample polygon, results have to be treated slightly more cautious, than if there are many more rock glaciers. In fact in 58% of the samples containing rock glaciers there were three or more rock glaciers. Also there are 21 samples with ten or more rock glaciers and a maximum of 21 rock glaciers in two samples.

The caption for Figure 5 reads now as the following: "Mean minimum elevation of rock glaciers per sample. The size of the square indicates on how many rock glaciers this value is based on. *This is for 24% one rock glacier, for 18% two rock glaciers and for 58% between three and 21 rock glaciers."* (New Manuscript l. 533)

If we scale up our results (our random samples represent about 2.5% of the entire area) then 700 rock glaciers scale to 28,000 over the entire area. These are only the ones mapped by both operators. Assuming that some features are hard or impossible to distinguish on images or may be counted as separate lobes when seen in the field, it is plausible to assume in excess of 100,000 rock glaciers in this area, fully in line with the proposition of this reviewer.

“Mean minimum elevations per sample” (Fig 5 etc)? Not sure what this implies. You seem to have a lot of cases with only one or two RGs per sample, making a mean minimum value seem meaningless? (eg. in Fig. 5). Conversely, how is it valid to compare such with others having three or more. Again, this disregards readily available evidence that, in valleys with numbers of RG’s, termini elevations typically vary and may range over 100’s, if not a thousand metres, when permafrost does not?

AC: We have chosen a mean value over an absolute minimum value, as it is more robust against potentially misinterpreted landforms (p. 5304 l. 4). We think it does give an appropriate indicator about permafrost conditions for a specific sample, where ground surface temperature, and thus permafrost, may vary considerably on even very small scales (Gubler et al., 2011). We share your concern about the comparability of values derived from differing amounts of RGs per sample and for that reason, Figure 5, already in the original manuscript provides a visual representation of the amount of rock glaciers mapped per sample. The caption for Figure 5 has been adjusted and now adds more detail: “Mean minimum elevation of rock glaciers per sample. The size of the square indicates how many rock glaciers this value is based on. *This is for 24% one rock glacier, for 18% two rock glaciers and for 58% between three and 21 rock glaciers.”* For the relation between rock glacier and permafrost please see our general answer

I am surprised just two operators are seen as sufficient to establish or preclude operator error in such a complex task and visual procedures -- even assuming you could get started without some common set of instructions and discussion with them, which is bound to affect selection procedures and make it entirely possible both would be wrong while producing identical results (?) With respect to operator error, the lowest elevation lines at RG snouts appear the critical ones and from what you show they seem to differ little. However, this begs two questions;

i) does one *or either* trace show the actual lower limit of the active RG. You appear to assume it does, but I am not at all sure. The images in my copy are not of the best resolution, but Figs 2.and 4 are good enough to raise doubts about how much of what you show *inside* each operator’s trace, can be confidently treated as active RG. They look suspiciously like examples I know that combine active, inactive and ‘fossil’ areas, while margins in this steep terrain may involve debris derived from RG activity, but not part of the active body.

AC: The rock glacier mapping was conducted by three operators (p. 5301 l.24), this resulted in two comprehensive mappings (p. 5302 l. 1). For the analysis we only used areas delineated in both mappings as rock glaciers (p. 5302 l. 1). Even after two independent mapping of each rock glacier we can not give a guarantee that every point within the delineated areas is part of an intact rock glacier. Still we are confident that in the majority of the cases the mapping is correct and even more though for the rock glacier snouts. To increase transparency and make results more reliable we attached both mappings as supplements to our manuscript.

ii) If RG termini are spread over a range of elevations, it is unclear to me how taking a mean value for two or three, or even ten or fifty, gets any closer to the lowest elevation of permafrost, being at most, a very crude value of where permafrost may occur

AC: Please see the answer to your comment above

iii) In such an exercise, the complete lack of any ground control is problematic, or any indication of attempts at field checks or experience with RGs anywhere. Nearly all our knowledge of rock glaciers and related permafrost issues is based on field studies, and translating from them to remotely sensed data needs to be spelled out.

AC: We agree with the referee that direct measurements of permafrost (boreholes) or indirect measurement (geophysics / seismology) to complement our results would be very beneficial and desirable. For the huge area we covered this is not really a valid option and we therefore decided to rely purely on satellite images. Rock glaciers have previously been mapped based on remote sensing images around the world (Janke, 2001, Brenning, 2005, Fukui et al., 2007b, Lilleøren and Etzelmüller, 2011, Lilleøren et al., 2013) (p. 5299 l. 10ff), but, to our knowledge, never using only Google Earth.

MINOR MATTERS

p. 5298 line 23-4? "Many of the investigated rock glaciers have developed out of Little Ice Age moraines…" Isn't this based on assumption? Of the tiny number of RGs investigated in the HKH, are there *any* actual age determinations or established histories, let alone "many'? Also, views of the LIA, its duration, intensities and uniformity or otherwise across High Asia, are all being contested; also whether Eurocentric views haven't misled us as to what has happened there.

AC: Agreed, sentence removed.

p.5298 l.22-3 Hewitt (2014) is cited but evidently not consulted. Nowhere does he state or imply there are "lowermost elevations… around 4,000 m". The tables and surveyed examples in his Chapter 11 include RA termini at 3,500 m and some down to 3,350m (this in the W. Karakoram, which might have led to a comment on the "lowest

elevation" you cite, in Northern Afghanistan of "3,554 m"). He also reports a nearly 1750 m difference between lowermost termini across the Greater Karakoram region surveyed (his p.275).

AC: The statement was corrected accordingly to Table 11.1 in Hewitt (2014) and reads now as the following: "*For the northern regions of India and Pakistan, in the Karakorum Range, lowermost elevations of active rock glaciers vary between 3,850 and 5,100 m a.s.l. Inactive rock glaciers were even recorded at lower elevations with a minimum elevation of 3,350 m a.s.l. in the Western Karakorum Range (Hewitt, 2014)."* (New Manuscript l. 145)

The lowest elevation of 3,554 m a.s.l. is based on our mapping and not a citation, nevertheless it is in agreement with Hewitt (2014)

p.5303, l.10 "…transversal and longitudinal flow structures, providing a subjectively acceptable, but here not objectively testable, level of confidence in interpreting landforms as intact." Does "intact" mean 'Active'? If so, this is not reliable, 'subjectively' or otherwise. In HKH 'ridge-and furrow' "flow structures" can be highly developed and may persist indefinitely in inactive features, even in relict RGs.

AC: Intact relates to rock glaciers which contain permafrost. To visually define the ground thermal conditions of permafrost related landforms is difficult, for both remote sensed based mappings and actual field mappings. To overcome this issue we mapped every scene two times independently taking into account flow structures (longitudinal and latitudinal), frontal appearance and outline visualization. The reformulated manuscript reads now as the following: "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)

Also, I suggest a further caution concerning; "…Vegetation coverage, an indicator of inactive or relict rock glaciers…"

Apart from the roles of lithology, elevation and local climate, there is extensive, intensively practiced mountain pastoralism almost throughout HKH areas where your RGs occur. Active RGs are avoided, but inactive and relict RGs can be heavily used, and modified by grazing, firewood collection and temporary summer residences. Also, vegetation cover is not everywhere a reliable indicator of 'inactive' RGs. In some areas I have observed *active* ones with a ground cover.

AC: Yes, we agree and have formulated that now 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). We have not discussed this in much detail before as only two cases were observed.

Your descriptions are highly interesting and we would be interested to know how you have assessed the inactive rock glaciers to still contain ice and how heavy their vegetation cover was.

p.5304 l.10 "If variations within close proximity occur, they follow regional patterns." In such a vast region and complex task, you need to specify just what the 'variations', and 'close proximity' mean here, and which "regional patterns" are followed?

AC: We forgot to refer to Fig 5 here, which we've corrected now. It is a description of what can be seen in Fig 5 and should be clear to the reader when looking at the figure.

p.5306 "A clear increase in the minimum elevation reached by rock glaciers can be observed between the south and the north side of *the mountain range*." The HKH region as shown in Fig.1 has many huge mountain ranges. Are you saying that in all of these you expect RGs to descend lower on northerly than southerly? Can the very limited and scattered identifications really support this conclusion? In my experience other factors reverse this relation in some areas, as they do for glaciers and snowlines.

AC: North and South did not refer to aspect, but to the position in our investigation area. To make matters more clear we changed the sentences to: "A clear increase in the minimum elevation reached by rock glaciers can be observed *towards the Tibetan Plateau."* (New Manuscript l. 354)

Referee 2

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 5.1~~5.1~~*, 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.

Referee 3

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.

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Manuscript with track changes:

Assessment of permafrost distribution maps in the Hindu Kush Himalayan region using rock glaciers mapped in Google Earth

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Abstract

The extent and distribution of permafrost in the mountainous parts of the Hindu Kush Himalayan (HKH) region have barely been investigated and are largely unknown. Only on the Tibetan Plateau a long tradition of permafrost research, predominantly on rather gentle relief, exists. Two permafrost maps are available that cover the HKH and provide estimates of permafrost extent, i.e. the areal proportion of permafrost: The manually delineated Circum-Arctic Map of Permafrost and Ground Ice Conditions (Brown et al., 1998) and the Global Permafrost Zonation Index, based on a computer model (Gruber, 2012). This article provides a first-order assessment of these permafrost maps in the HKH region based on the mapping of rock glaciers.

Rock glaciers were used as a proxy, because they are visual indicators of permafrost, often occurring near the lowermost regional occurrence of permafrost in mountains, and because they can be delineated based on high-resolution remote sensing imagery freely available on Google Earth. For the mapping, 4,000 square samples (approx. 30 km²) were randomly distributed over the HKH region. Every sample was investigated and rock glaciers were mapped by two independent researchers following precise mapping instructions. Samples with insufficient image quality were recorded but not mapped.

It is shown that mapping of rock glaciers in Google Earth can be used as first-order evidence for permafrost in mountain areas with severely limited ground truth. The minimum elevation

of rock glaciers varies between 3,500 and 5,500 m a.s.l. within the region. The Circum-Arctic Map of Permafrost and Ground Ice Conditions does not reproduce mapped conditions in the HKH region adequately, whereas the Global Permafrost Zonation Index appears to be a reasonable first-order prediction of permafrost in the HKH. ~~Only in~~In the central part of the region a considerable deviation exists that needs further investigations.

1 Introduction

Permafrost underlies much of the Earth's surface and interacts with climate, ecosystems and human systems. The interaction between permafrost, or its thaw, and human activity is diverse and varies with environmental and societal conditions. Examples include ground subsidence, vegetation change on pasture, slope instability, hydrological change, damage to infrastructure, and special requirements for construction. This list is not exhaustive and it is likely that climate change will bring about unexpected permafrost phenomena and societal impacts in the future (cf. Gruber, 2012). A large proportion of the global permafrost region is situated in mountain terrain; including densely populated areas especially in the European Alps and Asian high-mountain ranges. While permafrost in European mountains and its associated climate change impacts are comparably well investigated, little is known about permafrost in many Asian mountain ranges. In this study, we focus on the Hindu Kush Himalayan (HKH) region, which we use as one of many possible ways for delineating a study region in the mountains of South and Central Asia (Fig 1~~Fig 1~~).The HKH region includes mountains in parts of Afghanistan, Bhutan, China, India, Myanmar, Nepal and Pakistan (Fig 1~~Fig 1~~). Comprised mostly of high-elevation rugged terrain, including the Tibetan Plateau, the Hindu Kush, Karakoram and Himalayan mountain ranges, more than half of its 4.5 million km^2 are located above 3,500 m a.s.l. As the source of the ten largest Asian river systems, the HKH region provides water, ecosystem services and the basis for livelihoods to an estimated population of more than 210 million people in the mountains and 1.3 billion people when including downstream areas (Bajracharya and Shrestha, 2011). While glaciers and glacier change have received considerable research attention in recent years (Bolch et al., 2012), large areas of permafrost in the HKH region are barely investigated or constrained spatially. The Tibetan Plateau, as the only part of the HKH region, has a long tradition of permafrost research (Cheng and Wu, 2007; Yang et al., 2010; Zhang, 2005), most of these studies, however, focus on a narrow engineering corridor and/or on rather gentle relief. Ran et al. (2012) provide an overview and comparison of the several Chinese permafrost maps that include the Tibet Plateau and that reflect several decades of research and development in this area. For locations with mountainous topography only sporadic information exists, especially along the southern flanks of the Himalayas (Owen and England, 1998, Shroder et al., 2000, Ishikawa et al., 2001, Fukui et al., 2007a, Regmi, 2008). Two permafrost maps are available that cover the HKH region and provide estimates of permafrost extent, i.e. the areal extend of permafrost: (A) The Circum-Arctic Map of Permafrost and Ground Ice Conditions (cf. Heginbottom et al., 1993, Brown et al., 1998) published by the International Permafrost Association (IPA map). It is based on manually delineated polygons of classes (continuous, discontinuous, sporadic, isolated patches) of permafrost extent (Heginbottom, 2002). 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. (B) The Global Permafrost Zonation Index (PZI), available on a spatial grid of about 1 km resolution (Gruber, 2012). PZI is an index representing broad spatial patterns but it does not provide actual permafrost extent or probability of permafrost at a location.It is based on a mathematical formulation of permafrost extent as a function of mean annual air temperature, a 1 km digital elevation model and global climate data. The parameterization is based on similar rules employed for the IPA map. Additionally, the uncertainty range is explored (a) with three parameter sets describing a best guess as well as conservative and anti-conservative estimates of permafrost extent, and (b) using spatial fields of air temperature derived from global climate reanalysis (NCAR-NCEP) and from interpolated station measurements (CRU TS 2.0). Uncertainty is expressed in the resulting map product with a ‘fringe of uncertainty’, referring to a permafrost extent greater than 10% in the coldest of the diverse simulations performed.

The application of either map in the mountainous parts of the HKH region is not straightforward, because (a) little information on mountainous permafrost exists to establish their credibility, (b) the range of environmental conditions in the HKH region is large and subject to conditions (~~e.g.,~~such as monsoonal summer precipitation, hyperaridity~~,~~ or extreme elevation) for which only limited knowledge exists, and (c) only few remote, high elevation meteorological stations exist, usually in valley floors, making the application of gridded climate data or the estimation of conditions in remote high-elevation areas error-prone. The required testing or calibration of models (maps) of permafrost extent, unfortunately, is difficult and often avoided (Gruber, 2012), both for lack of data and for lack of methods for comparing point observations such as boreholes with spatial estimates of permafrost extent.

This study provides a first-order evaluation of permafrost maps in the mountainous part of the HKH region. We use rock glaciers as a proxy, because they are visual indicators of permafrost, frequently occurring near the lowermost regional occurrence of permafrost in mountains~~,~~ (Haeberli et al., 2006), and because they can be delineated based on high-resolution remote sensing imagery freely available on Google Earth. Our objectives are to (a) develop a rock glacier mapping procedure that is suitable for application on Google Earth, (b) map rock glaciers in randomly distributed square samples over the entire HKH region and perform quality control on the resulting data, and (c) based on the mapped rock glaciers assess available permafrost distribution maps.

Validation (cf. Rykiel 1996) is understood here as testing whether a model (map) has sufficient quality to serve a specific purpose. 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.

2 Background

The term rock glacier is used to describe a creeping mass of ice-rich debris on mountain slopes ~~(e.g. Haeberli, 1985)~~(e.g. Capps, 1910; Haeberli, 1985); the presence of ground ice at depth is indicative of permafrost. In areas with a continental climate, commonly found in the HKH region, surface ice interacts with permafrost and results in complex mixtures of buried glacier ice and segregated ice formed in the ground. In such environments all transitions from debris covered polythermal or cold glaciers to ice cored moraines and deep-seated creep of perennially frozen sediments occur (e.g. Owen and England, 1998, Shroder et al., 2000, Haeberli et al., 2006). In this paper we use the term rock glacier for all features with the morphological appearance of creeping permafrost. The most likely origin of the ice is not used as an exclusion criterion for glacier derived ice. Due to similar landforms, lava flow surfaces could possibly be mistaken for rock glaciers. Only one high altitude volcanic group, the Ashikule Volcano Group in the Western Kunlun Mountains at around 5000 m a.s.l. (Jiandong et al., 2011) exists within the mapped area. No rock glacier could be seen nor was mapped in the vicinity.

~~The terminus of rock glaciers frequently occurs at an elevation similar 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 ~~(cf. Haeberli et al., 2006). The ground thermal regime is one factor leading to the formation of rock glaciers. Other important~~

~~ones are availability of debris, slope angle and availability of avalanche snow. In mountainous terrain the slope angle is seldom a limiting factor, but more so the presence of glaciers and also the availability of debris and most importantly the ground thermal regime.~~(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. ~~As a result, the mapping of~~Mapped rock glaciers will ~~always give~~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.

Rock glaciers are a widespread feature in many parts of the HKH region, but very limited research has been conducted on them. For the northern regions of India and Pakistan, in the Karakorum Range, lowermost elevations of active rock glaciers vary between 3,850 and 5,100 m a.s.l. Inactive rock glaciers were even recorded at lower elevations with a minimum elevation of 3,350 m a.s.l. in the Western Karakorum Range (Hewitt, 2014). ~~For the northern regions of India and Pakistan lowermost elevations of rock glaciers are recorded to be around 4,000 m a.s.l (Hewitt, 2014).~~ A significant increase in the number of rock glaciers is seen from monsoon-influenced regions in the east to the dry westerly influenced regions with annual precipitation being below 1,000 mm (Owen and England, 1998). From the Khumbu region in Nepal the lower limit of active rock glaciers is reported to be between 5,000 and 5,300 m a.s.l. (Jakob, 1992). Further east in the Kangchenjunga Himal of Nepal, the distribution of rock glaciers varies from 4,800 m a.s.l. on northern aspect to 5,300 m a.s.l. on south- to east-facing slopes (Ishikawa et al., 2001). So far no studies have been conducted using rock glaciers as indicators for the presence of permafrost on the northern side of the Himalaya. Further north, the extremely dry and cold conditions on the Tibetan Plateau have resulted in a variety of permafrost related features for which no occurrences in other mountain ranges are described (Harris et al., 1998).

For remote sensing based derivation of glacier outlines over large areas traditionally ASTER and Landsat TM have been used. Data from higher resolution sensors have rarely been applied over larger areas due to costs and availability (e.g. Paul et al., 2013). With ASTER and Landsat TM images at resolution of 15 m and coarser, automated mapping of rock glaciers proved to be very challenging (Janke, 2001, Brenning, 2009). On a local scale rock glaciers have been successfully mapped using aerial photography in the Chilean Andes (Brenning, 2005) the Russian Altai mountains (Fukui et al., 2007b) in Norway (Lilleøren and Etzelmüller, 2011) and in Iceland (Lilleøren et al., 2013).The release of freely available high-resolution satellite images (i.e. Google Earth), which nearly reaches the quality of aerial photographs, opened up new possibilities. The images used in Google Earth are SPOT Images or products from DigitalGlobe (e.g. Ikonos, QuickBird), and they are georectified with a digital elevation model (DEM) based on the Shuttle Radar Topography Mission (SRTM) data which has a 90 m resolution in the research area. In mountain regions horizontal inaccuracy for the SRTM DEM can be of the same order, as Bolch et al. (2008) reported from the Khumbu region in Nepal.

In science, Google Earth is frequently used to display scientific results (e.g. Scambos et al., 2007, Gruber, 2012), but in some cases also as a data source (e.g. Sato & Harp, 2009). ~~Despite its huge potential for research, Google Earth has not yet become a commonly used tool.~~ Neither spectral nor spatial properties of the displayed satellite images are easily accessible. Thus the accuracy of the used remote sensing images and any created output is hard to quantify. Potere (2008) showed that the horizontal accuracy of 186 points in 46 Asian cities has a mean root mean square error (RMSE) of 44 m when comparing them to Landsat GeoCover. With regards to the accuracy of the rock glacier mapping, and the limitations of the available DEMs for the investigation area likely exceed the potential errors originating from the inaccuracy of Google Earth, the accuracy of Google Earth is sufficient for our purposes.

3 Methodology

The samples to map rock glaciers in Google Earth are created in the free statistical software R (R Core Team, 2014). Each sample consists of one square polygon with a specified latitudinal width [°]. The following approximate adjustment for the longitudinal width [°] has been applied, where LAT [°] is the latitude for the specific sample.

$$longitudinal\ width = \frac{latitudinal\ width}{\cos\left(\frac{\pi * LAT}{180}\right)} \tag{1}$$

To achieve a random distribution, the investigation area was tessellated with potential sample polygons, from which a predefined number of polygons were randomly selected using the R-function ~~‘sample’.~~ *sample*. Every sample received a unique name consisting of two capital letters and three numbers. With the R-function ~~kmlPolygons~~ *kmlPolygons* from the ~~maptools~~ *maptools* package (Bivand and Lewin-Koh, 2013) samples were exported into a Keyhole Markup Language (kml) file, which is one of the formats supported by Google Earth.

All sample polygons were mapped for rock glaciers. To support a systematic mapping of every sample polygon, the grid view in Google Earth was activated during this process. Historical images were browsed in order to find the most suitable one for detecting rock glaciers. The procedure for the mapping was: (1) Assessment of whole sample polygon, (2) delineation of the rock glacier outlines and (3) labelling the rock glaciers. In the following these steps are described in more detail.

(1) If no rock glaciers could be detected, the label NR (no rock glacier) was added to the sample polygon name. If any rock glaciers were encountered the label RM (rock glacier(s) mapped) was added. If the visual detection of rock glaciers was not possible due to ~~poor image quality~~an insufficient resolution of the satellite image, excessive snow or cloud coverage in the whole or any part of the sample, then the label IQ (insufficient quality) was added.

(2) Rock glaciers found in each sample were digitized using the *Polygon* ~~Polygon~~ tool in Google Earth. All features were mapped, also beyond the outlines of the sample polygon. The names are composed of the name of the sample, followed by the term RG (rock glacier) and a number starting from 1 for the first mapped feature of a specific sample. Therefore, every mapped feature has a unique name and can be traced to a specific sample. Examples for the delineation of different rock glaciers are shown in Fig 2~~Fig 2~~.

(3) Every rock glacier was attributed with information regarding imagery date, its origin, activity, flow structure, frontal appearance, outline visualization, snow coverage and the overall confidence was estimated to support later analysis and filtering of mapping results. This information was written into the *Description* ~~Description~~ field of each rock glacier polygon.

~~Manual~~Manually mapped outlines of debris covered glaciers based on high-resolution images vary significantly, even if mapped by experts (Paul et al., 2013). Due to similar visual properties, the same kind of issues can be expected when mapping rock glaciers. To reduce subjectivity, every sample is mapped by two persons independently.

4 Mapping

We mapped 4,000 samples within the HKH region. Each sample consists of one square shaped polygon with a latitudinal width of 0.05 decimal degrees equivalent to 5.53 km. Due to the imperfect latitude dependent correction in width, the area per sample varies from 26.1 km^2 in the south to 32.2 km^2 in the north. ~~The~~After two months 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. This resulted in two comprehensive mappings for each individual sample. Mapping guidelines were iteratively updated and improved and the final version of the guidelines was applied consistently to all samples. Regular meetings were held to resolve difficulties in the mapping.

The elevation characteristics of the mapped rock glaciers were extracted from SRTM DEM version 4.1 from CGIAR at a spatial resolution of 90 m (Jarvis et al., 2008) using ArcGIS 10. For the analysis only the mapped rock glacier area within the sample polygons were taken into account. Afterwards, extreme values (i.e. lowest and highest elevations of rock glacier snouts) were revisited and checked, ensuring plausible results from both mappings. Even though both mappings showed plausible and similar results, for the final analysis we chose to only use areas identified by both persons as rock glaciers. Thus the influence of subjectivity during the mapping process was further reduced, resulting in a much more conservative and firm data base.

5 Results

5.1 Data and data quality

Of the 4,000 samples 3,432 (86%) received the same classification ~~(No rock glaciers / Insufficient quality / Rock glaciers mapped)~~ by both mapping persons~~.~~: 70% did not have any rock glaciers, 12% had insufficient quality and 4% contained rock glaciers (Fig 3~~Fig 3~~). In 3% of all samples only one mapping contained rock glaciers ~~and~~ but the other did not. ~~Looking at the samples with the same classification in both mappings, most of the samples did not have any rock glaciers (70%), followed by samples with insufficient quality (12%) and finally 4% containing rock glaciers (Fig 3).~~

The spatial distribution of classified samples shows that nearly all mapped rock glaciers are located within the Himalayan arc (Fig 3~~Fig 3~~). Only very few samples north of the Tibetan Plateau contained rock glaciers. Also, the samples with insufficient quality of the Google

Earth images show distinct patterns, concentrated along the Himalayan arc and Eastern part of the Tibetan Plateau. However, as the reasons for insufficient image qualities were not noted down, no exact statements can be made. Impressions from the involved analysts were that in the Himalayan arc this was mainly due to snow cover and on the Eastern Tibetan Plateau mainly due to very coarse image resolutions. Clouds were only an issue in a few cases.

The high resolution of Google Earth images and the rigorous exclusion of samples with ~~minor~~poor 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 ~~intact. Vegetation coverage, an indicator of inactive or relict rock glaciers was only identified twice in the whole HKH region. This commonly observed phenomena in other mountain ranges seems to be absent in the investigation area, or not visible based on the imagery available~~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.

On the scale of one sample polygon, the mapped outlines of rock glaciers varied considerably between the two mappings by the analysts. Major differences occurred especially in the delineation of the upper limit of rock glaciers and the separation between individual objects, whereas a higher congruence existed for the termini of mapped rock glaciers (Fig 4~~Fig 4~~). This resulted in relatively small differences when comparing the mean minimum elevation of all mapped rock glaciers per sample from the two mappings. The mean difference between the two mappings is 46 m (Fig 4~~Fig 4~~). Samples with high differences were mostly a result of a different number of mapped rock glaciers.

The differences in sample size with changing latitude are not expected to influence the results for the minimum elevation of rock glaciers per sample. A slight error biased towards a higher minimum elevation for rock glaciers can be expected due to rock glaciers which are only partially within the mapped sample. In those cases their lowest point has been taken at the sample boarder and not at the rock glacier snout. Horizontal inaccuracies from Google Earth should mostly be outweighed by inaccuracies from the used SRTM DEM. With respect to the comparable large data base, neither inaccuracies from Google Earth nor from the SRTM DEM should distort the further products.

5.2 Regional rock glacier distribution

Minimum elevations reached by rock glaciers were expressed on the sample scale (approx. 30 km^2), taking into account all mapped rock glaciers and thus resulting in a mean minimum elevation per sample. This provided a more robust and conservative measure than~~ e.g.,~~ a minimum value, but also implies that some rock glaciers do reach lower elevations than indicated by the sample mean value. Mean minimum elevations reached by rock glaciers per sample vary significantly in the HKH region~~.~~ (Fig 5~~Fig 5~~). The lowest elevation was recorded in Northern Afghanistan at 3,554 m a.s.l. and the highest elevation at 5,735 m a.s.l. on the Tibetan Plateau. If variations within close proximity occur, they follow regional patterns. The most pronounced shift of the mean minimum elevation reached by rock glaciers occurs between the South and the North side of the Himalaya, where the mean minimum elevation rises several hundred meters within a short distance.

5.3 Assessment of permafrost distribution maps

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 this analysis, the mapped candidate area was therefore constrained by~~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.

Fig 6~~Fig 6~~ and Fig 7~~Fig 7~~ show how the terminus of all mapped rock glaciers relate to the signatures of the maps evaluated. The mapped rock glaciers are distributed evenly over all classes of the PZI (Fig 6~~Fig 6~~). Rock glacier density per class peaks for the medium PZI values and decreases towards both ends of the spectrum. The decrease is more pronounced towards lower PZI values (lower possibility of permafrost). Only 5 out of more than 700 mapped rock glaciers are reaching areas outside the PZI. Thus the PZI is in good agreement with our study, based on this summary evaluation.

When comparing the mapped rock glaciers with the IPA map (Fig 7~~Fig 7~~) the investigation area and the mapped rock glaciers are predominantly in the two classes Discontinuous ~~permafrost~~Permafrost and Sporadic ~~permafrost.~~Permafrost. A small part of the investigation area and a few mapped rock glaciers are in the class Isolated permafrost. The class Continuous permafrost does not exist in the HKH region. More than 250 of the mapped rock glaciers are outside the IPA map permafrost signature. Thus the IPA map does not coincide well with the findings from our study.

5.4 Regional comparison with the Permafrost Zonation Index

Spatial patterns of the agreement between the PZI and the mapped rock glaciers are shown in Fig 8~~Fig 8~~ aggregated to 1° x 1° resolution. Mapped rock glaciers are reaching low PZI values in most parts of the investigation area and thus indicate a good agreement. Only for the Northern side of the central part of the Himalayan arc the lowest elevation of mapped rock glacier remains in high PZI values, despite the presence of low PZI values, thus showing that the minimum elevation reached by rock glaciers and the predicted lowermost occurrence of permafrost are not in agreement. Therefore, either the PZI (due to its method or its driving data) fails to reproduce the local permafrost conditions or the conditions for rock glacier development in the particular area are different from other areas of the region. This may partially be caused by the topography of the Tibetan Plateau, where the lower elevations, and thus lower PZI values, correspond with a flatter topography. Further, there are very distinctive climatic conditions in this region, with a strong south-north precipitation gradient due to the Himalaya blocking the summer monsoon on the Southern slopes, resulting in extremely dry and continental conditions on the Tibetan Plateau. Consequently, we assume that rock glaciers may not reach the predicted lowermost occurrence of permafrost as they may not form because of sparse supply of snow to be incorporated in aggrading debris. But to test this hypothesis further investigations are needed.

6 Discussion and conclusions

Comparison of the two rock glacier mappings showed relatively small differences, as described in section 5.1, indicating that the proposed mapping procedure works consistently. By using only the intersected area from two independent mappings, subjectivity as described for the manual delineation of debris covered glaciers by Paul et al. (2013) could further be reduced. Thus the use of Google Earth as a data source to map rock glaciers in a data sparse region is shown to be feasible.

The diversity of the climate in the investigation area leads to a wide range of rock glaciers, or features of apparently moving debris, exceeding what is commonly observed in Europe and North America. 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). Over the whole investigation area, the minimum elevation of rock glaciers varies from 3,500 m a.s.l. in Northern Afghanistan to more than 5,500 m a.s.l. on the Tibetan Plateau. A clear increase in the minimum elevation reached by rock glaciers can be observed ~~between the South and the North side of the mountain range.~~ towards the Tibetan Plateau.

There are two permafrost distribution maps available for the HKH region, the IPA map with manually delineated permafrost classes (Brown et al., 1998) and the PZI which is based on a simple computer model (Gruber, 2012). Comparing these two maps with the mapped rock glaciers from our study is a first step in assessing their quality for the remote and data sparse mountainous parts of the HKH region. The IPA map falls short in adequately representing local permafrost conditions with more than 250 of the mapped rock glaciers falling outside the IPA map. This is likely due to simplification and subjectivity in the applied manual mapping, but in part may stem from inaccuracies in the digitization and coordinate transformation of the map into a digital product. The PZI map and the rock glacier mapping on the other hand are in good agreement, with only 5 mapped rock glaciers being outside the PZI. Based on the information available, PZI does exclude areas where no permafrost can be expected and is ~~thus a reasonable first-order~~currently the best prediction of the permafrost distribution in the HKH region~~ and suitable to inform further and more detailed investigations~~.

In addition, the mapped rock glaciers reach the lowermost elevations where the PZI predicts a possibility for permafrost occurrence. The disagreement in the central part of the region, where rock glaciers do not reach down to elevations with low PZI values, is at least partially caused by rock glaciers, which do not reach the regional lowermost occurrence of permafrost. This underscores the importance of the principle to use the presence of rock glaciers as an indicator of permafrost but not their absence as an indicator of permafrost free conditions. The comparison with the rock glacier mapping is a first step towards more thorough testing of the PZI, and other models and map products for this remote and data sparse region.

7 Data availability

The rock glaciers mapping, the source code to create the random samples and the outline of the HKH region is published as supplementary material. Both mappings include all 4,000 samples and all mapped rock glaciers. Different colours indicate the different persons involved in the mapping. Those files come in KML (Keyhole Markup Language) and can be opened with Google Earth and most GIS software. The file f.RandomPolygon.r contains the R-function to create the samples.

Author contribution

M.O.S. developed the method; conducted the analysis and prepared the manuscript. S.G. conceived the study, supervised the development of the method and the analysis, and contributed significantly to the writing. P.B, S.S. and T.S. did the mapping and provided general support. D.S. and P.W. contributed to conceiving the study, secured funding, provided overall supervision and contributed to the writing.

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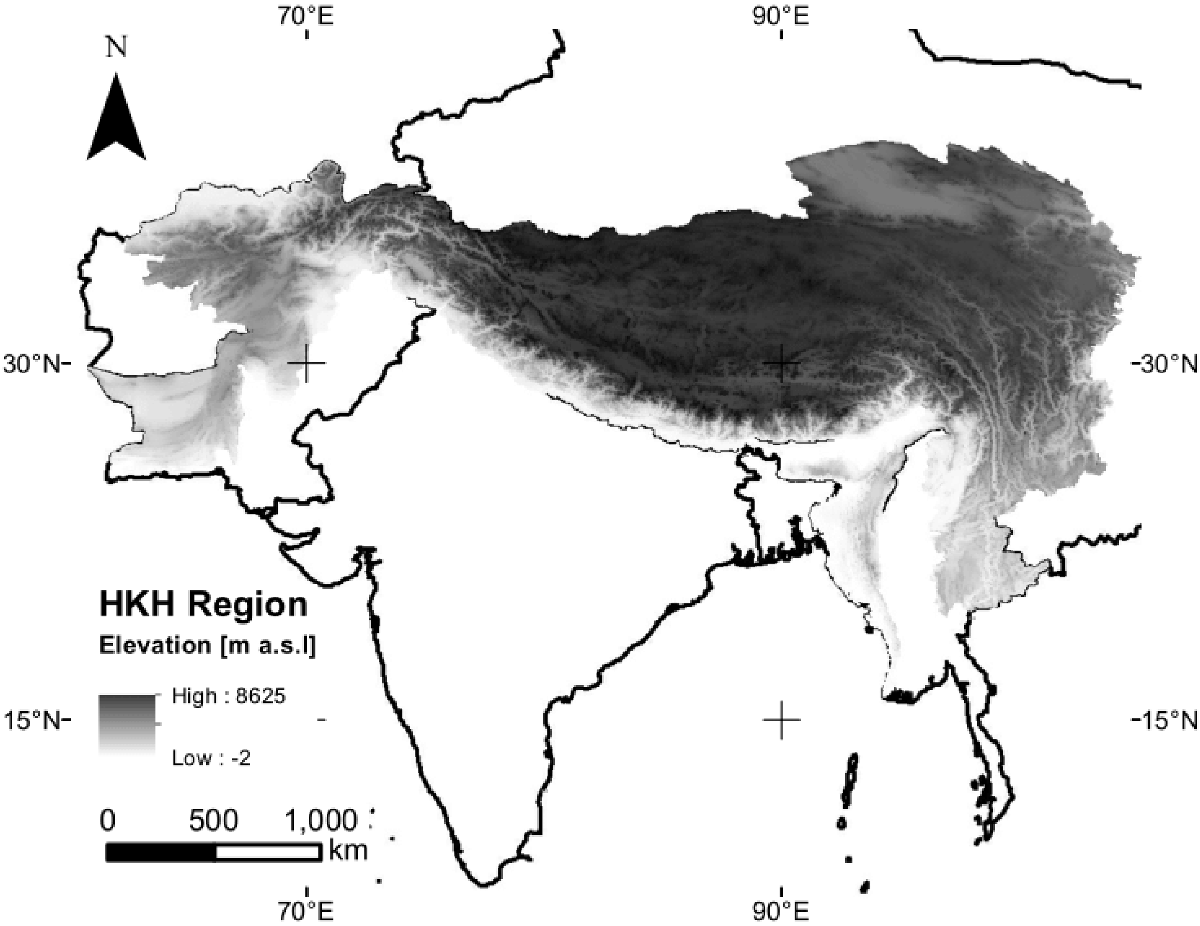

Fig 1~~: The HKH region as defined by ICIMOD which includes high mountains in Afghanistan, Bhutan, China, India, Myanmar, Nepal and Pakistan.~~: The HKH region as defined by ICIMOD which includes high mountains in Afghanistan, Bhutan, China, India, Myanmar, Nepal and Pakistan. SRTM DEM version 4.1 from CGIAR at a spatial resolution of 90 m (Jarvis et al., 2008) projected with the WGS84 coordinate system.

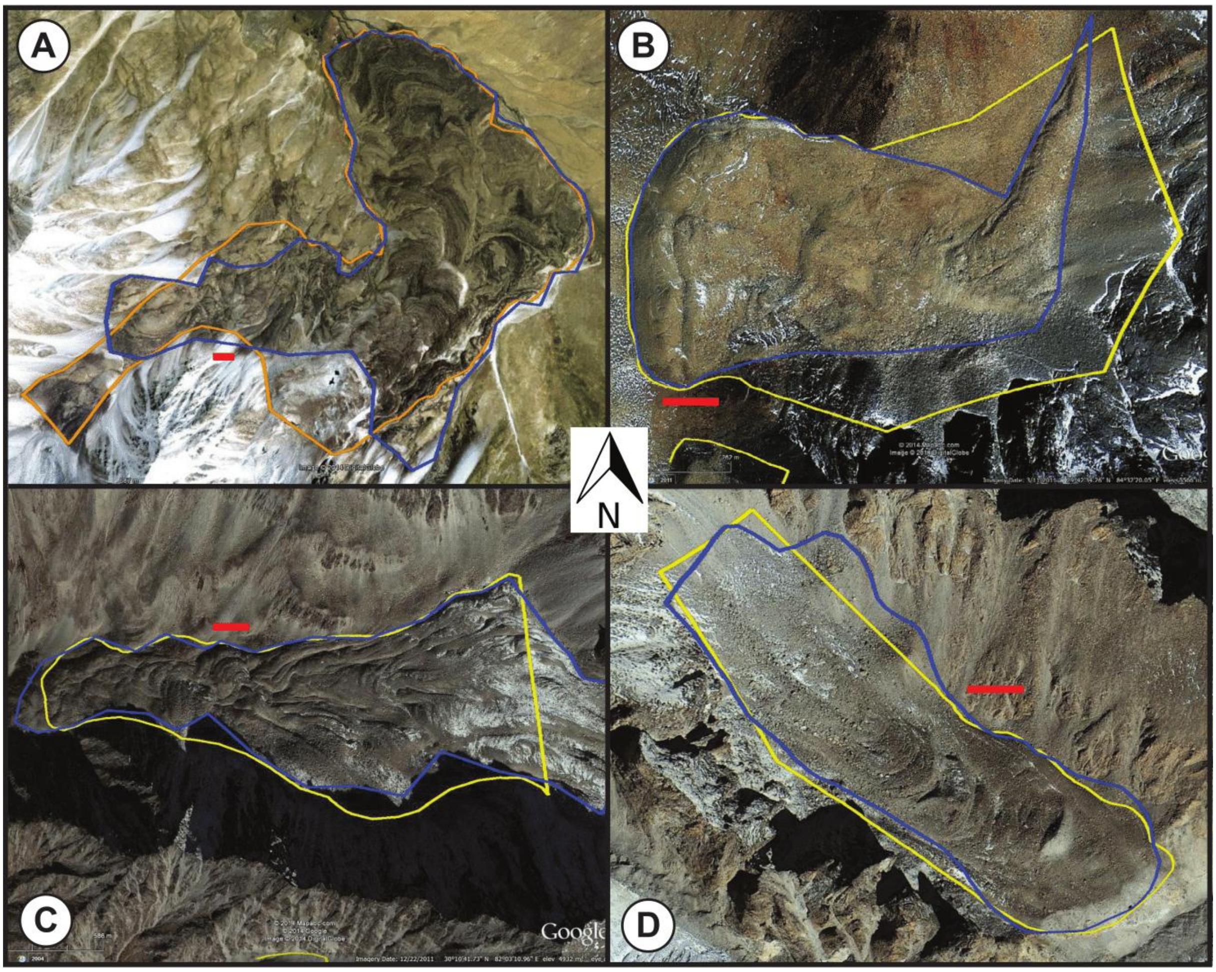

Fig 2: Examples of rock glaciers mapped by two different persons (red line = 100m). Coordinates (Lat / Lon) are for A: 37.07 / 72.92; B: 29.71 / 84.54; C: 30.18 / 82.05; D: 30.18 / 82.22. All copyrights Image © 2014 DigitalGlobe.

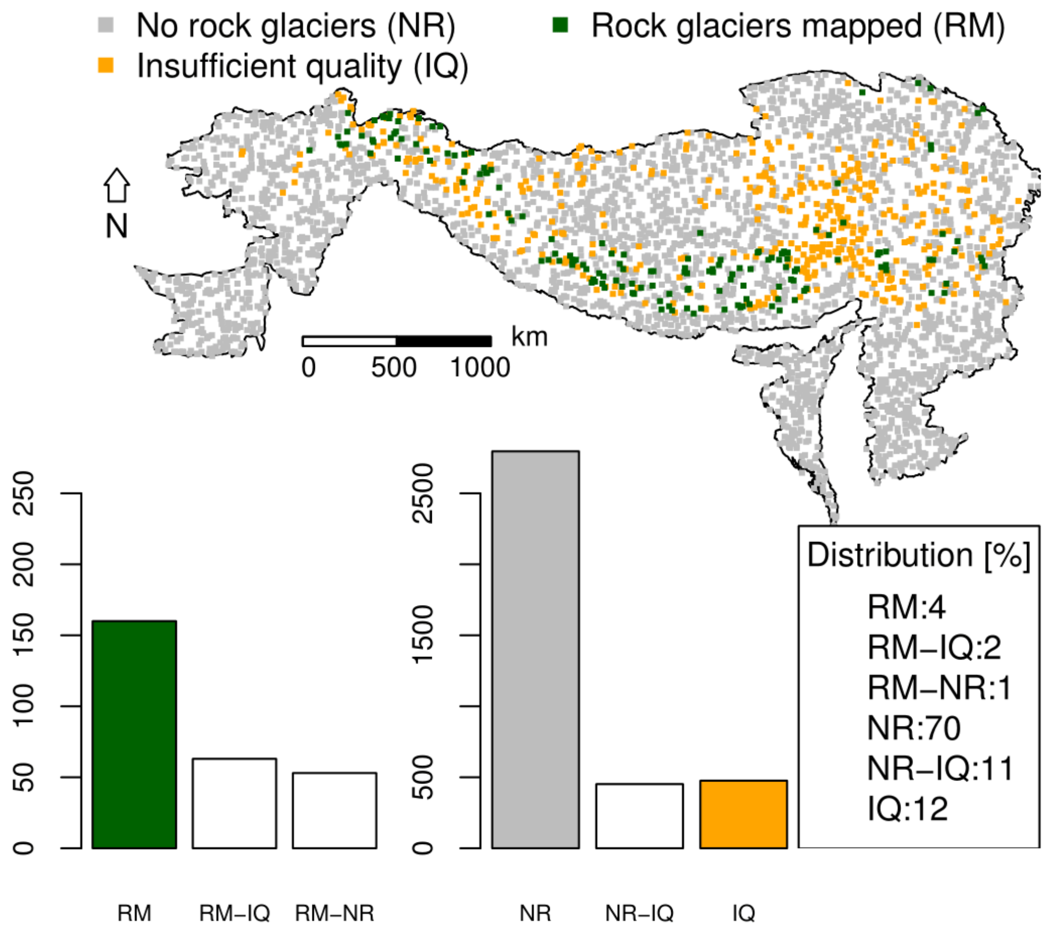

Fig 3: Overview of mapping results. All 3,432 samples with the same classification from both mappings are shown. In the barplots, identically classified samples are shown with filled bars and samples, which were classified differently in white. Note that the difference in scale between the samples containing rock glaciers on the left and all others samples on the right is one order of magnitude.

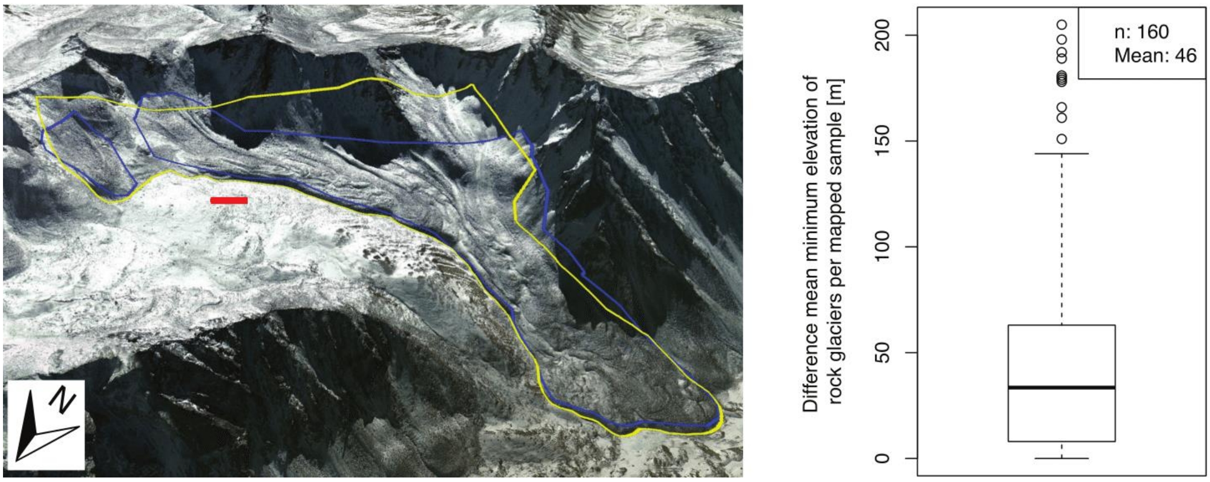

Fig 4: Example of differences between two mappings on the left (red line = 100m). Copyright Image © 2014 DigitalGlobe. For the boxplot on the right only samples where both analysts have mapped rock glaciers were taken into account. The samples with big differences typically have only few rock glaciers, therefore if one object got mapped by only one analyst the mean minimum elevation could change significantly.

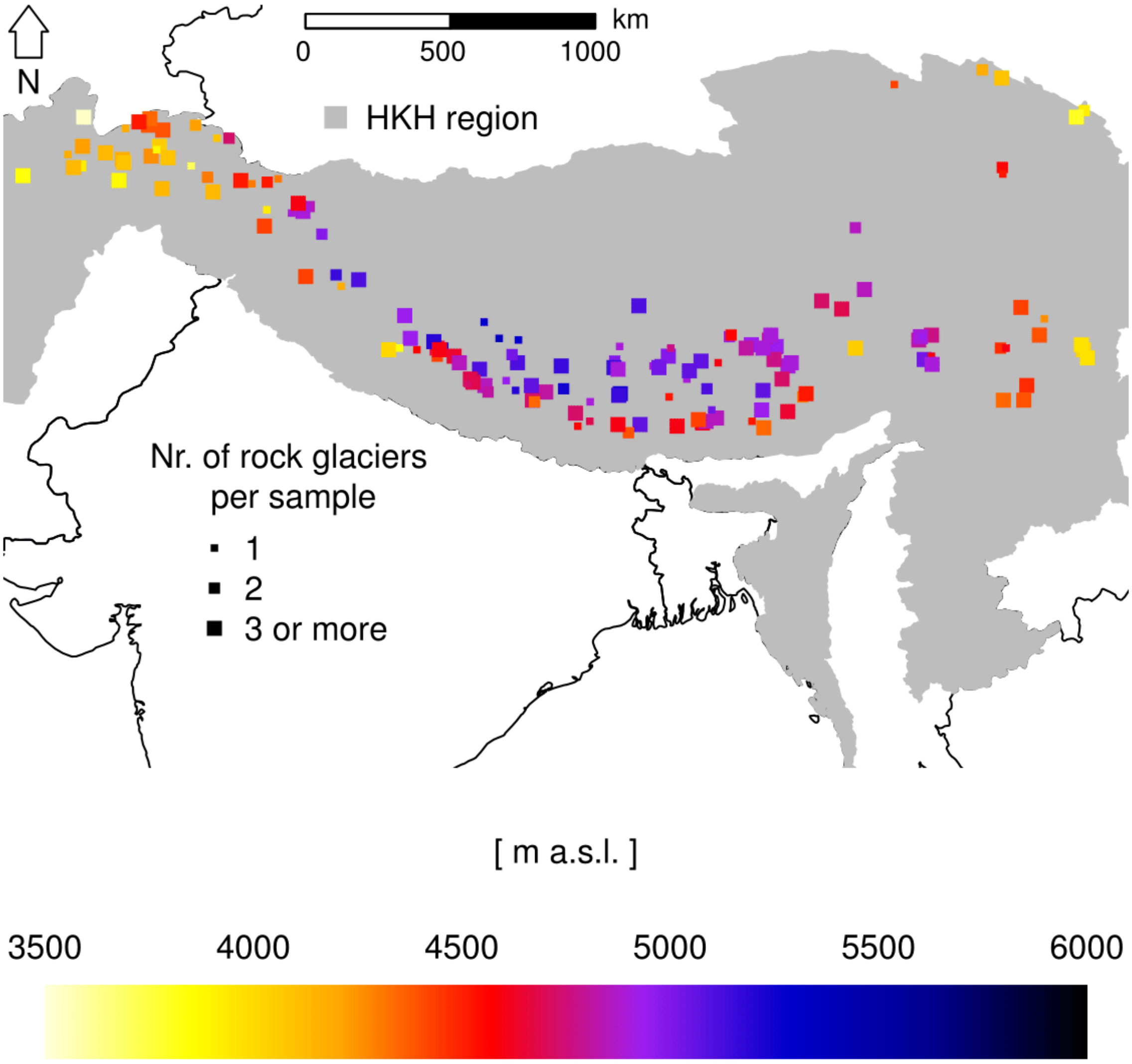

Fig 5: Mean minimum elevation of rock glaciers per sample. The size of the square indicates ~~on~~ how many rock glaciers this value is based on. This is for 24% one rock glacier, for 18% two rock glaciers and for 58% between three and 21 rock glaciers.

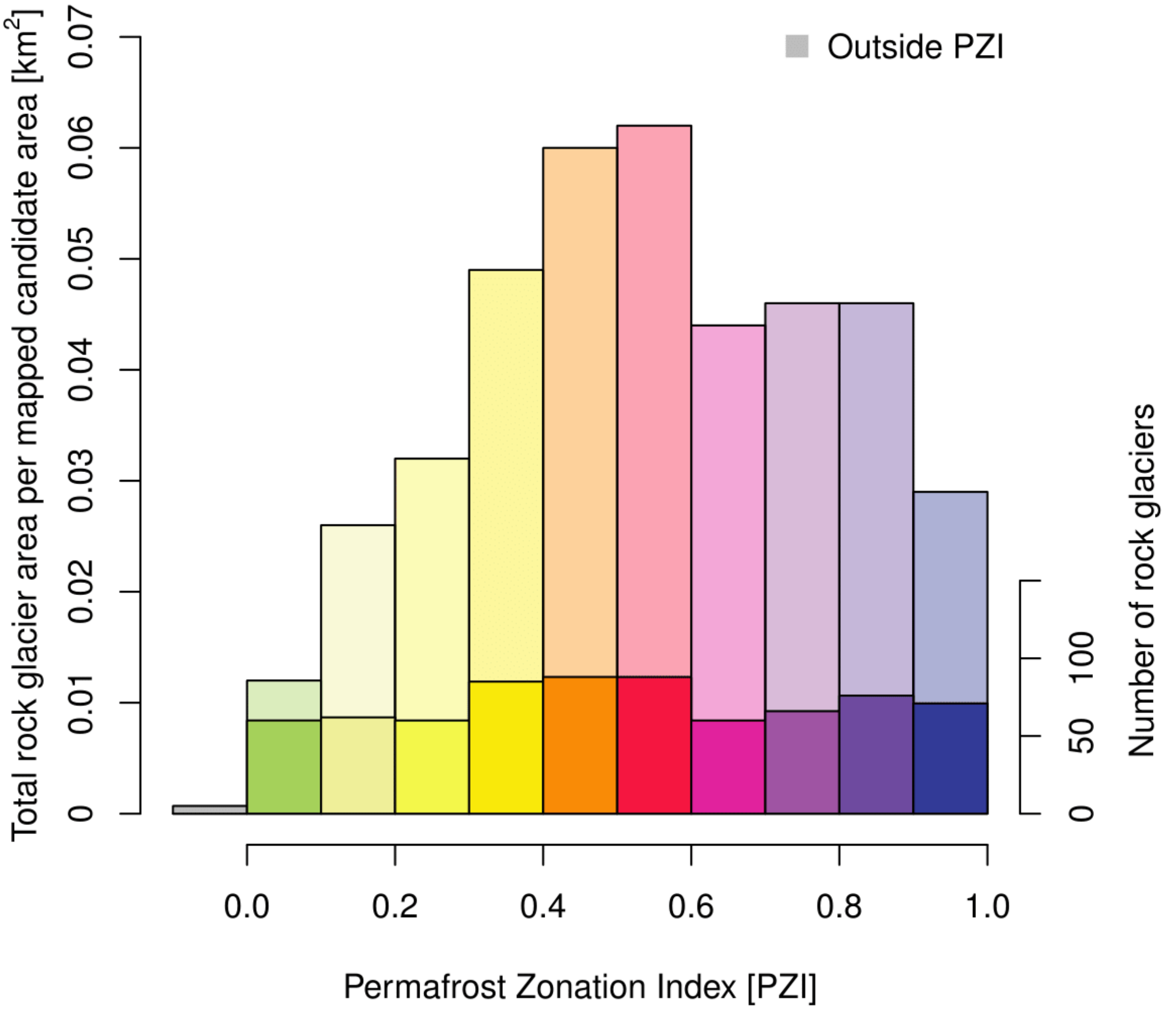

Fig 6: Mapped rock glaciers in relation to Permafrost Zonation Index summarized over the ~~entire~~mapped HKH region. Mapped candidate area refers to areas in where rock glaciers can be expected to occur and to be observed; for each pixel, this is determined based on (a) topography (standard deviation of SRTM90 > 85m in each sample), (b) sufficient image quality in Google Earth, and (c) the absence of glacier cover. The same colours as for the PZI map have been used where dark blue indicates permafrost in nearly all conditions and bright yellow indicates permafrost only in very favourable conditions. Green indicates the fringe of uncertainty. Intensive colours indicate the number of rock glaciers and pale colours represent the density of rock glaciers within a certain class. For more information on the PZI see Gruber (2012).

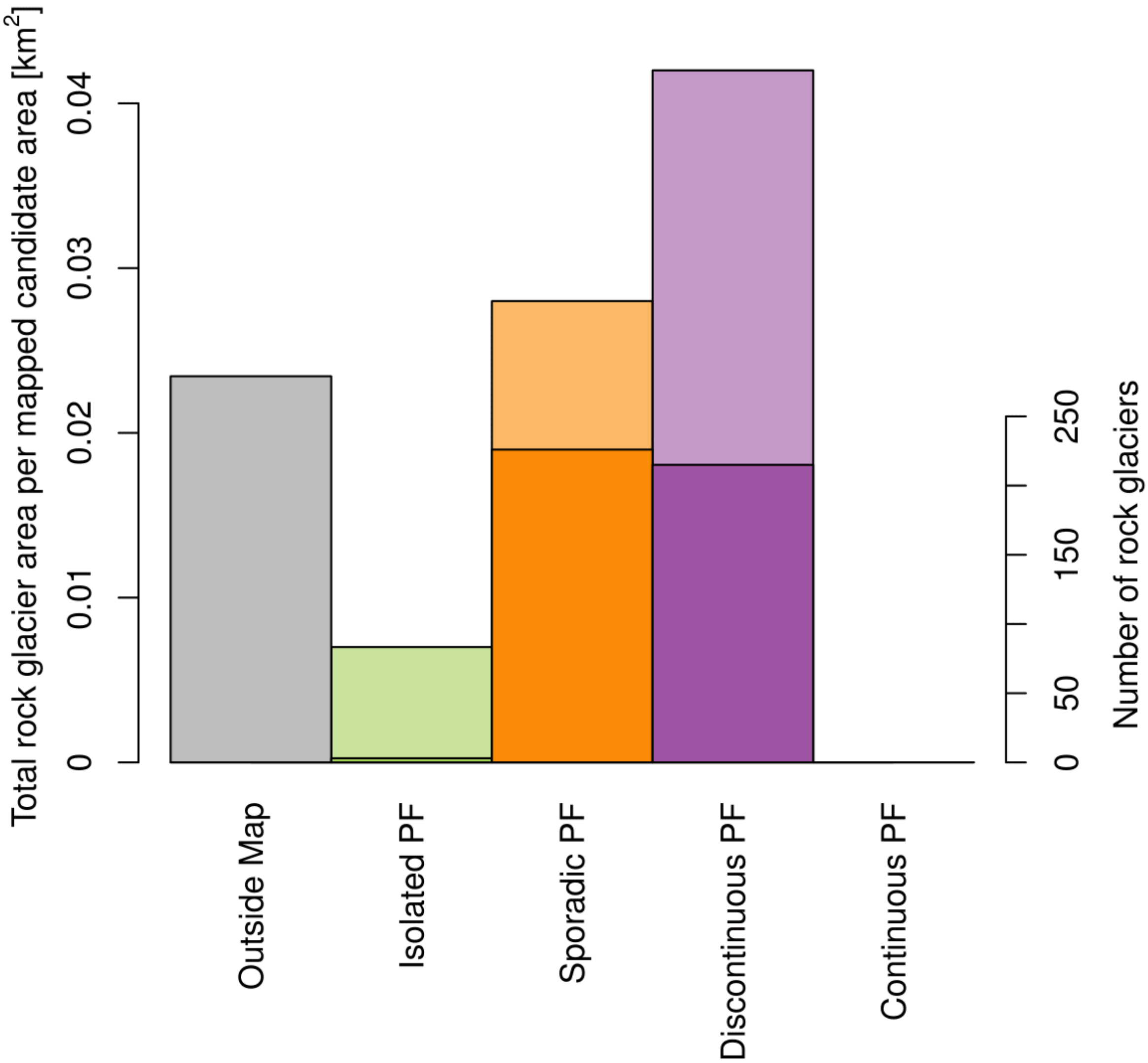

Fig 7: Comparison of all mapped rock glaciers with the Circum-Arctic Map of Permafrost (IPA map). Note that the category Continuous Permafrost does not occur in the investigation area. Mapped candidate area refers to areas in where rock glaciers can be expected to occur and to be observed; for each pixel, this is determined based on (a) topography (standard deviation of SRTM90 > 85m in each sample), (b) sufficient image quality in Google Earth, and (c) the absence of glacier cover. Intensive colours indicate the number of rock glaciers and pale colours represent the density of rock glaciers within a certain class.

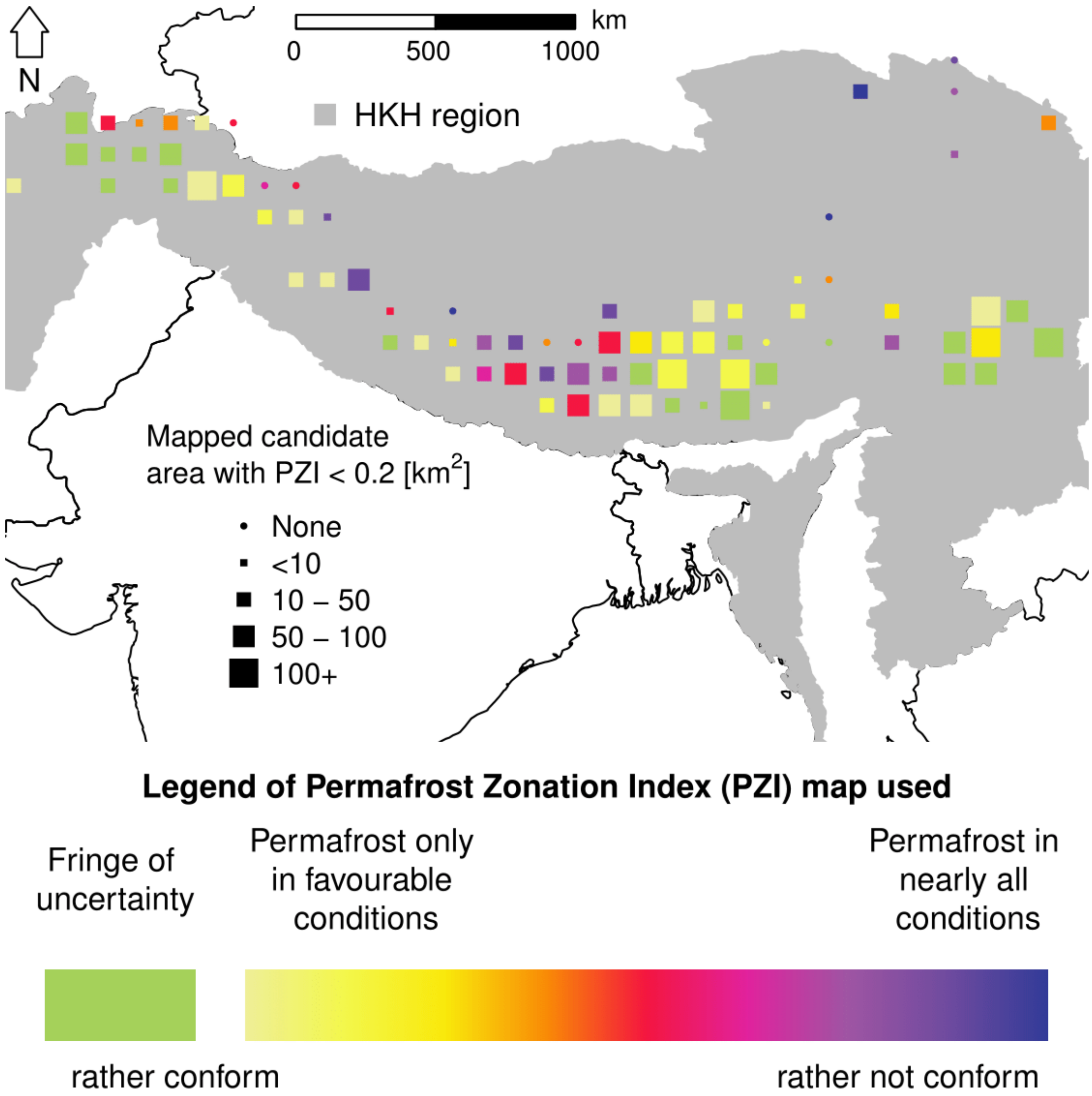

Fig 8: Spatial patterns of agreement between mapped rock glaciers and PZI. Colour indicates the lowest PZI value in the mapped rock glaciers within each 1° x 1° square. Green and yellow are signalling an apparent good agreement between lowest elevations reached by rock glaciers and predicted lowest possible elevations for permafrost by the PZI. The size of square symbols indicates the size of the mapped candidate area with PZI < 0.2. This is a proxy for whether or not rock glaciers with low PZI values can be expected in this area.