The Cryosphere Discuss., 8, 5293–5319, 2014
www.the-cryosphere-discuss.net/8/5293/2014/
doi:10.5194/tcd-8-5293-2014

The Cryosphere Discussions
Open Access

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

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Received: 30 July 2014 – Accepted: 22 September 2014 – Published: 15 October 2014

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Assessment of permafrost distribution maps in the HKH region using rock glaciers

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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 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 first-order assessment of permafrost maps of 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 4000 square samples (approx. 30 km^2) 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 3500 and 5500 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 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 changes on pastures, slope instability, hydrological changes, 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).

The HKH region includes mountains in parts of Afghanistan, Bhutan, China, India, Myanmar, Nepal and Pakistan (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 3500 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 proportion of permafrost: (a) the Circum-Arctic Map of Permafrost and Ground Ice Conditions (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 (cf. Heginbottom, 2002). (b) The Global Permafrost Zonation Index (PZI), available on a spatial grid of about 1 km resolution (Gruber, 2012). 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. monsoonal summer precipitation, hyperaridity, extreme elevation) for which only limited knowledge exists, and (c) only few 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, 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); 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 ice and 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

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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 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. 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 rock glaciers will always give a conservative estimate of the actual permafrost distribution.

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 lowermost elevations of rock glaciers are recorded to be around 4000 m a.s.l. (Hewitt, 2014). Many of the investigated rock glaciers have developed out of Little Ice Age moraines. 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 1000 mm (Owen and England, 1998). From the Khumbu region in Nepal the lower limit of active rock glaciers is reported to be between 5000 and 5300 m a.s.l. (Jakob, 1992). Further east in the Kangchenjunga Himal of Nepal, the distribution of rock glaciers varies from 4800 m a.s.l. on northern aspect to 5300 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 permafrost indicators 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 geo-rectified 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 and Harp, 2009). Despite its huge potential for research, Google Earth has not yet become a commonly used tool. This may partly be because neither spectral nor spatial properties of the displayed satellite images are easily acessible. 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.

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

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". Every sample received a unique name consisting of two capital letters and three numbers. With the R-function kmlPolygons from the 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

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not possible due to poor image quality, 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 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.

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 field of each rock glacier polygon.

Manual 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 4000 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 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).

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 4000 samples 3432 (86 %) received the same classification (No rock glaciers/Insufficient quality/Rock glaciers mapped) by both mapping persons. In 3 % of all samples only one mapping contained rock glaciers and 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). 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 image quality made it possible to discriminate rock glaciers from other (similar) landforms. It was possible to assess 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.

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). 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). 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.

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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. The lowest elevation was recorded in Northern Afghanistan at 3554 m a.s.l. and the highest elevation at 5735 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: (a) topography: only sample polygons where the vertical standard deviation of the SRTM 90 m 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. Figures 6 and 7 show how the terminus of

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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). 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) the investigation area and the mapped rock glaciers are predominantly in the two classes Discontinuous permafrost and Sporadic 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 aggregated to $1^{\circ} \times 1^{\circ}$ 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

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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 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 3500 m a.s.l. in Northern Afghanistan to more than 5500 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.

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

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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 rock glaciers being outside the PZI. Based on the information available, PZI is thus a reasonable first-order 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.

Data availability

The rock glaciers mapping, the source code to create the random samples and the outline of the HKH region is published as Supplement. Both mappings include all 4000 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.

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The Supplement related to this article is available online at doi:10.5194/tcd-8-5293-2014-supplement.

Author contributions. M.-O. Schmid developed the method; conducted the analysis and prepared the manuscript. S. Gruber conceived the study, supervised the development of the method and the analysis, and contributed significantly to the writing. P. Baral, S. Shahi and T. Shrestha did the mapping and provided general support. D. Stumm and P. Wester contributed to conceiving the study, secured funding, provided overall supervision and contributed to the writing.

Acknowledgements. This study was supported by ICIMOD through core funding by the Department for International Development (DFID) of the UK and by the governments of Afghanistan, Australia, Austria, Bangladesh, Bhutan, China, India, Myanmar, Nepal, Norway, Pakistan, and Switzerland. The views and interpretations in this publication are those of the authors. They are not necessarily attributable to ICIMOD and do not imply the expression of any opinion by ICIMOD concerning the legal status of any country, territory, city or area of its authority, or concerning the delimitation of its frontiers or boundaries, or the endorsement of any product.

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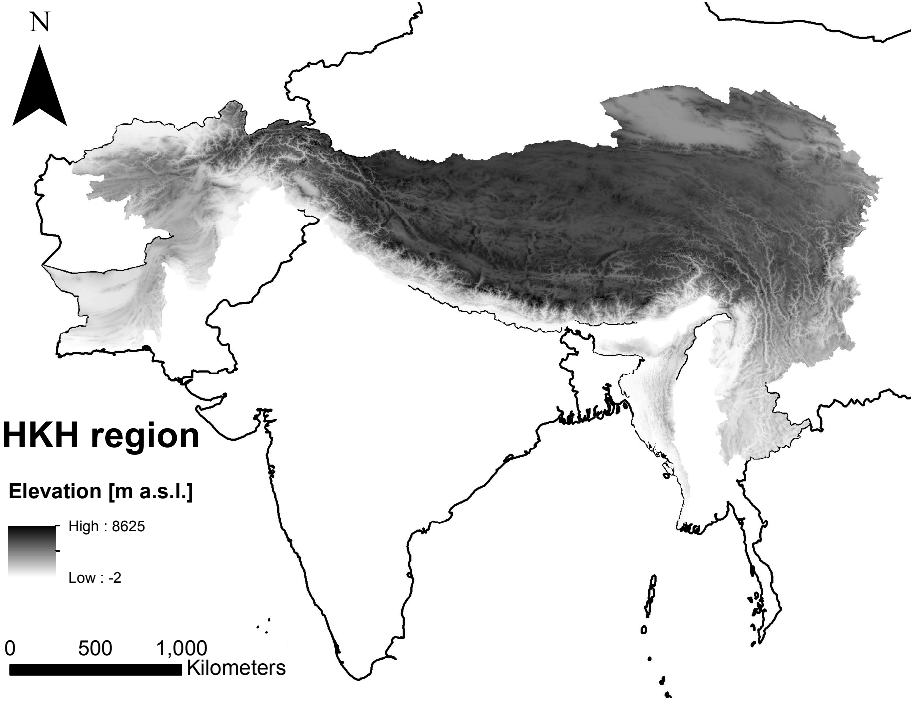

Figure 1. The HKH region as defined by ICIMOD which includes high mountains in Afghanistan, Bhutan, China, India, Myanmar, Nepal and Pakistan.

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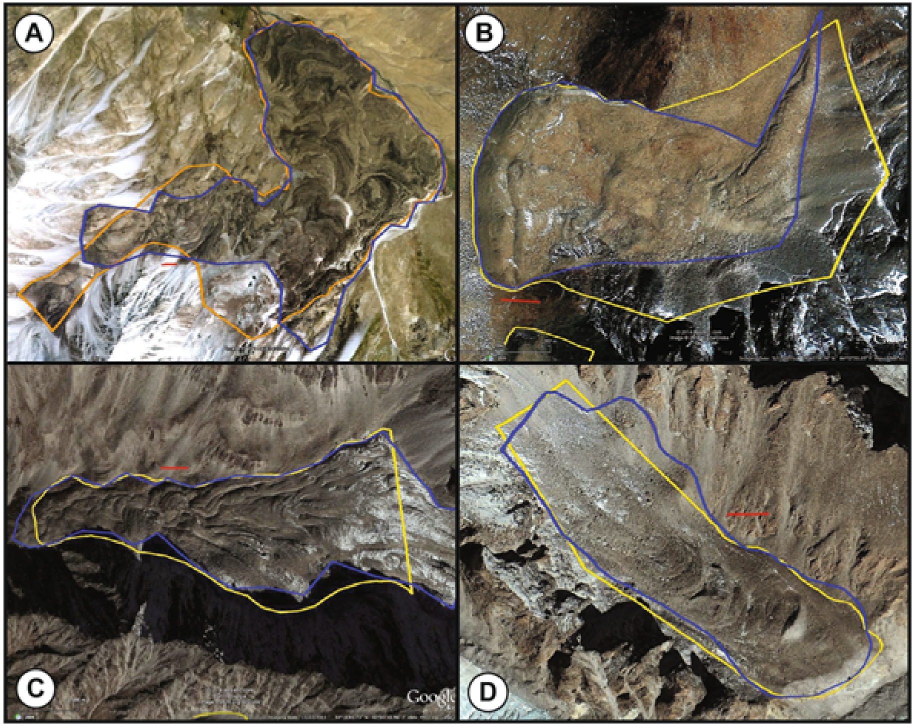

Figure 2. Examples of rock glaciers mapped by two different persons (red line = 100 m). All copyrights Image© 2014 DigitalGlobe.

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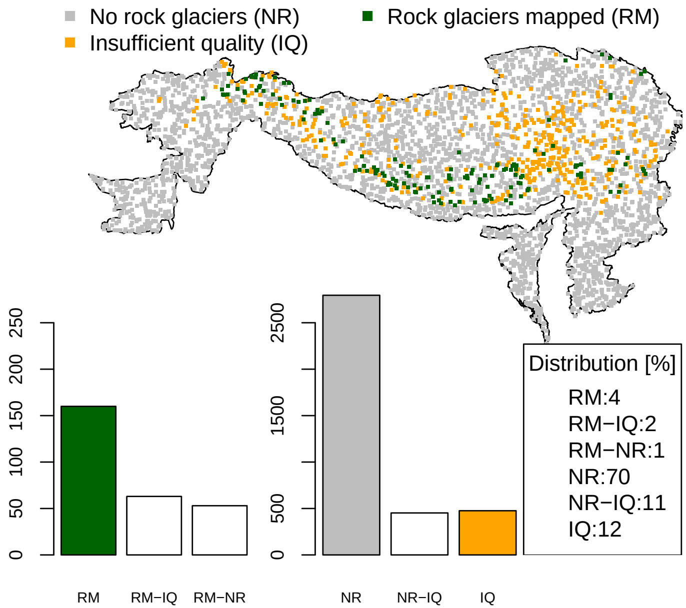

Figure 3. Overview of mapping results. All 3432 samples with the same classification from both mappings are shown. In the barplots, identically classified samples are shown with filled bars and samples, which were classified differently in white. Note that the difference in scale between the samples containing rock glaciers on the left and all others samples on the right is one order of magnitude.

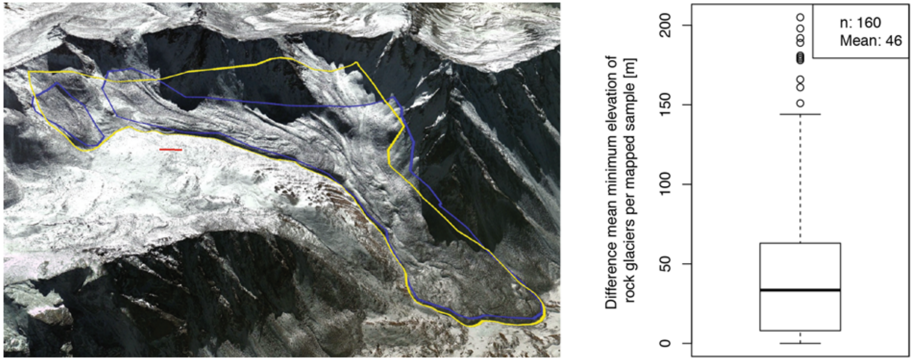

Figure 4. Example of differences between two mappings on the left (red line = 100 m). Copyright Image© 2014 DigitalGlobe. For the boxplot on the right only samples where both analysts have mapped rock glaciers were taken into account. The samples with big differences typically have only few rock glaciers,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

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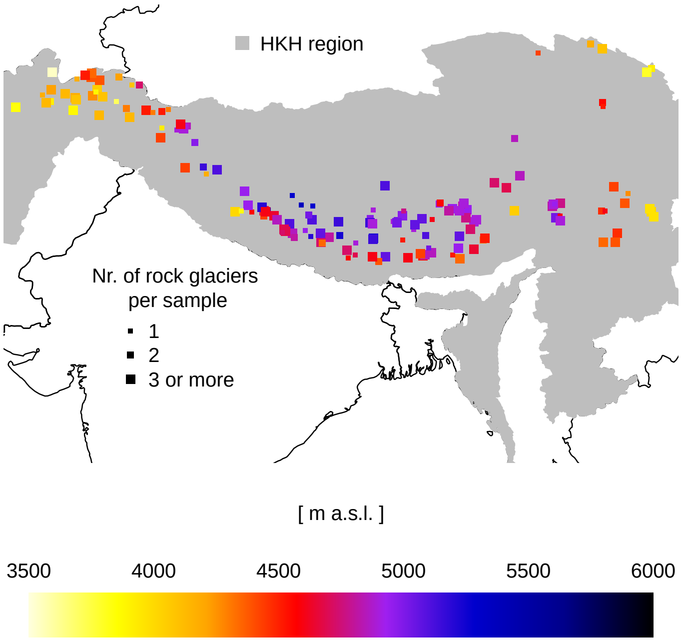

Figure 5. Mean minimum elevation of rock glaciers per sample. The size of the square indicates on how many rock glaciers this value is based on.

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Assessment of permafrost distribution maps in the HKH region using rock glaciers

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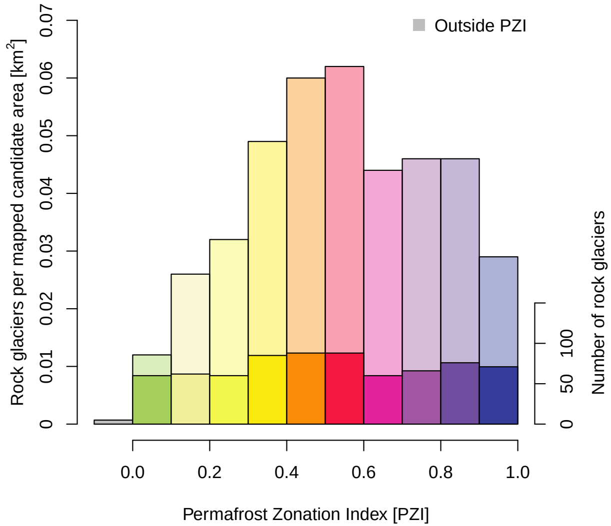

Figure 6. Mapped rock glaciers in relation to Permafrost Zonation Index summarized over the entire HKH region. Mapped candidate area refers to areas in where rock glaciers can be expected to occur and to be observed; for each pixel, this is determined based on **(a)** topography (standard deviation of SRTM90 > 85 m 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).

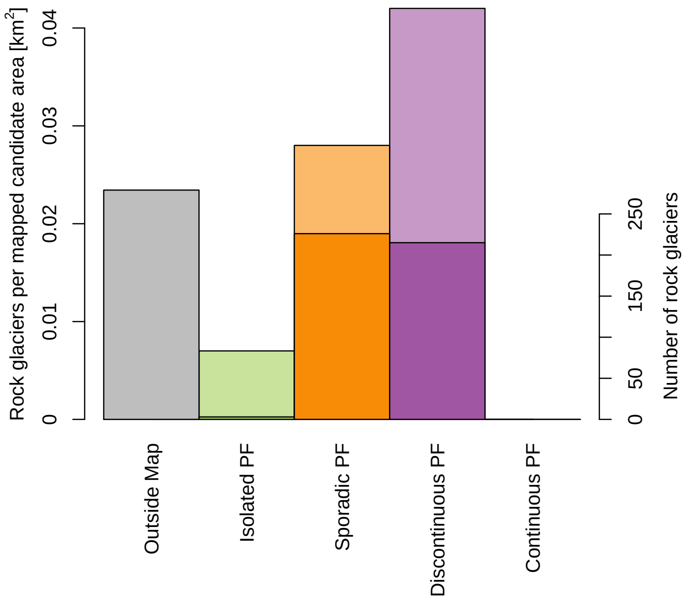

Figure 7. Comparison of all mapped rock glaciers with the Circum-Arctic Map of Permafrost (IPA map). Note that the category Continuous Permafrost does not occur in the investigation area. Mapped candidate area refers to areas in where rock glaciers can be expected to occur and to be observed; for each pixel, this is determined based on (a) topography (standard deviation of SRTM90 > 85 m 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.

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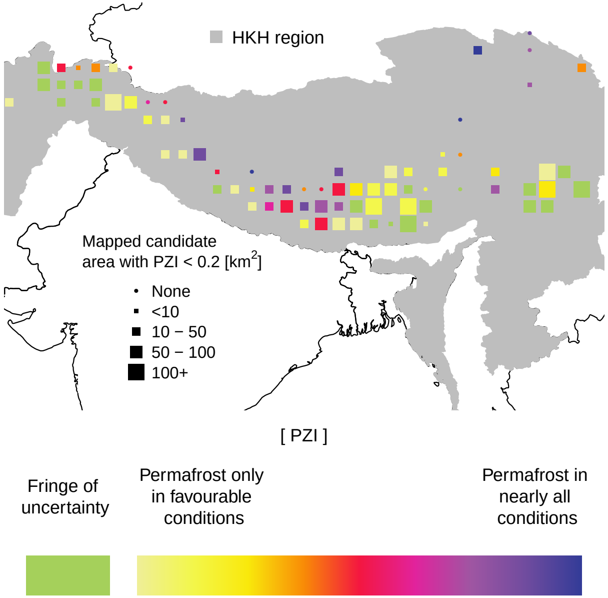

Figure 8. Spatial patterns of agreement between mapped rock glaciers and PZI. Colour indicates the lowest PZI value in the mapped rock glaciers within each 1° × 1° square. Green and yellow are signalling an apparent good agreement between lowest elevations reached by rock glaciers and predicted lowest 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.

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