Permafrost studies in Kullu district, Himachal Pradesh

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Collaborative Indo-Swiss research on permafrost has thrown new light on this rarely studied component of the Indian Himalayan cryosphere. Under a pilot study, first maps of estimated permafrost distribution in Kullu district, Himachal Pradesh, India have been produced, using a combination of simple topographic and climatic principles, more sophisticated numerical modelling, and mapping of permafrost indicators. Overall, 9% (420 sq. km) of the land area in Kullu is classified as permafrost terrain, extending down to as low as ~4200 m amsl in isolated instances. Between ~4200 and 5000 m amsl, permafrost underlies a surface area comparable in size to that overlaid by glacier ice. Hence, permafrost is identified as a significant component of the local cryosphere. These results now provide a scientific basis for assessing the wide-ranging potential impacts, hazards and risk associated with warming and thawing of frozen ground, with relevance for climate change adaptation studies across the entire Himalaya.

Keywords: Ground surface temperature, hazards, permafrost, rock glacier.

PERMAFROST is described as an essential climate variable by the World Meteorological Organization, yet little research on its occurrence and related landforms in the Indian Himalayan Region (IHR) has been reported so far[1–3]. Therefore, Indo-Swiss collaboration (within the Indian Himalayas Climate Adaptation Programme (IHCAP)) has recently been initiated to generate a first estimate of permafrost distribution in mountain areas of Kullu district, Himachal Pradesh, India, while strengthening local scientific capacity to ensure that the methodologies can be outscaled to the larger IHR. The methodology of the permafrost pilot study in Kullu, some preliminary results, and possible future activities are discussed in this research communication.

Permafrost refers to any ground material that remains at or below 0°C for at least two consecutive years[4]. Due to the close coupling between atmospheric and ground temperatures, permafrost is warming in many regions in response to global climate change[5]. The thawing of permafrost can have widespread impacts relating to destabilization of steep slopes, changes in subsurface hydrology, and increased sediment load in rivers[6,7]. As a consequence, permafrost thawing can strongly affect regional livelihoods, infrastructure and economies, and presents a particular threat to the rapidly expanding hydropower sector. There may also be benefits, as water released from slowly thawing permafrost may offset some of the diminished glacier resources in the mid to late 21st century, although this contribution is poorly constrained[8]. Therefore, determining the likely spatial extent of permafrost should be considered a fundamental component of any high mountain hazard and risk assessment. As subsurface

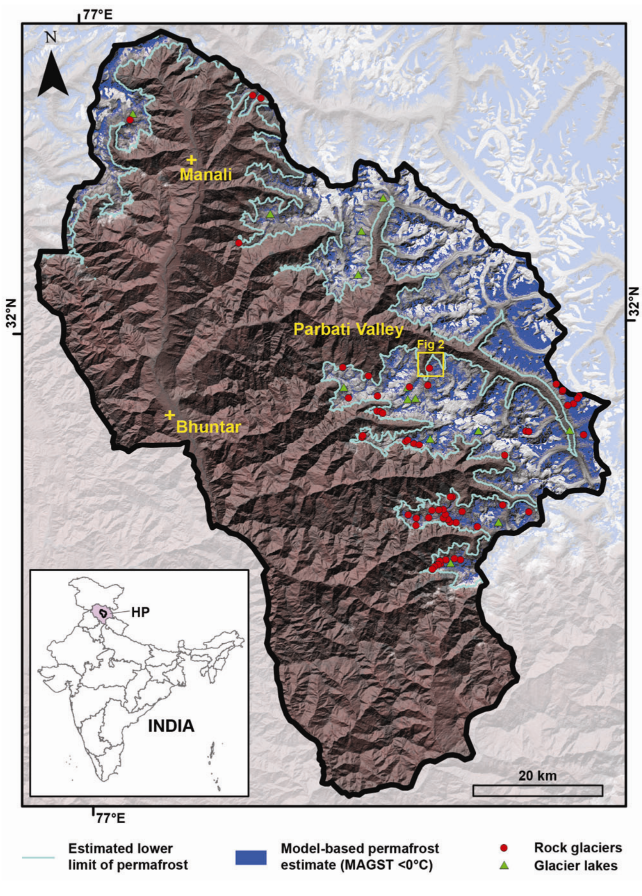

Figure 1. Mapped rock glaciers across Kullu district, Himachal Pradesh, India are compared with a model-based estimate of permafrost distribution. Also indicated is an empirically derived estimated lower limit of permafrost in Kullu district, where permafrost might be expected in extremely favourable topographic situations only. (Inset) Map showing the location of Kullu district within the Himalayan State of Himachal Pradesh (HP, shaded).

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temperatures are difficult and expensive to measure, permafrost extent is commonly inferred from measured and modelled air and ground surface temperatures. A first-order estimate of permafrost distribution for the entire Hindu Kush Himalayan region is provided by the ~1 km resolution Global Permafrost Zonation Index[9]. This approach shows good agreement with a randomly mapped sample of rock glaciers (a distinctive landform indicative of permafrost) across the Hindu Kush Himalaya, where minimum rock glacier elevations extend between 3500 and 5500 m amsl (ref. 3). However, for impact-relevant studies of permafrost, baseline information at higher spatial resolution is required that should include the influence of local climate and topography on ground temperature.

Kullu district is positioned in the western Himalaya (Figure 1) and is characterized by a sub-tropical monsoon climate. Largest glaciers occur above the Parbati river valley, a tributary of River Beas, and within the adjacent Great Himalayan National Park. High mountain peaks extend above 6500 m amsl, with typical debris-covered glacier snouts extending down to 3900–4450 m amsl. In response to atmospheric warming over the past century, glaciers in Kullu have fragmented and significantly reduced in size[10].

Our methodology for estimating permafrost distribution across Kullu draws on two modelling approaches with contrasting levels of sophistication. The first simple approach is based on fundamental European research beginning in the 1970s, which identified mean annual air temperature (MAAT) and slope topography as key factors governing permafrost distribution[11]. In Kullu, the local elevation of the 0°C MAAT isotherm was calculated from station data at Bhuntar (a central location at 1089 m amsl in the study region) and adjusted to all 30 m grid-cell elevations using a lapse rate of 5.6°C km^{-1} established from nearby station data at Manali (2050 m amsl) (see locations in Figure 1). Simple, empirically derived rules then provide a broad estimate of where permafrost is likely to occur based on topographic influences on solar radiation and snow thickness. These rules suggest that permafrost is most likely to be found at elevations some hundreds of metres above the 0°C isotherm (particularly on slopes with high insolation), but more rarely, it can also be found at considerably lower elevations (with MAAT >0°C) in the most topographically favourable situations, e.g. in shaded locations at the foot of steep slopes where late-lying snow can insulate from warm summer temperatures[12,13]. Such basic rules defining permafrost limits should not be simply transferred to the Himalayan setting. However, they provide a useful starting point for introducing and discussing topographic controls on ground temperature, and thereby set the stage for use of physically based numerical models that explicitly capture these driving processes. In a second, more sophisticated approach, such state-of-the-art numerical models were driven by downscaled atmospheric datasets (ERA-Interim), enabling large area simulations of the surface/subsurface at high spatial resolution (downscaled to ASTER 30 m DEM)[14,15]. The initial modelled area of 24,000 sq. km is centred on high mountain terrain of Kullu district, and permafrost conditions are inferred where modelled mean annual ground surface temperature (MAGST) is below 0°C (Figure 1).

Preliminary results indicate that permafrost may extend down to 4200 m amsl in favourable instances, which compares favourably with the observed lower elevation limit from the ca. 60 mapped rock glaciers in Kullu district (interquartile range 4280–4560 m amsl), and approximate lower limits to permafrost distribution established in relation to the local 0°C MAAT isotherm (Figures 1–3). This general consistency is promising, although it must be emphasized that in addition to the presence of permafrost, rock glaciers require other climatic, hydrological and geomorphological conditions to develop[16]. Therefore, the absence of rock glaciers, as seen in the heavily glaciated northeastern area of Kullu (Figure 1), does not indicate an absence of permafrost. Also, due to their slow dynamical downslope motion, the lower limit of rock glaciers does not necessarily correspond directly with the lower limit of permafrost; therefore, the rock glacier zone can extend down below current expected permafrost limits (Figure 3).

In total, around 9% (420 sq. km) of the modelled land area in Kullu district (excluding glaciers) is classified as permafrost, and between ca. 4200 and 5000 m amsl permafrost underlies a surface area comparable in size to that overlaid by glacier ice (Figure 3). Hence, permafrost is identified as a significant component of the local cryosphere. Given that MAAT over Kullu has warmed by up to 2°C over the past century[17], it is almost certain that permafrost distribution has altered substantially over recent decades. For example, other studies have recorded an increase in lower elevation limits of permafrost of up to 80 m in the Tibetan Plateau[7], and up to 300 m in the Khumbu region of Nepal[18] since the 1970s. Such a significant shift implies that slopes within certain critical elevation zones have recently thawed completely, or are continuing to thaw at depth (owing to an offset between surface warming, and warming at depth[19]), with implications for hazards and risk.

More than 50% of the modelled permafrost land area in Kullu is characterized by slopes less than 35°, a threshold commonly used to distinguish debris-covered slopes from steeper bedrock. Thawing of permafrost in such regions is a potential hazard that could lead to debris instabilities and increased sediment load in waterways and reservoirs, particularly during heavy monsoon rain, or snowmelt, or following large earthquakes. Permafrost also appears to be of potential relevance for all glacier lakes in the area, which are located within or immediately beneath permafrost terrain (Figures 1 and 3). Thawing of permafrost may destabilize lake dams, and rockfall or debris flows

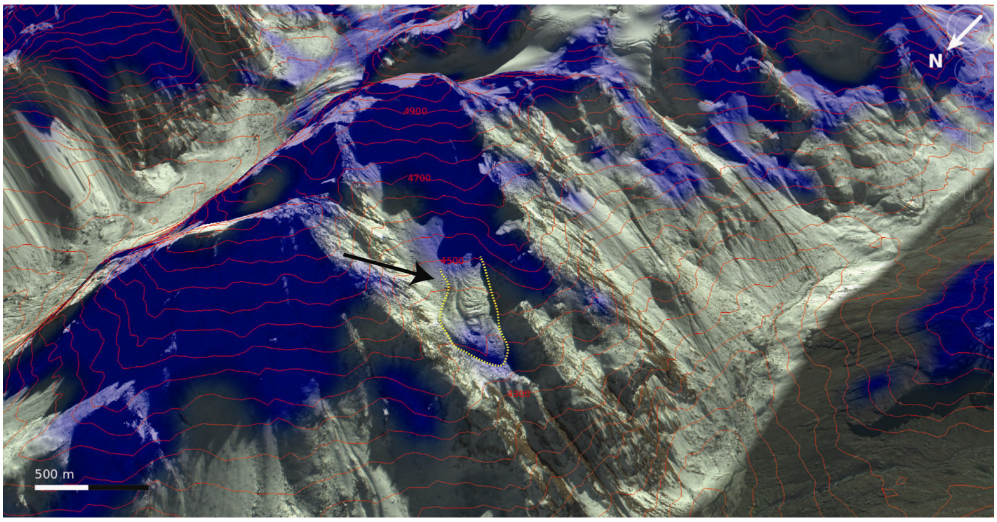

Figure 2. Model-based permafrost estimate (MAGST <0°C) in the upper Parbati Valley, Kullu district (shaded). In the centre of the *Google Earth* scene, the distinctive creeping, lobe-like formation of a rock glacier is evident (arrow – dashed outline), initiating around 4600 m amsl, and extending down to around 4350 m amsl. See Figure 1 for scene location.

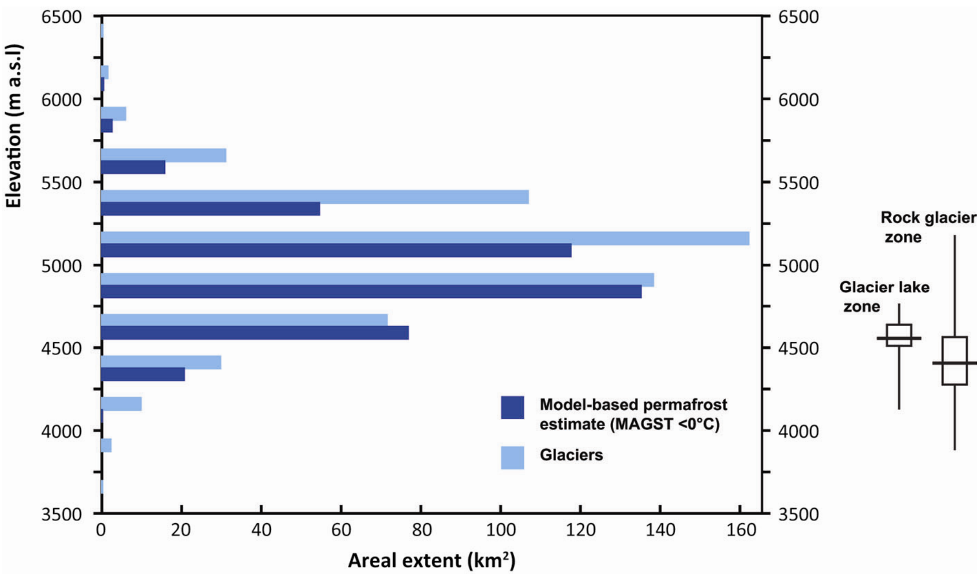

Figure 3. Distribution of permafrost classified terrain and mapped glacier area within 250 m elevation bands in Kullu district. The box and whisker plots on the right show the elevation distribution of mapped rock glaciers (frontal lobe position) and glacier lakes – the whiskers give the maximum and minimum elevations, the box shows the 25th to 75th percentile range and vertical bar gives the median elevation.

from surrounding slopes may cause overtopping waves or block outlet channels. Such concerns were not included in previous glacier lake outburst flood (GLOF) hazard assessment schemes in IHR[20,21].

The preliminary results presented here should be treated cautiously in the absence of comprehensive field validation. While some initial evaluation has been completed using mapped rock glaciers as indicators of permafrost, field validation is now required to improve confidence and enable outscaling of our modelling approaches to larger remote and data-poor mountain regions. A toolbox of permafrost measurement and monitoring techniques is available and applications should be prioritized based on available resources and local objectives. Cost-effective, miniature temperature data-loggers can record ground surface temperatures at high spatial and temporal resolution[22], and are required to validate modelled MAGST, the proxy that we are using to infer permafrost conditions. Direct validation of permafrost occurrences can only be based on temperatures measured at depth or geophysical techniques that can determine the presence of ground ice[23]. Other methods based on repeated digital terrain mapping or high precision GPS can identify surface deformation related to the activity of rock glaciers or thawing of frozen ground[24]. In general, field campaigns should be targeted towards critical locations, e.g. where lakes are dammed in permafrost terrain, and ideally areas where there is good access in view of long-term monitoring and repeat visits.

The Kullu pilot study has provided some preliminary understanding of the possible extent and relevance of permafrost in this region. Scientific partnerships established within this study now provide a sound basis for formulating further measurement and monitoring projects that may extend across the wider Himalayan area in future.

1. Mayewski, P. A. and Jeschke, P. A., An active rock glacier, Wavbal Pass, Jammu and Kashmir Himalaya, India. *J. Glaciol.*, 1981, **27**(95), 201–202.
2. Owen, L. A. and England, J., Observations on rock glaciers in the Himalayas and Karakoram Mountains of northern Pakistan and India. *Geomorphology*, 1998, **26**, 199–213.
3. Schmid, M.-O., Baral, P., Gruber, S., Shahi, S., Shrestha, T., Stumm, D. and Wester, P., Assessment of permafrost distribution maps in the Hindu Kush Himalayan region using rock glaciers mapped in Google Earth. *Cryosphere*, 2015, **9**, 2089–2099.
4. van Everdingen, R. (ed.), *Multi-Language Glossary of Permafrost and Related Ground-Ice Terms*, National Snow and Ice Data Center, Boulder, CO, USA, 1998.
5. Vaughan, D. G. *et al.*, *Observations: Cryosphere*, in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (eds Stocker, T. F. *et al.*), Cambridge University Press, Cambridge, United Kingdom, 2013, pp. 317–382.
6. Harris, C., Climate change, mountain permafrost degradation and geotechnical hazard. In *Global Change and Mountain Regions. An Overview of Current Knowledge* (eds Huber, U. M., Bugmann, H. K. M. and Reasoner, M. A.), Springer, Dordrecht, 2005, pp. 215–224.
7. Yang, M., Nelson, F. E., Shiklomanov, N. I., Guo, D. and Wan, G., Permafrost degradation and its environmental effects on the Tibetan Plateau: a review of recent research. *Earth-Sci. Rev.*, 2010, **103**, 31–44.
8. Sorg, A., Bolch, T., Stoffel, M., Solomina, O. and Beniston, M., Climate change impacts on glaciers and runoff in Tien Shan (Central Asia). *Nature Climate Change*, 2012, **2**, 725–731.
9. Gruber, S., Derivation and analysis of a high-resolution estimate of global permafrost zonation. *Cryosphere*, 2012, **6**, 221–233.
10. Kulkarni, A. V. and Karyakarte, Y., Observed changes in Himalayan glaciers. *Curr. Sci.*, 2014, **106**(2), 237–244.
11. Etzelmüller, B. *et al.*, Mapping and modelling the occurrence and distribution of mountain permafrost. *Norw. J. Geogra.*, 2001, **55**, 186–194.
12. Hoelzle, M., Permafrost occurrence from BTS measurements and climate parameters in the Eastern Swiss Alps. *Permafrost Periglacial Process.*, 1992, **3**, 143–147.
13. Imhof, M., Modelling and verification of the permafrost distribution in the Bernese Alps, Western Switzerland. *Permafrost Periglacial Process.*, 1996, **7**, 267–280.
14. Fiddes, J. and Gruber, S., TopoSUB: A tool for efficient large area numerical modelling in complex topography at sub-grid scales. *Geosci. Model Develop.*, 2012, **5**, 1245–1257.
15. Fiddes, J. and Gruber, S., TopoSCALE v.1.0: downscaling gridded climate data in complex terrain. *Geosci. Model Develop.*, 2014, **7**, 387–405.
16. Haeberli, W. *et al.*, Permafrost creep and rock glacier dynamics. *Permafrost Periglacial Process.*, 2006, **17**, 189–214.
17. Bhutiyani, M. R., Kale, V. S. and Pawar, N. J., Long-term trends in maximum, minimum and mean annual air temperatures across the Northwestern Himalaya during the twentieth century. *Climatic Change*, 2007, **85**, 159–177.
18. Fukui, K., Fujii, Y., Ageta, Y. and Asahi, K., Changes in the lower limit of mountain permafrost between 1973 and 2004 in the Khumbu Himal, the Nepal Himalayas. *Global Planet. Change*, 2007, **55**, 251–256.
19. Noetzli, J. and Gruber, S., Transient thermal effects in Alpine permafrost. *Cryosphere*, 2009, **3**, 85–99.
20. Ives, J. D., Shrestha, R. B. and Mool, P. K., Formation of glacial lakes in the Hindu Kush-Himalayas and GLOF risk assessment, ICIMOD, Kathmandu, 2010.
21. Worni, R., Huggel, C. and Stoffel, M., Glacier lakes in the Indian Himalayas – from an area-wide glacial lake inventory to on-site and modeling based risk assessment of critical glacial lakes. *Sci. Total Environ.*, 2013, **468–469**, s71–s84.
22. Gubler, S., Fiddes, J., Keller, M. and Gruber, S., Scale-dependent measurement and analysis of ground surface temperature variability in alpine terrain. *Cryosphere*, 2011, **5**, 431–443.
23. Hauck, C., New concepts in geophysical surveying and data interpretation for permafrost terrain. *Permafrost Periglacial Process.*, 2013, **24**, 131–137.
24. Kääb, A., Remote sensing of permafrost-related problems and hazards. *Permafrost Periglacial Process.*, 2008, **19**, 107–136.

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Identification of potential glacial lake sites and mapping maximum extent of existing glacier lakes in Drang Drung and Samudra Tapu glaciers, Indian Himalaya

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The Himalayan glaciers feed major Asian river systems sustaining the lives of more than 800 million people. Though the rates of retreat of individual glaciers are uncertain, on the whole the Himalayan

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