Landscape response will reduce glacier sensitivity to climate change in High Mountain Asia

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Preface

In High Mountain Asia (HMA) climate change threatens mountain water resources as glaciers melt, and the resulting changes in runoff and water availability are hypothesised to have considerable negative impacts on ecological and human systems. Numerous assessments of the ways in which glaciers will respond to climate warming have been published over the past decade. Many have used climate model projections to argue that HMA glaciers will melt significantly this century. However, we show that this is only one way in which glaciers might respond. An alternative scenario is one in which increasing valley-side instability releases large amounts of rock debris onto glacier surfaces. This then inhibits glacier melting to the extent that glacier ice becomes preserved under a thick rock debris cover. We call this alternative scenario the Paraglacial Transition and this has rarely been articulated in the context of HMA. In this paper we discuss this landscape transition and use understanding of past glacier dynamics to assess its likelihood. Better understanding of how HMA glaciers respond to climate change is critical for underpinning climate change adaptation strategies and to ensure that this highly populated region is in a strong position to meet sustainable development goals.

Key Words: High Mountain Asia. Glaciers. Paraglacial. Climate change.

1 Introduction

There is great interest in understanding how glaciers of High Mountain Asia (HMA) are likely to evolve under climate change[1]. Given the likely warming of 1.9 – 6.5 °C by the end of the twenty-first century under the Coupled Model Intercomparison Project Phase 6 (CMIP6) scenarios[2], this understanding becomes a critical issue. On this depends the livelihoods of hundreds of millions of people and the stability of ecosystems downstream. Eight of the 27 low-income and lower-middle-income economies identified by the United Nations Development Programme in Asia are currently affected by climate-driven water supply issues in the Himalaya and other parts of HMA. Given this, the Sustainability Development Goals (SDGs), adopted by all United Nations (UN) and Asian governments aims to substantially increase by 2030 the water-use efficiency across all sectors, to ensure sustainable withdrawals and supply of freshwater, while reducing the number of people experiencing water scarcity (e.g. [3,4]). There are also concerns about the impact of future glacier ice loss on global sea level change [5,6] and on glacier-related hazards such as glacier lake outburst floods (GLOFs; e.g.[7]), rock slides and falls (e.g. [8]) and rapid changes in sediment yield (e.g. [9]).

Given these concerns, there has been a long-standing scientific and policy focus on modelling changes in glacier mass balance and understanding the implications of climate change for water supplies and hydro-electric project infrastructure in downstream catchments (e.g.[10]). Numerous modelling studies have projected the impact of climate change on glacier mass loss in the HMA[11-15] and downstream river runoff[1,16-18] (Table 1). Since 2013, these have tended to use the outputs from CMIP5 set of model runs; while the latest CMIP6 model runs are now available, few projections from this have so far been employed.

Insert Table 1

While existing modelling approaches are useful to assess scenarios of future ice loss from the region (Table 1), these generally assume that the different ways in which mountain glaciers will evolve under future climate change has been accurately captured. This is not necessarily the case[19]. The common view is that climate change is expected to lead to the almost complete melting of glaciers in HMA by the end of this century[11,13] and this is supported by most modelling studies. This arises from a combination of reduction in accumulation as more precipitation falls in the form of rain and due to enhanced melting associated with rising temperatures. There are, however, regional differences in mass loss projections across HMA and this partly reflects model uncertainty at fine spatial scales[20]. Kraaijenbrink et al[13] used a global ensemble of 110 GCM runs from CMIP5 to assess the glacial response driven by emissions under RCP2.6 scenarios and a consequent increase in Global Mean Surface Temperature (GMST) of 1.5 °C above pre-industrial conditions. This suggests a probable warming of 2.1 ± 0.1 °C for the glacial regions of HMA, although this is likely to be an underestimate given current and future emissions. They also assessed likely regional changes and argue that the Hissar Alay in the western Pamir and the Qilian Shan of northern China will lose most of its glacier mass by 2100 with only 32 ± 14% and 30 ± 5% ice mass remaining respectively. The Karakoram region shows more resilience to climate warming, with a projected 80 ± 7 % of ice volume remaining by 2100. While this has been attributed partly to the role of supraglacial debris cover in maintaining ice mass and the role of winter precipitation in maintaining accumulation[21], the role of supraglacial debris remains controversial. Kraaijenbrink et al.[13] were one of the first to model the impact of debris cover on glacier melt under climate projections and they showed that under RCP4.5, RCP6.0 and RCP8.5 glacier mass losses would be 49 ± 7 %, 51 ± 6 % and 64 ± 5 %, respectively, by 2100 compared with the present day. Recently, Compagno et al[22] used five Shared Socioeconomic Pathways (SSP119, SSP126, SSP245, SSP370, and SSP585) from CMIP6 to assess the future evolution of debris cover and its impact on glacier dynamics for all HMA glaciers. They showed a general increase in glacier debris cover, as well as local increases in debris thickness on individual glaciers (see also [23,24]). At a smaller scale, Rowan et al[25] applied a numerical model to estimate the evolution of the debris-covered Khumbu Glacier and predicted a decrease in glacier volume of 8–10% by the year 2100.

Similarly, Shannon et al.[26] used high-sensitivity runs from an ensemble of CMIP5 models to model future glacier mass balance over the Himalayas using JULES. The (CMIP5) models were downscaled using the high-resolution HadGEM3-A GCM. The region was subdivided into South Asia West (covering the western Himalaya and Karakoram regions of India and Pakistan) and South Asia East (covering the Indian, Nepalese and Bhutan Himalaya) as defined in the Randolph Glacier inventory (RGI) version 6.0[27]. Results from this study are shown in Figures 1 and 2 discussed below, but they do suggest a reduction in glacier volume of between 98 ± 1 % for South Asia West (including the western Himalaya and Karakoram) and 95 ± 2 % for South Asia East (including India, Nepal and Bhutan) under a RCP8.5 forcing scenario by 2100.

Insert Figure 1 and 2

While such modelling experiments suggest high glacier volume loss by 2100, more work needs to focus on the likely geomorphic response to glacier mass loss. These include processes such as rock slope failures, debris flows and other mass movements into valley bottoms. All such processes deliver debris to glacier surfaces and therefore contribute to reduced melting through insulation of the ice beneath, alongside downstream changes in sediment supplies and changes in river transport capacity. In addition, given current estimates of Equilibrium Climate Sensitivity (ECS; e.g. [28,29]), it seems highly unlikely that the rise in GMST can be restricted to just 1.5 °C, and this makes such modelling with low radiative forcing scenarios (and presumed low ECS) rather conservative. This is made even more unlikely given a present increase of GMST compared with pre-industrial values of over 1.0 °C triggered by just 412 parts per million of atmospheric CO_2 concentrations and associated radiative forcing[30].

In this paper, we explore some of the implications of these modelling exercises (the majority of which project sustained reduction of glacier mass balance, e.g. [6]) and suggest some plausible alternative scenarios for how glacier systems in HMA might evolve over the rest of this century and beyond. We consider two broad scenarios of how mountain glaciers might respond to climate change: the Major Ice Loss view (MIL) and the Paraglacial Transition (PT) view. Both of these will necessarily represent gross simplifications of glacier behaviour and primarily explore how glaciers could evolve. Both, however, unintentionally mask significant regional variations in response to the physiographical and climatic differences over HMA. Given this caveat, we end by exploring some of these regional differences.

3. Scenarios

3.1 Major Ice Loss (MIL) view

The conventional MIL view is that future climate warming will result in widespread glacier recession and almost total ice loss in some parts of the Himalayas and the wider HMA, particularly the eastern HMA areas (e.g.,[6,11,13]). This is the current understanding of much of the scientific community and is supported by the modelling projections made by the Glacier Model Intercomparison Project (glacierMIP1[14], the subsequent glacierMIP2[5] and the third phase (glacierMIP3) which is underway, which focuses on the equilibration of glaciers under various climatic conditions. GlacierMIP was a coordinated intercomparison of global-scale glacier evolution models using standard initial glacier conditions - glacier outlines from the RGI v6 inventory[27,31] and ice thickness from [32] - forced with various GCMs under four climate change scenarios. The participating glacier models varied in complexity: for example, some models used temperature index schemes to calculate global-scale glacier volume projections by 2100 while others used full energy balance models. Models also differed in the complexity with which glacier evolution was represented and each model had a bespoke approach to calibration. The consensus view from the glacierMIPs, however, is that glaciers in the three RGI regions covering HMA will experience significant reductions in ice volumes under the business-as-usual RCP8.5 climate change scenario (Table 1).

3.1.1 Impacts associated with the MIL view

In essence, the MIL scenario eventually produces a HMA landscape consisting of much-reduced glacier cover with small glaciers remaining at the highest altitudes and in some niche locations. Associated with negative glacier mass balance and consequent glacier retreat is the hypothesised increased frequency and magnitude of a number of glacier-related hazards (e.g. [33,34]). Amongst the most important of these are GLOFs caused by the catastrophic drainage of glacial lakes dammed by unstable moraines (e.g. [7,35-37]) and

Landslide Lake Outburst Floods (LLOFs; [38]) caused by breaching of lakes created by landslides. Other negative impacts include ecosystem changes the potential reduction of water supplies downstream, increased seasonal discharge variability, increased sediment fluxes and the impacts this has on agriculture, hydroelectric power plants and dams in regional catchments[1,9,39,40].

Under this scenario, current glacier mass balance trends are exacerbated, leading to large numbers of proglacial lakes in overdeepened basins and dammed by unstable moraines, and the slow melting of clean ice and debris-covered glaciers (e.g. [41]). Locally these lakes are potentially hazardous, but by 2100 the HMA -wide GLOF peak will have already been reached and will be subsiding[7,42]. However, leading up to this end result would have been decades when GLOFs, LLOFs and other mountain hazards became more frequent and, perhaps, larger than in the recent historical period[43,44].

3.2 Paraglacial Transition (PT): an alternate view

Despite the focus of much research on the MIL view, we argue that this misrepresents the ways in which HMA glacier systems would evolve under climate warming, and here we suggest an alternative view. This alternative view is of a HMA glacial landscape modified and increasingly dominated by paraglacial processes, and we refer to this as the Paraglacial Transition (PT) view. Paraglacial processes develop in response to deglaciation and are characterised by increased rock slope failures from steep mountain slopes as these are de-buttressed by glacier down-wasting, and by increased debris flow activity from degrading lateral moraines and related fluvial adjustment [34,45,46].

In the PT scenario, one end result is the potential for many stagnant clean ice glaciers to become covered by rock debris and some of these undergoing renewed movement as rock glaciers[47,48]. Numerical modelling studies show the glacier debris-cover-rock glacier continuum[49]. However, none of the models used in glacierMIP1 and the subsequent glacierMIP2 project[5] consider a transition of ice or debris covered glaciers into rock glaciers. In addition, while historically little has been written on these features in the Himalaya, recent research has shown that rock glaciers are widely distributed in all parts of the Himalaya[50,51] (Figure 3) and there are suggestions that some ice glaciers and debris-covered glaciers are currently undergoing a transition to form rock glaciers[47-49]. The present distribution of rock glaciers across the Himalaya has recently been estimated by[50] (Figure 3).

If this PT scenario applies widely then rock glaciers eventually will largely replace clean ice glaciers (and perhaps debris-covered glaciers) as the main ice-bearing landforms in the HMA, perhaps alongside ice-cored moraines and ice-rich permafrost, with important implications for future water supplies[19,50].

This paraglacial path might result in a decreased GLOF hazard over time (although an increased rock slope failure hazard). There may be some lakes impounded by rock glaciers but these would expect to drain slowly rather than catastrophically given the armoured nature of the rock dam.

There are likely to be important regional variations in the response of clean ice glaciers, debris-covered glaciers and rock glaciers to future climate change. While these regional differences remain unexplored (although see [52]), we can hypothesise that the areas that will undergo the ice glacier to rock glacier transition most readily will be those where debris-covered glaciers are most common. Improved understanding of these processes is hampered by the relative lack of modelling at regional scales that specifically considers the role of debris cover on glacier dynamics and mass balance (e.g.[53]).

One way to assess which of the MIL and PT scenarios are more likely and their spatial distribution, is to understand how glaciers have behaved in the past in response to known climate forcing, and we can identify this as their glacier sensitivity[54]. If the glaciers have demonstrated a high sensitivity to past climate change then this tends to support the MIL scenario which argues that present glaciers will also be sensitive to future climate change. Alternatively, if the glaciers have shown low sensitivity to past climate change then this might make the PT more likely, even if the forcing is different at different times. To explore this we need to establish the extent to which clean ice glaciers and debris-covered glaciers have responded to the warming since the Last Glacial Maximum, Younger Dryas or the global Little Ice Age.

To do this, we compiled published studies that have dated Himalayan moraine sequences from the Western, Central and Eastern Himalaya. We analysed moraine ages from three time periods: the regional Last Glacial Maximum from 18 to 24 ka[55], a period covering the regional Younger Dryas from 12880 and 11640 ka[56] and the regional Little Ice Age between 1300-1600 AD[57](Figure 3). While there is evidence that glaciers in several areas reached their late Pleistocene limits earlier than Marine Isotope Stage (MIS) 2[55,58], overall these data show that glaciers in the Himalayas have not receded far behind dated glacier limits over these time periods. Figure 3 shows that glaciers in different regions of the Himalayas have responded differently to past climate change. The results are averaged by region and show considerable local variability. However, overall, glaciers in the western and central regions of HMA have retreated less over these time periods than those in the eastern part of the Himalaya, and this might reflect the reduction of monsoon and intensification of westerly influences on glacier mass balance towards the western Himalaya[59,60].

Insert Figure 3

Another way to assess glacier response to climate change is by monitoring their equilibrium-line altitude (ELA), i.e., the altitude on the glacier where mass balance is zero at a given point in time[61,62]. For instance, in the Khumbu region in the central Himalaya Marine Isotope Stage 2 moraines (equivalent in age to the global Last Glacial Maximum) are located just 5 km or so from modern ice limits and in many cases reflect a 200-300 m reduction in glacier ELA at this time compared with current glacial ELAs in the region[63] and also reduced insolation driving a weakened monsoon[55]. At the western end of the Himalayas much research has concentrated on the Nanga Parbat massif to the south of the Karakoram. Here work has shown that glaciers draining Nanga Parbat do not show an OIS/MIS Stage 2 advance, although moraines of OIS/MIS Stage 3 are present down-valley[64]. This lack of an LGM advance of the glacier probably reflects aridity during Stage 2 in this region and therefore low glacier sensitivity to atmospheric temperatures at this time[65].

Glacier recession since the regional Little Ice Age maximum of the late 18th century also supports the low sensitivity of many Himalayan glaciers to climate change[57]. For instance, Little Ice Age moraines below Ama Dablam and Lhotse in the Khumbu region show glacier recession of around 1 km since that time. Similarly, in the monsoon-transition zone of the

Indian Himalaya, the debris-covered Bara Shigri Glacier has retreated less than 3 km since the 1850s[66]. Overall, Figure 3 demonstrates that glacier termini in the western and central parts of the Himalaya have retreated less than 2km since the end of the LIA. Compared with considerable volumetric ice loss since the LIA[67], if past glacier response in the future mirrors that in the past then this supports our contention that future glacier loss will involve downwasting of glacier surfaces rather than terminus retreat. We argue that this favours the development of stagnant glacier tongues and therefore further transition to rock glaciers[47].

From this, we can show that glaciers from the western, eastern and northern parts of the Himalaya have displayed low sensitivity to climate change during Little Ice Age and LGM times, and we suggest that this supports the PT scenario of likely glacier response to future climate change.

4. Discussion

While the MIL scenario will also produce a range of paraglacial processes from deglaciating catchments, this will not essentially change the future evolution of glacier systems which just melts in response to climate warming and likely changes in precipitation. The MIL view continues to dominate the discussion of climate impacts in the Himalaya with numerous papers being published on climate model assessments of glacier melt. An analysis of published and archived work on glacier behaviour within Web of Science reveals that over the past two decades more than 1000 papers addressing glacier behaviour and referencing the terms ‘glacier’ and ‘Himalaya’ have been published in scientific journals (the precise number depends on a qualitative assessment of article content, which is beyond the scope of our work). However, just 17 of these 1000 papers have investigated rock glaciers in the Himalayan region, and only three have identified rock glaciers as important hydrological stores (data correct as at 13th October 2022). More research will therefore need to be conducted on rock glaciers and the paraglaciation of the region if the PT view is to be properly assessed**.** Such future work is hampered by the difficulty of assessing ice content in rock glaciers and other debris-covered landforms such as lateral and terminal moraines, especially in remote, high-altitude settings. How rock glaciers respond to climate change in HMA is also hardly known given their likely long response times.

Finally, it is currently unknown which clean or debris-covered glaciers will transition to rock glaciers and which will melt significantly in response to climate warming, or detach from the main valley glaciesr. We can however say, for example, based on current observations, that small glaciers located above the regional ELA are projected to disappear as they will not be able to adapt to future climate, as is the case in the Andes[68] and in the European Alps[61,69,70]. We hypothesise that the transition process is dominated by debris fluxes from mountain slopes and the connectivity between these sites and downwasting glacier surfaces below the ELA. Therefore, the transition process is most efficient in areas where high mountain slopes are producing rock slope failures, rock falls and debris flows, and where lateral moraine are absent or poorly developed and therefore allow sediment access from valley sides to the glaciers. Climate change therefore will represent a first order control on glacier behaviour but glacial processes creating lateral moraines will play a significant second order control.

5 Conclusions and work needed

Currently there is a general consensus from climate modelling that Himalayan glaciers will reduce their mass balance by up to 90% by 2100 and most small glaciers will completely disappear by 2100. However, we have produced an alternative scenario where many glaciers transform into rock glaciers and other ice-debris landforms which serve to inhibit ice melt and increase the resilience of the Himalayan glacial system to future climate change, a process which we name the “Paraglacial Transition”. The two scenarios discussed here (Major Ice Loss and Paraglacial Transition) represent end members of the likely glacial system response to future climate change. It is likely that there will be a pronounced regional variability, to the extent that both scenarios are possible in contrasting regions of the Himalayas.

Competing interest statement: the authors declare no competing interests.

Author contributions: SH developed the original research idea and wrote the initial manuscript. All other authors contributed to editing and writing of the manuscript. AR produced Figure 3 with A Ranger. SS produced Figure 1 and 2. DJ developed the rock glacier inventory and contributed to Figure 3 and was supervised by SH and KA.

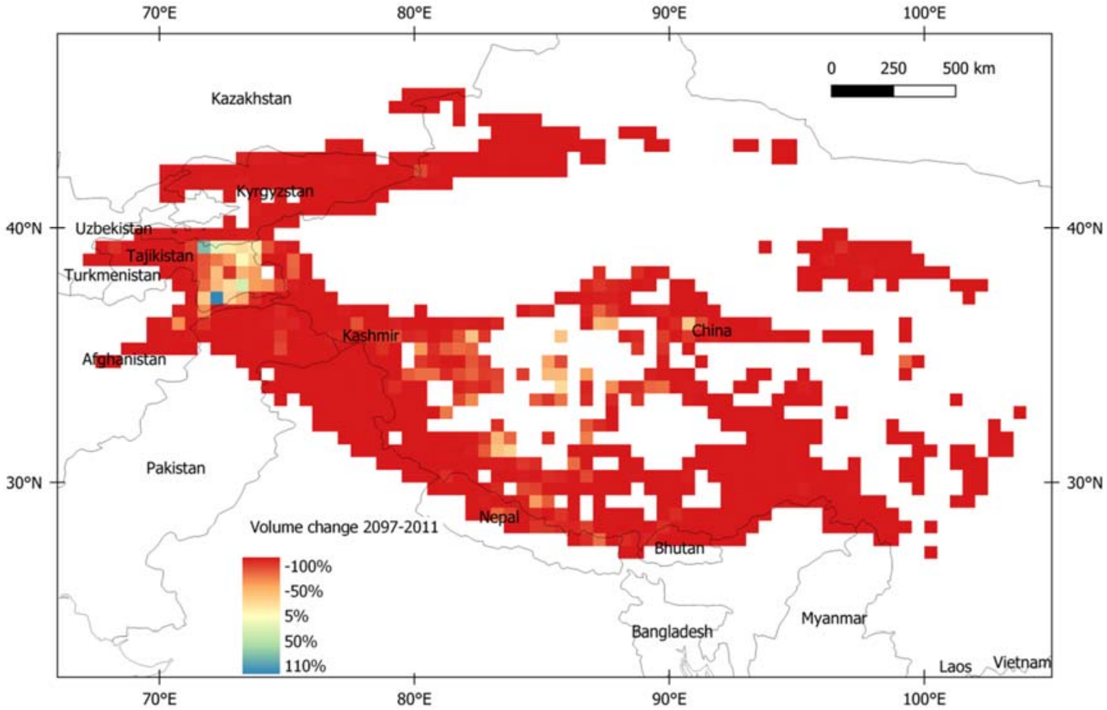

Figure 1. Ensemble mean ice volume change for the end of the century (2097) relative to 2011 for HMA calculated using the Joint UK Land Environment Simulator (JULES) for ice grid boxes[26].

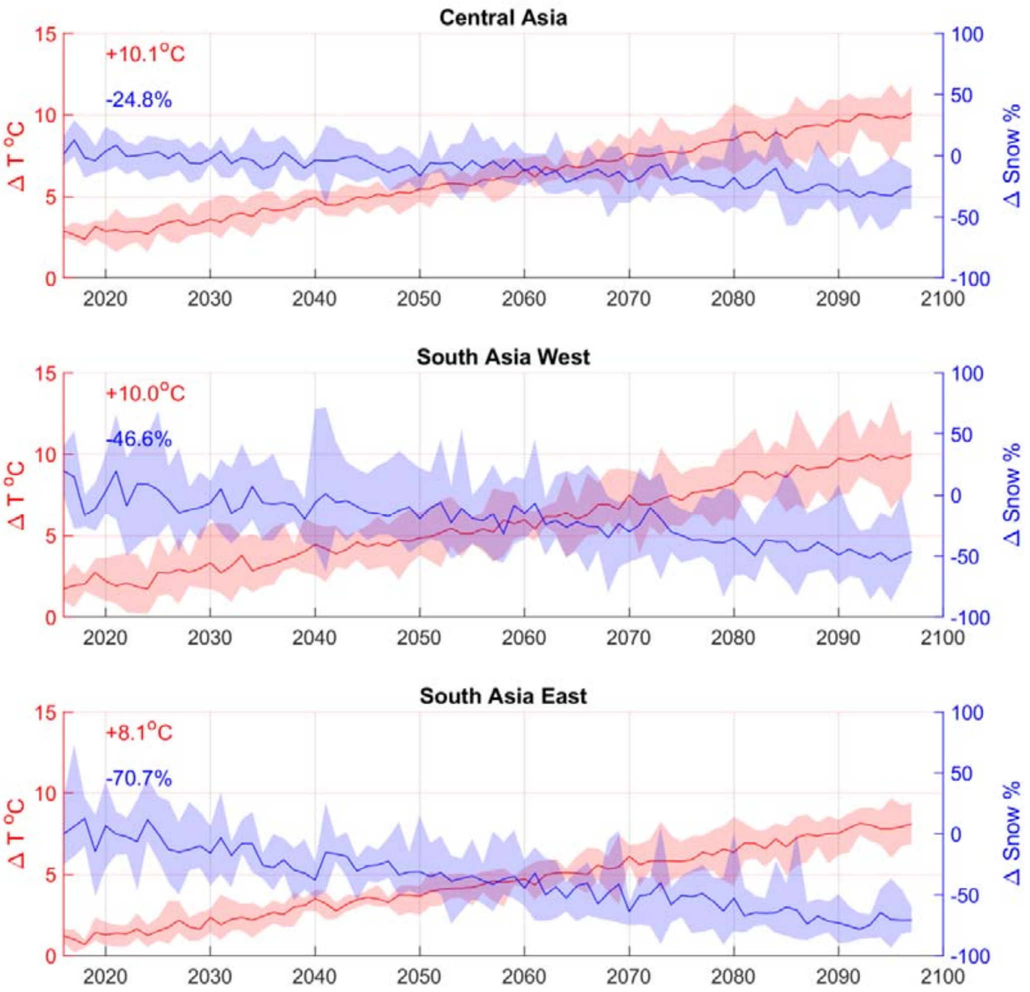

Figure 2. Temperature and snowfall projections over ice grid boxes used to generate the glacier volume losses shown in Figure 1. The climate projections come from six high-warming CMIP5 models that were downscaled using HadGEM3-A Global Atmosphere (GA) 6.0 model, where high-warming models were defined as those exceeding 2°C global average warming during this century relative to pre-industrial levels. The solid line is the ensemble mean and shaded envelope is the ensemble variability.

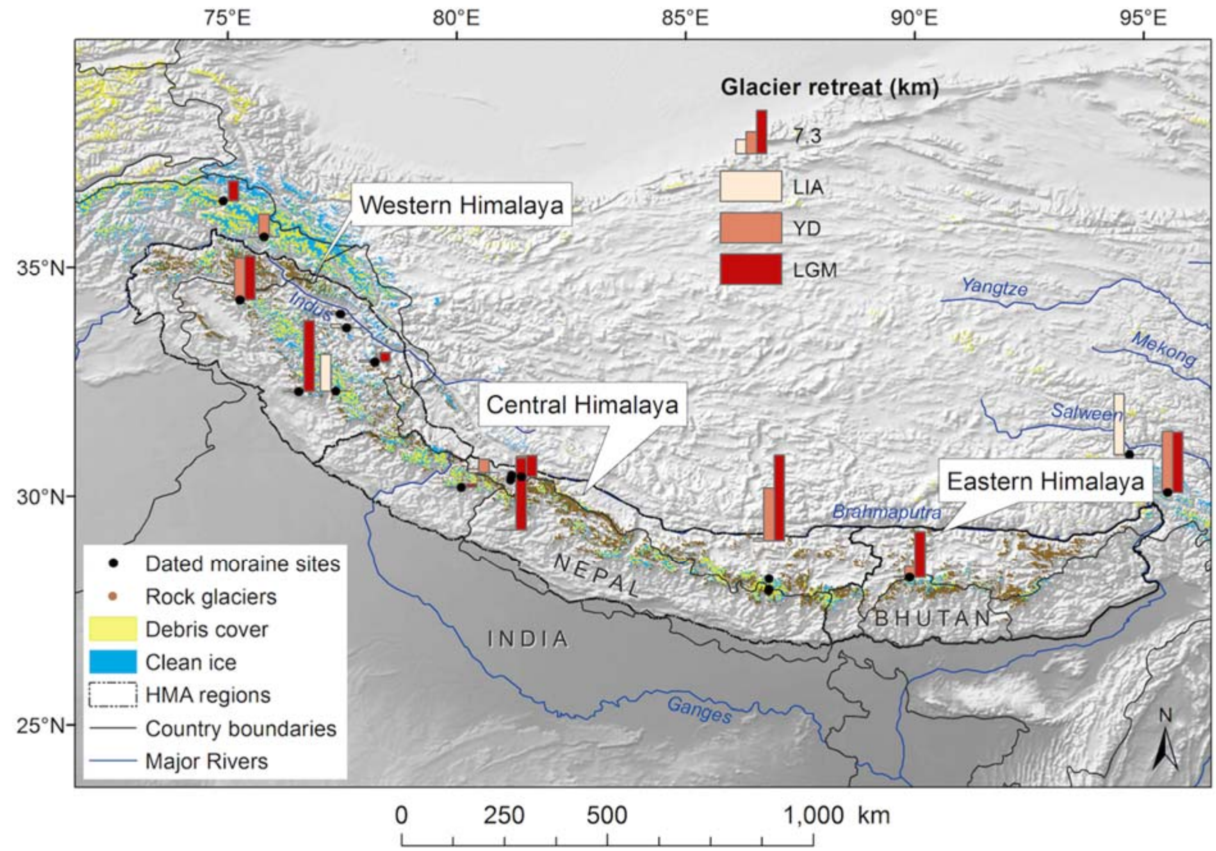

Figure 2. Distribution of the various types of glaciers (clean, debris-covered and rock glaciers) across the Himalaya. Clean ice outlines are based on the current RGI v6 inventory; debris-covered outlines are based on[71] and rock glacier locations (brown dots) from[50,72]. Also shown are the dated moraine sites (black dots) complied for this study, and river systems (blue).

	(Marzeion et al., 2012)*	(Giesen and Oerlemans, 2013)*	(Hirabayashi et al., 2013)*	(Radić et al., 2014)*	(Huss and Hock, 2015)*	(Shannon et al., 2019)**	(Rounce et al. 2023)*
Central Asia	63.7±6.8	67.2±8.7	61.0±6.6	73.6±11.0	88.3±7.8	80±7	80 ± 17 %
South Asia West	43.1±6.2	78.1±10.4	57.5±5.6	62.7±15.2	84.0±13.7	98±1	69 ± 20 %
South Asia East	62.9±8.2	93.7±4.3	42.3±8.5	76.4±9.9	86.0±24.2	95±2	94 ± 4 %

Table 1 Projected relative mass losses by the end of the Century for HMA. Regions are defined as in Randolph Glacier inventory (RGI) v6 (first-order region). The values refer to the multi-GCM means and their standard deviation.

** denotes the projections generated by glacierMIP1 using CMIP5 RCP8.5 climate forcing.*
*** denotes projections made with downscaled CMIP5 RCP8.5 model for high-end climate scenarios.*

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