https://doi.org/10.5194/egusphere-2024-4033
Preprint. Discussion started: 29 January 2025
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Will landscape responses reduce glacier sensitivity to climate change in High Mountain Asia?

Stephan Harrison[1], Adina Racoviteanu[2], Sarah Shannon[3], Darren Jones[1], Karen Anderson[4], Neil Glasser[5], Jasper Knight[6], Anna Ranger[1], Arindan Mandal[7], Brahma Dutt Vishwakarma[7], Jeffrey S. Kargel[8], Dan Shugar[9], Umesh Haritashya[10], Dongfeng Li[11], Aristeidis Koutroulis[12], Klaus Wyser[13], Sam Inglis[14]

Affiliations

1 College of Environment, Science and Economy, Exeter University, Exeter, UK

2 Université Grenoble Alpes, CNRS, IRD, IGE – 38400 Saint Martin d'Hères, France

3 Bristol Glaciology Centre, Department of Geographical Science, University Road, University of Bristol, BS8 1SS, UK

4 Environment and Sustainability Institute, University of Exeter, Penryn Campus, Penryn, Cornwall, TR10 9EZ, UK

5 Centre for Glaciology, Department of Geography and Earth Sciences, Aberystwyth University, Wales SY23 3DB, UK

6 School of Geography, Archaeology & Environmental Studies, University of the Witwatersrand, Johannesburg 2050, South Africa

7 Interdisciplinary Centre for Water Research, Indian Institute of Science, Bangalore 560012, India.

8 Planetary Science Institute, Tucson, AZ 85742 USA

9 Department of Earth, Energy, and Environment, University of Calgary, 2500 University Drive NW

Calgary, AB, T2N 1N4

https://doi.org/10.5194/egusphere-2024-4033
Preprint. Discussion started: 29 January 2025
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10 Department of Geology and Environmental Geosciences, University of Dayton, Dayton, OH 45458, USA

Sustainability Program, University of Dayton, Dayton, OH 45458, USA

11 Department of Geography, National University of Singapore, Singapore

12 School of Chemical and Environmental Engineering, Technical University of Crete, Chania 73100, Greece

13 Rossby Centre, Swedish Meteorological and Hydrological Institute, Norrköping 60176, Sweden

14 ADM Capital Foundation, Queen's Road Central, Hong Kong

Corresponding author: Stephan Harrison (Stephan.harrison@exeter.ac.uk) College of Environment, Science and Economy, Exeter University, Exeter, UK

https://doi.org/10.5194/egusphere-2024-4033
Preprint. Discussion started: 29 January 2025
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Abstract

In High Mountain Asia (HMA) ongoing climate change threatens mountain water resources as glaciers melt, and the resulting changes in runoff and water availability are likely to have considerable negative impacts on ecological and human systems. Numerous assessments of the ways in which these glaciers will respond to climate warming have been published over the past decade. Many of these assessments 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 these glaciers might respond. An alternative pathway is one in which increasing valley-side instability releases large amounts of rock debris onto glacier surfaces. The development of extensive glacier surface debris cover is common in HMA and, if thick enough, this surface debris inhibits glacier melting to the extent that glacier ice becomes preserved under the surface debris cover. In so doing, a transition to rock glaciers may prolong the lifetime of HMA glaciers in the landscape. We call this alternative pathway the Paraglacial Transition Model. In this Perspective Article we discuss the scientific basis of this alternative view in order to better understand how HMA glaciers may respond to climate change.

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

1 Introduction

Understanding the current status, recent changes, and likely future evolution of glaciers in High Mountain Asia (HMA) is important for a number of reasons. These include evaluating the status of glacial water resources and how these may evolve under climate change (Immerzeel et al. 2010; Rasul 2006; Lalande et al. 2021), and how glacier changes affect glacial hazards (e.g. Harrison et al. 2018; Shugar et al. 2021). Given the likely warming by the end of the twenty-first century in large parts of HMA, this understanding becomes a critical issue as cryosphere-derived water supply affects 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. The Sustainable Development Goals (SDGs), adopted by all United Nations (UN) and Asian governments, aim to substantially increase by 2030 the water-use efficiency across all sectors, to ensure sustainable withdrawals and supply of freshwater, whilst also reducing the number of people experiencing water scarcity (e.g.Bhaduri et al. 2016)). There are also concerns about the impact of future glacier ice loss on global sea level change (e.g. Marzeion et al. 2020) and on glacier-related hazards such as glacier lake outburst floods, rock slides and falls and rapid changes in slope and catchment sediment yield (e.g. Li et al. 2022).

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As a consequence of these concerns, there has been long-standing scientific and policy focus on modelling changes in glacier mass balance and understanding the implications of climate change for mountain water supplies (e.g.Nie et al. 2021). Numerous modelling studies have projected the impacts of climate change on glacier mass loss in HMA (e.g. Kraaijenbrink et al. 2017; Hock et al. 2019; Hugonnet et al. 2021; Rounce et al. 2020; 2023; (Table 1) and downstream river runoff (e.g. Sorg et al. 2012; Lutz et al. 2014; Huss and Hock 2018). 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.

Although existing modelling approaches are useful to assess pathways for 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. We argue that this is not necessarily the case (Harrison et al. 2021). The common view is that the expected rise in air temperature over this century is expected to lead to the almost complete melting of glaciers in HMA by 2100 (e.g. Rounce et al. 2023; Chen et al. 2023), thus that there is a simple deterministic and linear relationship between temperature forcing and glacier mass balance response. Current modelling studies support substantial but incomplete melting; for example, 60-98% reduction in glacier mass under RCP8.5 by the end of the century according to Shannon et al. 2019. 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 (see Table 1).

Table 1

There are, however, regional differences in mass loss projections across HMA and this partly reflects model uncertainty at fine spatial scales (Chen et al. 2023)^{0}. Kraaijenbrink et al. (2017) 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 result suggests a probable warming of 2.1±0.1°C for HMA by 2100, even at this low emissions scenario. They also assessed likely regional changes and argued that parts of the western Pamir and the Qilian Shan of northern China will lose most of its glacier mass compared with the present day by 2100 with only 32±14% and 30±5% ice mass remaining, respectively. In this study, the Karakoram region shows more resilience to climate warming, with a projected 80±7% of ice volume remaining by 2100. This is attributed partly to the role of supraglacial debris cover in maintaining ice mass, and the role of winter precipitation in maintaining accumulation.

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Supraglacial debris is now recognized as an important factor that may variably amplify or buffer glacier mass balance response to temperature forcing (e.g. Herreid and Pellicciotti 2020; Shrestha et al. 2020; Chen et al. 2023; Pratap et al. 2023). Kraaijenbrink et al.(2017) were among the first to model the impact of debris cover on glacier melt in HMA under different 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. More recently, Compagno et al. (2022) used the 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 with increasing radiative forcing, as well as local increases in debris thickness on individual glaciers (see also Scherler et al. 2018; Molg et al. 2020). At a smaller scale, Rowan et al. (2015) 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 2100.

Whilst such modelling experiments suggest high glacier volume loss in HMA by 2100, the physical response of glaciers to climate change varies enormously across the Himalaya and the wider HMA region and this is caused by varying exposure to monsoonal and westerly atmospheric flows (e.g. Molg et al. 2014), changes in surface albedo and the variability of local catchment characteristics such as local topography, aspect and geology (e.g. Fugger et al. 2022). For instance, glaciers experiencing accumulation in the summer months also undergo ablation at this time (e.g. Fujita and Ageta 2000). It is also known that the timing and amount of monsoon snowfall can impact on mass balance in different regions of the Himalaya, and for subsequent seasons (Molg et al. 2014; Bonekamp et al. 2019), and these factors are not fully captured in existing climate models.

Despite this body of research we argue that more work needs to focus on likely geomorphic responses to glacier mass loss across and within HMA if we are to better understand landscape evolution during future deglaciation and any hydrological implications that follow. The landscape responses that might increase in scale and spatial impact include rock surface weathering; slope sediment supply and downslope sediment yield; mass movements such as rock slope failures and debris flows; ecological succession and slope greening; and their biophysical feedbacks (e.g. Knight 2024) (Figure 1**)**. All such geomorphic processes can deliver debris to glacier surfaces and surrounding slopes and valley floors, thereby contributing to reduced melting through insulation of the ice beneath, alongside downstream changes in sediment supply and changes in river transport capacity.

https://doi.org/10.5194/egusphere-2024-4033
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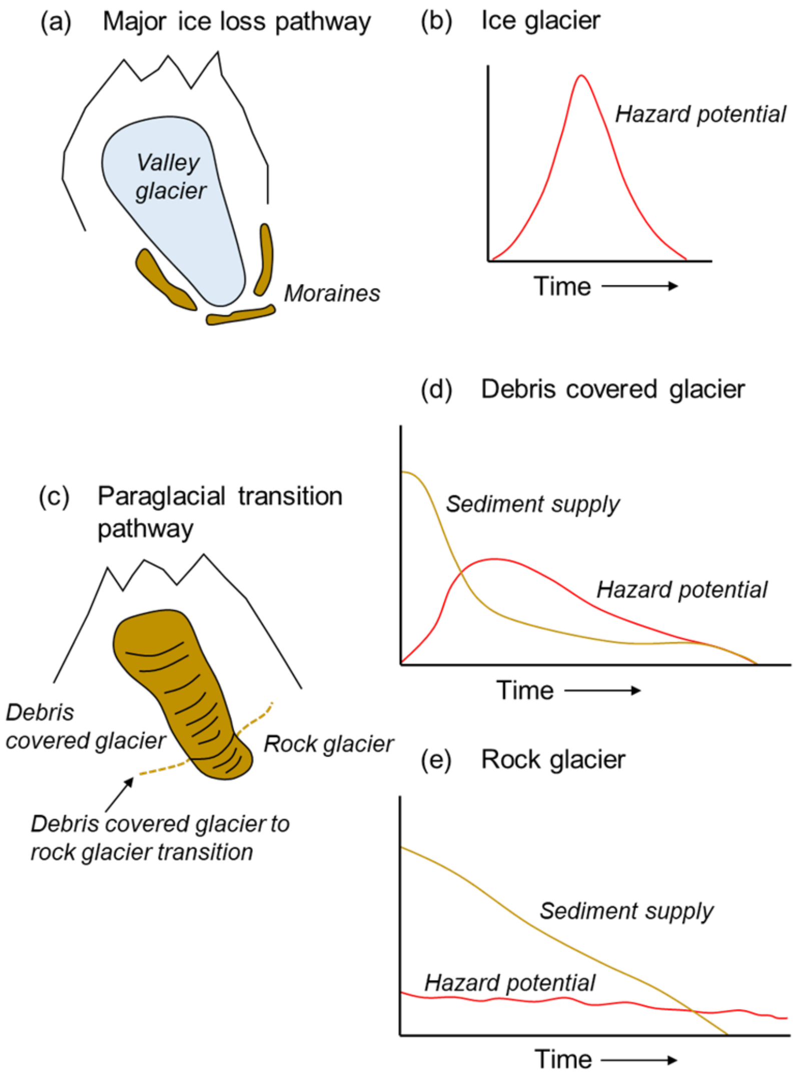

Figure 1. Schematic diagram showing the rapid increase and decrease in glacier hazards during the Major ice loss pathway (a, b). Most of these hazards will be GLOFs. Hazards associated with debris covered glaciers will show a rapid initial increase with a slowly falling reduction (c, d). Hazards associated with rock glaciers will remain low and decrease over time. The term 'Hazard potential' refers to the expectation that the probability of a named hazard will change over time as the MIL or PT pathways evolve.

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In this Perspective Article , we explore and highlight some of the implications of these modelling exercises (the majority of which project sustained reduction of glacier mass balance, e.g. Edwards et al. 2021) and highlight some plausible alternative scenarios for how glacier systems in HMA might evolve to 2100 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 view (PT). Both of these end-member evolutionary pathways necessarily represent simplifications of future glacier behaviour, yet they can usefully explore how HMA glaciers could evolve over future decades. The two pathways highlight the contingency of glacier evolution to the geomorphological, hypsometric, geological and climatic variations that exist over HMA and that conventional climate model outcomes do not successfully capture. It is already known, for instance, the glacier responses to recent climate changes have been spatially and temporally varable across HMA (e.g. Rounce et al. 2020). Thus, our approach is grounded in an understanding of known glacier behaviour and the properties of HMA glaciers, unlike the approach taken by climate models. Given these caveats, we end by exploring some of these regional differences.

2. Scenarios

2.1 Major Ice Loss (MIL) view

As we have discussed, 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 (e.g.Shannon et al. 2019; Rounce et al. 2020; 2023). This is supported by the modelling projections made by the Glacier Model Intercomparison Project (glacierMIP1(Hock et al. 2019) and the subsequent glacierMIP2. The same understanding is reflected in the third phase (glacierMIP3), which is underway and focuses on the equilibration of glaciers under various climatic conditions. GlacierMIP is a coordinated intercomparison of global-scale glacier evolution models using standard initial glacier conditions - glacier outlines from the RGI v6 inventory (Pfeffer et al. 2014; RGI 2017) and ice thickness from Huss and Farinoti (2012) - forced with various GCMs under four climate change scenarios. The participating glacier models varied in complexity: for example, some models use temperature index schemes to calculate global-scale glacier volume projections by 2100 while others use full energy balance models. Models also differ in the complexity with which glacier evolution is represented and each model therefore has a bespoke approach to calibration that may impact on their comparability. The consensus view from the glacierMIPs and other modelling studies, 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). The potential trajectory of evolution of HMA glaciers is shown diagrammatically in Figure 1.

2.1.1 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.Richardson and Reynolds 2000; Knight and Harrison 2014). Amongst the most important of these at a local scale are GLOFs caused by the rapid drainage of glacial lakes dammed by unstable moraines (e.g.Song et al. 2017; Nie et al. 2017; Emmer et al. 2022) and Landslide Lake Outburst Floods (LLOFs; Ruiz-Villanueva et al. 2017) caused by breaching of lakes created by landslides. Other negative impacts at a regional scale include ecosystem changes, warming of permafrost and subsequent rock mass collapse, the potential reduction of water supplies downstream, increased seasonal discharge variability, increased fluvial sediment fluxes and the impacts this has on agriculture, hydroelectric power plants and dams in regional catchments (Immerzeel et al. 2010; Biemans et al. 2019; Bosson et al. 2023).

Under this scenario, current glacier mass balance trends are exacerbated progressively over time, 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. Furian 2021). Locally these lakes are potentially hazardous, but by 2100 the HMA-wide GLOF peak will have already been reached and will be subsiding (Harrison et al. 2018; Veh et al. 2019). However, leading up to this end result would have been decades when GLOFs, LLOFs, large debris flows and other mountain hazards became more frequent and, perhaps, larger than in the recent historical period (e.g. Veh et al. 2020; Compagno et al. 2022).

2.2 Paraglacial Transition (PT) view

Despite the focus of much research on the MIL view, we argue that this misrepresents the ways in which HMA glacier systems might evolve under climate warming because it largely fails to reflect how glacial and mountain systems have responded in the past to deglaciation from the last glacial maximum (e.g. Church and Ryder 1972; Ballantyne 2002; Cossart et al. 2007; Mercier et al. 2013; Knight and Harrison 2014), and are responding at present to recent and ongoing climate warming (e.g. Knight et al., 2019). This alternative view of the future of HMA is that the glacial landscape will transition to a landscape dominated by paraglacial processes, and we refer to this as the Paraglacial Transition (PT) view. Paraglacial processes develop in response to deglaciation and are characterized, amongst others, by increased rock slope failures from steep mountain slopes as these are de-buttressed by glacier downwasting, and by increased debris flow activity from degrading lateral moraines and related fluvial adjustment (see Li et al. 2022 for a review).

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 their termini evolve to form rock glaciers (Jones et al. 2019; Knight et al. 2019).

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2.2.1 Impacts associated with the PT view

The PT scenario may eventually produce a HMA landscape dominated by relict ice masses of different sizes and in different altitudinal and topographic settings, covered by varying thicknesses of debris. This debris is released by enhanced weathering and rock slope failure under a paraglacial process regime. The nature of the debris cover can give rise to a variety of outcomes for buried ice masses. New rock glaciers can potentially develop as high-mountain talus and other rock debris that presently is in extreme cold conditions enters a condition where freeze-thaw is frequent and mobilized by periglacial processes. This would represent a 'periglacial' path for the evolution of rock glaciers (e.g. Haeberli et al. 2006). In addition, we can see examples of such landscapes where debris-covered glaciers are transitioning to ice-cored rock glaciers in other arid high mountains (Johnson 1980; Monnier and Kinnard 2017).

Numerical modelling studies show the glacier debris-cover-rock glacier continuum (e.g. Anderson et al. 2018), and we expect that rock glaciers in the Himalaya and other regions of HMA will populate many of the currently glaciated valleys. However, none of the models used in glacierMIP1 and the subsequent glacierMIP2 project consider a transition of ice or debris covered glaciers into rock glaciers, and nor does IPCC AR6 (Hock et al. 2019). In addition, while historically little has been written on these features in the Himalaya (although much in other parts of HMA), recent research has shown that rock glaciers are widely distributed in all parts of the Himalaya (Jones et al. 2021; Vishwakarma et al. 2022; Harrison et al 2024) and that some ice glaciers and debris-covered glaciers are currently undergoing a transition to form ice-cored rock glaciers (Jones et al. 2019).

If this PT scenario applies more widely then rock glaciers will eventually replace many clean-ice and debris-covered glaciers as the main ice-bearing landforms in parts of the HMA, perhaps alongside ice-cored moraines and ice-rich permafrost, with important implications for future water supplies (e.g. Jones et al. 2021). This PT will likely increase the resilience of ice bodies through increasing their longevity in the landscape. Although research shows that debris-covered glaciers are melting at similar rates to those without a substantial debris cover (e.g. Pellicciotti et al., 2015), this appears to reflect high melt rates around supraglacial ponds and declining ice discharge (e.g. Anderson et al. 2021). Supraglacial ponds are absent on RG, and the thick debris cover of these (Janke and Bolch 2021) will extend the persistence of buried ice (see Figure 1).

This paraglacial path might result in a decreased GLOF hazard risk 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. Thus, the nature of geomorphic and hydrological hazards are somewhat different between the MIL and PT pathways and this in itself may help

https://doi.org/10.5194/egusphere-2024-4033
Preprint. Discussion started: 29 January 2025
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understand which glaciers are following which evolutionary pathway. GLOFs and LLOFs may here also represent paraglacial landscape responses where, instead of meltwater passively draining away under low hazard risk (MIL response), it is impounded by paraglacial landslides that result in high hazard risk (PT response).

3. Discussion and relationships between the MIL and PT pathways

An important distinguishing feature between the MIL and PT pathways is that direct ice melt is only a factor while the ice mass still exists, ceasing when the ice mass is gone, and tends to affect local areas only. By contrast paraglaciation affects wider geographical areas outside of the ice mass, and can extend for decades to millennia after full ice mass loss (Ballantyne, 2002). Understanding which pathway of evolutionary development is followed by any ice mass at any point in time has implications for predictability, hazard risk and sustainable development. MIL and PT pathways represent end-members along an evolutionary trajectory. It is likely that the development of any one glacier is dependent on their initial conditions, and any changes in ice mass volume or surface debris (Figure 3). However, both of these elements are more than a simple volumetric analysis because this does not account for the detailed dynamics or spatial/temporal patterns of ice or debris. These different pathways are likely to display important regional variation in the response of clean ice glaciers, debris-covered glaciers and rock glaciers to future climate change in HMA. These responses will not only be driven by variations in regional temperatures, but also by changes in the behaviour of the Indian and East Asian summer monsoons, and the westerlies (e.g. Fugger et al. 2022). Whilst regional climatic differences remain largely unexplored (although see Brun et al. 2019), we can hypothesise that the areas that will undergo a transition from ice glacier to rock glacier most readily will be those where debris-covered glaciers are most common, because the debris supply in those areas is high. Furthermore, as high-elevation clean ice thins, and as freeze-thaw and frost shattering conditions move to higher altitudes, debris supply will increase in some high-elevation areas that presently produce little debris. Where these places move into high-elevation cirques, especially north-aspect cirques, ‘periglacial’ rock glacier development will be favoured (cf Haeberli et al. 2006) Because of the exceptionally high relief of the Himalaya, Karakoram, and many other parts of HMA, rock glacier development may proceed on regional scales not seen in other mountains globally today, though it will take centuries for rock glaciers to grow. Improved understanding of debris supply processes to valley bottoms 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. Racoviteanu et al. 2022).

How do we assess which of the MIL and PT scenarios are more likely and their probable future spatial distributions? A first-order understanding might be gained by a simple evaluation of how glaciers have behaved in the past in response to known climate forcings; from this we can suggest whether these glaciers have shown high or low-sensitivity to past

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or recent climate change (Harrison 2009). Although this is a uniformitarian view, if the glaciers have demonstrated a high sensitivity to past climate change then this tends to support the MIL scenario for the future responses of glaciers to climate change. Alternatively, if the glaciers have shown low sensitivity or delayed response to past climate change then this might make the PT more likely, even if the forcings are different at different times and glaciers today are in different states than they were in the past. To explore this we need to establish the extent to which glaciers have responded to the warming since the regional Last Glacial Maximum or the late Holocene Neoglacial Maximum (often seen as equivalent to the European Little Ice Age).

Therefore, we compiled published studies that have dated Himalayan moraine sequences from the Western, Central and Eastern Himalaya (Figure 2 and Supplementary Information File). We analysed moraine ages from three time periods: the regional Last Glacial Maximum from 18 to 24 ka (Owen et al. 2002), a period covering the regional Younger Dryas from 12,880 and 11,640 ka (Rawat et al. 2012), and the regional Little Ice Age between 1300-1600 AD (Rowan 2017) (Figure 2). While there is evidence that glaciers in several areas reached their late Pleistocene limits earlier than Marine Isotope Stage (MIS) 2 (Benn and Owen 1998; Owen et al. 2002), overall these data show that glaciers in the Himalaya have not receded far behind dated glacier limits over these time periods. Figure 3 shows that, as expected, glaciers in different regions of the Himalaya 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; this might reflect the reduction of the monsoon and intensification of westerly influences on glacier mass balance towards the western Himalaya (Kumar et al. 2020; Hunt 2023).

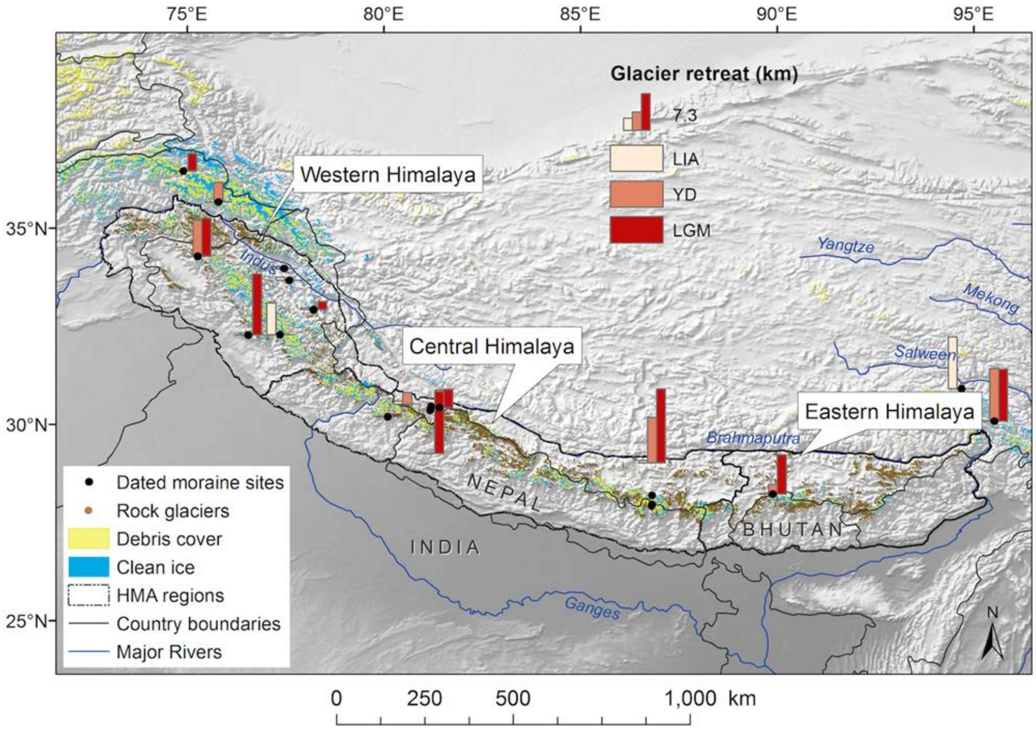

Figure 2. Distribution of the various types of glaciers (clean, debris-covered and rock glaciers) across the HMA region. Clean ice outlines are based on the current RGI v6 inventory; debris-covered outlines are based on Herreid and Pelliciotti (2020) and rock glacier locations (n = 24,968) (brown dots) from Jones et al. (2021). Also shown are the dated moraine sites (black dots) complied for this study, and river systems (blue) (see Supplementary Information file). Source: NextMap 2024.

One current limitation with this approach is that few moraines have been dated in HMA, and most that have been are dated to the regional Neoglacial (Rowan 2017). Further, most dated moraines are associated with fluctuations of large valley glaciers and therefore might not reflect the behaviour of the more numerous and climatically sensitive smaller glaciers.

However, another way to assess glacier response to climate change in general (and temperature rise in particular), and therefore the relative likelihood of the MIL or PT models being dominant, is by monitoring their equilibrium line altitude (ELA), i.e. the altitude on the

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glacier surface where the theoretical mass balance is zero at a given point in time (Zemp et al. 2006; Cogley 2011). For instance, in the Khumbu region in the central Himalaya MIS 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 (Richards et al. 2000) and also reduced insolation driving a weakened monsoon (Owen et al. 2002). At the western end of the Himalaya 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 MIS 2 maximum, although moraines of MIS 3 are present downvalley (Phillips et al. 2000). The absence of evidence for an LGM-age advance of the glacier may reflect aridity during MIS 2 in this region and therefore low glacier sensitivity to atmospheric temperatures at this time (e.g. Yan et al. 2021), i.e. that glacier dynamics here is precipitation-controlled rather than temperature-controlled.

Glacier recession since the regional Neoglacial maximum of the late 18th Century also supports the present low sensitivity of many Himalayan glaciers to climate change (Rowan 2017). For instance, at Ama Dablam and Lhotse in the Khumbu region, present glacier margins have retreated by around 1 km from Neoglacial moraine limits. 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 (Chand et al 2017). Overall, Figure 3 demonstrates that glacier termini in the western and central parts of the Himalaya have retreated less than 2 km since the end of the Neoglacial maximum. Compared with considerable volumetric ice loss since this time (Lee et al. 2021), if future glacier response mirrors that of the past then this supports our contention that future glacier loss will dominantly involve downwasting of glacier surfaces rather than terminus retreat. We argue that this favours the development of stagnant glacier tongues and enhances the likelihood of further transition to rock glaciers (Jones et al 2019) and thus the PT rather than the MIL pathway.

From this (albeit limited and incomplete) data set, we suggest that glaciers from the western, eastern and northern Himalaya displayed low sensitivity to climate change during the regional LGM and the Neoglacial, and this supports the PT scenario of glacier responses to future climate change.

It is also likely that different glaciers in HMA are at different stages of deglacial evolution, depending on their size, location and mass balance. This means that some show a MIL response, some a PT response, and some may be changing from the former to the latter (Figure 3). It is, however, uncertain as to which clean or debris-covered glaciers will transition to rock glaciers and which will melt significantly in response to climate warming. However, we can say, 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 (ICIMOD 2023), as is the case in the Andes (Ramirez et al. 2001) and the European Alps (e.g.

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Zemp et al. 2006; Zebre et al. 2021). Some of these features may completely disappear if debris supply is low, and others may undergo transitions to rock glaciers that may be stabilized by a combination of high snowfall and high debris production. 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 (Figure 3). Therefore, the transition between MIL and PT pathways is most efficient in areas where high mountain slopes are producing rock slope failures, rock falls and debris flows, and where lateral moraines are absent or poorly developed and therefore allow sediment access from valley sides to the glacier surface. 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.

Finally, the consequences of having more persistent glacial ice in HMA would be profound. This outcome would mean that there is more time to generate climate change mitigation and adaptation schemes in the wider region, and develop technological fixes to the challenges of changing hydrological resources (including total volumes and seasonality). In addition, several of the UN Sustainable Development Goals such as Clean Water and Sanitation might be more easily achieved than previously expected if cryospheric water sources persist longer.

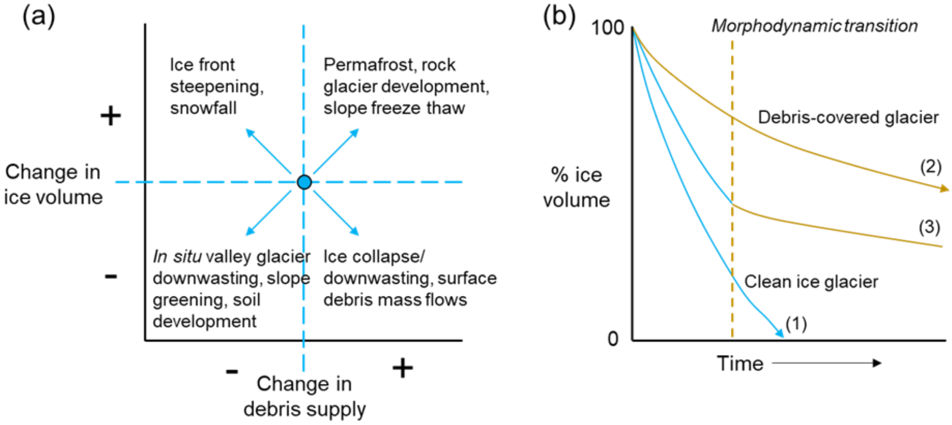

Figure 3. (a) Model of HMA glacier development as a consequence of certain changes in ice volume vs changes in debris supply to/from the glacier surface. From an initial starting point (blue circle), changes in ice volume and debris (blue arrows) are associated with certain glacier properties and processes that suggest the likely ways in which these glaciers will develop in future. The dashed blue lines represent zero balance in ice volume and debris

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supply. (b) Representation of the different trajectories of changes in ice volume over time between (1) a clean ice glacier (rapid melt), (2) a debris-covered glacier or rock glacier (slower melt), and (3) a scenario where a clean ice glacier starts melting but is then covered by debris, such as from a paraglacial landslide, that then slows down the ice melt. Such an event represents a morphodynamic transition in the response of such a glacier to climate forcing.

3 Conclusions and future research imperatives

Currently we have argued that there is a general consensus from climate modelling that Himalayan and wider HMA glaciers will reduce their volume by up to 90% by 2100 in response to projected warming, and most small glaciers will completely disappear by this time. However, we have produced an alternative Paraglacial Transition scenario where many glaciers transform into rock glaciers and other ice-debris landforms. This serves to inhibit ice melt and increase the resilience of the Himalayan glacial system to future climate change by increasing the longevity of ice bodies in the landscape. The Major Ice Loss (MIL) and Paraglacial Transition (PT) scenarios discussed here represent end members of possible glacial system responses to future climate change (Figure 3).

While the MIL scenario will also lead to a range of paraglacial responses from deglaciating catchments, we argue that this will not necessarily change the future evolution of individual glaciers which will continue to melt in response to ongoing climate warming (although increased snowfall might reduce net mass loss). This MIL viewpoint continues to dominate the literature based on climate model assessments of glacier melt. However, there are relatively few published studies on the development of rock glaciers and their importance in HMA (see Harrison et al. 2021 for a discussion of this). More research needs to be conducted on the different ice masses and rock glaciers of HMA, 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 many rock glaciers have derived from the downwasting of glacial ice (Knight et al. 2019) and how many are derived from the creep of ice-rich permafrost (e.g. Haeberli et al. 2024) is also unknown. How rock glaciers respond to climate change in HMA is also hardly known given their likely long response times.

Critical research is needed in order to evaluate the operations and outcomes of the MIL and PT scenarios, and their possible interactions on individual glaciers. Future research imperatives therefore include: 1) determination of debris fluxes throughout the region for the full range of geological materials, slopes, and microclimates and glacier types; 2) long-term monitoring of glacier mass balance across the region in order to evaluate cryospheric sensitivity to climate forcing; 3) measurement of contemporary debris fluxes and distributions on different glacier types; 4) present and past climate modelling with snow accumulation with concurrent debris loading, and 5) projections into the future for the full

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range of climate scenarios. Development of ultra-downscaled climate modelling that is responsive to the full range of HMA relief and slopes with resolutions enough to resolve individual cirques is also needed. This may be currently possible for small local geographic domains sufficient to sample different parts of HMA.

		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	80.0±7.0	80.0±17.0%
South Asia West		43.1±6.2	78.1±10.4	57.5±5.6	62.7±15.2	84.0±13.7	98.0±1.0	69.0±20.0%
South Asia East		62.9±8.2	93.7±4.3	42.3±8.5	76.4±9.9	86.0±24.2	95.0±2.0	94.0±4.0%

Table 1 Examples of projected relative mass losses by the end of 21st Century for HMA, from different recent studies (reduction as a percentage of ice loss from 1990). Regions are defined as in Randolph Glacier inventory (RGI) v6 (first-order region, shown in Figure 2). 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.*

Code/Data availability

Data are available in the Supplementary Information File (moraine inventory) and at the zenodo link(10.5281/zenodo.11237094) (rock glacier inventory).

Author contribution

SH developed the initial idea and wrote the first draft of the paper. The paper was developed with the insights of AR, NFG, KA, JK, UH, DS and JK . DJ produced the rock glacier inventory and ARanger produced the moraine inventory. JK developed figures 1 and 3 and AR developed figure 2. All authors contributed to the development of the paper.

Competing interests

We have no competing interests.

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