Will landscape responses reduce glacier sensitivity to climate change in High Mountain Asia?

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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 glacier-derived rock glaciers and other ice-debris landforms may prolong the lifetime of HMA glacial ice 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, including 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 related 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 HMA (Harrison et al. 2021). The Sustainable Development Goals (SDGs), adopted by all United Nations (UN) and Asian governments, aim to substantially increase 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) by 2030. 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).

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 the 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 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 outcome 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

However, there are regional differences in mass loss projections across HMA which partly reflects model uncertainty at fine spatial scales (Chen et al. 2023). 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 to 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 anomaly is attributed partly to the role of supraglacial debris cover in maintaining ice mass, and the role of winter precipitation in maintaining accumulation.

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

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133 Supraglacial debris is now recognized as an important factor that may variably amplify or
134 buffer glacier mass balance response to temperature forcing (e.g. Herreid and Pellicciotti
135 2020; Shrestha et al. 2020; Chen et al. 2023; Pratap et al. 2023). Kraaijenbrink et al. (2017)
136 were among the first to model the impact of debris cover on glacier melt in HMA under
137 different climate projections and they showed that under RCP4.5, RCP6.0 and RCP8.5 glacier
138 mass losses would be 49±7%, 51±6% and 64±5%, respectively, by 2100 compared with the
139 present day. More recently, Compagno et al. (2022) used the five Shared Socioeconomic
140 Pathways (SSP119, SSP126, SSP245, SSP370, and SSP585) from CMIP6 to assess the future
141 evolution of debris cover and its impact on glacier dynamics for all HMA glaciers. They
142 showed a general increase in glacier debris cover with increasing radiative forcing, as well as
143 local increases in debris thickness on individual glaciers (see also Scherler et al. 2018; Molg
144 et al. 2020). At a smaller scale, Rowan et al. (2015) applied a numerical model to estimate
145 the evolution of the debris-covered Khumbu Glacier and predicted a decrease in glacier
146 volume of 8–10% by 2100.

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

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162   In this Perspective Article we explore and highlight some of the implications of these
163   modelling exercises, the majority of which project sustained reduction of glacier mass
164   balance (e.g. Edwards et al. 2021), and highlight some plausible alternative scenarios for
165   how glacier systems in HMA might evolve to 2100 and beyond. We consider two broad
166   scenarios of how mountain glaciers might respond to climate change: the Major Ice Loss
167   view (MIL) and the Paraglacial Transition view (PT). Both of these end-member evolutionary
168   pathways necessarily represent simplifications of future glacier behaviour, yet they can
169   usefully explore how HMA glaciers could evolve over future decades. The two pathways
170   highlight the contingency of glacier evolution to the geomorphological, hypsometric,
171   geological and climatic variations that exist over HMA and that conventional climate model
172   outcomes do not successfully capture. It is already known, for instance, that the glacier
173   responses to recent climate changes have been spatially and temporally variable across
174   HMA (e.g. Rounce et al. 2020). Thus, our more generalised approach is grounded in an
175   understanding of known glacier behaviour and the properties of HMA glaciers. Given these
176   caveats, we end by discussing some of these regional differences.

177   **2. Scenarios**

178   **2.1 Major Ice Loss (MIL) view**

179   The conventional MIL view is that future climate warming will result in widespread glacier
180   recession and almost total ice loss in some parts of HMA, particularly the eastern HMA (e.g.
181   Shannon et al. 2019; Rounce et al. 2020; 2023). These conclusions are supported by the
182   modelling projections made by the Glacier Model Intercomparison Project (glacierMIP1;
183   Hock et al. 2019) and the subsequent glacierMIP2. The same understanding is reflected in
184   the third phase (glacierMIP3), which is underway and focuses on the equilibration of glaciers
185   under various climatic conditions. GlacierMIP is a coordinated intercomparison of global-
186   scale glacier evolution models using standard initial glacier conditions, glacier outlines from
187   the RGI v6 inventory (Pfeffer et al. 2014; RGI 2017) and ice thickness from Huss and Farinoti
188   (2012) forced with various GCMs under four climate change scenarios. The participating
189   glacier models varied in complexity: for example, some models use temperature index
190   schemes to calculate global-scale glacier volume projections by 2100 while others use full
191   energy balance models. Models also differ in the complexity with which glacier evolution is
192   represented and each model therefore has a bespoke approach to calibration that may
193   impact on their comparability. However, the consensus view from the glacierMIPs and other
194   modelling studies is that glaciers in the three RGI regions covering HMA (Western, Central,
195   Eastern Himalaya) will experience significant reductions in ice volumes under the business-
196   as-usual RCP8.5 climate change scenario (Table 1). The potential trajectory of evolution of
197   HMA glaciers is shown diagrammatically in Figure 1.

198   **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 glacier-related hazards (e.g. Richardson and Reynolds 2000; Knight and Harrison 2014). Amongst the most important of these at a local scale are Glacial Lake Outburst Floods (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, with negative glacier mass balance associated with 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, up to this end result would have been decades when GLOFs, LLOFs, large debris flows and other mountain hazards became more frequent and, potentially, 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 approach 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 geomorphologically 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 by increased rock slope failures from steep mountain slopes as these are de-buttressed by glacier downwasting and in response to increased water pressures in bedrock cliffs and permafrost melt; and by increased debris flow activity from degrading lateral moraines and related fluvial adjustment (see Li et al. 2022 for a review).

236 In the PT scenario, one end result is the potential for many stagnant clean ice glaciers to
237 become covered by rock debris and some of these undergoing renewed movement as their
238 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

241 The PT scenario may eventually produce a HMA landscape dominated by relict ice masses of
242 different sizes and in different altitudinal and topographic settings, covered by varying
243 thicknesses of rock debris and fine sediment. This debris is released by enhanced
244 weathering and rock slope failure under a paraglacial process regime. The nature of the
245 debris cover can give rise to a variety of outcomes for buried ice masses. New rock glaciers
246 can potentially develop as high-mountain talus and other rock debris that at present is in
247 extreme cold conditions enters a condition where freeze-thaw is frequent and mobilized by
248 periglacial processes. If these conditions persist, this would represent a 'periglacial' path for
249 the evolution of rock glaciers (e.g. Haeberli et al. 2006; and see Berthling 2011). In addition,
250 we can see examples of such landscapes where debris-covered glaciers are transitioning to
251 ice-cored rock glaciers in other arid high mountains (Johnson 1980; Monnier and Kinnard
252 2017).

253 Numerical modelling studies show the glacier debris-cover-rock glacier continuum (e.g.
254 Anderson et al. 2018), and we expect that rock glaciers in the Himalaya and other regions of
255 HMA will populate many of the currently glaciated valleys. However, none of the models
256 used in glacierMIP1 and the subsequent glacierMIP2 project consider a transition of ice or
257 debris covered glaciers into rock glaciers, and nor does IPCC AR6 (Hock et al. 2019a,b). In
258 addition, while historically little has been written on these features in the Himalaya
259 (although more so in other parts of HMA; see Bolch and Gorbunov 2014), recent research
260 has shown that rock glaciers are widely distributed in all parts of the Himalaya (Jones et al.
261 2021; Vishwakarma et al. 2022; Harrison et al 2024) and that some clean-ice glaciers and
262 debris-covered glaciers are currently undergoing a transition to form ice-cored rock glaciers
263 (Jones et al. 2019).

264 If this PT scenario applies more widely then rock glaciers will eventually replace many clean-
265 ice and debris-covered glaciers as the main ice-bearing landforms in parts of the HMA,
266 potentially alongside ice-cored moraines and ice-rich permafrost, with important
267 implications for future water supplies (e.g. Jones et al. 2021). The PT scenario will likely
268 increase the resilience of ice bodies through increasing their longevity in the landscape.
269 Although research shows that debris-covered glaciers are melting at similar rates to those
270 without a substantial debris cover (e.g. Pellicciotti et al., 2015), this appears to reflect high
271 melt rates around supraglacial ponds, ice cliffs and declining ice discharge (e.g. Sakai et al,
272 1998; Anderson et al. 2021). Supraglacial ponds are absent on rock glaciers and the thick
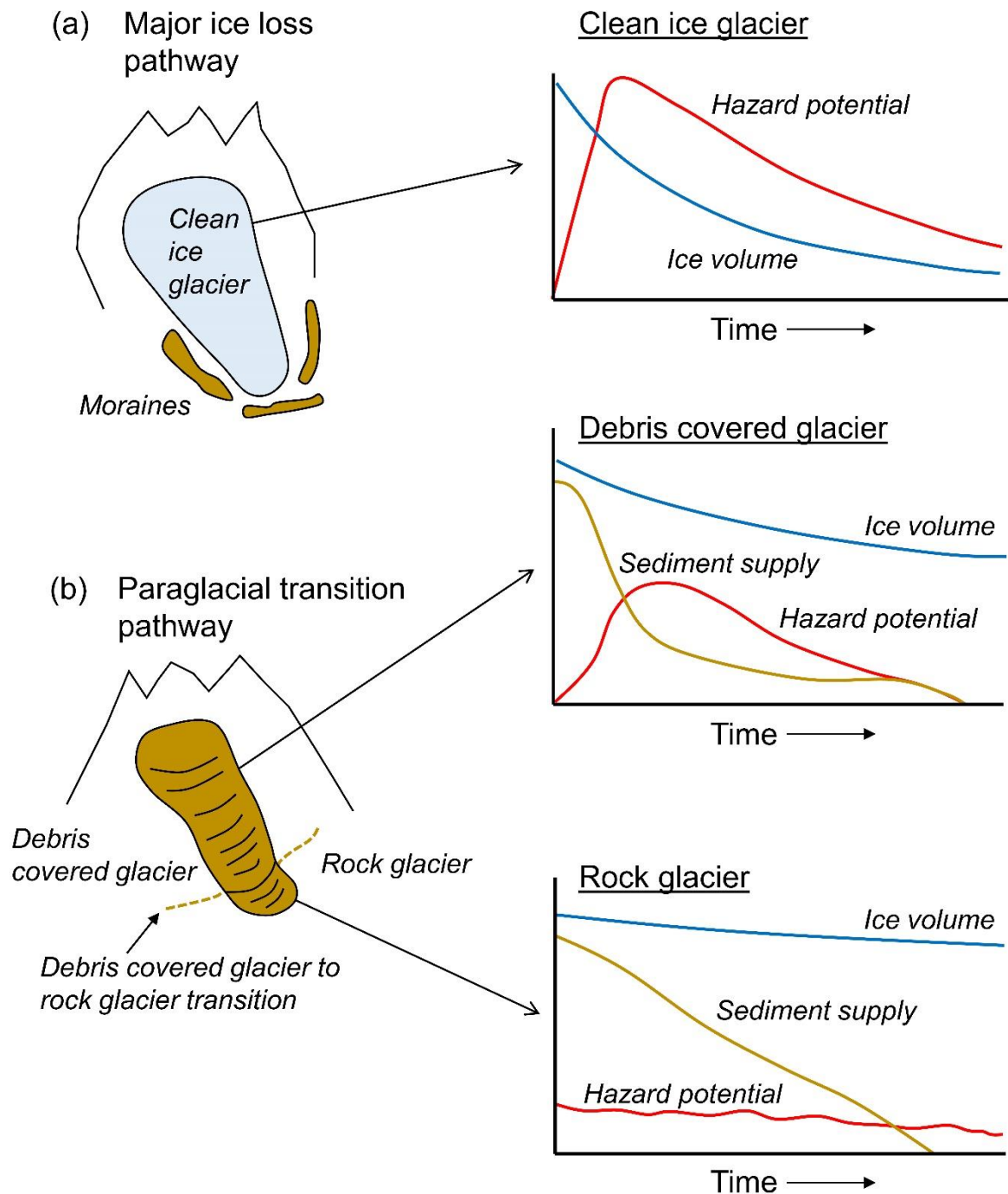273 debris cover of these (Janke and Bolch 2021) could extend the persistence of buried ice (see
274 Figure 1).
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(a) Major ice loss pathway

Clean ice glacier

Clean ice glacier

Moraines

Hazard potential

Ice volume

Time ⟶

(b) Paraglacial transition pathway

Debris covered glacier

Debris covered glacier

Rock glacier

Debris covered glacier to rock glacier transition

Sediment supply

Ice volume

Hazard potential

Time ⟶

Rock glacier

Ice volume

Sediment supply

Hazard potential

Time ⟶

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280 Figure 1. Schematic diagram showing the rapid increase and decrease in glacier hazards
281 during the Major ice loss pathway (a and top right) in HMA. Most of these hazards will be
282 Glacial lake outburst floods (GLOFs). Hazards associated with debris covered glaciers (b) will
283 show a rapid initial increase with a slowly falling reduction (middle right). Hazards

284 associated with rock glaciers will remain low and decrease over time (bottom right). The
285 term 'Hazard potential' refers to the expectation that the probability of a named hazard will
286 change over time as the MIL or PT pathways evolve. Sediment supply is from the glacier,
287 debris-covered glacier and rock glacier to the local valley floor.

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289 This paraglacial path might result in a decreased GLOF hazard risk over time, although an
290 increased rock slope failure hazard. There may be some lakes impounded by rock glaciers
291 but these would expect to drain slowly rather than catastrophically given the armoured
292 nature of the rock dam comprised of rock debris. Thus, the nature of geomorphic and
293 hydrological hazards are somewhat different between the MIL and PT pathways and this in
294 itself may help understand which glaciers are following which evolutionary pathway. GLOFs
295 and LLOFs may here also represent paraglacial landscape responses where, instead of
296 meltwater passively draining away under low hazard risk (MIL response), it is impounded by
297 paraglacial landslides that result in high hazard risk (PT response).

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299 **3. Discussion and relationships between the MIL and PT pathways**

300 An important distinguishing feature between the MIL and PT pathways is that direct ice melt
301 is only a factor while the ice mass still exists, ceasing when the ice mass is gone, and tends
302 to affect local areas only. By contrast paraglaciation affects wider geographical areas
303 outside of the ice mass, and can extend for decades to millennia after full ice mass loss
304 (Ballantyne, 2002). Understanding which pathway of evolutionary development is followed
305 by any ice mass at any point in time has implications for predictability, hazard risk and
306 sustainable development. MIL and PT pathways represent end-members along an
307 evolutionary trajectory. It is likely that the development of any one glacier is dependent on
308 their initial conditions, and changes in ice mass volume or surface debris. However, both of
309 these elements are more than a simple volumetric analysis because this does not account
310 for the detailed dynamics or spatial/temporal patterns of ice or debris. These different
311 pathways are likely to display important regional variation in the response of clean ice
312 glaciers, debris-covered glaciers and rock glaciers to future climate change in HMA. These
313 responses will not only be driven by variations in regional temperatures, but also by changes
314 in the behaviour of the Indian and East Asian summer monsoons, and the Western
315 Disturbance (e.g. Fugger et al. 2022). Whilst regional climatic differences remain largely
316 unexplored (although see Brun et al. 2019), we can hypothesise that the areas that will
317 undergo a transition from ice glaciers to rock glaciers and other ice-debris landforms most
318 readily will be those where debris-covered glaciers are already most common, because the
319 debris supply in those areas is high. Furthermore, as high-elevation clean ice thins, and as
320 freeze-thaw and frost shattering environments move to higher altitudes, debris supply will
321 increase in some high-elevation areas that presently produce little debris. Where these

322 environmental domains move into high-elevation cirques, especially north-aspect cirques,
323 'periglacial' rock glacier development associated with permafrost creep will be favoured (cf
324 Haeberli et al. 2006) Because of the exceptionally high relief of the Himalaya and many
325 other parts of HMA, rock glacier development may proceed on regional scales greater than
326 seen in other mountains globally today, though it will take centuries for rock glaciers to
327 develop. Improved understanding of debris supply processes to valley bottoms is restricted
328 by the relative lack of modelling at regional scales that specifically considers the role of
329 debris cover on glacier dynamics, and mass balance (e.g. Racoviteanu et al. 2022).

330 We can see then that the rock glacier response to deglaciation envisioned by the PT
331 scenario is likely to be highly complex, with the full suite of rock glaciers ('periglacial' and
332 'glacier-derived') and other ice-debris landforms developing in different locations, regions
333 and over different timescales. This complex response will be driven by climate change as a
334 first order control, and debris supply and glaciological factors as secondary factors.
335 Separate from rock glaciers, the evolution of undifferentiated ice-debris landforms during
336 glacier recession has hardly been discussed in the cryosphere literature from HMA (although
337 see Bolch et al. (2019). As a result, there is uncertainty in evaluating precisely how the PT
338 scenario would develop, how quickly and what form the equilibrium landscape might
339 present.

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341 How do we assess which of the MIL and PT scenarios are more likely and their probable
342 future spatial distributions? A first-order understanding might be gained by a simple
343 evaluation of how glaciers have behaved in the past in response to known climate forcings;
344 from this we can suggest whether these glaciers have shown high or low-sensitivity to past
345 or recent climate change (Harrison 2009). Although this is a uniformitarian view, if glaciers
346 have demonstrated a high sensitivity to past climate change then this tends to support the
347 MIL scenario for the future responses of glaciers to climate change. Alternatively, if the
348 glaciers have shown low sensitivity or delayed response to past climate change then this
349 might make the PT more likely, even if the forcings are different at different times and
350 glaciers today are in different states than they were in the past. To achieve this we need to
351 establish the extent to which glaciers have responded to the warming since the regional Last
352 Glacial Maximum or the late Holocene Neoglacial Maximum (often seen as equivalent to the
353 European Little Ice Age).

354 Therefore, we compiled published studies that have dated Himalayan moraine sequences
355 from the Western, Central and Eastern Himalaya (Figure 2 and Supplementary Information
356 File). We analysed moraine ages from three time periods: the regional Last Glacial
357 Maximum from 18 to 24 ka (Owen et al. 2002), a period covering the regional Younger Dryas
358 from 12,880 and 11,640 ka (Rawat et al. 2012), and the regional Little Ice Age between
359 1300-1600 AD (Rowan 2017) (Figure 2). While there is evidence that glaciers in several areas
360 reached their late Pleistocene limits earlier than Marine Isotope Stage (MIS) 2 (Benn and

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361 Owen 1998; Owen et al. 2002), overall these data show that glaciers in the Himalaya have
362 not receded much further behind dated glacier limits over these time periods. Figure 2
363 shows that, as expected, glaciers in different regions of the Himalaya have responded
364 differently to past climate change. The results are averaged by region and show
365 considerable local variability. However, overall, glaciers in the western and central regions
366 of HMA have retreated less over these time periods than those in the eastern part of the
367 Himalaya; this spatial pattern might reflect the reduction of the monsoon and intensification
368 of westerly influences on glacier mass balance towards the western Himalaya (Kumar et al.
369 2020; Hunt 2023).
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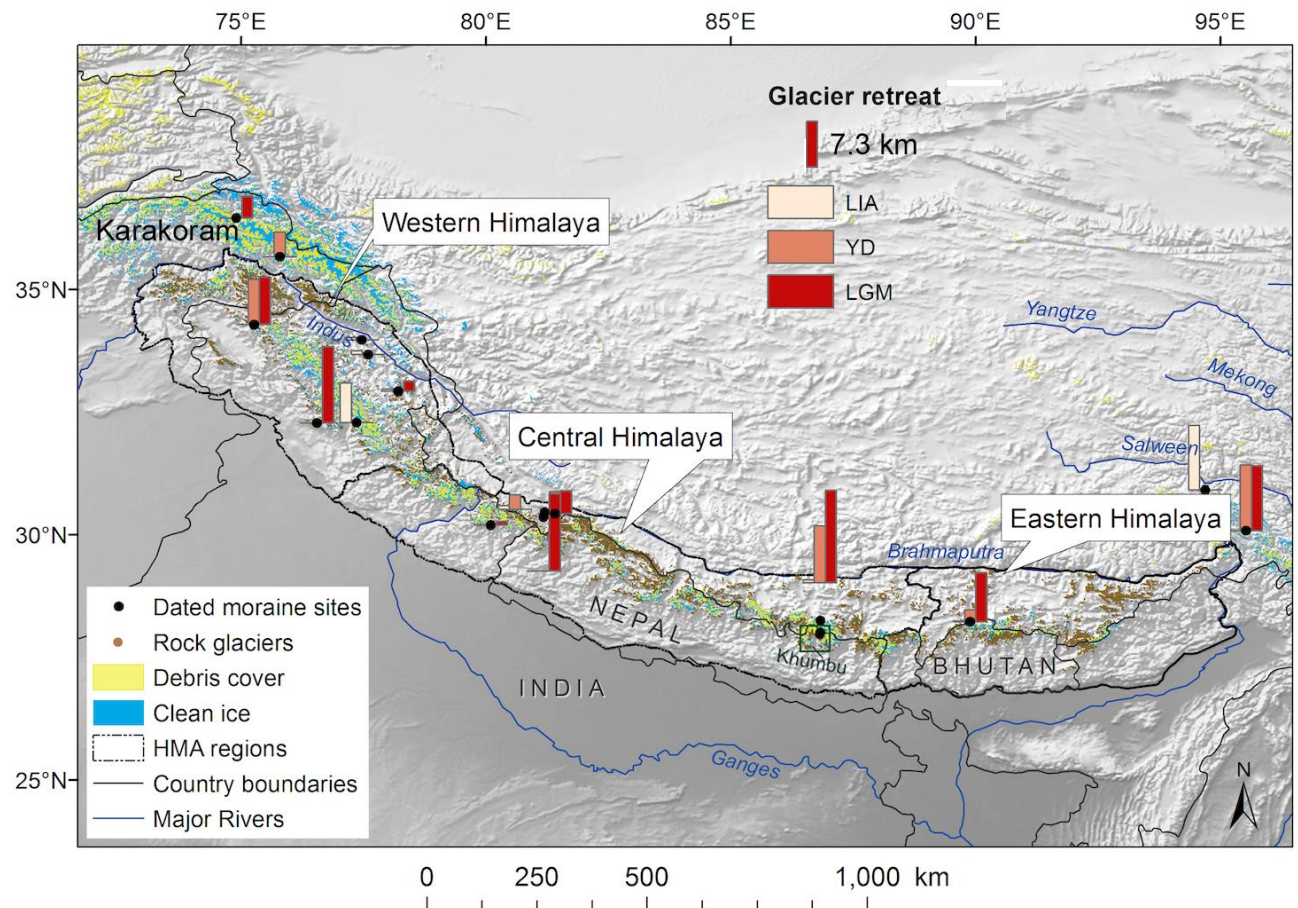380
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Figure 2. Distribution of the various types of glaciers (clean, debris-covered and rock glaciers) across the Himalaya and other parts of the HMA region. Clean ice outlines are based on the current RGI v6 inventory; debris-covered outlines are based on Herreid and Pelliciotti (2020) and rock glacier locations (n = 24,968; brown dots) compiled 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). Background map data from Natural Earth @ naturalearthdata.com

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 glacier surface where the theoretical mass balance is zero at a given point in time (Zemp

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409 et al. 2006; Cogley 2011). For instance, in the Khumbu region in the central Himalaya,
410 Marine Isotope Stage (MIS) 2 moraines (equivalent in age to the global Last Glacial
411 Maximum (LGM)) are located just 5 km or so from modern ice limits and in many cases
412 reflect a 200-300 m reduction in glacier ELA at this time compared with current glacial ELAs
413 in the region (Richards et al. 2000) and also reduced insolation driving a weakened monsoon
414 (Owen et al. 2002). At the western end of the Himalaya much research has concentrated on
415 the Nanga Parbat massif to the south of the Karakoram. Here, work has shown that glaciers
416 draining Nanga Parbat do not show an MIS 2 maximum, although moraines of MIS 3 are
417 present downvalley (Phillips et al. 2000). The absence of evidence for an LGM-age advance
418 of the glacier may reflect aridity during MIS 2 in this region and therefore low glacier
419 sensitivity to atmospheric temperatures at this time (e.g. Yan et al. 2021), i.e. that glacier
420 dynamics here is precipitation-controlled rather than temperature-controlled.

422 Glacier recession since the regional Neoglacial maximum of the late 18th Century also
423 supports the present low sensitivity of many Himalayan glaciers to climate change (Rowan,
424 2017). For instance, at Ama Dablam and Lhotse in the Khumbu region of Nepal, present
425 glacier margins have retreated by around 1 km from Neoglacial moraine limits. Similarly, in
426 the monsoon-transition zone of the Indian Himalaya, the debris-covered Bara Shigri Glacier
427 has retreated less than 3 km since the 1850s (Chand et al. 2017). Overall, Figure 2
428 demonstrates that glacier termini in the western and central parts of the Himalaya have
429 retreated less than 2 km since the end of the Neoglacial maximum. Compared with
430 considerable volumetric ice loss since this time (Lee et al. 2021), if future glacier response
431 mirrors that of the past then this supports our contention that future glacier loss will
432 dominantly involve downwasting of glacier surfaces rather than terminus retreat. We argue
433 that this favours the development of stagnant glacier tongues and enhances the likelihood
434 of further transition to rock glaciers (Jones et al 2019) and other ice-debris landforms (e.g.
435 Johnson 1980; Monnier and Kinnard 2015; 2017; Anderson et al. 2018; and thus the PT
436 rather than the MIL pathway. From this albeit limited and incomplete data set, we suggest
437 that glaciers from the western, eastern and northern Himalaya displayed low sensitivity to
438 climate change during the regional LGM and the Neoglacial, and this supports the PT
439 scenario of glacier responses to future climate change.

441 It is also likely that different glaciers in HMA are at different stages of deglacial evolution,
442 depending on their size, location and mass balance. This means that some show a MIL
443 response, some a PT response, and some may be changing from the former to the latter
444 (Figure 3). It is, however, uncertain as to which clean or debris-covered glaciers will
445 transition to rock glaciers and other ice-debris landforms, and which will melt significantly in
446 response to climate warming. However, we can say, based on current observations, that
447 small glaciers located below the regional ELA are projected to disappear as they will not be
448 able to adapt to future climate (ICIMOD 2023), as is the case in the Andes (Ramirez et al.,
449 2001) and the European Alps (e.g. Zemp et al., 2006; Zebre et al., 2021). Some of these

450 features may completely disappear if debris supply is low, and others may undergo
451 transitions to rock glaciers that may be stabilized by a combination of high snowfall and high
452 debris production. We hypothesise that the transition process is dominated by debris fluxes
453 from mountain slopes and the connectivity between these sites and downwasting glacier
454 surfaces below the ELA (Figure 3). Therefore, the transition between MIL and PT pathways is
455 most efficient in areas where high mountain slopes are producing rock slope failures, rock
456 falls and debris flows, and where lateral moraines are absent or poorly developed and
457 therefore allow sediment access from valley sides to the glacier surface. Climate change will
458 therefore represent a first order control on glacier behaviour but glacial processes creating
459 lateral moraines will play a significant second order control.

460 Finally, the consequences of having more persistent glacial ice in HMA would be profound.
461 This outcome would mean that there is more time to generate climate change mitigation
462 and adaptation schemes in the wider region, and develop technological fixes to the
463 challenges of changing hydrological resources (including total volumes and seasonality). In
464 addition, several of the UN Sustainable Development Goals such as Clean Water and
465 Sanitation might be more easily achieved than previously expected if cryospheric water
466 sources persist longer.
467
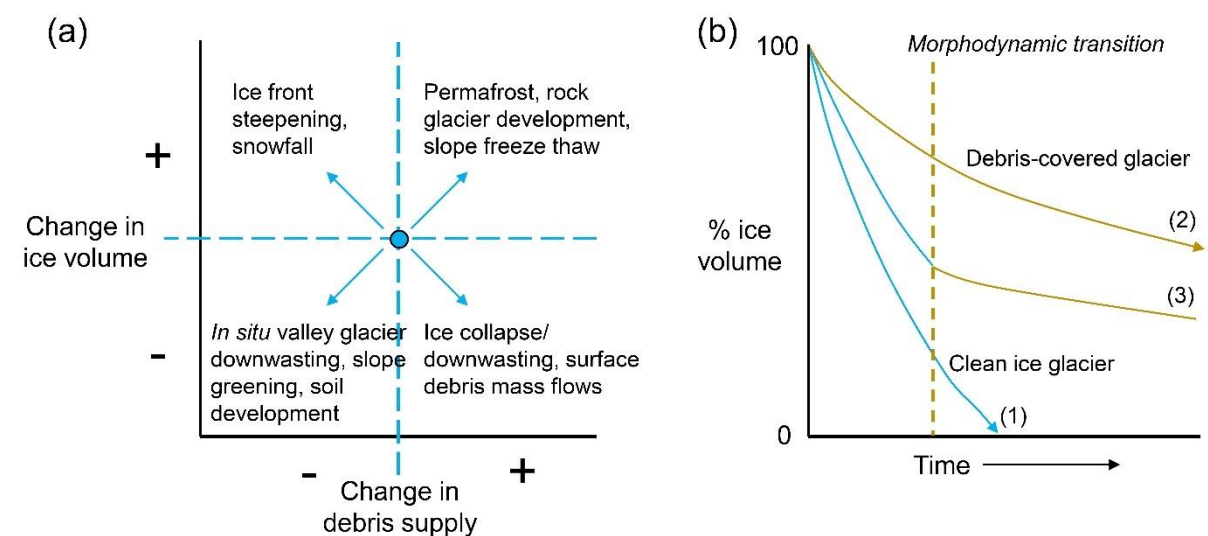468

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

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479   supply. (b) Representation of the different trajectories of changes in ice volume over time
480   between (1) a clean ice glacier (rapid melt), (2) a debris-covered glacier or rock glacier
481   (slower melt), and (3) a scenario where a clean ice glacier starts melting but is then covered
482   by debris, such as from a paraglacial landslide, that then slows down the ice melt. Such an
483   event represents a morphodynamic transition in the response of such a glacier to climate
484   forcing.
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487   **3 Conclusions and future research imperatives**

488   Currently we have argued that there is a general consensus from climate modelling that
489   Himalayan and wider HMA glaciers will reduce their volume significantly, (perhaps by up to
490   90% by 2100 in response to projected climate warming (see Shannon et al. 2018), and most
491   small glaciers will completely disappear by this time. However, we have presented an
492   alternative Paraglacial Transition scenario where many glaciers transform into rock glaciers
493   and other ice-debris landforms as climate change progresses. This serves to inhibit ice melt
494   and increase the resilience of the Himalayan glacial system to future climate change by
495   increasing the longevity of ice bodies in the landscape. The Major Ice Loss (MIL) and
496   Paraglacial Transition (PT) scenarios discussed here represent end members of possible
497   glacial system responses to future climate change (Figure 3).
498

499   While the MIL scenario will also lead to a range of paraglacial responses from deglaciating
500   catchments, we argue that this will not necessarily change the future evolution of individual
501   glaciers which will continue to melt in response to ongoing climate warming (although
502   increased snowfall associated with a warming atmosphere might reduce net mass loss). This
503   MIL scenario continues to dominate the literature based on climate model assessments of
504   glacier melt. However, there are relatively few published studies on the development of
505   rock glaciers and their importance in HMA (see Harrison et al. 2021 for a discussion of this).
506   More research needs to be conducted on the different ice masses and rock glaciers of HMA,
507   and the paraglaciation of the region if the PT view is to be properly assessed. Such future
508   work is made challenging by the difficulty of assessing ice content in rock glaciers and other
509   debris-covered landforms such as lateral and terminal moraines, especially in remote, high-
510   altitude settings. How many rock glaciers have derived from the downwasting of glacial ice
511   (Knight et al. 2019) and how many are derived from the creep of ice-rich permafrost (e.g.
512   Haeberli et al. 2024) is also unknown. How rock glaciers respond to climate change in HMA
513   is also hardly known particularly given their likely long response times.
514
515

516   Critical research is needed in order to evaluate the operations and outcomes of the MIL and
517   PT scenarios, and their possible interactions on individual glaciers. Future research
518   imperatives therefore include: 1) determination of debris fluxes throughout the region for
519   the full range of geological materials, slopes, and microclimates and glacier types; 2) long-
520   term monitoring of glacier mass balance across the region in order to evaluate cryospheric
521   sensitivity to climate forcing; 3) measurement of contemporary debris fluxes and
522   distributions on different glacier types; 4) present and past climate modelling at high

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523 resolution to include changing debris cover, and 5) projections into the future for the full
524 range of climate scenarios. Development of ultra-downscaled climate modelling that is
525 responsive to the full range of HMA relief and slopes with resolutions enough to resolve
526 individual cirques is also needed. This may be currently possible for small local geographic
527 domains sufficient to sample different parts of HMA.

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		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%

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532 **Table 1** Examples of projected relative mass losses by the end of 21st Century for HMA,
533 from different recent studies (reduction as a percentage of ice loss from 1990). Regions are
534 defined as in Randolph Glacier inventory (RGI) v6 (first-order region, shown in Figure 2). The
535 values refer to the multi-GCM means and their standard deviation.

536

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

540

541 Code/Data availability

542 Data are available at: DOI 10.5281/zenodo.15828526 for the moraine inventory and at the zenodo
543 link(10.5281/zenodo.11237094) (rock glacier inventory).

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Author contribution

SH developed the initial idea and wrote the first draft of the paper. The paper was developed with the insights of ARacoviteanu, NFG, KA, JKargel, UH, DS and JKnight . DJ produced the rock glacier inventory and AR produced the moraine inventory. JKnight 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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