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Opinion Piece

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Is ice in the Himalayas more resilient to climate change than we thought?

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ABSTRACT

In the Himalaya, climate change threatens mountain water resources as glaciers melt and changes in runoff and water availability are likely to have considerable negative impacts on ecological and human systems. While much has been written on the effect of climate change on glaciers in the Himalaya and its impact on sustainability, almost nothing has been published on rock glaciers in the region and their role in maintaining water supplies as the climate warms. Rock glaciers are important components of the Himalayan hydrological system because they are present in almost all regions of the Himalaya and are climatically more resilient than other glacier types owing to an insulating layer of debris cover. Research from other mountain regions shows that they contain potentially important water stores, although in the Himalaya, there is almost no information on their number, spatial distribution and response to future climate change. The extent to which this contributes to higher resilience of the Himalayan cryosphere as a whole is still an open question. This paper argues that research into Himalayan rock glaciers that reveals their hydrological significance 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.

KEYWORDS

Climate change; Himalaya; rock glaciers; water

The glaciers of the Himalaya regulate the water for around 40% of the world's population (Nuzhat et al. 2020). Over the past century, these glaciers have lost around 25% of their mass in response to recent climate change and they are predicted to lose more in the future (Immerzeel et al. 2020). While this has attracted much scientific research (e.g. Bolch et al. 2012), it has also initiated a vigorous conversation in the world's media (Carrington 2019) and among policymakers, concerned that the glaciers of the Himalaya and wider high mountain Asia region (HMA) will melt completely over the coming century with severe implications for those reliant on their water, especially as peak runoff has been reached in most hydrological basins (see Nüsser and Baghel 2014). While climate model projections suggest a continued reduction in glacier mass balance throughout the remainder of this century and beyond (e.g. Shannon et al. 2019), the precise evolution of mountain glaciers in the Himalayas and other regions of HMA is currently unclear. What is known, however, is that glacier recession in high mountains produces a characteristic geomorphological response (known as paraglaciation) where valley side slopes and mountainsides become unstable and increase sediment supply to glacier surfaces and valley

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bottoms (Ballantyne 2002). The resulting increased sediment deposition on the glacier surfaces (called supraglacial deposition) retards ice melt. It is important to include these paraglacial processes in a broader consideration of future mountain water supplies rather than assuming that the mountain cryosphere is comprised only of 'clean ice' with a singular response to climatic change.

In contrast, the mountain cryosphere must be considered, like other aspects of the global system as a complex geomorphic system with a variety of features which exhibit spatially and temporally variable responses to climatic change. These include the development of ice-cored moraines, ice-rich permafrost and rock glaciers. The latter are particularly important and are landforms formed of rock-ice mixtures which flow slowly downslope and are covered by a continuous overlying debris blanket 0.5–5 m thick that seasonally thaws each summer (known as the *active layer*). We argue that it is important to understand these systems and their dynamism and heterogeneity if accurate projections of mountain glacier behaviour and future water supplies are to be determined.

The goal of this opinion piece, therefore, is to shed light on the diversity of glacial landforms and highlight the likely importance of rock glaciers as hydrological stores in this vast region in the context of continued climate change. Until recently, these have been largely ignored and a rapid analysis of papers published and archived within Web of Science highlights the problem. Over 1000 papers addressing glacier behaviour and referencing the terms 'glacier' and 'Himalaya' have been published in scientific journals over the past two decades (the precise number depends on a qualitative assessment of article content, which is beyond the scope of this piece to undertake). Tellingly, just 16 of these 1000 papers have investigated rock glaciers in the Himalayan region, and only one has identified rock glaciers as important hydrological stores (data correct as of 22 September 2020). As we will go on to discuss, this gap in the scientific and sustainable development literature is a major problem for the Himalayan region because any accountancy of water stores that excludes rock glaciers as functional components of the hydrological system is biased.

Absent from much of the discussion around melting of Himalayan glaciers, therefore, is a nuanced appreciation of the precise ways in which cryospheric stores of water will respond to future climate change. The greatest concern relates to dwindling glacial water stores, and yet as we have seen the term 'glacier' belies the diversity of cryospheric features under threat in the region. While many glaciers will melt entirely with climate warming, this geomorphic diversity means that others will behave differently, undergoing transitions to more debris-covered landforms. Ice-cored features with debris cover exhibit retarded melting compared to pure ice glaciers (Nicholson et al. 2018) due to the insulation effects of surface debris. In detail, as glaciers melt and thin in response to climate change, surrounding mountain slopes become unstable and start to collapse, delivering large amounts of rock debris to the glacier surfaces. This period of rock slope failure in response to glacier melting is known as the 'paraglacial' period and has been seen as a characteristic response of many landscapes to deglaciation (Ballantyne 2002; Knight and Harrison 2009). Enhanced paraglacial debris production driven by deglaciation may therefore increase the accumulation of rock debris which, depending on debris cover thickness, can limit ice melting and increase the resilience of the glacier to climate change (Pellicciotti et al. 2014).

It is clear that the melt rate around and under debris-covered areas is sensitive to debris cover thickness (see Kayastha et al. 2000; Mihalcea et al. 2008; Benn et al. 2012; Nicholson et al. 2018; Miles et al. 2020). Melt is enhanced when debris cover is thin due to conduction of solar radiation, which is absorbed because of the lower albedo of debris compared with ice, but melt is reduced once the thickness of debris increases above a thickness of a few centimetres, because the debris then insulates the ice from surface heating. Thick supraglacial debris cover (above 10 cm or so) (Bosson and Lambiel 2016) reverses the mass balance gradient, with comparatively higher ablation (mass loss) rates upglacier than at the debris-covered terminus. Furthermore, this significantly influences glacier dynamics and behaviour of the glacier snout and can also lead, later in time, to the development of rock glaciers from debris-covered glaciers (Jones et al. 2019).

Many such debris-covered glaciers have already undergone this transition to form rock glaciers whose response to atmospheric warming and changes in precipitation is as yet unclear (Monnier and Kinnard 2017). Identification of rock glaciers is based on their distinctive characteristics that can enable them to be distinguished using field or remote sensing observations (Figure 1(a,b)) (Haeberli et al. 2006). However, our understanding of how ice glaciers transition to debris-covered glaciers and then to rock glaciers is incomplete. Working in the Khumbu valley of Nepal Jones et al. (2019) showed the complexities of this process. They argued that access to debris supply is one of the drivers of the debris-covered glacier to rock glacier transition. As a result, we argue that the topographic connectivity between glacier surfaces and surrounding unstable mountain slopes is a crucial component of this process. The presence of well-developed lateral moraines along glacier margins serves to reduce this connectivity and therefore reduce the opportunity for transition to rock glaciers.

Ice is stored within the main body of rock glaciers and beneath surface debris in debris-covered glaciers. Thermal conduction and cold-air circulation through the debris mean that ice melt is reduced as debris thickness increases, therefore, water storage in rock glaciers occurs at long, intermediate and short time-scales, corresponding to water in the solid phase (snow and ice) transitioning towards the liquid phase (water) (Bonnaventure and Lamoureux 2013; Monnier and Kinnard 2017).

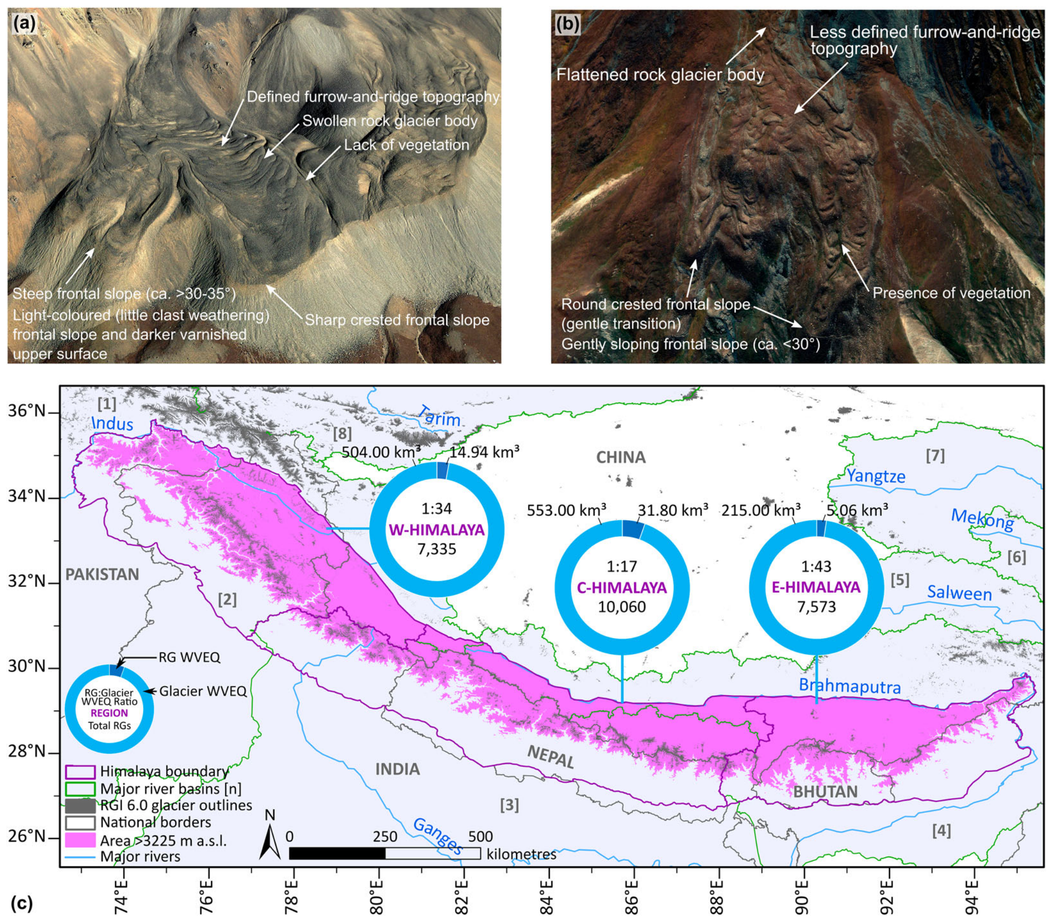

Figure 1. (a) represents the key characteristics of an active rock glacier and (b) is a relict rock glacier. Both examples are from the Himalayas. The coordinates for (a) are 28°43′24.90″N, 85°04′42.78″E (Image Date: 12/02/2010) and for (b) 29°17′26.35″N, 90° 17′06.02″E (Image Date: 10/13/2010). (c) Distribution of rock glaciers in the Himalayas.

As a result, rock glaciers form climatically resilient high-altitude frozen water stores of potentially significant hydrological value (Brenning 2005; Jones et al. 2019). Recent work (Jones et al. 2020) was the first to show that around 25,000 rock glaciers exist in the Himalayas, covering 3747 km² and containing 51.80 ± 10.36 km³ of water; equivalent to between 41 and 62 trillion L. The comparative importance of rock glacier ice content versus that in glaciers in the region was 1:25, ranging from 1:43 to 1:17 in the East and Central Himalaya, with the ratio falling to 1:9 in Nepal (Figure 1(c)).

Importantly, these are the ratios existing at the present time; we expect these ratios to reduce significantly as ice glaciers melt and undergo transitions to rock glaciers, yet the rates of transition from glacier- to rock glacier is not understood (Knight et al. 2019). We also expect rock glaciers to provide water supplies long after ice glaciers have melted; in other high arid mountains, such as the Andes, ice-cored rock glaciers have persisted in valleys long after glacier recession (see also Figure 2). As a result, the ways in which valley side mountain slopes shed rock debris into valley bottoms as ice glaciers melt, means that a likely outcome for Himalayan cryospheric systems in response to continued climate change is a landscape where ice glaciers have been replaced by rock glaciers. This view contrasts with most assessments of glacier recession in the Himalayas which argue that ice glaciers will largely melt and that ice will disappear from these regions over the rest of the century (see Shannon et al. 2019 for a discussion).

However, there have been no modelling studies to assess the likelihood of glacier-rock glacier transition and the hydrological implications of this process and we suggest that this should be a research priority. Our hypothesis is that, in the context of continued climate warming, glacier-rock glacier relationships may therefore enhance the resilience of the mountain cryosphere and play an increasingly important role in climate adaptation. Despite this, whereas much has been written on the role of glaciers in maintaining water supplies (Bolch 2017; Immerzeel et al. 2020), that of rock glaciers remains very poorly known. In addition, determining which glaciers will fully transition and which will simply downwaste and melt would enhance our understanding of future water supplies in these catchments. New work that delivers state-of-the-art knowledge of these processes and rates of change will support effective water resource management in the Himalayas and inform adaptation strategies in the context of future climate change. This research will also have to acknowledge the strong climate contrasts that exist in the Himalaya (for instance between the arid areas of Ladakh and Gilgit and the more humid Central and Easter Himalaya)

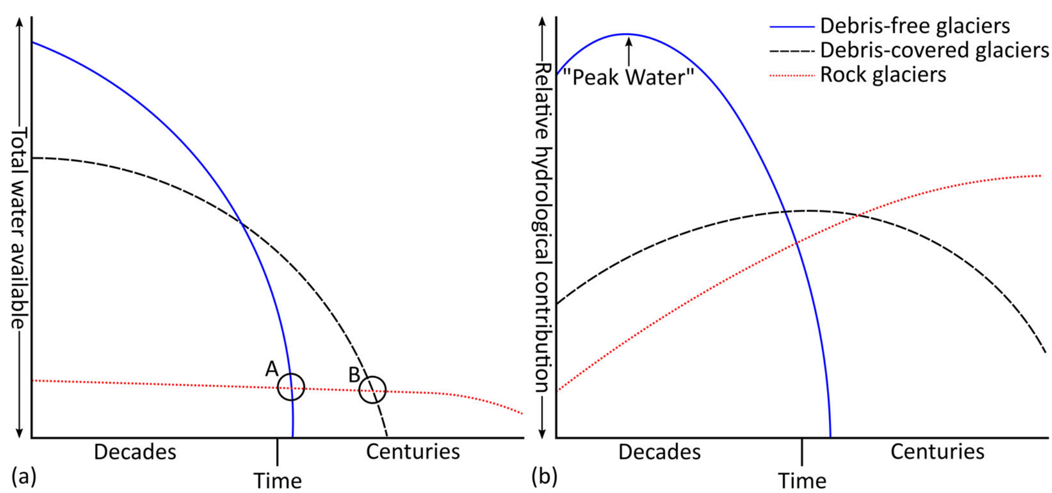

Figure 2. Projected changes in the relative contributions of glaciers, debris-covered glaciers and rock glaciers to hydrological resources in the Himalayas.

and the role this will play in glacier and rock glacier dynamics. In other regions of the world (e.g. in arid mountain catchments in the high Andes of central Chile and Argentina), some estimates put current rock glacier contribution to annual streamflow as high as 13–30% (Geiger et al. 2014; Schaffer et al. 2019); although considerable uncertainties exist we would expect a similar contribution to streamflow in the Himalayas.

We argue then that future research questions should focus on assessing how much ice and therefore potential water is contained within rock glaciers; how these might respond to future climate change and how quickly; and what their contribution might be to transboundary water resources. What is also unclear is how these landforms might contribute to hydrological resources at catchment scales, and the extent to which these additional water supplies will replace reduced glacier melt. With climate change, this becomes a critical issue; 8 of the 27 low-income and lower middle-income economies identified by the UNDP in Asia are impacted by climate change and water supply issues in the Himalaya and other parts of High Mountain Asia. Sustainable Development Goals adopted by all United Nations Member States in 2015 aim by 2030 to substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity, while substantially reducing the number of people suffering from water scarcity. Successful implementation of such initiatives will require a clearer understanding of how the cryosphere responds to warming. Finally, further policy implications of rock glacier storage that have not been explored include the extension of Glacier Protection Laws to regulate mining and other disruptive activities in areas where rock glaciers are common and where they are replacing ice glaciers in the landscape. Indeed, the recently adopted National Glacier Law of Argentina protects glaciers and rock glaciers as strategic water reserves, prohibiting detrimental human activities (e.g. mining and oil and gas activities) in their vicinity, recognising the potential hydrological value of such features. We argue that similar initiatives should be more widely adopted, especially in areas of High Mountain Asia.

In conclusion, it is clear that the glaciers in most regions of the Himalaya are in long-term decline and that this will have enormous implications for the people who rely on these ice masses for water supplies. What is less known is the precise ways in which these glaciers and snow packs will respond to warming; the assumption that they will all melt in a predictable way is likely to be too simplistic. Better understanding of the evolution of these ice masses is hampered by the uncertainties in climate and glacier modelling and the absence of long-term instrumental data sets with which to reconstruct climate variability and trends. We argue that many Himalayan glaciers will evolve into debris-covered glaciers, and many of these will further evolve to form rock glaciers whose response to warming is poorly studied and they may represent long-term solutions to water scarcity in arid mountains. Glacier recession will also produce a range of hazards and these can be seen within the context of paraglaciation. Relatively little research has focused on these issues yet these are areas where environmental and human crises are interconnected and we argue that the scientific community and journals need to better represent the broader spectrum of glacier-rock glacier diversity. Overall, we argue that rock glaciers and the water stores contained within them may have important implications for the resilience of future water resources, sustainable development goals and climate adaptation As a result, our view is that the Himalayan cryosphere is likely to be more resilient that has previously been assumed, even though long-term decline of ice glaciers is still expected. However, proper quantification of this needs to be achieved, as does a clearer assessment of the influence of paraglacial debris supply to glacier surfaces.

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Stephan Harrison is a climate scientist at Exeter University. His research focuses on the impact of climate change in high mountains. His contribution to this article included conceptualisation of the research project and writing the paper.

Darren Jones recently completed his PhD on rock glaciers and future water supplies in the Himalayas. His contribution to this article is in providing much of the empirical data on rock glaciers and water supply.

Karen Anderson is a remote sensing specialist at Exeter University. Her recent work looks at environmental and ecological change in the Himalayas. She contributed to this article by cosupervising Darren Jones' PhD thesis with SH and helping to write the paper.

Sarah Shannon is a climate modeller at Bristol University. She contributed to this article by producing the climate model projections for the wider project, and by helping to write the paper.

Richard A. Betts is a climate scientist at the University of Exeter Global Systems Institute and the Met Office Hadley Centre. His contribution to the paper included framing the climate change implications of this work.

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