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The sustainability of water resources in the High Mountain Asia in the context of recent and future glacier change

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Abstract

High Mountain Asia contains the largest volume of glacier ice outside the Polar regions, and contain the headwaters of some of the largest rivers in central Asia. These glaciers are losing mass at a mean rate of between –0.18 ± 0.04 m and –0.5 m water equivalent per year. While glaciers in the Himalaya are generally shrinking, those in the Karakoram have experienced a slight mass gain. Both changes have occurred in response to rising air temperatures due to Northern Hemisphere climatic change. In the Westerly influenced Indus catchment, glacier meltwater makes up a large proportion of the hydrological budget, and loss of glacier mass will ultimately lead to a decrease in water supplies. In the monsoon-influenced Ganges and Brahmaputra catchments, the contribution of glacial meltwater is relatively small compared to the Indus, and the decrease in annual water supplies will be less dramatic. Therefore, enhanced glacier melt will increase river flows until the middle of the 21st Century, but in the longer-term into the latter part of this century, river flows will decline as glaciers shrink. Declining meltwater supplies may be compensated by increases in precipitation, but this could exacerbate the risk of flooding.

1. Introduction

Millions of people rely on glaciers in the Himalaya, Karakoram and Hindu Kush mountains, collectively referred to as High Mountain Asia, as a water resource. These glaciers form the headwaters of the largest rivers in Asia, including the Indus, the Ganges and the Brahmaputra Rivers (Fig. 1) and as such the mountains are often referred to as the 'water towers of Asia' (Immerzeel *et al.* 2010). High Mountain Asia contains the largest glacierised area outside the

Polar regions (Bolch *et al.* 2012) and glaciers here are highly sensitive to climate change (Solomina *et al.* 2016). Glaciers in the Himalaya are predominantly shrinking (Kääb *et al.* 2012), and rates of glacier mass loss, although spatially variable, have accelerated since the 1990s (Bolch *et al.* 2012). If a constant rate of glacier mass loss after 1975 is assumed, then predictions indicate loss of 10–30 m water equivalent (w.e.) per year between 2010 and 2035, which is sufficient to result in the disappearance of many smaller glaciers across the mountain range (Cogley 2011). The catchments supplied by rivers draining High Mountain Asia are located in developing countries that use this water primarily for agriculture and hydroelectric power generation, and are extremely vulnerable to changes in their water supply (Kaser *et al.* 2010; Pritchard, 2017). Predictions are needed of how Asian water supplies are likely to change due to continued glacier mass loss in response to recent and future climate change. We therefore need to improve understanding of both the contribution of glaciers to the hydrological budgets of these large catchments, and discover how these glaciers are responding to recent and future climate change (e.g. Lutz *et al.* 2014; Brun *et al*. 2017).

Although only 1–3% of the area of the Indus, Ganges and Brahmaputra catchments are glacierised, these densely-populated catchments rely on glacial meltwater (Immerzeel *et al.* 2010). The contribution of glaciers to runoff varies regionally; from 18.8% in the Dudh Koshi catchment, which is a major tributary of the Ganges, up to 80.6% in the Hunza catchment that drains into the Indus (Lutz *et al.* 2014). The Indus and the Ganges provide important water supplies that are used to irrigate over 140,000 km^2 of agricultural land, and the largest irrigation network in the world is contained in the Indus catchment (Immerzeel *et al.* 2010). In particular, the importance of glacier meltwater relative to other water sources (e.g. precipitation, snow melt, groundwater) for regional hydrological budgets has only recently been documented (Immerzeel *et al.* 2010, Lutz *et al.* 2014). In the monsoon-influenced Central and Eastern Himalaya the majority of annual precipitation occurs during the warm summer monsoon months (June to September) (Bookhagen & Burbank 2010). The high summer rainfall and snowfall roughly coincide with the timing of the majority of glacier ablation (Benn & Lehmkuhl 2000), so that the relative contribution of glacial melt to river flows is minimised compared to regions to the west where summers are generally dry (Kaser *et al.* 2010). In the Western Himalaya, Karakoram and Hindu Kush mountains, where the majority of precipitation occurs as winter snowfall, glacier melt plays a much more important role in regulating seasonal river flows, with a relatively larger proportion of the annual flow in the Indus resulting directly from glacier melt compared to that in the Ganges and Brahmaputra catchments (Lutz *et al.* 2014).

The impact of climate change on these vital river flows from the Himalaya is, however, not straightforward. For example, climatic warming may cause glaciers to lose mass and release a greater volume of meltwater each year, but may also result in increased orographic precipitation that could sustain or enhance flows and trigger a gradual or abrupt change in the seasonality of peak flows (Immerzeel et al. 2010). Understanding regional and catchment-scale hydrological budgets and predicting how they will vary under a changing climate therefore requires coupling our understanding of glaciers processes with climate model forecasts. The Intergovernmental Panel on Climate Change (IPCC) climate scenarios for the 21st Century are used for this purpose, as they are compiled from comparison of an ensemble of state-of-the-art climate model outputs (Collins *et al.* 2013). Many regional hydrological models contain large uncertainties as they do not capture the processes that affect individual glaciers, and so detailed catchment-scale models validated by field data are also required to better constrain future hydrological changes (e.g. Ragettli *et al.* 2016).

Here we review recent and predicted glacier and hydrological change across High Mountain Asia (Fig. 1). Glaciers on the Tibetan Plateau are excluded from this review, as this region is strongly influenced by weather systems originating from the Arctic rather than the Asian monsoon, and show markedly different behaviour compared to these glaciers. The long-term response to climate change of Tibetan glaciers is described by Owen *et al.* (2008) and Owen (2009). We first summarise the current knowledge of the state of glaciers in High Mountain Asia, then discuss these changes in the context of observed longer-term glacier change since the late Holocene (the last 2,000 years). We then compare predictions of glacier change with current and future climate change and consider the likely impacts of these changes on regional hydrological budgets.

2. The current state of glaciers in High Mountain Asia

Glaciers in High Mountain Asia are discussed in terms of their location in sub-regional areas that are defined from the major regional climate controls (after Bolch *et al*. 2012; Fig. 1). From east to west these regions are: the monsoon-influenced Eastern and Central Himalaya, and the mid-latitude Western Himalaya, Karakoram and Hindu Kush ranges influenced by westerly weather systems. These areas follow the boundaries of the major river catchments within the high mountains, with the Western Himalaya, Karakoram and Hindu Kush draining into the Indus, the Central Himalaya into the Ganges, and the Eastern Himalaya and some of the Tibetan Plateau forming the headwaters of the Brahmaputra River.

2.1 Glacier extent and volume

The Himalaya and Karakoram mountains contain 32,353 glaciers with a total glacierised area of about 41,000 km^2 equivalent to 6% of the global glacierised area (Arendt *et al*. 2015).

Until recently, relatively little was known about the total number and size of glaciers in the Himalaya because perennial snow cover, debris-covered ice and ice-cored moraine impeded identification of glacier outlines from satellite observations. Improvements in satellite remote sensing imagery have allowed identification of the majority of glacier outlines, which are compiled in the 6th Randolph Glacier Inventory (released in July 2017) and cover most of High Mountain Asia (Arendt *et al*. 2015). Global glacier inventories comprising glacier area boundaries drawn by the glaciological community are now sufficiently complete to estimate the glacierised extents, but data describing other important characteristics such as ice thickness are highly spatially variable and are limited by the small number of field observations. Glacier volume is more difficult to measure than area, as ice thickness is also unknown for most of the range. Estimated mean ice thickness for all glaciers in the Global Land Ice Measurements from Space database are low compared to typical values from individual glaciers derived from field data. Mean ice thickness is estimated to be 86 m for the Himalaya, and 172 m for the Karakoram (http://glims.colorado.edu/glacierdata/ accessed on 30/09/16), although the uncertainty associated with these values is undoubtedly large (Cogley 2011; Frey *et al.* 2014) and likely biased by the majority of measurements being obtained from smaller glaciers.

More robust *in situ* ice thickness measurements have only been made for a handful of glaciers, using ground-penetrating radar or radio-echo sounding surveys. Access to large high-altitude glaciers can be challenging and so field observations are frequently made at more accessible glaciers. Accessible glaciers are generally at lower altitudes, smaller than the majority of the population, and have higher rates of mass loss than larger glaciers at higher altitude. These glaciers are not necessarily representative of regional-scale behaviour, and therefore field measurements often contain a bias that may skew understanding of regional mass balance trends (Fujita & Nuimura 2011). Ice thicknesses for three glaciers in Nepal in the Central Himalaya ranged from less than 20 near the terminus to 440 m near the icefall for the largest, Khumbu Glacier (glacier area is 39.5 km^2; Gades *et al.* 2000), 20–157 m for Lirung Glacier (13.5 km^2; Kadota *et al.* 1997) to 51–86 m for the smallest, Glacier AX010 (0.6 km^2; Kadota *et al.* 1997). Ice thickness was 124–270 m for Chhota Shigri Glacier (15.7 km^2) in the Western Himalaya (Azam *et al.* 2012). These values represent the centreline ice thickness, and in each case the glacier cross-section thins towards the valley sides (*cf*. Azam *et al.* 2012).

Across the Himalaya, 14–18% of the glacierised area is debris covered (Kääb *et al.* 2012), the extent of which increases to the east to reach 36% in the Everest region of Nepal (Thakuri *et al.* 2014). Supraglacial debris thickness typically increases down-glacier, as englacial and supraglacial debris transport concentrates sediment previously incorporated into the ice (Fig.

2) (Rowan *et al.* 2015). The thickness of supraglacial debris layers can exceed several metres (Nicholson & Benn 2013, Thakuri *et al.* 2014; Soncini *et al*. 2016). Supraglacial debris modifies glacier mass balance, either through enhancing ablation due to the decreased albedo of debris compared to ice, or by reducing ablation by insulating the glacier surface; feedbacks which are largely dependent on the thickness of the debris layer (Østrem 1959, Evatt *et al.* 2015, Nicholson & Benn 2006). The threshold between the enhancement or attenuation of ablation by supraglacial debris occurs at a critical thickness of around 0.05 m, as demonstrated both from field (Rounce *et al.* 2015) and laboratory measurements (Reznichenko *et al.* 2010). The influence of variations in debris thickness on ablation was demonstrated at Khumbu Glacier, where rates of surface lowering are highest mid-glacier just below the icefall where the surface is either debris free or only thinly mantled compared to the heavily debris-mantled terminus where ablation rates are an order of magnitude lower (Nakawo *et al.* 1999, Adhikari & Huybrechts 2009, Owen *et al.* 2009).

2.2 State of glacier mass balance and their Equilibrium Line Altitudes

Glacier mass balance is highly variable across High Mountain Asia. This variability in mass balance has been identified directly using the traditional glaciological method where stakes are inserted into the glacier surface to measure ice ablation and snow accumulation (e.g. Soncini *et al.* 2016). Equilibrium Line Altitude (ELA; the point on a glacier at which accumulation and ablation are balanced) can be estimated from the areal extent and hypsometry combined with climate data (Benn & Lehmkuhl 2000). The ELA method has the advantage of allowing reconstructions of past glacier mass balance from geological evidence of glacier extent (Benn *et al.* 2005, Owen & Benn 2005). Regional glacier mass balance can be estimated from geodetic methods using multi-temporal satellite imagery that measures changes in glacier surface elevations (e.g. Bolch *et al.* 2011, Kääb *et al.* 2012). Remote sensing can also be used to measure snowline altitudes at the end of the ablation season, from which the ELA can be derived (e.g. Harper & Humphrey 2003). Mass balance is more difficult to measure for debris-covered glaciers than for clean-ice glaciers due to the rapid variations in rates of ablation that occur across the glacier surface, influenced by the thermal conductivity of the debris layer, which is controlled by factors including debris thickness, debris grain size, porosity and water content (Benn *et al.* 2012).

Mass balance has only been measured directly for a small number of glaciers (Fig. 3), and the longest of the continuous records cover only 10 years. Mass balance for Shaune Garang Glacier in the Himachal Pradesh in northern India was –0.36 m w.e. a^{-1} between 1981 and 1991 (Pratap *et al*. 2015). Measurements of mass balance for small glaciers in the Central Himalaya indicate the extreme sensitivity of the monsoon-influenced glaciers to air temperature. Mass balance measurements through the 1978 monsoon for Glacier AX010 indicate that a 0.5°C decrease in mean summer air temperature would result in a transition between positive and negative mass balance (Ageta *et al.* 1980). Three annual ablation stake surveys indicate a mass balance of –1.6 m w.e. a^{-1} between 2003 and 2014 for Gangju La Glacier, a small clean-ice glacier in Bhutan in the Eastern Himalaya (Tshering & Fujita 2016). Mass balance modelling for the partially debris-covered Langtang Glacier in the Central Himalaya simulated a mass balance of –0.11 m w.e. a^{-1} between 1987 and 1997 (Sharma & Owen 1996). Mean present-day ELA calculated from snowline elevations in the Annapurna region of western Nepal was ~5050 m (Harper & Humphrey 2003) and in eastern Nepal the ELA ranged from 5300 m in the Langtang Valley to 5600 m in the Khumbu Valley (Kayastha & Harrison 2008).

The complete mass budget of all glaciers in High Mountain Asia between 2000 and 2016 was recently calculated from remote topographic measurements as −0.18 ± 0.04 m w.e. a^{-1} (Brun *et al*. 2017). This value is slightly lower than that given by glaciological mass balance records (summarised by Bolch *et al.* 2012) which gave a regional mass budget of about –0.3 m w.e. a^{-1} between the 1960s and 1990s, becoming increasingly more negative during the last two decades and similar to the global mean (around –0.5 m w.e. a^{-1}). Remote sensing studies have previously indicated a slightly more negative regional mass balance between 2003 and 2008 of –0.21 ± 0.05 m w.e. a^{-1}, lower than the global average due to the slightly positive mass budget in the Karakoram (Kääb *et al.* 2012)—the so-called 'Karakoram anomaly' (Gardelle *et al.* 2012). Karakoram glaciers have recently gained mass due to rising air temperatures delivering more winter snowfall from the Arabian Gulf (Kapnick *et al*. 2014). A large proportion of surge-type glaciers are found in the Karakoram, and this dynamic behavior can also result in short-term mass gain (Quincey *et al.* 2011; Quincey *et al.* 2015).

2.3 The "debris-cover anomaly"

The ablation areas of many glaciers in the Himalaya are covered with rock debris, which is deposited on glacier surfaces as a result of erosion and mass wasting of the surrounding landscape. Supraglacial debris affects mass balance and complicates understanding of the response of these debris-covered glaciers to climate change (Scherler *et al.* 2011). There are four main sources of debris on the surface of Himalayan glaciers: (1) rockfall debris which is angular in character; (2) mixed rock- and ice-avalanche debris, which is texturally similar, but which is entrained as prominent debris layers within the glacier (Fig. 2d); (3) material resulting from collapse from over-steepened moraines which is characterised by sandy boulder gravel and is typically sub-rounded to angular; (4) debris derived from the base of the glacier that has been transported to the surface by thrusting or shear from the bed, such as at the base of an icefall. This debris is a mixture of silt, sand and gravel, with some boulders bearing striations. These four lithofacies become intimately mixed on the surface of debris-covered glaciers due to local slope movements from uneven ablation (Figure 2c) (Hambrey *et al*. 2008). Many Himalayan glaciers are also bounded by prominent latero-terminal moraine systems. These moraines are comprised of a mixture of basally worked and rockfall debris, which texturally are typically sandy boulder-gravels. Downwasting of the glaciers since the Little Ice Age (LIA) about 1300–1600 (Rowan, 2017) have left ice-cored moraines up to a hundred metres above the glacier surface, which result in an unstable inner moraine face that is unstable and prone to collapse (Hambrey *et al*. 2008).

Debris-covered Himalayan glaciers tend to lose mass by surface lowering rather than terminus recession (Rowan *et al.* 2015, Quincey *et al.* 2009, Bolch *et al.* 2011). Surface lowering causes these debris-covered glaciers to develop very low or even reversed long-profile topographic gradients through their ablation areas, which promotes the formation of supraglacial water bodies. These ponds and lakes influence the seasonal transport of water through the glacial system, and can expand and coalesce to form substantial supraglacial or proglacial, moraine-dammed lakes that may eventually pose a potential flood hazard (Watson *et al.* 2016, Thompson *et al.* 2012). Such features are commonly bordered by steep, debris-free ice cliffs, which progressively backwaste, and, if connected to a supraglacial pond or lake, may undergo thermoerosional notch development at the ice-water interface, promoting the onset of calving processes (Fig. 2) (Hambrey *et al.* 2008, Thompson *et al.* 2016).

Satellite observations of glacier mass change suggest that debris-covered glaciers in the Himalaya and Karakoram may be losing mass at the same rate as those glaciers with clean-ice (debris-free) surfaces. This ‘debris-cover anomaly’ could be due to enhancement of ablation at ice cliff faces. Although the exposure of clean ice at these ice cliffs can dramatically enhance local ablation rates (Miles *et al.* 2016, Brun *et al.* 2016, Reid & Brock 2014) field observations from Changri Nup Glacier in the Everest region suggest that, despite the presence of these ablation ‘hotspots’, a continuous or near-continuous mantle of supraglacial debris reduces net ablation, such that glacier-wide mass loss is less than would be the case for an equivalent clean-ice glacier (Vincent *et al.* 2016). To fully understand the effect of ice cliffs on ablation from debris-covered glaciers, these features and their evolution need to be incorporated into glacier-wide surface energy balance modelling (e.g. Buri *et al.* 2016; Brun *et al.* 2016).

3. Changes in glacier volume during the Late Holocene

Changes in the areal extent and volume of glaciers over the last 2,000 years can be inferred from moraines that indicate the position of glacier margins, historical observations made by climbing expeditions, and field and satellite measurements of glacier geometries.

3.1 Late Holocene (2,000 years ago to present)

Many glaciers in High Mountain Asia have advanced and receded two or three times during the last 2,000 years in response to climate change (Owen & Dortch 2014, Murari *et al.* 2014, Rowan 2017) and followed the global trend of glacier recession and shrinkage since about 1850 (Thompson *et al.* 2006). The last period of regional glacier advance was the LIA which peaked between 1300 and 1600, although glaciers remained close to their LIA limits until the 20th Century (Rowan 2017). These observations are based on geochronological data for moraines compiled from studies using radiocarbon (^{14}C) dating (e.g. Muller 1961, Röthlisberger & Geyh 1986) and terrestrial cosmogenic nuclide dating (e.g. Owen 2009, Murari *et al.* 2014). More recent applications of these techniques generally provide more accurate results due to improvements in laboratory measurement protocols. Regional glacier volume change in the Himalaya over decadal to centennial timescales occurred in response to hemispheric changes in air temperature (Solomina *et al.* 2016, Rowan 2017). However, variations in the timing and extent of glacier volume change across this range are primarily driven by millennial-scale east–west and north–south variations in atmospheric circulation regimes (Vaux & Balk 2012). The characteristics of local weather systems, particularly precipitation distribution, are also important and probably governed by precession-scale insolation cycles (Thompson *et al.* 2006). Consequently, moraine ages indicate spatial variability in the amount and timing of glacier mass loss due to variations in the timing and intensity of monsoonal and Westerly snowfall across the region (Rowan 2017, Owen 2009).

3.2 20th and 21st Centuries (1900 to present)

Changes in glacier length and area during the early part of the 20th Century are described by historical accounts from early climbing expeditions. These records are based on visual comparison of the state of these glaciers to those in the European Alps, which has led to misinterpretation of ongoing glacier volume change (Grove 2004). Measurements of changes in length and area are of limited use for estimating the mass change of debris-covered glaciers that lose mass by surface lowering rather than terminus recession (e.g. Bolch *et al.* 2011). Geochronological techniques such as ^{14}C and terrestrial cosmogenic nuclide dating do not currently operate at sufficient temporal resolution to describe the ages of moraines formed in the last 100 years. However, changes in glacier volume over small areas can be accurately detected by comparing multi-temporal aerial and satellite topographic data, including historical imagery from the Corona and HEXAGON satellites that date back to the 1950s (e.g. Bolch *et al*. 2011; Berthier *et al.* 2014). Measurements of the gravitational field of the Earth's surface (the Gravity Recovery and Climate Experiment; GRACE; Tapley *et al.* 2004) combined with topographic data can be used to estimate changes in glacier mass across a broad spatial area (e.g. Ageta *et al.* 1980, Fujita & Nuimura 2011, Sarikaya *et al.* 2012) but with large uncertainties (Gardner *et al*. 2013).

Analyses of ice cores demonstrate a sharp decrease in accumulation on low-latitude (25–35°N) Himalayan glaciers, and an increase in ice volume at higher latitudes (35–70°N) on the Tibetan Plateau driven by variability in monsoon intensity and timing since 1950 (Hou *et al.* 2002). However, glacier mass loss at high elevations has exceeded that which could be attributed to change in monsoon intensity alone (Mölg *et al.* 2012). Mass balance is most negative in the Eastern Himalaya, and becomes less negative to the north and in the northern and eastern parts of the Karakoram where some glaciers showed slightly positive mass balances between 1999 and 2008 (Gardelle *et al.* 2012). The opposing trends in glacier mass balance between the Karakoram and the Eastern Himalaya over the last 50 years are attributed to spatial variations in the rates of change in temperature and precipitation (Gardelle *et al.* 2012, Nakawo *et al.* 1999), as rising Northern Hemisphere air temperatures deliver winter snowfall from the Arabian Gulf further into the range (Kapnick et al. 2014). Climate warming appears to have accelerated the mass loss from glaciers in the Himalaya after 1995, reflecting the high sensitivity of the regional energy balance to small changes in climate (Cogley 2011). Over the same period, a slight gain in mass has been observed for glaciers in the Karakoram, attributed to a greater influence of Westerly winter snowfall (Gardelle *et al.* 2012, Yao *et al.* 2012), although not all glaciers in the Karakoram gained mass in the last 40 years (Sarikaya *et al.* 2012).

4. Predictions of future glacier change

Predictions of how glaciers will continue to change from the present day requires quantifying, specifically: current glacier mass balances, the response time over which glaciers will reach equilibrium with climate, and how the climate will change over the period of interest. For the 21st and 22nd Centuries, climate model ensembles such as those produced by the IPCC (Collins *et al.* 2013) give a range of possible warming values for future emissions scenarios, which are useful for forcing meteorological and glacier modelling. Glacier models are often somewhat less sophisticated than these climate models and operate at different spatial scales, particularly in representing the dynamics of mountain glaciers, in which the processes controlling the flow of ice through steep rugged terrain and where feedbacks with often extreme topography and complex orographic meteorology are poorly documented. The rate of regional glacier change in High Mountain Asia may also be enhanced when compared to lower-altitude glacierised regions, as Northern Hemisphere warming is enhanced at altitudes above 5000 m (Xu et al. 2016), the elevation range where the ELAs of the many large glaciers are located (Benn & Lehmkuhl, 2000). To better understand better the impact of climate change on glacier mass balance, meteorological variables on a smaller spatial scale than the entire region are needed.

Predictions of glacier response to future climate change can be made either by extrapolating from observations of recent glacier change and present-day glacier characteristics, or by applying numerical glacier–climate models. These glacier models vary widely in their level of sophistication and complexity depending on the required application, but generally can either extrapolate from observed trends in the relationship between glacier mass balance and climate, or replicate the physical processes by which glacier change occurs and be forced by changing climate conditions. Numerical modelling of glacier mass balance forced by detailed simulations of mesoscale meteorology has been undertaken to better understand the atmospheric controls on Zhadang Glacier in central Tibet (Mölg *et al.* 2012), but is still in development for regional applications. Glacier-climate models can be used to make catchment-scale and regional-scale predictions of the contribution of glacial meltwater to hydrological budgets, and their contribution in the context of water supplied by precipitation or groundwater flow (e.g. Lutz *et al.* 2014). However, predictions based on numerical modelling must also consider the range of uncertainties associated with the data used to drive models. Many of these climatic and glaciological variables, such as the relationship between air temperature and ablation beneath supraglacial debris, or the subglacial conditions controlling ice flow, are poorly constrained both at present and in terms of future change in the Himalaya (Rowan *et al.* 2015).

Precipitation in the monsoon-influenced Eastern and Central Himalaya is predicted to increase by up to 10% during the 21st Century (IPCC scenario A2; Collins *et al.* 2013). Although this increase in precipitation would mean that widespread droughts are unlikely, with warmer air temperatures a greater proportion of precipitation will fall as rain rather than snow and will rapidly melt glacier ice (Meehl *et al.* 2007). The mass balances of the majority of glaciers in High Mountain Asia are out of equilibrium with present-day climate, as is the case for glaciers worldwide. A degree day model of the Eastern Himalaya based on a 20-year climate record demonstrated that loss of 25% of the glacierised area could occur with only 1°C warming from present (Rupper *et al.* 2012). Under an extreme scenario of 2.5°C warming by the end of the 21st Century, the glacierised area of Bhutan would be reduced by 50%, and the contribution of meltwater flux to annual hydrological budgets would become negligible (Rupper *et al.* 2012). Catchment-scale hydrological modelling of the Langtang catchment in Nepal, a typical high-altitude valley in the Central Himalaya, suggest a loss of

35–55% of the total glacierised area by 2100, with the contribution of areal loss from debris-covered glaciers only 25–33% over the same period (Ragettli *et al.* 2016).

5. Impacts on water resources with future glacier change

Until 2050, if only the contribution of glaciers to the hydrological budget is considered, river flows are likely to rise during the monsoon an effect called the 'deglaciation discharge dividend' (Kaser *et al.* 2010). River flows will reach 'peak water' then decline as glacier mass is dramatically reduced and rivers have a greater dependence on precipitation and snow melt (Soncini *et al.* 2016). 'Peak water' in monsoon-influenced regions is predicted to occur by the mid-21st Century, as identified by hydrological modelling of glacier meltwater production (Lutz *et al*. 2014). In Nepal, glacier mass loss is predicted to increase downstream water supplies during the first half of the 21st Century compared to 2001–2010, as the additional meltwater released each year will boost river flows. Water supplies are then either predicted to decline or remain stable depending on how the monsoon changes during this period, as the predicted 10% decrease in meltwater runoff could be compensated by a similar increase in precipitation (Ragettli *et al.* 2016). The contribution of glacier meltwater to future river flows may increase slightly during the monsoon due to enhanced ice melt, but decrease overall by 4% by 2050 as glacier mass rapidly declines (Soncini *et al.* 2016). Hydrological modelling predicts a decline in the glacial meltwater contribution to catchment hydrological budgets over the next century; by 2065 the change in mean catchment water supply is likely to be –8% in the Indus, –18% in the Ganges, and –20% in the Brahmaputra (Immerzeel *et al.* 2010). These decreases in meltwater supply are likely to be compensated, at least partially, by increasing rainfall of +25% in the Indus and Brahmaputra and +8% in the Ganges. However, these projections should be treated with caution, since changes in the monsoon are currently difficult to represent in predictive climate models (Immerzeel *et al.* 2010).

Short-term increases in river flow as rainfall becomes a more important constituent of the hydrological budget are likely to increase the risk of regional flooding (Ragettli *et al*. 2016). However, the magnitude and timing of peak flows relative to the present day are generally unknown (Fig. 4). The expansion and coalescence of supraglacial melt ponds to form larger supraglacial or proglacial lakes bounded by terminal and lateral moraines presents an additional risk in the form of the hazard posed by potentially catastrophic glacial lake outburst floods (Benn *et al*. 2012). These sudden-onset floods generally arise from the breaching of an impounding moraine, and are capable of generating peak flood discharges that can exceed seasonal high flow floods by over an order of magnitude (Cenderelli and Wohl, 2001). Large glacial lakes may also be considered as an intermediate storage component in the hydrological cascade of glacierised (and generally deglaciating) catchments and effectively regulate the downstream transmission of glacial meltwater (Carrivick and

Tweed, 2013). An anticipated increase in the number and extent of glacial lakes as a result of climate change is of concern, especially when considered in the context of the rapidly expanding Asian hydropower sector, which is likely to become increasingly exposed to climatically controlled glacial flood hazards (Schwanghart *et al*. 2016), and modified hydrological regimes.

Beyond 2050, sustained glacier mass loss will result in declining water supplies and possible shifting of seasonal river flows, as spring meltwater will no longer sufficiently compensate for the pre-monsoon dry season (Immerzeel *et al.* 2010). River flow will decline most dramtically in the Indus basin where a significant proportion of the annual hydrograph is derived from glacier melt (Fig. 5) (Lutz *et al.* 2014). Future river flows will depend on changes in the amount and timing of precipitation, and highly seasonal river flows are likely to change their timing compared to the present day, possibly resulting in enhanced spring flows (Immerzeel *et al.* 2010). Total hydrological budgets are likely to decline dramatically by 2100, with extreme scenarios predicting a 26% decrease in flow predicted by 2100 for the Everest region, due to glaciers losing over 50% of their volume compared to 2012–2014 (Soncini *et al.* 2016).

6. Improving understanding of glacier response to climate change

Whilst there are large uncertainties about the current state of and the ongoing changes experienced by glaciers, conclusions can nevertheless be drawn about important controls on their response to climate change to make predictions of their future state (Bolch *et al.* 2012). These predictions often contain large uncertainties, due to a lack of available data with which to validate models, and the suitability of existing glacier models which have often been developed for application to Polar ice sheets rather than glaciers flowing through steep, mountainous terrain. Many factors control the response of mountain glaciers to climate change (Fig. 6), and spatial and temporal variability in these controls can be challenging to represent in numerical models. Some key areas for possible future research to reduce these uncertainties are described here.

6.1 Modification of glacier response to climate change by catchment geomorphology

The dynamics and hydrology of individual glaciers are governed by characteristics such as glacier aspect, size, altitude, and hypsometry, collectively known as morphometry. These morphometric factors exert a significant control on the dynamics and mass balance of mountain glaciers (Quincey *et al.* 2009). Moreover, the pronounced interaction between high topography and atmospheric circulation systems such as the Indian summer monsoon results in distinctive local mesoscale meteorological patterns (Bookhagen & Burbank 2010). This interaction between the atmosphere, landscape and cryosphere can produce catchment-scale variations in energy and mass balance that cause adjacent glaciers to exhibit different responses to the same change in climate (e.g. Glasser *et al.* 2009). For this reason, a coupled mesoscale–energy balance modeling approach represents an important advance in the understanding of glacier–climate interactions in High Mountain Asia (Mölg *et al.* 2012). Robust dynamic or statistical methods are needed to downscale climate model outputs to a scale relevant to glacier mass balance that accounts for mountainous topography (e.g. Reichert *et al.* 2002). Furthermore, these relationships may need to be reconsidered for application using future climatologies (Meehl *et al.* 2007). The degree-day model applications, such as that used by Rupper *et al*. (2012) are useful to predict regional glaciological and hydrological changes with climate variations. However, the modification of glacier–climate relationships by factors such as surface debris cover and glacier morphometry requires further exploration and the acquisition of field data for model validation.

6.2 Sensitivity of debris-covered glaciers to climate change

As glaciers lose mass, debris accumulates on their surfaces, and as a result, the debris-covered glacierised area worldwide is increasing. Ablation under a supraglacial debris layer is primarily controlled by its thickness, but to a lesser extent by debris properties including lithology, moisture content and porosity (Benn *et al*. 2012). These parameters are spatially and temporally variable, due to variations in input, transport and exhumation of debris to the glacier surface in space and time (Anderson & Anderson, 2016; Gibson *et al.* 2017). Much recent work has focused on determining spatial variability in debris thickness, either remotely using thermal satellite imagery (e.g. Mihalcea *et al*. 2008; Foster *et al*. 2012; Rounce & McKinney, 2014) or directly using ground-penetrating radar (e.g. McCarthy *et al*. 2017) and, in some cases, the impact of this spatial variation on glacial hydrology (Minora *et al*. 2015; Soncini *et al*. 2016). Many of these inputs are validated with minimal field measurements of debris thickness, but such validation would greatly extent the scope of predictions that could be made considering debris-covered glacier change. Few studies currently consider the influence of spatial variation in moisture content (e.g. Collier *et al.* 2014), porosity (e.g. Evatt *et al.* 2015), albedo (e.g. Nicholson & Benn, 2013) or aerodynamic roughness length (e.g. Rounce *et al*. 2015; Miles *et al*. 2017; Quincey *et al*. 2017).

Predictions of glacier mass balance modified by debris cover requires distributed surface energy balance models that consider variations in debris cover across the glacier surface and through time, and ideally simulate the interaction of free air and moisture with the porosity of debris layers (e.g. Evatt *et al.* 2015, Collier *et al.* 2014). However, suitable models are few, often only consider one important variable (e.g. debris thickness or porosity), and are mainly driven by empirical relationships derived from limited field data (e.g. Mihalcea *et al*. 2008). Therefore, to comprehensively understand the influence of a debris layer on ablation, further field data is needed to quantify the extent of variations in debris parameters and to develop understanding of heat flux through supraglacial debris. It is potentially possible to use field measurements of debris thickness to calibrate and validate a method of classification of this variable from remote observations, which would greatly extent the scope of predictions that could be made considering debris-covered glacier change. Furthermore, as field-based research tends to focus on relatively accessible, often smaller lower altitude glaciers, a remote calibration method for debris thickness has the potential to dramatically advance knowledge of how these glaciers behave in response to climatic forcing.

6.3 Modification of glacier response to climate by glacier dynamics

Feedbacks between glacier mass balance and dynamics control the magnitude and timing of the response of individual glaciers to climate change. Ice flow also drives processes that affect glacier mass. For example, the transport of debris to the glacier surface from englacial or subglacial storage can cause the supraglacial debris layer to thicken and thereby reduce ablation. In contrast, ice flow stagnation may promote the development and expansion of supraglacial or moraine-dammed lakes, which promotes widespread calving of the lake-terminating glacier tongue and thereby accelerating mass loss (Gardelle *et al*. 2011). Debris cover frequently causes glacier tongues to lose mass by surface lowering rather than terminus recession, which in turn affects dynamics, since ice flow tends to stagnate with the loss of driving stress (Quincey *et al*. 2009). Commonly, supraglacial or proglacial lake formation coincides with this process, and once a lake crosses a threshold of depth of about 80 m deep the lake-marginal glacier ice starts to calve (Quincey *et al.* 2007, Robertson *et al.* 2012) with potentially dramatic consequences for glacier dynamics and mass balance. Under IPCC 21st Century climate change scenarios, proglacial lakes are increasingly likely to pose a potential hazard to human life through an increased risk of sudden-onset glacial lake outburst floods. However, the timing and magnitude of lake formation and growth are difficult to predict.

Rates of recent proglacial lake expansion have been quantified from satellite imagery and are particularly well-studied in the Khumbu Himal in the Central Himalaya (Watson *et al.* 2016) and the Lunana region of Bhutan in the Eastern Himalaya (Fujita *et al.* 2008). The primary process by which lakes expand appears to be via the subaerial loss of mass at the active calving front rather than the ablation of subaqueous ice, including ice at the lake bottom (Fujita *et al.* 2009). Controls on calving rates for glaciers terminating in freshwater rather than marine settings differ, and are dominated by wave fetch and lake temperature (Sakai *et al.* 2009). However, prediction of future change in these variables and the impact on lake development has not been investigated. Proglacial lake growth has typically accelerated with rapid glacier recession since the 1960s (Bajracharya & Mool 2010), but the impact of lake formation on future glacier change is poorly understood. Although it seems intuitive that lake-terminating glaciers should recede more rapidly than equivalent land-terminating glaciers, few conclusive data are yet available to confirm this (e.g. King *et al*. 2017).

7. Conclusions

Glaciers in High Mountain Asia are changing rapidly in response to recent climate change, with many glaciers losing mass at accelerated rates since the 1990s. Sustained glacier mass loss is predicted to continue through the 21st and 22nd Centuries even in the absence of further climate warming from the present day. In the monsoon-influenced Eastern and Central Himalaya, the majority of glacier mass loss occurs during the warm summer months (June to September), which coincides with the timing of maximum precipitation at high altitudes. As a result, the glacier meltwater contribution to the Ganges and Brahmaputra catchments is relatively less important than for the Indus catchment, which drains the Westerly influenced Western Himalaya, Karakoram and Hindu Kush and has a smaller rainfall component of the annual hydrological budget. Seasonal river flows in the Eastern and Central Himalaya are therefore unlikely to decrease during the next 50 years and may even increase slightly, the 'deglaciation discharge dividend', as climate models predict increased monsoon precipitation with warming during this century, and because accelerated glacier melt will provide additional water over the same period. In the Western Himalaya, Karakoram and Hindu Kush, river flows are much more dependent on glacier mass change than in the catchments further to the east. The future of these glaciers is a less clear, as those in the Karakoram appear to have recently experienced a slightly increase in ice mass which may be due to the increased extent of winter snowfall resulting from warming air temperatures. However, in the Western Himalaya, glacier mass loss appears similar to that elsewhere in the mountain range, suggesting that the hydrological budget of the Indus is likely to be severely affected by climate change.

Beyond the mid-21st Century, when large volumes of glacier ice have been lost, the hydrological budget of catchments in the monsoon-influenced regions will be more dependent on the timing and availability of monsoon precipitation than glacier melt. Therefore, water availability is unlikely to decrease in the short term, as a warming climate will result in decreasing glacier runoff compensated by increased monsoon precipitation, with little change in the seasonality of river flows. In the Westerly influenced regions, glacier mass loss will likely lead to decreased river flows, and although glaciers in the Karakoram are at present showing slightly positive mass balances, this trend is unlikely to continue with sustained climate warming in the longer-term. As rainfall becomes a more important component of the total hydrological budget, the risk of flooding is predicted to increase as rainfall is transferred much more rapidly into rivers than snow that accumulates as glacier ice. In the longer term, by the start of the 22nd Century, the predicted loss of over 50% of glacier volume and the complete removal of smaller, lower-altitude glaciers across High Mountain Asia is likely to result in a widespread decline in water supplies, which will have a dramatic impact on the large populations relying on these glacier-fed rivers.

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Figure captions

Figure 1. High Mountain Asia, showing the Himalaya, Karakoram and Hindu Kush regions defined by Bolch *et al*. (2012) and major rivers. The location of glaciers for which glaciological mass balance records exist and the length of the record in years (Bolch *et al*. 2012; Pratap *et al*. 2016; Soncini *et al*. 2016; Tshering & Fujita 2016), and Vincent *et al*. (2016), and the location of automatic weather stations (AWS) collecting data at high altitudes are also indicated. The names of individual glaciers or glacierised regions referred to in the text are highlighted in bold.

Figure 2. The surface features of Khumbu Glacier in the Everest region of Nepal, showing (a) the debris-covered ablation area, looking to the south, (b) the Khumbu Icefall marking the transition between the clean-ice accumulation area and the debris-covered ablation area, (c and d) typical ice cliffs and supraglacial ponds in the ablation area showing englacial debris layers within the ice, likely resulting from ice-rock avalanching (note figures circled in red for scale).

Figure 3. Direct measurements of mass balance for six glaciers in the Himalaya between 1992 and 2012, showing; (a) annual mass balance, (b) cumulative annual mass balance, and (c) cumulative mass balance normalised by glacier terminus altitude. Note that the data for Kangwure Glacier between 1994 and 2008 (dashed line) are reconstructed mass balance values derived from meteorological data using the relationship between *in situ* mass balance measurements made in other years. Redrawn from Yao *et al*. (2012). See Figure 1 for the locations of these glaciers.

Figure 4. Schematic diagram showing hypothetical changes in glacier volume and meltwater release from mountain glaciers in response to regional climate warming over a period equivalent to their last advance and recession, from the Little Ice Age maximum through the present day and 21st Century.

Figure 5. Annual hydrographs for headwaters of the major Himalayan catchments produced using a hydrological model for a present-day reference period of 1998–2007, showing the contribution to the total hydrological budget from glacier melt, snow melt, rainfall–runoff and base (groundwater) flow [redrawn from Lutz *et al.* (2014)], for (a) the Indus in the westerly influenced Western Himalaya, (b) the Ganges in the transition between the westerly and monsoon-influenced Central Himalaya, and (c) the Brahmaputra in the monsoon-influenced Central and Eastern Himalaya. (d) shows the catchment boundaries used to make these calculations, with topographic imagery from Google OpenLayers.

Figure 6. Climatic, glaciological and landscape space–time controls on glacier and climate change in the Himalaya and Karakoram.

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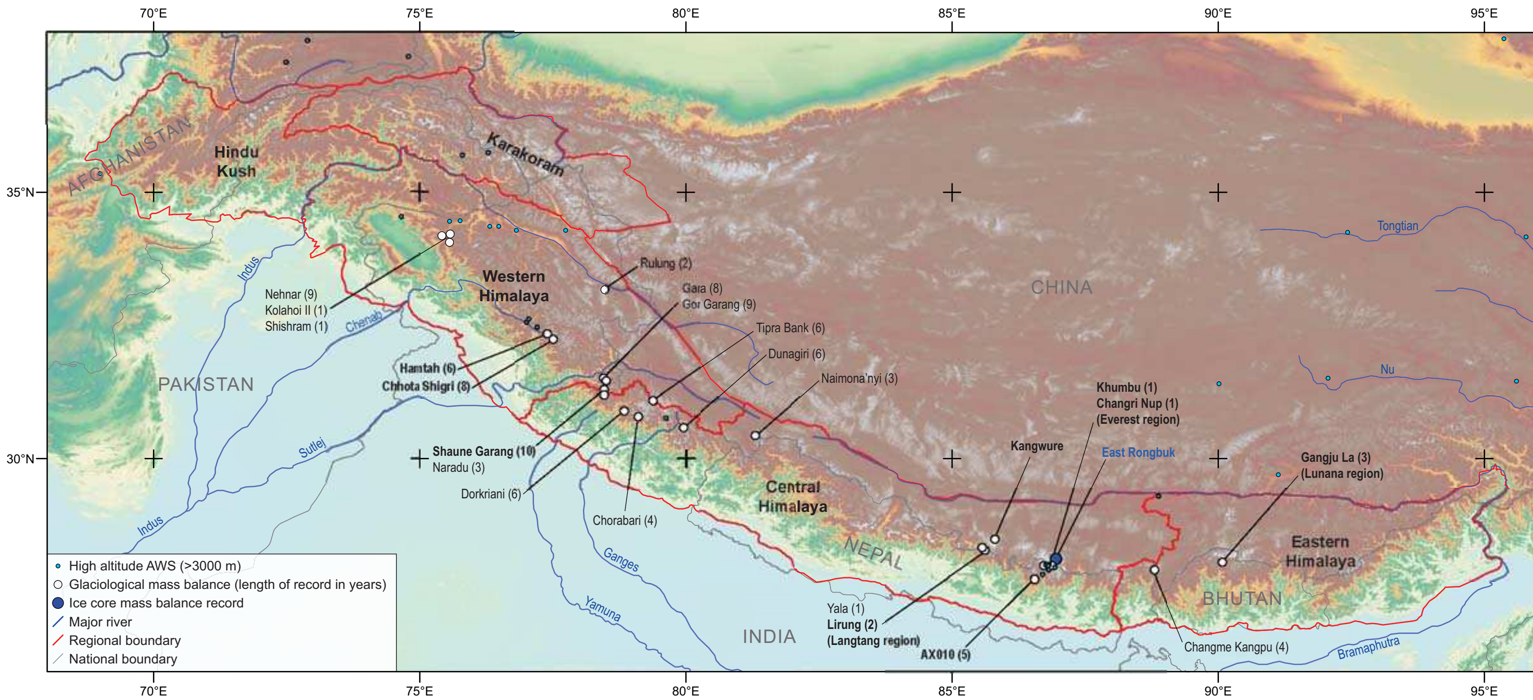
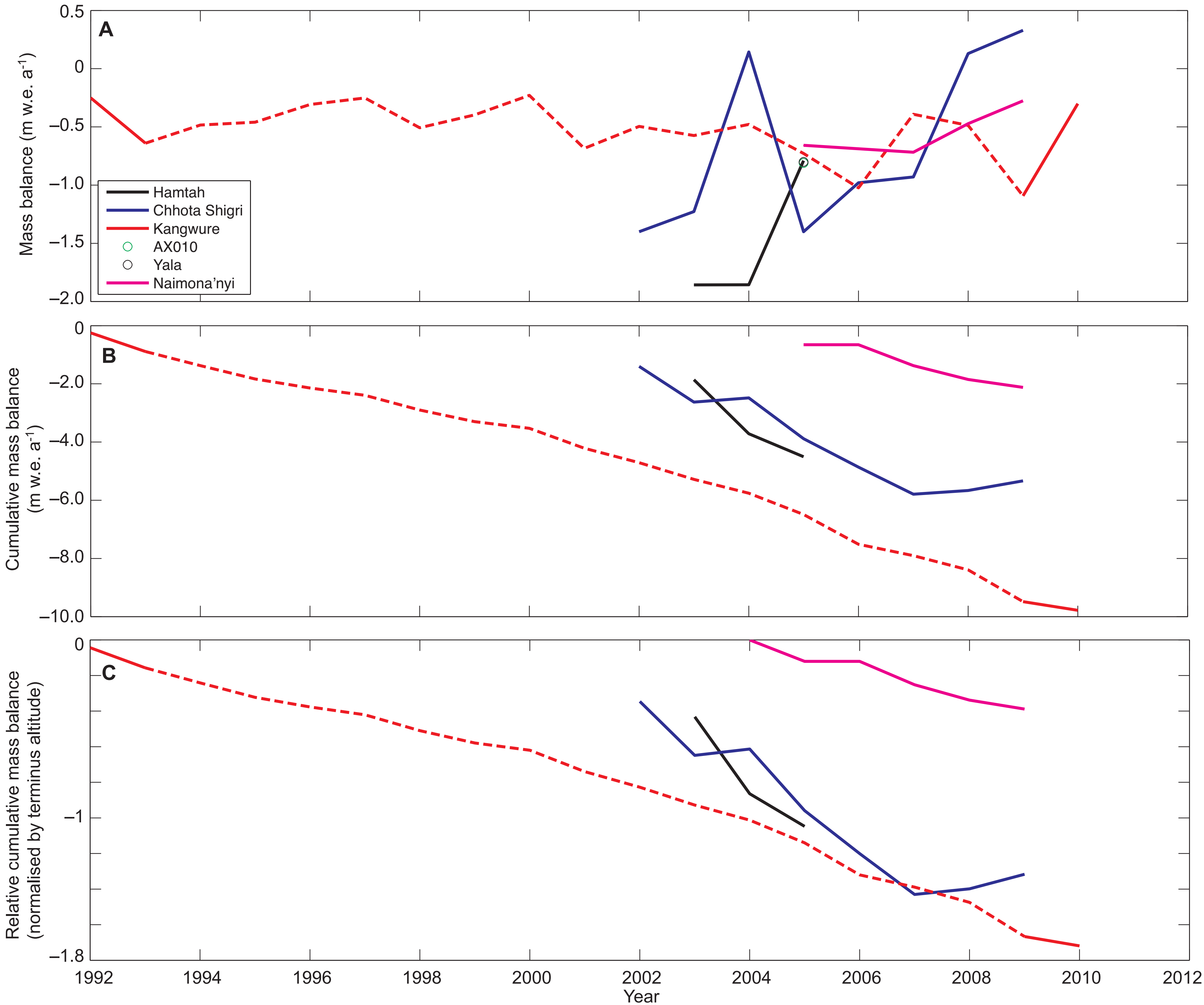
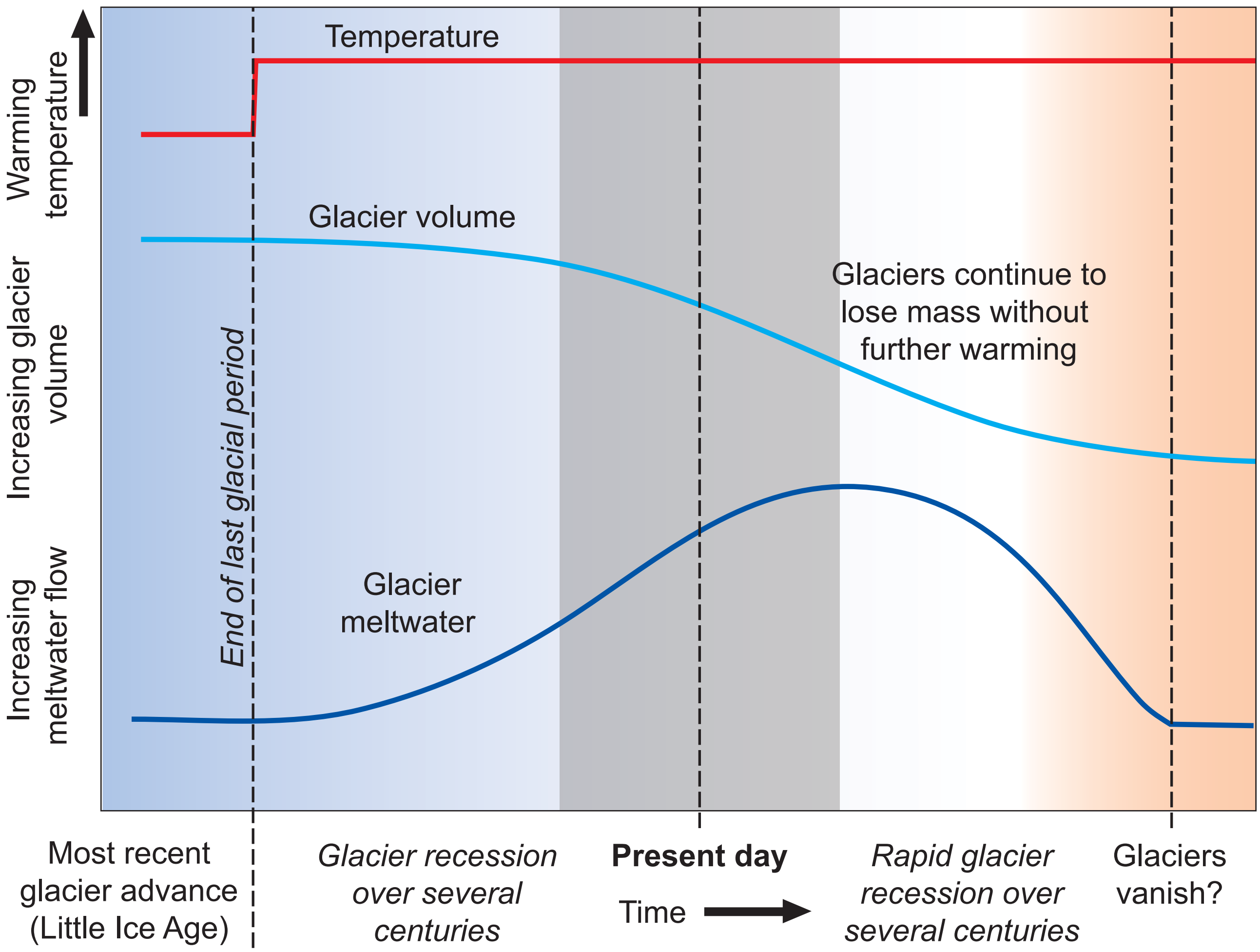


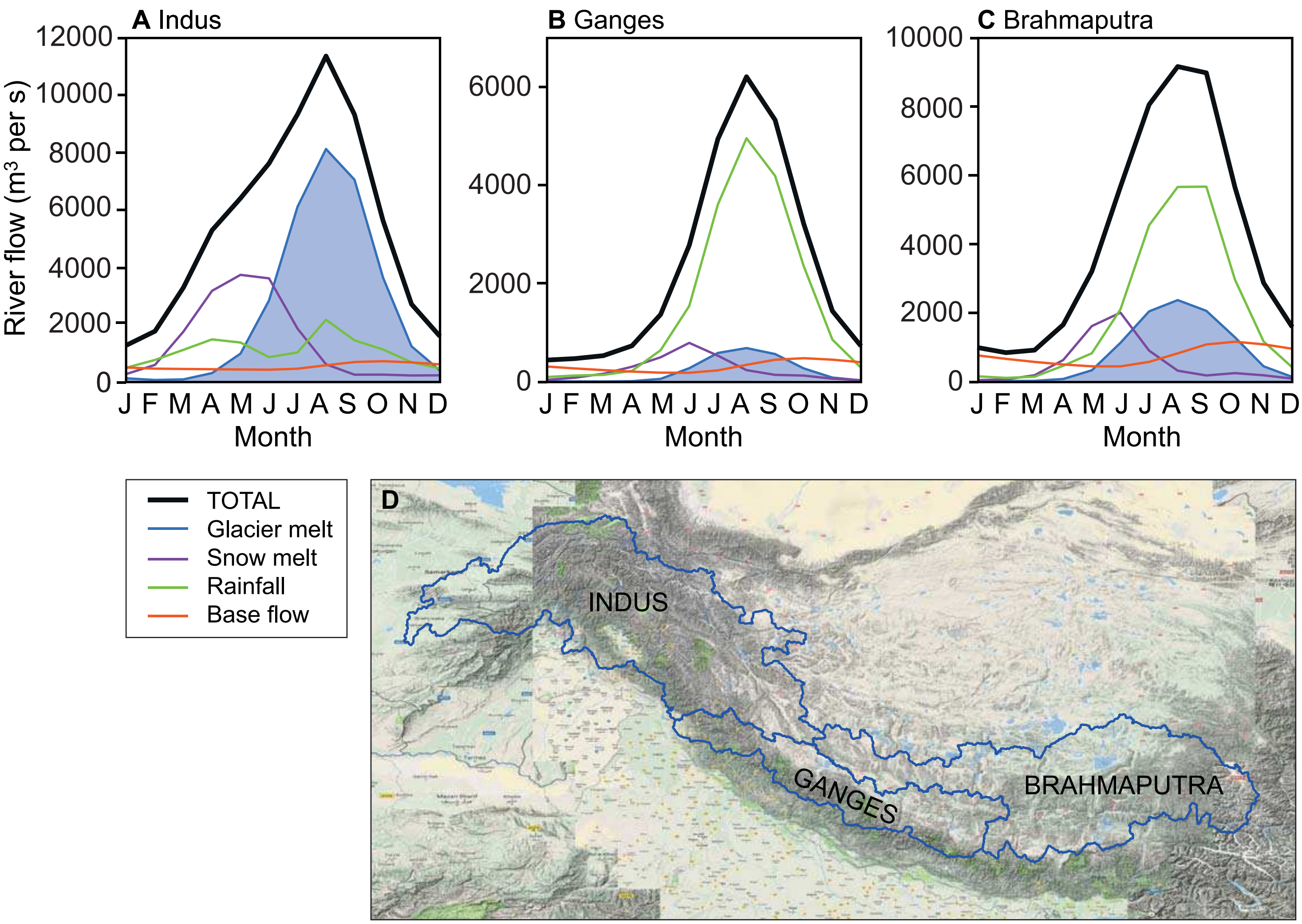
70°E
75°E
80°E
85°E
90°E
95°E
35°N
30°N
AFGHANISTAN
Hindu Kush
Karakoram
Western Himalaya
PAKISTAN
CHINA
Central Himalaya
NEPAL
INDIA
BHUTAN
Eastern Himalaya
Indus
Chenab
Sutlej
Ganges
Yamuna
Bramaputhra
Tongtian
Nu
Rulung (2)
Gara (8)
Gor Garang (9)
Tipra Bank (6)
Dunagiri (6)
Naimona'nyi (3)
Nehnar (9)
Kolahoi II (1)
Shishram (1)
Hamtah (6)
Chhota Shigri (8)
Shaune Garang (10)
Naradu (3)
Dorkriani (6)
Chorabari (4)
Khumbu (1)
Changri Nup (1)
(Everest region)
East Rongbuk
Kangwure
Gangju La (3)
(Lunana region)
Yala (1)
Lirung (2)
(Langtang region)
AX010 (5)
Changme Kangpu (4)
High altitude AWS (>3000 m)
Glaciological mass balance (length of record in years)
Ice core mass balance record
Major river
Regional boundary
National boundary

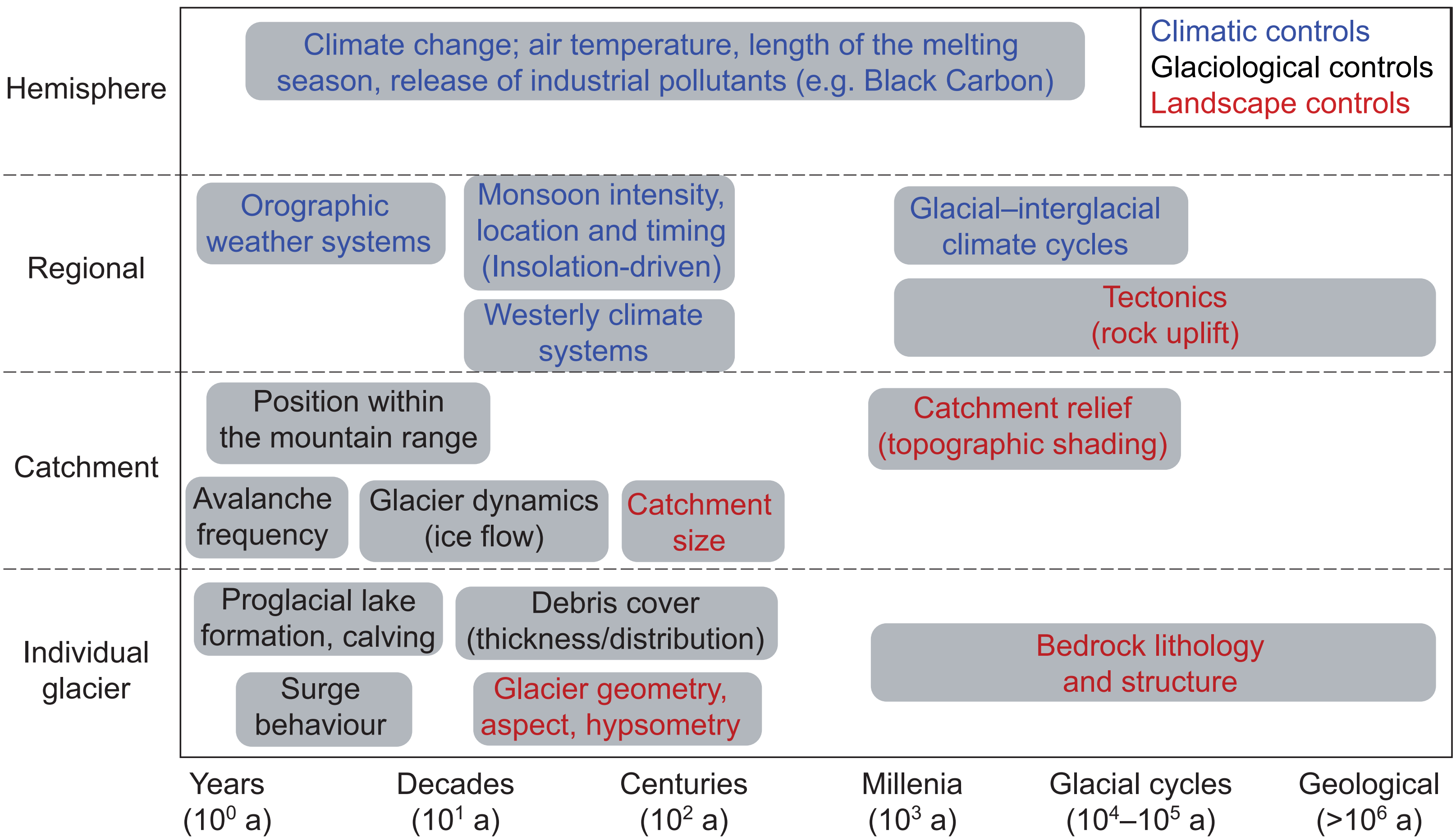

A
B
C
D



A
B
C
Mass balance (m w.e. a-1)
Cumulative mass balance (m w.e. a-1)
Relative cumulative mass balance (normalised by terminus altitude)
Year
Hamtah
Chhota Shigri
Kangwure
AX010
Yala
Naimona'nyi
0.5
0
−0.5
−1.0
−1.5
−2.0
−2.0
−4.0
−6.0
−8.0
−10.0
−1
−1.8
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012


Temperature
Warming temperature
Glacier volume
Increasing glacier volume
Glaciers continue to lose mass without further warming
End of last glacial period
Glacier meltwater
Increasing meltwater flow
Most recent glacier advance (Little Ice Age)
Glacier recession over several centuries
Present day
Time
Rapid glacier recession over several centuries
Glaciers vanish?


A Indus
B Ganges
C Brahmaputra
River flow (m3 per s)
Month
J F M A M J J A S O N D
12000
10000
8000
6000
4000
2000
0
TOTAL
Glacier melt
Snow melt
Rainfall
Base flow
D
INDUS
GANGES
BRAHMAPUTRA



Climatic controls
Glaciological controls
Landscape controls
Hemisphere
Climate change; air temperature, length of the melting season, release of industrial pollutants (e.g. Black Carbon)
Regional
Orographic weather systems
Monsoon intensity, location and timing (Insolation-driven)
Westerly climate systems
Glacial–interglacial climate cycles
Tectonics (rock uplift)
Catchment
Position within the mountain range
Catchment relief (topographic shading)
Avalanche frequency
Glacier dynamics (ice flow)
Catchment size
Individual glacier
Proglacial lake formation, calving
Debris cover (thickness/distribution)
Bedrock lithology and structure
Surge behaviour
Glacier geometry, aspect, hypsometry
Years (10^0 a)
Decades (10^1 a)
Centuries (10^2 a)
Millenia (10^3 a)
Glacial cycles (10^4–10^5 a)
Geological (>10^6 a)