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Climate change implications for the glaciers of the Hindu-Kush, Karakoram and Himalayan region

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Abstract

The Hindu-Kush, Karakoram Himalaya (HKKH) region has a negative average glacial mass balance despite anomalous possible gains in the Karakoram. However, changes in climate may influence the mass balance across the HKKH. We use high resolution climate modelling to analyse the implications of unmitigated climate change on precipitation, snowfall, air temperature and accumulated degree days for the Hindu Kush, Karakoram, Jammu-Kashmir, Himachal Pradesh and West Nepal regions, and East Nepal and Bhutan. In our analysis we focus on the climate drivers of change rather than the glaciological response. We find a complex regional response to climate change, with possible increases in snowfall over the western HKKH and decreases in the east. Accumulated degree days are less spatially variable than precipitation and show an increase in potential ablation in all regions. Overall, the eastern Himalayan glaciers are expected to be most sensitive to climate change due to the decreases in snowfall and increased ablation associated with warming. The eastern glaciers are therefore projected to decline over the 21st century despite increasing precipitation. The western glaciers are expected to decline at a slower rate over the 21st century as a response to unmitigated climate compared to the glaciers of the east. Importantly, the glacier response depends on important glaciological factors, such as the extent of debris cover, which may be of critical importance in moderating the response to climatic change. Decadal variability has a large effect highlighting the need for long-term observation records to fully understand the impact of climate on the glaciers of the HKKH cryosphere. Spatial variability in projected snowfall patterns are likely to be a key driver of glacier mass balance over the 21st century. Importantly, the regional trends in snowfall do not necessarily follow the trends in precipitation. A key change in the HKKH cryosphere is a switch from snowfall to rainfall in the eastern Himalaya. Although glacial mass balance is likely to be sensitive to climate change, as overall precipitation is projected to increase this may lead to an overall increase in water resources. In the west, projections suggest that glacial mass balance could respond

less to climate change than those in the east. However, projection uncertainty covers a small increase to a decrease in precipitation for the western HKKH and Indus basin and as a result the water resources of the highly populated Indus region may be more vulnerable to unmitigated climate change.

1 Introduction

The high mountains of South Asia covering the Hindu-Kush, Karakoram Himalaya (HKKH) belt have been described as the “Water Tower of Asia” (Viviroli et al., 2007; Immerzeel et al., 2010) due to their important role in feeding the major rivers of the South Asia. Water resources are considered vulnerable in the region due to the important role of snow and ice in the hydrology of the region (Barnett et al., 2005). Seasonal storage of water in snow and ice acts to delay the timing of runoff (Kaser et al., 2010; Immerzeel et al., 2010; Siderius et al., 2013; Schaner et al., 2012). The retreat and loss of glaciers may therefore have a significant impact on the quantity and timing of water availability as is currently observed in parts of the tropical Andes (Rabatel et al., 2013).

The vulnerability of water resources to climate is further enhanced due to the coincidence of a large and growing population. For example, the Indus originates in the Tibetan plateau and carries meltwater from the glaciated Karakoram and Jammu-Kashmir region to a highly populated region, and thus has a large flow component controlled by glacial melt (Immerzeel et al., 2010; Schaner et al., 2012). Regionally over 1.4 billion people depend on water from the Indus, Ganges, Brahmaputra, Yangtze, and Yellow rivers (Moors et al., 2011; Immerzeel et al., 2010) which arise in the HKKH and Tibetan plateau (not considered here) regions. There is therefore a need to better quantify the potential impacts of climate change on the regional water resources.

The HKKH have attracted controversy over reported rates of glacier ice loss. The IPCC WGII AR4 (Cruz et al., 2007) reported an erroneous statement from WWF (2005) that glaciers may disappear by 2035 (Cogley et al., 2010) with significant implications for water resources. More recent work has shown that in some parts of the region glaciers have been increasing in mass over the last decade (Kääb et al., 2012; Gardelle et al., 2012). There are few direct observations from the region (Bolch et al., 2012) however, a number of recent studies have demonstrated the glaciers of the region are in a state of negative mass balance (Jacob et al., 2012; Kääb et al., 2012). However, the projected rates of loss are less negative than other glaciated regions of the world (Radić and Hock, 2011). Observational data suggest that the change in glacier state is spatially heterogeneous across the region (Fujita and Nuimura, 2011) potentially due to climate (Fowler and Archer, 2006) and glaciological issues, such as elevation and glacier debris cover (Scherler et al., 2011). The "Karakorum Anomaly" is a sub-region of the HKKH in which glaciers may have increased mass or remained relatively stable over the last decade (Copland et al., 2011; Fowler and Archer, 2006; Gardelle et al., 2012; Hewitt, 2005, 2011; Kääb et al., 2012; Matsuo and Heki, 2010) in contrast to other parts of the region. A recent study using satellite altimetry data (Kääb et al., 2012) revealed a complex pattern in mass-balance, with the Karakoram glaciers thinning by only a few centimetres a year with greater rates of loss in the Hindu-Kush and the central and eastern Himalaya. The greatest rates of loss were found in the Jammu-Kashmir region. Overall, the HKKH regions are losing mass at a lower rate than other glaciated regions. The overall negative trend in mass balance is confirmed by other satellite studies (e.g. Jacob et al., 2012)

Evidence for the Karakoram anomaly comes from other sources, for instance (Fowler and Archer, 2006) found evidence of a cooling trend between 1961 and 2000 consistent with glacier thickening. Copland (2011) found evidence of increased glacier surging in the 1990s compared with previous decades consistent with increased precipitation. Another satellite study found a slight positive mass balance (Gardelle et al., 2012). The only in situ data source for the Karakoram indicates an average budget of $-0.51\,\mathrm{m\,yr^{-1}}$ w.e. for Siachen Glacier (1986 to 1991) (Bhutiyani, 1999).

Although some evidence points to climate change as potential a cause of the Karakoram anomaly other explanations include the existence of large areas of debris cover on

Karakoram glaciers which may reduce sensitivity to change (Scherler et al., 2011) and thus contribute to the spatial heterogeneity, although Kääb (2012) found no evidence for this. Other factors include the steep and rugged terrain pointing to snow avalanches as an important mass balance component in the Karakoram.

Outside of the Karakoram all existing mass budget data indicate that glaciers are losing mass (Bolch et al., 2012). A study by Fujita and Nuimura (2011) looking at three benchmark glaciers found evidence of rapid glacier wastage since the 1970s. The humid lower glaciers having a more negative mass balance than the arid high elevation benchmark glacier, possibly implying the lower glaciers are more sensitive to change.

The spatial heterogeneity in mass balance is therefore likely to be partly linked to spatial variation in climate change and variability, the short length of observational data available and the variation in glaciological conditions. Other non-climatic drivers such as deposition of dust and soot may also play a role, with some evidence that this may already be having an effect on some Tibetan glaciers (Xu et al., 2009).

There are relatively few studies that aim to make a comprehensive assessment of the future glacier state under climate change. A global study by Radic and Hock (2010) focused on sea-level rise, found an average ice volume loss of 10 ± 16 % between 2000 and 2100 under the SRES A1B scenario. The large uncertainty in the change of glacier volume spanning a possible increase to decrease is related to the future regional climate uncertainty (Cruz et al., 2007; Meehl et al., 2007). This uncertainty is further exacerbated by the complex orography of the HKKH which is not captured in coarse scale global climate models. However, this possibility of a future increase in glacier volume highlights the importance of changing precipitation patterns and the potential for increasing snowfall in the future and therefore accumulation to offset any increased ablation due to warming, potentially leading to glacier thickening and advance.

In this study we aim to increase understanding of the potential impacts of climate change on the Himalaya Hindu-Kush. In particular we aim to address the issue of the relative roles of changing accumulation and ablation in the context of climate uncertainty. We use a regional climate model (RCM) to downscale global GCM simulations under the SRES A1B scenario (Nakicenovic et al., 2006). The simulations are performed at 25 km to capture the complex role of orography. Two GCM simulations are used from models shown to capture the dynamics of the Monsoon; the two models are chosen to sample the spread in precipitation uncertainty from a possible future increase to a decrease. The simulations are analysed in terms of the possible climate drivers of glacier accumulation and ablation across the HKKH in the context of climate uncertainty and spatial heterogeneity. As this study is focused on the climatic drivers we do not consider factors that may influence the complex glaciological response which is moderated by factors such as debris cover which is common within the Himalaya.

1.1 Baseline regional climate

The climate of the HKKH is heavily influenced by two circulation systems; Western Disturbances (WD) and the Indian Summer Monsoon (ISM) (an associated pair of papers looks at the issue of Westerlies in more detail, Ridley et al., 2013; Dimri et al., 2013). These two systems are largely responsible for the patterns of seasonal precipitation that can be seen in Fig. 1, with much of the precipitation in the region occurring over the extended summer monsoon months (May to October). The region has a strong temperature contrast with the high mountains having an annual mean temperature below zero, and the lower plains in excess of 20 °C. Across the Himalayan arc the Karakoram Range is cooler, related to higher altitudes, than the rest of the region (Fig. 2).

The Western Disturbances bring moisture from the Mediterranean Sea over the north-western parts of the Indian subcontinent. The system is particularly responsible for bringing snowfall during the winter and pre-ISM months (Fig. 3). The ISM brings moisture from the Bay of Bengal, causing intense rainfall to the region over the summer months and is partly responsible for snowfall during the summer months towards the eastern end of the Himalayan Arc (Fig. 3). The influence of the ISM decreases strongly further west of approximately ~ 77° E in the Garhwal Himalaya (Bookhagen and Burbank, 2010, 2006), separating the Jammu-Kashmir region from Himachal Pradesh, Uttarakhand and West Nepal. West of this divide precipitation is dominated by Western Disturbances.

The mountains of the Himalayan arc provide a barrier to the northward progression of moisture (Fig. 4), separating the plains of South Asia from the relatively dry Tibetan plateau to the north (Figs. 1 and 5). Some moisture is able to move north through the deep valleys cut by rivers flowing south to join the Ganges. The rise of the Himalayan Arc through the foothills to the high Himalaya leads to considerable orographic uplift and thus considerable precipitation along the orographic barrier.

The combination of the interaction between the two circulation systems and the Himalaya's leads to a strong gradient in precipitation from the Hindu Kush in the west to the Eastern Himalayas, as well as a strong gradient from the Himalayan foreland into the Tibetan plateau. This gradient in precipitation can be seen in Figs. 6 and 7 which show a gradient in simulated precipitation running from the Karakoram ($\sim 2\,\mathrm{mm\,day}^{-1}$) to the Nepal–Bhutan region ($\sim 5\,\mathrm{mm\,day}^{-1}$) with a stronger gradient at lower elevations (Fig. 5). There is less of a gradient in total snowfall along the HKKH arc but there is a variation in the seasonal timing of snowfall. The further west regions are dominated by winter accumulation with summer snowfall dominating further east (Fig. 3). The glaciers in the east are therefore primarily summer accumulating, whilst those to the west winter accumulating. The timing of potential melt as defined by seasonality of monthly degree days (Figs. 6 and 7) shows less spatial variation with all regions demonstrating summer ablation. This has important implications for seasonal water storage and water resources. The eastern glaciers are summer accumulation, summer ablation and therefore do not store water seasonally to the same extent as the western glaciers. Summer accumulation glaciers are also likely to be more sensitive to warming (Fujita, 2008a, b) as any increase in degree days will have a double effect; increasing potential melt as well decreasing the likelihood of precipitation falling as snow.

2 Methods

This study employs high resolution regional climate modelling (RCM) of selected global climate simulations to capture the spatial heterogeneous patterns in meteorology across the HKKH that may be driving some of the changes in mass balance. Rather than simulate mass balance directly we look at changes in simulated precipitation, temperature and snowfall. We use snowfall as a measure of change in the future accumulation of glaciers, and from daily air temperature we calculate degree-days (DD) that can be linked to potential melt through degree-day factors (Hock, 2003, 2005). A degree day is defined as the cumulative sum of daily mean temperatures over zero for a month. Temperature index modelling using degree-days is thus a simplification of complex processes controlling the energy-balance at the surface. The physical basis for degree day modelling is the close relationship between the two main components of the energy-balance; net long-wave radiation and sensible heat flux which often drives melt (Hock, 2003). Temperature-index models are therefore widely used and perform comparatively to energy-balance models at large scales (Hock, 2005).

2.1 Regional climate modelling

The porosity of spatially explicit meteorological observation data across the HKKH region is a significant barrier to understand the climate interactions with the HKKH cryosphere. For instance, there are few precipitation gauges within the Himalayas (Bookhagen and Burbank, 2010; Yatagai et al., 2009). For this region Akhtar et al. (2008), found a better performance with a hydrological model when using RCM data than using poor quality observation data. Global datasets are typically coarse and do not capture the complex topography in the region (Kang et al., 2002). To address this we employ a version of the HadRM3 Regional Climate Model to dynamically downscale ERA-Interim reanalysis (Dee et al., 2011) and climate simulations from two GCMs. HadRM3 is a regional version of the HadAM3 global atmosphere model (Pope et al., 2000; Gordon et al., 2000). To capture the role of orography on regional climate we run high resolution simulations at a fine 25 km for the whole Indian subcontinent (Fig. 1). The simulations are currently the finest resolution modeling available and form part of the climate ensemble produced as part of the EU-HighNoon program (http://www.eu-highnoon.org). The use of regional climate modelling over the Indian subcontinent have been shown to significantly improve the regional detail of projected climate changes (Lucas-Picher et al., 2011; Mathison et al., 2013; Kumar et al., 2006, 2013) and capture the processes relating to orography and regional atmospheric circulation (Dimri et al., 2013; Ridley et al., 2013). However, regional downscaling does introduce some uncertainty according to the choice of downscaling model (Lucas-Picher et al., 2011).

To better understand the past climate we employ the RCM to downscale the ERA-Interim reanalysis (Uppala et al., 2005). The meteorological reanalysis provides a consistent best estimate of the atmospheric state of the past, and the downscaled product is thus our best estimate of the climate of recent past despite additional errors and uncertainty from the reanalysis process and the downscaling itself. The downscaled ERA-Interim scenario thus enables the evaluation of the regional climate biases in the climate simulations. In addition we downscale two global climate simulations covering 1960–2100 for the SRES A1B scenario (Nakicenovic et al., 2006). The two scenarios are from versions of ECHAM5 (Roeckner et al., 2003) and HadCM3 (Pope et al., 2000; Gordon et al., 2000). The choice of two GCMs is to sample climate model uncertainty and is discussed in more detail below. The evaluation of the regional model simulations is examined in more detail in two companion papers (Kumar et al., 2013; Mathison et al., 2013)

2.2 Sub-regional definitions and baseline glacier state

To understand the spatial variation in climate drivers and in glacier mass balance we define distinct sub-regions across the HKKH to capture the variation in climate and observed glaciological patterns (Kääb et al., 2012). We follow the division of Kääb (2012) and define five sub-regions (Fig. 2): Hindu Kush (HK), Karakoram (KK), Jammu-

Kashmir (JK), Himachal Pradesh, Uttarakhand and West Nepal (HP) and East Nepal and Bhutan (NB). In further analysis we use these sub-regions above 2500 m a.s.l. to form area-averages. The choice of regions covers the majority of the glaciers in the extended World Glacier Inventory (Cogley, 2010) and Randolph (Arendt et al., 2012) glacier data inventories (Fig. 2)

The use of regional definitions consistent with Kääb (2012) allows us to use their mass balance observations as a baseline from which to assess the possible impacts of climate change. Table 1 gives the 2003–2009 mass balance and shows that only the Karakoram is possibly gaining mass within the given uncertainties.

3 Results and discussion

3.1 Projected changes in South Asian climate

The impact of climate change on the Indian Summer Monsoon is considerably uncertain in the IPCC AR4 CMIP3 (IPCC, 2007) models with model responses uncertain on the sign of the direction of change (Christensen et al., 2007). Climate models also show significant differences in their ability to simulate the Indian Summer Monsoon (ISM) in the present day. Some of the future uncertainty may therefore be associated with models with a lack of skill in simulating the ISM. Of the CMIP3 ensemble only four models were shown to be able to capture the large scale statistics of the Monsoon under the present climate (Annamalai et al., 2007; Kripalani et al., 2007; Turner and Annamalai, 2012). The uncertainty in the monsoon precipitation response to global warming is related to two key opposing processes responding to global warming; the thermodynamic forcing whereby atmospheric moisture content increases; and the dynamical weakening of the monsoon due to weakening of circulation patterns (Ueda et al., 2006).

The standard CMIP3 HadCM3 model was not able to capture the Monsoon dynamics; however a version of HadCM3 using flux correction performed better. The flux adjustment of HadCM3 improved the mean state of the tropical Pacific improving the simulation of ENSO, this in turned improved the Monsoon–ENSO relationship and the overall simulation of the ISM (Turner et al., 2005). There are therefore five possible GCMs that we consider able to capture the Monsoon dynamics (Fig. 5) critical to appropriately simulating the impact of climate change on the high mountain cryosphere of South Asia. In this study we use the ECHAM5 and HadCM3 simulations which enable us to sample uncertainty in precipitation with ECHAM5 simulating a decrease in precipitation for the HKKH region and HadCM3 an increase.

Figures 6 and 7 show the downscaled climate scenario climatologies against the ERA-Interim simulation. In most cases we find that the GCM scenarios do a good job of the present day climate with a general case of overestimating degree-days. Downscaled HadCM3 does a remarkably good job of capturing the seasonal and spatial patterns in precipitation and snowfall (Fig. 6).

3.2 Projected changes in HKKH climate

Over the 21st century under the SRES A1B emissions scenario the HKKH region is projected to warm by 4–5.5 °C relative to 1971–2000 (Fig. 8). This is a faster rate of warming than the global and regional rates of increase. This is partly due to the land warming faster than the oceans and reductions in the simulated seasonal and perennial snow cover decreasing the surface albedo. The ECHAM5 simulation has the higher rate of warming, which may be associated with the greater reductions in snowfall and seasonal snow cover in this simulation. In both simulations we find the majority of the HKKH remains below freezing but there is an increase in the height of the annual mean zero degree isotherm. Although rapid warming is projected in the HKKH this does not necessarily translate into higher rates of ablation. The index of ablation used here are degree days above zero (DD). Changes in DD are highest where this is a seasonal transition in air temperature from below freezing to above. Relatively very cold regions and very hot regions will show small changes in DD. This can be seen in Fig. 8, which shows the greatest increases, are in the mountains with small changes across the Indo–Gangetic plain. The highest and coldest parts of the HKKH show small changes in DD. By the 2080s the mean temperature difference between the ECHAM5 and HadCM3 simulations in HK and JK is around 0.5 to 1 °C; however this small temperature change corresponds to a substantially bigger increase in degree days and thus potential melt. We therefore find a consensus of warming across the HKKH with an associated increase in potential ablation.

Changes in precipitation show a more complex response with HadCM3 giving increasing precipitation in the west and ECHAM5 an increase in the east. Significantly, ECHAM5 gives a decrease in the west by the 2080s. However, increased precipitation does not necessarily lead to accumulation and the latent heat in rainfall falling on snow may be a significant contribution to the energy available for melt. Changes in snowfall amounts are a better indicator of possible changes in accumulation. By the 2080s the two simulations show an overall decrease in snowfall across the HKKH with the greatest decreases around the zero degree isotherm. The HadCM3 simulations have an overall increase in KK, HK and JK whilst ECHAM5 only had an increase in the highest parts of KK. A study by Ridley et al. (2013) found this could partly be explained by changes in circulation with HadCM3 simulating increased occurrence of WDs, with an associated overall 37 % increase in winter snowfall, whilst ECHAM5 showed no change in occurrence of WDs. Both models show a strong decrease in snowfall in the HP and NB regions despite an overall increase in precipitation.

The modelling performed here reveals a complex pattern of climatic change across the HKKH corresponding to changes in circulation patterns and regional warming. All regions have an increase in potential ablation, whilst the western part of HKKH may have an increase in accumulation whilst the eastern part a decrease (Figs. 8 and 9). The eastern part of the HKKH has a substantial reduction in the fraction of precipitation falling as snow. This can be seen in the seasonal climatologies of the different sub-regions (Figs. 6 and 7). The glaciers in the eastern HKKH are predominantly summer accumulating with winter accumulation types dominating in the west. The summers show the largest increases in DD despite the winters having a comparatively greater warming (Fig. 10). The glaciers in the east therefore coincide the timing of snowfall with the greater increases in potential melt. The result is that despite an intensification of the precipitation in the east, less of the precipitation falls as snow and thus accumulation is decreased suggesting summer accumulating glaciers are more sensitive to warming (Fujita, 2008a, b). Given that the climate projections shown here demonstrate an increase in potential melt and a decrease in snowfall, the glaciers in the eastern HKKH (in the absence of glaciological factors) are likely to see greater reductions in their mass balance than in the western HKKN. Despite the warming patterns, glaciers in the west may possibly have increased accumulation. However, this increase in snowfall by the 2080s is offset by a large increase in possible ablation. The net mass balance is thus a function of the efficiency of the increase in degree-days at melting snow and ice. Deriving a melt degree day factor suggests that for a zero change in mass balance the melt associated with single degree-day is 0.005 mm w.e. d^{-1} °C^{-1}, which is much lower than observations from the Dokriani glacier (Hock, 2003; Singh et al., 2000) in HP which for clean snow is 5.7 mm w.e. d^{-1} °C^{-1}. Given this, and satellite observations imply the 2003–2009 KK mass balance is slightly negative (Table 1). This, in the absence of glaciological factors, it is likely that by the 2080s under the SRES A1B scenario the trend in mass balance will be negative in the Karakoram region. Of particular note is the role of debris cover in moderating the glaciological response to climatic change. It may well be the case that debris substantially alters the glacial response to the climate drivers (Scherler et al., 2011).

Within the projections presented here there is the large amount of inter-annual variability seen in snowfall across the. The variability in accumulation and ablation as well as the non equilibrium state of glaciers means that the long-term mean glacier mass balance may be considerably different from that derived from the short satellite record. The ECHAM5 simulation (Figs. 7 and 9) shows an increase in snowfall in HK and JK in the 2020s despite an overall decline by the 2080s. This is associated with a moderate degree of warming, thus raising the counter-intuitive possibility that for small amounts of warming, snowfall may increase in the western part of the HKKH. It is therefore plausible that the Karakoram anomaly and associated glacier thickening is not inconsistent with an overall warming trend in the region and may continue. Although it should be noted that this requires further investigation.

The overall impact of a declining future glacier mass balance on future water resources is complicated by the glaciological response, in which glaciers retreat to form new more stable equilibriums. The initial response maybe increased wastage and thus an initial increase in runoff – the de-glaciation dividend – however this reduces as glaciers form a new equilibrium. A major driver of change in the eastern HKKH is the decline in snowfall; however this is due to a switch from snow to rain and is accompanied with an overall increase in precipitation. This, combined with the low seasonal storage of water in the snowpack (coincidence of summer accumulation – summer ablation) implies that renewable water resources are likely to increase under climate change. This is not necessarily the case in the western part of the HKKH, which is a major source of runoff for the populated Indus. The projections given here span a possible decrease to increase in precipitation. In this case, the Indus might be more sensitive to changes in glaciers mass and extent.

4 Conclusions

In this study we use a pair of high resolution regional climate simulations to capture the implications of unmitigated climate change on the HKKH cryosphere. The implications of climate on accumulation and ablation are complex and spatially variable. To fully investigate these interactions requires high resolution physically based modelling to capture the important role of orography in the region. The lack of observational data limits the possible evaluation of climate model performance but we find that downscaling meteorological reanalysis data provides a reasonable evaluation for the climate simulations.

Overall, we find that the eastern Himalaya is likely to be more sensitive to unmitigated climate change as these glaciers predominantly accumulate mass during the summer monsoon which brings snowfall to the region. The effect of warming is twofold; the first to decrease the fraction of precipitation falling as snow; and secondly to increase the rates of ablation. It is therefore projected that the eastern Himalaya will have the strongest negative regional trend in mass balance, consistent with trends in present day mass balance derived form satellite (Table 1, Kääb et al., 2012). However, the projected increase in rainfall may reduce the significance of glacial melt for regional water resources. The western HKKH shows possible increases in snowfall and thus mass accumulation under climate change partly due to increased strength of the western disturbances in HadCM3. However, over the 21st century the warming trend and corresponding increased ablation is likely to dominate any increase in accumulation leading to reduced mass balance. Despite this, glaciers in this region seem to be less sensitive to climate change than those in the east. There is considerably uncertainty in the regional detail and ECHAM5 does not capture the increasing snowfall trend in the Karakoram, instead showing a more complex response of an initial increase for moderate warming with an overall decrease at higher levels of warming. The implication is that mitigation of climate change at moderate levels may avoid some of the long term projected loss of glacier ice in the region.

The impact of climate change on renewable water resources is likely to be positive in the eastern HKKH mainly due to the increase in precipitation. The direct impact of climate change on water resources may therefore be more important than the glaciological role. This is despite the sensitivity of glaciers of the eastern region to climate change. However, the western HKKH and the Indus will possibly see a decrease in precipitation. Water sourced from glacier melt may therefore be of more importance to this highly populated catchment and thus will be more sensitive in terms of water resources to the projected long-term glacial loss.

The focus of this study has been on the climatic drivers of glacial change, however the actual glacial reponse is dependent on local processes such as glacier steepness and extent of debris cover. There is clearly a need for further glaciological modelling

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work considering projected changes in climate that consider important processes such as the role of debris cover.

Climate variability, particularly in snowfall and precipitation is a large factor in the overall trends in precipitation and snowfall. Thus, an analysis based on short-term observations may not fully capture the signal of climate change.

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Table 1. Satellite derived glacier mass balance 2003–2009 from Kääb (2012). Mass balances are from scenario ab.

	Mass Balance $\mathrm{m\,w.e.\,yr^{-1}}$
Hindu-Kush	-0.2 ± 0.06
Karakoram	-0.03 ± 0.04
Jammu-Kashmir	-0.55 ± 0.08
Himachal Pradesh, Uttarakhand and West Nepal	-0.32 ± 0.06
East Nepal and Bhutan	-0.3 ± 0.09

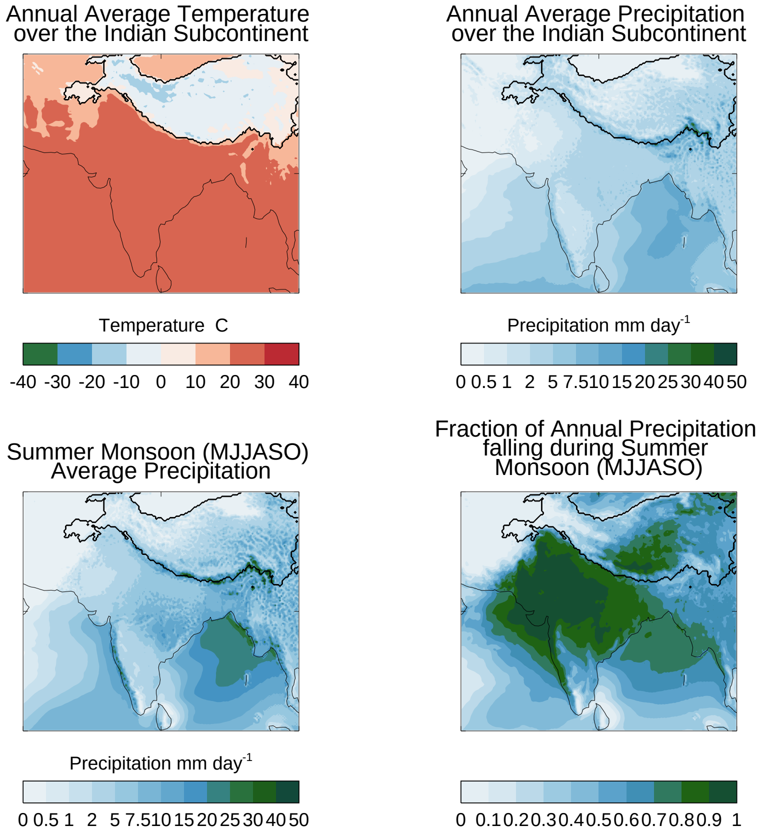

Fig. 1. The climate of the Indian subcontinent (1992–2007) as simulated by downscaling ERA-Interim reanalysis using the HadRM3 regional climate model. The region above 2500 m a.s.l. is indicated.

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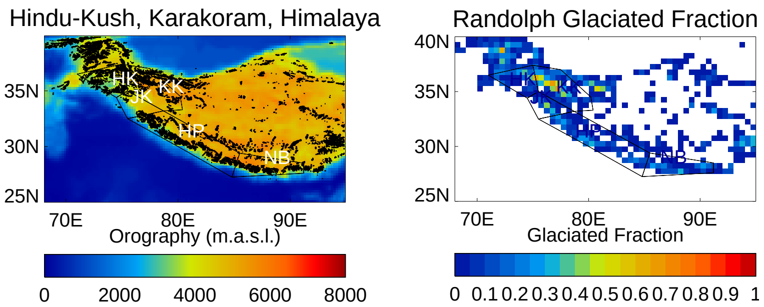

Fig. 2. location map of the Hindu-Kush, Karakoram Himalaya region showing the location of glaciers from the extended World Glacier Inventory (Cogley, 2010) (left), and the glaciated fraction aggregated to half degree from the Randolph glacier inventory (Arendt et al., 2012) (right). Highlighted are the Hindu Kush (HK), Karakoram (KK), Jammu-Kashmir (JK), Himachal Pradesh, Uttarakhand and West Nepal (HP) and East Nepal and Bhutan (NB) sub-regions used in this study.

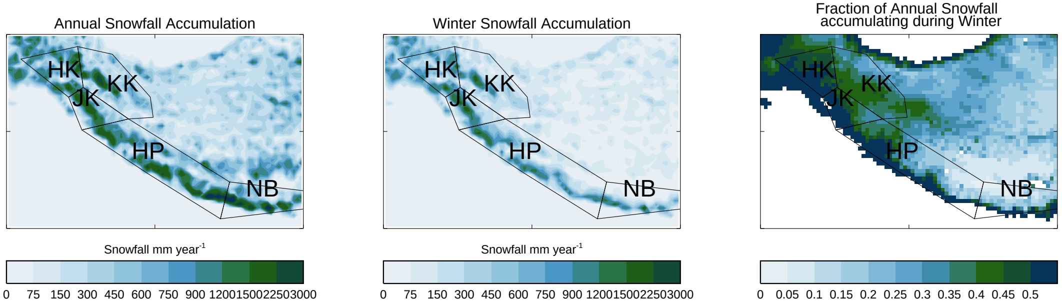

Fig. 3. Annual snowfall accumulation along the Himalayan belt (left), winter snowfall accumulation (centre) and the fraction of annual snowfall occurring during the winter. Data are 1992–2008 averages from ERA-Interim downscaled with the HadRM3 regional climate model.

Fig. 4. Moisture, cloud and snowfall at the edge of the Himalayan Arc and Tibetan plateau. The image shows the barrier the Himalaya's present to the passage of moisture north. Clouds are formed on the Himalayan foothills, and snow on the high mountains of the Himalaya. North is the relatively dry Tibetan plateau. Image part of the NASA "Earth from Space Collection." (Image Science and Analysis Laboratory, NASA-Johnson Space Center. "The Gateway to Astronaut Photography of Earth." http://eol.jsc.nasa.gov/scripts/sseop/photo.pl?mission=STS41G&roll=120&frame=22).

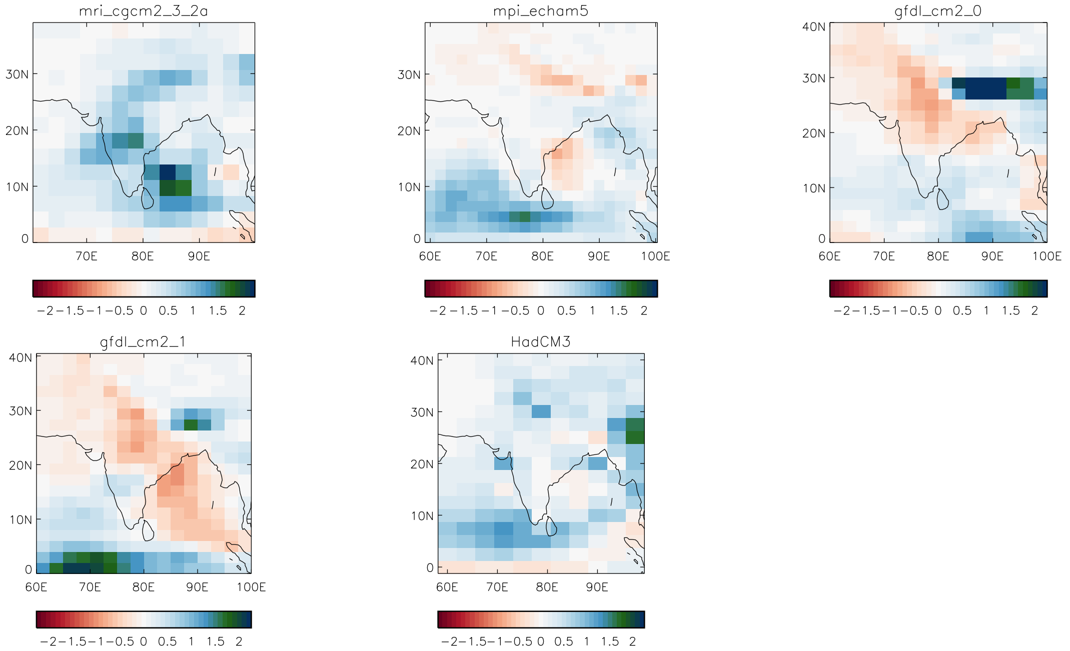

Fig. 5. Change in precipitation (mm day^{-1}) by the 2080s relative to 1961–1990 under the SRES A1B scenario for four selected CMIP3 models and a flux-corrected version of HadCM3. The region above 2500 m a.s.l. is indicated.

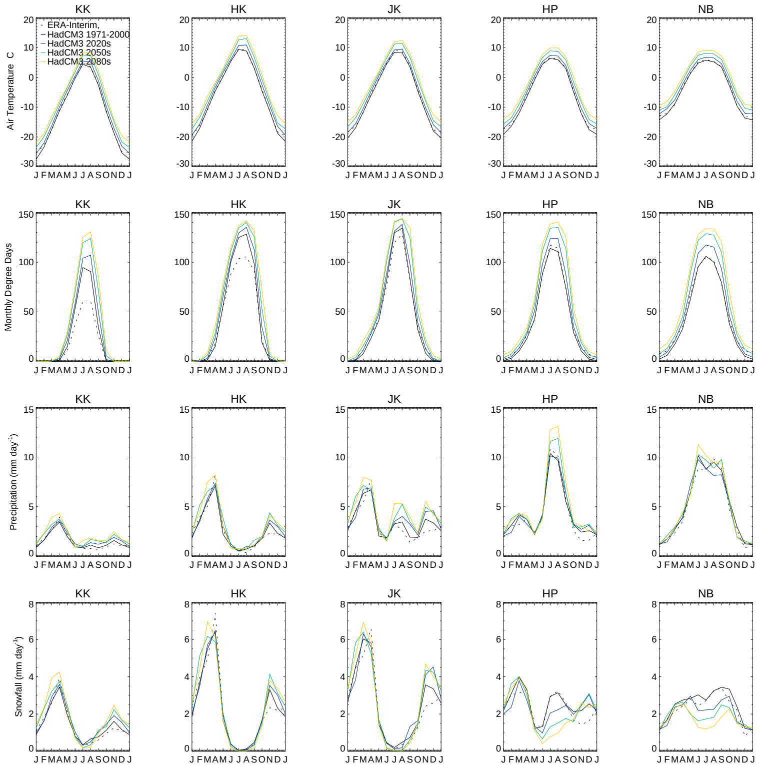

Fig. 6. 30 yr mean climatologies of air temperature, degree days, precipitation and snowfall for the five sub-regions defined in this study from the downscaled HadCM3 A1B scenario. Shown are 30 yr climatologies for 1971–2000 (black), 2020s (blue), 2050s (green) and 2080s (yellow). Also shown is the 1992–2008 climatology from the downscaled ERA-Interim simulation (black dashed). The regions are Hindu Kush (HK), Karakoram (KK), Jammu-Kashmir (JK), Himachal Pradesh, Uttarakhand and West Nepal (HP) and East Nepal and Bhutan (NB).

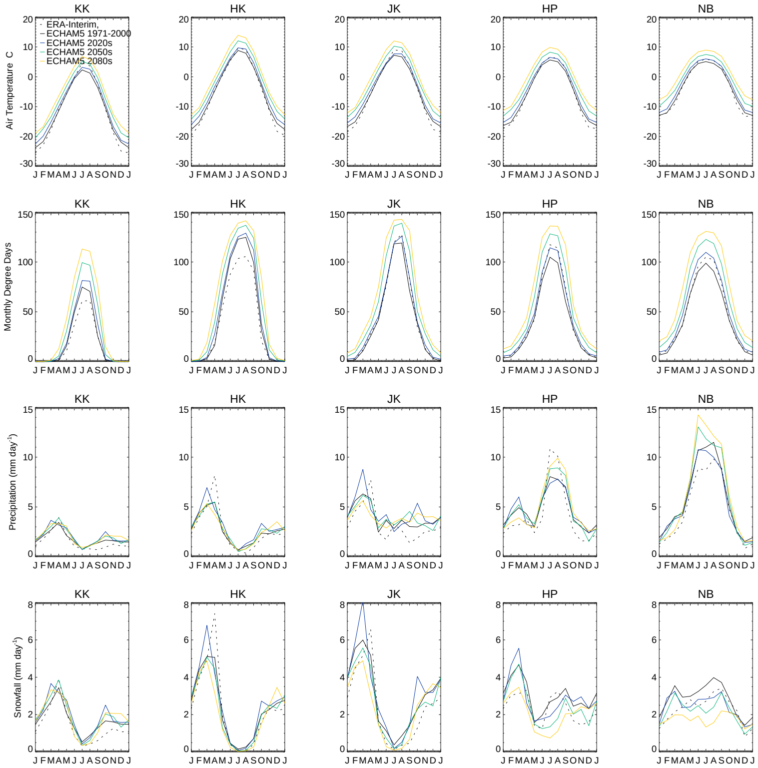

Fig. 7. 30 yr mean climatologies of air temperature, degree days, precipitation and snowfall for the five sub-regions defined in this study from the downscaled ECHAM5 A1B scenario. Shown are 30 yr climatologies for 1971–2000 (black), 2020s (blue), 2050s (green) and 2080s (yellow). Also shown is the 1992–2008 climatology from the downscaled ERA-Interim simulation (black dashed). The regions are Hindu Kush (HK), Karakoram (KK), Jammu-Kashmir (JK), Himachal Pradesh, Uttarakhand and West Nepal (HP) and East Nepal and Bhutan (NB).

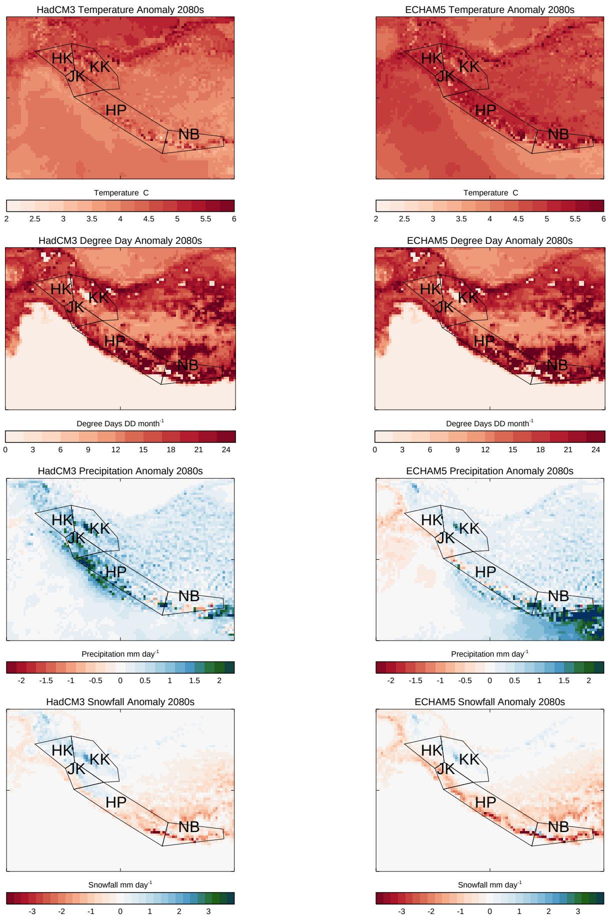

Fig. 8. Projected changes in regional climate by the 2080s relative to 1971–2000 from the downscaled HadCM3 and ECHAM5 A1B simulations. Plots show change in annual average temperature, degree days, precipitation and snowfall.

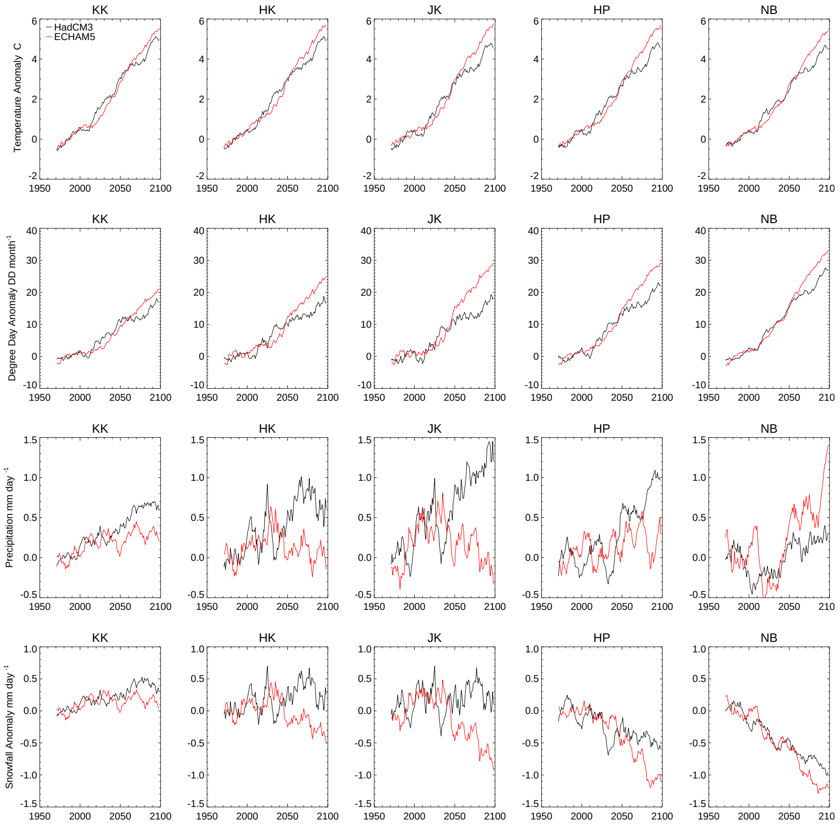

Fig. 9. Projected change in annual mean air temperature, degree days precipitation and snowfall from the HadCM3 (black) and ECHAM5 (red) downscaled A1B simulations. Data are anomalies over the 21st century relative to 1971–2000. Data are smoothed with a 10 yr moving average. The regions are Hindu Kush (HK), Karakoram (KK), Jammu-Kashmir (JK), Himachal Pradesh, Uttarakhand and West Nepal (HP) and East Nepal and Bhutan (NB).

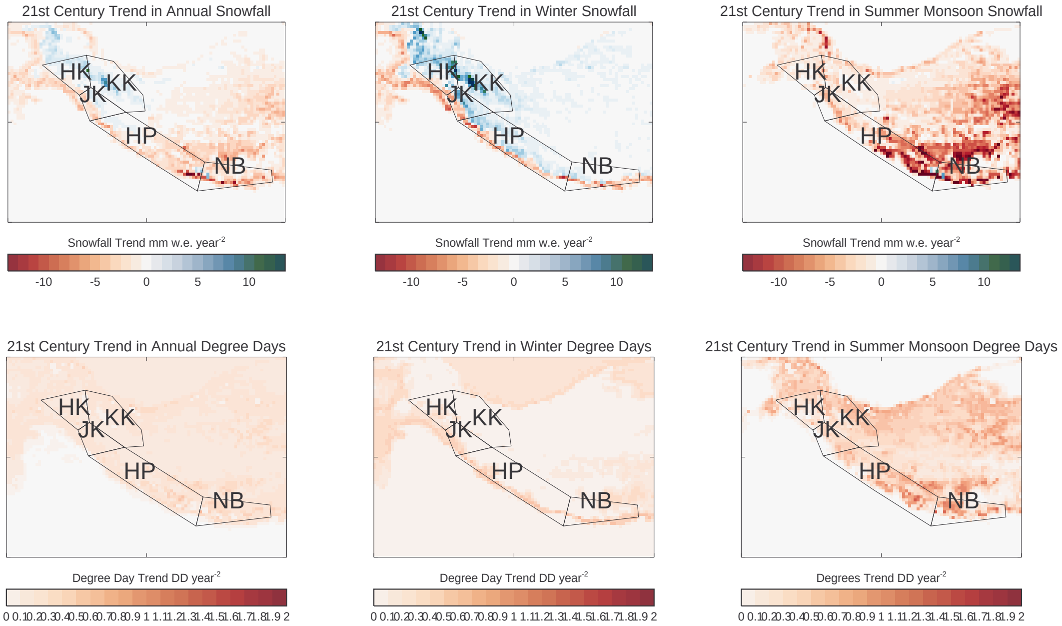

Fig. 10. 21st century trends in snowfall (top) and Degrees Days (bottom) annually (left), winter (centre) and summer monsoon (right) for the downscaled HadCM3 A1B simulation. Trends are linear between 2000 and 2100.

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