LETTERS
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Rising river flows throughout the twenty-first century in two Himalayan glacierized watersheds

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Greater Himalayan glaciers are retreating and losing mass at rates comparable to glaciers in other regions of the world[1–5]. Assessments of future changes and their associated hydrological impacts are scarce, oversimplify glacier dynamics or include a limited number of climate models[6–9]. Here, we use results from the latest ensemble of climate models in combination with a high-resolution glacio-hydrological model to assess the hydrological impact of climate change on two climatically contrasting watersheds in the Greater Himalaya, the Baltoro and Langtang watersheds that drain into the Indus and Ganges rivers, respectively. We show that the largest uncertainty in future runoff is a result of variations in projected precipitation between climate models. In both watersheds, strong, but highly variable, increases in future runoff are projected and, despite the different characteristics of the watersheds, their responses are surprisingly similar. In both cases, glaciers will recede but net glacier melt runoff is on a rising limb at least until 2050. In combination with a positive change in precipitation, water availability during this century is not likely to decline. We conclude that river basins that depend on monsoon rains and glacier melt will continue to sustain the increasing water demands expected in these areas[10].

Glaciers play a crucial but erratic role in the water supply of Asia's main river basins[6]. The degree to which glacier and snow melt are significant components of the water balance on the large-river-basin scale depends on the basin's hypsometry, the glacierized fraction and the pluvial and thermal regimes (Supplementary Table S3). In that sense, the Amu Darya and the Indus clearly stand out, with a large share of the total basin area above 2,000 m, cold upstream climates and substantial precipitation during the boreal winter. The result is a persistent snow cover and relatively strong glacierization, which in combination with dry and warm downstream climates, makes the role of meltwater in these basins very significant. The Ganges and Brahmaputra basins also contain significant glacier areas. Yet more than 70% of their annual precipitation occurs during the monsoon season coincident with the main melt season, which in combination with a wet downstream climate moderates the importance of meltwater. In the other basins, the glacierized area is so small that its role in basin-scale hydrology is limited. Regardless of the role that meltwater plays, rain runoff and base flow may be important runoff components too[11], in particular when the timing is similar to that of the meltwater hydrograph. This water is available to be stored in reservoirs and released when downstream demands are highest. Here we assess how changes in future precipitation and temperature will affect the glacier and snow melt, change the magnitude and timing of the annual hydrograph and cause shifts in the runoff components.

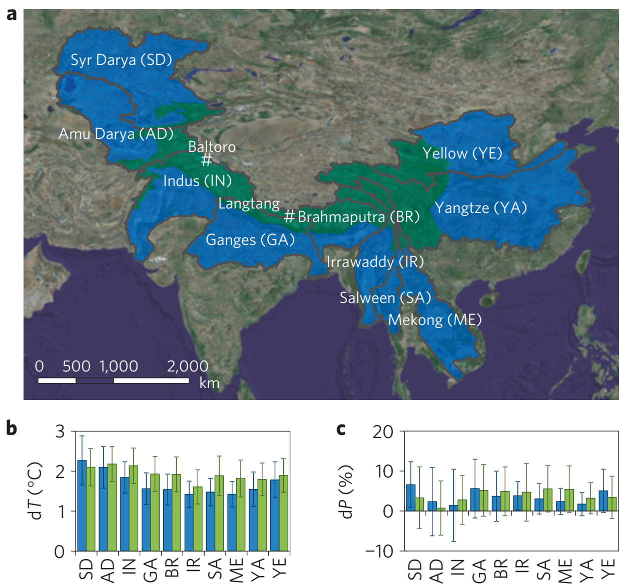

Figure 1 | Overview of main Asian river basins and their projected changes in precipitation and temperature. a, The boundaries of the main river basins with areas in blue < 2,000 m above sea level (a.s.l.) and areas in green > 2,000 m a.s.l. The hash symbols show the locations of the glacierized watersheds of the Langtang and the Baltoro. **b**, The projected changes in temperature. **c**, The projected precipitation changes for the period 2021–2050 relative to 1961–1990 for RCP45. The error bars depict the standard deviation of 43 different CMIP5 RCP45 runs.

The uncertainty about glacier evolution, combined with a poor representation of monsoon precipitation in general circulation models (GCMs; ref. 12) and a positive correlation between temperature rise and elevation[13–15], contributes to the uncertainty about the future of high-altitude water resources in Asia. We first assess the spatial variability and uncertainty in climate change projections for the ten largest river basins in Asia with source areas in the Greater Himalaya (Fig. 1). We use the latest GCM ensemble generated for the upcoming Intergovernmental Panel on Climate Change fifth assessment report provided through phase five of the Climate Model Intercomparison Project (CMIP5). We analyse two main scenarios (representative concentration pathways, RCPs) that may lead to a radiative forcing of 4.5 W m^{-2} (RCP45) and 8.5 W m^{-2} (RCP85) in 2100 (ref. 16) and we use all available GCM runs in the CMIP5 database. The temperature projections for RCP45 reveal a region-wide warming of close to 2 °C (2021–2050

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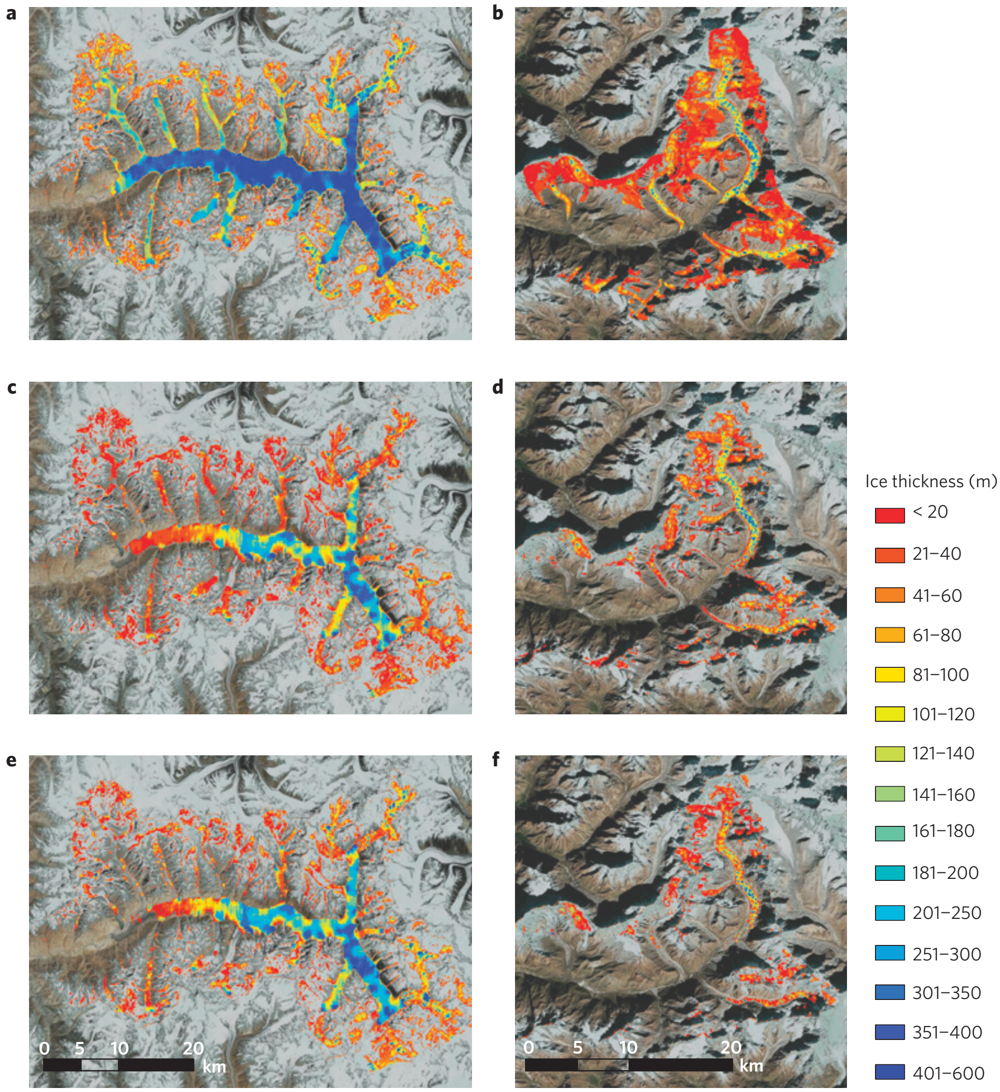

Figure 2 | Present-day and future ice thickness for the Baltoro and Langtang watersheds. **a**, Baltoro and **b**, Langtang show the simulated ice thickness in 2008; **c**, Baltoro and **d**, Langtang for RCP45 in 2100; and **e**, Baltoro and **f**, Langtang for RCP85 in 2100. The RCP45 and RCP85 results are based on the average of the four different downscaled GCM runs. The scale bar in **e** applies to **a**, **c** and **e**; the scale bar in **f** applies to **b**, **d** and **f**.

relative to 1961–1990). The projected warming in the upper basins is 2.2 °C. The lower latitude and monsoon-dominated basins show the smallest absolute warming, but the largest difference between up- and downstream warming. Precipitation projections reveal a modest increase of up to a few per cent on average but there is a large spread among GCMs (inset Fig. 1). This has strong repercussions for uncertainty in hydrological response and indicates that it is essential to take the variability of GCM projections into account when studying hydrological impacts of climate change. The warming and wetting trend is further exacerbated for RCP85 (Supplementary Fig. S6).

We then use a high-resolution fully distributed glacio-hydrological model[17] in two allegedly contrasting watersheds (Supplementary Table S3) in the upstream part of the Indus (Baltoro) and the Ganges (Langtang; Fig. 1) to quantify how these climate change projections and the uncertainties translate into hydrological impacts. Our model includes all relevant cryospheric processes either explicitly or with parameterizations. Snow and ice melt is simulated using a degree-day approach[18] that distinguishes the effects of debris cover and aspect (Supplementary Methods). Avalanching, which is an important feature of Greater Himalayan glaciers[19], is modelled explicitly (Supplementary Methods) and the model includes a fully distributed dynamic ice flow model at a 90 m resolution (Supplementary Methods). Moreover, the model is set up for relatively large watersheds with complex glacier systems, whereas existing models generally operate on much smaller scales or analyse individual glacier systems in a lumped or semi-distributed mode[18,20,21]. For each RCP and for each watershed four GCM runs are selected that represent the range of possible futures. These GCM runs are downscaled to reconstruct transient daily time series of precipitation (P) and temperature (T) until the year 2100 (Supplementary Methods).

In the Baltoro the glaciers are much larger and thicker than in the Langtang. Our simulations show strong retreat, downwasting and disintegration of glacier tributaries in both cases (Fig. 2). The glacier retreat in the Langtang is more pronounced because the glaciers are smaller, for example for RCP85 the glacier area is reduced by 54% in 2100 compared with 33% in the Baltoro. The changes in projected ice volume are more similar. In the Baltoro the ice volume is reduced by 50% to 46 km^3 in 2100 for RCP85 as opposed to a reduction of 60% to 2.8 km^3 for the Langtang. There are significant differences in projected glacier extent between RCP45 and RCP85 and the spread between the scenarios becomes larger in the second half of this century. In the Langtang, for example, the glacier area shrinkage

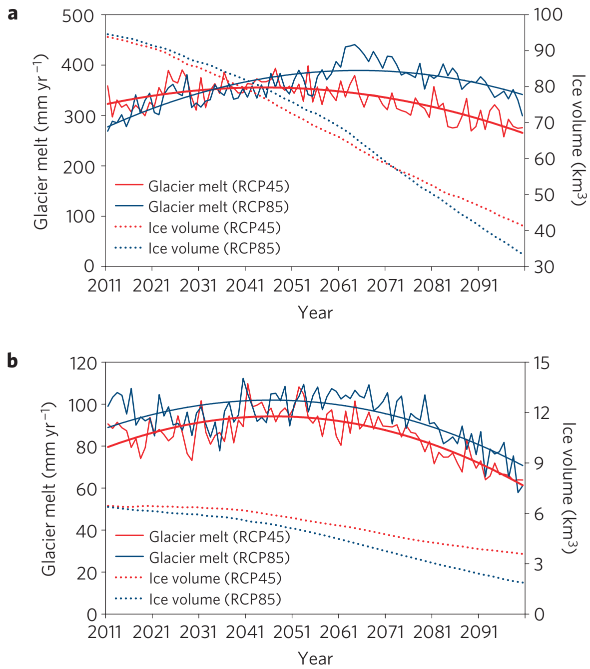

Figure 3 | Future melt and ice volumes. a, Baltoro and **b**, Langtang for RCP45 (red) and RCP85 (blue). The RCP45 and RCP85 results are based on the average of the four different downscaled GCM runs. The glacier melt values are expressed as a catchment average in mm yr^{-1}.

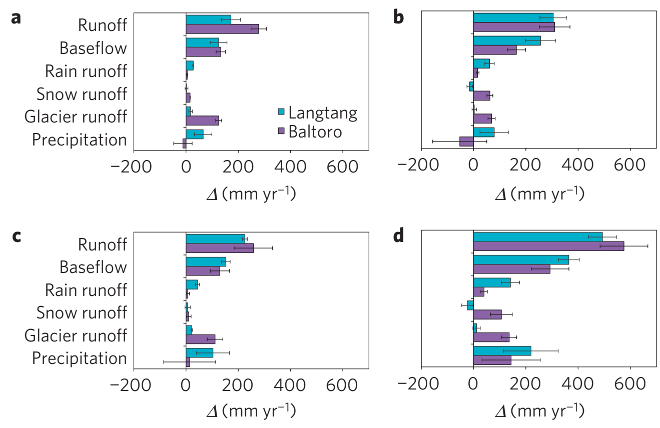

Figure 4 | Projected future changes in water balance components for the Baltoro and Langtang watersheds. All changes are relative to 1961–1990. Runoff is the sum of base flow, rain runoff, direct snow runoff and direct glacier runoff. All values are expressed as a watershed average in mm yr^{-1}. **a**–**d**, Changes are shown for RCP45 for the period 2021–2050 (**a**) and 2071–2100 (**b**) and for RCP85 for 2021–2050 (**c**) and 2071–2100 (**d**). The error bars show the standard deviation of four selected GCM runs.

averaged over 2021–2050 is 9% for RCP45 and 14% for RCP85, whereas for 2071–2100 the retreat is 37% and 54% respectively.

In both watersheds warming results in a decline of glacier area and an increased glacier-specific yield (melt rate per unit glacier area). The total glacial melt, which is the product of both, will peak at a certain time in the future assuming that accumulation (that is, precipitation) remains constant. The timing of this peak is crucial to the future water supply in basins highly dependent on glacier melt. On the global scale, it is estimated that the meltwater peak will occur around 2075 (ref. 22). However, for the specific conditions of the Greater Himalaya we show that the meltwater peak occurs in 2044 and 2065 for RCP45 and RCP85, respectively, in the Baltoro and in 2045 and 2048 for the Langtang (Fig. 3), despite the persistent negative trend in ice volume until 2100. The change in glacier mass balance and the resulting glacier melt is, in addition to temperature, also a function of changes in accumulation. This is evident in the Baltoro plot of Fig. 3. Up to 2070, the simulated ice volume of RCP85 is larger than the ice volume of RCP45 because of the higher snow accumulation, which more than compensates for the stronger warming. Consequently the meltwater peak of RCP85 also occurs much later than for RCP45, whereas for the Langtang there is only a three-year difference between RCP45 and RCP85.

Glacier melt is an important water balance component in both the Baltoro and the Langtang, yet an assessment of the change in total runoff, here defined as the sum of all runoff components from the catchment per unit catchment area, is more complex. The average annual runoff is 558 mm in the Langtang and 602 mm in the Baltoro, which is much higher than what would be expected based on available large-scale-precipitation data sets (Supplementary Table S3). However, there is both direct[23] and indirect[24] evidence that the Karakoram is characterized by strong vertical precipitation lapse rates and this largely explains the observed glacier extents (Supplementary Fig. S3), the glacier flow velocity (Supplementary Fig. S4) and the simulated runoff. As a result, the magnitude of the total runoff and its intra-annual distribution (Supplementary Fig. S7) show a remarkable resemblance to those of the Langtang.

Figure 4 shows a consistent increase in total runoff for both watersheds at least until 2100 for both RCP45 and RCP85. These increases range from 172 mm yr^{-1} (Langtang, 31%) to 278 mm yr^{-1} (Baltoro, 46%) in 2021–2050 for RCP45 to 493 mm yr^{-1} (Langtang, 88%) to 576 mm yr^{-1} (Baltoro, 96%) in 2071–2100 for RCP85. In the Baltoro, glacier melt is a larger component of total runoff and the increased melt is the main cause of the strong increase in total runoff. In Langtang, the main cause of the increased total runoff is the increase in precipitation. An increase in glacial melt also has direct repercussions on the base flow as a major part of the glacier runoff percolates to the groundwater. We also observe a consistent increase in surface runoff owing to an increase in summer rainfall and a decrease in glacierized area. This trend is particularly strong for the Langtang and for RCP85, because of the stronger projected increases in precipitation. The Baltoro also shows a positive change in snow melt runoff, which is not observed in the Langtang. This is probably explained by the fact that a significant portion of the annual precipitation falls during winter and spring (Supplementary Fig. S8) in the Baltoro, which results in a seasonal snow cover in areas that were previously glacierized. On larger scales, when the role of glacier meltwater in the total runoff dilutes further, future runoff will depend even more strongly on changes in precipitation.

There are considerable differences in total runoff between the GCMs (Supplementary Figs S9–S10). For the Baltoro these are mostly dependent on whether net glacier melt has already reached the peak, whereas for Langtang it is purely a variation in precipitation between the GCMs. Within the year we observe strong changes in particular for the Baltoro (Supplementary Fig. S11). In May, for example, we simulate a 126% and 300% increase in total runoff for 2071–2100 for RCP45 and RCP85, respectively, and this may have a large impact on basin-water management as the large reservoirs in the upper Indus such as Tarbela, Mangla and Bhakra may fill more quickly. This would increase water availability in the Indus Basin irrigation scheme early in the growing season.

These findings seemingly contradict earlier research on the very large scale, which suggested a reduction in future runoff in both the upper Indus and upper Ganges basins[6]. There are several reasons for these differences: the scale of model application is different and consequently the physical detail of the underlying model has much improved; different time slices are compared and here we use the latest GCMs, which project a stronger increase in precipitation. The most prominent reason is that the earlier study used a crude mass balance approach to estimate glacier retreat and did not consider strong vertical precipitation lapse rates. This may have resulted in an overestimation of glacier retreat by 2050 in the large-scale study and consequently an underestimation of future glacier melt. We now conclude that at least until 2100 there will be an increase in total runoff in both the Baltoro and the Langtang and that, although there are distinct changes in the underlying causes, their future response to climate change is similar. This similarity, combined with a favourable shift in monthly total runoff, may help to satisfy the increasing future water demands in particular in vulnerable basins such as the Indus[10].

Methods

We use a high-resolution (90 m) glacio-hydrological model for two glacierized watersheds in the Himalaya and the Karakoram[17]. The model simulates snow and ice ablation, snow accumulation and redistribution and the flow of glaciers in combination with major hydrological processes on the watershed scale. The glacier dynamics are based on Weertman's sliding law, which combines the processes of basal viscous deformation and regelation[25]. Ablation is simulated with a degree-day approach that includes the role of debris in reducing melt rates and we have included a model to simulate mass redistribution owing to avalanching (Supplementary Fig. S2). We force the model using a combination of local meteorological data and reanalysis data and we calibrate it in a two-step approach in which we separate cryospheric parameters from hydrological parameters. We validate the model using an observed glacier flow velocity field derived from cross-correlation feature tracking on radar imagery. We select four GCMs spanning the dry–cold, dry–warm, wet–cold and wet–warm space for the RCP45 and RCP85 scenarios from the latest set of GCMs and we use an advanced statistical downscaling methodology[26] to generate a daily time series until 2100. We force the model with the downscaled GCM time series and we analyse change in total runoff and stream flow components (see also Supplementary Methods). Details on the data sets used can be found in the Supplementary Information. The GCM data can be downloaded at http://cmip-pcmdi.llnl.gov/cmip5 and all other requests for data can be addressed to the corresponding author.

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Author contributions

All authors contributed significantly to this work. W.W.I. conceived the study, designed and implemented the glacio-hydrological model, conducted the analysis and prepared the manuscript. F.P. contributed to glacio-hydrological model and the writing . M.F.P.B. conceived the study together with W.W.I. and contributed to the writing.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to W.W.I.

Competing financial interests

The authors declare no competing financial interests.