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Quantifying present and future glacier melt-water contribution to runoff in a Central Himalayan river basin

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Abstract

Water supply of most lowland cultures heavily depends on rain and melt-water from the upstream mountains. Especially melt-water release of alpine mountain ranges is usually attributed a pivotal role for the water supply of large downstream regions. Water scarcity is assumed as consequence of glacier shrinkage and possible disappearance due to Global Climate Change, particular for large parts of Central and South East Asia. In this paper, the application and validation of a coupled modeling approach with Regional Climate Model outputs and a process-oriented glacier and hydrological model is presented for a Central Himalayan river basin despite scarce data availability. Current and possible future contributions of ice-melt to runoff along the river network are spatially explicitly shown. Its role among the other water balance components is presented. Although glaciers have retreated and will continue to retreat according to the chosen climate scenarios, water availability is and will be primarily determined by monsoon precipitation and snow-melt. Ice-melt from glaciers is and will be a minor runoff component in summer monsoon-dominated Himalayan river basins.

1 Introduction

Water supply of most lowland cultures heavily depends on rain and melt-water from the upstream mountains, because mountain watersheds can store considerable amounts of precipitation as snowpack and glaciers (Viviroli et al., 2007). Its delayed release through snow- and glacier-ice-melt can augment river runoff during dry periods (Viviroli et al., 2007; Weber et al., 2010) with ice-melt often being the last water source after melt out of snow. Especially melt-water release of glaciers in the Alps, the Himalaya and other alpine mountain ranges, is usually attributed a pivotal role for the water supply of large downstream regions (Cruz et al., 2007; Barnett et al., 2005; Huss, 2011). But snowpack and glaciers are among the land surface compartments most susceptible to Global Climate Change (GCC). Glacier retreat has attracted wide public interest and serves as symbol for the impact of GCC. As consequence of glacier shrinkage and possible disappearance water scarcity is assumed (Cruz et al., 2007) due to GCC, particular for large parts of Central and South East Asia (Cruz et al., 2007; Barnett et al., 2005; Casassa et al., 2009; Singh et al., 2006; Xu et al., 2009). Especially in High Asia this was brought into focus by the IPCC statement on Himalayan glacier retreat and its assumed consequences for water availability (Cruz et al., 2007). Despite recent studies pointing to the differing influences of ice-melt water on runoff due to regionally varying climatic and hydrological conditions along the Hindu Kush–Himalayas (Rees and Collins, 2006; Thayyen and Gergan, 2010; Immerzeel et al., 2010; Kaser et al., 2010), the future rate of recession of Himalayan glaciers as well as their present and future role for the downstream regions remain controversial.

The studies address the influence of ice-melt in Asia on runoff either only qualitatively (Barnett et al., 2005), for hypothetical catchments (Rees and Collins, 2006) or at almost continental scales (Immerzeel et al., 2010). Some results are limited to present climatic conditions (Thayyen and Gergan, 2010; Kaser et al., 2010). Detailed studies of the ice-melt contribution to runoff in relation to snow-melt and the other water balance components and of their changing composition due to GCC are needed to assess the current and future role of glaciers for downstream water management (Kaltenborn et al., 2010; Viviroli et al., 2011). They are so far rare in monitored regions like the Alps (Weber et al., 2010) and not available in remote regions as the Himalayas. Since there is no feasible method to distinguish river water according to its generation at the scale of large watersheds and because GCC deals with the future, model studies, properly validated with recorded data, are currently the only feasible approaches to quantify the contributions of rainfall, snow- and ice-melt to river runoff.

We present a model-based analysis of the temporal dynamics and spatial pattern of the rainfall, snow- and ice-melt contribution to river runoff under past and future climatic conditions for the Lhasa River basin (LRB) in the Central Himalaya (Fig. 1, Sect. 2). To account for the specific and unique role of the glaciers for the downstream regions, we wanted to quantify the contribution of glacier ice-melt water to river runoff not only for the highly glacierized head-watersheds but also for the downstream regions where people usually live and use the water.

First, the application and validation of a coupled modeling approach with Regional Climate Model outputs and a process-oriented glacier and hydrological model is explained for a Central Himalayan river basin despite scarce data availability (Sects. 3, 4). Then, the results are shown: the spatial contribution of ice-melt to river runoff along the river network of the LRB (Sect. 5.1), the amount of ice-melt water related to other water balance components (Sect. 5.2) and the timing of the melt contribution in its seasonal course (Sect. 5.3) for past and future climatic conditions from 1971–2080.

2 Study area

The LRB was chosen as a representative glacierized, complex headwatershed of the Brahmaputra in High Asia, which is together with the Ganges a major water source for app. 300 million people in the lowlands in India and Bangladesh. The Lhasa River is the largest tributary in the middle reach of the mountainous Upper Brahmaputra with a drainage area of 32 800 km^2 (Fig. 1). The location on the Tibetan Plateau characterizes the physio-geographic conditions of the basin. The relief ranges from 3535 m a.s.l. at the conjunction with the Brahmaputra up to 7162 m a.s.l. at the peak of the Nyainqêntanglha Mountains, forming the north-western watershed. Most glaciers in the LRB are found along this mountain range, one of the main glacierized areas of Central Asia (Yao et al., 2006), due to their altitude and orientation to the southeast from where the monsoon triggers orographic precipitation. Altogether 670 km^2, equating to 2 % of the total basin area, were glacierized in 1970 according to the Chinese Glacier Inventory (World Data Center For Glaciology and Geocryology, 2009). During the last decades a continuous retreat was recorded, similar to most parts of the Tibetan Plateau (Bolch et al., 2010; Yao et al., 2007). Until the year 2000, about 6 to 10 m w.e. (water equivalent) (Frauenfelder and Kääb, 2009; Kääb et al., 2008) melted away on average.

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Climatic conditions in the LRB are determined by a strong seasonal course of the precipitation, which falls during the monsoon months in summer. Mean annual air temperatures vary between −9 °C in the Nyainqêntanglha Mountains and +10 °C in the Lhasa River valley near the river's mouth. Due to the pronounced wet season during the summer monsoon and the dry season lasting the rest of the year, the runoff shows a clear seasonal cycle, with the flood peak reached in August. About 90 % of the mean annual runoff is observed between May and November, whereas in the winter season, runoff is low. The important synchronous ablation and accumulation period during the monsoon season in summer largely determines the importance of glacier melt for water availability in the LRB similar to large, summer-monsoon dominated areas in the Himalayas.

However, the glacierization is only 2 % of the watershed area, it was chosen, because the study wants not only to analyze the contribution of glacier melt water in the highly glacierized head-watersheds, but it also wants to analyze the influence of ice-melt in the downstream regions, where usually people live and use water. Despite scarce data availability the successful application of a coupled modeling approach with RCM outputs and a process-oriented glacier and hydrological model can be demonstrated.

3 Methods

3.1 Model description

In our modeling approach (see Fig. 2) the PROMET watershed model (Mauser and Bach, 2009) is coupled with the SURGES glacier model (Weber et al., 2010) to clarify the influence of glacier melt water on river runoff in a Himalayan river basin. In order to quantify the contribution of glacier melt water to river runoff not only for the highly glacierized head-watersheds, but also for the downstream regions where people usually live and use the water, the full water balance components of a heterogeneous, large-scale river basin have to be taken into account. Therefore the models consider the water flows in vegetation, soils and river channels and the complete rainfall-runoff, snow and ice dynamics: Runoff = rainfall + snowfall – evapotranspiration + changes in groundwater storage + changes in snow storage + changes in ice storage. Particularly evapotranspiration and the complex interactions of rainfall and snow-melt forming surface runoff, infiltrating into the soil and groundwater, forming interflow and base flow are important for runoff generation in the large downstream areas, which enables, together with the melt water release of the glacier-ice the determination of the importance of ice-melt water throughout a mesoscale river basin. This is the underlying motivation to couple a complex hydrological model with a glacier mass- and energy balance model. The small-scale processes leading to melt-water release on the heterogeneous surfaces of mountains and glaciers are considered by SURGES using a subscale approach in calculating the surface mass and energy balance of all glaciers in the basin (see Sect. 3.1.3).

Furthermore, the method should allow determining the relevance of ice-melt among the other water balance components. Consequently, we separated ice- and snow-melt in the entire basin. The term "snow-melt" is seen in a purely physical sense as "snow that melts at the surface of a snow cover" be it on the glacier or not. Therefore it consists of both, snow-melt from non-glacierized and glacierized parts of the basin, because for the water balance of the basin it does not matter whether the melt water is released by a snow cover from the glacier surface or from the non-glacierized parts. Furthermore, regardless of a glacier existing or not, a snow cover would be built up and the melt water would be released at these altitudes. Snow therefore melts after the same physical principles (and only with different model parameters surface roughness, surface temperature etc.) regardless whether on glaciers or on non-glacierized areas. On each location on a glacier ice-melt can only set in after all snow has melted and the ice is exposed to energy transfer from radiation and/or atmosphere.

Since the modeling approach consists of process-oriented, on elementary physics based models, calculating the energy- and mass balance beside several other processes, a consistent meteorological data set (near surface air temperature,

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precipitation, air humidity, wind speed, incoming short and longwave radiation in a temporal resolution of one hour) is required for each raster element. The scaling tool SCALMET (Marke et al., 2011a, b) is applied to downscale outputs of Regional Climate Models (RCMs) during runtime.

3.1.1 The PROMET watershed model

The PROMET (Processes of Radiation, Mass and Energy Transfer) model used in this study was developed in order to study the impacts of climate change on the water balance in heterogeneous, large-scale river basins ($A \sim 100\,000\,\mathrm{km}^2$). PROMET runs with a temporal resolution of one hour and is a spatially distributed model. It is based on physical principles and mass- and energy balances are closed. The model is not calibrated to measured runoff and the parameterizations are invariant in space and time across the whole basin. Varying climatic conditions and hydrological regimes of complex catchments (e.g. mountain headwatersheds and large river valleys in the forelands) are modeled synchronously by PROMET (Mauser and Bach, 2009). The model was successfully applied in the complex river basin of the Upper Danube in Central Europe ($A = 77\,000\,\mathrm{km}^2$) with comparably good data availability under past and future climate conditions. Due to its characteristics PROMET fulfills the requirements for impact studies of climate change on the regional scale (Mauser and Bach, 2009). The local heterogeneities in the LRB are considered through a model raster with a resolution of 1 × 1 km.

3.1.2 The scaling tool SCALMET

In this study the scaling tool SCALMET (Marke et al., 2011a, b) applies statistical downscaling functions without any further bias correction to expand from the RCM scale (45 × 45 km) to the scale of the hydrological simulations (1 × 1 km). Topographical information (elevation, slope, aspect) is included in order to consider subgrid-scale heterogeneities and related natural climate gradients, which are particularly important in

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mountainous terrain. For each time step, the elevation dependency of meteorological variables, strongly varying with terrain elevation, e.g. air temperature or air humidity is analyzed. A regression function is determined, which is then applied to adjust these variables. The scaling methods applied consist of bilinear interpolation and statistical downscaling with conservation of mass and energy (Marke et al., 2011b). Since the temporal resolution of the regional climate model used in this study is less than one hour, a temporal interpolation routine is also implemented. In these cases a cubic spline function is applied to all meteorological parameters except precipitation. The latter is classified under short events for a single recording and under long-term events for consecutive observations. Afterwards, the precipitation is distributed to the hours before the single event using a Gaussian distribution, or equally distributed in time for the continuous case following (Mauser and Bach, 2009). This routine runs prior to the downscaling processes. The downscaling techniques implemented in SCALMET are based on physical and statistical approaches, so they are completely general and can be applied without any further parameterization in various regions. For further details it is referred to Marke et al. (2011a, b).

3.1.3 The SURGES glacier model

Concerning the strong variation with elevation of the processes, SURGES uses an area-elevation-distribution with subscale units (Fig. 3a) to parameterize the complex terrain of mountain glaciers within all glacierized 1 km^2 raster elements of the full river basin. If a glacier covers several raster elements (Fig. 3b) the elevation belts of one glacier are spread over several raster elements. Each subscale unit is characterized by a homogenous ice thickness and surface elevation. The subscale approach thus enables the coexistence of accumulation zones at the higher altitudes and ablation zones at the lower altitudes within one raster element (Fig. 4a). The algorithms of SURGES to calculate accumulation and melt rates are designed to use data as measured at a local climate station as input. Hence, the meteorological data precipitation, air temperature, air humidity, incoming shortwave and longwave radiation, air pressure and wind

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speed, provided by SCALMET, has to be extrapolated to the elevation levels. Therefore air temperature, air pressure, wet bulb temperature (for differentiation of rain from snowfall by iteratively solving the psychrometer formula) and the wind speed on the glacier for air temperatures above 0 °C (a katabatic flow over glaciers, which is caused by the differences in heat between the snow-free, surrounding areas of a glacier and the comparatively cold glacier surface, which is very common over melting surfaces) are extrapolated due to the different elevation at the subscale glacier belts. All the other meteorological variables, e.g. precipitation or incoming radiation, are assumed to be constant throughout the raster element and are taken from SCALMET without any adaptation.

Due to a threshold wet-bulb temperature a distinction is made between rain and snowfall. The latter accumulates until melt sets in. In order to determine the ablation, mass and surface energy balance, taking into account the radiation balance, the latent and sensible heat fluxes, and the energy supplied by solid or liquid precipitation of snow and ice are calculated for every subscale unit to calculate the amount of glacier melt, which largely occurs on snow-free glacier areas (Prasch et al., 2008). As long as snow covers the glacier surface it is protected against melt. The melt water (first of snow and after snow vanished of glacier ice) is aggregated for each raster element and injected into river runoff within the routing component of PROMET. Snow to ice metamorphism is considered in partly adding snow, which outlasted a defined number of ablation periods, to the ice layer (Fig. 4b). In the test site of the Lhasa River catchment, not only accumulation but also ablation takes place during the monsoon. Furthermore, alternating melting and refreezing was observed up to 5800 m a.s.l. (Kang et al., 2007). These processes accelerate snow metamorphism. Thus, after a period of one year, similar to the estimation of Kang et al. (2007), half of the snow layer is transformed to ice in this study. Even though firn is not distinguished specifically, changes with respect to the energy balance are taken into account by the simulation of changes in the albedo. In the case of melt water release at these glacier parts, the amount of snow which is added to the ice body after considering the metamorphism from snow to ice, fully contributes to ice-melt.

Finally, glacier geometry is adjusted both in the case of melt out or growth of the ice reservoir on different elevation levels in reducing or respectively increasing glacier area (Fig. 4c). Since snow that accumulates at the higher elevation levels is transformed to ice as explained above, it does not accumulate endlessly. Additionally, the model chain is applied under future climate conditions which are characterized in this region according to the climate model outputs by increasing temperatures and only slight changes in the amount of precipitation, so that glacier retreat goes along with a reduction of the ice flow. Although an ice flow model is not explicitly implemented, the approximation of glacier geometry changes is considered in a first step. Moreover, the complexity of the relevant processes requires detailed information about the glacier's geometry and cannot be simulated in a simple approach on the catchment scale. This is the reason why glacier changes are crudely considered in long-term studies (e.g. Rees and Collins, 2006).

3.2 Input data

Outputs of the Regional Climate Model (RCM) COSMO-CLM (Climate Limited-area Modeling Community, 2012) for past and future are used as meteorological drivers. CLM, driven by the coupled ocean-atmosphere GCM ECHAM 5/MPI-OM, was chosen, because it realistically simulates the 20th century South Asian monsoon compared to other GCMs following Kripalani et al. (2007). The CLM outputs air temperature and precipitation are bias corrected for the whole Upper Brahmaputra basin (Dobler and Ahrens, 2008, 2010), using available station data. Then the CLM data were downscaled to the spatial resolution of 1 × 1 km through the scaling tool SCALMET (Marke et al., 2011a, b) without adding further bias correction. For all further model parameters we used open access data like SRTM (Jarvis et al., 2006) and Aster (ERSDAC, 2009) digital elevation models, the NASA Terra/Modis land cover product (Boston University, 2004), the Harmonized World Soil Database (FAO et al., 2009) and the Chinese Glacier

Inventory (World Data Center For Glaciology and Geocryology, 2009). Further details to the applied input data can be found in Prasch et al. (2011b).

4 Validation of the modeling approach

The models PROMET, SURGES and SCALMET have been developed and successfully applied within the integrative research project GLOWA-Danube (www.glowa-danube.de). Additionally, PROMET and SCALMET were applied in the Upper Brahmaputra Basin (Prasch et al., 2011a, b) to study the impacts of climate change on water availability within the framework of the project BRAHMATWINN (Flügel, 2011). The full model chain was already applied in the Upper Danube River basin and validated in detail (Weber et al., 2010). Therefore, here the validation of the modeling approach in the LRB is shown. This includes validating downscaled air temperature and precipitation, glacier development, and runoff in the LRB.

4.1 Validation of air temperature and precipitation in the LRB

To validate the downscaled air temperatures and precipitation sums in the Lhasa River basin the recorded air temperature and precipitation at five meteorological station data (Fig. 1, yellow circles) are compared with downscaled CLM ERA 40 and CLM ECHAM 5 data, and subsequently, the tool SCALMET is run (Table 1). The recorded air temperature is reproduced for the stations by both CLM model outputs, except that in Damshung for the ECHAM 5 driven model run where the temperature is overestimated by 0.6 K. The mean precipitation sum of Damshung and Pangdo is overestimated by the CLM ECHAM 5 data, but the deviations are within 10 %, whereas in Lhasa the overestimation reaches 22 %. The precipitation sum is slightly underestimated for Meldro Gungkar and Tangga. In comparison to the CLM ERA 40-driven temperature and precipitation values, the deviations seen are smaller. Consequently, the mean meteorological conditions are reproduced by the CLM ECHAM 5 model run, particularly when

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considering the coarse resolution of the CLM outputs. Taking into account technical difficulties in precipitation observation and the resulting deviations, the average results seem to be reasonable together with the seasonal course shown in Fig. 12.

4.2 Validation of glacier development in the LRB

As part of the Brahmatwinn project, a detailed glacier change study for the Lhasa River basin was conducted by comparing multi-temporal optical remote sensing data from the Landsat and ASTER sensors with the Chinese Glacier Inventory (Frauenfelder and Kääb, 2009; Kääb et al., 2008). A total change of −21 % in glacier area from 1970 to 2000 was found. Using various area-volume relations a mass balance change of −0.2 to −0.3 m w.e. per year was estimated (Frauenfelder and Kääb, 2009; Kääb et al., 2008).

For the past 30 yr, a decrease of 20 % (CLM ECHAM 5) of the glacier area is modeled. This is within the range of the observed glacier area reduction. For the ice-water reservoir, an average mass loss of 0.3 m (CLM ECHAM 5) is calculated. In comparison with the results for this area, the mass loss is consistent.

4.3 Validation of runoff in the LRB

To validate the simulated runoff in the Lhasa River basin, two models runs, driven by downscaled CLM ERA 40 and CLM ECHAM 5 meteorological data, were carried out from 1 January 1970 to 31 December 2000, on a temporal resolution of one hour. Due to PROMET's spin up, the first model year is not considered in the validation. The model results are compared to runoff observations at three gauging stations in the LRB (Fig. 1). Figures 5, 6 and 7 show the comparison of daily and monthly runoff values for the CLM ERA 40 driven model run together with quality criteria in Tables 2 and 3, whereas for the CLM ECHAM 5 driven results the mean annual runoff is validated as climate signal (Table 4). Although there are biases, the seasonal course is reproduced by the model, especially when taking into account the coarse spatial and temporal

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resolution of the CLM output data as meteorological drivers. Furthermore, the modeling approach is not calibrated to observed runoff in order to be applicable also for changing future watershed conditions or climates.

5 Results

The seasonal contribution of snow- and ice-melt to total runoff is analyzed for the past 30 yr and the IPCC SRES-A1B, -A2 and -B1 emission scenarios (Nakićenović et al., 2000) until 2080. Figure 8 shows the development of the modeled total ice volume in the LRB between 1970 and 2080 for the three selected emission scenarios. The observed continuous glacier retreat during the last decades (Yao et al., 2007; Bolch et al., 2010; Frauenfelder and Kääb, 2009; Kääb et al., 2008) will continuously proceed regardless of the selected scenario, but glaciers will not completely disappear until 2080, because the large ice reservoirs between altitudes from 5600 to 6100 m a.s.l. and glaciers extending up to 7200 m a.s.l. resist melting for a long time. Since the results do not principally differ among the scenarios, we focus on the A1B analysis in the following.

5.1 Contribution of ice-melt to river runoff along the river network

To determine the contribution of glacier ice-melt water, the model is run under two different model settings. In the first setting, glaciers are considered and ice-melt is directly injected into the river channels. In the second setting, glacier volumes are set to zero. We consider, for each time step, the difference in runoff between the two model settings as the ice-melt runoff component. In order to specifically quantify the contribution of ice-melt to total runoff, it is treated separately since, contrary to snow-melt, which occurs throughout the whole basin, it only occurs in the glacierized areas. Divided by total runoff including ice-melt, it represents the contribution of ice-melt to total runoff, shown in Fig. 9. While ice-melt amounts to more than 50 % of total runoff in the glacierized head-watersheds, its contribution rapidly decreases as watershed area increases. In the larger tributaries ($A > 3000\,\mathrm{km}^2$) and at the outlet of the LRB only 0.1–5 % of the water can be attributed to ice-melt during the past period from 1971–2000.

In the future periods 2011–2040 and 2051–2080 the spatial patterns of the contribution of ice-melt water remain similar (Fig. 9). However, total melt out of glaciers occurs in the north-eastern and southern basin, which reduces ice-melt contribution to zero. Despite the continuous future reduction of glacierization (Fig. 8), which would suggest a decreasing fraction of ice-melt, it hardly changes in the main rivers and even slightly increases in the highly glacierized head-watersheds. In depth analysis of this astonishing finding shows that the reason lies in an altitudinal shift of the snow conditions of about +500 to +1000 m because of rising air temperatures (Fig. 10). This altitudinal shift extends the snow-free period by two to three months (Fig. 11) and thereby increases ice-melt per area and year. A detailed look at the modeled glaciers shows that the increasing ice-melt compensates their shrinking areal extent and leads to an almost stable fraction of ice-melt in the river runoff.

5.2 Ice-melt related to other water balance components

The following analysis of all water balance components gives deeper insight. For each hourly model time-step runoff is composed of rainfall, snow- and ice-melt, which, together with evapotranspiration and changes in snow, ice, soil and ground water storage close the water balance (Tables 5, 6 and 7). Since long term changes in soil water content and groundwater in the LRB are modeled to be below 1 %, they are neglected. To determine the relative contribution of ice-melt in comparison to the other runoff and water balance components, we separated them for the five gauges in the LRB marked in Fig. 1. Table 8 shows that today about 30 % of the water in the LRB evaporate, whereas 70 % is released as runoff. The most important runoff component at the outlet today originates from snow-melt. Rainfall generates 40 % of the runoff whereas ice-melt contributes between 2 and 3 % (max. 11 % at Yangbajing).

Under future climatic conditions, increasing evapotranspiration is modeled due to rising temperatures. Together with a slight decrease in precipitation this results in a considerable decrease in runoff at all gauges except at Yangbajing during both future periods. There, evapotranspiration increases only marginally and the modeled annual ice-melt contribution slightly increases because of the large decrease in snow-melt during both simulated future periods. The latter is due to the compensational effect described above. Consequently, the importance of ice-melt will remain low at the outlet and in most parts of the LRB (see also Fig. 9).

5.3 The seasonal timing of melt contribution

In contrast to man-made reservoirs snow- and ice-reservoirs are filled or emptied by natural processes in either a cyclic or anti-cyclic behavior, and therefore cannot be managed for downstream agriculture, hydropower, industry and households. If snow- and ice-melt occur during the rainy season (cyclic behavior), they may add a small fraction to the large amount of runoff generated by heavy rainfall. When snow- and ice-reservoirs melt during the dry season (anti-cyclic behavior) the generated runoff can be used to compensate potential water shortages. A closer look at the seasonal dynamics of the runoff components in the LRB and at Yangbajing, which are shown in Fig. 12, therefore creates additional insight into the possible future role of glaciers in the LRB for water supply of the downstream lowlands.

The daily runoff course at the basin outlet (Fig. 12, left), averaged over the period from 1971–2000, shows a very distinct and consistent runoff maximum during the summer months caused by monsoon rainfall (Fig. 12a, left). Runoff is low during winter because of reduced precipitation, which predominantly falls and is stored as snow. The fraction of ice-melt approaches zero during winter, since the glaciers are snow-covered. Any melt during warm spells in winter occurs as snow-melt. With increasing temperatures in spring snow-melt sets in first, is infiltrated into the soil or evaporated into the atmosphere, and peaks in late May before monsoon precipitation fully sets in. At that time, the glacierized area is still protected from ice-melt by a snow cover. As snow vanishes in high altitudes, ice-melt starts to increase to a maximum of 5 % of total runoff until late June. Then, the increasing monsoon precipitation also increasingly causes snow to fall in high altitudes. This snow cover partly protects the glaciers from melting. Coincidently, increasing cloudiness reduces radiation and snow-melt from its peak in early June. The decreasing rainfall and cloud cover towards the end of the rainy season in September and October cause snow-melt to increase again. Since glaciers are still protected by a snow cover, ice-melt is not increasing. Falling temperatures in September decrease ice-melt until it stops in late October. Accordingly, runoff generated from rainfall and ice-melt is almost cyclic at the outlet of the LRB. The close match between total modeled runoff with and without ice-melt confirms the minor contribution of ice-melt (Figs. 9, 12). From the point of view of water management this is unfavorable since ice-melt cannot augment low flow conditions during the dry winter season.

The average seasonal course of runoff remains similar under assumed future climatic conditions (2011–2040, 2051–2080; Fig. 12b, c). The main difference compared to the past is a clear decrease of the melt-water contribution both from snow and ice during summer. Increasing temperatures at all altitudes also sharply reduce the amount of snowfall (Fig. 11). The protective snow-cover on glaciers is removed much earlier in the year by increasing snow-melt. Ice-melt becomes the dominating melt-contribution to runoff in early June, reaching a peak of 10 % at the basin outlet. The onset of the monsoon reduces ice-melt from the glaciers as described above. These processes are similar for the sub-basin of Yangbajing with larger glacierization (Fig. 12, right).

6 Conclusion

From these results we conclude that glacier volumes in the LRB will be strongly reduced by GCC, but glaciers will not completely disappear until 2080. Nevertheless, ice-melt, on average, has played and will play a minor role in the downstream water supply from the Lhasa River, contributing less than 5 %. This is mainly due to the cyclic behavior of runoff generated from rainfall and from ice-melt in the past and future,

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because precipitation and ice-melt will remain cyclic under GCC according to the scenarios. Thus, the contribution of ice-melt to total runoff will almost remain stable until 2080, although there will be a slight increase during a short period in spring. Contrary, the contribution of snow-melt to river runoff will generally decrease with GCC in the LRB and result in changes in water availability. Additionally, the increase of evapotranspiration with increasing air temperatures also will reduce water availability.

The model exercise and the following analysis give valuable insight into the complex interaction of a reducing glacier area and increasing melt intensity, which for the LRB compensate each other. Since the LRB is representative for glacierized, summer-monsoon dominated Himalayan basins, this result can be generalized for summer-monsoon dominated regions in the Himalayas as for instance the Ganges and Brahmaputra river basin (Fig. 1).

Focusing on the effect of the processes in determining the melt water release under changing climatic conditions throughout a complex mesoscale river basin in the presented modeling approach results in the neglect of some small-scale processes on the glacier so far. Wind-induced snow transport and the small-scale shading caused by the surrounding mountains which principally facilitate the formation of glaciers in some cases, has so far been neglected. The effect of transporting ice from the accumulation to the ablation area due to the ice flow has so far been excluded, but the snow-to-ice metamorphism and glacier geometry changes are considered in a first step as well as sublimation. Accordingly, snow that accumulates at the higher elevation levels is transformed to ice and does not accumulate endlessly as explained in Sect. 3.1.3. Since the model chain is applied under future climate conditions which are characterized in this region according to the climate model outputs by increasing temperatures and only slight changes in the amount of precipitation, glacier mass balances are negative and consequently cause glacier geometry changes, which are considered. This process is partly compensated by the ice flow of large glaciers, which is so far not explicitly implemented. The enhancement of the model with an ice flow model is intended for future work.

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The approach nevertheless enables the distributed simulation of the main processes for determination of the melt water release of all glaciers in a mesoscale river basin. The properties of each single glacier are considered in as much detail as possible by the approximation of the ice thickness-area-elevation distribution. This includes capturing the small-scale glacier properties below the process scale of PROMET of 1 × 1 km for the simulation of energy and mass balances. Furthermore, the coexistence of rain- and snowfall, of the accumulation and ablation zones of a glacier and the neighboring non-glacierized areas on one raster element can be handled. Geometry changes in the glacier are considered in reducing the glacier area after the ice-melt at given elevation levels, although the implementation of ice flow effects could improve the determination. Moreover, SURGES can be applied under past as well as future climatic conditions, since it is process oriented and uses globally valid parameterizations. Through the implementation of SURGES in PROMET, the influence of the melt water release of glaciers for the water balance can be determined in a spatially distributed way over the complete large-scale catchment, considering the full water balance processes. Finally, in applying the SCALMET tool, RCMs can be applied as meteorological input data. They make the application of the modeling approach independent of meteorological station data. This is especially important in remote mountain regions.

Although the models require a broad range of input data due to the complexity of the subject to be modeled, this study demonstrates their applicability in remote regions. The validation for the Lhasa River catchment presented proves the reliability of the model results for glaciers and for the hydrological water balance. Particularly uncertainties still exist in the simulation of future monsoon precipitation in current GCMs (Kripalani et al., 2007), the presented modeling approach offers the possibility to model the spatial pattern of the fraction of glacier ice-melt on runoff in relation to the other water balance parameters at a regional scale. Spatial distribution is still especially difficult to simulate (Kripalani et al., 2007; Dobler and Ahrens, 2010). Hence, significantly increased monsoon precipitation would modify the simulation result for runoff and glacier changes. However, an extensive precipitation increase of 25 % in annual precipitation

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would be required to compensate mass loss due to a 1 K warming and to stop glacier retreat (Oerlemans, 2005).

The consideration of regional variations provides a detailed basis for the development of appropriate adaptations strategies to GCC in order to support future water availability. Since there is no indication from the currently available climate model results that monsoon timing and dynamics will drastically change in the upcoming future as consequence of GCC, the results of the study strongly suggest a re-evaluation of the future role of the glaciers for the water management in the Himalaya region and its lowlands.

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Table 1. Validation of simulated CLM ERA 40 and CLM ECHAM 5 and observed mean values of air temperature and precipitation in the LRB.

Global model, driving CLM	Station and time period	Air temperature [°C]			Precipitation sum [mm]		
		Observation	Down-scaled CLM data	Δ	Observation	Down-scaled CLM data	Δ
ERA 40	Lhasa (1980–2000)	8.1	7.2	−0.9	426	584	158
	Meldro Gungkar (1980–2000)	6.0	5.3	−0.7	548	532	−16
	Damshung (1980–2000)	1.8	1.7	−0.1	464	543	80
	Pangdo (1976–2000)		no data		538	647	91
	Tangga (1971–2000)		no data		517	561	44
ECHAM 5	Lhasa (1980–2000)	8.1	7.9	−0.2	426	524	97
	Meldro Gungkar (1980–2000)	6.0	6.0	0.0	548	481	−67
	Damshung (1980–2000)	1.8	2.4	0.6	464	511	48
	Pangdo (1976–2000)		no data		538	587	41
	Tangga (1971–2000)		no data		517	513	−4

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Table 2. Quality criteria for modeled monthly runoff [$m^3 s^{-1}$] for CLM ERA40-driven model runs.

Quality criteria	Lhasa (1971–2000)	Pangdo (1976–2000)	Tangga (1971–2000)
Coefficient of determination R^2	0.79	0.78	0.80
Slope of linear regression	1.37	1.30	1.29
Nash-Sutcliffe efficiency coefficient	0.31	0.39	0.48

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Table 3. Quality criteria for modeled daily runoff [$m^3 s^{-1}$] for CLM ERA40-driven model runs.

Quality criteria	Lhasa (1996–2000)	Pangdo (1996–2000)	Tangga (1997–2000)
Coefficient of determination R^2	0.72	0.70	0.74
Slope of linear regression	1.00	0.92	0.93
Nash-Sutcliffe efficiency coefficient	0.67	0.70	0.73

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Table 4. Validation of mean annual runoff [$m^3 s^{-1}$] for ERA40- and ECHAM 5-driven model runs.

Period	Mean annual runoff [$m^3 s^{-1}$]	Lhasa *R*	Pangdo *R*	Tangga *R*
1971–2000	Observed	279	196	237
	ERA 40	408	270	321
	Δ ERA 40 [%]	+46	+37	+36
	ECHAM 5	351	233	278
	Δ ECHAM 5 [%]	+26	+19	+17

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Table 5. Annual average water balance components (precipitation + reduction of ice storage = evapotranspiration + runoff + storage changes of snow cover, soil water content and groundwater) in mm for the presented gauges in the LRB.

Gauge	1971–2000	2011–2040 (A1B)	2051–2080 (A1B)
Outlet	630 + 7 = 207 + 429 + 1	621 + 8 = 231 + 399 – 1	596 + 9 = 263 + 342 + 0
Lhasa	627 + 6 = 206 + 425 + 0	613 + 5 = 233 + 386 – 1	590 + 5 = 267 + 328 + 0
Tangga	624 + 7 = 190 + 440 + 1	604 + 6 = 219 + 392 – 1	581 + 6 = 252 + 335 + 0
Pangdo	621 + 9 = 183 + 446 + 1	601 + 7 = 212 + 397 – 1	578 + 7 = 244 + 341 + 0
Yangbajing	657 + 20 = 177 + 499 + 1	662 + 46 = 191 + 521 – 4	621 + 62 = 209 + 474 + 0

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Table 6. Values for runoff originating from liquid rainfall, snow-melt and ice-melt in mm for the presented gauges in the LRB.

Gauge	1971–2000	2011–2040 (A1B)	2051–2080 (A1B)
Outlet	240 + 177 + 12 = 429	250 + 139 + 10 = 399	248 + 84 + 10 = 342
Lhasa	232 + 184 + 9 = 425	234 + 146 + 6 = 386	234 + 89 + 5 = 328
Tangga	221 + 208 + 11 = 440	217 + 165 + 10 = 392	227 + 100 + 8 = 335
Pangdo	214 + 219 + 13 = 446	211 + 176 + 10 = 397	226 + 106 + 9 = 341
Yangbajing	245 + 198 + 56 = 499	300 + 154 + 67 = 521	319 + 87 + 68 = 474

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Table 7. Values of ice-melt, snow-melt water release on glacier surfaces and non-glacierized areas of the subbasins for the presented gauges in the LRB in mm.

Gauge	1971–2000	2011–2040 (A1B)	2051–2080 (A1B)
Outlet	12/6/171	10/5/134	10/3/81
Lhasa	9/4/180	6/4/242	5/2/87
Tangga	11/5/203	10/4/161	8/3/97
Pangdo	13/6/213	10/6/170	9/3/103
Yangbajing	56/30/168	67/30/124	68/18/69

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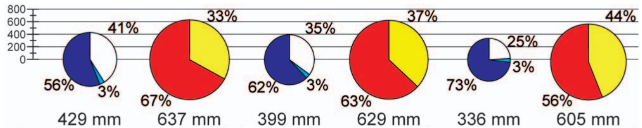
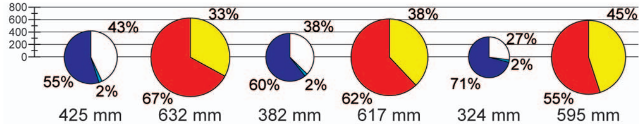
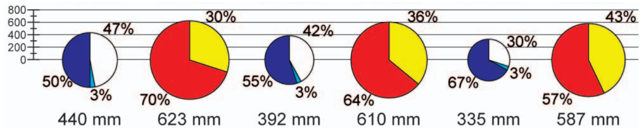
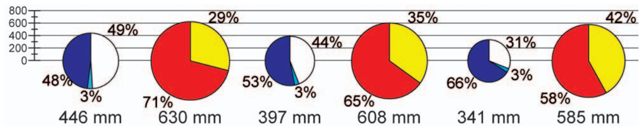
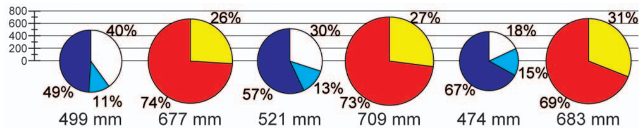
Table 8. Fraction of past and future water balance components. Right circles show the water balance components evapotranspiration (yellow) and runoff (red); left circles show runoff components rainfall (blue), snow-melt (white) and ice-melt (cyan); the diameter of the circles reflects the magnitude of runoff (bluish, left) and precipitation plus ice-storage changes (yellow/red, right) in the watersheds represented by the gauges in column 1 (see Fig. 1). The detailed water balance components can be found in the Tables 5, 6 and 7.

Gauge	Area (km^2)	Glacierization (1970) (%)	Water Quantity (mm)	1971–2000 Runoff Generation	1971–2000 Water Balance	2011–2040 (A1B) Runoff Generation	2011–2040 (A1B) Water Balance	2051–2080 (A1B) Runoff Generation	2051–2080 (A1B) Water Balance
Outlet	32 798	2.0							
Lhasa	26 339	1.3							
Tangga	20 195	1.7							
Pangdo	16 496	2.0							
Yang-bajing	2719	11.5							

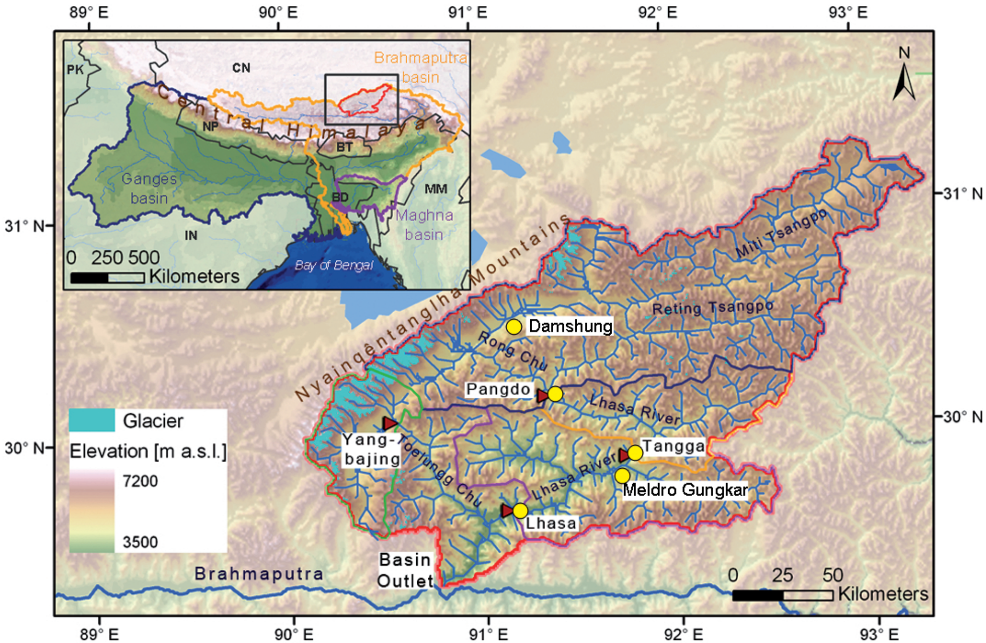


Fig. 1. Location of the Lhasa River basin in the Central Himalaya and basin characteristics. The runoff gauges and the sub-basins analyzed in detail are marked with red triangles, the meteorological stations are marked with yellow circles.

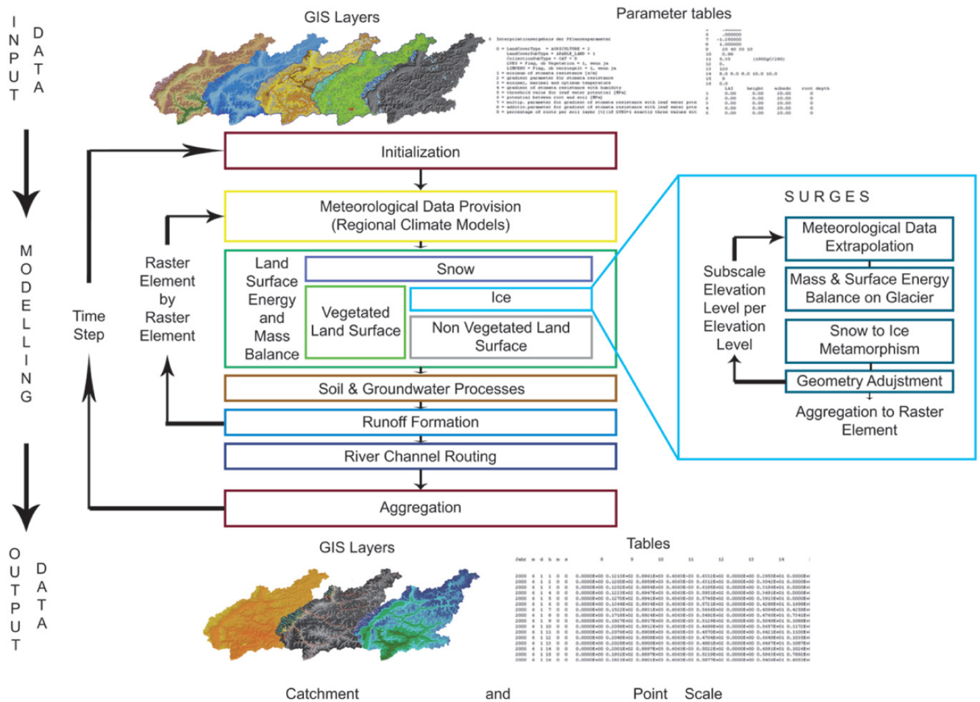


Fig. 2. Modeling approach. Scheme of implementation of the glacier model SURGES into PROMET, describing the spatial and temporal modeling cycle through the model components.

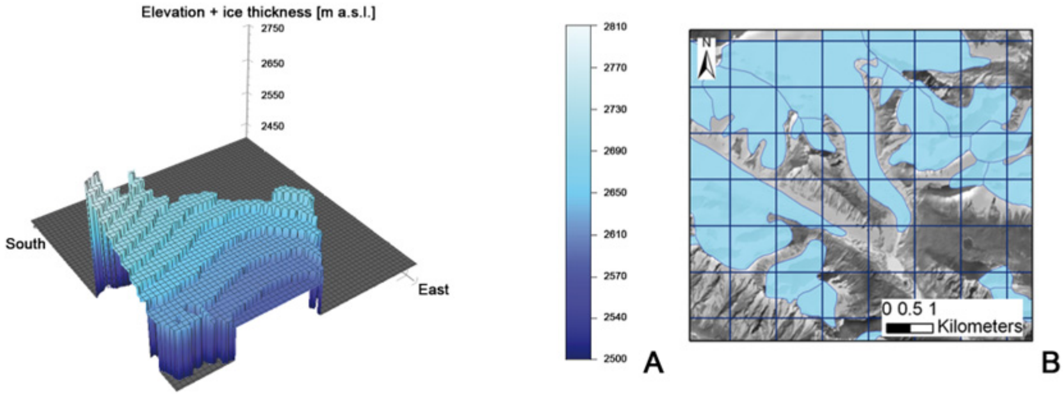


Fig. 3. Approximation of area-elevation distribution of a glacier by SURGES for one raster element **(A)** and elevation levels of a glacier covering several raster elements **(B)**.

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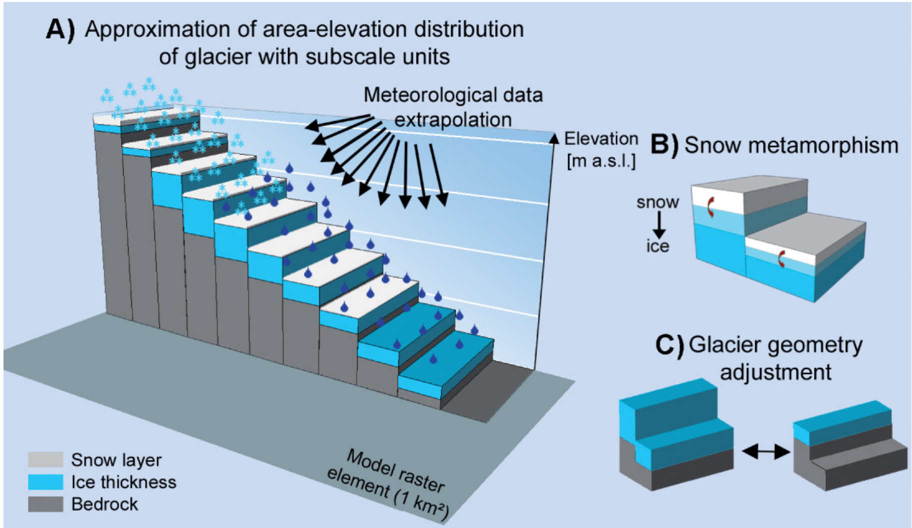

Fig. 4. Scheme of subscale approach of the glacier model SURGES.

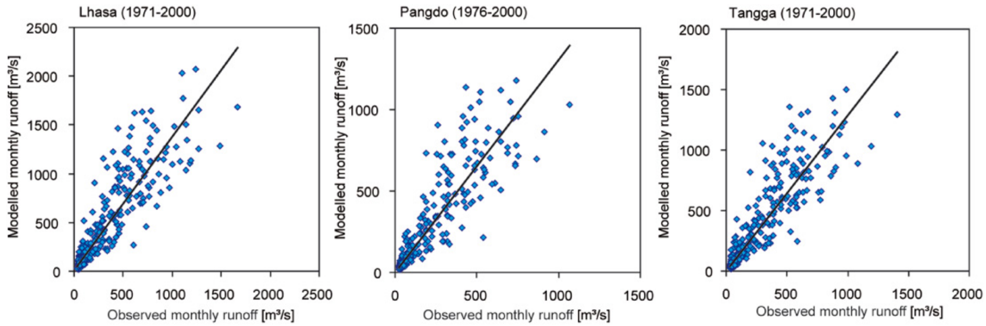

Fig. 5. Comparison of observed and modeled monthly runoff.

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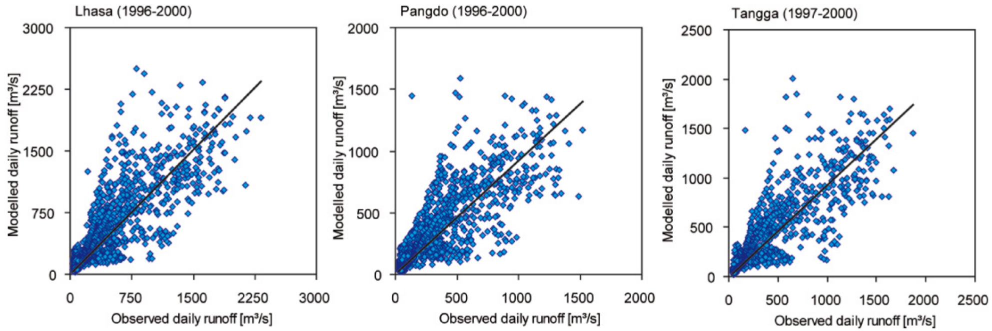

Fig. 6. Comparison of observed and modeled daily runoff.

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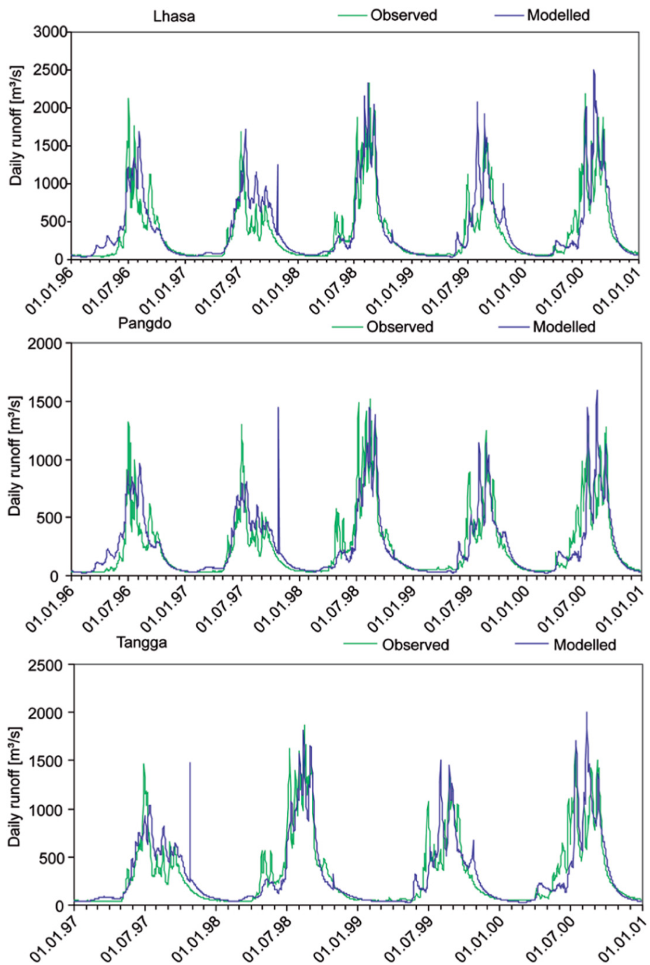

Fig. 7. Development of daily observed and modeled runoff.

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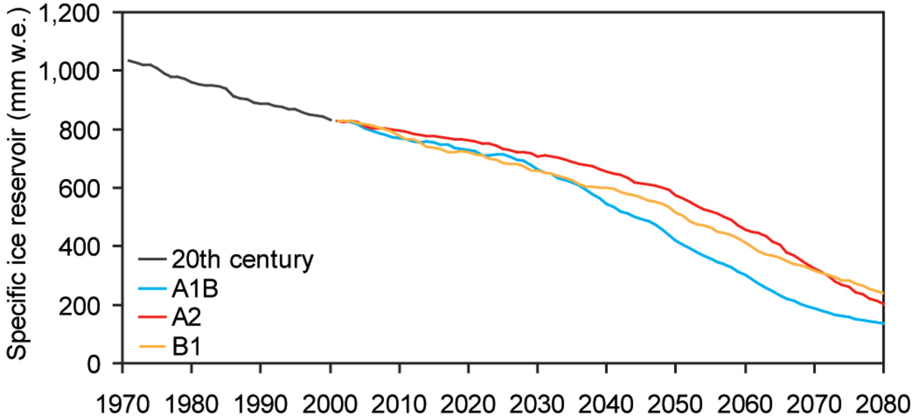

Fig. 8. Modeled development of the specific ice reservoir in the LRB from 1970 to 2080. The evolution is shown for the past (1970–2000) and for the IPCC SRES-A1B, -A2 and -B1 emission scenarios15 (2000–2080).

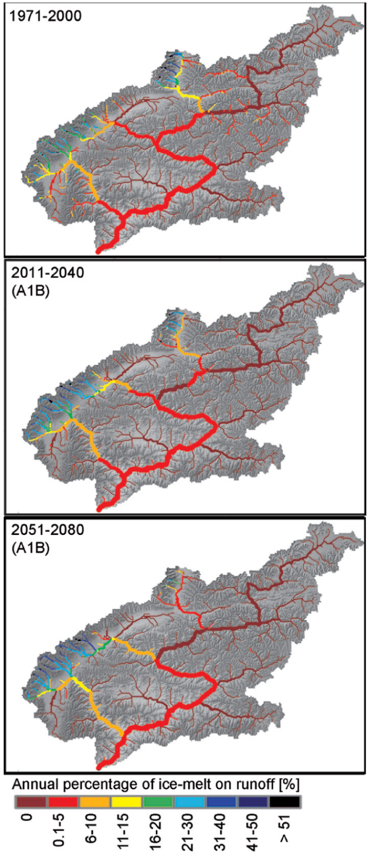

Fig. 9. Mean annual runoff fraction of ice-melt throughout the river network. Colored rivers contain ice-melt water; no ice-melt contributes to runoff of brown rivers. The percentage is shown for rivers with average runoff above 0.5 $m^3 s^{-1}$ for the past (1971 to 2000) and the future SRES-A1B scenario periods (2011–2040 and 2051–2080); river width symbolizes runoff quantity between 0.5 and 450 $m^3 s^{-1}$.

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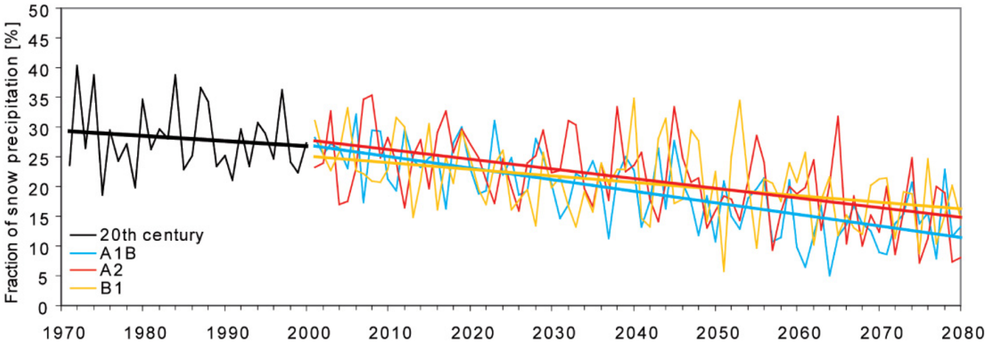

Fig. 10. Modeled development of the fraction of snow precipitation in the LRB.

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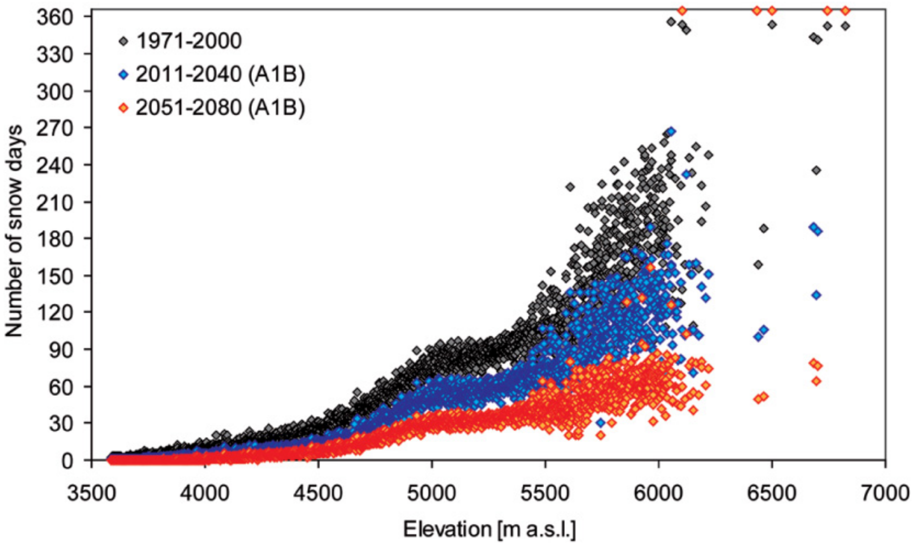

Fig. 11. Modeled number of snow days at different altitudes in the LRB.

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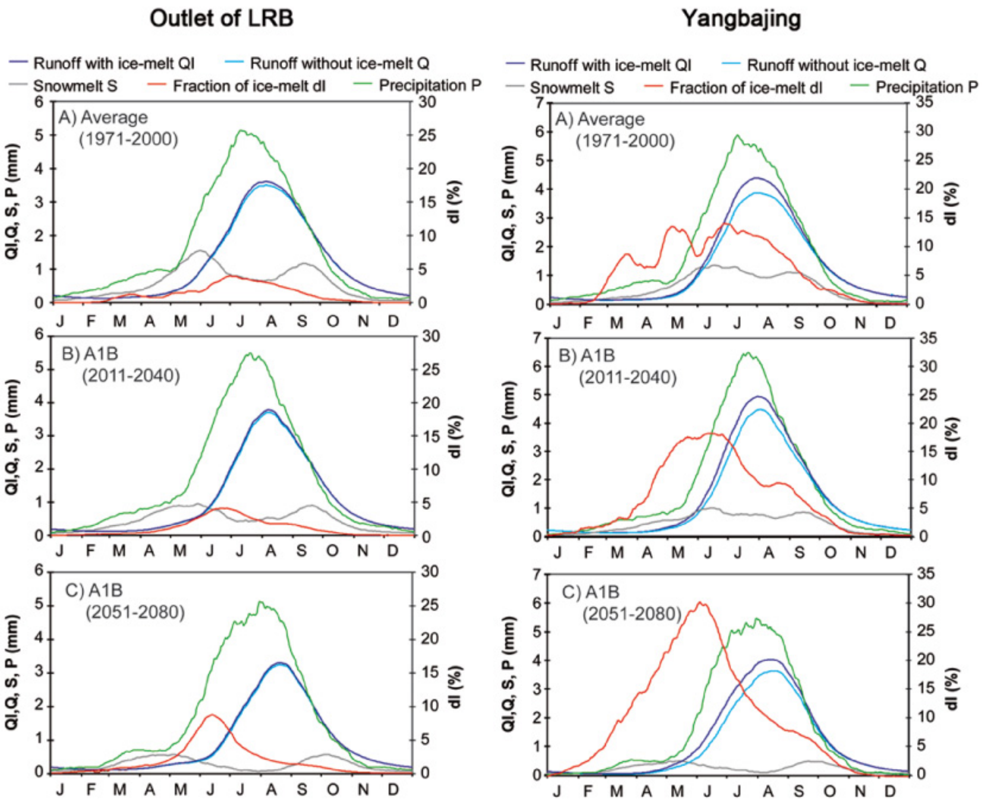

Fig. 12. Average annual dynamics of daily different runoff components at the outlet of the LRB (left) and at Yangbajing (right) (moving average over 30 days); river runoff with (blue) and without (cyan) ice-melt (left y-axis) together with snow-melt water release of the basin (grey, left y-axis), precipitation (green, left y-axis) and fraction of ice-melt (red, right y-axis) for the periods 1971–2000 **(A)**, 2011–2040 **(B)** and 2051–2080 **(C)** are shown.