Response to interactive comment on „Quantifying present and future glacier melt-water contribution to runoff in a Central Himalayan river basin“ by M. Prasch et al.

M. Prasch, W. Mauser and M. Weber

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Dear Referee,

Thank you very much for your detailed revision of our manuscript, which helped to improve our manuscript. In the following you can find our answers to your comments.

Monika Prasch, Wolfram Mauser and Markus Weber

General comments

The authors present the application of a hydrological model (PROMET) coupled with an energy balance glacier model (SURGES) to the Lhasa River Basin (32’000 km2) in the Central Himalaya. The model system is further coupled with the scaling tool SCALMET which provides the statistical downscaling of RCM inputs (45km x 45km scale) to the scale of the hydrological simulations (1km x 1km). RCM climate inputs are used to force the model, for both the validation period (1970- 2000) and for future simulations (until 2080).

The application of glacio-hydrological models to high elevation catchments in the Himalaya is a difficult exercise because of notorious data scarcity. The author’s strategy to minimize data requirements is to use a “process-oriented” modeling approach, which relies on “globally valid parameterizations”. The climate input downscaling technique relies on “physical and statistical approaches” which are “completely general and can be applied without any further parameterization in various regions”.

The intention to simulate present and future glacier melt water contribution to runoff in a large Himalayan watershed with a physically-oriented model is well-founded and certainly the Himalayas are in bad need for such studies. However, the applicability of the model system used by Prasch et al. to the study catchment is questionable for the following reasons:

a) The performance of the model is poorly validated: the lumped response of the catchment is assessed by comparing simulated with observed runoff at three locations, where streamflow is systematically overestimated. The Nash-Sutcliffe values are very low (Table 2). Which model components are responsible for the bias? Except for a 30yr mean value of glacier area and mass change which is compared to literature values the authors do not validate internal processes representation.

In this paper, the model validation focuses on the application in the LRB which is restricted by the availability of observations. However, precipitation and air temperature as meteorological input data, glacier development and runoff is validated in the LRB as far as validation data are available (Section

4). For further clarification, the validation section is enlarged (Section 4.3) and supplementary material is provided (see also answer to general comment 4 and detailed comment 31). Besides the validation in the LRB presented in this paper, the model components have been validated in the Upper Danube River Basin where data are available as referenced (p. 4567, l. 4ff). The validation of model components of PROMET is shown in Mauser and Bach (2009).

The validation of modeled runoff shows an overestimation during the summer months, but this overestimation (see also answer to detailed comment 34) changes during the validation period from 1971 to 2000. While it is large in the 70ies and 80ies, it is clearly reduced in the 90ies. The reason for the change can be found in the input data of the amount of precipitation which is then also in better accordance with the observations as shown in the Table below.

Furthermore, it should be taken into account that the model algorithms are based on fundamental physics without calibration to measured runoff, and RCM outputs in an hourly resolution are used as meteorological drivers, reducing the NSC or R^2. Nevertheless, in our opinion, the results in the LRB are satisfying, particularly for the last decade in a daily resolution (Fig. 7, Table 3).

Table S2: Quality criteria for modeled monthly runoff R and precipitation data P, driven by CLM ERA 40 meteorological data.

Period	Criterion	Lhasa		Pangdo		Tangga	
		R	P	R	P	R	P
1971 – 1980	R^2	0.84	0.72	-	-	0.85	0.75
	NSC	0.22	0.46	-	-	0.47	0.71
1981 – 1990	R^2	0.79	0.61	0.79	0.64	0.79	0.69
	NSC	0.14	0.17	0.22	0.51	0.33	0.69
1991 – 2000	R^2	0.79	0.71	0.78	0.75	0.80	0.76
	NSC	0.49	0.50	0.56	0.73	0.61	0.76
1996 – 2000	R^2	0.88	0.78	0.87	0.79	0.89	0.78
	NSC	0.85	0.70	0.86	0.79	0.88	0.77
1971 – 2000	R^2	0.80	0.68	0.78	0.72	0.81	0.73
	NSC	0.31	0.39	0.39	0.66	0.48	0.72

This table is included in the Supplements (Table S2).

The following text is added in the revised paper version in Section 4.3 (revised version P13, L22):

The validation of modeled runoff shows an overestimation during the summer months, but this overestimation changes during the validation period from 1971 to 2000. While it is large in the 70ies and 80ies, it is clearly reduced in the 90ies. The reason for the change can be found in the input of the amount of precipitation which is then also in better accordance with the observations as shown in the Supplementary Table S2.

Detailed observation data are required for validation of the processes on glaciers, which are generally rare. Additionally, the model results must not be affected by errors in the input data. Consequently, the significant boundary conditions such as topography and atmosphere must be as reliable as possible. For this reason, SURGES is applied to locations which fulfill these requirements to validate local accumulation and ablation in detail. Since neither detailed meteorological station recordings nor glacier observations are available in the Lhasa River basin, SURGES was validated for instance at the

Schneeferner at the Zugspitze in Germany, the Vernagt Ferner in Austria and the gauge of Huben of the Ötztaler Ache in Austria. Results are included in the Supplementary Material (p. 10f). Since the model components are process-oriented and based on physical principles, they can be applied in other regions, which is confirmed by the reproduction of the conditions in the LRB as far as data availability allows validation. Although glacier area and mass balance validation is very limited by the available data, the glacier development of the past is in an sufficient accordance with observations (Section 4.2).

b) It is not clear how the authors justify that the parameterizations are "globally valid". PROMET, SURGES and SCALMET apparently have been developed for central Europe, for the GLOWA-Danube project (L5, p. 4567). The term "parameterizations" implies already that the models are not completely physically-based and that therefore the models might have to be recalibrated for a different setting, especially as climate and morphology are completely differing in the Himalaya from the Alps.

PROMET, SCALMET and SURGES have been developed for central Europe, but they are process-oriented models based on physical principles. In the models, we use universal constants which are globally valid, e.g. the Stefan-Boltzmann constant for the calculation of the incoming longwave radiation balance as follows:

$Q_l = R_{li} - \sigma \cdot \varepsilon \cdot T_S^4$ *with Rli = incoming longwave radiation, σ=Stefan Boltzmann constant, ε = emissivity of snow (1) and ice (0,98) and TS = surface temperature.*

Furthermore, universal algorithms for process descriptions are applied, which allow the consideration of local conditions, where required, e.g. the calculation of the absorption of shortwave radiation with the albedo, determined as described in answer to detailed comment 24. Both, the constants and the algorithms are not changed between the model applications in river basins, e.g. the Upper Danube or the Lhasa River basin, so that they are universal, although they enable the modification of parameters to local conditions. Additionally, the parameters are invariant in space and time across the whole basin.

In the revised paper version, the parameterizations are described in detail (see answers to detailed comments 12, 14, 20, 21, 29, 49). Additionally, the validation of the model performance in Section 4 in the LRB shows that the conditions in the Central Himalaya can be reproduced by the models, and we changed the wording to "… uses universal constants and universal algorithms, which are invariant in space and time throughout the basin." (revised version P10, L23).

c) The authors do not specify the particular characteristics of the study region, in comparison to other study regions, where the model system has been applied with identical parameterizations, and how these particular characteristics are taken into account (this goes in a line with what is said in the previous point).

The characteristics of the study region are explained in Section 2. The differences of the conditions of the LRB and the Alps are not discussed, because, as explained in the previous point, the models are process-oriented and the algorithms for the parameterizations are neither changed between the *model application in the river basins nor during run-time nor between past, present or future climate conditions with the exception of local differences, e.g. relief. Therefore the differences are not relevant in the model application, but they are considered with the different input data (see also answer to detailed comment 12). Additionally, this paper focuses on the LRB and model performance also is shown for the LRB. For clarification, further model details and validation steps are included in the revised paper version (for details see answers to general and detailed comments).*

d) The authors do not mention all the relevant details of the models they are using: what are the parameters, the variables and the input data they are using. The authors also do not provide sufficient references for their models or they provide circular references to publications of their own in non ISI listed journals, to publications which are under review or to conference proceedings.

The model descriptions of PROMET and SCALMET are brief, because current model details are given in the referenced ISI – papers (Mauser and Bach, 2009; Marke et al., 2011a,b) and should in our opinion not be repeated here again (For further details of the development and application of PROMET see answer to general comment two). SURGES and SCALMET were specifically developed for the application under future climate conditions and are relatively new, so that all relevant references to the models are provided independent of the number of references.

SURGES was specifically developed to calculate the processes determining melt-water generation of numerous mountain glaciers in a large river basin simultaneously, but in considering the different characteristics of each glacier surface with its area-elevation distribution on each grid element. Such a subscale parameterization of the topography was used because the processes on mountain glaciers depend highly on altitude. Model details are given in this paper. More details are added for clarification as Supplementary Material (see answers to detailed comments 6 - 26).

See also answers to general comment 2 and detailed comments 6-26.

Considering these points, the author's choice not to calibrate the model ("in order to be applicable also for changing future watershed conditions or climates" P. 4569, L3), is not convincing. The model performance is at least questionable for the present, and therefore any conclusions based on future projections might be misleading. Given the insufficient validation of the model for the present and the uncertainties about the performance of the model in general, the present study is not suitable for publication in The Cryosphere. The authors should first validate their model in the Himalaya for the present, providing a detailed description of the models they are using and of all "completely general physical and statistical approaches" which justify the application of the model system to the Central Himalaya without recalibration. Only then the model system can be used for future projections.

The model is not calibrated to measured runoff and the parameterizations are invariant in space and time across the whole basin, which is a requirement for the application under future climate conditions, because it is not clear if the model calibration is valid under changed climatic conditions. Models of this category require a broad range of input data and are therefore rarely applied in remote regions, although they can be transferred to other regions because of not requiring a calibration. Moreover, the quality criteria are lower than for calibrated models. Nevertheless, as *shown in the validation section (which is, together with the model description, extended in the revised version and the supplements – see comments to previous points), the presented model approach can reproduce conditions of the past in the LRB. Although improvements of the approach are intended for future work, e.g. ice-flow, this paper presents a successful study to apply complex models, capturing hydrological relevant processes on the glacier as well as the complete runoff generation considering processes in plants or soil and using RCM outputs with air temperature, precipitation, radiation, humidity and wind velocity as meteorological input data.*

Therefore, the study shows a way of the application of such a model system in a remote region under past and future climate conditions. The analysis of the ice-melt contribution among the other water balance components and the spatial distribution of the fraction of ice-melt on streamflow along the river network are new and provide new insights, particularly under the consideration of the present climate change discussions in the Himalayas. Accordingly, it is of interest and should be published.

The following, detailed answers to the general and detailed comments and the consequent changes of the manuscript in the revised version hopefully further clarify the raised issues.

Further major comments

1. The state of the art for physically-based or satellite-based glacio-hydrological modeling in the Himalaya or other data scarce regions is not sufficiently presented (e.g. Bookhagen and Burbank, 2010, Immerzeel et al., 2012, Pellicciotti et al., 2012).

Thank you. We implemented additional references in the revised introduction as follows:

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 (Jansson et al., 2003, 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 (Baraer et al., 2012, Barnett et al., 2005, Bookhagen and Burbank, 2010, Collins and Tayler, 1990, Cruz et al., 2007, Huss et al., 2008, Huss, 2011, Moore et al., 2009, Pellicciotti et al., 2012). 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 (Barnett et al., 2005, Casassa et al., 2009, Cruz et al., 2007, 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 (Bolch et al., 2012, Immerzeel et al., 2010, 2012, Kaser et al., 2010, Kääb et al., 2012, Pellicciotti et al., 2012, Rees and Collins, 2006, Thayyen and Gergan, 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), at almost continental scales (Bookhagen and Burbank, 2010, Immerzeel et al., 2010) or at small scales (Immerzeel et al., 2012). Some results are limited to present climatic *conditions ((Bookhagen and Burbank, 2010, Kaser et al., 2010, Pellicciotti et al, 2012, Thayyen and Gergan, 2010). This is also the case for the important analysis of changes in runoff in relation to glacier volume and area changes (e.g. Collins and Taylor, 1990, Huss et al., 2008, Jansson et al., 2003, Moore et al., 2009) or future impacts are estimated in using a hypothetical development of climate and glaciers (e.g. Baraer et al., 2012) and no future climate model outputs. Different approaches, e.g. using the glacier mass balance to calculate glacier melt water release (e.g. Huss et al., 2008), often do not have a high temporal resolution and do not consider melt water release in the case of a balanced mass balance. Although the negative mass balance in the ablation area is balanced by the positive mass balance in the accumulation area, melt water is released in the lower parts. 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 (e.g. Collins and Taylor, 1990, Huss et al., 2008, Jansson et al., 2003, Moore et al., 2009). 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.*

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2. The model descriptions are very general and only few references are provided. For the SURGES glacier model no references are provided at all. How does this model compare to other state-of-the art models?

The model descriptions of PROMET and SCALMET are brief, because current model details are given in the referenced ISI – papers (Mauser and Bach, 2009; Marke et al., 2011a,b).

The distributed, physically based hydrologic model PROMET (Processes of Radiation, Mass and Energy Transfer) is developed as an integrative tool to model the fluxes of energy and matter (presently water, carbon, nitrogen) on the land surface. It evolved from a SVAT-scheme, which was originally developed by Mauser and Schädlich (1998) to model evapotranspiration using remote sensing data. This version of PROMET has been applied at different scales from single fields (Bach et al., 2000, 2003b) over a microscale region (100 km²) to a mesoscale catchment (100,000 km²) as well as for numerous locations and climatic conditions in a variety of studies (Strasser and Mauser, 2001, Ludwig and Mauser, 2000, Ludwig et al., 2003b, Bach et al., 2003a, Ludwig et al., 2009, Vescovi et al. 2009).

PROMET was developed to study the impact of climate change on the water cycle of large scale, complex watersheds influenced by different hydrologic regimes. It therefore has some key features: it targets at coupling with regional climate models and it avoids calibration of the model with measured runoff in order to be able to mirror different future watershed without being tied to past watershed conditions. In order to prove its applicability it was built up and tested in the Upper Danube catchment in Central Europe, which due to its size (A = 77,000 km²), complexity and data availability serves as an ideal test case for the Upper Brahmaputra. Given successful tests using historic data, PROMET is then used to simulate the change in hydrology over the next 50-80 years due to a changing climate.

PROMET has been developed and tested within the integrative research project GLOWA-Danube (Mauser and Ludwig, 2002, Ludwig et al., 2003a, GLOWA-Danube, 2011). The project focuses on the investigation of impacts of global change on the regional water resources and on the development of decision alternatives and strategies to adapt to the expected changes in climate, demography, life styles, etc. For this purpose, GLOWA-Danube integrates approaches from a broad range of natural and social science disciplines into the common decision support system DANUBIA. The processes covered by PROMET are part of DANUBIA. They should bridge the gap between the outputs of the regional climate models on the one side and the socio-economic models on the other side, which, using a multi-agent raster-based approach, simulate the water-related decisions of farmers, water suppliers, households and tourists (Mauser and Bach, 2009, p. 364). Thereby also the SCALMET tool (Marke et al., 2011a,b) and SURGES were applied (Weber et al. 2010).

Additionally, PROMET and SCALMET were applied in the Upper Brahmaputra Basin (Prasch et al., 2011b) to study the impacts of climate change on water availability within the framework of the project BRAHMATWINN (Flügel, 2011, Brahmatwinn, 2011) as described in the paper.

SURGES was specifically developed to calculate the processes determining melt-water generation of numerous mountain glaciers in a large river basin simultaneously, but in considering the different characteristics of each glacier surface with its area-elevation distribution on each grid element. Such a subscale parameterization of the topography was used because the processes on mountain glaciers *depend highly on altitude. Model details are given in this paper. More details are added for clarification as Supplementary Material (p.6f) (see answers to detailed comments 6 - 26).*

The full model chain was already applied in the Upper Danube River basin and validated in detail (Marke et al., 2011a,b, Mauser and Bach, 2009, Weber et al., 2011).

We feel that in order to properly address the issue of future changes in the snow- and ice-dynamics it is necessary and also current state-of-art to couple several complex models (climate - scaling - hydrology - glacier). In our view the attached list shows that the models used have already proved their validity in a wide range of applications.

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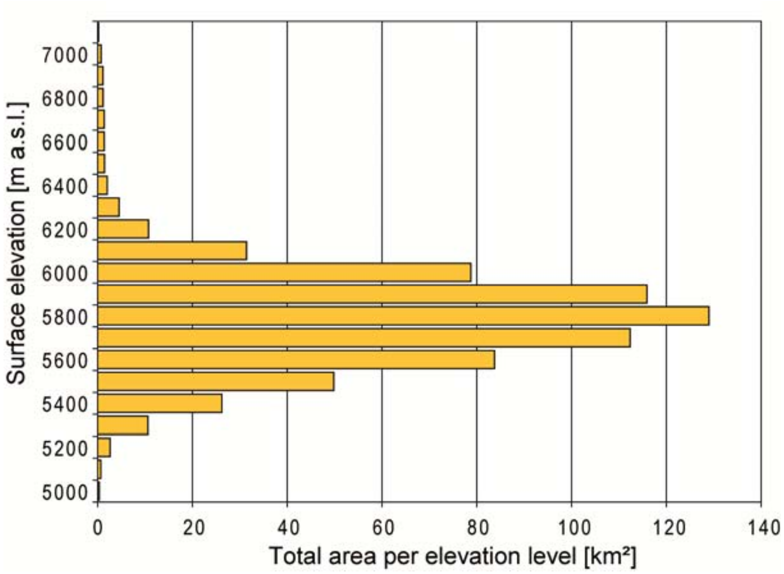
3. A static mass balance is applied in the SURGES glacier model and ice accumulates therefore endlessly above the equilibrium line altitude. For simulations over more than 100 years this might be a considerable quantity of water which is lost from the water cycle. What does this mean for model results?

SURGES considers the snow-to-ice metamorphism as explained in answer to detailed comment 3. Further processes as sublimation, evaporation and melt are taken into account, too. Accordingly, snow that accumulates at the higher elevation levels is transformed to ice and doesn't accumulate endlessly. 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 retreat goes along with a reduction of the ice flow, so an ice flow model is not explicitly implemented, but an approximation of glacier geometry changes is considered in a first step.

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). In the first case, the ice on an elevation level melts away and then the glacier area is reduced by the area of the elevation level (Fig. 4C, left to right). In the second case, snow accumulates and ice is build on an ice-free elevation level and then the glacier area is increased by the area of the elevation level (Fig. 4C, right to left). These changes are based on the calculation of the mass and energy balance and explained in the model description of SURGES.

The main implication of this approach is that in the case of large, growing glaciers, where ice flow is important for glacier geometry, cannot be modeled accurately. 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 are not growing. The caused glacier retreat is considered in a first step. Nevertheless, the loss of ice thickness in the accumulation area is underestimated and glaciers melt slightly earlier in the lower ranges in the model because of missing ice transport. This in turn leads to a smaller ablation area in the lower ranges. Thus the melt water release is slightly underestimated and the glacier's existence may be longer in simulations than in *reality. Since areas, where this takes place in the catchment are very small (see area-elevation distribution of glacier in the LRB below), the effect on the water balance is negligible. The enhancement of the model with an ice flow model is intended for future work.*

The reason to choose this approach rather than a parameterization was that "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)" (p. 4566, l. 11-15). Huss et al. (2010) proposed promising correlations between ice thickness changes and the mass balance, size and geometry of the glacier. Nevertheless, their application still requires further investigation since the approach is site specific. In a model enhancement this can also be tested before implementing an ice flow model as intended for future work as already mentioned.



Area-elevation distribution of glaciers in the Lhasa River catchment.

*Following RC 1 (***There is no glacier flow component, and the authors do acknowledge and discuss these limitations well)***, the manuscript is not changed here, but we added the following explanation for further clarification:*

P4566, L5 (revised version P9, L12) Since snow that accumulates at the higher elevation levels is transformed to ice as explained above and sublimation, evaporation and melt are taken into account, it does not accumulate endlessly, although the loss of ice thickness there is underestimated because of the missing consideration of subsidence caused by ice-flow.

See also answer to detailed comment 26.

4. How are initial ice thicknesses estimated? This is not explained in the text.

Ice thickness is determined depending on the study area and is therefore part of the input data section. The Chinese Glacier Inventory provides mean ice thickness data for the glaciers. "To consider the different ice thickness distribution of a glacier in more details than assuming a homogenous ice block, the means ice thickness is modified for all elevation levels of the glacier. Thereby a correlation between surface slope and ice thickness (Haeberli and Hoelzle, 1995), and the thinning out of the glacier to its edges and their glacier front are considered" (Prasch et al., 2011b, p. 4).

For further clarification we added the following to P 4567, L1 (revised version P11, L14):

… Inventory (…), which provides mean ice thickness for the glaciers in the LRB. The mean ice thickness is then modified considering surface slope (Haeberli and Hoelzle, 1995) and the thinning out of the glacier to its edges and front.

Haeberli, W. and M. Hoelzle: Application of inventory data for estimating characteristics of and regional climate-change effects on mountain glaciers: a pilot study with the European Alps, Ann. Glaciol., 21, 206–212, 1995.

5. One should validate SCALMET results against station data, and not the RCM outputs. RCM results are not representative on the point scale, since they reflect the mean climate of a 45km x 45km grid cell. SCALEMET results for 1km x 1km raster cells with the same elevation and aspect as the stations would be much more representative. Based on this crude comparison of RCM outputs with station data it is not possible to say which downscaled GCM performs better.

There is a misunderstanding, because in section 4.1 we show the validation of the downscaled CLM ERA40 and ECHAM 5 driven output data after the final downscaling with SCALMET. That means air temperature and precipitation, which are used as input data for our modeling approach are validated. Therefore, the deviation of the elevation of the stations and the output 1 x 1 km² grid cell are negligible. Unfortunately, our wording was misunderstanding. Our apologies.

Additionally, the validation of the seasonal course of temperature and precipitation of ERA 40 driven outputs after SCALMET is run, can be shown as follows as far as validation data are available, adding besides additional explanations, Figs. 5-7:

In the revised version section 4.1 is changed as follows:

To validate the downscaled air temperature and precipitation sums in the LRB, the recorded air temperature and precipitation at five meteorological station data (Fig. 1, Table S 1) are compared with the downscaled values after SCALMET is run. Both, CLM ERA 40 and CLM ECHAM 5 data are used as input for SCALMET in the validation, because ECHAM 5 driven SCALMET outputs, as driven by a climate model, cannot reproduce the chronology of the meteorological conditions contrary to ERA 40 data, which are based on observations. The SCALMET outputs of CLM ECHAM 5 should, however, reproduce the meteorological conditions and the climate signal. Consequently, the average values, the general seasonal course without matching single years and the trend of the data should be comparable to observed data. ERA 40 driven outputs should additionally represent the seasonal course of single years.

As shown in Table 2, the recorded air temperature is reproduced for the stations by both CLM model driven SCALMET 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 driven SCLAMET outputs, but the deviations are within 10 percent, whereas in Lhasa the overestimation reaches 22 percent. The precipitation sum is slightly underestimated for Meldro Gungkar and Tangga. In comparison to the CLM ERA 40 driven SCALMET temperature and precipitation values, the deviations seen are smaller. The comparison of CLM ERA 40 *driven SCALMET outputs with observed daily air temperatures (Fig. 5) and monthly precipitation sums (Fig. 6) show that the seasonal course can be reproduced despite deviations. The exemplarily comparison of observed and modeled monthly air temperature and precipitation of the CLM ECHAM 5 driven SCALMET outputs are illustrated for the station Lhasa in Fig. 7. The seasonal cycles are captured by the model output, with the monsoon precipitation during the summer months and the dry winters, although there are overestimations of precipitation during the pre-monsoon time in April and May, taking into account that the annual values cannot be reproduced by a climate model. The comparison of the monthly simulated and observed values also shows modeling of a reasonable range of minimum and maximum values. Two January temperatures, however (1987, 1988), are simulated at a clearly lower level than all observations. Consequently, the mean meteorological conditions are reproduced by the CLM ECHAM 5 model run, particularly when 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.*

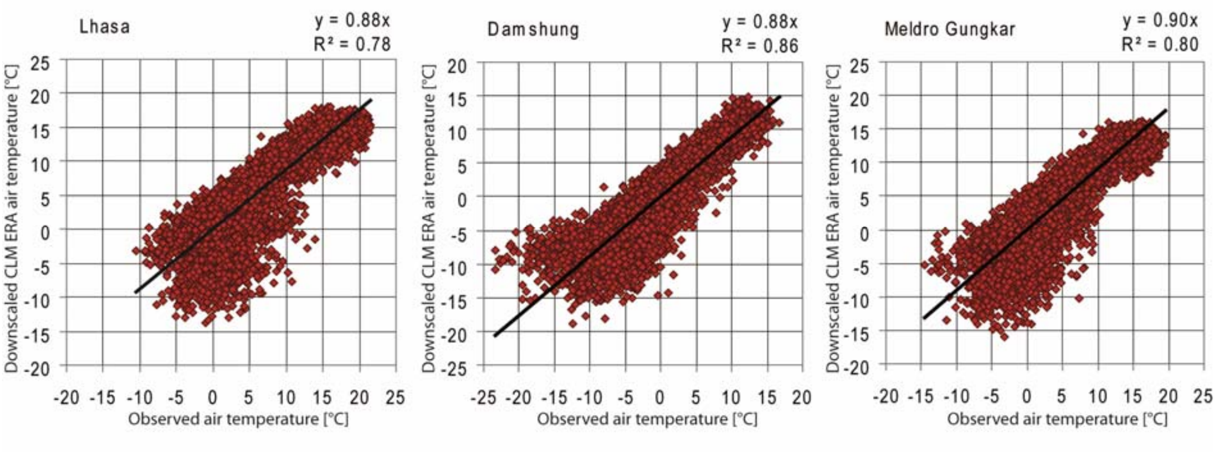


Figure 5: Comparison of modeled (CLM ERA 40 driven SCALMET outputs) and observed daily air temperatures for the Lhasa, Damshung and Meldro Gungkar stations.

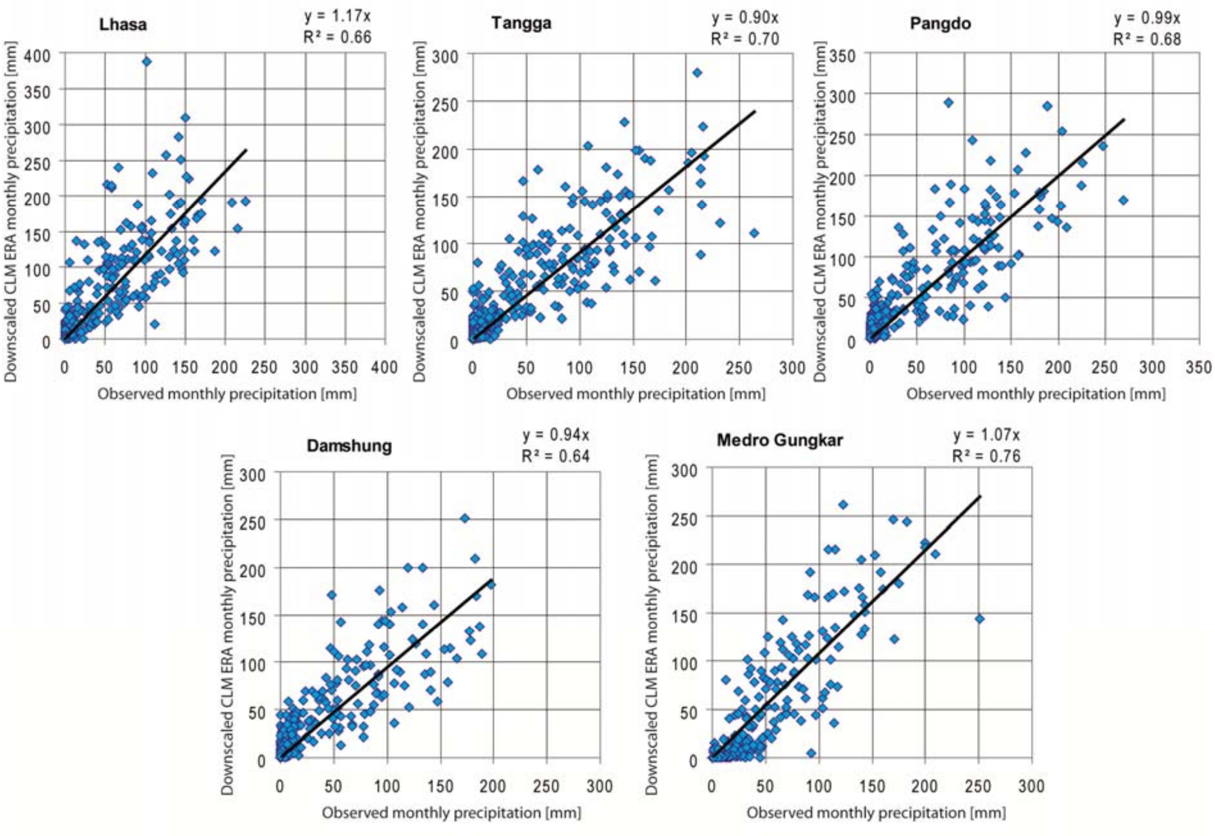


Figure 6: Comparison of modeled (CLM ERA 40 driven SCALMET outputs) and observed monthly precipitation for the Lhasa and Tangga (1971-2000), Pangdo (1976-2000) and Damshung and Meldro Gungkar stations (1980-2000).

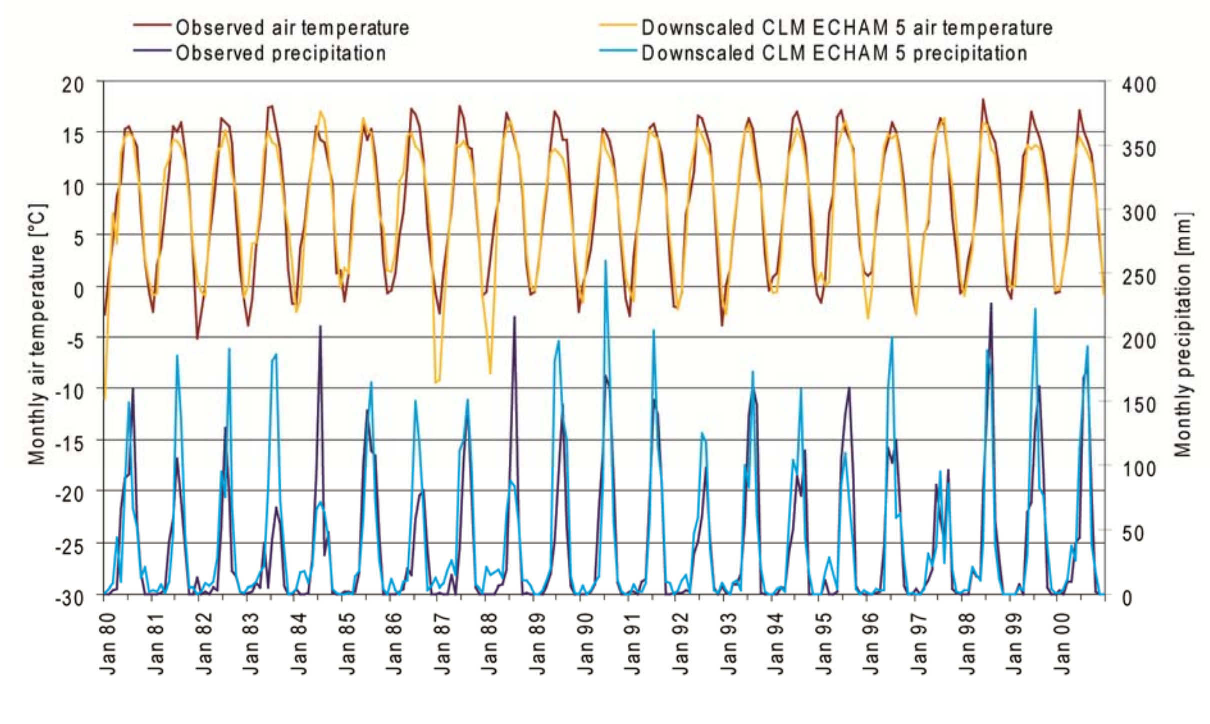


Figure7: Development of observed and modeled (CLM ECHAM 5 driven SCALMET outputs) monthly air temperature and precipitation at the Lhasa station for 1980-2000.

6. Only two GCMs are used for simulations and only ECHAM-5 is retained for the discussion of modeling results. The reason for this choice is not clear, since ECHAM- 5 was not the only model which performed well in the cited study of Kripalani et al. (2007). The application of more GCMs would allow attributing some uncertainty range to model outputs.

The authors are aware of the large uncertainties in global and regional climate modeling, which currently is subject to numerous scientific studies worldwide. Especially when looking at the South Asian monsoon not all models are capable of realistically reproducing past conditions. These models should not be used for studies of the future. CLM, driven by the coupled ocean-atmosphere GCM ECHAM 5 / MPI-OM, was chosen, because it realistically simulates the 20th century South Asian monsoon among others compared to other GCMs following Kripalani et al. (2007). Additionally, the validation of the model outputs (see section 4) showed that the conditions in the LRB are reproduced by using CLM-data as meteorological drivers for our modeling approach. In order to cover and document a range of uncertainties introduced by the assumed CO2 emissions, we applied different emission scenarios IPCC SRES-A1B, -A2 and –B1. Since the selected emission scenarios cover a large range of possible climate change, less would have been insufficient. Undoubtedly, using more RCMs and GCMs would have provided valuable further insight into the statistical behavior of the inherent uncertainties of the applied modeling chain on the model results. We feel that these studies, though important, go beyond the scope of this paper (to show the application of such a complex model chain in a remote region) and are therefore intended for future work.

7. Given the main objective of the authors to quantify the contribution of glacier meltwater to runoff at different scales, the authors should make an effort to shed more light on the effect of scale on the connection between runoff evolution and changing contribution of glacier melt. The authors present as an "astonishing" finding that the fraction of ice-melt is increasing with time, despite the reduction of glacierization. Apart from the fact that this is hardly astonishing since similar trends have been observed in the Alps (e.g. Pellicciotti et al., 2010), this finding could be put more into focus: e.g. at which scale the effect of increasing glacier contribution becomes invisible in river runoff and when is the peak runoff reached exactly?

The presented approach offers the possibility to analyze the temporal and spatial pattern of the rainfall, snow- and ice-melt contribution to river runoff under past and future climatic conditions. The resulting quantification of the contribution of glacier ice-melt water to river runoff among the other water balance components, as the main objective of this study, not only in the highly glacierized head-watersheds, but also for the downstream regions, is shown. Fig. 9 illustrates the ice-melt contribution and amount of runoff along the full river network of the LRB for past and future climate conditions. As discussed in section 5.1, in the highly glacierized headwatersheds the ice-melt fraction on runoff is high whereas with increasing watershed area and consequently increasing runoff and decreasing glacierization, the fraction is reduced. This fact is not surprising. However, this particular form of display (to show the contribution along the full river network) is new and was only presented for the UDRB by Weber et al. (2010). Moreover, this result is not a simple relation between the amount of runoff and glacierization, but it calculates in detail all the hydrological processes on the glacier and in the watershed. In this respect, evapotranspiration is particularly important and often neglected in estimating the fraction of ice-melt for larger basins outside the headwatersheds (e.g. Huss, 2011, Junghans et al., 2011). In our approach, the quality of the quantification of ice-melt *contribution is increasing downstream, because the accurate reproduction of single glaciers cannot exactly be captured with the focus on considering all processes of a heterogeneous river basin*

Based on this, the ice-melt contribution is analyzed and quantified among the other water balance components (section 5.2, Table 8) for five gauges within the basin with different glacierization. Finally, the seasonal dynamics of the components at the catchment outlet and at Yangbajing as the gauge with the highest glacierization are shown and discussed (section 5.3 and Figure 12). The focus of this paper is not to discuss different scales, but the spatial distribution and the relation to other water balance components.

This analysis is also presented for future periods. Despite continuous glacier retreat, the fraction of ice-melt hardly changes in the main rivers. The reason for this finding is explained by increasing ice melt area, which compensates reservoir reduction. As shown by the Interactive Comment to this publication, this is not obvious for everyone. In the revised version we changed the wording "astonishing" by "remarkable". Although there are publications which analyze trends in the past in the Alps with an increase in glacier runoff, followed by a reduction, (e.g. Pellicciotti et al., 2010), they do not separate snow- and ice-melt contribution to runoff contrary to our approach. As shown in Figure 9 by the spatial distribution of the ice-melt fraction on runoff along the river network, a slight increase in the contribution is triggered by the ice reservoirs of the glaciers and the glacierized area. Therefore, both, in the Toelung and Rong Chu this effect can be seen despite different catchment areas (Figure 9C). The ice reservoir also determines the peak of the contribution and cannot be generalized. However, Figure 12 shows a maximum contribution as fraction but not in the total amount in mm in the last future period during spring and summer contrary to examples in the Alps (Weber et al., 2010), because the glaciers can be found until altitudes of 7000 m a.s.l., so that the melt out is not yet reached in the scenario period until 2080. Nevertheless, the amount of runoff is reduced. Reasons for the reduction are explained in section 5.2, 5.3 and by Table 8 (reduced snow cover, increase in evapotranspiration).

For further clarification we changed Figure 12 (now Fig. 16) with uniform the sales at the y-axis for the outlet and Yangbajing. Additionally, we included a Supplementary Figure S2, which shows the seasonal course of runoff, precipitation, snowmelt release in the catchment, ice-melt and evapotranspiration for the three climate periods (1971-2000, 2011-2040, 2051-2080) each in one plot, and changed descriptions in Sections 5.1 and 5.3 as follows (see also answers to detailed comments 39, 40 and 45):

Section 5.3:

"The annual runoff course at the basin outlet in a daily resolution (Fig. 16, left, Fig. S2, 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. 16a, left, Fig. S2D). 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 (see Sect. 2) 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. 13, 16, S2). 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; Figs. 16b,c, S2). The main difference compared to the past is a clear decrease of the melt-water contribution from snow during summer and an increase in evapotranspiration. Increasing temperatures at all altitudes sharply reduce the amount of snowfall (Figs. 14, 15). 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. Together with the glacier retreat the ice-melt contribution during summer becomes lower in the scenario periods. Consequently, runoff is reduced, mainly caused by changes in the amount of precipitation. Additionally the reduction of snow-melt and increasing evaotranspiration forces the runoff reduction during early summer, particularly for the period from 2051 to 2080 (Figs. 16, S2).

These processes are basically similar for the sub-basin of Yangbajing with larger glacierization and accordingly larger ice-melt contribution to runoff (Figs. 16, right, S2, right). Although the amount of ice-melt increases in future periods not only in spring as described above (Sects. 5.1, 5.2), but also in early summer, runoff is reduced during these months taking into account the increase in precipitation in the second scenario period. Only in May the increasing ice-melt up to 30% can augment the missing snow-melt and reduced precipitation, whereas during the summer months, this effect is negligible. Again, the strong decrease of snow-melt and increase of evapotranspiration are the reasons despite higher altitudes and larger ice reservoirs with the described compensational effect (Sect. 5.1).”

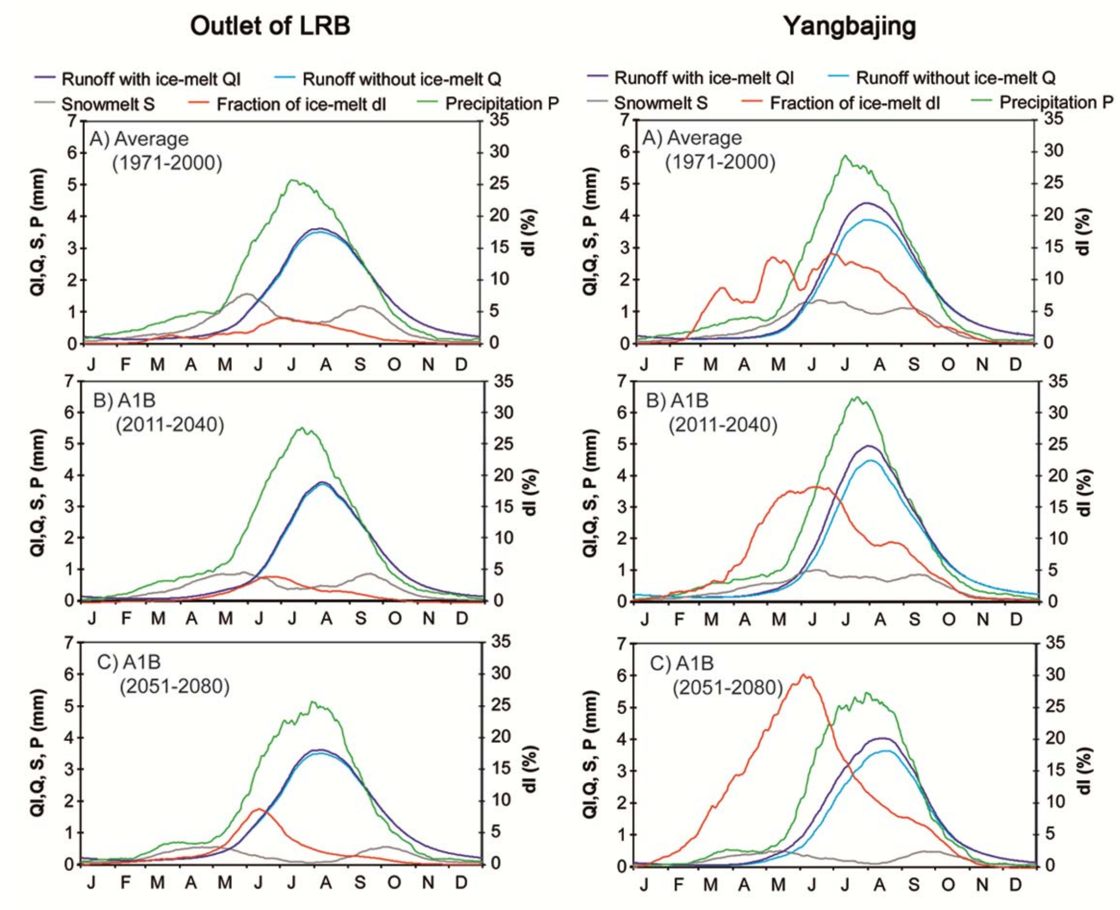


Figure 12 (now 16): Average annual dynamics of daily different runoff components at the outlet of the LRB (left) and at Yangbajing (right) (moving average over 30 days); river runoff with (blue) and without (cyan) ice-melt (left y-axis) together with snow-melt water release of the basin (grey, left y-axis), 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 (see also Supplementary Fig. S 2).

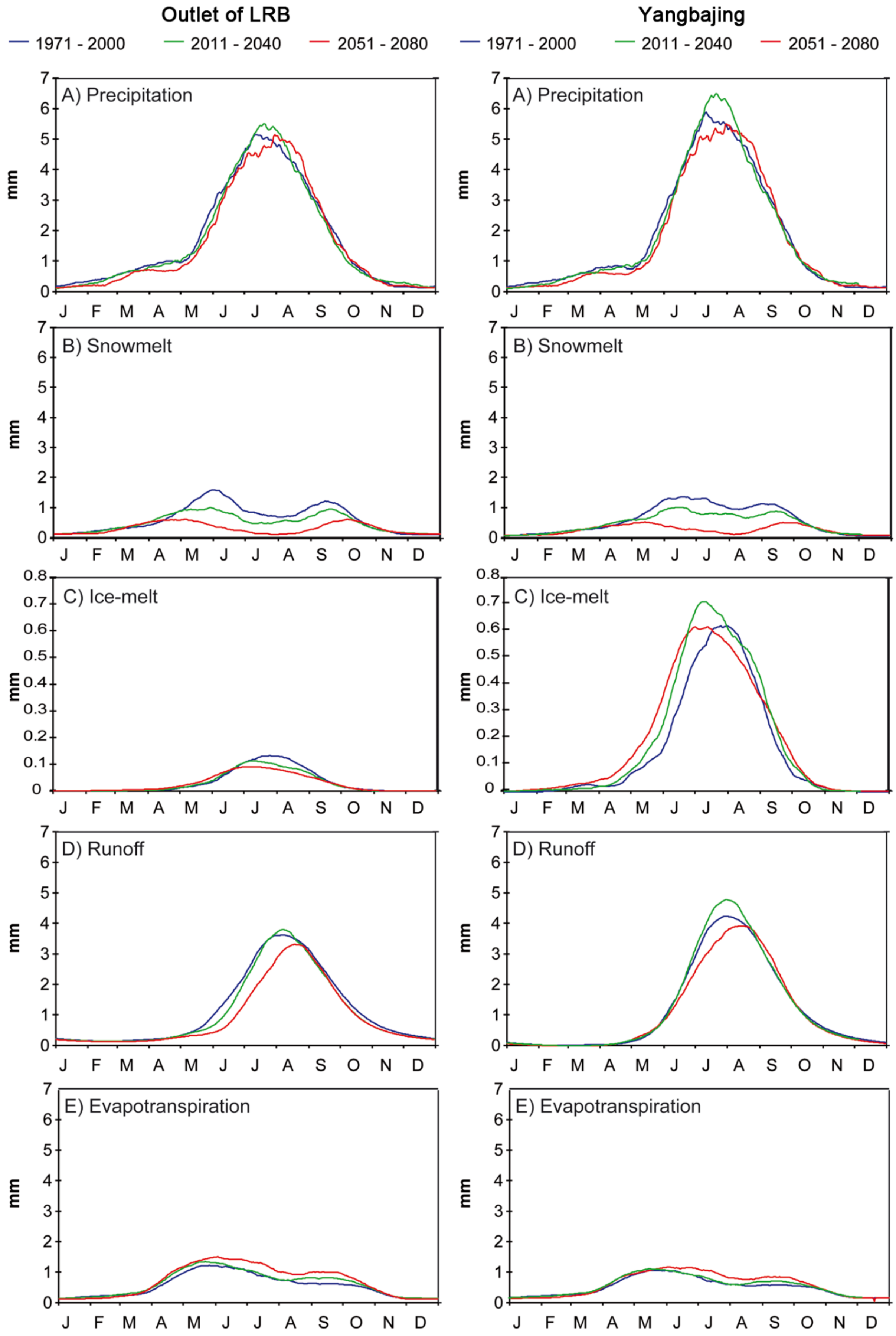

Outlet of LRB
Yangbajing
1971 - 2000
2011 - 2040
2051 - 2080
A) Precipitation
B) Snowmelt
C) Ice-melt
D) Runoff
E) Evapotranspiration
mm
0
1
2
3
4
5
6
7
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
J
F
M
A
M
J
J
A
S
O
N
D

Figure S2: Average annual dynamics of daily different runoff components at the outlet of the LRB (left) and at Yangbajing (right) (moving average over 30 days); precipitation (A), snow-melt water release of the basin (B), ice-melt (C), river runoff (D), and evapotranspiration (E) for the periods 1971-2000 (blue), 2011-2040 (green) and 2051-2080 (red) are shown.

The annual runoff for different gauges in the three periods is shown in Table 8 (now Table 5) and already discussed in section 5.2. The following description is added in Section 5.1 for further clarification (P4570, L7 (P15, L31)):

5.1: "… Despite the continuous future reduction of glacierization (Fig. 12, Supplementary Fig. S1), 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, similar to trends analyzed for the Alps (Pellicciotti et al., 2010). In depth analysis of this remarkable 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. This altitudinal shift extends the snow-free period by two to three months (Figs. 14 and 15) and thereby increases ice-melt per area and year. Since this shift is proceeding continuously, similar to glacier retreat, the simulated changes of the snow-free glacier area, decisive for ice-melt, are small despite the shrinking overall areal extent of the glaciers. 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. "

Huss, M.: Present and future contribution of glacier storage change to runoff from macroscale drainage basins in Europe, Water Resour. Res., 47, W07511, doi:10.1029/2010WR010299, 2011.

Pellicciotti, F., Bauder, A., and Parola, M.: Effect of glaciers on streamflow trends in the Swiss Alps, Water Resour. Res., 46, W10522, doi: 10.1029/2009WR009039, 2010.

Junghans, N., Culham, J., and Huss, M.: Evalulating the effect of snow and ice melt in an Alpine headwater catchment and further downstream in the River Rhine, Hydrolog. Sci. J., 981-993, doi: 10.1080/02626667.2011.595372, 2011.

8. Is supraglacial debris taken into account? This important characteristic of many Himalayan glaciers (e.g. Scherler et al., 2011) and the corresponding effect on glacier melt is not mentioned in the paper.

Supraglacial debris is not taken into account. We totally agree that this is an important characteristic of many Himalayan glaciers, but it is almost absent in the LRB, which is located on the Tibetan Plateau. This is in accordance to the analysis of Scherler et al. (2011). Therefore it has been excluded in the modeling.

Scherler, D., Bookhagen, B. and Strecker, M. R.: Spatially variable response of Himalayan glaciers to climate change affected by debris cover. Nature Geoscience, 4, 156 - 159, DOI 10.1038/NGEO1068, 2011.

Detailed comments

In the following, numbers of pages and lines refer to the TC manuscript; in parenthesis it is referred to pages and lines of the revised version:

1. Abstract, L9: Mention here already which is the study catchment

P4558, L7 (P1, L15): The Abstract is changed as follows: 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 the Central Himalayan Lhasa River basin despite scarce data availability.

2. P. 4559, L9: Some key references are missing: Bolch et al. 2012, Kääb et al. 2012

Thank you. They are implemented

P. 4559, L9 *(P2, L16): (Bolch et al., 2012, Immerzeel et al., 2010, 2012, Kaser et al., 2010, Kääb et al., 2012, Pellicciotti et al., 2012, Rees and Collins, 2006, Thayyen and Gergan, 2010)*

Bolch, T.,Kulkarni, A., Kääb, A, Huggel. C, Paul, F., Cogley, J.G., Frey, H., Kargel, J.S., Fujita, K., Scheel, M, Bajracharya, S. and Stoffel, M.: The State and Fate of Himalayan Glaciers, Science, 336, 310-314, 10.1126/science.1215828, 2012.

Kääb, A., Berthier, E., Nuth, Ch., Gardelle, J., and Arnaud, Y.: Contrasting patterns of early twenty-first-century glacier mass change in the Himalaya, Nature, 488, 495-498, 10.1038/nature11324, 2012.

3. P. 4559, L11-L15: Here you could provide some references to applications of physically-oriented glacio-hydrological on the smaller scale (e.g. Immerzeel et al., 2012).

Ok:

P4559, L11 (P2,L22): … at almost continental scales (Immerzeel et al., 2010) or at small scales (Immerzeel et al., 2012).

Immerzeel, W.W., van Beek, L.P.H., Konz, M., Shresta, A.B., and Bierkens, M.F.P.: Hydrological response to climate change in a glacierized catchment in the Himalayas, Climatic Change, 110, 721-736, DOI 10.1007/s10584-011-0143-4, 2012.

4. P. 4560, L11: What is the definition of a 'complex' headwatershed? What does 'representative glacierized' mean?

"Complex" watershed means, that the phyiso-geographic conditions are varying within the basin. In the LRB, we have varying natural conditions, ranging from the Lhasa River valley, which is agriculturally used, up to the high, glacierized mountains along the Nyainqêngtanglha Mountains.

"Representative" is not only connected to glacierized, but also to complex. We mean a river basin, which is similar to the neighbouring headwatershed of the Brahmaputra and Ganges with glacierized mountains and river valleys where people use the water, e.g. for agriculture.

For better clarification, we changed the sentence as follows:

P4560, L11 (P4, L2): The LRB was chosen as a basin, being representative for a glacierized, complex headwatershed of the Brahmaputra in High Asia with varying physio-geographic conditions. The Brahmaputra is together with…

5. P. 4560, L26: these are both no proper references.

A detailed study about glacier changes in the Lhasa River Basin is so far only published in the cited references. They provide a deeper insight of glacier changes in the LRB than the other more general studies about glacier changes on the Tibetan Plateau and therefore should not be missed in our opinion in this paper, although these references are not ISI listed.

6. P. 4561 L8-L10: the “synchronous ablation and accumulation period . . . determines the importance of glacier melt for water availability” – what does that mean?

The ablation period in summer coincides with the accumulation period during the summer monsoon season. The importance of glacier melt for water availability is determined by this coincidence, because glacier melt water is of higher importance during dry periods than during wet periods as it is the case in the LRB, when water is already available because of the monsoon precipitation.

For better clarification, the sentence is changed in the revised manuscript as follows:

P4561, L8 (P4, L27): The coincidence of the ablation period and 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, because melt water is of higher importance during dry periods and vice versa.

7. P. 4562, L2-3: Use acronyms and show the water balance as an equation, and not in the text.

Ok:

P4562, L2-3 (P5, L22): … and ice dynamics (Eq. 1):

$$Q = R + S - E + \Delta GS + \Delta SS + \Delta IS \qquad \text{Eq. (1)}$$

where Q = runoff, , R = rainfall, S = snowfall, E = evapotranspiration, ΔGS *= changes in groundwater storage,* ΔSS *= changes in snow storage, and* ΔIS *= changes in ice storage.*

8. P. 4562, L11: please specify what is meant by “subscale approach”

Ok:

P4562,L11 (P6, L1): 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. Accordingly these processes are calculated on a scale, which is finer than the applied process scale of the PROMET watershed model and parameterizes the subscale terrain using an area-elevation-ice thickness classification table (see Sect. 3.1.3).

9. P.4562, L14-L24: some of this seems obvious and can be removed from the text, e.g. that snow melt comes from both glacierized and non-glacierized cells, and that it does not make a difference for

the water balance where it comes from. It is not true however that the same physical principles are valid on- and off-glacier. Also, if this was true, why are different model parameters used on- and off-glacier? Which are the model parameters exactly that are different? How is surface roughness estimated?

Although this is obvious, snow melt from glaciers and off glaciers is often treated separately in models. Undoubtedly there is a physical influence of the glacier ice on the snow cover properties (e.g. surface temperature, boundary layer), as it exists for other surfaces as forest, residential areas, rock and many more. There are also additional processes like wind-induced, preferential distribution of snow on glaciers which is not yet considered in our approach. What we mean by "same physical principles" is that the energy balance determines the amount of snowmelt regardless of the surface below the snowcover. For details of the calculation of the energy balance including surface roughness see answer to comment 21.

This section is shortened as follows and thereby hopefully changes the misleading wording as follows:

P4562, L14 (P6, L7): 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. 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.

10. P.4562, L29: what is a "consistent" meteorological data set? Please specify.

A "consistent" meteorological data set comprises the listed meteorological values (near surface air temperature, precipitation, air humidity, wind speed, incoming short and longwave radiation in a temporal resolution of one hour) without mismatches, e.g. incoming shortwave radiation is not large in the case of precipitation, reflecting the meaning of the word "consistent". Although this should be taken for granted, it was checked because the meteorological data are extrapolated to the temporal resolution of one hour which is required for the models.

11. P. 4563, L8: The Lhasa river basin is much smaller than 100'000 km2. Does this have any implications? Are there any trade-offs in model structure (more conceptual solutions rather than being physically-based) which were accepted in order be applicable on the very large scale?

The basin area of the LRB is 32 800 km², which is smaller than 100 000 km², but there are no implications or trade-offs in the model structure depending on the basin area. Since no changes are made in the model physics, only the runtime is longer for large basins. The model can and was applied at different scales from the single field (1 ha) up to large basins, e.g. the Upper Brahmaputra River basin (A ≃ 510 000 km²) in a variety of studies (Strasser and Mauser, 2001, Ludwig and Mauser, 2000, Ludwig et al., 2003, Mauser and Bach, 2009, Prasch et al., 2011a) (see also answer to major comment 2).

Strasser, U. and Mauser, W.: Modelling the spatial and temporal variations of the water balance for the Weser catchment 1965-1994. J. Hydrol., 254, 199-214, 2001

Ludwig, R. and Mauser, W.: Modelling catchment hydrology within a GIS based SVAT-model framework, Hydrol. Earth Syst. Sci., 4, 239–249, 2000.

Ludwig, R., Mauser, W., Niemeyer, S., Colgan, A., Stolz, R., Escher-Vetter, H., Kuhn, M., Reichstein, M., Tenhunen, J., Kraus, A., Ludwig, M., Barth, M., and Hennicker, R.: Web-based modelling of energy, water and matter fluxes to support decision making in mesoscale catchments – the integrative perspective of GLOWA-Danube, Phys. Chem. Earth, 28, 621–634, 2003.

Mauser, W., and Bach, H.: PROMET – Large scale distributed hydrological modeling to study the impact of climate change on the water flows of mountain watersheds, J. Hydrol., 376, 362-377, doi:10.1016/j.hydrol.2009.07.046, 2009.

Prasch, M., Marke, T., Strasser, U., and Mauser, W.: Large scale integrated hydrological modelling of the impact of climate change on the water balance with DANUBIA, Adv. Sci. Res., 7, 61-70, doi:10.5194/asr-7-61-2011, 2011a.

12. P. 4563, L11: which are the parameterizations? Are there components which are really physically-based? For which components more conceptual solution had to be chosen?

The parameterizations and all components of the PROMET model are described in detail in Mauser and Bach (2009). The following table lists the parameters used in PROMET and the sources for the Upper Danube River basin (Mauser and Bach 2009, p. 370), for the sources for the LRB see answer to comment 29:

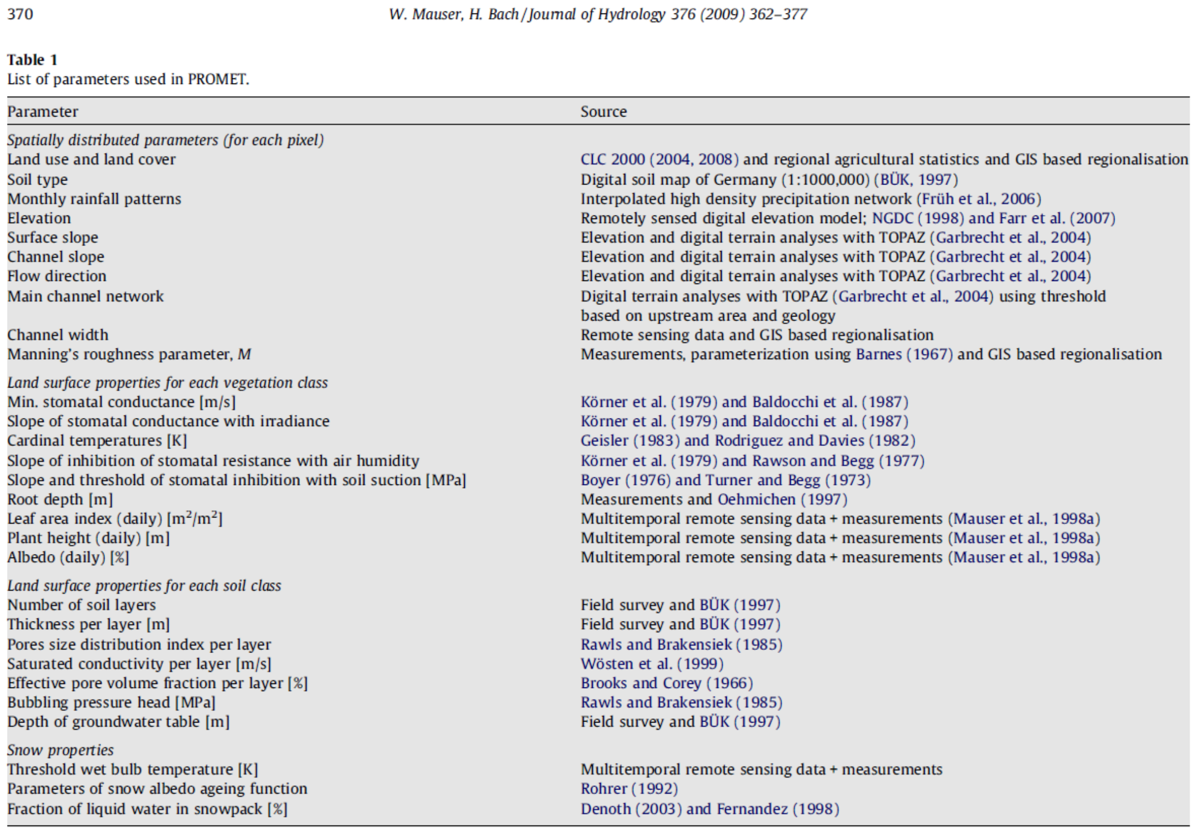


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Table 1
List of parameters used in PROMET.

Parameter	Source
Spatially distributed parameters (for each pixel)	
Land use and land cover	CLC 2000 (2004, 2008) and regional agricultural statistics and GIS based regionalisation
Soil type	Digital soil map of Germany (1:1000,000) (BÜK, 1997)
Monthly rainfall patterns	Interpolated high density precipitation network (Früh et al., 2006)
Elevation	Remotely sensed digital elevation model; NGDC (1998) and Farr et al. (2007)
Surface slope	Elevation and digital terrain analyses with TOPAZ (Garbrecht et al., 2004)
Channel slope	Elevation and digital terrain analyses with TOPAZ (Garbrecht et al., 2004)
Flow direction	Elevation and digital terrain analyses with TOPAZ (Garbrecht et al., 2004)
Main channel network	Digital terrain analyses with TOPAZ (Garbrecht et al., 2004) using threshold based on upstream area and geology
Channel width	Remote sensing data and GIS based regionalisation
Manning's roughness parameter, *M*	Measurements, parameterization using Barnes (1967) and GIS based regionalisation
Land surface properties for each vegetation class	
Min. stomatal conductance [m/s]	Körner et al. (1979) and Baldocchi et al. (1987)
Slope of stomatal conductance with irradiance	Körner et al. (1979) and Baldocchi et al. (1987)
Cardinal temperatures [K]	Geisler (1983) and Rodriguez and Davies (1982)
Slope of inhibition of stomatal resistance with air humidity	Körner et al. (1979) and Rawson and Begg (1977)
Slope and threshold of stomatal inhibition with soil suction [MPa]	Boyer (1976) and Turner and Begg (1973)
Root depth [m]	Measurements and Oehmichen (1997)
Leaf area index (daily) [m^2/m^2]	Multitemporal remote sensing data + measurements (Mauser et al., 1998a)
Plant height (daily) [m]	Multitemporal remote sensing data + measurements (Mauser et al., 1998a)
Albedo (daily) [%]	Multitemporal remote sensing data + measurements (Mauser et al., 1998a)
Land surface properties for each soil class	
Number of soil layers	Field survey and BÜK (1997)
Thickness per layer [m]	Field survey and BÜK (1997)
Pores size distribution index per layer	Rawls and Brakensiek (1985)
Saturated conductivity per layer [m/s]	Wösten et al. (1999)
Effective pore volume fraction per layer [%]	Brooks and Corey (1966)
Bubbling pressure head [MPa]	Rawls and Brakensiek (1985)
Depth of groundwater table [m]	Field survey and BÜK (1997)
Snow properties	
Threshold wet bulb temperature [K]	Multitemporal remote sensing data + measurements
Parameters of snow albedo ageing function	Rohrer (1992)
Fraction of liquid water in snowpack [%]	Denoth (2003) and Fernandez (1998)

Since the aim of this paper is not to describe the PROMET model, we refer for details to Mauser and Bach (2009). Additionally, due to the length of the paper the reproduction of already ISI- published model details is not possible.

13. P. 4564, L6: what is the temporal resolution of the RCMs?

The temporal resolution is 3 hours. We will change this sentence as follows:

P 4565, L6 (P7, L17): Since the temporal resolution of the regional climate model used in this study is three hours, a temporal…

14. P. 4564, L14: which are the "physical and statistical approaches"? Are they really "completely general"? Without further explanations this is not convincing.

In order to adequately remap RCM outputs, SCALMET uses different scaling techniques. Air temperature for example is statistically downscaled. Therefore the elevation dependency of air temperature is analysed first. Then a linear regression function is determined, which is applied and then air temperature is adjusted due to elevation. For physical downscaling submodels are implemented to downscale wind speed, incoming shortwave and longwave radiation (Liston and Elder 2006, Iziomon et al. 2003) to account for subscale heterogeneities within the remapping process. To maintain the mass and energy balance predetermined by the RCM outputs, special algorithms are integrated into SCALMET which systematically assure the conservation of mass and energy between the model scales.

For further clarification, we enlarged the SCALMET section 3.1.2 as follows. For further details, we refer to the publications of Marke et al. (2011 a,b), because the description of the SCALMET model is not the aim of this paper.

P4564, L14 (P7, L14): ... (Marke et al, 2011b). For physical downscaling, submodels are implemented to downscale wind speed, shortwave and longwave radiation (Liston and Elder, 2006, Izimon et al., 2003) to account for subscale heterogeneities within the remapping process (Marke 2008).

Liston, G. E., and Elder, K.: A Meteorological Distribution System for High-Resolution Terrestrial Modeling (MicroMet), J. Hydrometeorol.,7, 217–234, 2006.

Iziomon, M. G., Mayer, H., and Matzarakis, A.: Downward atmospheric longwave irradiance under clear and cloudy skies: Measurement and parameterization. J. Atmos. Sol-Terr. Phy., 65, 1107-1116, 2003.

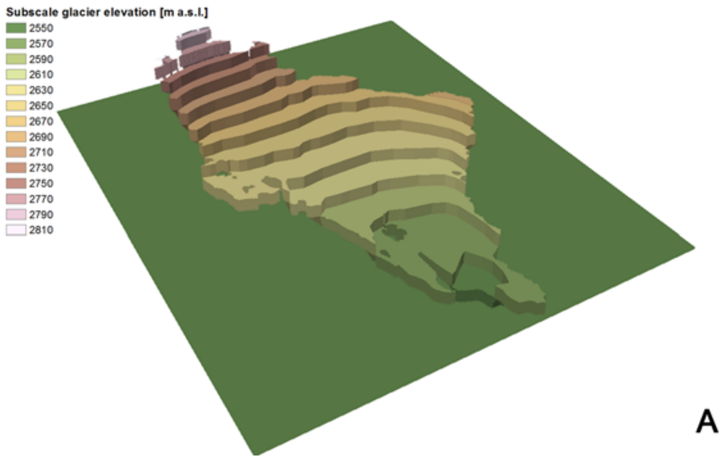
Marke, T.: Development and Application of a Model Interface to couple Regional Climate Models with Land Surface Models for Climate Change Risk Assessment in the Upper Danube Watershed, Ph.D. thesis, Ludwig-Maximilians-Universität Munich, Germany, 188pp, 2008, available at: http://edoc.ub.uni-muenchen.de/9162/.

15. P. 4564, L19: what is the resolution of the subscale units? Are they raster based or discretized in elevation belts? This is not clear from Fig. 3a.

The glaciers are subdivided in subscale units to approximate the area-elevation distribution by an elevation interval of 100 m. They are not raster based but they are divided in discrete elevation belts. In a revised version we will change this:

P 4564, L19 (P8, L3): … with subscale units (for the LRB elevation levels with intervals of 100 m are applied) (Fig. 3A) to approximate…

Additionally, Fig. 3a is improved as follows (Approximation of area-elevation distribution of a glacier by SURGES for one raster element (A)):



16. P. 4564, L19: Is it the area-elevation-distribution which is parameterized? What are the parameters? Please specify.

No, the complex terrain of mountain glaciers, where glaciers extend over an elevation range of up to 1200 m within one 1 x 1 km² grid cell in the LRB, is parameterized by the parameters elevation and area per elevation level. Additionally, for every elevation level a mean ice thickness is given.

For further clarification we changed the sentence as follows:

*P4564, L19 (P8, L4): …, SURGES uses an area-elevation-distribution with subscale units to **approximate** the complex terrain of mountain glaciers…*

17. P. 4564, L23: how are ice thicknesses calculated / estimated? This might be a crucial point for the modeling.

Ice thickness is determined depending on the study area and is therefore part of the input data section. The Chinese Glacier Inventory provides mean ice thickness data for the glaciers. "To consider the different ice thickness distribution of a glacier in more details than assuming a homogenous ice block, the means ice thickness is modified for all elevation levels of the glacier. Thereby a correlation between surface slope and ice thickness (Haeberli and Hoelzle, 1995), and the thinning out of the glacier to its edges and their glacier front are considered" (Prasch et al., 2011b, p. 4).

For further clarification we added the following to P 4567 L.1 (P12, L13):

… Inventory (…), which provides mean ice thickness for the glaciers in the LRB. The mean ice thickness is then modified considering surface slope (Haeberli and Hoelzle, 1995) and the thinning out of the glacier to its edges and front…

Haeberli, W. and M. Hoelzle: Application of inventory data for estimating characteristics of and regional climate-change effects on mountain glaciers: a pilot study with the European Alps. Ann. Glaciol., 21, 206–212, 1995.

18. P. 4564, L24-25: are all these variables provided by the RCM and downscaled by SCALMET? Mention in the previous section 3.1.2 which are the variables that are downscaled by SCALMET and how.

Yes, these meteorological variables are provided by the RCM and then downscaled by SCALMET.

In section 3.1, P.4562, L30, P4563, L1,2 the meteorological required data are listed. Additionally, we included in section 3.1.2 the following (P4564, L13 (P7, L23): In this study, the meteorological data precipitation, air temperature, air humidity, incoming shortwave and longwave radiation, air pressure and wind speed of the RCM are downscaled by SCALMET.

The description of the SCALMET model is also not the aim of this paper, so that we refer to the publication of Marke et al. (2011a,b) for further details. Additionally, due to the length of the paper the reproduction of already ISI- published model details is not possible (see also answer to detailed comment 14).

19. P. 4565, L4: this is not the correct definition of katabatic winds.

Katabatic winds are fall winds going downhill caused by differences of the density of the air. They originate from cooling of air on the top of e.g. a mountain glacier. This air becomes denser by the cooling than the air at the same elevation not on the glacier. Therefore it begins to flow downwards. Accordingly, the description of the katabatic wind on a mountain glacier in our paper is not wrong in our opinion.

For clarification, we changed the explanation as follows:

P4565, L4 (P8, L16): …, which is caused by the differences in the density of air….

20. P. 4565, L7: How are all these variables extrapolated exactly to the subscale level? Which are the parameterizations that are used and how are parameter values estimated?

For clarification, model details, describing the extrapolation of the meteorological data to the subscale levels and the calculation of the energy balance, are included in the supplementary material, p. 6 onwards.

21. P. 4565, L12-16: this section misses a detailed description of the energy balance model which is used to calculate melt. Variables, parameters and input data have to be specified.

P4565, L12-16 (P8, L28): The calculation of the energy balance is described in detail in Prasch et al. (2008). Repeating the model details would go beyond this paper, but for the sake of completeness the description is included in the supplementary material (p. 6 onwards).

22. P. 4565, L19: is there not glacier routing component, or at least a glacier reservoir which delays the injection of glacier melt (both snow and ice) into river runoff?

No. Due to the quick release of glacier melt water and the generally large amount of surface runoff in the mountains (Lambrecht and Mayer, 2009), in SURGES, the melt water of glaciers is immediately supplied to the surface runoff of PROMET. By contrast, the melt water release of snow out a glacier *surface is handled similarly to rain, and drains into the soil layers or supplies surface runoff, taking into account varying land cover characteristics (see also Supplementary Material, p.10).*

Lambrecht, A. and Mayer, Ch.: Temporal variability of the non-steady contribution from glaciers to water discharge in western Austria. J. Hydrol., 376, 353-361, 2009.

23. P. 4565, L20: what exactly is a “defined” number of ablation periods? Please specify.

In this study, the defined number is one year as described on P4565, L24 (P9, L6): “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.”

24. P. 4565, L27: how are changes in the albedo calculated?

Albedo is of great importance, because absorption of shortwave solar radiation is the most significant component of the surface energy balance under melting conditions. For snow and ice, it depends on many factors, e.g. grain size, density, impurity content, solar elevation etc. In this study, the albedo is set to 0.5 in the case of snow-free ice for the Lhasa River catchment, which is a relatively high value for glacier ice, similar to clean ice (Paterson 1994). This value was chosen because of extremely dry and clean air on the Tibetan Plateau due to its elevation and latitude. In the case of snow covering the glacier, the albedo of freshly fallen snow (0.9) decreases due to changes in grain size, density and impurity content of the snow surface. The decrement of the albedo with time of freshly fallen snow is parameterized following Rohrer (1992): $\alpha = \alpha_{min}(t) + (\alpha(t-1) - \alpha_{min})e^{-k\frac{1}{24}}$

The exponential reduction during the time interval Δt [s] since the last considerable snow fall (0.5 mm per hour) differs between air temperatures above and below freezing point, accounted for by changing recession coefficients k. For air temperatures above freezing point, k is set to 0.05 per day, whereas for air temperatures below, it is set to 0.12 per day. The decrease continues until a minimum value α_{min} *of 0.55 is reached, or until the next considerable snowfall happens. In this case it is reset to the maximum value of 0.9.*

Different values of the albedo of snow and glacier ice are considered in calculating the amount of melt-water contribution with the energy balance and therefore albedo is a key parameter. Their difference is the main cause for the larger amount of melt water from ice than from snow. In our view these differences are one (but not the only) important reason to distinguish between snow- and ice-melt water.

For further clarification we added the following information in the revised paper and the calculation of the albedo is described in the supplements (p. 8):

P4656, L26 (P9, L9)): … changes with respect to the energy balance are taken into account by the simulation of changes in the albedo, varying between 0.5 (snow free ice) and 0.9 (freshly fallen snow).

References

Paterson, W.S.B. The Physics of Glaciers. Third Edition. Butterworth-Heinemann, Oxford, 481,1994.

Rohrer, M.B. Die Schneedecke im Schweizer Alpenraum und ihre Modellierung. Züricher Geographische Schriften 49, 178, 1992.

25. P. 4565, L27 “In the case of melt water. . .” until end of paragraph: it is somewhat obvious that snow that is transformed into ice contributes to icemelt once it is melts. Consider removing or rephrasing.

Ok. We removed this sentence in the revised version.

26. P. 4566, L10-15: should be mentioned that this is a static mass balance approach. What are the implications for the modeling? In Prasch et al. 2011a a simple parameterization of ice flow is used. Simple parameterizations of glacier geometry changes are also suggested in Huss et al. 2010 or used in Immerzeel et al. 2010. What was the reason to choose a static mass balance approach rather than using a parameterization?

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). In the first case, the ice on an elevation level melts away and then the glacier area is reduced by the area of the elevation level (Fig. 4C, left to right). In the second case, snow accumulates and ice is build on an ice-free elevation level and then the glacier area is increased by the area of the elevation level (Fig. 4C, right to left). That these changes are based on the calculation of the mass and energy balance is obvious and already explained above.

The main implication of this approach is that in the case of large, growing glaciers, where ice flow is important for glacier geometry, cannot be modeled accurately. 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 are not growing. The caused glacier retreat is considered in a first step. The enhancement of the model with an ice flow model is intended for future work.

The reason to choose this approach rather than a parameterization was that “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)” (P 4566, L11-15, (P9, L23)).

Huss et al. (2010) proposed promising correlations between ice thickness changes and the mass balance, size and geometry of the glacier. Nevertheless, their application still requires further investigation since the approach is site specific. In a model enhancement this can also be tested before implementing an ice flow model as intended for future work as already mentioned.

Immerzeel et al. (2010) describe no application of a parameterization for glacier geometry change.

*Following RC 1 (***There is no glacier flow component, and the authors do acknowledge and discuss these limitations well)***, the manuscript is not changed here.*

27. P. 4566, L19: what about ERA40? This GCM is mentioned only later in the paper.

Thank you. ERA 40 driven RCM outputs as reanalysis data were applied for the validation, because ECHAM 5 as a climate model, cannot reproduce the chronology of the meteorological conditions. The model output should, however, reproduce the meteorological conditions and the climate signal.

We included ERA 40 as follows (P4566, L21 (P11, L10)):

"… (Kripalani et al. (2007). Additionally, ERA 40 was applied for the past (particularly for the model validation) to reduce GCM simulation biases, since they are based on meteorological observations."

28. P. 4566, L23-L25: How are CLM data downscaled? Are any station data used for that?

The CLM data were downscaled with SCALMET as described and referenced in the SCALMET section without using any station data. See also answer to comment 14.

29. P. 4566, L26-L28: please specify for each of these datasets for which model parameters/model components they are required.

Ok: Therefore we added Table 1 and further information in the text as follows (Section 3.2 (P11, L6):

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). Additionally, ERA 40 was applied for the past (particularly for the model validation) to reduce GCM simulation biases, since they are based on meteorological observations. 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 x 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), which provides mean ice thickness for the glaciers in the LRB. The mean ice thickness is then modified considering surface slope (Haeberli and Hoelzle, 1995) and the thinning out of the glacier to its edges and front. Additionally, a digital terrain analysis was carried out with TOPAZ (Gabrecht and Martz, 1999) and field data were applied. Further details to the applied input data in the models can be found in Table 1 and Prasch et al. (2011b).

Table 1: Required input data layers to run the models PROMET, SCALMET and SURGES and data sources for the Lhasa River catchment.

Input data set	***Data source***	***Model***
Watershed	*Digital terrain analysis of SRTM with TOPAZ (Garbrecht and Martz 1999)*	*PROMET*
Elevation [m a.s.l.]	*SRTM (Jarvis et al., 2006)*	*PROMET*
Surface slope [%]	*Digital terrain analysis of SRTM with TOPAZ*	*PROMET*
Surface aspect	*Digital terrain analysis of SRTM with TOPAZ*	*PROMET*
Land use / land cover classes	*NASA TERRA/MODIS land cover product (Boston University, 2004)*	*PROMET*
Soil texture classes	*Harmonized World Soil Database (FAO et al., 2009)*	*PROMET*
Accumulated upstream area [km²]	*Digital terrain analysis of SRTM with TOPAZ*	*PROMET*
Channel slope [%]	*Digital terrain analysis of SRTM with TOPAZ*	*PROMET*
Flow direction	*Digital terrain analysis of SRTM with TOPAZ*	*PROMET*
Channel width [m]	*Deduced, based on field data*	*PROMET*
Manning's roughness parameter	*Deduced, based on field data*	*PROMET*
Groundwater storage time [h]	*Deduced, based on the digital terrain analysis of SRTM with TOPAZ*	*PROMET*
Meteorological values (near surface air temperature, precipitation, air humidity, wind speed, incoming short and longwave radiation)	*COSMO-CLM outputs (Climate Limited-area Modeling Community, 201), driven by the GCM ECHAM % /MPI-OM and ERA 40 and downscaled with SCALMET*	*SCALMET/ PROMET / SURGES*
Subscale glacier area [m²]	*Chinese glacier inventory (World Data Center For Glaciology and Geocryology, 2009)*	*SURGES*
Subscale glacier elevation [m a.s.l.]	*Aster GDEM (ERSDAC, 2009)*	*SURGES*
Subscale glacier slope [%]	*Aster GDEM (ERSDAC, 2009)*	*SURGES*
Subscale ice thickness [m]	*Deduced, based on WDC (2009) and ERSDAC (2009)*	*SURGES*

30. P. 4567, L7: please make clear what are the differences between Prasch et al. 2011a and this study. Some of the plots are identical (e.g. Figure 8 in Prasch et al. 2011a and Fig. 6a and 7a in the present study).

In this paper we present detailed results for the Lhasa River Basin, which were not published before. Particularly, the in depth validation of the approach for the LRB and the analysis of ice-melt among the other water balance parameters (snow melt, evapotranspiration, runoff, precipitation) and its spatially distributed contribution throughout the river network are novel and were not published before elsewhere. This is also the case for presenting the seasonal course of the runoff components in the LRB. Furthermore, as far as we know, such a comprehensive analysis of the ice-melt contribution in relation to other water balance parameters in a basin for past and future conditions in this spatial and temporal resolution does not yet exist.

The projects Brahmatwinn and Glowa Danube built the background to this analysis, but the results, presented here were generated after the end of these projects and after the publication of Prasch et al. (2011 a). In Prasch et al. (2011a) the results for the Upper Danube River Basin and the Upper Brahmaputra River Basin are presented, but details are not given. Figures of this publication (Prasch et al. 2011a) are not identical to that published now in TCD: they are strongly modified and extended (Fig. 4), are identical in one part of Figs. 6 and 7 (but here we include the validation at the other gauges to not only show one selected result). Therefore the figure captions will be changed as follows:

Fig. 4: … (modified after Prasch et al., 2011a, p.63)

Figs. 6 and 7: … (Lhasa data are from Prasch et al., 2011, p.66).

We clearly explained and referenced the work related to this publication in section 4, because in this publication we do not want to repeat validation steps and results presented in other papers, which build the background for the results of this publication.

Therefore we are convinced of the novelty of the work published here and can hopefully have clarified any doubts.

For further clarification, we also explain the results of this paper in relation to work published before in the introduction as follows:

P4560, L2 to 9 (P3, L16):

… use the water. The results presented here are based on the approach developed in the integrative research projects GLOWA-Danube (www.glowa-danube.de) and BRAHMATWINN (Flügel, 2011) to study the impacts of climate change on water availability. The full model chain with PROMET, SCALMET and SURGES was already applied in the Upper Danube River basin with excellent data availability and validated in detail (Weber et al., 2010). General hydrological results were presented in Prasch et al., (2011a) for the Upper Brahmaputra River Basin. Here, the application and validation of the coupled modeling approach with Regional Climate Model outputs and a process-oriented glacier and hydrological model is explained for the Central Himalayan LRB despite scarce data availability (Sects. 3, 4). Then, the results are shown in depth: 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.

31. Section 4.1: Here a better discussion of the station data compared to the downscaled climate data would be essential. The paper does not show any seasonal course of temperature or precipitation. Further the elevation of the station and the elevation range of the CLM raster cells need to be provided. See also point 5 major comments.

Thank you. You are right. There is a misunderstanding, because in section 4.1 we show the validation of the downscaled CLM ERA 40 and ECHAM 5 driven output data after the final downscaling with SCALMET. That means air temperature and precipitation, which are used as input data for our modeling approach are validated. Therefore, the deviation of the elevation of the stations and the output 1 x 1 km² grid cell are negligible. Unfortunately, our wording was misunderstanding.

Additionally, the validation of the seasonal course of temperature and precipitation of ERA 40 driven outputs after SCALMET is run, can be shown as follows as far as validation data are available, adding a further figure.

In the revised version section 4.1 is changed as follows:

To validate the downscaled air temperature and precipitation sums in the LRB, the recorded air temperature and precipitation at five meteorological station data (Fig. 1, Table S 1) are compared with the downscaled values after SCALMET is run. Both, CLM ERA 40 and CLM ECHAM 5 data are used as input for SCALMET in the validation, because ECHAM 5 driven SCALMET outputs, as driven by a climate model, cannot reproduce the chronology of the meteorological conditions contrary to ERA 40 data, which are based on observations. The SCALMET outputs of CLM ECHAM 5 should, however, reproduce the meteorological conditions and the climate signal. Consequently, the average values, the general seasonal course without matching single years and the trend of the data should be comparable to observed data. ERA 40 driven outputs should additionally represent the seasonal course of single years.

As shown in Table 2, the recorded air temperature is reproduced for the stations by both CLM model driven SCALMET 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 driven SCLAMET outputs, but the deviations are within 10 percent, whereas in Lhasa the overestimation reaches 22 percent. The precipitation sum is slightly underestimated for Meldro Gungkar and Tangga. In comparison to the CLM ERA 40 driven SCALMET temperature and precipitation values, the deviations seen are smaller. The comparison of CLM ERA 40 driven SCALMET outputs with observed daily air temperatures (Fig. 5) and monthly precipitation sums (Fig. 6) show that the seasonal course can be reproduced despite deviations. The exemplarily comparison of observed and modeled monthly air temperature and precipitation of the CLM ECHAM 5 driven SCALMET outputs are illustrated for the station Lhasa in Fig. 7. The seasonal cycles are captured by the model output, with the monsoon precipitation during the summer months and the dry winters, although there are overestimations of precipitation during the pre-monsoon time in April and May, taking into account that the annual values cannot be reproduced by a climate model. The comparison of the monthly simulated and observed values also shows modeling of a reasonable *range of minimum and maximum values. Two January temperatures, however (1987, 1988), are simulated at a clearly lower level than all observations. Consequently, the mean meteorological conditions are reproduced by the CLM ECHAM 5 model run, particularly when 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.*

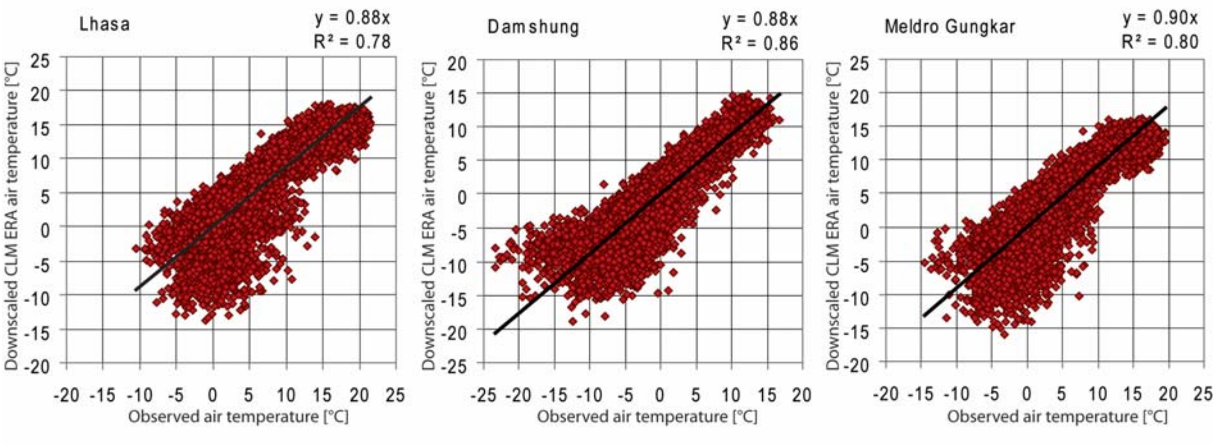


Figure 5: Comparison of modeled (CLM ERA 40 driven SCALMET outputs) and observed daily air temperatures for the Lhasa, Damshung and Meldro Gungkar stations.

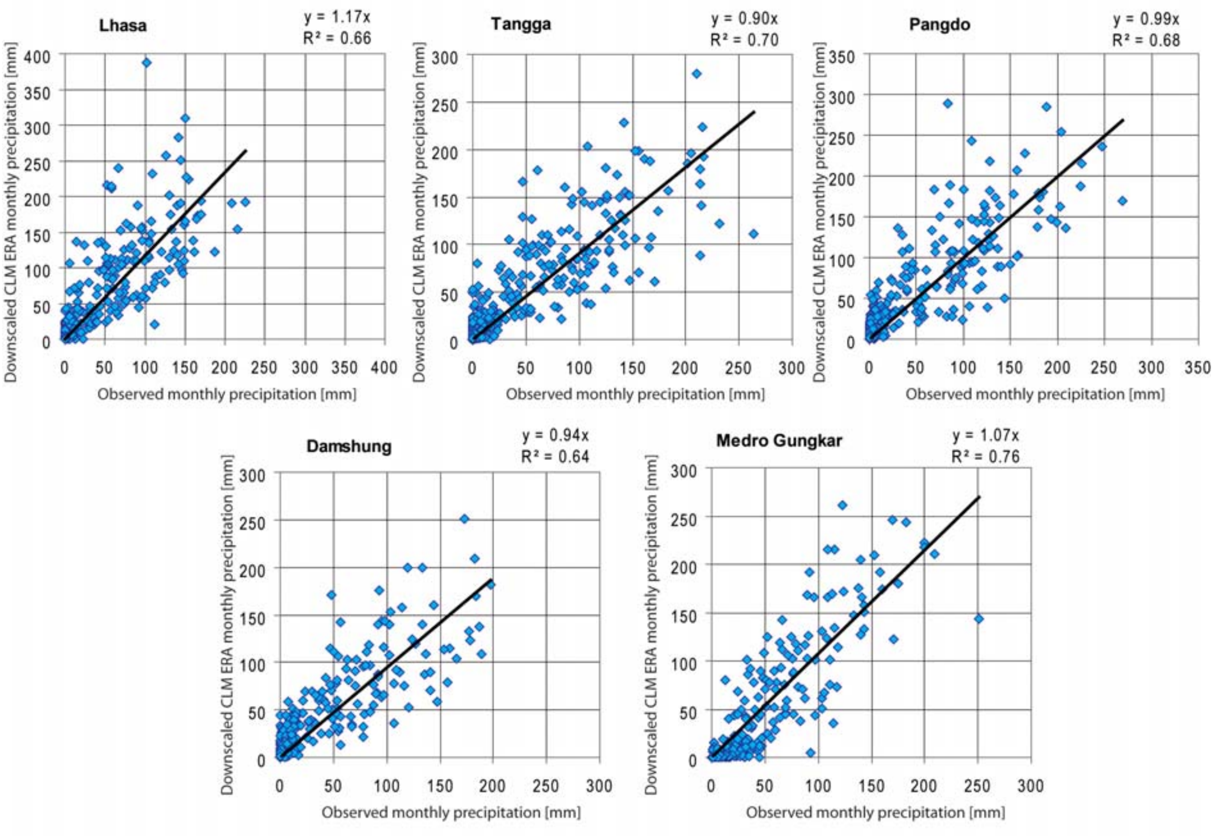


Figure 6: Comparison of modeled (CLM ERA 40 driven SCALMET outputs) and observed monthly precipitation for the Lhasa and Tangga (1971-2000), Pangdo (1976-2000) and Damshung and Meldro Gungkar stations (1980-2000).

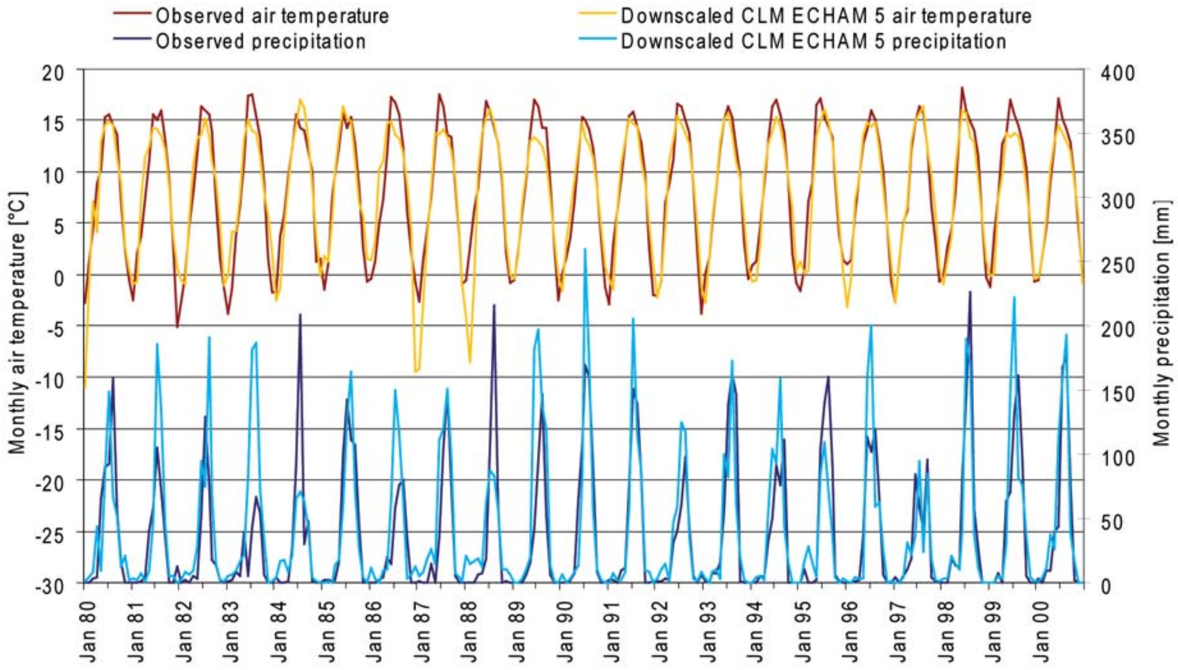


Figure 7: Development of observed and modeled (CLM ECHAM 5 driven SCALMET outputs) monthly air temperature and precipitation at the Lhasa station for 1980-2000.

32. Section 4.3: Why are model simulations with CLM ERA 40 and CLM ECHAM5 validated in a different way? The same plots and the same goodness-of-fit values should be presented for both model runs and then discussed.

ECHAM 5 as climate model cannot reproduce the daily, monthly or annual course, because only the seasonal course of the meteorological conditions and the climate signal (30 years average) should be reproduced. Contrary, CLM ERA 40 outputs as reanalysis data are based on observations, so that in this case, daily, monthly and annual values should be represented. That's the reason for the different validation steps.

33. Fig. 7: There should be a similar figure which shows runoff for the periods where the model does not perform well (Table 2).

The figures are included in monthly resolution as Fig. 10, because for this period, only monthly observations are available:

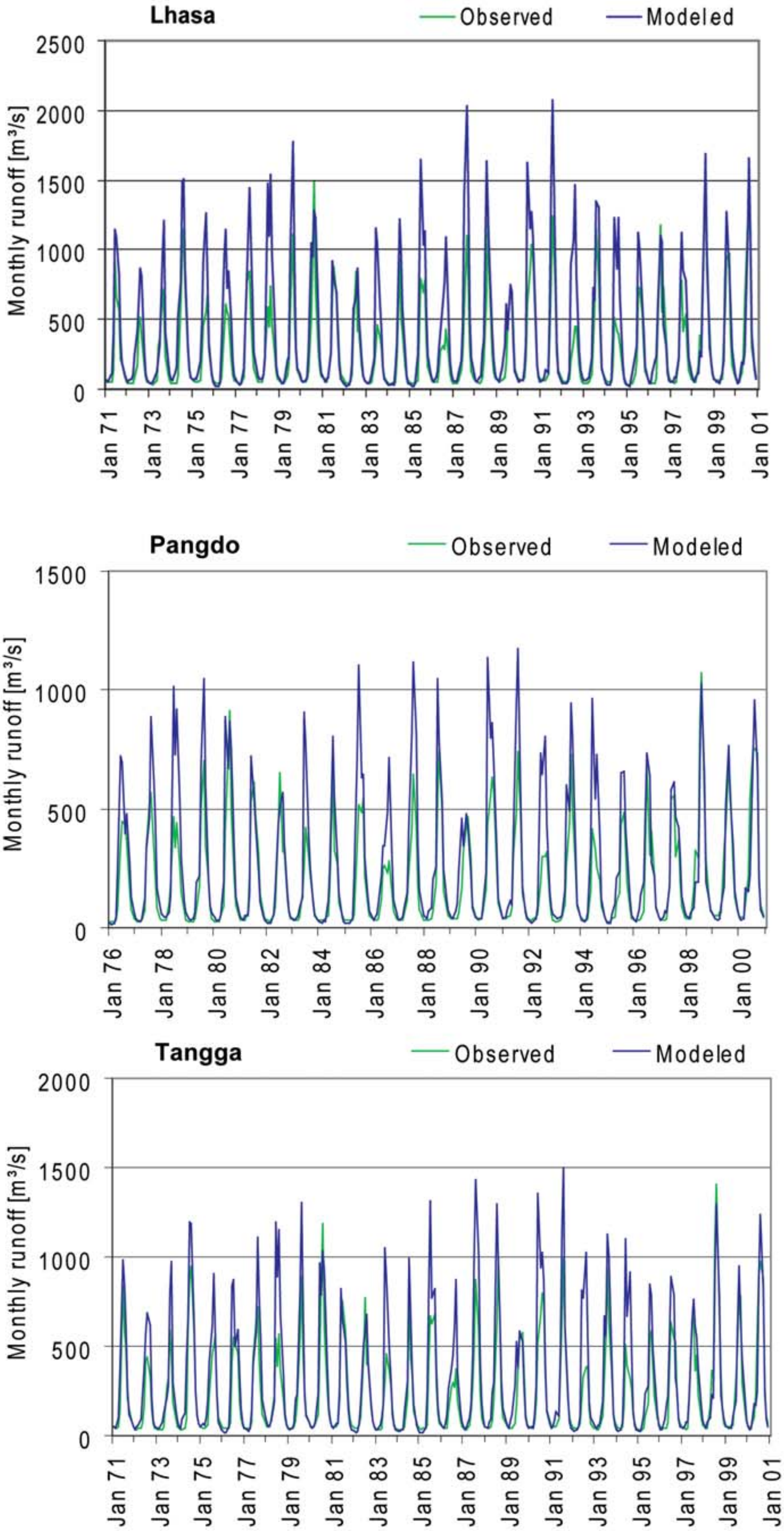


Figure 10: Development of monthly observed and modeled runoff at Lhasa, Pangdo and Tangga gauges from 1971 (1976) – 2000.

34. Tables 2 and 3 could be combined. Why does the model perform so badly for the longer validation period? Do you have runoff overestimation only in summer or also in winter? This is not evident from Fig. 5.

Ok – the new table:

Table 3: Quality criteria for modeled monthly and daily runoff [m³/s] for CLM ERA40-driven model runs.

Quality criteria	Monthly runoff			Daily runoff		
	Lhasa (1971-2000)	Pangdo (1976-2000)	Tangga (1971-2000)	Lhasa (1996-2000)	Pangdo (1996-2000)	Tangga (1997-2000)
Coefficient of determination R^2	0.79	0.78	0.80	0.72	0.70	0.74
Slope of linear regression	1.37	1.30	1.29	1.00	0.92	0.93
Nash-Sutcliffe efficiency coefficient	0.31	0.39	0.48	0.67	0.70	0.73

The figure above (comment 33) shows the monthly development, supplementing Figs. 10, 11. During summer there is an overestimation of runoff, whereas the winter runoff is in accordance with the observations. This overestimation is large in the 70ies and 80ies and is then clearly reduced in the 90ies. That's the reason for the differences between the short and long validation period, which is also the case for precipitation at the stations.

35. P. 4568, L24: "the mean annual runoff is validated as climate signal". This is not clear to me. What do you mean by that?

See answer to comment 32.

36. General comment on section 4: consider separating this section into a subsection in the 'methods' section and a subsection in the 'results' section. The methods which are chosen to validate the models are essential for the modeling experiment, and the performance of the models could be considered as a result. If the performance of the model is already assessed in Prasch et al. 2011a this has to be mentioned clearly.

In section 4 the validation of the application of the modeling approach in the LRB is shown. Therefore the heading of section 4 is changed to "Validation of the modeling approach in the Lhasa River basin" for clarification in the revised paper. From our point of view the analysis producing the results (the role of glacier melt water) cannot be carried out before the validation described in section 4 has been conducted. Therefore, section 4 will be left as a separate section.

In Prasch et al. (2011a) the validation of the models was mentioned but without presenting details or several validation stations. For the sake of completeness, we also include the results for the Lhasa gauge, partly modified in the presentation in this paper. The references are given as follows:

Fig. 4: (modified after Prasch et al., 2011a, p.63)

Fig. 6 and 7: (Lhasa data are from Prasch et al., 2011, p.66)

37. P. 4569, L12: where are the ELAs in 2080, for each of the simulations?

The ELA is an important parameter to validate glacier mass balance modeling besides others for individual glaciers. Since we do not focus on single glaciers in this study, we did not analyze the ELA of all the glaciers in the LRB. We analyzed in detail the future development in the four scenarios and compared the values of glacier area, ice water reservoir and mean annual mass balance of the future climate periods to the past period from 1971 to 2000, shown in the following table, which is included in the Supplements as Table S3. In order to directly compare the size of the ice water reservoir to annual precipitation, the total amount is distributed across all grid cells of the catchment. In the past, about one and a half times annual precipitation were stored as ice. However, about 20 percent of ice water storage for each grid cell in the basin melted away from 1971 to 2000. In the first future period, 2011 to 2040, both the retreat of the ice water reservoir and the glacier area are quite similar for all scenarios, varying between 21 and 26 percent for the water reservoir. A retreat of 35 to 37 percent is simulated for the glacial coverage. In the second scenario period, the decrease fluctuates at around 65 percent for the A2 and B1 scenario. For the A1B scenario, a maximum reduction of around 75 percent for both the ice water and the glacier area is simulated. The different mass balances confirm the results. While the retreat in the first future period is slightly larger than that of the past, at about 0.4 m per year, it increases to more than one meter in the second scenario phase, with a maximum of 1.4 m for the A2 simulation.

Table S3. Changes in glacial coverage and stored ice water reservoir in the Lhasa River basin for the CLM ECHAM5 IPCC A1B, A2 and B1 driven scenario model runs.

Glacier characteristics	**1971 – 2000**	**Scenario**	**2011 – 2040**	**Δ [%]**	**2051 – 2080**	**Δ [%]**
Glacier Area [km^2]	629	A1B	395	-37	147	-77
		A2	406	-35	215	-66
		B1	392	-38	202	-68
Ice water reservoir [mm/km^2]	928	A1B	686	-26	247	-73
		A2	731	-21	386	-58
		B1	682	-26	362	-61
Mean annual mass balance [m]	-0.33	A1B	-0.54		-1.23	
		A2	-0.33		-1.39	
		B1	-0.39		-1.09	

The development of the spatial distribution of the future ice water reservoir for the year 2000 and 2080 is illustrated in the following figures for the scenarios A1B, A2 and B1, included in the Supplements as Fig. S1. A strong retreat can be seen, but around the highest peak of the Nyainqêngtanglha Mountains still glaciers exist.

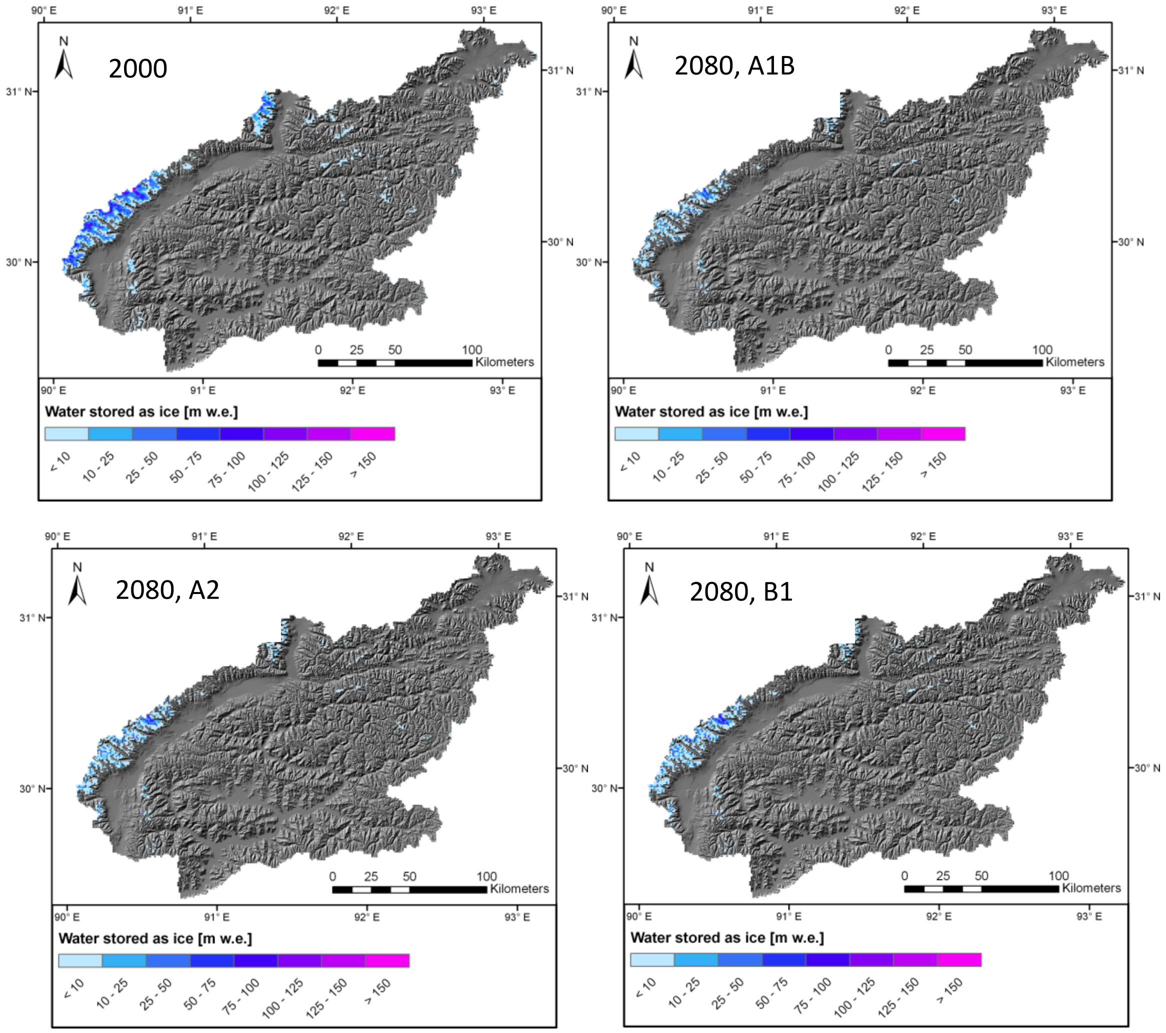


Figure S1: The spatial distribution of the simulated ice water equivalent in 2000 and 2080 according to the CLM ECHAM5 IPCC A1B, A2 and B1 driven scenario model runs.

38. P. 4569, L21-L23: “In order to . . .only occurs in the glacierized areas.” Ice-melt occurs only in the glacierized areas? This is evident. Please remove.

Ok. It is evident that ice-melt only occurs in the glacierized areas, but the separation of snow- and ice-melt from glaciers often is not made. Therefore the sentence will be changed as follows:

P4569, L21-23 (P14, L23): In order to specifically quantify the contribution of ice-melt to total runoff, it is treated separately from snow-melt, which occurs contrary to ice-melt throughout the whole basin.

39. P. 4570, L9: “astonishing” is not very scientific, and neither is the use of the word justified here. See major comment 7.

Increasing ice melt area compensates reservoir reduction. As shown in the Interactive Comment to this publication, this also can be seen different, so that many people may be surprised by this result. In the revised paper we changed „astonishing“ (p. 4570, ln.9/10) by “remarkable” and added a reference for similar findings of the Alps (Pellicciotti et al., 2010):

P4570, L9 (P15, L8): … 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, similar to trends analyzed for the Alps (Pellicciotti et al., 2010). In depth analysis of this remarkable finding shows that …

40. P. 4570, L17: provide reference to equation, see detailed comment 7.

Ok: P4570, L17 (P15, L22): see Eq. (1)

41. P. 4570, L24: 30% evaporate; how does this number compare to other studies, in the Himalaya or elsewhere?

30 % evapotranspiration is in accordance with values of a study conducted in the Himalayas by Sharma et al. (2000).

In the revised version, we added the reference as follows:

P4570, L24 (P15, L26)… about 30 % of the water in the LRB evaporates, which is in accordance to Sharma et al., (2000), whereas …

Sharma,K.P., Vorosmarty, Ch. J., and Moore III, B.: Sensitivity of the Himalayan hydrology to land-use and climatic changes, Climatic Change, 47, 117-139, 2000.

42. P. 4571, L10-16: this should not go into the result section. Either remove or move to the introduction.

Following the interactive comment of Prof. Pelto, we moved this to 4561-11, the description of the study area.

43. P. 4571, L20: "daily runoff course"? This should be annual runoff course.

Thank you: P4571, L20 (P16, L10): The annual runoff course at the basin outlet in a daily resolution …

44. P. 4571, L22-23: "runoff is low during winter. . ." This should go into a data section, as P. 4572, L8-9 "Accordingly, runoff generated. . ." and elsewhere in section 5.3. Much of this is data/study area description.

From our point of view, the mentioned sentences explain the results in detail and do not only describe the data, so that we want to leave these explanations.

45. P. 4572, L14: In order to show future runoff evolution, show the seasonal course of runoff for different periods together on the same plot. Or plot annual mean runoff over time, for different scales, in order to discuss the effect of variable glacier contribution depending on scale (see also major comment 7).

Figure 12 (16) shows the runoff dynamics for two different gauges with varying area and glacierization, each for the past and the two scenario periods. The uniform scale for each gauge allows the comparison of the shown values. We improved the possibility to compare the two gauges in uniforming the sales for the outlet and Yangbajing (see Figure below). Additionally, we included a Figure showing the seasonal course of runoff, precipitation, snowmelt release in the catchment, ice-

melt and evapotranspiration for the three periods, each in one plot in the Supplements (S2) and change the description in the manuscript as follows (P4572, L14 (P16, L10)):

"The annual runoff course at the basin outlet in a daily resolution (Fig. 16, left, Fig. S2, 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. 16a, left, Fig. S2D). 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 (see Sect. 2) 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. 13, 16, S2). 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; Figs. 16b,c, S2). The main difference compared to the past is a clear decrease of the melt-water contribution from snow during summer and an increase in evapotranspiration. Increasing temperatures at all altitudes sharply reduce the amount of snowfall (Figs. 14, 15). 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. Together with the glacier retreat the ice-melt contribution during summer becomes lower in the scenario periods. Consequently, runoff is reduced, mainly caused by changes in the amount of precipitation. Additionally the reduction of snow-melt and increasing evaotranspiration forces the runoff reduction during early summer, particularly for the period from 2051 to 2080 (Figs. 16, S2).

These processes are basically similar for the sub-basin of Yangbajing with larger glacierization and accordingly larger ice-melt contribution to runoff (Figs. 16, right, S2, right). Although the amount of ice-melt increases in future periods not only in spring as described above (Sects. 5.1, 5.2), but also in early summer, runoff is reduced during these months taking into account the increase in precipitation in the second scenario period. Only in May the increasing ice-melt up to 30% can augment the missing snow-melt and reduced precipitation, whereas during the summer months, this effect is negligible. Again, the strong decrease of snow-melt and increase of evapotranspiration are the reasons despite higher altitudes and larger ice reservoirs with the described compensational effect (Sect. 5.1)."

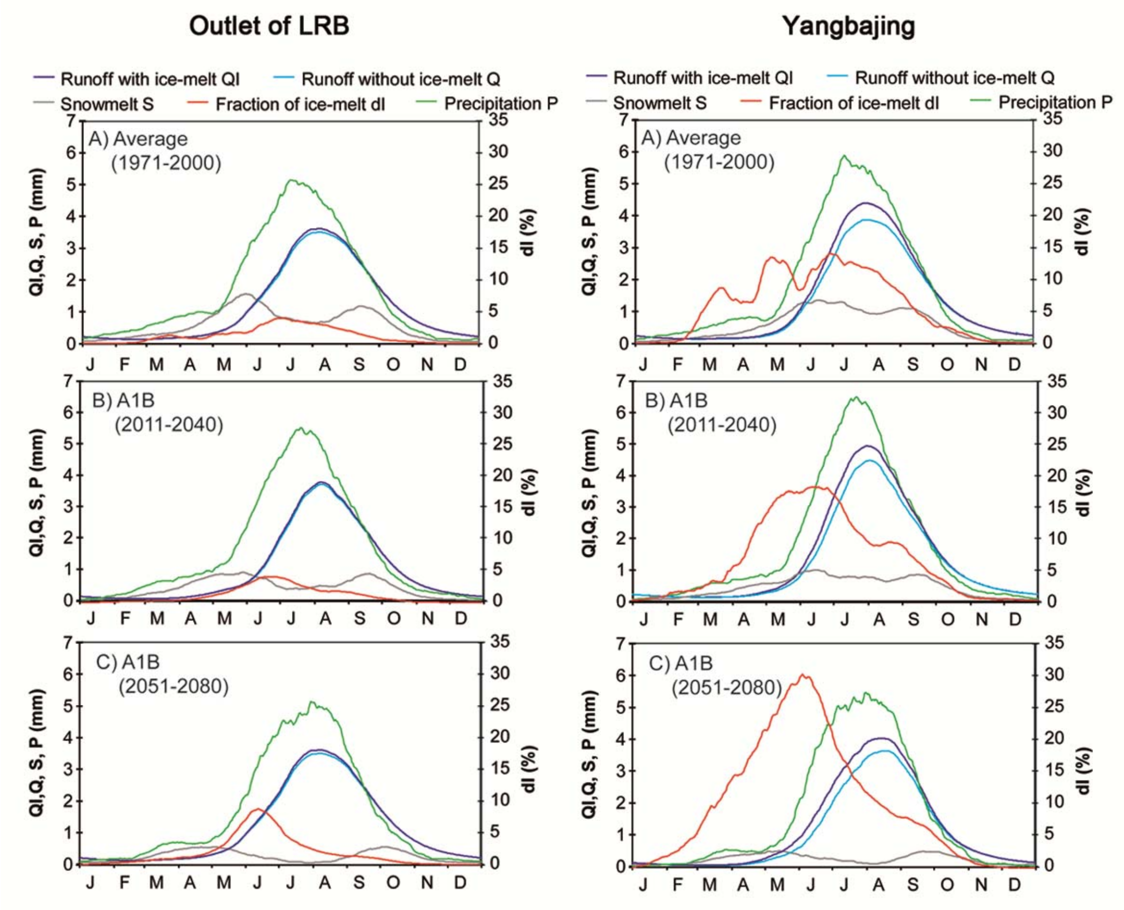


Figure 16. Average annual dynamics of daily different runoff components at the outlet of the LRB (left) and at Yangbajing (right) (moving average over 30 days); river runoff with (blue) and without (cyan) ice-melt (left y-axis) together with snow-melt water release of the basin (grey, left y-axis), precipitation (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 (see also Supplementary Fig. S 2).

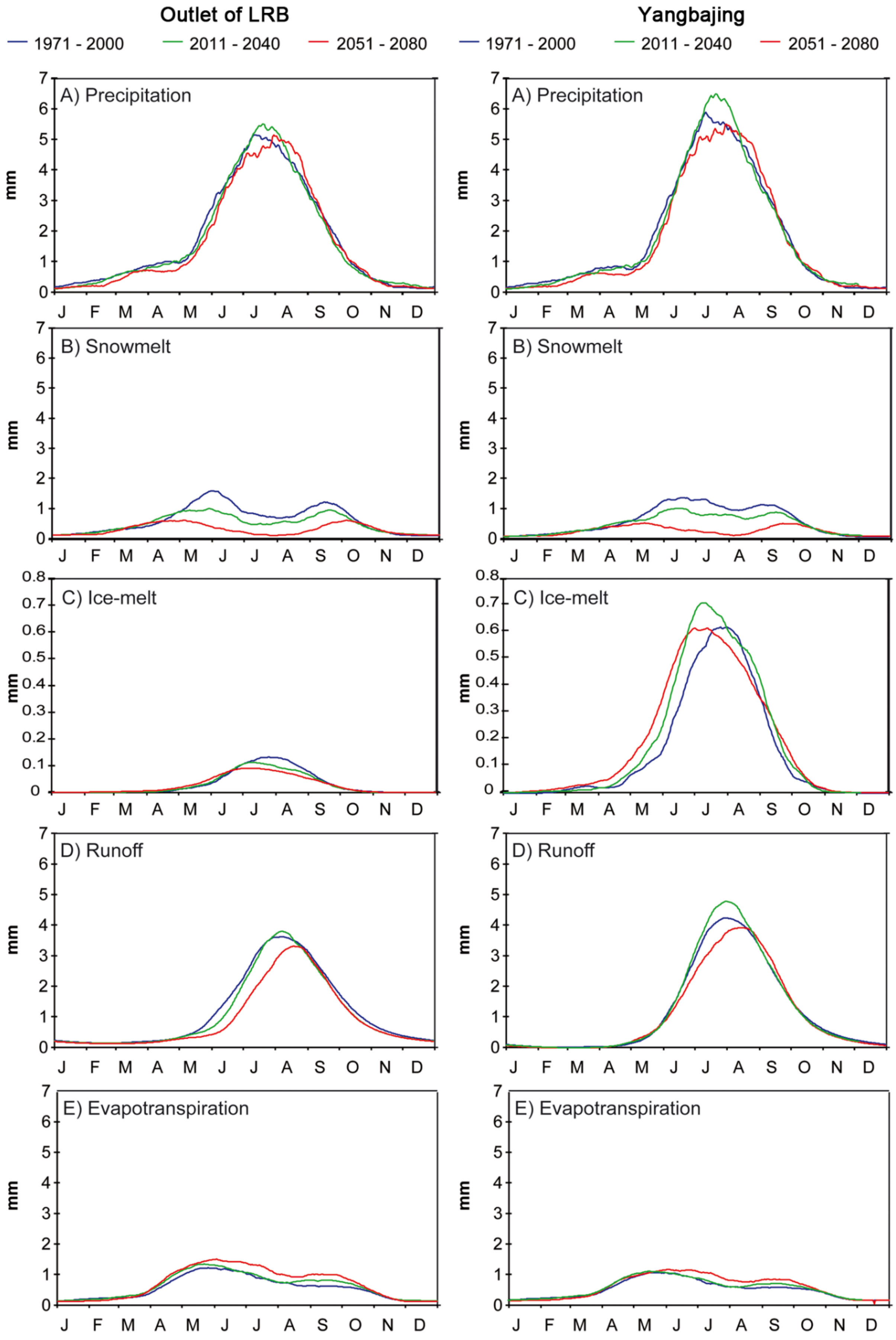

Outlet of LRB
Yangbajing
1971 - 2000
2011 - 2040
2051 - 2080
A) Precipitation
B) Snowmelt
C) Ice-melt
D) Runoff
E) Evapotranspiration
mm
0
1
2
3
4
5
6
7
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
J F M A M J J A S O N D

Figure S2: Average annual dynamics of daily different runoff components at the outlet of the LRB (left) and at Yangbajing (right) (moving average over 30 days); precipitation (A), snow-melt water release of the basin (B), ice-melt (C), river runoff (D), and evapotranspiration (E) for the periods 1971-2000 (blue), 2011-2040 (green) and 2051-2080 (red) are shown.

The annual runoff for different gauges in the three periods is shown in Table 5 and already discussed in section 5.2. The following description is added in Section 5.1 for further clarification (P4570, L7 (P15, L5)):

5.1: "Despite the continuous future reduction of glacierization (Fig. 12, Supplementary Fig. S1), 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, similar to trends analyzed for the Alps (Pellicciotti et al., 2010). In depth analysis of this remarkable 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. This altitudinal shift extends the snow-free period by two to three months (Figs. 14 and 15) and thereby increases ice-melt per area and year. Since this shift is proceeding continuously, similar to glacier retreat, the simulated changes of the snow-free glacier area, decisive for ice-melt, are small despite the shrinking overall areal extent of the glaciers. 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."

46. P. 4573, L7: if insights can be considered "valuable" depends on the point of view. For whom exactly they are valuable. If this is a subjective judgment then rather remove.

The insights are valuable for water users and managers in this region which deal with the question of climate change impacts and how to adapt, but the sentence is removed in changing the conclusion.

47. P. 4573, L21: This is the first time that sublimation is mentioned in this paper. How is sublimation calculated? By PROMET or by SURGES? Does sublimation affect the water balance?

In order to determine the glacier mass balance per elevation level, the sublimation or resublimation process is considered (besides mass gain by snowfall, melt determined with the energy balance) by SURGES. The mass change conducted by this process se [mm] per time step Δt [s] is calculated considering the latent heat flux L [W m^{-1}] and the specific sublimation heat of snow and ice H of 2,835,500 J kg^{-1}:

$$se = \frac{LE \cdot \Delta t}{H}$$

For the non-glacierized parts sublimation and resublimation is calculated by PROMET.

The amount of sublimation/resublimation affects the water balance (Strasser et al. 2008) and is considered in the water balance in the amount of evapotranspiration (Tables 5, 6, 8 (Table 5, Supplementary Tables S4 and S5), but not analysed separately.

Since we agree that sublimation is mentioned too late, in the revised version sublimation is described in the methods section as follows and details are provided in the supplementary material (p. 10):

P4565, L16 (P8, L28): The mass change conducted by sublimation / resublimation is also calculated by SURGES.

Additionally, it is also mentioned on P4566, L5 (P 9, L16): Since snow that accumulates at the higher elevation levels is transformed to ice as explained above and sublimation, evaporation and melt are taken into account, it does not accumulate endlessly, although the loss of ice thickness there is underestimated because of the missing consideration of subsidence caused by ice-flow. Released melt water is aggregated for each raster cell and then redirected to the stream flow from all cells by PROMET's routing component as described in Mauser and Bach (2009). Additionally,…

Strasser, U., Bernhard, M., Weber M., Listen G.E., and Mauser, W.: Is snow sublimation important in the alpine water balance?, The Cryosphere, 2, 53-66, doi:10.5194/tc-2-53-2008, 2008.

48. General comment on conclusion section: much of this really is model description, which should go into the method section. The conclusion does not focus on the main results of the study. It should be mentioned what were the main objectives and what were the corresponding results.

Ok. The conclusion is changed as follows also taking the interactive comment of Prof. Pelto into account: The third and fourth paragraph of the conclusion will be inserted as section "3.1.4 Discussion of the modeling approach" in the methods section. We fully agree that focusing on the main objectives (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 (1), the quantification and impact of the contribution of glacier ice-melt water to river runoff not only for the highly glacierized head-watersheds but also for the downstream regions (2)) in the conclusion will support the reader in focusing on the key points as follows, ending with a final statement after the short discussion of the uncertainty in monsoon precipitation.

Conclusion

The presented approach offers the possibility to analyze the temporal and spatial pattern of the rainfall, snow- and ice-melt contribution to river runoff under past and future climatic conditions. 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. 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.

The resulting quantification of the contribution of glacier ice-melt water to river runoff not only in the highly glacierized head-watersheds but also for the downstream regions as the main objective of this study let us conclude that 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 percent. Although glaciers will be strongly reduced by GCC, this is mainly due to the cyclic behavior of runoff generated from rainfall and from ice-melt in the past and future in accordance to Thayyen and Gergan (2010), 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. 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).*

Uncertainties still exist in the simulation of future monsoon precipitation in current GCMs (Kripalani et al., 2007) and 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. 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.

49. P. 4574, L12: “globally valid parameterizations”; not clear how this is justified.

PROMET, SCALMET and SURGES have been developed for central Europe, but they are process-oriented models based on physical principles. In the models, we use universal constants which are globally valid, e.g. the Stefan-Boltzmann constant for the calculation of the incoming longwave radiation balance as follows:

$Q_l = R_{li} - \sigma \cdot \varepsilon \cdot T_S^4$ *with Rli = incoming longwave radiation, σ=Stefan Boltzmann constant, ε = emissivity of snow (1) and ice (0,98) and TS = surface temperature.*

Furthermore, universal algorithms for process descriptions are applied, which allow the consideration of local conditions, where required, e.g. the calculation of the absorption of shortwave radiation with the albedo, determined as described in answer to detailed comment 24. Both, the constants and the algorithms are not changed between the model applications in river basins, e.g. the Upper Danube or the Lhasa River basin, so that they are universal, although they enable the modification of parameters to local conditions. Additionally, the parameters are invariant in space and time across the whole basin.

In the revised paper version, the parameterizations are described in detail (see answers to detailed comments 12, 14, 20, 21, 29, 49). Additionally, the validation of the model performance in Section 4 in the LRB shows that the conditions in the Central Himalaya can be reproduced by the models, and we changed the wording to “… uses universal constants and universal algorithms, which are invariant in space and time throughout the basin.” (revised version P10, L23).

50. P. 4574, L19-L22: a proper description of type and quality of input data is missing, which is exactly one of the reasons why the applicability of the model could not be demonstrated. Also, the validation for the Lhasa River catchment revealed that the model performance is insufficient for the 30 year validation period, and did not prove the reliability of the model.

The input data section is enlarged and the used data are described in detail (see also answer to comment 12).

The applicability of the model could be demonstrated in our opinion, since the validation results showed that the outputs for the past are reasonable considering the application of RCM outputs and the general data availability together with the fact that the model is not calibrated to observed runoff in order to be also applicable for changing future watershed conditions or climates. Although there are biases, the seasonal course of runoff, air temperature and precipitation as well as the past glacier development is reproduced by the model, especially when taking into account the coarse spatial and temporal resolution of the CLM output data as meteorological drivers. In general we see that this procedure has a prize which consists in slightly larger biases than when using calibrated models. Therefore, in our opinion, the model results are sufficient considering that we use a physically based, process oriented model in a remote region of scarce data availability. With more comprehensive sets of input data, e.g. meteorological station data the model performance could be improved (see also answers to comments 31-36).

The lack of studies with the application of physically based hydrological and glacier models coupled with RCMs in such regions and the generally low number of such studies shows the basic difficulties on the one hand, but on the other hand, that the performance of our approach is sufficient. Furthermore, waiting until detailed data can be obtained and accordingly a higher performance can be reached will not help in analyzing the impact of GCC in remote regions.

51. P. 4574, L23: uncertainties in current GCMs; this is exactly the reason why more than just one GCM should have been considered for the discussion of modeling results.

The authors are aware of the large uncertainties in global and regional climate modeling, which currently is subject to numerous scientific studies worldwide. Especially when looking at the South Asian monsoon not all models are capable of realistically reproducing past conditions. These models should not be used for studies of the future. 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). Additionally, the validation of the model outputs (see section 4) showed that the conditions in the LRB are reproduced by using CLM-data as meteorological drivers for our modeling approach. In order to cover and document a range of uncertainties introduced by the assumed CO2 emissions, we applied different emission scenarios IPCC SRES-A1B, -A2 and –B1. Since the selected emission scenarios cover a large range of possible climate change, less would have been insufficient. Undoubtedly, using more RCMs and GCMs would have provided valuable further insight into the statistical behavior of the inherent uncertainties of the applied modeling chain on the model results. We feel that these studies, though important, go beyond the scope of this paper and are therefore intended for future work.

52. P. 4575, L2: is the value provided by Oerlemans 2005 representative for this study region?

There are no regional limits quoted from ("Mass-balance modeling for a large number of glaciers has shown that 25% increase in annual precipitation is typically needed to compensate for the mass loss due to a uniform 1 K warming" (Oerlemans 2005, p. 676)), but the value was derived for European conditions. So we better delete this sentence.