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 comment which will help to improve our manuscript.

In the following you can find our answers to your comments, including a detailed explanation to the novelty of the presented results.

Monika Prasch, Wolfram Mauser and Markus Weber

General comments:

This is an impressive study from an equally impressive larger project (BRAHMATWINN), with meritorious goals of modeling changing hydrology through an entire catchment and distinguishing contributions from various components, including explicitly changing glacier storage. The Lhasa River Basin (LRB) is an important study site, too. This region has drawn attention as a site of climate change impact, since it features large populations downstream and large concentrations of ice (glaciers, permafrost) upstream. Observations are sparse, glacier climate science is controversial, and the future implications have been poorly cited (i.e. IPCC FAR). The authors state (multiple times) that this motivates them to not only understand future climate change impacts close to glaciers, but also where people "live and use" the water further downstream. Notably their PROMET model is a spatially distributed, process-based (using physics to solve energy/mass balance) integration that does not rely on close calibration and parameterization. This is excellent work, and the authors should be congratulated.

However, the merits of this paper should be reviewed not on the overall project or modeling framework, because such has already been established and published elsewhere. Here, the authors claim to present a coupled glacier (SURGES)-climate downscaling (SCALMET)-hydrology (PROMET) model-based "analysis of the temporal dynamics and spatial pattern of the rainfall, snow- and ice-melt contribution to river runoff under past and future climatic conditions for the Lhasa River basin LRB. . ..to account for the specific and unique role of the glaciers for the downstream regions."

But in fact, how much of the results presented here are novel?

This paper actually reports on a previously published hydrologic modeling experiment; the model results (both "past" 1970-2000 and "future" scenarios A1B1, A2, B1 through 2080) for the LRB have already been published for the Upper Brahmaputra River Basin (UBRB); many of the figures in this paper are re-printed (or slightly altered) from Prasch et al., 2011a, Adv. Sci. Tech (http://www.adv-sci-res.net/7/61/2011/asr-7-61-2011.pdf). Presumably the authors justify this additional

publication as a report on details of the model verification in order to make further comments upon the implications for the glacier melt contributions (or actually lack thereof) to surface runoff in the LRB. But the authors should explicitly mention this overlap, and clarify exactly how this paper is distinct up front in the Introduction; as written, the information on the scientific context is not given until the opening paragraph of Part 4. This should be moved forward and amplified to clarify the contributions of this work, and how it is actually different.

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, or present different data for a different catchment (Fig. 10; see also answers to the specific comments).

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 can explain the results of this paper in relation to work published before in the introduction as follows:

p. 4560, ln. 2 to 9:

… 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.

Results: Authors do not see a major change in % ice melt given future scenarios of altered (warmer) climate, except in most glacierized sub-catchment. They imply this is "astounding" which may be overstating the significance. Glaciers at this scale are a very minor component. It is known that they have a temporary capacity to increase flow, and decrease variability, but that this changes as the ice reservoir is depleted. Here, the rate of reservoir reduction is offset by the increase in ice melt area. This underscores the importance of being able to dynamically model ice flux, and also account for the historical progression of the hydrograph rather than 30 yr averages to account for interannual variability, and perhaps groundwater residence time. Nevertheless, it is a compelling conclusion and the authors make a strong case for more careful empirical observations of hydrological fluxes in this (and other) glacierized headwater region.

As presented here and published recently (e.g. Rees and Collins, 2006; Thayyen and Gergan, 2010; Immerzeel et al., 2010; Kaser et al., 2010) glaciers play a minor role in this region at the basin scale. Nevertheless, many publications attributed a pivotal role of melt-water release by glaciers for water supply, particularly under the impact of Global Change, peaking in the IPCC publication for the Himalayas. Additionally, the influence of ice-melt for large River Basins as the Danube is still controversial (e.g. Weber et al., 2010; Huss, 2011).

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 can change „astonishing" (p. 4570, ln.9/10) by "remarkable".

We agree that dynamically modeling ice flux is important but explained the reasons for our approach as acknowledged by the referee. Since this study focuses on the impact of climate change, we aggregated the results to climate periods of 30 years. However, the approach also allows the analysis of interannual variability, e.g. what will happen if monsoon precipitation is delayed. But this is not the focus of the paper.

Also, it is critical to establish parameters of "successful" model application given lack of data. Perhaps because the model is only physics-based (and not parameterized), the model performance metrics are a bit low (especially for Table 2, where Nash-Sutcliffe efficiencies, the cited quality criteria, are <0.50 for full monthly values).

The „successfull" application (p. 4563, ln. 15; p.4567, ln. 5) refers to the UDRB (Mauser and Bach, 2009) with good data availability. The results in the LRB are satisfying, although there are biases because of using RCM outputs in an hourly resolution as meteorological drivers and, as stated by the referee, the use of model algorithms based on fundamental physics. Furthermore, the Nash-Sutcliffe efficiencies improve in the last decade from 1991 to 2000, because the modeled precipitation sum is in better accordance with the observations (see Table below).

Quality criteria for modelled 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	R²	0.84	0.72	-	-	0.85	0.75
	NSC	0.22	0.46	-	-	0.47	0.71
1981 – 1990	R²	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	R²	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	R²	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	R²	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

Presuming sufficient justification for novel material, this is a nicely written paper. What follows are some more specific comments on some aspects that were not clear and a list of specific technical edits to assist minor revisions.

Thank you. In the following your helpful specific comments are answered and will be considered as described below in the revised paper.

Specific comments

In the Intro, the authors also elaborate the utility of their approach to the problem of making meaningful predictions of future hydrology in the face of changing climate and a dearth of monitoring. Other theoretical work that has considered the nature of glacier storage release and transient impact (buffering) to streamflow seems important to mention (e.g. Collins and Taylor, 1990; Jansson et al., 2003; Huss et al., 2008; Moore et al., 2009). Also, the timing and magnitude of the expected glacier melt 'peak' in discharge is important to diagnose for water resources in changing mountain environments. Other research should be noted, particularly the integration of modeling and observations by Baraer et al., 2012 in the Andes, a region that is predicted to be highly vulnerable to changes in ice mass.

In the introduction we focused on work in Asia. For the consideration of related work in other regions and different approaches, the mentioned papers will be included in the introduction as follows, although in doing this, only a selection of conducted work can be cited :

Water supply of most lowland cultures heavily depends on rain and melt-water from the upstream mountains, because mountain watersheds can store considerable amounts of precipitation as snowpack and glaciers (Viviroli et al., 2007). Its delayed release through snow- and glacier-ice-melt can augment river runoff during dry periods (Viviroli et al., 2007, Weber et al., 2010, Jansson et al., 2003) with ice-melt often being the last water source after melt out of snow. Especially melt-water release of glaciers in the Alps, the Himalaya and other alpine mountain ranges, is usually attributed a pivotal role for the water supply of large downstream regions

(Cruz et al., 2007, Barnett et al., 2005, Huss et al., 2008, Huss, 2011, Moore et al., 2009, Baraer et al., 2012, Collins and Tayler, 1990). But snowpack and glaciers are among the land surface compartments most susceptible to Global Climate Change (GCC). Glacier retreat has attracted wide public interest and serves as symbol for the impact of GCC. As consequence of glacier shrinkage and possible disappearance water scarcity is assumed (Cruz et al., 2007) due to GCC, particular for large parts of Central and South East Asia (Cruz et al., 2007, Barnett et al., 2005, Casassa et al., 2009, Singh et al., 2006, Xu et al., 2009). Especially in High Asia this was brought into focus by the IPCC statement on Himalayan glacier retreat and its assumed consequences for water availability (Cruz et al, 2007). Despite recent studies pointing to the differing influences of ice-melt water on runoff due to regionally varying climatic and hydrological conditions along the Hindu Kush–Himalayas (Rees and Collins, 2006, Thayyen and Gergan, 2010, Immerzeel et al., 2010, Kaser et al., 2010), the future rate of recession of Himalayan glaciers as well as their present and future role for the downstream regions remain controversial.

The studies address the influence of ice-melt in Asia on runoff either only qualitatively (Barnett et al., 2005), for hypothetical catchments (Rees and Collins, 2006) or at almost continental scales (Immerzeel et al., 2010). Some results are limited to present climatic conditions (Thayyen and Gergan, 2010, Kaser et al., 2010). 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, Jansson et al., 2003, Huss et al., 2008, 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 (Kaltenborn et al., 2010, Viviroli et al., 2011, Jansson et al., 2003). 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.

Baraer, M., Mark, B.G., McKenzie, J.M., Condom, Th., Bury, J., Huh, K., Portocarrero, C., Gómez, J., and Rathay, S.: Glacier recession and water resources in Peru's Cordillera Blanca. J. Glaciol., 58, 134-150, doi:10.3189/2012JOG11J186, 2012.

Huss, M., Farinotti, D., Bauder, A., and Funk, M.: Modelling runoff from highly glacierized alpine drainage basins in a changing climate. Hydrol. Process., 22, 3888-3902, doi: 10.1002/hyp.7055, 2008.

Jansson, P., Hock, R., and Schneider, Th.: The concept of glacier storage: a review. J. Hydrol., 282, 116-129, doi:10.1016/S0022-1694(03)00258-0, 2003.

Moore, R.D., Fleming, S.W., Menounos, B., Wheate, R., Fountain. A, Stahl, K., Holm, K., and Jakob, M.: Glacier change in western North America: Influences on hydrology, geomorphic hazards and water quality. Hydrol. Process., 23, 42-61,doi: 10.1002/hyp.7162, 2009.

The glacier model: The glacier model is presented as explicitly solving subgrid scale processes, but the paper is not very forthcoming on details, and tends to cite work from obscure publications for details. The glacier model seems able to extrapolate temp, wet-bulb temp, pressure and wind at sub-grid scale resolution but what scale is this? How is it determined? Is it SRTM? Yet, it uses the 1x1km grid for precipitation and radiation. This seems to overgeneralize the most important

potentially heterogeneous variables. There is no glacier flow component, and the authors do acknowledge and discuss these limitations well. They describe a snow metamorphism component visà- vis changes in albedo. But how is albedo represented, and how sensitive is this parameter?

The glacier model parameterizes the subscale terrain using an area-elevation-distribution with subscale units within the 1 km² raster elements. These are determined in using glacier inventory data if available (e.g. for the Alps in Weber et al. (2010)) or publicly available data as described in Prasch et al. (2011b, p.60) for the LRB as referenced in the Input data section: "In general, the availability of glacier data is poor in the LRB, but the Chinese Glacier Inventory (CGI) provides polygons of the glacier areas of 1970 and additional information of their mean ice thickness. By intersecting the glacier boundaries with the ASTER GDEM and aggregating the elevation values to levels at intervals of 100m, the elevation levels for all glaciers in the LRB are deduced. In this process, each glacier is considered separately, and so the elevation levels are not aggregated among different glaciers. Next, the area per elevation level is calculated. To consider the different ice thickness distribution of a glacier in more detail than assuming a homogenous ice block, the mean ice thickness provided by the CGI is modified for all elevation levels of the glacier. Thereby a correlation between surface slope and ice thickness (Haeberli & Hoelzle, 1995), and the thinning out of the glacier to its edges and the glacier front are considered."

For these 100 m elevation levels air temperature, air pressure and wind speed are extrapolated, wet-bulb temperature is then calculated in iteratively solving the psychrometer formula.

The air temperature T [K] and air pressure P [hPa] are calculated for the various glacier levels. According to the present surface elevation z_s [m], the level air temperature T_l [K] is determined by extrapolating the air temperature T [K] of the raster cell with the mean elevation z_{gc} [m], assuming a linear, either dry or moist adiabatic lapse rate Γ [K m-1]: $T_l = T + \Gamma(z_{gc}-z_s)$

The dry adiabatic lapse rate is set to 0.0098 K m^{-1} as the quotient of the gravitational acceleration g_0 of 9.81 m s-², and the specific heat capacity of dry air at a constant air pressure c_P of 1,004.67 J kg^{-1} K^{1}. The moist adiabatic lapse rate is determined by the process of condensation of water vapour, so that latent heat is released. Since this process depends on air temperature, the gradient is inversely proportional to air temperature and varies between 0.003 and 0.009 K m^{-1}. In this study it is set to an average value of 0.0065 K m^{-1} for an air pressure of 1,000 hPa and an air temperature of 273.15 K.

The level air pressure P_l [hPa] is calculated by the barometric formula with the gravitational acceleration on Earth g_0 [9.81 m s^{-2}], the molar mass of the atmosphere M [0.028964 kg mol^{-1}] and the universal gas constant for air R [8.3143 Nm mol^{1} K^{-1}]: $P_l = P(1 + \frac{\Gamma(z_s - z_{gc})}{T})^{\frac{g_0 M}{R\Gamma}}$

As the wind speed on a glacier is different from the wind above nonglacier areas, as provided by the climate model, it has to be adopted. The glacier wind v, a katabatic flow over glaciers is caused by the differences in heat between the snow-free, surrounding areas of a glacier and the comparatively cold glacier surface. The glacier wind is characterized by speeds of 3 to 5 m s^{-1} and increases with proximity to the glacier tongue (Weber 2008). As it is very common over melting surfaces (Oerlemans and Grisogono 2002), it is considered in SURGES in a rather simple way for air temperatures above 0°C: $v_l = v + 0.0015 v (z - z_s)$

The lower limit of the level glacier wind v_l [m s^{-1}] is given by half of the wind speed of the grid cell v/2,

whereas the upper limit vl,max is determined by a simple parameterization of the maximum velocity of the glacier wind using air temperature according to Kuhn (1978) as follows: vl,max = 0.61T

For differentiation of rain from snowfall by iteratively solving the psychrometer formula, the wet-bulb temperature T_w [K] is calculated for all levels, considering the water vapour pressure e [hPa], the saturation vapour pressure of a wet surface E_w [hPa], the specific heat of air cP [J kg^{-1} K^{-1}] at a constant air pressure P [hPa] and the latent heat of vaporization r [J kg^{-1}]: $e = E_w - \frac{c_p P}{0.623 r}(T - T_w)$

The saturation vapour pressure of a wet surface E_w [hPa] is computed with the Magnus formula.

For simulation of the longwave radiation balance Q_l [W m^{-2}], the incoming longwave radiation R_{li} [W m^{-2}], provided by PROMET or SCALMET, is reduced, through the emission after the Stefan-Boltzmann Law. In addition to the emissivity ε, which is 1 for snow and 0.98 for ice, it also depends on the current level surface temperature T_S [K], which is set to 273.15 K for air temperatures above freezing point. If the air temperature is below this, the surface temperature is determined in an iterative procedure closing the energy balance (Strasser 2008): $Q_l = R_{li} - \sigma \cdot \varepsilon \cdot T_S^4$

All the other meteorological variables, e.g. precipitation or incoming radiation, are assumed to be constant throughout the grid cell and are taken from the meteorology component of PROMET or SCALMET without any adaptation. There is no indication in which way the intensity of precipitation varies on the area of one square kilometer. Additionally, wind- and leeward effects are not considered in the modeling approach, because the approach has been developed not for a single glacier but for all glaciers of a mesoscale river basin. Nevertheless, the approach can be enhanced in adding a detailed radiation model considering shading.

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.

References

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Oerlemans, J. and Grisogono, B.: Glacier winds and parameterisation of the related surface heat fluxes. Tellus, 54 A, 440-452, 2002.

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.

Strasser, U. Modelling of the mountain snow cover in the Berchtesgaden National Park. Berchtesgaden National Park research report, 55, Berchtesgaden, Germany, 104, 2008.

Weber, M.: Mikrometeorologische Prozesse bei der Ablation eines Alpengletschers. Abhandlungen – Bayerische Akademie der Wissenschaften, Mathematisch –Naturwissenschaftliche Klasse, Neue Folge, 177, Munich, Germany, 258, 2008.

We tried to give enough model details to understand the approach in our paper. For further clarification we will change the model section providing additional information, marked yellow:

Section 3.1.3 (p. 4564, ln. 18ff):

Concerning the strong variation with elevation of the processes, SURGES uses an area-elevation-distribution with subscale units (for the LRB elevation levels with intervals of 100m) (Fig. 3a) to parameterize the complex terrain…

p. 4656, ln. 26ff:

… 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).

Additionally, the third and fourth paragraph of the conclusion (p. 4573, ln.13 ff) discusses the modeling approach. This will be inserted as section "3.1.4 Discussion of the modeling approach" in the methods section as suggested by the interactive comment of Prof. Pelto. This also includes an explanation of neglecting some small-scale processes like shading caused by the surrounding mountains, which is a reason for not modifying radiation on the subscale.

Detailed formulas of the model calculations can be added as supplementary material if required. In the paper this information is too detailed and not necessary for understanding the approach in our opinion.

"Since snow that accumulates at the higher elevation levels is transformed to ice as explained above, it does not accumulate endlessly" This needs more explanation. So mass is not transferred down slope; rather, melt is instantly redirected to the stream flow from all cells (?)

SURGES considers the snow-to-ice metamorphism. Accordingly, snow that accumulates at the higher elevation levels is transformed to ice and doesn't accumulate endlessly. Further processes as sublimation, evaporation and melt are taken into account, too. Although ice flow is not considered, a significant increase in ice-mass is not simulated because of the future climate warming conditions. Nevertheless the loss of ice thickness there 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.

Released melt water is aggregated for each raster cell and then redirected to the stream flow from all cells as described in Mauser and Bach (2009). The runoff components of surface, fast and slow interflow and base flow are modeled per grid cell. On the assumption that every grid cell of the basin is part of the channel network, all cells are linked downstream following topography. The flow components are concentrated and routed through the channel network according to topography by the channel flow component. Surface flow is directly supplied to the channel, whereas interflow is delivered to major tributaries. Flow velocities and changes in water storage in the channel are simulated using the Muskingum-Cunge-Todini approach, which also maintains mass conservation.

*In the revised paper version, we will add the following explanation:*

(p. 4566, ln. 5) 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, …

Likewise, in lieu of a dynamic ice flow model, "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." This is not clear how all this works; what does Fig. 4B and C actually show? There is no demonstration of the glacier geometry "adjustment". . .is this a forced re-shaping to fit valley morphology? It would be important to show how this glacier model compares to actual glacier area evolution over the historical time span. Since the future conditions are thus mostly a temperature signal, then this model will reach a sudden threshold and instantly release melt. This appears to be what happens in the scenarios.

Fig. 4B shows the simple consideration of the impact to the snow to ice metamorphism. This process is considered in partly adding snow, which outlasted a defined number of ablation periods, to the ice layer. In Fig. 4, B snow is illustrated in white above and ice in light blue below. In between the fraction of snow, which is added to the ice-layer after the defined number of ablation periods (in the case of the LRB: half of the snow layer is added to the ice after one year), is symbolized.

Fig. 4C symbolizes the glacier geometry adjustment to the glacier bed. In the first case, the snow and ice layer on an elevation level are melted away and then the glacier area is reduced by the ice-free area of the elevation level (Fig. 4C left to right). In the second case, snow accumulates, lasts out melting periods, is partly transformed to ice and then the area of the level with new ice is added to the glacier, so that the glacier area increases (Fig. 4C right to left). In our model, glacier area can be reduced by the elevation levels or respectively increased by elevation levels, which are considered in the subscale approach below the glacier tongue as ice free levels following valley geometry. For warming climate conditions this approach seems to be sufficient, because glaciers mainly retreat. For cooling climate with extensively growing glaciers this approach might not be sufficient.

The performance of the glacier geometry adjustment has been validated as an example for the Northern and Southern Schneeferner at the Zugspitze in Germany, because in the LRB no equivalent data were available. By comparing modeled and observed ice thickness observations on the glacier scale of the Northern Schneeferner at the Zugspitze in Germany from 1970 to 2006, the accurate simulation of glacier development is validated over a long period. The following Figure shows the observed ice thickness of the years 1970, 1979, 1990, 2000 and 2006 (red) with the simulated ice thickness (light blue) and the evolution of the snow water equivalent (blue). The observations are correctly reproduced by the model. Furthermore, the period with high snowfall rates during the winters at the beginning of the 1980s and the subsequent gain in ice mass is captured by SURGES. The extraordinarily long ablation period of summer 2003 is also accurately simulated. Although this validation step only offers the comparison at five time steps during this period, it shows the performance of the model over a long time period. Only if snow and ice accumulation and ablation are simulated correctly over the complete period, the observed ice thickness values are reproduced by the model.
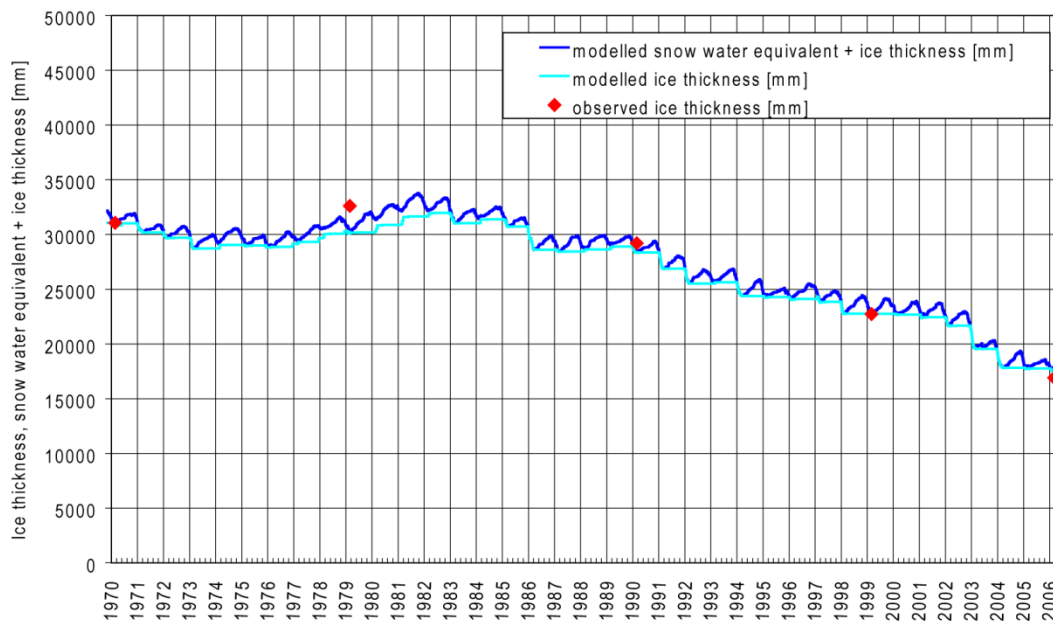

Modelled and observed ice thickness of the Northern Schneeferner at the Zugspitze in Germany (based on BAYERISCHE GLETSCHER (2009)).

In order to validate glacier geometry changes, the modelled and observed glacier areas were compared for the Northern and Southern Schneeferner as presented in the following figure. The original areas of 1979 are illustrated in black, whereas the grey areas show the extent mapped in 2006. The blue areas symbolize the modelled areas of the year 2006. The comparison shows deviations at the edges of the glaciers, in particular at the glacier tongues, where the model result is falsified by anthropogenic modifications in the skiing area (MAROWSKY 2010). Additionally, ice redistribution is not considered in this simulation. The ice flow is low because of the small extent of the Zugspitze glaciers, and so this effect can be neglected. Since the longwave radiation flux of neighbouring snow-free rocks is not simulated in SURGES, the accelerated melting during the breakup of glaciers in different parts with increasing surrounding rock areas is not reproduced. In this case, the melting is simulated too slowly, and a uniform ice thickness distribution on the elevation levels enforces this effect on the edges. In contrast, the melt from thick areas is simulated too quickly, so a conclusion of at least a partial compensation by the two effects can be drawn. Nevertheless, the

congruence over a modelling period of 26 years dominates, especially in the parts of the glaciers where most ice is stored.

A similar validation study was carried out for a larger glacier (8km²), the Vernagtferner in the Oetztal Alps in Austria.
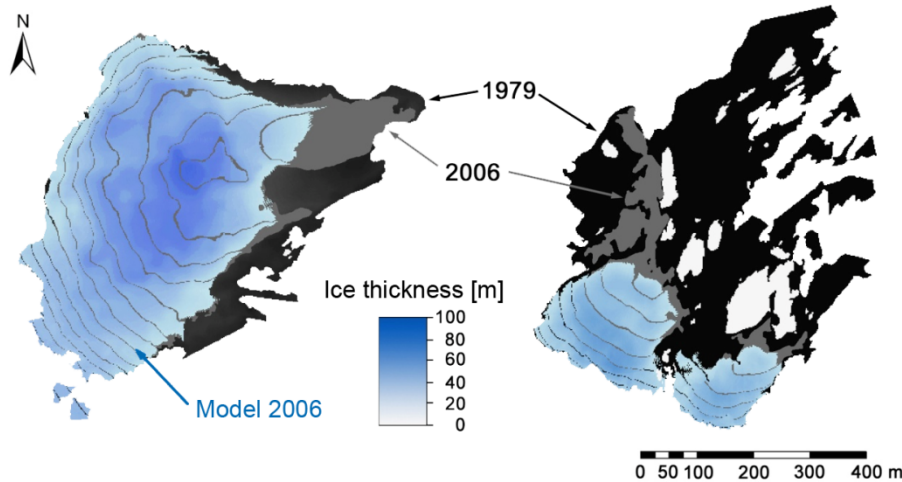
Comparison of modelled (blue) and observed glacier extent (grey and black) for the Northern (left) and Southern (right) Schneeferner at the Zugspitze in Germany between 1979 and 20006 (MAROWSKY (2010), p.70, modified).

In our approach the snow and ice melt are calculated in solving the energy balance (p 4565. ln 12f: In order to determine the ablation, mass and surface energy balance, taking into account the radiation balance, the latent and sensible heat fluxes, and the energy supplied by solid or liquid precipitation of snow and ice are calculated for every subscale unit to calculate the amount of glacier melt, which largely occurs on snow-free glacier areas (Prasch et al., 2008)). Melt can only appear for air temperatures above the freezing point, so that with climate warming glacier retreat is simulated. However, glaciers also could grow if an increase in snowfall augments temperature increase (an extensive precipitation increase of 25% in annual precipitation would be required to compensate mass loss due to a 1 K warming and to stop glacier retreat (Oerlemans, 2005), which is not the case in the applied scenarios, because changes in the amount of precipitations are small.

In the revised paper we will modify the following sections to further clarify Fig. 4. The validation example of the past for the Northern and Southern Schneeferner at the Zugspitze is too detailed in the paper itself, but can be put into Supplements.

p. 4565 ln. 19ff: Snow (Fig. 4b, white, above) to ice metamorphism is considered in partly adding snow, which outlasted a defined number of ablation periods, (Fig. 4 b, blue in between) to the ice layer (Fig. 4 b, light blue, below).

p. 4566 ln.3: Finally, glacier geometry is adjusted both in the case of melt out or growth of the ice reservoir on different elevation levels in reducing or respectively increasing glacier area (Fig. 4, C). 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. 4 C, right to left).

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References:

Bayerische Gletscher (2009): Bayerische Gletscher. http://www.bayerische-gletscher.de

MAROWSKY, K.: Die Validierung des Gletschermodells SURGES am Beispiel von Vernagtferner sowie Nördlichem und Südlichem Schneeferner. Diplomarbeit an der Kommission für Glaziologie der Bayerischen Akademie der Wissenschaften München und der Katholischen Universität Eichstätt-Ingolstadt, 147, 2010.

Detailed edits:

Fig. 1: mention that the sub-basins are labeled (presuming they are, and not the met stations?).

Sub-basins and met stations (differentiated by red triangles and yellow circles) are labeled. This will be included in the figure caption as follows:

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

Interestingly, the pour point to Brahmaputra River is ungagged, so there is no ground truth (?). There is a gage at Lhasa, but the upper glacierized catchment of Yang-baijing is hydrologically disconnected to Lhasa.

The catchment outlet to the Brahmaputra is ungauged. Gauging data of Yangbajing, Lhasa, Pangdo and Tangga are available and used in the study for the validation. In this paper we focused on the results of Yangbajing as a highly glacierized gauge and the catchment outlet to show the contribution of the Lhasa River to the Brahmaputra.

P4560, L25: "until 2000" is not as clear; does this mean from 1970-2000?

This means 1970 to 2000 and will be changed in the revised paper.

P4561 (last paragraph of section): re-write. "While the basin is only 2% glacierized as of 1970, it was selected for study because. . ."

Thank you. This will be changed in the revised paper.

It would add to continuity of the paper to describe what data are available at this point, since readers have already been directed to location Fig. 1 that includes symbols for met and discharge (what sensors, length of record?).

For clarification, we can add the following table with the description of available validation data, which were provided by ICIMOD and ITP. Details of the sensors are not known.

Station	Observed value	Observation period	Temporal resolution
Damshung	Air temperature	1980-2000	Daily
	Precipitation	1980-2000	Daily
Lhasa	Air temperature	1980-2000	Daily
	Precipitation	1980-2000	Daily
	Precipitation	1971-2000	Monthly
	Runoff	1971-2000	Monthly
	Runoff	1996-2000	Daily
Meldro Gungkar	Air temperature	1980-2000	Daily
	Precipitation	1980-2000	daily
Pangdo	Precipitation	1976-2000	Monthly
	Runoff	1976-2000	Monthly
	Runoff	1997-2000	Daily
Tangga	Precipitation	1971-2000	Monthly
	Runoff	1971-2000	Monthly
	Runoff	1996-2000	Daily

P4562 L3-8: too long; break into 2 sentences.

This sentence will be changes as follows:

Particularly evapotranspiration and the complex interactions of rainfall and snow-melt forming surface runoff, infiltrating into the soil and groundwater, forming interflow and base flow are important for runoff generation in the large downstream areas. Together with the melt water release of the glacier-ice the determination of the importance of ice-melt water throughout a mesoscale river basin are enabled.

P4562, L27: this paragraph is unclear, and too wordy.

In this paragraph the third component of our approach SCALMET and its necessity is introduced. In order to clarify this paragraph, it will be changed as follows:

A consistent meteorological data set (near surface air temperature, precipitation, air humidity, wind speed, incoming short and longwave radiation in a temporal resolution of one hour) is required for each raster element to run the models. Therefore, the scaling tool SCALEMET (Marke et al., 2011 a,b) is applied to downscale outputs of Regional Climate Models (RCMs) during runtime.

P4565, L18: change to "vanishes"

Ok – Thank you.

P4570, L24: should be evaporates

Ok – Thank you.

Fig. 4: this is a replicate from Prasch et al., 2011a:

This figure is strongly modified and extended, but we can add the citation: … (modified after Prasch et al., 2011a, p.63)

Figs. 6 and 7: the Lhasa data are identical to Prasch et al., 2011a.

This is true, but here we include the validation at the other gauges to not only show one selected result. Furthermore, here the model validation in the LRB is one focus of the paper whereas the Prasch et al.,, 2011 a focuses on the Upper Brahmaputra and the Upper Danube River Basin. If required, we can add the following after the caption:

… (Lhasa data are from Prasch et al., 2011, p.66).

Fig. 10 is just the fraction of snow/precip that is already published in Fig. 12 of Prasch et al., 2011a.

*This is not the case because Fig. 10 shows the fraction of snow precipitation only in the **LRB**, whereas Fig. 12 of Prasch et al., 2011 a shows the annual precipitation sum and the fraction of snow precipitation in the **UBRB**. That's why the shown fraction values are clearly different, also the trend is similar.*

Table 1: some redundancy in observed variables reported; can this be consolidated?

We changed the table as follows to consolidate redundancy as far as possible.

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

Table 5: clarify this is modeled output

The caption will be changed as follows:

*Annual **modeled** average water balance components (…) in mm for the presented gauges in the LRB.*

Table 7: Lhasa in 2011-2040: is 242 correct or typo? This table is not clear from caption; use "/" in explanation of values.

Thank you – 242 is a typo. The correct value is 142. We will use "/" in the explanation of the values:

Values of ice-melt / snow-melt water release on glacier surfaces / snow-melt water release on non-glacierized areas of the subbasins…

Table 8: this is complex, and re-iterates the values seen in previous tables. Are all necessary? Either way, the caption that explains that the diameter of the red/orange circles should be clarified; it accounts for "precip plus ice storage changes" but this is awkward; is it not actually "precip + storage change + ET" to be inclusive of GW? Isn't the while/"bluish" circle recording the ice storage change?

The background values for Table 8 of Tables 5 to 7 can also be put into supplements.

The white – bluish (will be changed in caption) circles show the three runoff components ice-melt, snow-melt and rainfall. Accordingly, the diameter reflects the magnitude of total runoff.

The yellow-red circles show evapotranspiration and runoff. According to the water balance "precipitation +- storage changes = runoff + evapotranspiration" the diameter represents the amount of precipitation + storage changes. Since only ice-melt changes during the periods of 30 years in our case, the yellow-red circles show the amount of precipitation + ice-storage changes which is indeed similar to the sum of runoff + evapotranspiration (see Table 5).

For better clarification the caption will be changed as follows:

… (white – bluish, left) and evapotranspiration + runoff which is similar to precipitation plus ice-storage changes (yellow/red, right)…