The modifications in the revised manuscript are given below (in blue) following the referees' comments (in black).
All line numbers in our replies refer to the revised version of the manuscript.

Response to report # 1

This manuscript describes the effect of different model variants on model performance and simulated flow components. They perform various model tests using the physically-based DHSVM model. Especially the evaluation of flow components is a novel aspect.
However, I am afraid that I have a list of rather major concerns as described in detail below. Major revisions, including new computations, are needed to bring this manuscript to its full potential.

- *Flow component definition*

Defining and simulating flow components is not trivial and it is interesting that the authors here test different definitions. However, this discussion would be even more valuable if the authors could relate their definitions to those suggested by Weiler et al.(2018) (this reference is included, but not put in relation to the definitions used here).
The section 3.2.5 "Quantification of the flow components" was modified in order to present the different types of contributions of the flow components as defined in Weiler et al. (2018):

p.10 l.12: "Quantifying the relative contributions of ice melt, snow melt, and rainfall in the river discharge at different time scales is a difficult task because hydrological models usually do not track the origin of water during transfer within the catchment (Weiler et al., 2018).
There are also different ways of defining the origins of the streamflow. Weiler et al. (2018) lists three types of contributions: 1) contributions from the source areas i.e. from each class of landcover, 2) contributions from the runoff generation (overland flow, subsurface flow, and groundwater flow), and 3) input contributions (ice melt, snowmelt, and rain).

p.10 l.17: In this study, two different definitions were used to estimate the hydrological contributions. First, we estimate the input contributions to the total production of runoff (definition 1) according to the following equations […].

p.11 l.1: In order to evaluate the seasonal components of the outflow at the catchment's outlet, we also define the hydrological contributions as fractions of the outflow coming from the different contributing areas (definition 2): […].

p.11 l.10: The definition 2 combines contributions from source areas (glacierized and non-glacierized areas) and contributions from runoff generation (direct runoff, englacial contribution, and soil contribution)."

Depending on the definition of flow components it can be required to track the different types of water through the model. For instance, glacier melt which is added to the groundwater (or 'soil', see below) might there mix with water coming from rain or snow melt. I am not fully sure, whether and, if yes, how this is done in DHSVM. Please clarify!
The following sentence was added to the section 3.2.5 "Quantification of the flow components" in order to clarify this point:
p.11 l.9: "These contributions are obtained from the amount of water reaching the soil surface simulated by DHSVM-GDM. On each grid cell, this volume is a mixture of ice melt, snowmelt and rainfall and can either infiltrate into the soil or produce runoff."

- *Model evaluation*

I am missing a comparison of daily observed and simulated flows using a measure like the NSE. Why are these results not shown?
p.16: Table 3 with all calculated NSE and KGE values for the daily discharges for each model configuration was added to section 4.1.3 "Simulated Outflow and flow components" (with comments p.15 l.21)

Furthermore, NSE and KGE values were added to Figure 13 (p.23).

Given the uncertainties in observed snow cover and mass balances: are the differences in model performances really significant? Overall, I am missing a quantification of uncertainties (please see Pappenberger and Beven (2006)

In this study we did not conduct a complete analysis of uncertainties of our simulations such as presented in Pappenberger and Beven (2006) since the existing DHSVM-GDM framework is not designed to support general uncertainty analysis. Instead, we analysed the dependency on model factors (point 9.5 according to Pappenberger and Beven, 2006) by using a multiple signal (snow, glacier and discharge) and criteria (NSE and KGE) approach to evaluate the quality of our results. Our work can be considered as a contribution to the point 9.2 (Taking account of uncertainty in model choice) as proposed by Pappenberger and Beven (2006) giving a better documentation of the model development.

This study also analyses a large variety of sources of uncertainty by comparing results obtained with (i) different representations of the processes in the model (configurations v0, v1, v2, and v3), (ii) different parametrizations (melt coefficient for debris-covered glaciers ranging from 0.3 to 0.5, soil depth under glaciers ranging between 1 and 5 m), and (iii) different descriptions of the glacierized areas (Racoviteanu et al, 2013, GAMDAM and ICIMOD glacier inventories).

Overall, a large number of simulations were realized to analyse the uncertainties. The synthesis of these simulations (presented in Mimeau, 2018) showed that the main uncertainty is related to the precipitation forcing data (point 9.3 according to Pappenberger and Beven, 2006). A manuscript on the uncertainties associated to the precipitation forcing data was recently submitted (Mimeau et al., 2018).

Mimeau, L., Quantification des contributions aux écoulements dans un bassin englacé par modélisation glacio-hydrologique. Application à un sous-bassin de la Dudh Koshi (Népal, Himalaya), Ph.D. thesis, University Grenoble Alpes, 2018

Mimeau , L., Esteves , M., Jacobi , H.W., Zin , I. [2018]. “Impact of precipitation uncertainty on the simulated hydrological response of a small glacierized Himalayan catchment”. Submitted to Journal of Hydrometeorology.

- *Model parameterization*

I am not convinced about the choice of the parameter values. Can one really use standard values for the parameters for this application in a high-mountain environment?

The authors also state: “As a results, soil depth outside glacierized areas ranges between 0.5 and 1 m. Under the glaciers, the soil depth was set to 2 m.” Why should we expect deeper soils under a glacier than elsewhere?!? This seems more like a trick to ensure a delayed response rather than a physically-based representation. As there is no description of groundwater, I assume that groundwater is not represented explicitly. The unrealistic soil depths are probably needed to compensate for the missing groundwater.

For the more sensitive parameters: how would changes in reasonable ranges affect results?

p.10 l.4: The sentence in section 3.2.4 “Glaciers parametrization” referring to the soil depth under glaciers was modified to:

“in the original DHSVM-GDM version, glacier melt is instantaneously transferred to the soil surface which is parameterized as bedrock under glaciers (Naz et al., 2014). This significantly underestimates the transfer time through glaciers. In this study we modified the soil parameterization in glacierized areas by increasing the soil depth to 2 m under glaciers. This modification of the soil depth under glaciers enables to compensate the absence of representation of the englacial liquid water storage in the model. This new parametrization also implies to change the values of three soil parameters under glaciers: the vertical and the lateral conductivities, as well as the porosity (Table A2). These were fixed by optimizing the recession shape of the hydrographs.”

p.29: A sensitivity analysis of the parameters was added to the new section “5.3.2 Sensitivity to the soil and glacier parametrization”

Please also address the devil’s advocate question: the tested model variants might just compensate differently for other model errors and if the rest of the model would be ‘more correct’ results would be different.

p.27 l6-16: A new paragraph was added discussing the possibility of the compensation of errors in the different model versions.

- *Avalanche routine*

I have several concerns with this routine. First of all, while I agree with the authors on the need to consider snow redistribution, the way it is described it largely ignores other ways of snow redistribution than avalanches (see Freudiger et al, 2017, for a recent review on snow redistribution in hydrological models).
Secondly, the routine and its parameterization seem rather ad hoc and not fully motivated. Can the parameters be motivated? What is the effect of varying them?
Furthermore, as far as I understand the text, only cardinal directions are considered. Isn't that an unrealistic assumption?
Also, from my understanding, I would assume that the avalanche routine would result in unrealistic line patterns of snow accumulation.
The glaciers located in the Pheriche catchment are known for being partially fed by avalanches, especially the West Changri Nup glacier, which are used in this study for the validation of mass balances (Sherpa et al, 2017). Ragettli et al, 2015 also showed the significant impact of avalanches on the river discharges in the Langtang region. In order to consider these processes in the model we implemented a simplified avalanche module in the model and tested the sensitivity of the routine for the simulated water balance (snow cover, glacier mass balance, and river discharge). The implementation of the avalanche routine led to an improvement of the simulated snow cover area and glacier mass balances compared to the versions without avalanches and confirmed the importance of considering snow redistribution in glacio-hydrological models. Apparently, further improvements are possible by: 1) considering eight directions for the snow redistribution would indeed be more realistic, but would need the implementation of a more complex routine (in this study the avalanche routine is based on the overland flow routing algorithm of DHSVM-GDM, which only considers 4 directions), 2) considering the redistribution of snow by wind. However, such modifications are beyond the scope of this study since they require more detailed data on the snow distribution based on in-situ observations for the study area. A sentence was added to section 5.2 'Representation of the cryospheric processes in the model' in order to present these potential model developments:
p.27 l.28: "The avalanche routine implemented in this study is simplified and only considers 4 directions for the snow redistribution. A perspective of this study is to improve the representation of the avalanches in DHSVM-GDM by considering eight directions for the snow redistribution and considering other parameters such as the age of the snow cover, the snow density and the type of land-cover as it was proposed in Frey and Holzmann (2015)."

Finally, the avalanche routine is based on Wortmann et al. (2016). This, however, is a reference to a manuscript which had been in review (HESS-D) but then has never been published in HESS. I do not think we should refer to rejected manuscripts. This means a much better description (and motivation) of the routine is needed in this manuscript.
The avalanche module presented in Wortmann et al. (2016) (based on slope and snow height thresholds) seems realistic and the referees' comments do not address this module, which is why we decided to cite this study although it has not been accepted for publication after the peer review, but it can be removed if needed.

- *Structure and language*

Please do not mix results and discussion. This makes reading the manuscript much more difficult. I strongly suggest separating these two sections.
There are a number of typos and places were grammar or words could be improved
The structure of the manuscript was modified to separate the results and discussion sections (see also our response to the first comment of referee # 2).

Response to report # 2

This manuscript proposes to quantify the origin of streamflow in a Himalayan basin, using a physically-based snow hydrological model.

The underlying research question is interesting for the readership of HESS but I have the following major concern:

In this paper, two definitions of the origin of streamflow are used: A) annual contributions of snow fall, rainfall and ice melt to total runoff, and B) fractions of contributions coming from different areas. Both definitions can answer different questions and both are certainly useful. But my main question is: Is the

water partitioning and associated water flowpaths reliably enough represented in the used hydrological model to give reliable answers under definition A and B? What evidence do you have for such a reliable representation?
Based on the model description, I am not confident that this is the case.

Overall, the paper does not yet convincingly convey that the obtained results reliably represent the dominant hydrological processes. The paper validates snow and glacier mass balance simulations but no evidence is provided for a reliably parameterization of water partitioning and release from the subsoil.
In order to present our approach more clearly, the "Results and discussion" section of the manuscript was rearranged in:

- a first part, presenting the contributions to the outflow simulated in the Pheriche catchment with an improved version of the glacio-hydrological model (Section 4. Results p.15-25),
- a second part, discussing all limitations for the quantification of the contributions to the outflow (representation of the processes in the model, parametrization, initialization and water partitioning). In particular, a discussion concerning the uncertainty related to the partitioning between direct and delayed contributions was added (Section 5. Discussion p.25-31).

Delayed water release by glaciers is e.g. emulated with a deep soil under glaciers (as far as I understand), which does not necessarily give wrong results but the implications should be clearly discussed.
A test of the sensitivity of the simulated hydrological response regarding the soil water depth under glaciers was added to section "5.3.2 Sensitivity to the soil and glaciers parametrization" p.29

Detailed comments:

- Abstract: it is stated that "In general, it is shown that the choice of a given parametrization for the snow and glacier processes has a significant impact on the simulated water balance." Should there not be a more quantitative statement, including why the approach is nevertheless deemed useful to quantify the origin of water?
I suggest mentioning all used validation data in the abstract (MODIS, mass balances)
The following information was added to the abstract:
p.1 l.15: "The choice of a given parametrization for the snow and glacier processes has a significant impact on the simulated water balance: the different parametrizations tested in this study lead to an ice melt contribution to the outflow ranging from 45 to 70 %."
p.1 l.11: "The validation of the snow, glacier and hydrological processes was established using three types of validation data (MODIS images, glacier mass balances and in situ discharge measurements)."

- Introduction: it would be nice to better say why it is interesting to know the proportion of snow / ice melt and rainfall. One reason is that this can give insights into how much water is seasonally delayed and that this delay might change in the future. Another reason is that snow melt / ice melt might have a completely different hydrological pathway (in particular in terms of groundwater recharge) than rainfall. This might e.g. cause a shift in the overall water balance if the ratio snowfall to rainfall changes (Berghuij Woods, Nature Climate Change, 2015). Another interesting question is how much water is currently available that has been accumulated long time ago in the glaciers.
The authors want to thank the referee for these suggestions, which were used to improve the introduction p.2 l.8-16.

- How does the model handle transpiration by vegetation? The loss via transpiration should be accounted for in the equations 4- 7 to quantify runoff production
In DHSVM-GDM, the losses by evapotranspiration are withdrawn from the overall soil moisture. Since there is no possibility of quantifying the partitioning between ice melt, snow melt, and rainfall in the soils simulated by the model, the contributions estimated with the definition 1 are calculated based on the volume of liquid water reaching the soil surface before evapotranspiration.

There is indeed an error in the equations 4 – 7, which was corrected as following:
Equation (8) was added p.10 to account for losses by evapotranspiration

p.10 l.28-31: “It is worth noting that the sum of these contributions Vrunoff is not equal to the outflow at the catchment outlet Q as it represents all liquid water reaching the soil surface (before infiltration in the soils and glaciers and before evapotranspiration ET).
Moreover, at daily or monthly time scale, Vrunoff may not be equal to Q - ET as liquid water can be stored by or evacuated from the soil or glaciers.”

- Results on winter flows controlled by release from the englacial water storage: what are the similar results in the literature? What provides confidence that the model parameterization is reliable?
Since it is difficult to separate groundwater and englacial flows with the used model parametrization, the sentences p.23 l.2 were replaced by:
“Groundwater and englacial water represent a significant fraction of the monthly outflow as they contribute more than 50 % during the monsoon season and can contribute up to 90 % during winter (Figure 14b).”

A comparison of our results with other studies is included in the section “5.1 Simulation of the discharge and flow components”:
p.26 l.12: “The studies of Ragettli et al. (2015) and Racoviteanu et al. (2013) concerning the Upper Langtang and the Dudh Koshi basin respectively, showed that most of the winter outflow surges from soil, channel, surface, and englacial storage changes, which is consistent with our results.”

A discussion about the uncertainty on the estimation of the delayed contributions with DHSVM-GDM was added to the discussion (5.1 Simulation of the discharge and flow components and 5.3.2 Sensitivity to the soil and glaciers parametrization).

- Throughout the paper: what is net rainfall? There is no generally accepted definition.
In this study, net rainfall is defined as the liquid precipitation minus interception by the vegetation (equation 7 p.10).

- The cited observed geodetic mass balances have a very wide range of uncertainty and stem from different areas / different time periods. It is unclear why they are nevertheless useful for validating the modelling results. This should be justified. If the geodetic estimates are from a completely different period (period is not given), this might be questionable.
A new paragraph was added to section “5.3.3 Validation and forcing data uncertainties “ (p.30 l.6 to p.31 l.4) to justify the use of the geodetic mass balances as well as the limits of such validating data.

- Figure 10: I do not clearly see which model version is the best; in terms of RMSE, v3 might (slightly) outperform v0. What about the bias? Is it a good or a bad thing that v0 has less variability of the point mass balances than v3?
The following sentence was added to the section “4.1.2 Snow cover dynamics”:
p.19 l.10: “For the Pokalde glacier, the mass balances simulated with configuration v3 show a larger variability than the mass balances simulated with configuration v0, but the point mass balances are spread around the diagonal axis which leads to a bias ten times smaller (mean bias of 1 m with v0 and 0.1 m with v3).”

- Gauging curve uncertainty: what is the design of the gauge? Does the cross-section move? Is the uncertainty estimate not far too conservative? Please provide more details than “A 15
The gauging station is located in a gorge downstream from the village of Pheriche. The geometry of the measurement section was stationary. We did not observe any change of the channel cross section. The river stage was measured every 30 minutes with a pressure transducer (resolution ±1 mm). 44 discharge measurements were performed using a tracer (fluorescein) dilution method (sudden injection). The tracer concentrations were measured every five seconds in the river downstream of the mixing zone using a fluorometer. A calibration was completed in the field for each gauging. This method is a powerful tool for measuring stream discharge, especially in steep, rough streams that cannot be gauged accurately using the velocity-area method (Hamilton and Moore, 2012). These measurements cover a range of water stages representing 95% of the range of variation observed during the study period.
The global uncertainty associated with a discharge time series combines three main sources of errors: the uncertainties in the discharge measurement, in the measurement of the stage, and in the plot of the stage-discharge relationship (Tomkins, 2012). In the case of natural channels it is difficult to predict this uncertainty precisely. In this study an estimation of its magnitude was proposed at 15%.

This estimation combines the 3 sources of uncertainty (Di Baldassarre and Montanari, 2009; McMillan et al., 2012): discharge measurements by the dilution method (5 %); the uncertainties in stage measurement and time interpolation (negligible), and the uncertainty of the rating curve (10 %).
Di Baldassarre, G., Montanari, A., 2009. Uncertainty in river discharge observations: a quantitative analysis. Hydrol. Earth Syst. Sci., 13, 913–921. doi:10.5194/hess-13-913-2009

Hamilton, A.S., Moore, R.D., 2012. Quantifying Uncertainty in Streamflow Records. Canadian Water Resources Journal 37, 3–21. doi.org/10.4296/cwrj3701865

McMillan, H., Krueger, T., Freer, J., 2012. Benchmarking observational uncertainties for hydrology: rainfall, river discharge and water quality. Hydrological Processes 26, 4078–4111. doi.org/10.1002/hyp.9384

Tomkins, K.M., 2014. Uncertainty in streamflow rating curves: methods, controls and consequences. Hydrological Processes 28, 464–481. doi.org/10.1002/hyp.9567

- General comment on conclusion: I strongly suggest to separate the discussion from the conclusion, it is very unusual to discuss results in the conclusion section
The structure of the revised manuscript was modified to separate the discussion and conclusions sections.

- Conclusion: can you really affirm that the model has an improved parameterization of the storage and transport of melt water within glaciers, or is the modified model just emulating it with the selected parameters?
In this study, we indeed did not modify the parametrization of the storage and transport of melt water within glaciers. Therefore, we replaced the following sentence:
"In this study, an improvement of the parameterization of cryospheric processes in DHSVM-GDM was proposed in order to better represent ice melt under debris covered glaciers, avalanches, the storage and transport of melt water within glaciers."
with:
"Some improvements on the cryospheric processes parameterization in DHSVM-GDM were proposed in order to better represent the snow cover dynamics, the ice melt under debris-covered glaciers, and avalanches." (p.31 l.18)

- Conclusion: instead of just stating that "The albedo parametrization (..) enabled to simulate the snow cover spatial distribution and the glacier mass balances more accurately", would be useful to refer to the validation data used
The following sentence was added to the conclusion:
p.31 l.20: "Simulated SCA were compared with MODIS images and calculated glacier mass balances with local in situ and geodetic measurements".

- Conclusion: "water is withdrawn every year from the catchment through ice melt"; strange formulation, difficult to understand; better something like "part of the streamflow leaving the catchment results from negative glacier mass balance changes".
- Conclusion: "Thus, if the precipitation regime (in terms of both intensity and phase) does not change within the next decades, the access to water resources is likely to be reduced, especially during the fall and the winter seasons, as the glaciers outflow will decrease due to glaciers shrinkage, even without taking into account climate warming." This sentence should be deleted, it is pure guessing and perhaps wrong. Continued glacier retreat means continued negative mass balances, means water input in addition to annual precipitation. The moment of peak water remains to be determined.
These sentences were deleted.

- I am not a specialist in debris covered glaciers but I think that there should be some more literature review on how important a good representation of debris cover in glacio- hydrological models is, especially in the Himalaya
The following sentences were added to the introduction:
p.2 l.24-30: "Debris-covered glaciers represent about 23 % of all glaciers in the Himalaya-Karakoram region (Scheler et al, 2011). The debris layers have been expanding during the last decades due to the glacier recession (Shukla et al., 2009; Bhambri et al., 2011; Benn et al., 2012) and are expected to keep expanding in the near future (Rowan et al., 2015). Since the study of Østrem (1959) it is known

that the debris thickness has a strong impact on the melt water generation, which means that a good representation of the debris-covered glaciers in glacio-hydrological models is essential for estimating the amount of melt water generated in glacierized catchments in the Himalayas.”

Quantification of different flow components in a high-altitude glacierized catchment (Dudh Koshi, Nepalese Himalaya)

Louise Mimeau[1], Michel Esteves[1], Isabella Zin[1], Hans-Werner Jacobi[1], Fanny Brun[1], Patrick Wagnon[1], Devesh Koirala[2], and Yves Arnaud[1]

[1]Université Grenoble Alpes, IRD, Grenoble INP, CNRS, IGE, Grenoble, France
[2]Nepal Academy of Science and Technology, NAST, Kathmandu, Nepal

Correspondence to: Michel Esteves (michel.esteves@ird.fr)

Abstract. In a context of climate change and water demand growth, understanding the origin of water flows in the Himalayas is a key issue for assessing the current and future water resources availability and planning the future uses of water in downstream regions. This study estimates the relative contributions of rainfall, glacier and snow melt to the Khumbu River streamflow (Upper Dudh Koshi, Nepal, 146 km^2, 43 % glacierized, elevation range from 4260 to 8848 m a.s.l.), as well as their seasonal variability during the period 2012-2015, by using the physically based glacio-hydrological model DHSVM-GDM (Distributed Hydrological Soil Vegetation Model - Glaciers Dynamics Model). One of the main issues in high elevated and glacierized catchments hydrology is the limited representation of cryospheric processes, which control the evolution of ice and snow, in distributed hydrological models. Here, the impact of different snow and glacier ~~parametrizations~~ parameterizations was tested by modifying the original DHSVM-GDM snow albedo ~~parametrization~~parameterization, by adding an avalanche module, and by adding a reduction factor for the melt of debris covered glaciers. The validation of the snow, glacier and hydrological processes was established using three types of validation data (MODIS images, glacier mass balances and in situ discharge measurements). Results show that this new version of ~~DHSVM~~ DHSVM-GDM improves the simulation of the snow covered area and the glacier mass balances, thus improving the reliability of the overall hydrological simulation. In the presented case study, ice and snow melt contribute each more than 40 % to the annual outflow. 69 % of the outflow originates from glacierized areas. Our simulations also highlight that winter flows are mainly controlled by the release from the englacial water storage. ~~In general, it is shown that the~~ The choice of a given parametrization for the snow and glacier processes has a significant impact on the simulated water balance: the different parametrizations tested in this study lead to an ice melt contribution to the outflow ranging from 45 to 70 %. The sensitivity of the model to the glaciers inventory was tested, demonstrating that the uncertainty related to the glacierized surface leads to an uncertainty of 20 % on the simulated ice melt component.

1 Introduction

The Himalayan mountain range is known for being the water tower of Central and South Asia (Immerzeel et al., 2010). Its high elevated glaciers and snow cover play an important role in the regional hydrological system (Kaser et al., 2010; Racoviteanu et al., 2013) and provide water resources for the population living in the surrounding countries (Viviroli et al., 2007; Singh et al., 2016; Pritchard, 2017).

In the Hindu Kush-Himalaya (HKH) region climate change is expected to cause shrinkage of the snow and ice cover (Bolch et al., 2012; Benn et al., 2012; Kraaijenbrink et al., 2017). Changes in glacier and snow cover runoff are likely to have a significant impact on the hydrological regime (Akhtar et al., 2008; Immerzeel et al., 2012; Lutz et al., 2014; Nepal, 2016). Development of tourism is also affecting the accessibility to water during the peak of tourist season. In the Everest region in Nepal water needs have increased within the past decades due to higher demand in water supply for tourists and hydroelectricity production, leading to water shortage during months with low flows (winter and spring) (McDowell et al., 2013). Understanding the past and present hydrological regime and more particularly estimating the seasonal contribution of ~~glacier and snow melt~~ice melt, snow melt, and rainfall to outflows is thus a key issue for managing water resources within the next decades. Indeed, the quantification of the ice melt contribution enables to assess the proportion of water currently available which is coming from a long term accumulation in the glaciers, and thus to assess the annual decrease of the basin water storage due to glacier melt. Moreover, knowing the fraction of snow melt, ice melt, and rainfall to the river outflow, and understanding their hydrological pathways can give insights into how much water is currently seasonally delayed and how the seasonal outflow and the overall water balance might be impacted in the future when this delay changes or if the ratio snowfall to rainfall changes (Berghuijs et al., 2014).

Recent studies have estimated present glacier and snow melt contributions to the outflow in Nepalese Himalayan catchments (e.g., Andermann et al., 2012; Savéan et al., 2015; Ragettli et al., 2015) and simulated future hydrological regimes using glacio-hydrological models (Rees and Collins, 2006; Nepal, 2016; Soncini et al., 2016). Results have demonstrated large differences in the estimates of the contribution of glaciers to the annual outflows of the Dudh Koshi catchment in Nepal, which range from 4 to 60 % (Andermann et al., 2012; Racoviteanu et al., 2013; Nepal et al., 2014; Savéan et al., 2015).

One of the main sources of uncertainty in modelling the outflow of Himalayan catchments is the representation of cryospheric processes, which control the evolution of ice and snow-covered surfaces in hydrological models. ~~Many~~ For instance, the representation of the debris covered glaciers in glacio-hydrological models is a challenge. Debris covered glaciers represent about 23 % of all glaciers in the Himalaya-Karakoram region (Scheler et al, 2011). The debris layers have been expanding during the last decades due to the glacier recession (Shukla et al., 2009; Bhambri et al., 2011; Benn et al., 2012) and are expected to keep expanding in the near future due to global warming (Rowan et al., 2015). Since the study of Østrem (1959) it is known that the debris thickness has a strong impact on the meltwater generation, which means that a good representation of the debris covered glaciers in glacio-hydrological models is essential for estimating the right amount of meltwater generated in glacierized catchment in the Himalayas. Many other cryospheric processes such as the ~~impact of debris cover on glaciers,~~ liquid water storage and transfer through glaciers, snow transport by avalanches or wind, glacial lake dynamics and snow albedo evolution are either very simplified or not at all represented by the models (Chen et al., 2017). It is therefore important to estimate the impact of such simplified representations of cryospheric processes on modelling results.

Delineation of the glacierized areas is another key entry-element to the glacio-hydrological model. Glacier inventories are commonly used as forcing data to delineate glacierized areas in glacio-hydrological modelling studies. There are three global major glacier inventories such as the World Glacier Inventory (Cogley, 2009), GlobGlacier (Paul et al., 2009) and the Randolph Glacier Inventory (Pfeffer et al., 2014), and several regional glacier inventories in the HKH region (ICIMOD (Bajracharya et al., 2010), Racoviteanu et al. (2013)), showing substantial differences. These can be due to the definition of the glacierized area itself (Paul et al., 2013; Brun et al., 2017) as well as to the characteristics of the satellite image (date, resolution, spectral properties) used for the delineation (Kääb et al., 2015), and to difficulties related to the interpretation of satellite images for outlying the glaciers, especially when they are debris covered (Bhambri et al., 2011; Racoviteanu et al., 2013; Robson et al., 2015). Thus, the question whether the glacier delineation has a significant impact on the model results needs to be addressed.

These issues of the representation of cryospheric processes and of glaciers delineation in the hydrological modelling are addressed in the present study by (i) adapting the ~~parametrization~~ parameterization of the snow albedo evolution of DHSVM-GDM, in order to improve the simulation of the snow cover dynamics; (ii) implementing an avalanche module; (iii) introducing a melting factor for debris covered glaciers and (iv) testing the sensitivity of simulated outflows and flow components with respect to these modifications as well as to glacier delineation for three different outlines coming from different glacier inventories. Both in-situ measurements and satellite data were used for evaluating the outflow simulations as well as snow cover and glacier evolutions focusing on a small headwater catchment.

An uncertainty on the estimation of the glacier contribution also results from how the contributions to the outflow are defined. There are indeed several ways to define the glacier contribution to runoff (Radić and Hock, 2014) : it can be either considered as the total outflow coming from glacierized areas, the outflow produced by the glacier itself (snow, firn and ice melt) or the outflow produced only by the ice melt. The definition of the glacial contribution is dependent to the hydrological model (distributed or lumped, representation of glaciers and snow in the model) and cannot always be chosen. In the Dudh Koshi basin, Andermann et al. (2012); Racoviteanu et al. (2013); Savéan et al. (2015) estimated the fraction of the outflow produced by ice melt, whereas Nepal et al. (2014) defined the glacier contribution as the fraction of the outflow coming from glacierized areas. Here, flow components were estimated using two different definitions of the hydrological contributions in order to control and make the best evaluation of all the terms of the water balance. Finally, the model results are analyzed at the annual, monthly, daily and sub-daily scale in order to explain the origin of the water flows and their seasonal and daily variations.

2 Study area

This study focuses on the Pheriche sub-catchment of the Dudh Koshi basin (outlet at coordinates 27.89° N, 86.82° E) located in Nepal on the southern slopes of Mt. Everest in the Sagarmatha National Park (SNP) (Fig. 1). The catchment's area is 146 km^2 and its elevation extends from 4260 to 8848 m a.s.l.

Local climate is mainly controlled by the Indian summer monsoon (Bookhagen and Burbank, 2006) and is characterized by four different seasons: a cold dry winter from December to March with limited precipitation, a warm and moist summer with most of the annual precipitation occurring during the monsoon from June until September, and two transition seasons: the pre-monsoon season in April and May and the post-monsoon season in October and November (Shrestha et al., 2000).

At 5000 m, the annual precipitation is around 600 mm of and the mean monthly temperature ranges from -8.4°C in January to 3.5°C in July, according to temperature and precipitation data from the Pyramid EvK2 station (Fig. 2 and Table 1). The hydrological regime follows the precipitation cycle with high flows during the monsoon season, when most of the annual precipitation occurs, complemented by the melting of snow and ice, and low flows during winter.

Due to high elevation, the vegetation in the catchment is scarce. The basin area is mainly covered by rocks and moraines (43 %) (Bajracharya et al., 2010) and glaciers (43 %) (Racoviteanu et al., 2013). Only 14 % of the basin area is covered by grasslands and shrublands. Glaciers belong to the summer-accumulation type (Wagnon et al., 2013) and are partially fed by avalanches (King et al., 2016; Sherpa et al., 2017). 60 % of the glaciers are located between 5000 and 6000 m a.s.l.. Debris-covered glaciers are found at low elevations mainly on the ablation tongues of the glaciers (Fig. 3). According to the Racoviteanu et al. (2013) glacier inventory, they represent 30 % of the glacierized area with smaller melting rates at similar elevations than debris-free glaciers due to the insulating effect of the debris layer (Vincent et al., 2016).

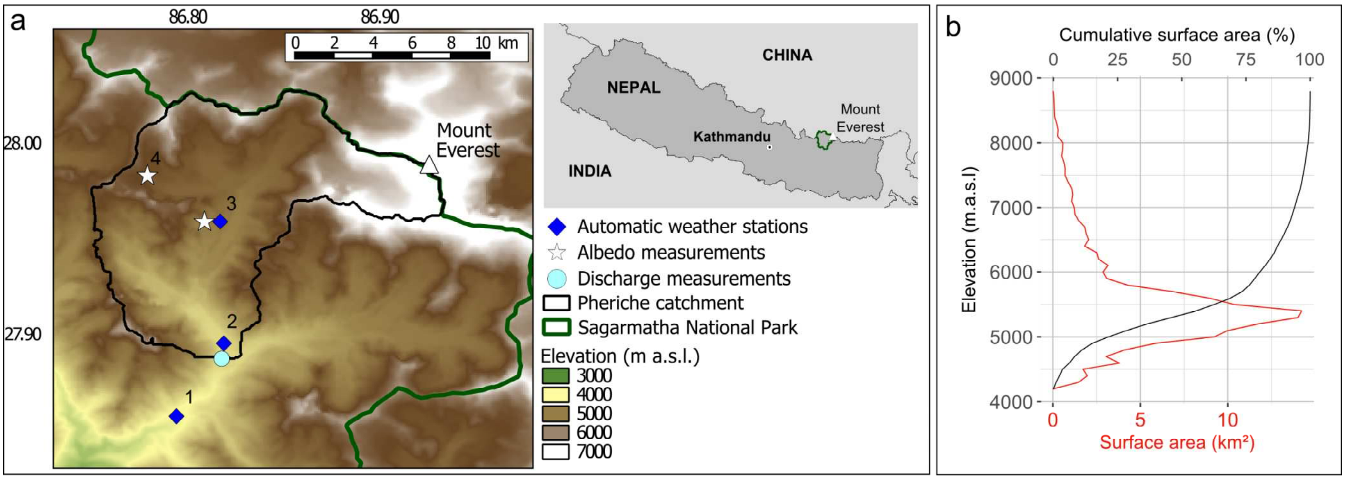

Figure 1. Study area : (a) Location map of Pheriche catchment (black) in the Sagarmatha National Park (green) in Nepal. Characteristics of the meteorological stations are summarized in Table 1. (b) Hypsometric curve of the Pheriche catchment.

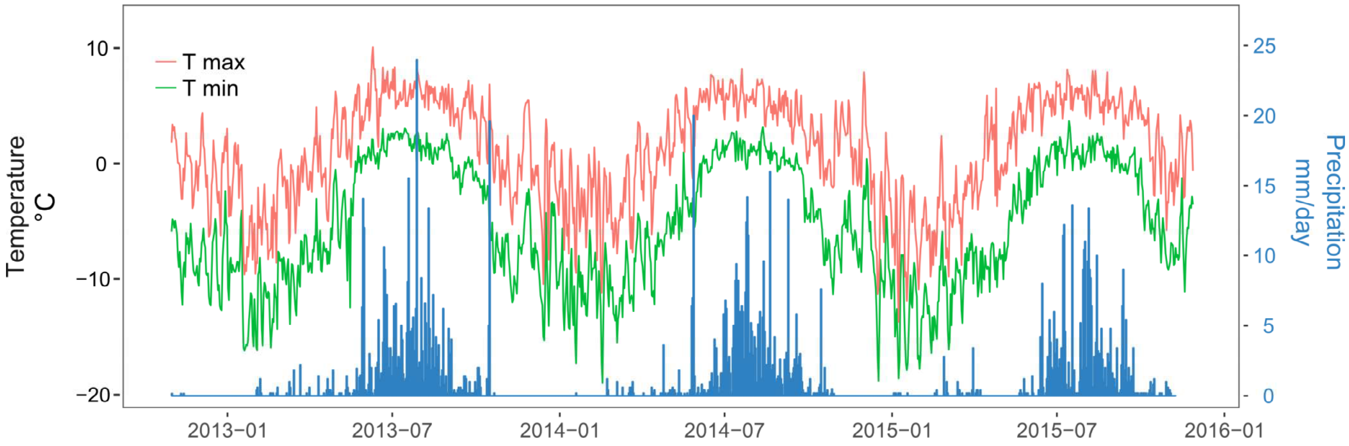

Figure 2. Daily minimal and maximal air temperature and daily precipitation measured at the Pyramid station.

3 Data and model setup

3.1 Database

To describe the topography of the study area, an ASTER DEM originally at 30 m resolution was resampled to a 100 m resolution. The SOTER Nepal soil classification (Dijkshoorn and Huting, 2009) and a landcover classification from ICIMOD (Bajracharya, 2014) were used for the soil and landcover description.

Meteorological data were available at hourly time steps from three automatic weather stations (AWS) located at Pangboche (3950 m a.s.l.), Pheriche (4260 m a.s.l.) and Pyramid (5035 m a.s.l.) (Table 1). Since December 2012, the precipitation has been recorded at the Pheriche and Pyramid AWS by two Geonor T-200 sensors designed to measure both liquid and solid precipitations. Data were corrected for potential undercatch following the method used by Lejeune et al. (2007) and Sherpa et al. (2017). Precipitation at the Pangboche station was recorded with a tipping bucket. Air temperature, wind speed, relative humidity short-wave radiation and long-wave radiation measurements at Pheriche and Pyramid were provided by the EvK2-CNR stations.

Discharge measurements of the Khumbu River at Pheriche were obtained using a pressure water level sensor at ~~1 h~~ a 30 minutes time step since October 2010.

Glacier outline	Area	Satellite imagery used for delineation	Acquisition dates	Spatial resolution of the satellite images used for delineation
Racoviteanu et al. (2013)	Dudh Koshi, Langtang	ASTER, IKONOS-2	2003-2008	1 - 90 m
GAMDAM (Nuimura et al., 2015)	Asian glaciers	SRTM, LANDSAT	1999-2003	30 - 120 m
ICIMOD (Bajracharya et al., 2010)	Nepal	IKONOS, LANDSAT, ASTER	1992-2006	1 - 120 m

Table 2. Glacier outlines characteristics

N°	Name	Elevation (m)	Lat (°)	Lon (°)	Measured parameters	Manager
1	Pangboche	3950	27.857	86.794	T, P	IRD
2	Pheriche	4260	27.895	86.819	T, P, WS, RH, SWin	EvK2-CNR, IRD
3	Pyramid	5035	27.959	86.813	T, P, WS, RH, SWin, SWout, LWin	EvK2-CNR, IRD
4	Changri Nup	5363	27.983	86.779	SWin, SWout	GLACIOCLIM

Table 1. Location of measurements. **T** air temperature, **P** precipitation, **WS** wind speed, **RH** relative humidity, **SWin** incoming shortwave radiation, **SWout** outgoing shortwave radiation, **LWin** incoming longwave radiation.

The MODImLab algorithm developed by Sirguey et al. (2009) was applied to MODIS reflectances data to obtain daily albedo and snow fraction satellite images for the period 2010-2015. We used the Sirguey et al. (2009) algorithm rather than the MOD10A1 500 m snow products because it generates daily regional snow cover images at 250 m resolution and applies corrections on atmospheric and topographic effects which makes the snow cover maps more realistic on mountainous areas. 27 cloud free Landsat8 images were used to generate snow maps at 30 m resolution between 1 November 2014 and 31 December 2015. A NDSI (Normalized-Difference Snow Index) threshold of 0.15 was taken to separate snow free and snow covered pixels on Landsat8 data as proposed by Zhu and Woodcock (2012). Daily snow cover maps were then retrieved from the MODImLab snow fraction product: areas with a snow fraction above 0.15 were defined as snow covered areas so that the MODImLab Snow cover area (SCA) matches the Landsat8 SCA on the common dates. For the rest of this study we call MODIS data albedo and snow cover data obtained with the MODImLab algorithm. We also used snow albedo data from in-situ measurements at Pyramid and Changri Nup (Table 1).

For describing the glacierized area in the basin we compared three different glacier outlines available as vector layers for the Khumbu region: the glacier delineation proposed by Racoviteanu et al. (2013) specifically set up for the Dudh Koshi basin; the GAMDAM inventory covering the entire Himalayan range (Nuimura et al., 2015); and the ICIMOD inventory (Bajracharya et al., 2010) (Fig. 3). The three outlines have been derived on different grids, from different datasets at different spatial resolutions and covering different temporal periods (see Table 2), thus leading at different results.

Mass balances estimated by Sherpa et al. (2017) for the clean-ice West Changri Nup and Pokalde glaciers located in the Pheriche basin (Fig. 3) were used as reference, as well as mean annual glacier mass balances calculated over the Pheriche basin area for the period 2000-2016 by Brun et al. (2017).

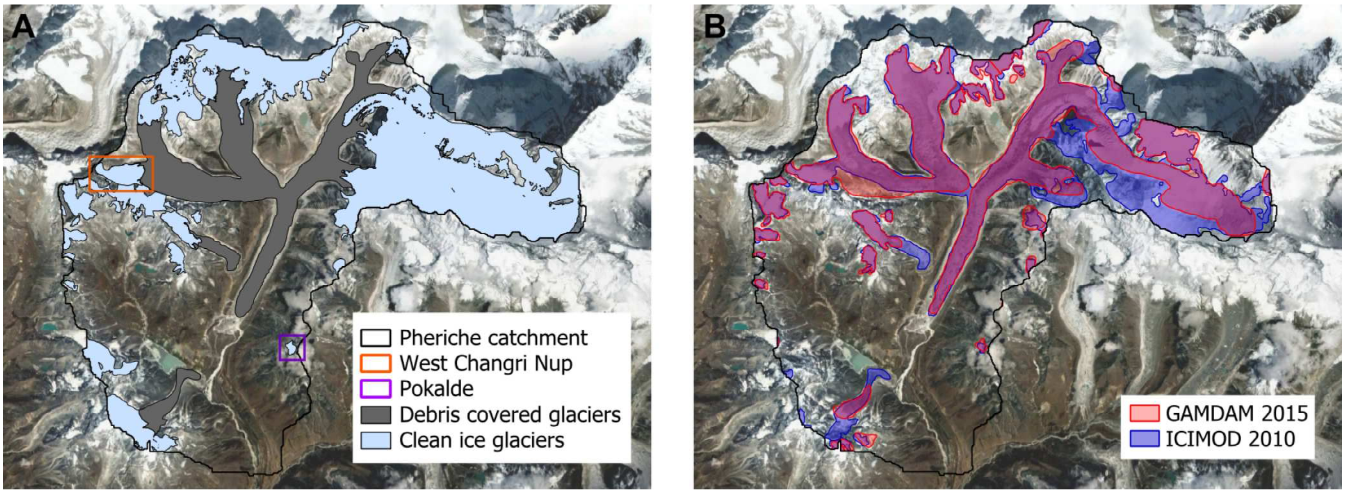

Figure 3. Glacier outlines in the Pheriche catchment. (a) Clean glaciers and debris-covered glaciers from Racoviteanu et al. (2013) and location of the clean ice West Changri Nup and Pokalde glaciers (b) GAMDAM (red) and ICIMOD (blue) glacier outlines

3.2 Glacio-hydrological modelling

3.2.1 General description of the model

The glacio-hydrological model DHSVM-GDM (Distributed Hydrological Soil Vegetation Model - Glaciers Dynamics Model) was used for simulating outflows at Pheriche. DHSVM is a physically based, spatially distributed model which was developed for mountain basins with rain and snow hydrological regimes ~~(Wigmosta et al., 1994; Nijssen et al., 1997; Wigmosta and Burges, 1997)~~(W A glacier dynamics module was recently implemented in DHSVM by Naz et al. (2014) to simulate glacier mass balance and the runoff production in catchments with glaciers, thus extending the application to ice dominated hydrological regimes. The resulting DHSVM-GDM simulates the spatial distribution and the temporal evolution of the principal water balance terms (soil moisture, evapotranspiration, sublimation, glacier mass balance, snow cover, and runoff) at hourly to daily time scales. It uses a two-layer energy and mass balance module for simulating snow cover evolution and a single layer energy and mass balance module for glaciers (Andreadis et al., 2009; Naz et al., 2014) and has been applied in a number of studies for snow and cold regions hydrology (e.g., Leung et al., 1996; Leung and Wigmosta, 1999; Westrick et al., 2002; Whitaker et al., 2003; Zhao et al., 2009; Bewley et al., 2010; Cristea et al., 2014; Frans et al., 2015). Distributed meteorological data (air temperature, precipitation, relative humidity, wind speed, and shortwave and longwave incoming radiation) are requested as input, as well as distributed geographical information (elevation, soil type, landcover, soil depth, and ice thickness).

3.2.2 Snow albedo ~~parametrization~~parameterization

In the original DHSVM-GDM version, the snow albedo α_s [-] is set to its maximum value α_{smax} (to be fixed either by calibration or from observed albedo values), after a snowfall event and then decreases with time according to the following equations (Wigmosta et al., 1994):

$$\begin{aligned} \alpha_s &= \alpha_{smax}\,(\lambda_a)^{N^{0.58}} \quad if \quad T_s < 0 \\ \alpha_s &= \alpha_{smax}\,(\lambda_m)^{N^{0.46}} \quad if \quad T_s \geqslant 0 \end{aligned} \tag{1}$$

Where N is the number of days since the last snowfall, λ_a [-] and λ_m [-] correspond to 0.92 and 0.70 for the accumulation season and the melt season, respectively, and T_s is the snow surface temperature [°C].

MODIS albedo images and the albedo measurements from Pyramid and Changri Nup were used to analyse the decrease of snow albedo with age in various locations of our study area. Figure 4 compares the observed albedo decay as a function of time for snow events with at least three consecutive days without clouds after the snowfall with the albedo ~~parametrization~~ parameterization in DHSVM-GDM. Since the observed values are not well represented by the standard albedo decrease, the ~~parametrization~~ parameterization was replaced by Eq. 2, with a decay of the albedo when there is no new snowfall inspired by the ISBA model albedo ~~parametrization~~ parameterization (Douville et al., 1995) and with the fresh snow albedo modified as a function of the amount of snowfall:

$$\begin{aligned} \alpha_s &= (\alpha_{st-1} - \alpha_{smin})\,exp(-cN) + \alpha_{smin} && if \quad i_{snowfall} = 0\ mm/h \\ \alpha_s &= max(0.6,\ \alpha_{st-1}) && if \quad 0\ mm/h < i_{snowfall} \leqslant 1\ mm/h \\ \alpha_s &= max(0.6,\ \alpha_{st-1}) + (\alpha_{smax} - max(0.6,\ \alpha_{st-1}))\,\frac{i_{snowfall}-1}{3-1} && if \quad 1\ mm/h < i_{snowfall} \leqslant 3\ mm/h \\ \alpha_s &= \alpha_{smax} && if \quad i_{snowfall} > 3\ mm/h \end{aligned} \tag{2}$$

Where α_{st-1} is the albedo from the previous time step, α_{smin} is the minimal snow albedo of 0.3 (estimated using the mean minimal albedo values observed at the station and on MODIS images), N is the number of days since the last snowfall, c is the coefficient of the exponential decrease [days^{-1}], and $i_{snowfall}$ the snowfall intensity [mm/h]. Since the observed decrease is dependent on elevation, the coefficient c is calculated as a function of elevation according to Eq. 3:

$$c = 20\ exp(-0.001\ Z) \tag{3}$$

Where Z is the elevation of the cell in m a.s.l.

The new function for the decrease of the snow albedo is also shown in Fig. 4.

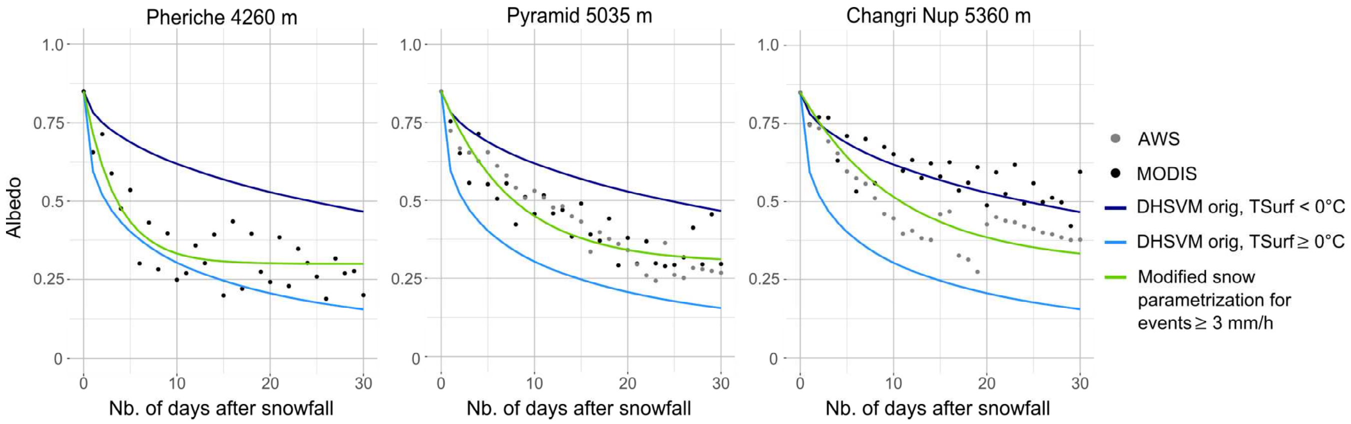

Figure 4. Original and modified ~~parametrization~~ parameterization of the snow albedo evolution in DHSVM-GDM and comparison with observed albedo data (2010-2015) in Pheriche, Pyramide and Changri Nup.

3.2.3 Avalanches ~~parametrization~~parameterization

The transport of snow by avalanches is not represented in the original version of DHSVM-GDM. The absence of avalanches in the model can lead to an unrealistic accumulation of snow in steep high elevated cells, where the air temperature remains below 0 °C, and to a deficit of snow in the lower areas, where snow melt occurs during the melting season. The simulated water balance directly depends on the snow cover, thus not considering avalanches can lead to significant errors. In order to address these discrepancies, an avalanche module inspired by Wortmann et al. (2016) was implemented in DHSVM-GDM. The avalanche model transfers snow to downslope neighbour cells under the following conditions:

- if the terrain slope is steeper than 35 ° and the amount of dry snow water equivalent (total snow water equivalent minus liquid water content) is higher than 30 cm: 5 cm of snow water equivalent remains in the cell and the rest is removed by avalanches;
- if the terrain slope is less steep than 35 ° but the difference in snow water equivalent compared to the downslope neighbour cells is larger than ~~5~~50 cm: 95 % of the difference is removed by avalanches.

The transfer of snow by avalanches is based on the surface runoff routing in DHSVM-GDM: at every time step starting from the highest cell of the DEM to the lowest, each cell can transfer snow to its closest downslope neighbour cells (between 1 and 4 cells). Within the same time step, the amount of snow in the receiving cells is actualised and the avalanches propagate downslope until the conditions cited above are no longer respected.

3.2.4 Glacier ~~parametrization~~parameterization

The distributed ice thickness is derived from the terrain slope following the method described in Haeberli and Hölzle (1995).

Since the standard DHSVM-GDM model does not take into account the impact of the debris layer on melting of the glaciers, the insulating effect of the debris layer is not represented. Here, we implemented a reduction factor for ice melt generated in grid cells with debris-covered glaciers (see Sect. 3.3).

Moreover, in the original DHSVM-GDM version~~glacier, melt water~~ , glacier melt is instantaneously transferred to the ~~surface of the soil layer~~ soil surface which is parameterized as bedrock under glaciers (Naz et al., 2014). This significantly underestimates the transfer time through glaciers. In this study we modified the soil ~~parametrization in order to include the liquid water storage~~ parameterization in glacierized areas by increasing the soil depth to 2 m under ~~all glaciers, in order to include the~~ glaciers. This modification of the soil depth under glaciers enables to compensate the absence of representation of the englacial liquid water storage ~~and the delayed englacial transfer. This~~ in the model. This new parametrization also implies to change the values of three soil parameters under glaciers: the vertical and the lateral conductivities, as well as the porosity (Table A2). These were fixed by optimizing the recession shape of the hydrographs.

3.2.5 Quantification of the flow components

Quantifying the relative contributions of ice melt, snow melt and rainfall in the river discharge at different time scales is a difficult task because hydrological models usually do not track the origin of water particles during transfer within the catchment ~~Weiler et al. (2018).~~ (Weiler et al., 2018). There are also different ways of defining the origins of the streamflow. Weiler et al. (2018) lists three types of contributions: 1) contributions from the source areas i.e. from each class of landcover , 2) contributions from the runoff generation (overland flow, subsurface flow, and groundwater flow), and 3) input contributions (ice melt, snowmelt, and rain).

In this study, two different definitions were used to estimate the hydrological contributions. First, we estimate the ~~contributions of~~ input contributions (ice melt (~~$V_{icemelt}$~~$V_{icemelt}$), snow melt ($V_{snowmelt}$), and net rainfall ($V_{rainNet}$)) to the total production of runoff (V_{runoff}) (definition 1) according to the following equations:

$$\begin{aligned} V_{runoff} &= V_{icemelt\,icemelt} + V_{snowmelt} + V_{rainNet} && (4)\\ V_{icemelt\,icemelt} &= V_{glAcc} - S_{ice} - \frac{dI_{wq}}{dt} && (5)\\ V_{snowmelt} &= P_{solid} - S_{snow} - V_{glAcc} - \frac{dS_{wq}}{dt} && (6)\\ V_{rainNet} &= P_{liquid} - E_{int} && (7)\\ Q &= V_{runoff} + ET && (8) \end{aligned}$$

Where V_{glAcc} is the amount of snow that is transferred to the ice layer by compaction on glaciers (Naz et al., 2014), S_{ice} and S_{snow} are the amounts of sublimation from the ice and snow layers, $\frac{dI_{wq}}{dt}$ and $\frac{dS_{wq}}{dt}$ are the variations of the ice and snow storages, P_{solid} and P_{liquid} are the amounts of solid and liquid precipitation, and E_{int} is the amount of evaporation from intercepted water stored in the canopy. It is worth noting that ~~at daily or monthly time scale,~~ the sum of these contributions ~~may not be~~ V_{runoff} is not equal to the outflow at the catchment outlet ~~as liquid water~~ Q as it represents all liquid water reaching the soil surface (before infiltration in the soils and glaciers and before evapotranspiration ET). Moreover, at daily or monthly time scale, V_{runoff} may not be equal to $Q - ET$ as liquid water can be stored by or evacuated from the soil or glaciers.

In order to evaluate the seasonal components of the outflow at the catchment's outlet, we also define the hydrological contributions as fractions of the outflow coming from the different contributive areas (definition 2):

- direct glacier contribution: direct runoff from glacierized areas,
- delayed glacier contribution: resurging melt water stored inside glaciers,
- direct snow contribution: direct outflow from snow covered non-glacierized areas,
- direct runoff: direct runoff from areas without snow and glaciers,
- subsurface and groundwater contribution: resurging water from the soil in non-glacierized areas resulting from infiltrated rainfall, snow melt, as well as upstream lateral subsurface flows.

These contributions are obtained from the amount of water reaching the soil surface simulated by DHSVM-GDM. On each grid cell, this volume is a mix of ice melt, snowmelt and rainfall and can either infiltrate in the soil or produce runoff. The definition 2 combines contributions from source areas (glacierized and non-glacierized areas) and contributions from runoff generation (direct runoff, englacial contribution, and soil contribution).

Figure 5 illustrates the two definitions of the different contributions to outflows. Definition 1 allows assessing the annual impact of glaciers and snow cover on the water production, while Definition 2 describes the intra-annual routing of the water within the catchment. Moreover, using the two definitions allows to directly compare our results with other hydrological modelling studies in the Dudh Koshi basin, which have estimated glaciers contributions either from effective ice melt (Savéan et al., 2015; Ragettli et al., 2015; Soncini et al., 2016) or runoff from glacierized areas (Immerzeel et al., 2012; Nepal et al., 2014). Further, we assessed the impact of the definition of hydrological components on the estimated glaciers contribution.

Flow components were estimated for the period 2012-2015 at annual scale, on the basis of the glaciological year (from 1 December to 30 November), as well as monthly, daily, and sub-daily scales, in order to have a better understanding of the seasonal variation of the hydrological contributions.

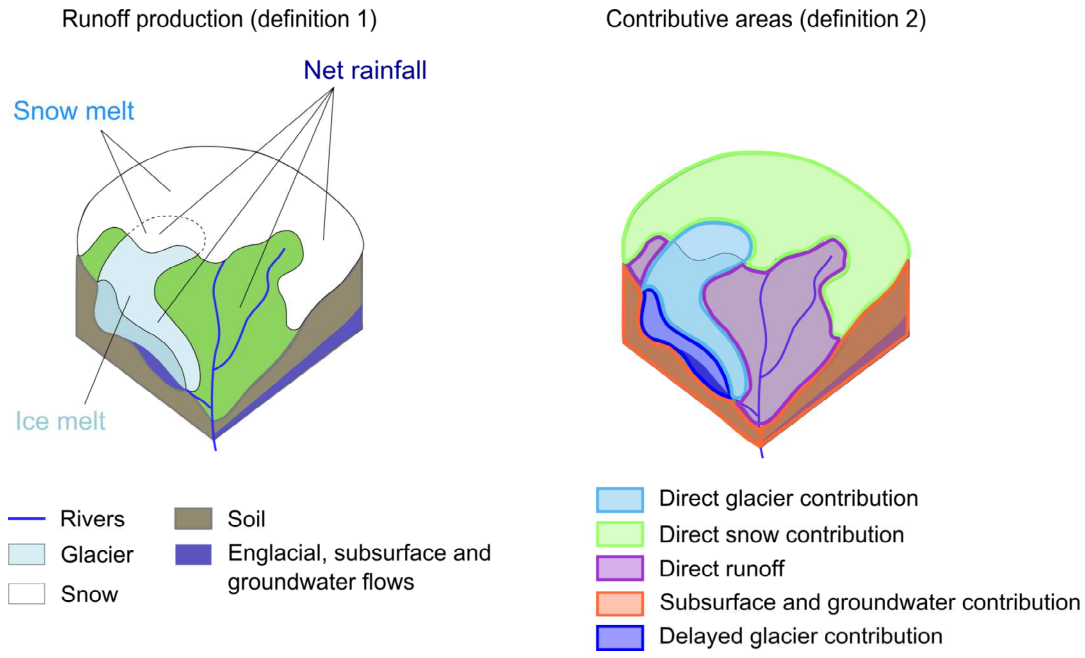

Figure 5. Definitions of the flow components.

3.3 Experimental set-up

Simulations were run with a 1 h time step and a spatial resolution of 100 m for the period from 1 November 2012 to 27 November 2015 corresponding to the period with most available meteorological and discharge data.

A soil depth map was derived from the DEM using the method proposed in the DHSVM-GDM documentation (Wigmosta et al., 1994). As a ~~results~~result, soil depth outside glacierized areas ranges between 0.5 and 1 m. Under the glaciers, the soil depth was set to 2 m. All parameter values retained for the simulations (with no calibration) are summarized in Appendix A.

In order to test the impact of the representation of the cryospheric processes on the hydrological modelling, we performed simulations with the four following configurations:

- v0: original DHSVM-GDM snow and glacier ~~parametrization~~parameterization;
- v1: modified snow albedo ~~parametrization~~parameterization;
- v2: modified snow albedo ~~parametrization~~ parameterization and avalanche module;
- v3: modified snow albedo ~~parametrization~~parameterization, avalanche module and melt coefficient for debris covered glaciers.

All four configurations were run with the Racoviteanu et al. (2013) glaciers outline. Concerning the melt of the debris-covered glaciers, we use a reduction factor of 0.4 as estimated by Vincent et al. (2016) from a study on uncovered and debris covered areas of the Changri Nup glacier.

Using configuration v3, we also tested the impact of using different glaciers outlines (the GAMDAM and ICIMOD inventories were also considered for simulations). The debris-covered glacier melt reduction factor estimated in Konz et al. (2007), Nepal et al. (2014) and Shea et al. (2015) are respectively equal to 0.3, 0.33 and 0.47. Thus, values between 0.3 and 0.5 were also considered (in addition to the reference of 0.4) in order to evaluate the sensitivity of the model to the debris covered glacier reduction factor.

3.3.1 Model forcing

Meteorological data from the Pheriche and Pyramid stations (Table 1) were spatialized over the basin by an inverse distance interpolation method. Altitudinal lapse rates of precipitation and temperature were calculated at 1 h time step from data collected at Pangboche (3950 m a.s.l.), Pheriche (4260 m a.s.l.) and Pyramid (5035 m a.s.l.) (Fig. 6). Only significant lapse rates with R^2 values higher than 0.75 were retained for precipitation (43 % of the dataset). For smaller R^2, the lapse rate is considered as not significant and thus set to 0.

In this study, the precipitation lapse rates show a large seasonal variability with daily lapse rates ranging from -41 to 9 mm km^{-1}. Precipitation decreases with elevation during the monsoon season and increases with elevation in winter: during the simulation period, we found 450 days (40 %) with no precipitation, 83 days (8 %) with a strictly negative lapse rate and 165 days (15 %) with a strictly positive lapse rate. Concerning temperatures, daily lapse rates range from -0.009 to +0.006 °C m^{-1}. We found only 10 days (1 %) showing a temperature inversion with a positive daily lapse rate.

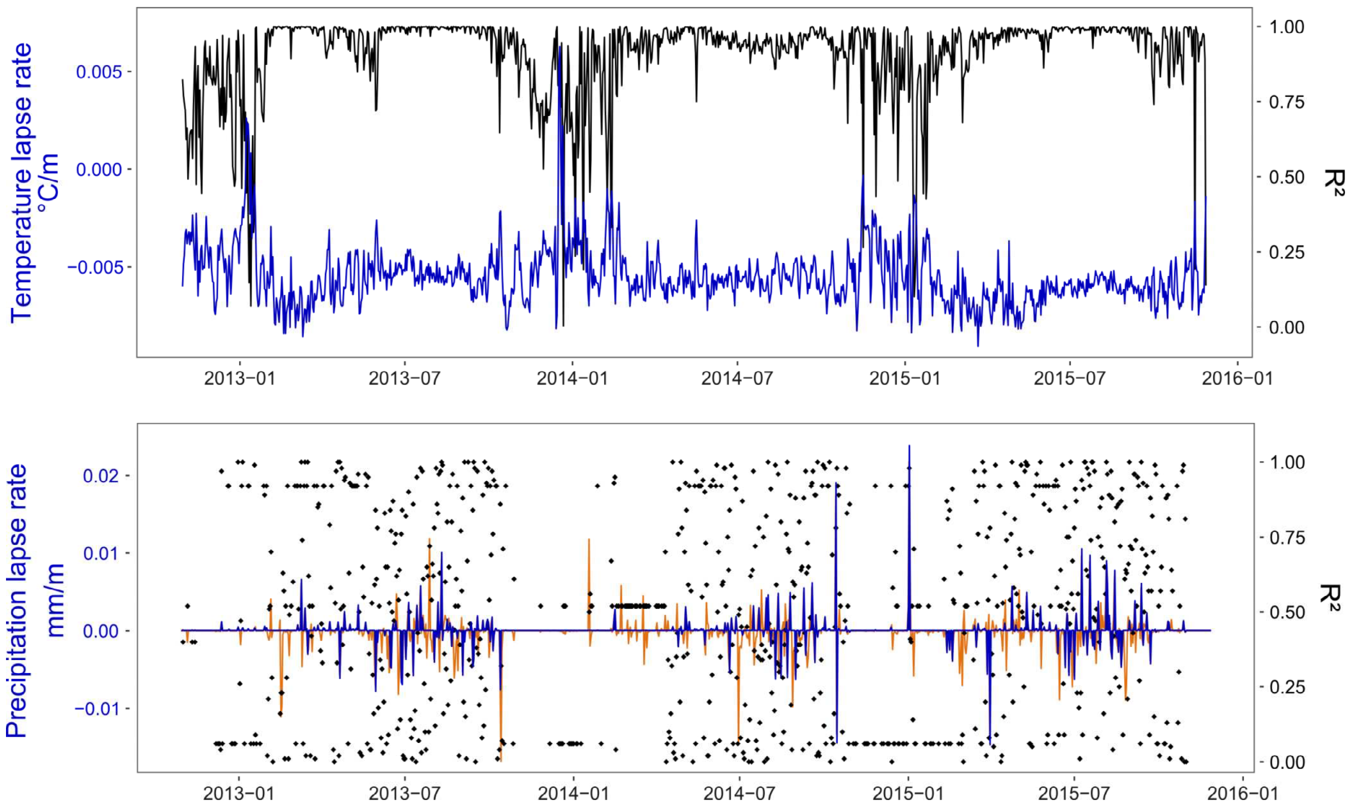

Figure 6. Daily temperature and precipitation lapse rates. Discarded precipitation lapse rates (with a R^2 <0.75) are represented in orange.

3.3.2 Model evaluation

A multi criteria evaluation was made considering simulated outflows, SCA and glacier mass balances. Discharge measurements at Pheriche station were used as reference for the evaluation of simulated outflows. A 15 % confidence interval was retrieved as representative of the uncertainty of measured discharge. Nash-Sutcliffe Efficiency (NSE) (Nash and Sutcliffe, 1970) and Kling-Gupta Efficiency (KGE) (Gupta et al., 2009) were chosen as objective functions and applied to daily discharges. The simulated SCA was evaluated in comparison to daily SCA derived from MODIS images. Because a large number of MODIS images suffer from cloud coverage, we only compared the simulated and observed SCA during days with less than 5 % of cloud cover on the catchment. The simulated glacier mass balances were evaluated at basin scale by a comparison with published regional geodetic mass balances and at local scale using available stake measurements on the clean ice West Changri Nup and the Pokalde glaciers (Sherpa et al., 2017).

4 Results~~and discussion~~

4.1 Impact of the snow and glacier ~~parametrizations~~ parameterizations on the simulated results

This section presents the simulation results obtained with the different configurations of the model DHSVM-GDM (configurations v0, v1, v2, and v3, see ch. 3.3) and the analysis of the impact of the snow and glacier parameterizations on the annual outflow, the daily SCA, annual glacier mass balances.

4.1.1 Annual outflow

Figure 7 represents the annual outflow and flow components (definition 1) simulated with the different model configurations, indicating the impact of each modification of the snow and glacier parameterization on the simulated annual outflow and the glacier contribution to the runoff. Configuration v1 leads to a drastically increased outflow due to an enhanced ice melt component. Implementing the avalanche module (v2) reduces the ice melt component and increases the snow melt component by 21 %. Configuration v3 including debris-covered glaciers further reduces the ice melt, resulting in a simulated annual outflow close to the observations.

Figure 7 shows that configuration v2, which does not consider the debris-covered glaciers, overestimates the outflow at Pheriche with a mean bias of +32 % compared to the annual observed outflow. Without the debris layer, the ice melt component represents 817 mm, which is nearly twice the amount of ice melt obtained with v3 that includes debris-covered glacier melt.

The configuration with all three modifications (v3) gives results similar to the original parameterization of DHSVM-GDM (v0) in terms of glacier mass balance, improving slightly the annual outflow. The ice melt factor for debris covered glaciers and the avalanches compensate the increase of ice melt caused by the new snow albedo parameterization, but the modifications implemented in v3 impact the results for the flow components: on average, less ice melt and more snow melt are generated. Moreover, the configuration v3 modifies the seasonal variation of the outflow by increasing winter discharges and reducing monsoon discharges (not illustrated here) which improves the daily NSE and KGE (Table 3).

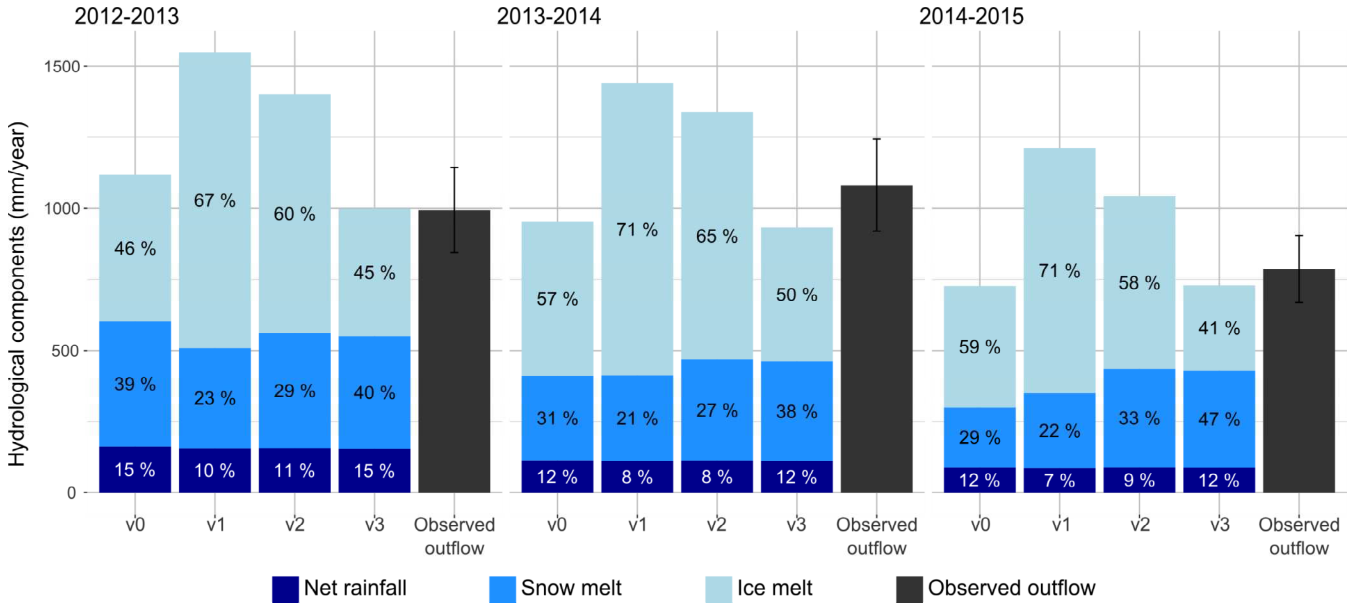

Figure 7. Simulated annual hydrological contributions (Definition 1) to Pheriche outflow for 3 glaciological years from 12/2013 to 11/2015.

	v0	v1	v2	v3
NSE	0.87	0.53	0.74	0.91
KGE	0.83	0.5	0.65	0.88

Table 3. NSE and KGE values calculated on the daily discharges on the period 2012-2015 for each model configuration.

4.1.2 Snow cover dynamics

Figures 8 and 9 compare the simulated snow cover area (SCA) and duration obtained with the configurations v0, v1, v2, and v3 to data derived from MODIS images. The SCA is ~~clearly~~ strongly overestimated using the original ~~parametrization~~ parameterization v0: Figure 8 shows that after full coverage it does not decrease fast enough compared to the MODIS data. Figure 9 demonstrates that the snow cover duration is over-estimated for the entire catchment area. This indicates that in the simulations snow does not melt fast enough ~~with the original parametrization~~using the original parameterization. Configuration v1 with the modified snow albedo ~~parametrization~~ parameterization (Eq. 2) accelerates the snow melt and improves the SCA simulation (Fig. 8). The RMSE between the simulated and observed SCA decreases from 29 % using v0 to 14 % using v1 and v2. Figure 9 shows that with configuration v1 in some areas located at high elevation the snow cover duration is underestimated. This ~~biais~~ bias is rectified in configuration v2 since the avalanche module transfers snow from high elevated and sloping cells downward and corrects the lack of snow ~~observed~~ simulated with configuration v1 at the edges of the permanent snow cover (Fig. 9). The results for the SCA and snow cover duration using the ~~configuration v3 show no difference compared to the configuration~~ configurations v2 and v3 are the same since only the ice melt rate for debris covered glaciers is modified.

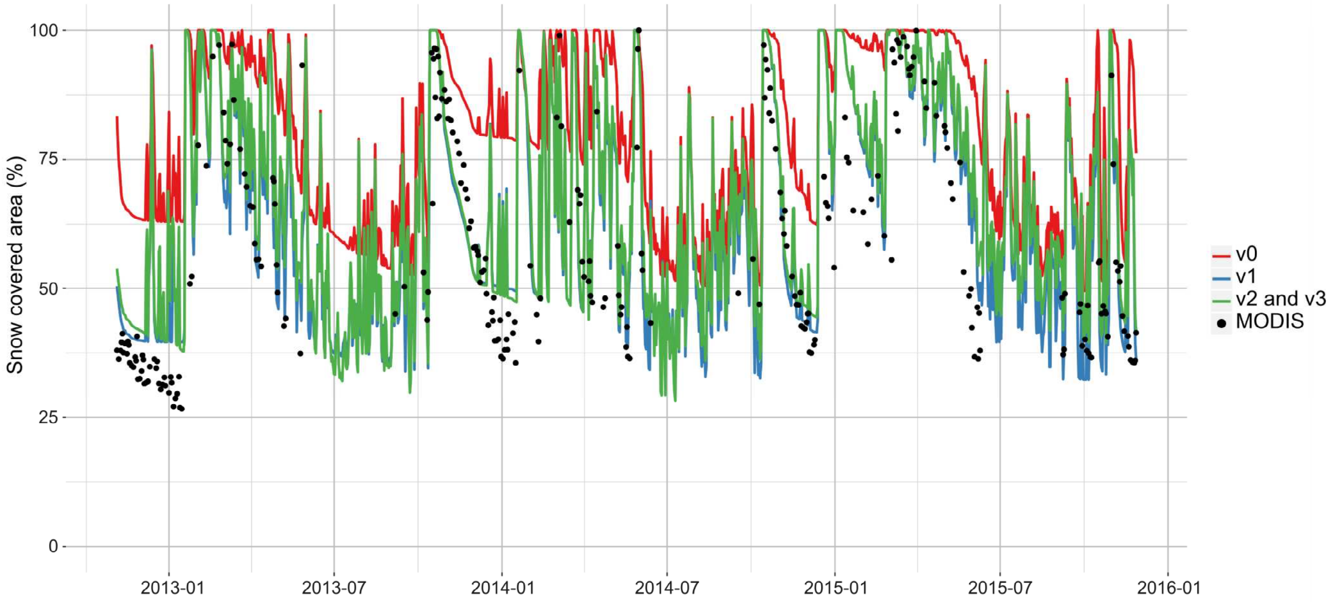

Figure 8. Comparison of the MODIS SCA and the simulated daily SCA with the four modelling configurations (v0, v1, v2 and v3) for the Pheriche catchment.

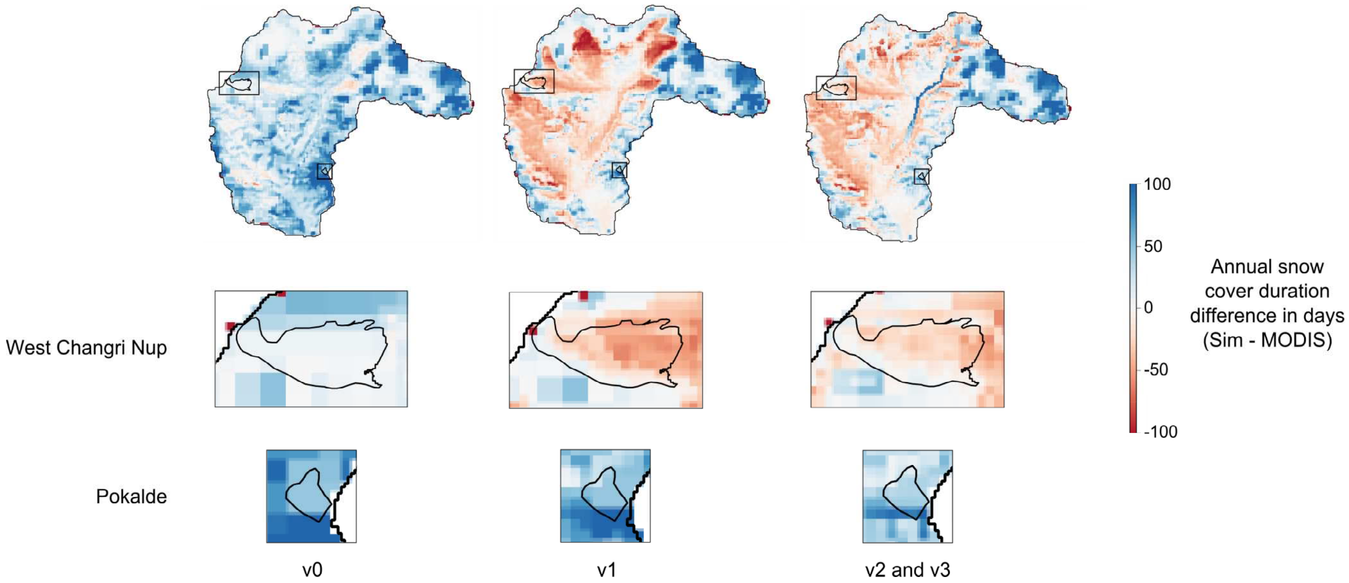

Figure 9. Difference between the mean annual snow cover duration simulated with DHSVM-GDM and derived from MODIS images (in days) for the Pheriche catchment (top panels), with a focus on West Changri Nup (medium panels) and Pokalde glaciers (bottom panels).

4.1.3 Glacier mass balances

Figure 10 compares the simulated mean annual glacier mass balances obtained with the different model configurations with mass balances determined with geodetic methods (Bolch et al., 2012; Gardelle et al., 2013; Nuimura et al., 2015; King et al., 2016; Brun et al., 2017). These geodetic mass balances range from -0.67 ± 0.45 m w.e.yr^{-1} (Nuimura et al., 2015) to -0.32 ± 0.09 m w.e.yr^{-1} (Brun et al., 2017).

Our results show that the snow ~~parametrization~~ parameterization has a significant impact on the simulated glacier mass balance. The mass balance simulated with v0 is on average -0.82 m w.e.yr^{-1} and decreases to -2.02 m w.e.yr^{-1} with the corrected snow albedo (v1) since the modified snow albedo ~~parametrization~~ parameterization accelerates the snow melt which leads to more uncovered ice and stronger glacier melt. The avalanche module (v2) adds snow on glaciers and increases the accumulation and, thus, reduces the glacier melt to -1.69 m w.e.yr^{-1}. Nevertheless the mass balance remains too negative compared to geodetic mass balances, which suggests that the model produces too much ice melt. The implementation of debris-covered glaciers (v3) gives a mean annual glacier mass balance of -0.84 ±0.14 m w.e.yr^{-1}, which is within the intervals of uncertainty and~~thus~~, thus, in good agreement with ~~geodetic methods.~~ the results from geodetic methods.

~~It is worth notify that only the order of magnitude of the simulated and geodetic mass balances can be compared because the considered areas are not exactly the same in the different studies and the considered time periods differ. Indeed, four of the geodetic mass balances are estimated for the Khumbu-Changri glacier, while mass balances from this study and from Brun et al. (2017) represent the mean mass balance for all the glaciers located in the Pheriche basin. Moreover, the mean annual glacier mass balance is estimated here from a three years simulation run (2012-2015), whereas the geodetic mass balances were~~

~~estimated for longer intervals (5 to 15 years) covering different periods and the inter-annual variability is thus not taken into account.~~

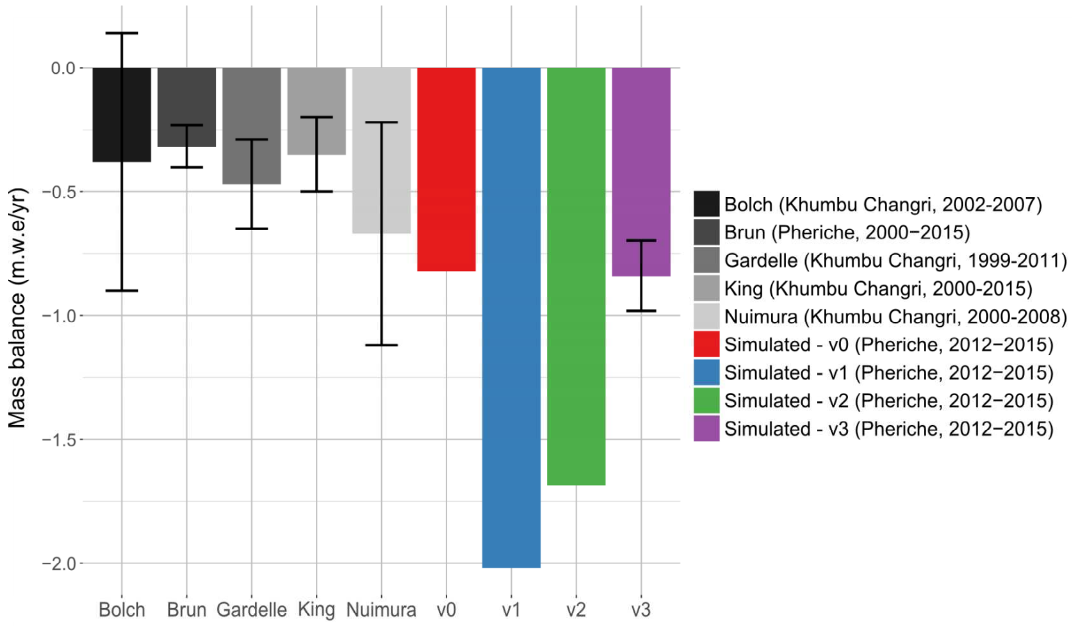

Figure 10. Mean annual glacier mass balances simulated with configurations v0, v1, v2 and v3. The error bar for configuration v3 represents the uncertainty related to the debris layer coefficient melt varying between 0.3 and 0.5.

We also evaluated the mass balance at the point scale. Figure 11 shows the simulated mass balances with ~~parametrizations~~ parameterizations v0, v1, v2 and v3 versus the observed mass balances of the two debris-free glaciers West Changri Nup and Pokalde measured in-situ for the three glaciological years (2012-2015). Here, the configuration v3 gives the same results ~~than~~ as the configuration v2 because ~~the~~ in configuration v3 only ~~modifies~~ the ice melt ~~rates~~ rate on debris-covered glaciers ~~. As previously, the~~ is modified. The simulated mass balances vary according to the model configuration~~and the variability between the different configurations is larger than the spatial and inter-annual variability.~~

. With configuration v0, the model overestimates the point mass balances because of ~~low~~ small snow melt rates (see also section 4.1.2). With configuration v1, the model ~~simulates too much~~ overestimates the ice melt on the West Changri Nup glacier due to a lack of accumulation in the western part of the catchment and a too strong accumulation on the Pokalde glacier (Fig. 9). The configuration v2 improves the simulated mass balance by ~~transfering~~ transferring snow due to avalanches on the West Changri Nup glacier and by removing exceeding snow accumulation on the Pokalde glacier. For the Pokalde glacier, the mass balances simulated with configuration v3 show a larger variability than the mass balances simulated with configuration v0, but the point mass balances are spread around the diagonal axis which leads to a bias ten times smaller (mean bias of 1 m with v0 and 0.1 m with v3).

~~These results~~ The results at basin scale and point scale show that the snow ~~parametrization~~ parameterization has a strong impact on the simulated glacier mass balance and that the new snow albedo ~~parametrization~~ parameterization and the avalanching module clearly improve the simulated glacier mass balance on debris-free glaciers. Nevertheless, regarding point mass balances, the agreement is far from being perfect, due either to simulation errors (including errors depending on the interpolated input fields and errors induced by the representation of slopes and expositions by the DEM) and/or from a lack of representativeness of the measurements.

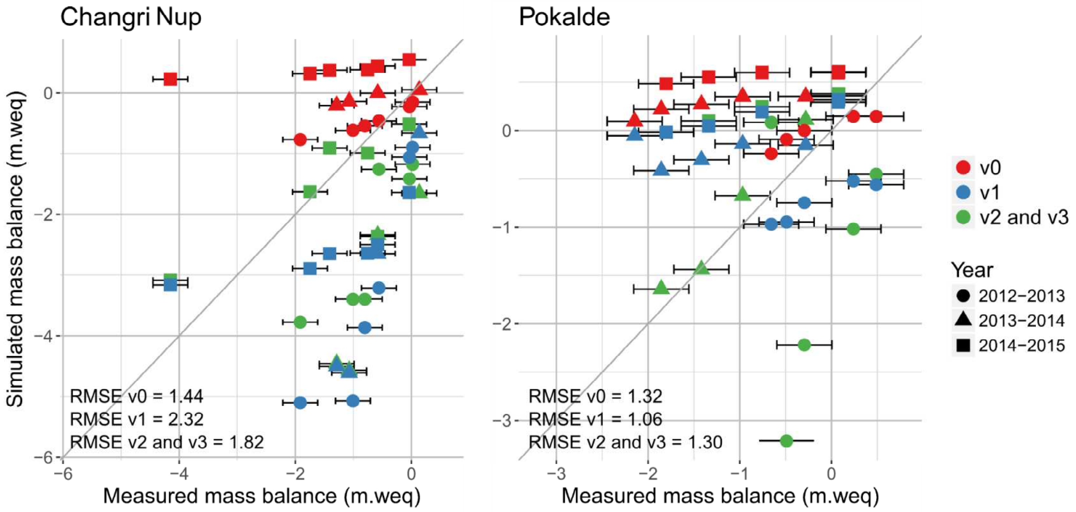

Figure 11. Annual simulated and measured point mass balances on West Changri Nup (left panel) and Pokalde (right panel) glaciers; also shown is the 1:1 line.

4.1.4 ~~Annual outflow and flow components~~

~~Figure ?? represents the annual outflow~~

4.2 Simulated outflows and flow components

This section presents the outflows and flow components simulated ~~with the different model configurations, indicating the impact of each modification of the snow and glacier parametrization on the simulated annual outflow and the glacier contribution to the runoff. Configuration v1 leads to a drastically increased outflow and ice melt component. This increase of ice melt is due to the acceleration of the snow melt compared to v0. Implementing the avalanche module (v2) reduces the ice melt component since more snow is maintained on the glaciers and also increases the snow melt component because snow that was originally accumulated at high elevation is transported downwards by avalanches. Configuration~~ in the Pheriche basin during the period 2012-2015 with the modified version of DHSVM-GDM (configuration v3~~including debris covered glaciers further reduces the ice melt, resulting in a simulated annual outflow close to the observations. This shows that the modification of one specific~~

~~hydrological process (here, the representation of avalanches) can have a significant impact on the simulated hydrological response of the catchment and requires improving other processes (here, considering specific representation of debris-covered glaciers).~~

~~The configurationwith all three modifications (v3~~)~~gives results similar to the original parametrization of DHSVM-GDM~~ . The simulation results are analysed using two different definitions of the flow components (definitions 1 and 2, see ch. 3.2.5).

4.2.1 Annual simulated outflow and hydrological contributions

The annual outflows simulated with the new parametrization of the model (~~v0) in terms of glaciers mass balance, improving slightly the annual outflow. The ice melt factor for debris covered glaciers and the avalanches compensate the increase of ice melt caused by the new snow albedo parametrization, but the modifications implemented in v3 impact the results for the flow components : on average, less ice melt and more snow melt are generated. This is particularly true for the glaciological year 2014-2015, when the ice melt contribution decreases from 60% with v0 to 41% with v3 and the snow melt contribution increases from 29% to 47%. This can be explained by the fact that 2015 is a particularly snowy year (Fujita et al., 2017), which highlights the importance of a correct representation of snow processes in the model . This also shows the need to use as much validation data as possible to assess the coherence between the ice, snow and hydrological processes and reduce the uncertainty on the flow components estimation. Moreover, the~~ configuration v3~~modifies the seasonal variation of the outflow by increasing winter discharges and reducing monsoon discharges (not illustrated here) which improves the monthly KGE (0.9 with configuration v3 versus 0.83 with configuration v0).~~

~~Configuration v2, which does not consider the debris-covered glaciers, overestimates the outflow at Pheriche with a mean bias of +32% compared to the annual observed outflow. Without the debris layer, the ice melt component represents 61% of the annual outflow, which is nearly twice the amount of ice melt obtained with v3 that includes debris-covered glacier melt.When the coefficient for debris covered glaciers melt varies between 0.3 and 0.5 (~~) are in good agreement with the annual observed outflows since they remain within the 15 % interval of estimated error (Fig. 12 and Table 4)~~, it modifies the simulated annual outflow by ± 7% and the ice melt flow component ranges from 42 to 50%~~.

~~Using configuration v3, the simulated annual outflow always stays within the interval of confidence of the observed outflow. The losses by evaporation and sublimation are rather constant trough the simulation period ranging between 140 and 150 mm/yr. Results~~ The results show an inter-annual variability of the hydrological contributions to the overall outflow. During the period 2013-2015, the ice melt component ~~ranges~~ ranged from 41 to 50 %, the snow melt component from 37 to 47 % and the net rainfall component from 12 to 16 %. These variations are related to the meteorological annual variability. The amount of rainfall ~~decreases~~ decreased from 2013 to 2015 and explains the decrease of the net rainfall components from 155 mm in 2013 to 88 mm in 2015. The snow melt component is higher in 2013 because of warmer pre-monsoon and monsoon seasons. The ice melt component is mainly controlled by the amount of winter snowfall. In 2014 a low amount of snowfall was observed, so the snowpack ~~melts~~ melted more rapidly and the glaciers ~~start~~ started melting earlier. In contrast, 2015 ~~is~~ was a year with a lot of winter snowfall, which ~~delays~~ delayed the beginning of the ~~glaciers~~ glacier melt and explains the lower ice melt component. The losses by evaporation and sublimation are rather constant through the simulation period ranging from 140 to 150 mm/yr.

The runoff coefficients (ratio between the annual outflow and annual precipitation) were on average equal to 1.4, which means that a considerable amount of water is withdrawn each year from the catchment through ice melt (eventually in the form of a delayed groundwater flow).

On average, we find that ~~69% of the annual outflow comes from glacierized areas and that~~ the outflow is mainly produced by meltwater as 46 % of the annual outflow is due to ice melt and 41 % to snow melt (~~Fig. ??). Soncini et al. (2016) studied flow components in the Pheriche catchment on the period 2013-2014 and estimated an annual ice melt component of 55% and a snow melt component for 20%. The ice melt components are thus quite similar in terms of relative contributions to outflow, which is not the case for the snow melt components. We think that the main reason of such a difference is that we use different precipitation input. Indeed, precipitation data are measured here by Geonor sensors, while in Soncini et al. (2016) precipitation data come from tipping buckets. At the Pyramid station, where both sensors are installed, the Geonor sensor measures 60% more precipitation than the tipping bucket over the period 2013-2015 and the main differences are in terms of solid precipitation (309 mm of mean annual snowfall measured by the Geonor sensor versus 83 mm measured by the tipping bucket, which is known to badly perform with solid precipitation)~~definition 1). The contributions estimated according to definition 2 show the importance of infiltration and subsurface flows in the water balance since more than 40 % of the outflow was coming from water infiltrated in glaciers and more than 20 % from subsurface and groundwater flows.

The choice of the ~~hydrological components definition~~ definition of the hydrological components leads to different perceptions of the glacier contribution to the outflow~~(Fig. ??a and ??b). When considering configuration v3, the~~. The glacier contribution to the total outflow is 69~~% if we consider~~ % if the contribution from the entire glacierized area (i.e. contributions of ice melt, snow melt and net rainfall) ~~and 46% if we consider only~~ is considered like in definition 2. However, the contribution from ice melt ~~. Likewise, the snow components with definition~~alone, included in definition 1~~and 2 are equal to 41% and 6% respectively, and the rain component to 13% and 1% (Table 4) which clearly shows the importance of infiltration and subsurface flows in the water balance. The comparison between the two definitions of the hydrological shows that contributions must be explicitly specified in order to allow inter-comparison between models, especially for catchment with a large glacierized area.~~ , corresponds to only 46 % of the outflow.

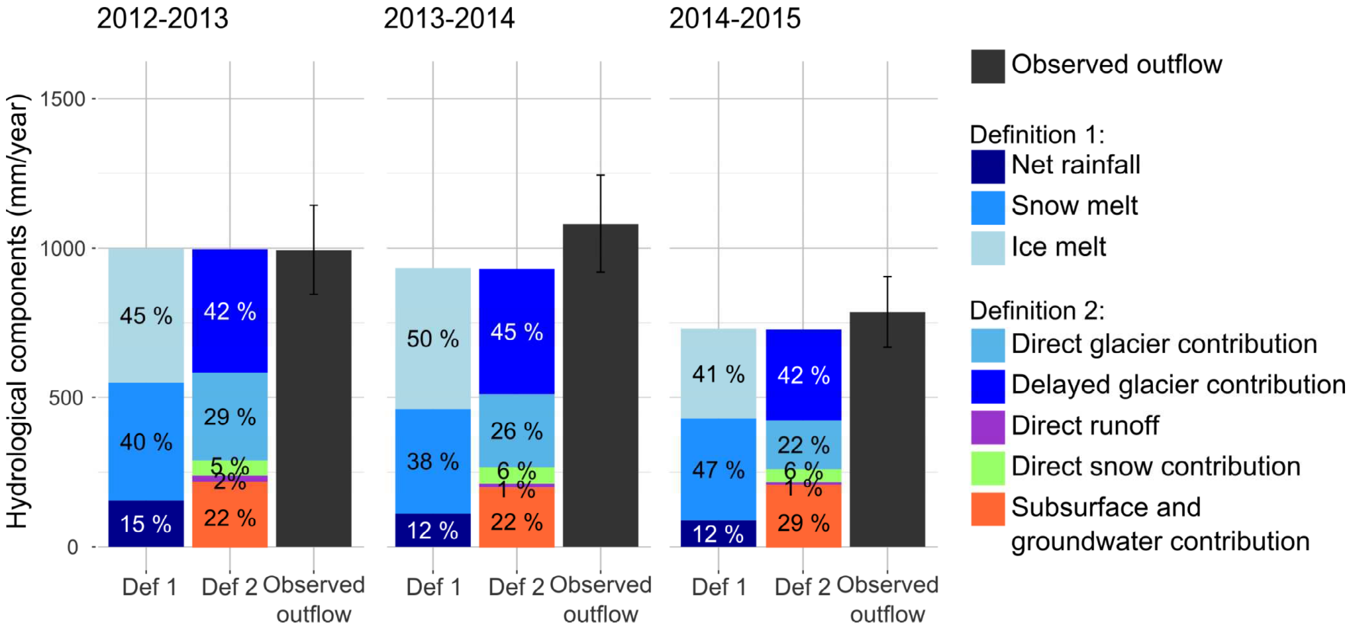

Figure 12. Simulated annual hydrological contributions to Pheriche outflow for the two definitions of the flow components ~~:~~ (~~a)~~ definition 1 ~~, (b)~~ and definition 2) and for 3 the glaciological years from ~~12/~~December 2013 to ~~11/~~November 2015.

	2012-2013	2013-2014
~~Debris coefficient 0.3 0.4 (v3) 0.5 0.3 0.4 (v3) 0.5 0.3 0.4 (v3) 0.5~~ height**Total precipitation (mm)**	**708**	**644**
Snowfall (mm)	501	492
Qobs (mm)	**994**	**1081**
Qobs ±15 % (mm)	845 - 1143	919 - 1244
Qsim (mm)	**~~932~~ 999**	**~~1066 865~~ 933**
~~Biais~~ Bias (%)	~~-6~~ +1	~~+7 -20~~ -14
Evapotranspiration (mm)	61	~~61 61~~ 48
Sublimation (mm)	91	~~91 91~~ 96
~~Flow components 1~~ **Flow components (Definition 1)**		
Net rainfall (mm)	~~154~~ 141	~~155~~ 106
Snow melt (mm)	~~394~~ 375	~~396~~ 336
Ice melt (mm)	~~384~~ 422	~~449~~ 443
~~Flow components 2~~ **Flow components (Definition 2)**		
Direct ~~runoff~~ glacier contribution (mm)	~~21~~ 293	~~21~~ 244
~~Direct Snow~~ Delayed glacier contribution (mm)	~~51~~ 414	~~51~~ 420
Direct ~~Glacier~~ runoff (mm)	~~258~~ 21	~~293~~ 14
~~Delayed Glacier~~ Direct snow contribution (mm)	~~383~~ 51	~~414~~ 55
~~Soil~~ Subsurface and groundwater contribution (mm)	~~219~~ 220	~~220~~ 200

Table 4. Annual hydrological balance ~~for~~ simulated with configuration v3 ~~and sensitivity to the debris covered melt reduction factor ranging from 0.3 to 0.5 (from left to right),~~ for the 3 glaciological years from December 2013 to November 2015.

4.2.2 ~~Sensitivity to~~ Seasonal variations of the ~~glacier outline~~flow components

~~Glaciers inventory Glacier MB km^2 % m w.e.yr^{-1} mm Biais Net rainfall Snow melt Ice melt Racoviteanu et al. (2013) 60 43 -0.84 887 -7% 118 (13%) 363 (41%) 407 (46%)GAMDAM 38 24 -1.17 824 -13% 117 (14%)359 (44%) 349 (42%)ICIMOD 44 30 -0.89 811 -15% 118 (14%) 365 (46%) 329 (40%)Mean annual glaciers mass balance (MB), outflow and flow components simulated with different glaciers inventories (configuration v3)~~

~~The three inventories used in this study result in very different estimates of the glacierized area: between 43% and 26% of the Pheriche basin with the inventories proposed by Racoviteanu et al. (2013) and GAMDAM (Fig. 3). Table 5 presents the mean annual results of glacier mass balance, outflow, and flow components for the configuration~~ Figure 13 presents the daily simulated discharges simulated with configuration v3 ~~using the three inventories. The GAMDAM inventory leads to a more negative glacier mass balance than the two others inventories with -1.17 m w.e.yr^{-1} against -0.84~~ and ~~-0.89 m w.e.yr^{-1} for the Racoviteanu et al. (2013) and ICIMOD inventories. This is due to smaller glacier accumulation areas in the GAMDAM~~

~~inventory. The amount of snowfalls collected over those areas is lower, leading to more negative mass balances: glaciers receive less snowfall for accumulation, which lowers the mass balance value. Concerning the simulated outflow and flow components, the GAMDAM and ICIMOD inventories lead to fewer ice melt than the Racoviteanu et al. (2013) inventory due to their smaller surfaces in ablation areas, which leads to a smaller simulated annual outflow. From these results we estimate an uncertainty of 20% (407 mm with the Racoviteanu et al. (2013) inventory versus 327 mm with the ICIMOD inventory, cf. Table 5) on the simulated annual ice melt volume related to the glaciers outline. The glacier outline mainly affects the simulated outflow during the monsoon season, when the ice melt contribution to the outflow is more important and leads to an uncertainty of 8% (154 mm with the Racoviteanu et al. (2013) inventory versus 141 mm with the ICIMOD inventory) on the monthly discharges during monsoon season. This result shows that the choice of the glacier inventory as an input data of the glacio-hydrological model affects the simulations and is crucial for the results. Here, the Racoviteanu et al. (2013) inventory gives the best results in terms of glacier mass balance and the smallest bias with respect to the annual outflow. As its area is significantly larger than the other inventories, it gives the largest amount of ice melt. This potentially compensates a lack of precipitation due to a poor knowledge of the precipitation distribution over the catchment, specifically in the areas above 5000 m a.s.l. which constitute more than three quarters of the total area and for which no observations exist. It is worth noting that the glacier mass balances obtained with the Racoviteanu et al. (2013) and ICIMOD inventories are very similar, which shows that glacier mass balances alone are not sufficient for model evaluation: a consistent mass balance can lead to errors on the simulated glacier contributions and total outflow. It also shows that in a region with a large uncertainty in the precipitation forcing data (Savéan et al., 2015; Eeckman et al., 2017) and on the delimination of glacierized areas, calibrating glacier parameters on the mass balance can lead to inaccurate estimations of the total ice melt volume.~~

4.3 ~~Simulated seasonal and diurnal flows and contributions~~

~~In this section we analyse the hydrological contributions to the outflow simulated with configurationv3, which gives the best results for snow cover area, glacier mass balance, and discharges (as previously pointed out). Figure 13 presents the daily simulated discharges and the~~ the flow components estimated with the two different definitions~~(runoff production vs. contributive areas). Daily discharges are well simulated in 2013 and 2015~~. Daily discharges were well simulated for 2012-2013 and 2014-2015 by the model, with NSE equal to ~~0.9~~ 0.91 and KGE equal to ~~0.86~~0.88. However, ~~outflow is~~ the outflow was under-estimated by the model during the monsoon season in 2014.

The simulated total runoff ~~is~~ (i.e. the sum of snow melt, ice melt and net rainfall) is always higher than the simulated outflow at the catchment outlet before the monsoon season (from February to June) and lower during post-monsoon and winter seasons. This is mainly due to glacier melt water stored inside the glaciers during pre-monsoon and monsoon seasons and continuing surging during winter, as well as to changes in the soil water storage (Fig. 13b and 14b).

Figure 14 ~~show~~ shows the mean monthly flow components averaged over the simulation period. From February to ~~May/June~~May-June, the runoff production is ~~mainly~~ entirely controlled by snow ~~melt (~~and ice melt (snow melt between 50 and 60~~%) and by ice melt (~~ % ice melt between 40 and 48 %) (Fig. 14a). The net rainfall, snow melt and ice melt absolute contributions are ~~all~~ at their maxima in July and August during the monsoon season. During these two months, 24 % of the runoff is generated ~~at~~

~~24%~~ by net rainfall, 37 % by snow melt, and 38 % by ice melt. From October to January, the runoff is ~~mainly~~ produced by ice melt (up to 80 % in December) and snow melt ~~. This is consistent with the results from Soncini et al. (2016), who found a main contribution of snow melt during the pre-monsoon season, mixed contributions of rainfall, snow melt and ice melt during the monsoon season and mixed contributions of snow melt and ice melt during post-monsoon and winter season. Figure 14b shows that liquid water stored inside glaciers contributes to more than~~ (between 20 and 30 %). Groundwater and englacial water represent a significant fraction of the monthly outflow as they contribute more than 50 % of the outflow during the monsoon season and can contribute up to ~~78~~90 % during winter ~~. This corresponds well to the studies of Ragettli et al. (2015) and Racoviteanu et al. (2013) concerning the Upper Langtang and the Dudh Koshi basin respectively, who found that most of the winter outflow surges from soil, channel, surface, and englacial storage changes. The soil contribution includes snow melt and rainfall that infiltrate in the upper soil layers and contribute rapidly to the outflow. It represents a significant share of the monthly outflow with a maximum between March and May (more than 30%)and a minimum in post-monsoon and winter (less than 20%). The response of the soil storage is faster than the englacial storage as the main part of the soil infiltrated water resurges within a day, whereas liquid water can be stored for several months within the glaciers.~~ (Figure 14b). Direct contributions from glacierized areas, snow areas, and direct runoff are highest during the monsoon season, when the englacial and soil storage is saturated.

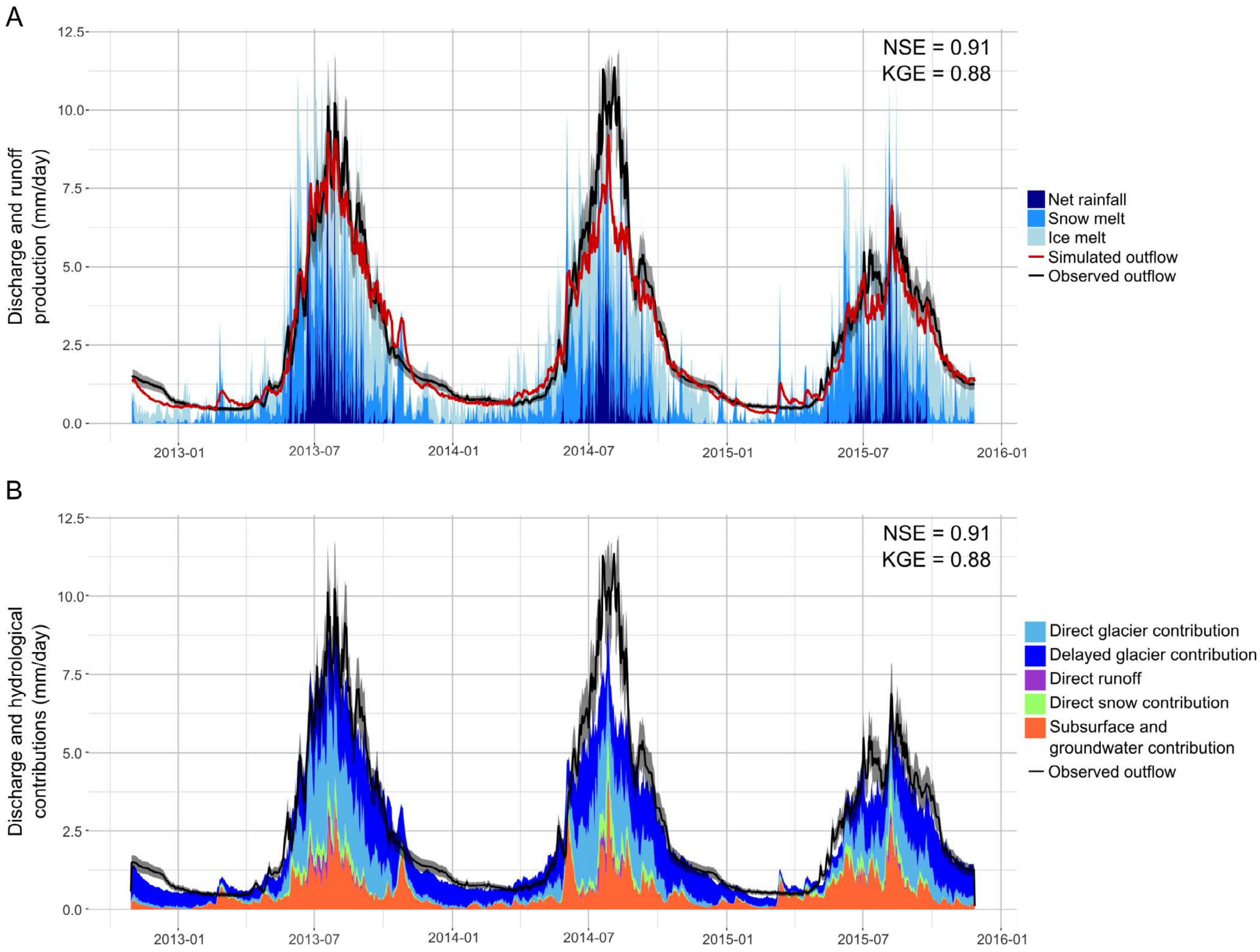

Figure 13. Daily discharges and flow components simulated with configuration v3: (a) production of ice melt, snow melt and net rainfall (note that the sum of the flow components represent the total runoff and is not equal to the discharge at the catchmant outlet, see definition 1~~at section~~, ch. 3.2.5) (b) hydrological contributions to the outflow (definition 2~~at Sect~~, ch. 3.2.5). Observed discharges are represented by the black line with a 15 % interval of ~~uncertainty~~error.

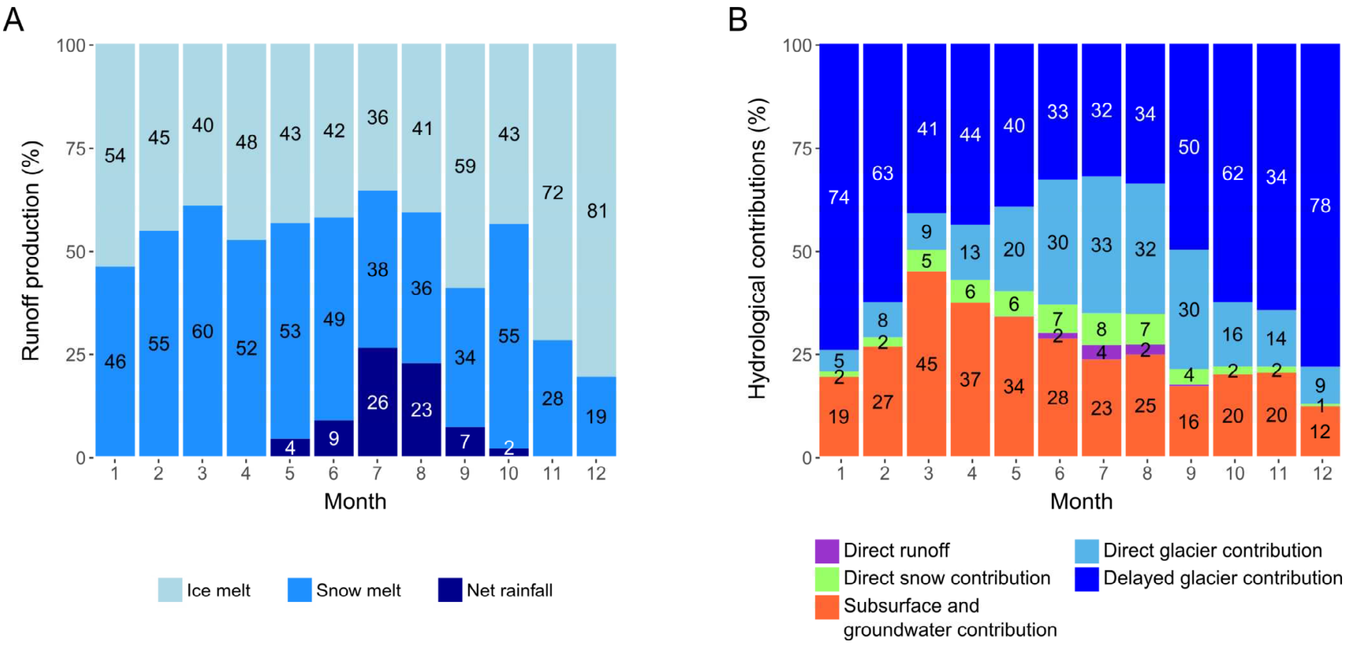

Figure 14. ~~Monthly share of~~ Average monthly contributions to the runoff production (definition 1, ch. 3.2.5) (a) and hydrological contributions (definition 2, ch. 3.2.5) (b) simulated with configuration v3 for the years 2012-2015.~~Water balance contributions are introduced at section 3.2.5.~~

~~Mean hourly precipitation, discharge and flow components by seasons (DJFM: winter, AM: pre-monsoon, JJAS: monsoon, ON: post-monsoon) simulated with configuration v3. Water balance contributions are introduced at Sect. 3.2.5. Note that the y-axis scale is different for each season.~~

4.2.1 Diurnal cycle

Figure 15 presents the ~~different~~ diurnal cycles of precipitation and hydrological components averaged for each considered season (winter, pre-monsoon, monsoon, and post-monsoon) obtained with configuration v3. During winter, pre-monsoon, and post-monsoon, the observed outflow is rather constant during the day, with a weak peak around noon when the temperature is at its maximum. ~~Almost~~ During this period, almost all of the precipitation is in the form of snowfall ~~,~~ leading to no direct response for the outflow. The peak around noon can be explained by snow melt or the melting of small frozen streams. During the monsoon season, there is a strong diurnal cycle of the precipitation with a maximum occurring during late afternoon or at night ~~and a discharge peak occurring~~ causing a peak in the discharge around midnight.

The model simulates ice and snow melt during day time with a maximum at noon as ~~it was~~ expected. Except for the monsoon season, it seems to simulate accurately the baseflow during night ~~when there is no melt production;~~ without melt production: the discharge is ~~then~~ rather controlled by the release of the ~~glaciers~~ glacier and soil storage. ~~Unfortunately~~ However, the model simulates a peak of discharge ~~coming mostly from glacierized areas~~ around 14 h originating mostly from glacierized areas, two hours after the ~~peak~~ maximum of ice and snow melt, which does not correspond to ~~the~~ observed discharges. At ~~the daily scale~~ ~~(~~daily and longer time scales ~~)~~ the water balance is correctly simulated. However, at a sub-daily scale the model responds too quickly to the snow and ice melt production.

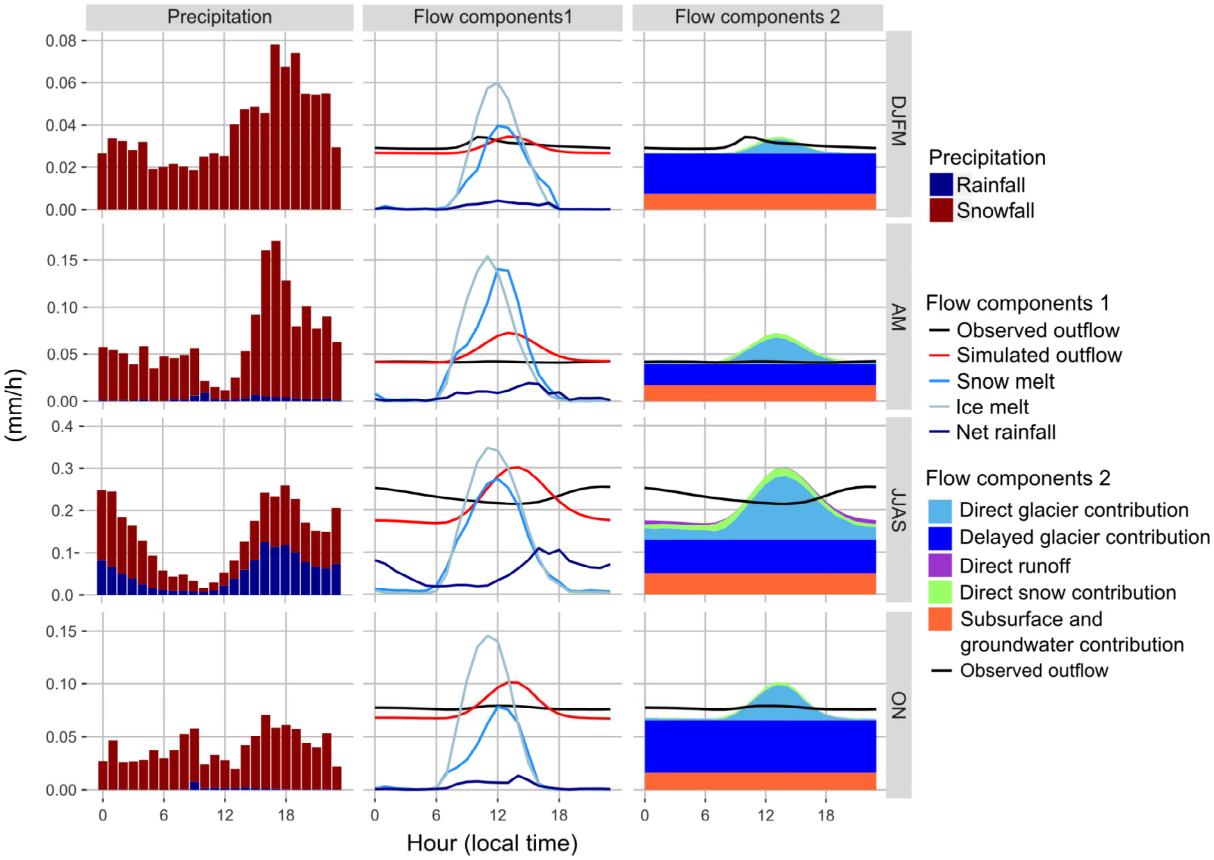

Figure 15. Mean hourly precipitation, discharge and flow components simulated with configuration v3 and averaged for the winter (DJFM), pre-monsoon (AM), monsoon (JJAS), and post-monsoon (ON) seasons. Note different y-axis scales for each season.

5 Discussion

5.1 Simulation of the discharge and flow components

Overall, the comparison between the two definitions of the hydrological contributions shows that contributions must be explicitly specified in order to allow inter-comparison between models, especially for catchments with a large glacierized area. Moreover, the use of two different definitions allows to get complementary information on the origin of the outflow (processes at the origin of the runoff, types of flow generation, contributive zones). A perspective to improve the quantification of the hydrological contributions to the outflow is to track the ice melt, snowmelt and rainfall component pathways in the model as suggested in Weiler et al. (2018). This would enable to quantify the fractions of the three components contributing to subsurface and groundwater flow, which is not possible with the current version of DHSVM-GDM.

Soncini et al. (2016) studied flow components in the Pheriche catchment for the period 2013-2014 and estimated an annual ice melt component of 55 % and a snow melt component of 20 % of the annual outflow. The ice melt components are thus quite similar in terms of relative contributions to outflow, which is not the case for the snow melt components. We think that the main reason of such a difference is that we use different precipitation input. Indeed, precipitation data are measured here by Geonor sensors, while in Soncini et al. (2016) precipitation data come from tipping buckets. At the Pyramid station, where both sensors are installed, the Geonor sensor measures 60 % more precipitation than the tipping bucket over the period 2013-2015 and the main differences are in terms of solid precipitation (309 mm of mean annual snowfall measured by the Geonor sensor versus 83 mm measured by the tipping bucket, which is known to badly perform with solid precipitation).

Concerning the seasonal contributions to the outflow, our results are consistent with the results from Soncini et al. (2016), who found a main contribution of snow melt during the pre-monsoon season, mixed contributions of rainfall, snow melt and ice melt during the monsoon season and mixed contributions of snow melt and ice melt during post-monsoon and winter season. The studies of Ragettli et al. (2015) and Racoviteanu et al. (2013) concerning the Upper Langtang and the Dudh Koshi basin respectively, showed that most of the winter outflow surges from soil, channel, surface, and englacial storage changes, which is also consistent with our results. However, the estimated flow components presented in this study, particularly the soil and englacial contributions, are estimations which strongly depends on the model set-up. Figure 13 shows that the main part of the soil infiltrated water resurges within a day, whereas liquid water can be stored for several months within the glaciers. This difference between the response of the soil storage and the englacial storage results from the soil and glacier parameterization (see sensitivity analysis in ch. 5.3.2).

At hourly scale, the results show that the model cannot represent the diurnal cycle of the outflow correctly as the simulated hydrological response is anticipated. Irvine-Fynn et al. (2017) found that on the Khumbu glacier the presence of supraglacial ponds buffers the runoff by storing diurnally more than 20 % of the discharge. This could explain the longer transfer time observed on the measured ~~outflow~~ outflows which are not represented by the model. This ~~also~~ shows that the current representation of the glacier and soil storage in DHSVM-GDM does not allow to reproduce accurately the diurnal variations of discharge and further studies are needed in order to ~~determine the causes of such a shortcoming.~~

~~In this study we used a distributed physically-based glacio-hydrological model(DHSVM-GDM) to simulate the outflow of a small catchment in the Everest region and to estimate the different contributions to flows, which can be useful for water resources and water-related risks management~~improve the model.

5.2 Representation of the cryospheric processes in the model

One of the main difficulties for hydrological modelling of highly glacierized catchments is to correctly simulate at the same time the ~~hydrograph~~outflows, the dynamics of the snow cover, and the glacier mass balances. ~~In this study, an improvement of the parameterization of~~

The results showed that two different representations of the cryospheric processes in ~~DHSVM-GDM was proposed in order to better represent ice melt under debris covered glaciers, avalanches, the storage and transport of melt water within glaciers. Snow cover dynamics has been shown to play an important role for the simulated water balance. The albedo parametrization proposed in this study and the implemented avalanche module enabled to simulate the snow cover spatial distribution and the glacier mass balances more accurately than in the original version of DHSVM-GDM by increasing the glacier accumulation and reducing ice melt . However, only after the consideration of~~ the model (v0 and v3) can lead to similar simulated annual outflows but different estimations of the ice melt and snow melt contributions to the ~~insulating effect of~~ outflow. This is particularly true for the glaciological year 2014-2015, when the ice melt contribution decreases from 59 % with v0 to 41 % with v3 and the snow melt contribution increases from 29 % to 47 % (Fig. 7). This can be explained by the fact that 2014-2015 was a year with a high amount of snowfall (Fujita et al., 2017), therefore, the representation of snow processes in the model has a larger impact on the ~~debris layer on glaciers the overestimation of more than 30% of the annual outflow is rectified.~~ simulated runoff production than the two other years. This highlights the importance of a correct representation of snow processes in the model. This also shows the need to use as much validation data as possible to assess the coherence between the ice, snow and hydrological processes and reduce the uncertainty on the flow components estimation.

~~Among the different snow and glacier parametrizations that were tested, the most satisfactory (configuration v3) shows major contributions from glaciers and snow to~~ The results also showed that the modification of one specific hydrological process (here, the ~~outflow with 46% of the annual outflow produced by iceand 41% by snow melt. Winter flows are mainly controlled by the release of englacial water storage (up to 78% in December), which corroborates other studies (Racoviteanu et al., 2013; Ragettli et al., 2015 We estimate an uncertainty related to the ice melt reduction factor by debris (ranging from 0.3 to 0.5) of ±0.14 m w.e.yr^{-1} for the annual glacier mass balance and ±7% for the annual outflow. The glacier inventories used to outline the glacierized areas have also an important~~ representation of the snow albedo evolution) can have a significant impact on the ~~simulation results. The three inventories tested in this study give estimations of the glacierized area ranging from 26 to 43% of the basin area and a corresponding uncertainty of 20% for the ice melt production~~simulated hydrological response of the catchment and requires improving other processes (here, considering specific representation of avalanches and debris-covered glaciers).

~~The runoff coefficient (ratio between the annual outflow and annual precipitation) is on average equal to 1.4, which means that a considerable amount of water is withdrawn every year from the catchment through ice melt (eventually in the form of a delayed groundwater flow). Thus, if the precipitation regime (in terms of both intensity and phase) does not change within the next decades, the access to water resources is likely to be reduced, especially during the fall and the winter seasons, as the glaciers outflow will decrease due to glaciers shrinkage, even without taking into account climate warming. By the way, this study also reminds that glacial and snow contributions to~~ Further modifications of the model could also lead to different model results and it is also not excluded that different model errors are compensating each other. For example, the results showed that the original model version leads to a correct simulation of the ~~streamflow must be clearly defined, as considering glacial contribution as the total outflow from the glacierized area or as outflow produced by ice melt can lead to very different estimations~~river discharges because the non-representation of the insulation effect for debris covered glaciers on the ice melt was compensated by the incorrect representation of the snow albedo decrease. Due to the complexity of the model and the represented processes, no guarantee can be given that similar compensating effects still occur in the model. In this study, the validation of the model output was extended beyond the annual river discharge to discharges at different time scales, the snow cover area, and glacier mass balances in order to validate the simulations of the snow cover, glacier melt and discharges separately. The results demonstrate that the new version of the model performs well for all three signals. Moreover, the new parametrizations of the snow albedo and ice melt under debris were based on observed data (MODIS and in situ albedo measurements, and coefficient for ice melt under debris from Vincent et al. (2016)) and do not result from a calibration in order to avoid compensation effects. Therefore, it is very likely that the new implementation improved the quality of the represented processes.

~~Previous results are already useful for decision makers and stakeholders, but~~ The results presented in this study also indicate possible forthcoming works for increasing the simulations reliability and reducing uncertainties, especially at short time steps. Indeed, at daily and longer scales, the different hydrological components seem to be well reproduced by the model. However, an analysis of the diurnal cycle (~~Figure~~Fig. 15) showed that DHSVM-GDM responds too rapidly to the ice melt production and that the representation of the water storage within the glaciers needs to be improved. Further improvements should be based on studies that analyze the mechanisms of glaciers drainage systems in the Khumbu region and their influence on glaciers outflow (e.g., Gulley et al., 2009; Benn et al., 2017). These studies show that englacial conduits and supraglacial channels, ponds and lakes play a key role in the response of glaciers: DHSVM-GDM could thus be upgraded by implementing a parameterization of such systems and delay the response of glacierized areas, as successfully proposed, for instance, in the model developed by Flowers and Clarke (2002). Other processes such as supraglacial ponds and ice cliffs melting, transport of snow by wind or variation of temperature in the ice pack are not considered in DHSVM-GDM and their impact on the hydrological modelling should also be studied.

The avalanche routine implemented in this study is simplified and only considers 4 directions for the snow redistribution. A perspective of this study is too improve the representation of the avalanches in DHSVM-GDM by considering 8 directions for the snow redistribution and considering other parameters such as the age of the snow cover, the snow density and the type of land-cover as it was proposed in Frey and Holzmann (2015).

5.3 Uncertainties and other open-ended questions

5.3.1 Sensitivity to the glacier outline

The three inventories used in this study result in very different estimates of the glacierized area: between 43 % and 24 % of the Pheriche basin with the inventories proposed by Racoviteanu et al. (2013) and GAMDAM (Fig. 3). Table 5 presents the average annual glacier mass balances, outflows, and flow components for the configuration v3 using the three inventories. The GAMDAM inventory leads to a more negative glacier mass balance than the two others inventories with -1.17 m w.e.yr^{-1} compared to -0.84 and -0.89 m w.e.yr^{-1} for the Racoviteanu et al. (2013) and ICIMOD inventories. This is due to smaller glacier accumulation areas in the GAMDAM inventory. The amount of snowfalls collected over those areas is lower, leading to more negative mass balances: glaciers receive less snowfall for accumulation, which lowers the mass balance value. Concerning the

Glaciers inventory	Basin glacier area		Glacier MB	Qsim		Flow components (mm)		
	km^2	%	m w.e.yr^{-1}	mm	Bias	Net rainfall	Snow melt	Ice melt
Racoviteanu et al. (2013)	60	43	-0.84	887	-7%	118 (13%)	363 (41%)	406 (46%)
GAMDAM	38	24	-1.17	824	-13%	117 (14%)	359 (44%)	348 (42%)
ICIMOD	44	30	-0.89	811	-15%	118 (14%)	365 (46%)	328 (40%)

Table 5. Mean annual glaciers mass balance (MB), outflow and flow components simulated with different glaciers inventories (configuration v3)

simulated outflow and flow components, the GAMDAM and ICIMOD inventories lead to fewer ice melt than the Racoviteanu et al. (2013) i due to their smaller areas in ablation zones, which leads to a smaller simulated annual outflow. From these results we estimate an uncertainty of 20 % (407 mm with the Racoviteanu et al. (2013) inventory versus 327 mm with the ICIMOD inventory, cf. Table 5) on the simulated annual ice melt volume related to the glaciers outline. The glacier outline mainly affects the simulated outflow during the monsoon season, when the ice melt contribution to the outflow is more important and leads to an uncertainty of 8 % (154 mm with the Racoviteanu et al. (2013) inventory versus 141 mm with the ICIMOD inventory) on the monthly discharges during monsoon season. This result shows that the choice of the glacier inventory as an input data of the glacio-hydrological model contributes to the uncertainty on the simulation results. Here, the Racoviteanu et al. (2013) inventory gives the best results in terms of glacier mass balance and the smallest bias with respect to the annual outflow. As its area is significantly larger than the other inventories, it gives the largest amount of ice melt. This potentially compensates a lack of precipitation due to a poor knowledge of the precipitation distribution over the catchment, specifically in the areas above 5000 m a.s.l. which constitute more than three quarters of the total area and for which no observations exist. It is worth noting that the glacier mass balances obtained with the Racoviteanu et al. (2013) and ICIMOD inventories are very similar but the amounts of simulated ice melt are different, which shows that a consistent mass balance can lead to errors on the simulated glacier contributions and total outflow.

5.3.2 Sensitivity to the soil and glaciers parametrization

A major limitation to the estimation of the contributions from the runoff generation (overland flow, subsurface flow, and groundwater flow) is the representation of the groundwater and englacial flows in the model. In this study, we selected standard soil parameters for the simulations since there is very little information about soil properties in high-mountain environments. Moreover, data to validate subsurface and groundwater flows do not exist making it very difficult to adapt the parameter values to the study area. Here, three different values of soil depth under glaciers were tested in order to assess the sensitivity of the soil parametrization on the simulated discharges. Figure 16a shows the simulated discharges and flow components (definition 2) simulated with configuration v3 for a soil depth under glaciers equals to 1 m, 2 m and 5 m. The soil depth under glaciers does not impact the simulated annual outflow and the total annual contributions from glacierized and non-glacierized areas. The soil depth under glaciers only impacts the partitioning between direct and delayed contributions (soil water and englacial water contributions): when the soil depth under glaciers ranges between 1 m and 5 m, the direct glaciers contribution ranges from 34 to 20 %, and the delayed glacier contribution ranges from 35 to 47 %. At seasonal scale, an increase of the soil depth under glaciers leads to a delay of the outflow as there is more infiltration simulated during the pre-monsoon and monsoon seasons, but this has a limited impact on the NSE and KGE values (respectively ranging from 0.92 to 0.94 and 0.83 to 0.91).

Another limitation of our model lies in the application of a uniform reduction factor for ice melt under debris covered glaciers. Figure 16b shows the sensitivity of the model to the ice melt reduction factor on debris covered glaciers. When the reduction factor varies between 0.3 and 0.5, the simulated annual outflow is modified by ± 7 % and the mean ice melt flow component ranges from 42 to 50 %. This shows that the results are sensitive to the representation of the debris cover in the model. In order to have a more realistic representation of the debris, the reduction factor could be spatially distributed, at least following elevation or slope exposition, and eventually taken as time-variant. As an example, Ragettli et al. (2015) considered a distributed debris thickness in their glacio-hydrological model and obtained a mean reduction of ice melt under debris of 84 %.

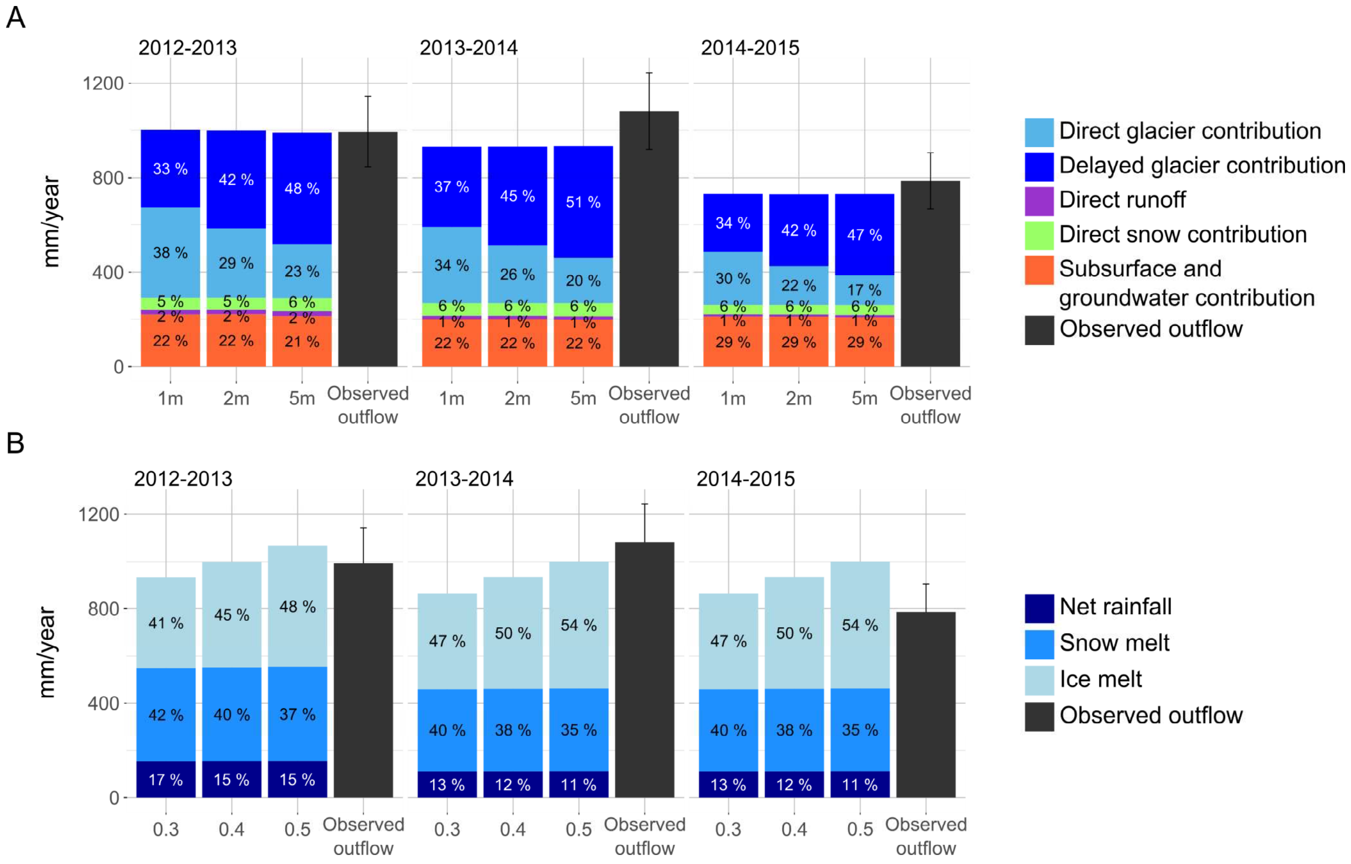

Figure 16. Annual discharges and flow components simulated with configuration v3 with a) three different soil depths under glaciers (1 m, 2 m, and 5 m) (definition 2), b) three different values for the debris-covered ice melt reduction factor (0.3, 0.4, and 0.5) (definition 1).

5.3.3 Validation and forcing data uncertainties

A main issue is related to the availability of data for validating the glacio-hydrological modelling ~~parametrizations~~ parameterizations and outputs. The lack of in-situ measurements at high elevations and the uncertainty related to the available data prevent from assessing the performance of the model in simulating the different cryospheric processes we consider. They only allow to evaluate integrated variables such as the annual glacier mass balance, the seasonal snow cover area dynamics and the outflow at the catchment outlet with significant uncertainties that impact the estimation of the different flow components. ~~It is~~ For instance, concerning the validation of the simulated glacier mass balances, only the order of magnitude of the simulated and geodetic mass balances used in this study can be compared because the considered areas are not the same in the different studies and the considered time periods differ as well. Indeed, four of the geodetic mass balances were derived for the Khumbu-Changri glacier, while mass balances from this study and from Brun et al. (2017) represent the mean mass balance for all glaciers located in the Pheriche basin. Moreover, the mean annual glacier mass balance is estimated here for the three simulated years (2012-2015), whereas the geodetic mass balances correspond to longer (5 to 15 years) as well as earlier periods beginning between 1999 and 2002 (see Figure 10) and do not take into account the inter-annual variability of the glacier mass balances. Nevertheless, on figure 10, the variability of the simulated glacier mass balances is much larger than the variability of the geodetic mass balances, showing the significant impact of the snow and glacier parameterization on the simulation results. It is also worth noting that the snow cover distribution evaluation is particularly challenging on the Pheriche catchment, as clouds cover more than 50 % of the catchment during more than 150 days per year on average (and almost all the time during the monsoon season).

Finally, a major source of uncertainty lies in the lack of meteorological data at high elevation (because of the inaccessibility on the terrain) and in the measurement errors when observations are available, due to extreme meteorological conditions. Indeed, precipitation is known to be underestimated due to the difficulty of measuring solid precipitation with rain gauges ~~(Wagnon et al., 2013)~~(Wolff et al., 2015). Precipitation fields provided by different atmospheric models and satellites show also high discrepancies in this region of the Himalayas (Andermann et al., 2011; Palazzi et al., 2013; Ceglar et al., 2017): ~~another~~ a perspective of this study is to test the sensitivity of the model to different precipitation forcing data sets (in-situ, reanalysis, and satellite) and analyze the impact of different precipitation amounts and spatial distributions on the simulated discharges and flow components.

6 Conclusions

In this study we used a distributed physically-based glacio-hydrological model (DHSVM-GDM) to simulate the outflow of a small catchment in the Everest region and to estimate the different contributions to streamflows, which can be useful for water resources and water-related risks management. Some improvements on the cryospheric processes parameterization in DHSVM-GDM were proposed in order to better represent the snowcover dynamics, the ice melt under debris covered glaciers, and avalanches. Simulated SCA were compared with MODIS images and calculated glacier mass balances with local in situ measurements and geodetic mass balances.

Results showed that the representation of the cryospheric processes in the model has a significant impact on the simulated outflow and flow components. Despite some outstanding issues that have been discussed, we can argue that the most satisfactory snow and glacier parameterizations proposed in this study (model configuration v3) enabled to simulate the snow cover spatial distribution and the glacier mass balance more accurately than the original version of DHSVM-GDM, by increasing the glacier accumulation and reducing ice melt. Major contributions from glaciers and and snow to the outflow were found, with 46 % of the anual outflow produced by ice melt and 41 % by snow melt. Winter flows are mainly controlled by the release of englacial and soil water storage (up to 78 % in December), which corroborates other studies (Racoviteanu et al., 2013; Ragettli et al., 2015). We estimate an uncertainty related to the ice melt reduction factor by debris (ranging from 0.3 to 0.5) of ±0.14 m w.e.yr^{-1} for the annual glacier mass balance and ±7 % for the annual outflow. The glacier inventories used to outline the glacierized areas have also an important impact on the simulation results. The three inventories tested in this study give estimations of the glacierized area ranging from 26 to 43 % of the basin area and a corresponding uncertainty of 20 % for the ice melt production.

This study also reminds that glacial and snow contributions to the streamflow must be clearly defined, as considering glacial contribution as the total outflow from the glacierized area or as outflow produced by ice melt can lead to very different estimations.

Appendix A: Parameter values used in DHSVM-GDM

Name	**Unit**	**Value(s)**	**Reference**
Ground Roughness	m	0.04	Brutsaert (2005)
Reference Height	m	2	-
LAI Multiplier for rain interception	-	0.0005	Brutsaert (2005)
LAI Mulitplier for snow interception	-	0.00005	Andreadis et al. (2009)
Tree Height	m	2	-
Vegetation Density	-	0.25	-
Distance from bank to canopy	m	2	-
Snow			
Snow Roughness	m	0.001	Brock et al. (2006)
Rain Threshold	°C	0	L'hôte et al. (2005)
Snow Threshold	°C	2	L'hôte et al. (2005)
Snow Water Capacity	-	0.05	Singh (2001)
Minimum Intercepted snow	m	0.005	-
Maximum Snow Albedo	-	0.85	MODImLab
Glaciers			
Glacier Albedo	-	0.3	MODImLab
Melt coefficient for debris-covered glacier	-	0.4	Vincent et al. (2016)

Table A1. Global parameter values used for the glacio-hydrological simulation with DHSVM-GDM

Name	**Unit**	**Value(s)**	**Reference**
Soil type	-	Regosol	
Lateral Conductivity	m/s	0.0053	Clapp and Hornberger (1978)
Exponential Decrease	-	2	Niu et al. (2005)
Depth Threshold	m	10	-
Capillary Drive	-	0.0756	Morel-Seytoux and Nimmo (1999)
Maximum Infiltration	m/s	6.94E-06	FAO
Surface Albedo	-	0.35	ModimLab
Number of Soil Layers	-	3	-
Porosity	-	0.6	calibrated
Pore Size Distribution	-	0.43	Rawls et al. (1982)
Bubbling Pressure	-	0.302	Rawls et al. (1982)
Field Capacity	-	0.31	Meyer et al. (1997)
Wilting Point	-	0.23	Meyer et al. (1997)
Vertical Conductivity	m/s	5.30E-05	Clapp and Hornberger (1978)
Thermal Conductivity layer 1	W/m.°C	7.114	Burns (2012)
Thermal Conductivity layer 2 et 3	W/m.°C	6.923	Burns (2012)
Thermal Capacity	J/m3.°C	1.40E+06	Burns (2012)

Table A2. Soil parameter values used for the glacio-hydrological simulation with DHSVM-GDM. Under glaciers, the values of the vertical and lateral conductivities were adjusted to 0.0003 m/s and the porosity value to 0.8.

Name	Unit	Value(s)				Reference
Vegetation type	-	Shrubland	Grassland	Agriculture	Bare	
Overstory Present	-	FALSE	FALSE	FALSE	FALSE	-
Understory Present	-	TRUE	TRUE	TRUE	TRUE	-
Impervious Fraction	-	0	0	0	0	-
Height	m	1	0.3	1	0.15	-
Maximum Resistance	s/m	600	600	600	600	Wigmosta et al. (1994)
Minimum Resistance	s/m	200	200	120	120	Wigmosta et al. (1994)
Moisture Threshold	-	0.6	0.6	0.33	0.8	calibrated
Vapor Pressure Deficit	Pa	2880	2880	4000	2000	Wigmosta et al. (1994)
Rpc	-	10	10	10	10	Dickinson et al. (1991)
Number of Root Zones	-	3	3	3	3	-
Root Zone Depths 1	m	0.06	0.1	0.06	0.045	-
Root Zone Depths 2	m	0.13	0.05	0.13	0.025	-
Root Zone Depths 3	m	0.2	0.05	0.2	0.025	-
Understory Root Fraction 1	-	0.4	0.4	0.4	0.4	-
Understory Root Fraction 2	-	0.6	0.6	0.6	0.6	-
Understory Root Fraction 3	-	0	0	0	0	-
Understory Monthly LAI	-	5.0 5.0 5.0 5.0 5.0 5.0 5.0 5.0 5.0 5.0 5.0 5.0	0.8 0.9 1.0 1.1 1.8 3.7 4.8 4.2 2.0 1.2 1.0 0.9	3.0 3.0 3.0 3.0 3.0 3.0 3.0 3.0 3.0 3.0 3.0 3.0	1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0	Wigmosta et al. (1994)
Understory Albedo	-	0.2	0.1	0.2	0.2	Wigmosta et al. (1994)

Table A3. Vegetation parameter values used for the glacio-hydrological simulation with DHSVM-GDM.

Competing interests. The authors declare that they have no conflict of interest.

Acknowledgements. This work has been supported by the French National Research Agency (ANR) through the ANR-13-SENV-0005-04/05-PRESHINE project and by a grant from Labex OSUG@2020 (investissement d'avenir, ANR 10 LABX56). It has benefited of data from the French Service d'Observation GLACIOCLIM (https://glacioclim.osug.fr/) and from Ev-K2-CNR (www.evk2cnr.org). The DHSVM-GDM model was made available by Chris Frans (Department of Civil and Environmental Engineering, University of Washington). The works of Yves Lejeune (CNRM-GAME) for correcting precipitation data in the GLACIOCLIM database and Ahmed Alatrash for processing MODIS data have been particularly helpful. Authors had fruitful discussions with Pierre Chevalier, Francois Delclaux, Luc Neppel and Judith Eeckman (HSM).

References

Akhtar, M., Ahmad, N., and Booij, M.: The impact of climate change on the water resources of Hindukush–Karakorum–Himalaya region under different glacier coverage scenarios, Journal of hydrology, 355, 148–163, 2008.

Andermann, C., Bonnet, S., and Gloaguen, R.: Evaluation of precipitation data sets along the Himalayan front, Geochemistry, Geophysics, Geosystems, 12, 2011.

Andermann, C., Longuevergne, L., Bonnet, S., Crave, A., Davy, P., and Gloaguen, R.: Impact of transient groundwater storage on the discharge of Himalayan rivers, Nature Geoscience, 5, 127, 2012.

Andreadis, K. M., Storck, P., and Lettenmaier, D. P.: Modeling snow accumulation and ablation processes in forested environments, Water Resources Research, 45, 2009.

Bajracharya, B., Uddin, K., Chettri, N., Shrestha, B., and Siddiqui, S. A.: Understanding land cover change using a harmonized classification system in the Himalaya: a case study from Sagarmatha National Park, Nepal, Mountain Research and Development, 30, 143–156, 2010.

Bajracharya, S. R.: Glacier status in Nepal and decadal change from 1980 to 2010 based on Landsat data, International Centre for Integrated Mountain Development, 2014.

Benn, D., Bolch, T., Hands, K., Gulley, J., Luckman, A., Nicholson, L., Quincey, D., Thompson, S., Toumi, R., and Wiseman, S.: Response of debris-covered glaciers in the Mount Everest region to recent warming, and implications for outburst flood hazards, Earth-Science Reviews, 114, 156–174, 2012.

Benn, D. I., Thompson, S., Gulley, J., Mertes, J., Luckman, A., and Nicholson, L.: Structure and evolution of the drainage system of a Himalayan debris-covered glacier, and its relationship with patterns of mass loss, The Cryosphere, 11, 2247, 2017.

Berghuijs, W., Woods, R., and Hrachowitz, M.: A precipitation shift from snow towards rain leads to a decrease in streamflow, Nature Climate Change, 4, 583, 2014.

Bewley, D., Alila, Y., and Varhola, A.: Variability of snow water equivalent and snow energetics across a large catchment subject to Mountain Pine Beetle infestation and rapid salvage logging, Journal of Hydrology, 388, 464–479, 2010.

Bhambri, R., Bolch, T., Chaujar, R. K., and Kulshreshtha, S. C.: Glacier changes in the Garhwal Himalaya, India, from 1968 to 2006 based on remote sensing, Journal of Glaciology, 57, 543–556, 2011.

Bolch, T., Kulkarni, A., Kääb, A., Huggel, C., Paul, F., Cogley, J. G., Frey, H., Kargel, J. S., Fujita, K., Scheel, M., et al.: The state and fate of Himalayan glaciers, Science, 336, 310–314, 2012.

Bookhagen, B. and Burbank, D. W.: Topography, relief, and TRMM-derived rainfall variations along the Himalaya, Geophysical Research Letters, 33, 2006.

Brock, B. W., Willis, I. C., and Sharp, M. J.: Measurement and parameterization of aerodynamic roughness length variations at Haut Glacier d'Arolla, Switzerland, Journal of Glaciology, 52, 281–297, 2006.

Brun, F., Berthier, E., Wagnon, P., Kääb, A., and Treichler, D.: A spatially resolved estimate of High Mountain Asia glacier mass balances from 2000 to 2016, Nature Geoscience, 2017.

Brutsaert, W.: Hydrology: an introduction, Cambridge University Press, 2005.

Burns, P. J.: Glacier change in a basin of the Peruvian Andes and implications for water resources, Ph.D. thesis, Oregon State University, 2012.

Ceglar, A., Toreti, A., Balsamo, G., and Kobayashi, S.: Precipitation over Monsoon Asia: A Comparison of Reanalyses and Observations, Journal of Climate, 30, 465–476, 2017.

Chen, Y., Li, W., Fang, G., and Li, Z.: Hydrological modeling in glacierized catchments of central Asia-status and challenges, Hydrology and Earth System Sciences, 21, 669, 2017.

Clapp, R. B. and Hornberger, G. M.: Empirical equations for some soil hydraulic properties, Water resources research, 14, 601–604, 1978.

Cogley, J. G.: A more complete version of the World Glacier Inventory, Annals of Glaciology, 50, 32–38, 2009.

Cristea, N. C., Lundquist, J. D., Loheide, S. P., Lowry, C. S., and Moore, C. E.: Modelling how vegetation cover affects climate change impacts on streamflow timing and magnitude in the snowmelt-dominated upper Tuolumne Basin, Sierra Nevada, Hydrological processes, 28, 3896–3918, 2014.

Dickinson, R. E., Henderson-Sellers, A., Rosenzweig, C., and Sellers, P. J.: Evapotranspiration models with canopy resistance for use in climate models, a review, Agricultural and Forest Meteorology, 54, 373–388, 1991.

Dijkshoorn, K. and Huting, J.: Soil and Terrain database for Nepal, 2009.

Douville, H., Royer, J.-F., and Mahfouf, J.-F.: A new snow parameterization for the Meteo-France climate model, Climate Dynamics, 12, 21–35, 1995.

Eeckman, J., Chevallier, P., Boone, A., Neppel, L., De Rouw, A., Delclaux, F., and Koirala, D.: Providing a non-deterministic representation of spatial variability of precipitation in the Everest region, Hydrology and Earth System Sciences, 21, 4879, 2017.

Flowers, G. E. and Clarke, G. K.: A multicomponent coupled model of glacier hydrology 2. Application to Trapridge Glacier, Yukon, Canada, Journal of Geophysical Research: Solid Earth, 107, 2002.

Frans, C., Istanbulluoglu, E., Lettenmaier, D. P., Naz, B. S., Clarke, G. K., Condom, T., Burns, P., and Nolin, A. W.: Predicting glacio-hydrologic change in the headwaters of the Zongo River, Cordillera Real, Bolivia, Water Resources Research, 51, 9029–9052, 2015.

Frey, S. and Holzmann, H.: A conceptual, distributed snow redistribution model, Hydrology and Earth System Sciences, 19, 4517, 2015.

Fujita, K., Inoue, H., Izumi, T., Yamaguchi, S., Sadakane, A., Sunako, S., Nishimura, K., Immerzeel, W. W., Shea, J. M., Kayastha, R. B., et al.: Anomalous winter-snow-amplified earthquake-induced disaster of the 2015 Langtang avalanche in Nepal, Natural Hazards and Earth System Sciences, 17, 749, 2017.

Gardelle, J., Berthier, E., Arnaud, Y., and Kaab, A.: Region-wide glacier mass balances over the Pamir-Karakoram-Himalaya during 1999-2011 (vol 7, pg 1263, 2013), Cryosphere, 7, 1885–1886, 2013.

Gulley, J., Benn, D., Screaton, E., and Martin, J.: Mechanisms of englacial conduit formation and their implications for subglacial recharge, Quaternary Science Reviews, 28, 1984–1999, 2009.

Gupta, H. V., Kling, H., Yilmaz, K. K., and Martinez, G. F.: Decomposition of the mean squared error and NSE performance criteria: Implications for improving hydrological modelling, Journal of Hydrology, 377, 80–91, 2009.

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

Immerzeel, W. W., Van Beek, L. P., and Bierkens, M. F.: Climate change will affect the Asian water towers, Science, 328, 1382–1385, 2010.

Immerzeel, W. W., Van Beek, L., Konz, M., Shrestha, A., and Bierkens, M.: Hydrological response to climate change in a glacierized catchment in the Himalayas, Climatic change, 110, 721–736, 2012.

Irvine-Fynn, T. D., Porter, P. R., Rowan, A. V., Quincey, D. J., Gibson, M. J., Bridge, J. W., Watson, C. S., Hubbard, A., and Glasser, N. F.: Supraglacial ponds regulate runoff from Himalayan debris-covered glaciers, Geophysical Research Letters, 2017.

Kääb, A., Treichler, D., Nuth, C., and Berthier, E.: Brief Communication: Contending estimates of 2003–2008 glacier mass balance over the Pamir–Karakoram–Himalaya, The Cryosphere, 9, 557–564, 2015.

Kaser, G., Großhauser, M., and Marzeion, B.: Contribution potential of glaciers to water availability in different climate regimes, Proceedings of the National Academy of Sciences, 107, 20 223–20 227, 2010.

King, O., Quincey, D. J., Carrivick, J. L., and Rowan, A. V.: Spatial variability in mass change of glaciers in the Everest region, central Himalaya, between 2000 and 2015, The Cryosphere Discussions, pp. 1–35, 2016.

Konz, M., Uhlenbrook, S., Braun, L., Shrestha, A., and Demuth, S.: Implementation of a process-based catchment model in a poorly gauged, highly glacierized Himalayan headwater, Hydrology and Earth System Sciences Discussions, 11, 1323–1339, 2007.

Kraaijenbrink, P., Bierkens, M., Lutz, A., and Immerzeel, W.: Impact of a global temperature rise of 1.5 degrees Celsius on Asia's glaciers, Nature, 549, 257–260, 2017.

Lejeune, Y., Bouilloud, L., Etchevers, P., Wagnon, P., Chevallier, P., Sicart, J.-E., Martin, E., and Habets, F.: Melting of snow cover in a tropical mountain environment in Bolivia: Processes and modeling, Journal of Hydrometeorology, 8, 922–937, 2007.

Leung, L., Wigmosta, M., Ghan, S., Epstein, D., and Vail, L.: Application of a subgrid orographic precipitation/surface hydrology scheme to a mountain watershed, Journal of Geophysical Research: Atmospheres, 101, 12 803–12 817, 1996.

Leung, L. R. and Wigmosta, M. S.: Potential climate change impacts on mountain watersheds in the Pacific Northwest, JAWRA Journal of the American Water Resources Association, 35, 1463–1471, 1999.

L'hôte, Y., Chevallier, P., Coudrain, A., Lejeune, Y., and Etchevers, P.: Relationship between precipitation phase and air temperature: comparison between the Bolivian Andes and the Swiss Alps/Relation entre phase de précipitation et température de l'air: comparaison entre les Andes Boliviennes et les Alpes Suisses, Hydrological Sciences Journal, 50, 2005.

Lutz, A., Immerzeel, W., Shrestha, A., and Bierkens, M.: Consistent increase in High Asia's runoff due to increasing glacier melt and precipitation, Nature Climate Change, 4, 587–592, 2014.

McDowell, G., Ford, J. D., Lehner, B., Berrang-Ford, L., and Sherpa, A.: Climate-related hydrological change and human vulnerability in remote mountain regions: a case study from Khumbu, Nepal, Regional Environmental Change, 13, 299–310, 2013.

Meyer, P., Rockhold, M., and Gee, G.: Uncertainty analyses of infiltration and subsurface flow and transport for SDMP sites, Tech. rep., Nuclear Regulatory Commission, Washington, DC (United States). Div. of Regulatory Applications; Pacific Northwest National Lab., Richland, WA (United States), 1997.

Morel-Seytoux, H. J. and Nimmo, J. R.: Soil water retention and maximum capillary drive from saturation to oven dryness, Water resources research, 35, 2031–2041, 1999.

Nash, J. E. and Sutcliffe, J. V.: River flow forecasting through conceptual models part I—A discussion of principles, Journal of hydrology, 10, 282–290, 1970.

Naz, B. S., Frans, C., Clarke, G., Burns, P., and Lettenmaier, D.: Modeling the effect of glacier recession on streamflow response using a coupled glacio-hydrological model, Hydrology and Earth System Sciences, 18, 787–802, 2014.

Nepal, S.: Impacts of climate change on the hydrological regime of the Koshi river basin in the Himalayan region, Journal of Hydro-environment Research, 10, 76–89, 2016.

Nepal, S., Krause, P., Flügel, W.-A., Fink, M., and Fischer, C.: Understanding the hydrological system dynamics of a glaciated alpine catchment in the Himalayan region using the J2000 hydrological model, Hydrological Processes, 28, 1329–1344, 2014.

Nijssen, B., Haddeland, I., and Lettenmaier, D. P.: Point evaluation of a surface hydrology model for BOREAS, Journal of Geophysical Research: Atmospheres, 102, 29 367–29 378, 1997.

Niu, G.-Y., Yang, Z.-L., Dickinson, R. E., and Gulden, L. E.: A simple TOPMODEL-based runoff parameterization (SIMTOP) for use in global climate models, Journal of Geophysical Research: Atmospheres, 110, 2005.

Nuimura, T., Sakai, A., Taniguchi, K., Nagai, H., Lamsal, D., Tsutaki, S., Kozawa, A., Hoshina, Y., Takenaka, S., Omiya, S., et al.: The GAMDAM glacier inventory: a quality-controlled inventory of Asian glaciers, The Cryosphere, 9, 849–864, 2015.

Østrem, G.: Ice melting under a thin layer of moraine, and the existence of ice cores in moraine ridges, Geografiska Annaler, 41, 228–230, 1959.

Palazzi, E., Hardenberg, J. v., and Provenzale, A.: Precipitation in the Hindu-Kush Karakoram Himalaya: Observations and future scenarios, Journal of Geophysical Research: Atmospheres, 118, 85–100, 2013.

Paul, F., Kääb, A., Rott, H., Shepherd, A., Strozzi, T., Volden, E., et al.: GlobGlacier: a new ESA project to map the world's glaciers and ice caps from space, EARSeL eProceedings, 8, 11–25, 2009.

Paul, F., Barrand, N. E., Baumann, S., Berthier, E., Bolch, T., Casey, K., Frey, H., Joshi, S., Konovalov, V., Bris, R. L., et al.: On the accuracy of glacier outlines derived from remote-sensing data, Annals of Glaciology, 54, 171–182, 2013.

Pfeffer, W. T., Arendt, A. A., Bliss, A., Bolch, T., Cogley, J. G., Gardner, A. S., Hagen, J.-O., Hock, R., Kaser, G., Kienholz, C., et al.: The Randolph Glacier Inventory: a globally complete inventory of glaciers, Journal of Glaciology, 60, 537–552, 2014.

Pritchard, H. D.: Asia's glaciers are a regionally important buffer against drought, Nature, 545, 169–174, 2017.

Racoviteanu, A. E., Armstrong, R., and Williams, M. W.: Evaluation of an ice ablation model to estimate the contribution of melting glacier ice to annual discharge in the Nepal Himalaya, Water Resources Research, 49, 5117–5133, 2013.

Radić, V. and Hock, R.: Glaciers in the Earth's hydrological cycle: assessments of glacier mass and runoff changes on global and regional scales, Surveys in geophysics, 35, 813–837, 2014.

Ragettli, S., Pellicciotti, F., Immerzeel, W., Miles, E., Petersen, L., Heynen, M., Shea, J., Stumm, D., Joshi, S., and Shrestha, A.: Unraveling the hydrology of a Himalayan catchment through integration of high resolution in situ data and remote sensing with an advanced simulation model, Advances in Water Resources, 78, 94–111, 2015.

Rawls, W. J., Brakensiek, D., and Saxtonn, K.: Estimation of soil water properties, Transactions of the ASAE, 25, 1316–1320, 1982.

Rees, H. G. and Collins, D. N.: Regional differences in response of flow in glacier-fed Himalayan rivers to climatic warming, Hydrological processes, 20, 2157–2169, 2006.

Robson, B. A., Nuth, C., Dahl, S. O., Hölbling, D., Strozzi, T., and Nielsen, P. R.: Automated classification of debris-covered glaciers combining optical, SAR and topographic data in an object-based environment, Remote Sensing of Environment, 170, 372–387, 2015.

Rowan, A. V., Egholm, D. L., Quincey, D. J., and Glasser, N. F.: Modelling the feedbacks between mass balance, ice flow and debris transport to predict the response to climate change of debris-covered glaciers in the Himalaya, Earth and Planetary Science Letters, 430, 427–438, 2015.

Savéan, M., Delclaux, F., Chevallier, P., Wagnon, P., Gonga-Saholiariliva, N., Sharma, R., Neppel, L., and Arnaud, Y.: Water budget on the Dudh Koshi River (Nepal): uncertainties on precipitation, Journal of Hydrology, 531, 850–862, 2015.

Shea, J., Immerzeel, W., Wagnon, P., Vincent, C., and Bajracharya, S.: Modelling glacier change in the Everest region, Nepal Himalaya, The Cryosphere, 9, 1105–1128, 2015.

Sherpa, S. F., Wagnon, P., Brun, F., Berthier, E., Vincent, C., Lejeune, Y., Arnaud, Y., Kayastha, R. B., and Sinisalo, A.: Contrasted surface mass balances of debris-free glaciers observed between the southern and the inner parts of the Everest region (2007-15), Journal of Glaciology, pp. 1–15, 2017.

Shrestha, A. B., Wake, C. P., Dibb, J. E., Mayewski, P. A., et al.: Precipitation fluctuations in the Nepal Himalaya and its vicinity and relationship with some large scale climatological parameters, International Journal of Climatology, 20, 317–327, 2000.

Shukla, A., Gupta, R., and Arora, M.: Estimation of debris cover and its temporal variation using optical satellite sensor data: a case study in Chenab basin, Himalaya, Journal of Glaciology, 55, 444–452, 2009.

Singh, P.: Snow and glacier hydrology, vol. 37, Springer Science & Business Media, 2001.

Singh, S., Kumar, R., Bhardwaj, A., Sam, L., Shekhar, M., Singh, A., Kumar, R., and Gupta, A.: Changing climate and glacio-hydrology in Indian Himalayan Region: a review, Wiley Interdisciplinary Reviews: Climate Change, 7, 393–410, 2016.

Sirguey, P., Mathieu, R., and Arnaud, Y.: Subpixel monitoring of the seasonal snow cover with MODIS at 250 m spatial resolution in the Southern Alps of New Zealand: Methodology and accuracy assessment, Remote Sensing of Environment, 113, 160–181, 2009.

Soncini, A., Bocchiola, D., Confortola, G., Minora, U., Vuillermoz, E., Salerno, F., Viviano, G., Shrestha, D., Senese, A., Smiraglia, C., et al.: Future hydrological regimes and glacier cover in the Everest region: The case study of the upper Dudh Koshi basin, Science of the Total Environment, 565, 1084–1101, 2016.

Vincent, C., Wagnon, P., Shea, J. M., Immerzeel, W. W., Kraaijenbrink, P., Shrestha, D., Soruco, A., Arnaud, Y., Brun, F., Berthier, E., and Sherpa, S.: Reduced melt on debris-covered glaciers: investigations from Changri Nup Glacier, Nepal, The Cryosphere, 10, 1845, 2016.

Viviroli, D., Dürr, H. H., Messerli, B., Meybeck, M., and Weingartner, R.: Mountains of the world, water towers for humanity: Typology, mapping, and global significance, Water resources research, 43, 2007.

Wagnon, P., Vincent, C., Arnaud, Y., Berthier, E., Vuillermoz, E., Gruber, S., Ménégoz, M., Gilbert, A., Dumont, M., Shea, J., et al.: Seasonal and annual mass balances of Mera and Pokalde glaciers (Nepal Himalaya) since 2007, The Cryosphere, 7, 1769–1786, 2013.

Weiler, M., Seibert, J., and Stahl, K.: Magic components—why quantifying rain, snowmelt, and icemelt in river discharge is not easy, Hydrological Processes, 32, 160–166, 2018.

Westrick, K. J., Storck, P., and Mass, C. F.: Description and evaluation of a hydrometeorological forecast system for mountainous watersheds, Weather and Forecasting, 17, 250–262, 2002.

Whitaker, A., Alila, Y., Beckers, J., and Toews, D.: Application of the distributed hydrology soil vegetation model to Redfish Creek, British Columbia: model evaluation using internal catchment data, Hydrological processes, 17, 199–224, 2003.

Wigmosta, M. S. and Burges, S. J.: An adaptive modeling and monitoring approach to describe the hydrologic behavior of small catchments, Journal of Hydrology, 202, 48–77, 1997.

Wigmosta, M. S., Vail, L. W., and Lettenmaier, D. P.: A distributed hydrology-vegetation model for complex terrain, Water resources research, 30, 1665–1679, 1994.

Wolff, M., Isaksen, K., Petersen-Øverleir, A., Ødemark, K., Reitan, T., and Brækkan, R.: Derivation of a new continuous adjustment function for correcting wind-induced loss of solid precipitation: results of a Norwegian field study, Hydrology and Earth System Sciences, 19, 951, 2015.

Wortmann, M., Bolch, T., Krysanova, V., and Buda, S.: Bridging glacier and river catchment scales: an efficient representation of glacier dynamics in a hydrological model, Hydrol. Earth Syst. Sci. Discuss., 2016, 1–37, doi:10.5194/hess-2016-272, http://www.hydrol-earth-syst-sci-discuss.net/hess-2016-272/, 2016.

Zhao, Q., Liu, Z., Ye, B., Qin, Y., Wei, Z., and Fang, S.: A snowmelt runoff forecasting model coupling WRF and DHSVM, Hydrology and Earth System Sciences, 13, 1897–1906, 2009.

Zhu, Z. and Woodcock, C. E.: Object-based cloud and cloud shadow detection in Landsat imagery, Remote Sensing of Environment, 118, 83–94, 2012.