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Effects of univariate and multivariate bias correction on hydrological impact projections in alpine catchments

Judith Meyer[1], Irene Kohn[1], Kerstin Stahl[1], Kirsti Hakala[2], Jan Seibert[2], and Alex J. Cannon[3]

[1]Faculty of Environment and Natural Resources, University of Freiburg, Freiburg, 79098, Germany
[2]Department of Geography, University of Zurich, Zurich, 8057, Switzerland
[3]Climate Research Division, Environment and Climate Change Canada, BC V8W 2Y2, Victoria, Canada

Correspondence to: Irene Kohn (irene.kohn@hydrology.uni-freiburg.de)

Abstract. Alpine catchments show a high sensitivity to climate variation as they include the elevation range of the snow line. Therefore, the correct representation of climate variables and their interdependence is crucial when describing or predicting hydrological processes. When using climate model simulations in hydrological impact studies, forcing meteorological data are usually downscaled and bias corrected, most often by univariate approaches such as quantile mapping of individual variables. However, univariate correction neglects the relationships that exist between climate variables. In this study glacio-hydrological simulations were performed for two partly glacierized alpine catchments using a recently developed multivariate bias correction method to post-process EURO-CORDEX regional climate model outputs between 1976 and 2100. These simulations were compared to those obtained by using the common univariate quantile mapping for bias correction. As both methods correct each climate variable's distribution in the same way, the marginal distributions of the individual variables show no differences. Yet, regarding the interdependence of precipitation and air temperature, clear differences are notable in the studied catchments. Simultaneous correction based on the multivariate approach lead to more precipitation below air temperatures of 0 °C and therefore more simulated snowfall than with the data of the univariate approach. This difference translated to considerable consequences for the hydrological responses of the catchments. The multivariate bias correction forced simulations showed distinctly different results for projected snow cover characteristics, snowmelt-driven streamflow components, and expected glacier disappearance dates in the future. For the historical period the fraction of precipitation above and below 0 °C, the simulated snow water equivalents, glacier volumes, and the streamflow regime resulting from the multivariate-corrected data corresponded better with reference data than the results of univariate bias correction. Differences in simulated total streamflow due to the different bias correction approaches may be considered negligible given the generally large spread of the projections, but systematic differences in the seasonally delayed streamflow components from snowmelt in particular will matter from a planning perspective. While this study does not allow concluding definitively that multivariate bias correction approaches are generally preferable, it clearly demonstrates that incorporating or ignoring inter-variable relationships between air temperature and precipitation data can impact the conclusions drawn in hydrological climate change impact studies.

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1 Introduction

As the Earth's global climate changes, hydrological processes in high elevation regions have been significantly impacted (Messerli et al., 2004). In the European Alps, an increase in air temperature was witnessed during the last century – a trend that is expected to continue in the future. Future trends in precipitation are less clear, however, a slight increase in winter precipitation is expected (Gobiet et al., 2014; Kotlarski et al., 2016). The hydrology of alpine catchments is especially sensitive to these changing climate parameters (Köplin et al., 2010). High elevations in the Alps are still characterized by snow cover and the existence of glaciers. However, rising air temperatures and a consequent upward shift of the zero-degree isotherm has led to a decrease in snow accumulation and an increase in glacier melt (Pellicciotti et al., 2010). Due to shrinking glacier areas, the glacial influence in the streamflow regimes has decreased. This is especially notable during late summer when water from ice melt can constitute a notable percentage of total streamflow. With progressive glacier retreat, the ice melt contribution to streamflow is expected to decrease (Jansson et al., 2003; Hock, 2005; Moore et al., 2009; Huss and Hock, 2018). The interdependence of air temperature and precipitation is particularly important for hydrological systems as it determines the physical state of precipitation. Bosshard et al. (2014) show that an air temperature dependent shift from snowfall to rain has notable effects on catchment water storage and seasonal water availability. A correct representation of climate variables and their interdependence is therefore essential in hydrological simulations of glacierized catchments.

In hydrological climate change impact studies, post-processing of climate model data has become a standard procedure. Despite continuous progress, raw outputs from regional climate models differ largely from observational reference data due to both spatial mismatches and systematic biases. Therefore, climate model outputs are downscaled and biases are adjusted statistically before being used in hydrological simulations (Ehret et al., 2012; Maraun, 2016; Teutschbein and Seibert, 2012). Many empirical statistical techniques have been developed to post-process climate model outputs for these purposes. For hydrological impact studies quantile mapping approaches, which correct for the data's entire distribution, have often been recommended (Teutschbein and Seibert, 2012; Gudmundsson et al., 2012; Chen et al., 2013). However, these approaches correct the climate variables independently from one another. The interdependence of climate variables can be especially important when modelling snow-dominated catchments due to threshold effects. To account for interdependencies, multivariate bias correction approaches have been developed that allow for the preservation of the interdependence of climate variables throughout the bias correction process (Li et al., 2014; Cannon, 2016, 2018; Mehrotra and Sharma, 2016). A correction procedure that preserves the climate variables' interdependence may be considered more appropriate for subsequent impact analyses, such as the application of a calibrated hydrological model using multiple variables, than univariate techniques that ignore biases in inter-variable relationships (Cannon, 2018). So far, there have been only few studies (Räty et al., 2018; Chen et al., 2018) that investigated the effect of using a multivariate bias correction technique on hydrological projections. Chen et al. (2018) found that jointly corrected precipitation and air temperature data better modelled eleven out of twelve catchments in the calibration period than the meteorological data that was corrected based on a univariate method. An advantage of using a bivariate bias correction approach was not evident for the coldest snow-

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dominated catchment of the sample though. According to Räty et al. (2018) their hydrological simulations did not substantially benefit from bivariate bias correction approaches, whereas simulations of high flows and snow water equivalents in snow-influenced catchments improved slightly in comparison to simulations using univariate-corrected climate model data.

The objective of this study was to compare the effects of univariate and multivariate bias correction of precipitation and air temperature in hydrological impact modelling of alpine catchments. This was done by systematically comparing hydrological simulations driven by climate data corrected with the two different bias correction methods. The model experiment was conducted for two meso-scale partly glacierized catchments in the Swiss Alps, for which snow accumulation, glacier mass balance, and streamflow were simulated from 1976 to 2100.

2 Study catchments and data

2.1 Study area

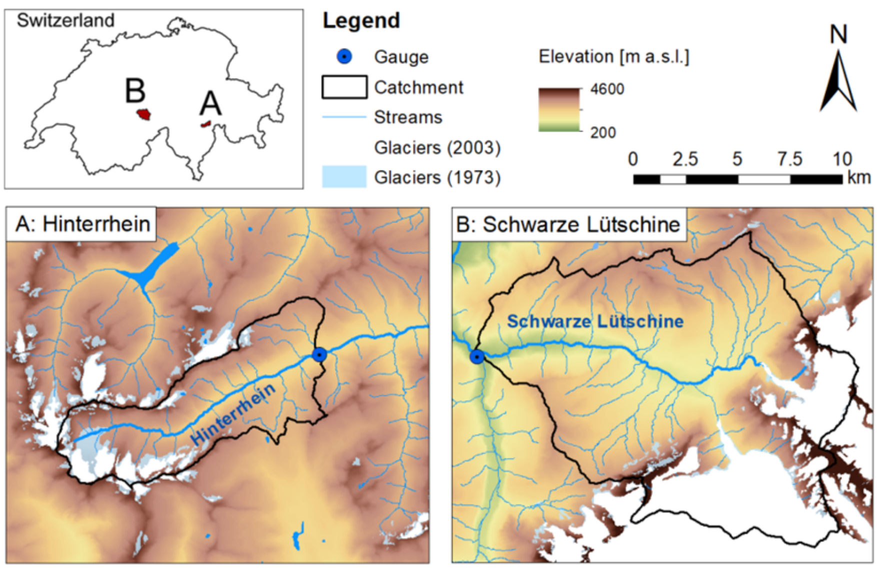

Figure 1: Map of the two study catchments and their location in Switzerland: Hinterrhein (A) and Schwarze Lütschine (B).

Two partly glacierized meso-scale catchments in the Swiss Alps, in the headwater of the Rhine River, were examined in this study: the Hinterrhein catchment and the larger Schwarze Lütschine catchment (Fig. 1, Table 1). Based on the dataset by Freudiger et al. (2018), used in this study, around the year 1900 glacier coverage was approximately 32% of the Hinterrhein catchment area and around 25% of the Schwarze Lütschine catchment area. Glaciers in both catchments retreated considerably during the 20th century. The Hinterrhein catchment is characterized by small, scattered glaciers, which by 1973 lost around half their area, leading to a glacier coverage of only 7% in 2010 (Table 1). The Schwarze Lütschine catchment, in contrast, holds some of the largest glaciers in the Swiss Alps such as the Grindelwald glacier. Consequently, losses in relative glacier area have been smaller. This difference in glacier coverage is related to elevation with considerably higher maximum elevations in the Schwarze Lütschine catchment compared to the Hinterrhein catchment (Table 1).

Table 1: Catchment characteristics including glacier cover information.

	Area	Elevation			Glacier cover*					
		mean	min	max	1973		2003		2010	
	[km²]		[m a.s.l.]		[km²]	[%]	[km²]	[%]	[km²]	[%]
Hinterrhein	53.9	2357	1387	3387	9.1	17.8	4.7	8.7	3.8	7.1
Schwarze Lütschine	179.9	2059	648	4086	37.0	23.5	34.4	19.1	29.7	16.5

* Based on glacier inventories by Müller et al. (1976) / Maisch et al. (2000) for 1973, Paul et al. (2011) for 2003, and Fischer et al.(2014) for 2010.

2.2 Data and data preparation

The application of bias correction algorithms to climate model outputs is generally based on three datasets: historical observations as reference (also called 'target') data, historical climate model simulations, and the corresponding climate model projections. In the present study the historical reference data for the study catchments were derived from an observation based interpolation product, i.e. the 1x1km² gridded daily air temperature and precipitation datasets from the HYRAS product (Rauthe et al., 2013; Frick et al., 2014). Area-weighted mean values of precipitation and temperature were extracted for the study catchments. The extracted catchment mean precipitation time series were corrected for undercatch based on the method by Sevruk (1989) and were then further adjusted through a validation with long-term annual mean precipitation sums resulting from a water balance approach (for details see Stahl et al. 2017). The resulting time series of catchment mean precipitation and temperature were used as input for the calibration of the glacio-hydrological model and as historically observed climate data (HOCD) for the bias correction.

The climate model datasets were obtained from the Coordinated Regional Climate Downscaling Experiment (CORDEX, www.cordex.org) via the CH2018 archive (http://www.ch2018.ch/en/home-2/). CORDEX is a collaborative effort within the climate modelling community where general circulation models (GCMs) are downscaled using regional climate models (RCMs). Since all catchments in this study are located in Switzerland, GCM–RCMs were selected from the European domain of the CORDEX project (EURO-CORDEX, http://www.euro-cordex.net/). EURO-CORDEX provides simulations at 0.11° (~12.5 km horizontal resolution) and 0.44 (~50 km horizontal resolution). Given that the catchments used in this study are situated in the Alpine domain, only the higher resolution 0.11° simulations were used. Two Representative Concentration Pathways (RCPs) were selected for this study: RCP 4.5 represents an intermediate mitigation scenario, where greenhouse gas (GHG) emissions will peak around 2040 and then steadily decrease, and RCP 8.5 represents a more pessimistic scenario, which assumes that GHG will continue to increase throughout the 21st century (Meinshausen et al., 2011).

Table 2: GCM–RCM combinations from the EURO-CORDEX initiative used in this study.

Driving GCM	RCM	RCM institution
CNRM-CM5-LR [1)]	CCLM4-8-17	Climate Limited-area Modelling Community
CNRM-CM5 [1)]	RCA4	Swedish Meteorological and Hydrological Institute
EC-EARTH [2)]	CCLM4-8-17	Climate Limited-area Modelling Community
EC-EARTH [2)]	HIRHAM5	Danish Meteorological Institute
EC-EARTH [2)]	RACMO22E	Royal Netherlands Meteorological Institute
EC-EARTH [2)]	RCA4	Swedish Meteorological and Hydrological Institute
IPSL-CM5A-MR [3)]	WRF331F	Laboratoire des Sciences du Climat et de l'Environnement
IPSL-CM5A-MR [3)]	RCA4	Swedish Meteorological and Hydrological Institute
MPI-ESM-LR [4)]	CCLM4-8-17	Climate Limited-area Modelling Community
MPI-ESM-LR [4)]	RCA4	Swedish Meteorological & Hydrological Institute

GCM institutions: [1)] CNRM-CERFACS (Centre National de Recherches Météorologiques-Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique), [2)] EC-Earth consortium, [3)] IPSL (Institut Pierre-Simon Laplace), [4)] MPI-M (Max Planck Institute for Meteorology)

Precipitation (P) and air temperature (T_a) data were provided by the ten GCM–RCMs shown in Table 2 for the time period 1970–2100. For each catchment, raw GCM–RCM data were extracted using an area-weighted method as shown in Hakala et al. (in review). Based on the areal fraction of an RCM grid cell overlying a particular catchment, 5 RCM grid cells contribute to each catchment. All GCM–RCMs used in this study utilize a Gregorian calendar.

The application of the hydrological model requires time series of P and T_a. These were subjected to bias correction. Further data used as model input and for model calibration were not directly bias corrected. Daily potential evapotranspiration was calculated with a temperature based approach provided by Oudin et al. (2005). Catchment specific air temperature lapse rates were determined based on daily values from the HYRAS product. Based on the reference period from 1976–2006 a mean for each day of the year was calculated and smoothed using an 11-day moving average. A mean precipitation gradient (in % per 100 m a.s.l.) was determined from the corrected HYRAS data and applied as constant value in all simulations. Daily streamflow data for model calibration were provided by the Swiss Federal Office for the Environment (FOEN). Snow water equivalent (SWE) and snow cover data were derived from a snow map (interpolated grid) product by the OSHD-SLF (2013). The glacier area was assessed based on glacier inventory data by Müller et al. (1976) and Maisch et al. (2000) for the state in the year 1973, by Paul et al. (2011) for the state in 2003, and by Fischer et al. (2014) for the year 2010 (see Table 1). Estimates of glacier volume were derived based on gridded ice thickness data available for the years 1973 and 2010, which were computed using the approach by Huss and Farinotti (2012) and provided by Matthias Huss. Glacier volume for the year 2003 was estimated based on the glacier cover according to Paul et al. (2011) and glacier volume–area scaling. The glacier volume estimate for 1973 was used for model initialization. The estimate for 2003 was incorporated in the model calibration for the period 1976–2006. The estimate for 2010 was not directly used in the calibration but served the validation of model simulations beyond the year 2006.

3 Methods

3.1 Bias correction of climate data

Depending on the GCM–RCM combination, raw climate variables (noBC) of the control period (1976–2006) differ from the reference data (HOCD). To correct these biases, two different bias correction methods were applied to each climate model's T_a and P series: univariate Quantile Delta Mapping (QDM) and a Multivariate Bias Correction (MBCn). Univariate QDM was used because of its often and widely accepted application. QDM is a quantile mapping approach by Cannon et al. (2015) that was designed to avoid artificial deterioration of trends arising as a statistical artefact of quantile mapping. Therefore, the climate change signal (Δ) is extracted from all projected future quantiles in a first step. The quantile mapping is then applied to the detrended series, before the projected trends in quantiles are reintroduced to the bias corrected model output. Quantile mapping is based on a transfer function that transforms the cumulative distribution(s) of the modelled data to match the distribution(s) of the observed series. The obtained transfer function is then applied to all climate model data, historical and projected. Thus it corrects systematic distributional biases relative to historical observations and preserves model-projected relative changes (Cannon et al., 2015).

The multivariate bias correction algorithm by Cannon (2018) is based on the N-dimensional probability density function transform. This approach was originally developed for image processing (Pitié et al., 2007) but has been converted for post-processing climate model data. MBCn combines QDM and random orthogonal rotations to match the multivariate distributions of climate model data and observed data. In the MBCn approach, a random orthogonal rotation of the data points is applied before QDM. This exposes QDM to a linear combination of the original variables, which is then used to correct the marginal distributions of the rotated data. The QDM-corrected dataset is then rotated back and convergence to the observed multivariate distribution is checked. These steps are conducted iteratively until the multivariate distributions of model and observed data match. In this case, 100 iterations were conducted.

Data is often simultaneously bias corrected and downscaled as the reference data stems from stations or higher resolution observations in comparison to the coarse grid resolution of RCMs. Undesirable effects in downscaling to finer scales have been one of the major limitations of current bias correction methods (Maraun, 2013; Ehret et al., 2012; Maraun et al., 2017). Such artefacts can occur especially in complex terrain and if the scale gap between climate model outputs and impact model data is considerable. In general, bias correction based on spatial resolutions that differ substantially should be avoided or handled with great care. Since the hydrological model simulations in this study are based on spatially aggregated mean climate variables for the meso-scale catchments the discrepancy in resolution is assumed acceptable.

3.2 Hydrological model simulations

The HBV model (Bergström, 1976; Lindström et al., 1997) is a semi-distributed bucket-type runoff model. Here the software implementation HBV-light (Seibert and Vis, 2012) was used, which recently has been extended to represent coupled glacio-hydrological processes of partly glacierized catchments (Seibert et al., 2018). This version of the HBV model also allows tracking the different components of streamflow resulting from rainfall (Q_R), snowmelt (Q_S) and glacier ice melt (Q_I) (Weiler et al., 2018; Seibert et al., 2018). The HBV model requires daily precipitation, air temperature, and potential evapotranspiration data as input to simulate daily runoff. In addition, linear gradients of air temperature and precipitation are needed for the interpolation over elevation zones. A general description of the basic model structure and the process conceptualization of the HBV model are found elsewhere (e.g., Lindström et al., 1997; Seibert and Vis, 2012; Seibert et al., 2018). Snow and ice accumulation and melt are based on a widely used air temperature index approach using a threshold air temperature as a model parameter to differentiate between precipitation falling as snow and rain as well as to simulate snow and ice melt by additionally using a degree-day factor. Differences in the melt of glacier ice compared to snow are represented by another model parameter. The influence of differences in aspect on snow and ice melt was taken into account by distinguishing three aspect classes and applying an additional aspect factor parameter (Hagg et al., 2007; Hottelet et al., 1993). The latest version of the HBV-light software with the implementation of the coupled glacio-hydrological processes and the adjustment of glacier geometry to glacier mass changes based on the *Δh*-parametrization by Huss et al. (2010) is explained in detail in Seibert et al. (2018). It should be noted that with the implementation in HBV-light only one glacier per catchment or subcatchment can be represented. Hence, glacier cover areas in each of the two case study catchments were aggregated and simulated as one 'virtual' model glacier.

The model was calibrated for the reference period from 1976–2006, preceded by a 3-year warm-up period, by optimizing a weighted objective function, giving special attention to streamflow dynamics (50%), snow simulation (25%), and glacier volume change (25%). The Lindström measure (Lindström, 1997) was used for the streamflow's general dynamic and volume errors, while the Nash-Sutcliffe efficiency (Nash and Sutcliffe, 1970) was computed based on logarithmically-transformed streamflow. Additionally the Nash-Sutcliffe efficiency was computed for the streamflow only during the summer months from June to September. For evaluation of the snow simulations the snow covered area fraction was used as well as the mean snow water equivalent of the elevation range between 2000–2500 m a.s.l., which is the crucial elevation range for the snow line. The glacier volume was considered in the calibration process using glacier volume estimates for the years 1973 and 2003. The automated multi-criteria calibration was based on a genetic algorithm for parameter optimization (see Seibert, 2000). The retreat of the glaciers required all experiments to be run in a transient mode, i.e. the model was forced with climate model scenario data for the period from October 1976 to September 2099.

3.3 Data analysis

Effects of the bias correction approaches on the hydrological simulation were based on comparisons of the simulation results for the historical reference period 1976–2006 using P and T_a time series derived from the HYRAS datasets as input (Sim_{HOCD}) and simulations forced with P and T_a series from the output of the ten different GCM-RCMs for the two different RCP scenarios, each uncorrected (Sim_{noBC}) and bias corrected based on QDM (Sim_{QDM}) and on MBC_n (Sim_{MBCn}). In total, this leads to 61 hydrological model runs (1 Sim_{HOCD}, 20 Sim_{noBC}, 20 Sim_{QDM}, and 20 Sim_{MBCn}) per catchment. In a first step (Results Section 4.1), the different P and T_a series were evaluated for the amount of precipitation occurring at air temperatures above and below of 0 °C due to the importance for the simulation of snow accumulation and melt processes, since within HBV-light, as in many other hydrological models, the air temperature determines the state of precipitation. Furthermore, the simulation results were assessed in terms of the SWE, glacier ice volume (V_I) evolution (Results Section 4.2), and eventually streamflow with its three individual components Q_R, Q_S, and Q_I (Results Section 4.3).

4 Results

4.1 Climate variables bias correction

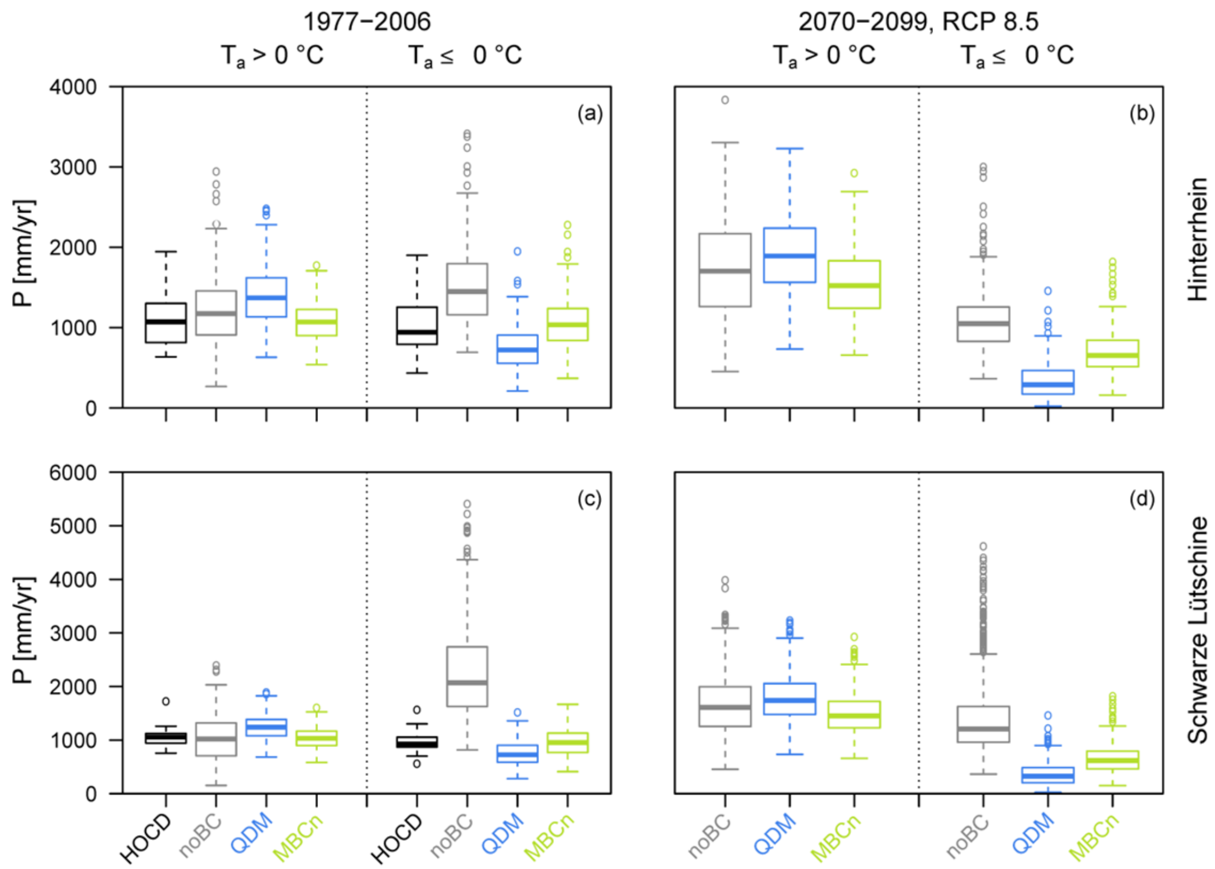

Figure 2: Annual precipitation sums for days with air temperatures above or below 0 °C.

The two applied bias correction methods lead to differences concerning the interdependence of P and T_a. The distribution of annual precipitation sums during air temperatures above and below 0 °C of the entire ensemble is represented in Fig. 2. Generally, the uncorrected climate model data (noBC) have a wider variability than the reference data (HOCD). Particularly for the Schwarze Lütschine the uncorrected data yielded precipitation amounts remarkably higher than historically observed. However, differences also exist between the correction methods. For both catchments precipitation falling above air temperatures of 0 °C was overestimated with QDM. Accordingly, precipitation falling below air temperatures of 0 °C was underestimated in the univariate bias corrected data. MBCn appears to better reproduce the historical reference data in this respect.

4.2 Hydrological model simulations – cryosphere

Application of the climate scenarios clearly revealed a decreasing role of snow for both study catchments. Figure 3 illustrates a distinctly smaller snow accumulation in the course of a year simulated for the period 2070–2099 compared to the historical reference period (1977–2006) and a more complete melt during the summer. This extended the snow free period during the summer in the Hinterrhein catchment. The spread between the simulations diverges for the future simulations. In the Schwarze Lütschine catchment with its higher maximum elevations all effects are comparable, yet a permanent snow cover was still present based on most scenarios. As expected, simulations based on the RCP 4.5 scenario (not shown) led to a clear but less severe decrease in mean SWE than for the RCP 8.5 scenario.

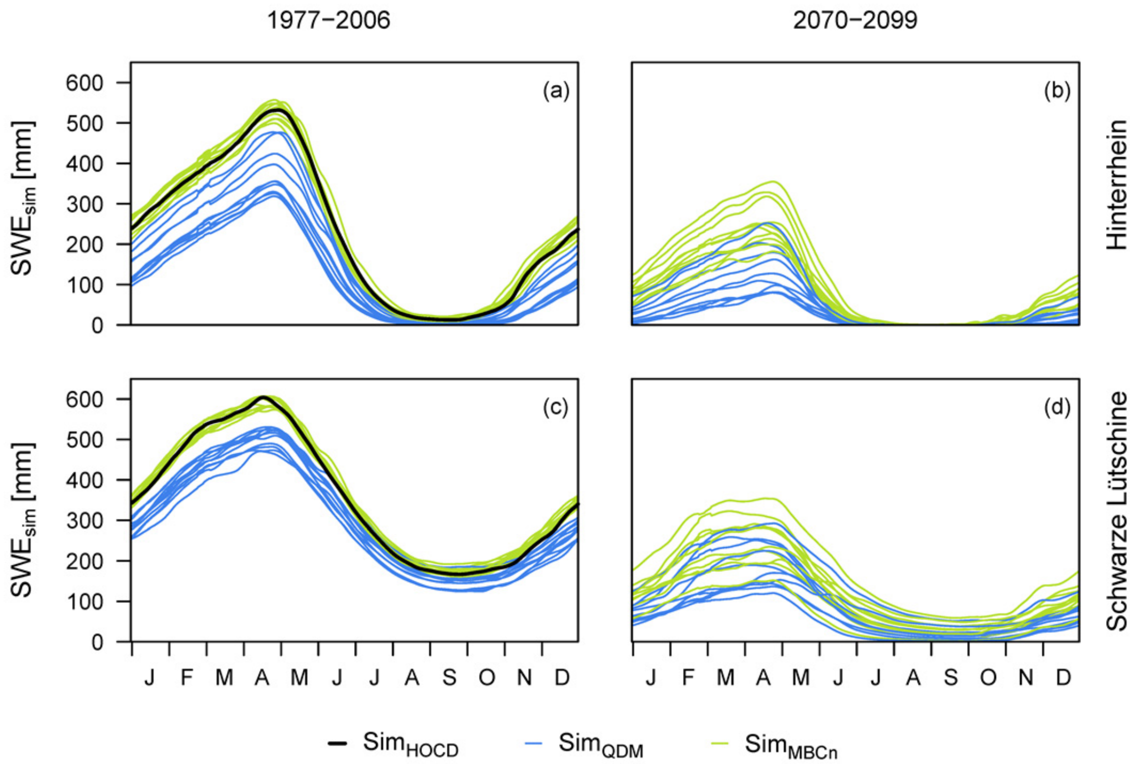

Figure 3: Mean annual SWE regime, calculated using the 11-day moving average of daily simulated SWE (catchment mean) for a) and c) the historical reference period and b) and d) at the end of the scenario period based on the RCP 8.5 scenario.

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The differences in the interdependence of precipitation and air temperature resulting from the application of QDM versus MBCn to the GCM–RCM data can be seen in the simulated SWE. The state of precipitation defined by the calibrated threshold temperature parameter TT (Schwarze Lütschine TT = -0.47 °C; Hinterrhein TT = -0.7 °C) influenced the snow accumulation and therefore led to differences in the annual SWE regime (Fig. 3). As MBCn-corrected GCM–RCM data caused more precipitation to fall as snow, SWE was simulated to be up to around 100 mm higher during snow accumulation in the historical reference period compared to simulations based on QDM-corrected forcing data for both study catchments. Simulated SWE based on the two different bias correction methods differed notably. Comparing the results with the reference simulation (Sim_{HOCD}) indicates that MBCn performed better. The systematic difference in simulated SWE resulting from the bias correction methods was less clear for the Schwarze Lütschine catchment in the scenario period, yet overall the differing tendencies between QDM- and MBCn-corrected data were considerable.

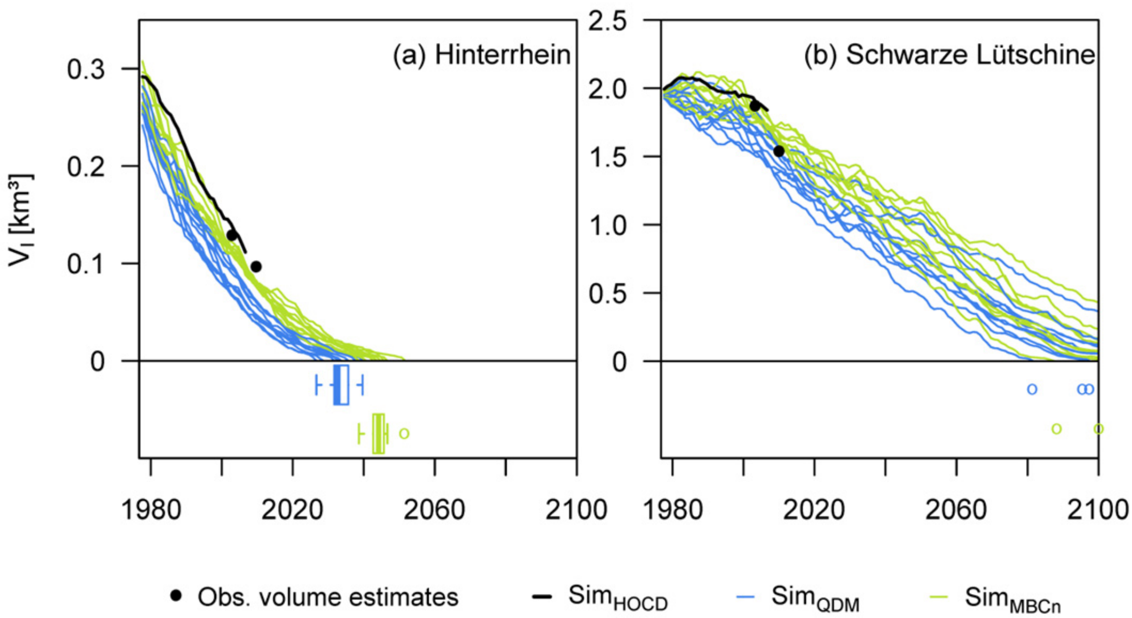

Figure 4: Simulated glacier ice volume from 1977 to 2100 using the RCP 8.5 scenario forcing in the two catchments (a, b). In the lower part of the graphs the boxes in the left figure and the dots in both figures indicate the simulated years of the complete glacier ice melt. Filled black circles are glacier volume estimates based on observed glacier area data in 2003 and 2010.

For the period 1976 to 2100 the glacier volume was simulated to decrease in both catchments. In the Hinterrhein catchment, glaciers diminished continuously from the beginning of the simulation period for both, the RCP 4.5 and the RCP 8.5 scenario, and were simulated to have disappeared between 2030 and 2055 depending on the GCM–RCMs and the applied bias correction method (Fig. 4). In the Schwarze Lütschine catchment, data from a few GCM–RCMs resulted in an increase in simulated glacier volume in the 1970s and 1980s, which is in line with the historical reference simulation (Sim_{HOCD}). In the following years, glacier volume decreased continuously. In contrast to the Hinterrhein catchment, glaciers were not simulated to have disappeared by 2100 based on the RCP 4.5 scenario (not shown). However, in the simulations the glacier volume diminished to roughly a third of its initial size at the beginning of the simulation period. The RCP 8.5 scenario from a few certain GCM–RCM combinations even led to complete glacier disappearance in the Schwarze Lütschine catchment within the 21st century.

Focusing on systematic differences between simulations using data corrected based on QDM and MBCn, the simulations of glacier volume showed similar tendencies as were found for SWE. For both catchments, but again more clearly for the Hinterrhein catchment, MBCn-corrected GCM–RCM data resulted in a slower decline in glacier volume in comparison to simulations based on QDM-corrected data. All projections led to complete glacier disappearance in the Hinterrhein catchment by about the year 2050 with a clear tendency towards earlier dates for QDM-based simulations (2026–2039, mean: 2033) compared to MBCn-based simulations (2038–2051, mean: 2044). For the Schwarze Lütschine catchment the range of QDM- and MBCn-based glacier volume simulations overlaps largely as simulations in general diverge considerably. However, for each individual GCM–RCM dataset, glacier melt was simulated to be faster using the QDM-corrected data compared to the MBCn-corrected data. In contrast to the inconclusive results for the SWE regimes, the less intense decline in glacier volumes resulting from MBCn-corrected forcing data appeared to correspond better with the reference simulation (Sim_{HOCD}) in the initial phase of the historical period and with the observation-based glacier volume estimates for the year 2003 (and also for the year 2010 in case of the Hinterrhein catchment). MBCn thus led to more realistic results for the historical reference period.

4.3 Hydrological model simulations – streamflow

Time changes of annual variables and mean monthly hydrological regimes were assessed for streamflow Q and for the individual streamflow components, i.e. the rain component Q_R, the snowmelt component Q_S, and the ice melt component Q_I. Mean annual streamflow of the study catchments appeared to stay relatively unchanged over the entire simulation period from 1976 to 2100 (Fig. 5). However, the simulations based on different GCM–RCM outputs diverge over time. Streamflow slightly decreased in some simulations and increased in others. While the total annual streamflow stayed largely unchanged, its composition changed. The streamflow component from glacier ice melt decreased slowly over time as the glaciers retreat. Likewise, the snowmelt component of streamflow decreased over time. On average, for the RCP 4.5 scenario's MBCn-corrected data these decreases are around 6% in the Hinterrhein and 10% in the Schwarze Lütschine; for the RCP 8.5 scenario's QDM-corrected data they are more than 60% in the Hinterrhein and 45% in the Schwarze Lütschine.

The streamflow simulations also reflect the changes from the different bias correction methods found for the cryosphere. Simulations based on QDM-corrected data mostly show higher streamflow than MBCn-corrected data (Fig. 5 a, d, e). These differences are even more pronounced regarding the individual streamflow components. Modelling based on QDM-corrected climate data led to an approximately 10% higher rain component of streamflow Q_R in comparison to MBCn-corrected

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simulations. The snowmelt component of streamflow Q_S varies proportionally, being notably smaller for models using QDM-corrected GCM–RCM data. Comparing the means of the ice melt components of streamflow Q_I for the 30-year periods in the beginning and in the end of the entire simulation period showed no differences from the bias correction methods for the Hinterrhein catchment and differences in the range of only 1% for the Schwarze Lütschine catchment.

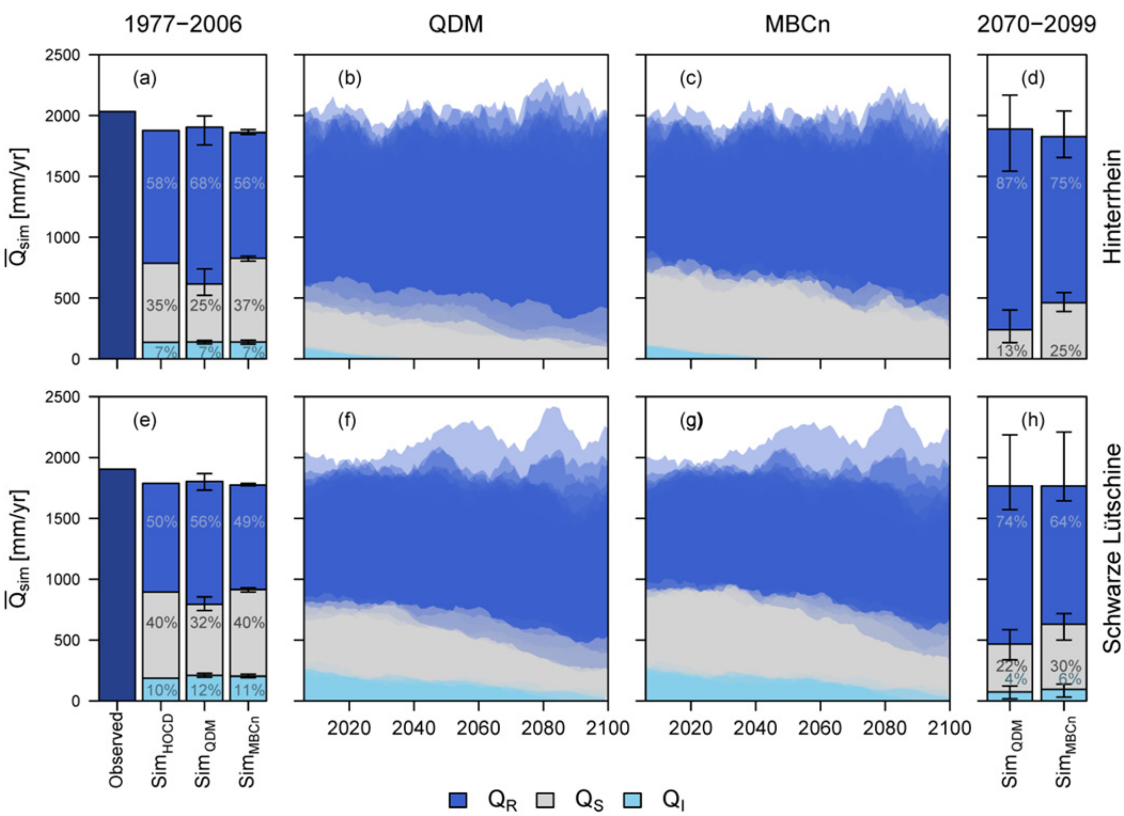

Figure 5: Observed total streamflow and simulated streamflow components for the historical reference period and for the different simulations under the RCP 8.5 scenario. Stacked bar plots show mean values over the historical reference period (plot a and e) and for the period 2070–2099 (plot d and h), stacked bar plots for Sim_{QDM} and Sim_{MBCn} show ensemble mean with ensemble spread (error bars). Simulation results over the scenario period 2006–2100 (plots b, c, f, and g) are shown as semi-transparent polygons for each GCM–RCM combination.

Simulated streamflow and its components, Q_I, Q_S, and Q_R, also changed seasonally (Fig 6). In the historical reference period (1977–2006), the two catchments had a nivo-glacial streamflow regime peaking in the summer due to snow and ice melt and little streamflow during winter. According to the projections the streamflow peak in early summer remains a dominant characteristic until the end of the simulation period. Yet, for the Hinterrhein catchment, the peak's timing was simulated to shift causing streamflow to concentrate in May and the peak to become much narrower than in the past. For the Schwarze

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Lütschine catchment the simulations for the RCP 8.5 scenario result in very variable summer streamflow regimes for 2070–2099. In the reference period, the glaciers' influence showed during late summer, where it extended the melt peak into autumn. This effect was simulated to diminish and then decrease streamflow in late summer. During autumn and winter, simulated streamflow is nearly doubled based on an increase in the rainfall component of streamflow. Despite similar tendencies of reduced Q_S in the future, differences arising from the different bias correction methods are notable. Q_S was more prominent in all regimes based on MBCn-corrected GCM–RCM outputs, which simulated higher peaks during the snowmelt season and a generally higher fraction during the rest of the year, especially for the future periods. Accordingly, QDM-corrected data supported a larger Q_R component beyond the summer. As a consequence, during low flow periods in winter, QDM-corrected forcing data overestimated the streamflow in the historical reference period. Whereas during the summer month QDM-corrected forced simulations tended to slightly underestimate the streamflow as Q_s was underestimated. Generally, MBCn-corrected data matched more closely with the reference simulations based on observed data.

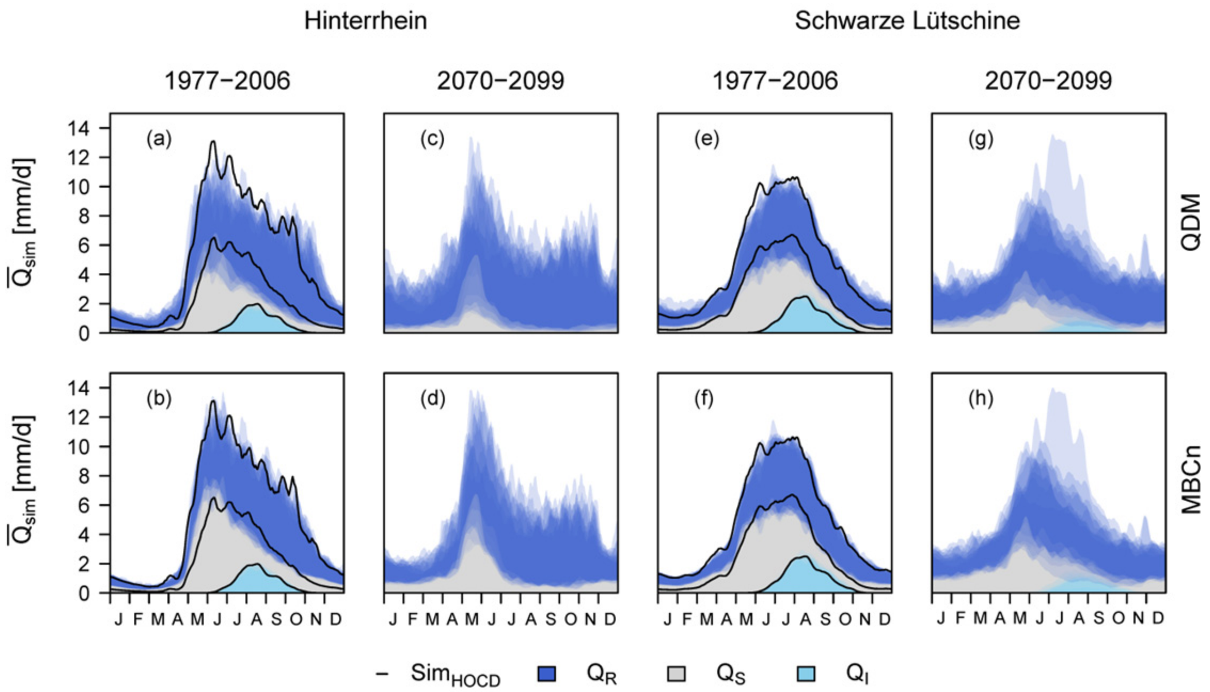

Figure 6: Streamflow regimes based on 11-day moving averages of daily streamflow during 30-year periods in the historical reference period and as projected for the period 2070–2099 under the RCP 8.5 scenario for the two catchments. Simulation results for each ensemble member are shown as semi-transparent polygons. For the historical reference period also the results of the simulations based on the historical reference P and T_a time series are shown (black lines).

5 Discussion

Both bias correction methods employed within this study, univariate QDM (Cannon et al., 2015) and multivariate MBCn (Cannon, 2018), are based on the same quantile mapping approach and by definition the marginal distributions of the corrected P and T_a series are the same as those of the historical reference data. However, the bias correction methods do result in differences in terms of P and T_a interdependency. As air temperature determines the distinction between liquid precipitation and snow, differences in the climate variables' interdependence can lead to differences in simulated snowfall, and consequently in snow accumulation and the catchments' seasonal water storage. For the MBCn-corrected data in this study there was clearly more precipitation at air temperatures below 0 °C in comparison to the QDM-corrected data, resulting in more precipitation falling as snow, being stored, and accumulated than for univariate bias corrected forcing data. In glacierized catchments the higher amounts of snow from MBCn compared to QDM also affect the glaciers with higher winter mass balances and a later start of the melt season in spring/summer. The existence or non-existence of water storages in the form of snow and ice as well as the liquid precipitation directly contributing to streamflow have notable influences on the streamflow composition and regime. For instance, the larger fraction of liquid precipitation at the cost of snow simulated with QDM-corrected data led to a systematic overestimation of streamflow during the winter months in the historical reference period. This error was not present in simulations based on MBCn-corrected P and T_a forcing.

There have long been concerns over climate change impacts on mountain water towers. Many climate impact studies for alpine/snow-dominated catchments agree that due to continued warming, a decrease in snow cover characteristics and time-shifted snowmelt contributions to streamflow are to be expected under climate change scenarios (e.g. Barnett et al., 2005; Farinotti et al., 2012; Köplin et al., 2014; Addor et al., 2014; Milano et al., 2015; Coppola et al., 2016; Jenicek et al., 2018; Hanzer et al., 2018). In fact, the shift and loss of the snowmelt peak is one of the most robust results of such studies. In this study we showed that the magnitude of decrease in the snow component strongly depends not only on the GCM–RCM outputs but also on the bias correction method applied. The simulated glacier volume also showed a clearly decreasing trend over the scenario period. However, net mass balances and hence rates of glacier ice melt and the mean timing of the final glacier disappearance varies by over a decade in the Hinterrhein catchment. While the ensemble covers a wide range, the bias correction makes a difference for each GCM–RCM forcing. The changes of snow accumulation and glacier melt then propagate into changes of streamflow regimes. In future, snowmelt peaks tend to occur earlier and with a more concentrated melt season. A delayed effect visible only from the component modelling is the potential contribution of stored water to streamflow year-round. The simulations suggest that this contribution depends on the chosen bias correction method and hence the interdependence of air temperature and precipitation. Furthermore, streamflow during the late summer decreases as the release of stored water from glaciers, which makes up a notable percentage of streamflow during the late summer, will have diminished. Rate and timing of all of these effects are influenced by the bias correction method applied to the GCM–RCM data. These systematic differences in hydrological impact scenarios originating from the applied univariate or multivariate bias correction method such as those found here, e.g. differences in glacier disappearance dates or differences in seasonal (summer vs. winter) water availability, may appear negligible given the overall large uncertainties of climate impact modelling yet may still be of relevance for some specific adaptation management questions. The timing of 'peak water' occurrence or complete disappearance of glaciers may be relevant for the planning horizon of hydropower schemes (Hänggi and Weingartner, 2012; Schaefli, 2015). Earlier recession of the melt peak may sooner or later affect early-summer flood hazard or increase the hazard of late-summer low flow due to the loss of ice and snow components of streamflow (Beaulieu et al., 2012; Godsey et al., 2014) requiring the planning of respective measures.

The study's results also require discussion of implications on common conceptual hydrological modelling concepts that are needed to simplify meteorological and hydrological complexity. The use of a threshold air temperature for the distinction of precipitation in snow and rainfall is a key concept of the HBV model and many other hydrological models. Hence, it may be expected that the simulations of the snow-dominated catchments respond particularly sensitive to changes/biases in T_a–P interdependencies. The question is the degree to which this may influence the hydrological variables discussed above. So far, few studies have evaluated multivariate-corrected GCM–RCM data in hydrological modelling. Chen et al. (2018) found that the joint bias correction of precipitation and air temperature led to a much better performance in terms of hydrological modelling for all their study basins located in various climates except for the coldest Canadian basin. In contrast, an overall additional benefit of using bivariate bias correction methods for hydrological impact projections was not evident in results by Räty et al. (2018) when compared to using a univariate quantile mapping applied as a delta change method, i.e. retaining present-day correlation structures. However, their analysis of SWE simulations indicated that the selection of the bias correction method was most important and the added value of using multivariate approaches most clearly found for this hydrological variable, supporting the findings of this study. Based on these case studies, it may be assumed that simulations with any hydrological model that include calibration over a historical reference period will be somewhat affected by a biased representation of inter-variable dependence of its input variables in GCM–RCM outputs. Further studies are needed to investigate other effects of multivariate bias correction for other types of climatological input variables, hydrological models, catchment types, and dominating processes.

This study demonstrates the importance of considering the representation of the interdependence of precipitation and air temperature in the specific case of hydrological impact modelling of snow and glacier dominated catchments. As shown, in the representation of the climate variables' interdependence, the multivariate bias correction approach leads to results closer to the climatological historical reference data as well as partly to hydrological simulations closer to the historical reference simulations as for instance for the simulated glacier volumes. Cannon (2016, 2018) also demonstrated better results for multivariate-corrected data in other examples, including fire weather indices and atmospheric river detection. In practice, some kind of bias correction is needed for many impact studies, although it is known that recent literature is rich in controversial debate of its use and major limitations of the application of empirical-statistical bias methods (e.g. Ehret et al., 2012; Addor and Seibert, 2014; Maraun, 2013, 2016; Clark et al., 2016; Maraun et al., 2017). Some of the fundamental issues, the details of which will be beyond the scope of this study, are shared with univariate bias correction, for example, the question of stationarity (re bias in margin distributions). In addition, joint correction is based on the assumption that the structure of the bias in variables' interdependence is stationary, i.e. the same for control as for projections. Furthermore, correction of the multivariate dependence structure will necessarily affect the time sequencing of the climate model variables (Cannon, 2016), which can lead to modification of temporal autocorrelation. Maraun (2016) cautions that modifications of spatial, temporal or multi-variable interdependence may break the consistency with the driving climate model and many others have argued for the least possible transformation of GCM–RCM outputs for this reason. This study does not address these fundamental questions/critiques nor does it generally recommend or not recommend the use of multivariate bias correction methods. The objective of the study was to compare the differences resulting from univariate vs. multivariate methods. We demonstrated a case in which biases in inter-variable dependencies can affect hydrological simulations considerably. This is notable, particularly as it is common practice to use hydrological models calibrated to climatic conditions represented by historical climate variable series. In the same way that the use of several climate and hydrological models is recommended, the incorporation of uncorrected, univariate-, and multivariate-corrected scenario data in the ensemble may be considered as one part of a transparent and honest communication of the full range of uncertainties.

6 Conclusions

In this study the effects of a univariate and a multivariate bias correction of projected air temperature and precipitation on hydrological impact modelling were compared. Jointly corrected air temperature and precipitation series simulated more snowfall and consequently up to 50% more snow accumulation than univariate-corrected GCM–RCM data. Subsequently, glacier volume was simulated to decrease by up to a decade slower under multivariate-corrected scenarios. These differences also impact the simulations of streamflow and its components with higher snowmelt components and accordingly smaller rainfall components under multivariate-corrected scenarios compared to univariate-corrected scenarios. These are relevant systematic differences despite variations of the GCM–RCM ensemble. They may have implications for future water resources planning, as the snow component presents an important seasonal storage, and for the protection against hydrological hazards such as a higher vulnerability to drought.

The study therefore demonstrates a case, where the interdependence of air temperature and precipitation is of such importance that multivariate correction methods perform more accurately compared to univariate quantile mapping approaches. The results achieved by these two different bias correction methods may be generalizable for other catchments that include the elevation range of the snow line. Especially in alpine catchments, the correct representation of the interdependence of air temperature and precipitation plays a crucial role in hydrological modelling that uses a threshold temperature concept for the distinction of liquid and solid precipitation. This study can therefore be regarded as an argument for the explicit consideration of interdependencies of climate variables by using multivariate bias correction methods in hydrological climate change impact studies in snow-dominated catchments. It also supports a call to study similar effects in hydrological systems that may be dominated by other climate variable interdependencies.

Code availability

An R package (R Core Team 2015) including the MBCn and the QDM algorithm is available for download from https://CRAN.R-project.org/package=MBC. The HBV-light software is freely available for download from https://www.geo.uzh.ch/en/units/h2k/Services/HBV-Model.html.

Data availability

EURO-CORDEX data can be accessed via different European datanodes, available at https://www.euro-cordex.net/060378/index.php.en. The HYRAS interpolation product used to derive the historical reference climate time series was made available by the German Weather Service (DWD) and the German Federal Institute of Hydrology (BfG). Streamflow time series were provided by the Swiss Federal Office for the Environment (FOEN). Snow data of the "SLF-Schneekartenserie Winter 1972-2012" used for model calibration are available upon request by the WSL Institute for Snow and Avalanche Research (SLF). Glacier ice thickness data were provided by Matthias Huss, other glacier data are available according to the given references.

Author contribution

JM, IK, KS, and JS designed the study. JM carried out modelling and all analyses and wrote the first draft. IK calibrated the hydrological model and prepared snow, glacier, and hydrological data. KH prepared the EURO-CORDEX data for the catchments. AC provided and helped with his bias correction scripts. All co-authors contributed to and edited the manuscript.

Competing interests

The authors declare that they have no conflict of interest.

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