Hydrological response of the Ötztal glacierized catchments to climate change

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ABSTRACT

This paper investigates the hydrological response of glacierized headwater catchments to future climate change in the Ötztal Alps, Austria. To this end, two conceptual hydrological models, HBV *(Hydrologiska Byråns Vattenbalansavdelning)* and HQsim, are applied for the simulation of future daily discharge in three (nested) catchments with varying degrees of glaciation. The models are forced with downscaled climate change projections, and outputs from an empirical glacier model, which is able to simulate future glacial evolution. Under the future conditions, the outcomes show initially that runoff increases for all catchments without changes in the runoff regimes. In the long term, summer runoff is expected to decrease and winter/spring runoff is expected to increase in all catchments. These runoff changes are accompanied with regime shifts from glacial/glacio-nival runoff regimes to runoff regimes with a higher nival component. Changing runoff conditions might also lead to changes in the seasonality of annual flood peaks with an earlier appearance of flood peaks, and an increasing appearance of low flow conditions during summer months. The outcomes of the two hydrological models show minor differences. The results of this study provide improved understanding of the future impact of climate change on the water cycle of glacierized Alpine catchments.

Key words | climate change, glacier change, glacierized catchments, HBV, HQsim, hydrological response

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INTRODUCTION

Millions of citizens living in large river basins are dependent on the water supply from mountain ranges, such as the Himalayas and the European Alps (EEA 2009; Immerzeel *et al.* 2010). The water supply is thereby largely determined by the contribution of meltwater originating from glaciers and snow storage. Water supply is generally lowest during winter as water is stored in the form of snow and ice, and highest during the summer season (i.e. when water demand is high) (Casassa *et al.* 2009). The timing and magnitude of water supply underlines the hydrological importance of mountain ranges for river basins and therefore mountain ranges can be defined as the 'water towers' of these areas (Viviroli *et al.* 2007). Viviroli & Weingartner (2004) show for instance that the European Alps have a mean contribution varying from 26% to 53% to the total discharge at the outlets of the Danube and Po Rivers, respectively. In summer, the mean contributions are even higher with proportions varying from 36 to 80% for the same respective rivers, which is caused by a combination of high amounts of meltwater originating from glaciers and snow storages located in the Alps and an evapotranspiration surplus in lowland regions.

Future climate change is expected to have an impact on the runoff characteristics of river basins (IPCC 2013), especially in glacierized headwater catchments that are characterized by high runoff contributions from ice and snow storages. The expectation is that due to climate change glaciers will retreat or even disappear (Huss *et al.*

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2008) and seasonal snow cover will decline, which eventually will affect runoff characteristics (Huss *et al.* 2014; Salzmann *et al.* 2014). These changes are considered to have consequences for the water availability of, for instance, drinking water supply, agricultural purposes (e.g. irrigation), and energy production (e.g. hydropower) (Immerzeel *et al.* 2010; Viviroli *et al.* 2011), especially for water originating from glacierized headwater catchments. For this reason, it is important to understand and assess the impact of climate change on the hydrology of these catchments and to use this knowledge for developing adaptation strategies that aim at reducing the possible adverse impacts in light of integrated water resources management (IWRM).

There have been quite a number of studies dedicated to assessing the impact of climate change on runoff characteristics in glacierized headwater catchments. To assess these impacts, mostly conceptual hydrological models (e.g. Bergström *et al.* 1992; Huss *et al.* 2008) and, to a lesser extent, also physically based hydrological models (e.g. Weber *et al.* 2010; Ragettli & Pellicciotti 2012) were used. These models were often forced by climate projections derived from General Circulation Models (GCMs) or Regional Climate Models (RCMs) (e.g. Weber *et al.* 2010; Farinotti *et al.* 2012; Lutz *et al.* 2014). Depending on the modelling approach, glacial melt was simulated by a combination of assuming a hypothetical reduction of glacier area and temperature–index approaches (Hagg *et al.* 2007), by the combination of temperature-index approaches and parameterizations of future glacier change (e.g. Farinotti *et al.* 2012; Lutz *et al.* 2014; Li *et al.* 2015), by the use of temperature–index approaches alone (e.g. Einarsson & Jónsson 2010), or by the use of energy-balance models (e.g. Weber *et al.* 2010), among others. In most of these studies, runoff increases were generally projected until 2050 for catchments located in areas such as Iceland (e.g. Einarsson & Jónsson 2010), the European Alps (e.g. Farinotti *et al.* 2012), and the Himalayas (e.g. Lutz *et al.* 2014). After 2050, annual runoff decreases, summer runoff decreases, and winter/spring runoff increases were generally projected for catchments located in areas such as the European Alps (e.g. Weber *et al.* 2010; Farinotti *et al.* 2012), Central Asia (e.g. Hagg *et al.* 2007), and the Canadian Coast Range (e.g. Stahl *et al.* 2008). Thus, projected changes particularly affect the seasonal distribution of runoff.

The aim of this study is to investigate how glacierized catchments in the Ötztal Alps (Austria) will respond hydrologically to future climate change. To this end, we apply two conceptual semi-distributed hydrological models with different degrees of complexity, HBV (Light) and HQsim, to three different catchments in the Ötztal Alps. These models are forced with downscaled climate change projections and outputs from an empirical glacier model, able to simulate future glacial evolution as a result of climate change. Subsequently, the outcomes of the hydrological models are used to analyse changes in the seasonality of high runoff conditions, absolute changes, relative changes, the seasonality of annual flood peaks, and low flow characteristics. This study stands out compared to previous studies in the region (e.g. Tecklenburg *et al.* 2012) in that it is first to use a combination of multiple hydrological models, multiple downscaled climate models, and a glacier model. It is expected that the changes estimated from these catchments are exemplary for changes in the drier parts of the European Alpine regions.

The remainder of the paper is set up as follows. First, the study area is described, followed by a description of data and methods used, i.e. the field data, the hydrological modelling, the future climate forcing, and modelling change of glacial extent. Next, results are presented and discussed, followed by the main conclusions.

STUDY AREA

This study focuses on catchments in the Ötztal Alps, which are the catchments of the Ötztaler Ache (ÖA) and its headwaters, the Venter Ache (VA) and the Gurgler Ache (GA). The reason for choosing the Ötztal Alps as the study area is the high research activity and data availability in this area.

The ÖA, located in the Austrian Federal Province of Tyrol (see Figure 1), is, with a total length of 67 km, the largest tributary of the river Inn (Achleitner *et al.* 2012). In the ÖA catchment (catchment area of 891 km^2) elevation ranges from 710 to 3,766 m above sea level (a.s.l.). The degree of glaciation is 11.7% (based on the Austrian glacier inventory of 2006; Abermann *et al.* 2012). In the headwaters of the VA (catchment area of 165 km^2) and GA (catchment area of 72 km^2) the degree of glaciation is 32.2% and 29.4%,

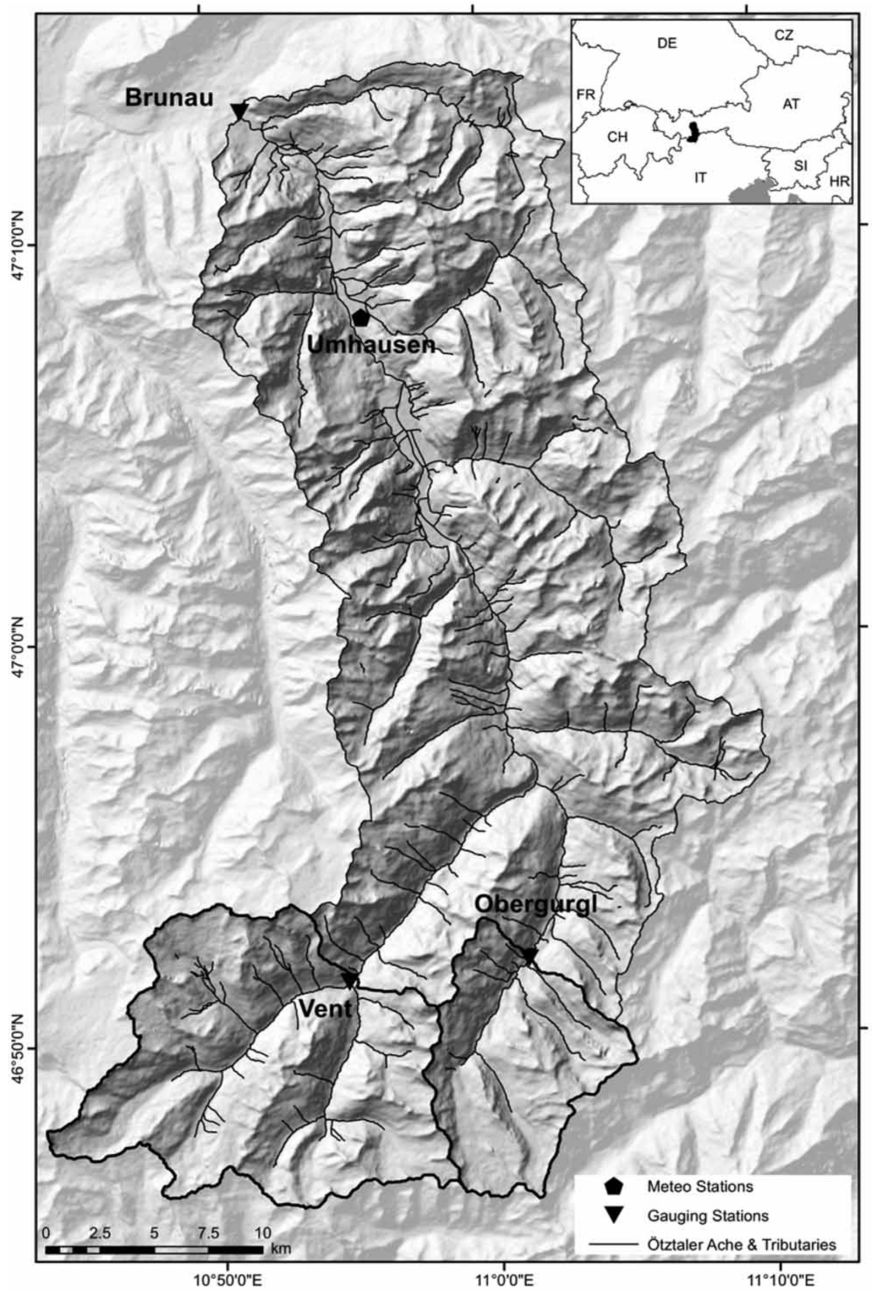

Figure 1 | Study area Ötztal.

respectively. The higher parts of the ÖA catchment are dominated by glacial cover and bare vegetated rock surfaces where coniferous woodlands and alpine meadows are the main land cover types in the lower parts (coordination of Information on the Environment (CORINE) land cover (Bossard *et al.* 2000)). The ÖA catchment experiences a dry inner-alpine climate with annual precipitation sums varying from 650 mm (Umhausen; 1,041 m a.s.l.) to 850 mm (Obergurgl; 1,938 m a.s.l.) (ZAMG 2013) with the highest precipitation sums in the summer period, mainly due to convective events (Hagg 2003), and the lowest precipitation sums in the winter period. The explanation for the comparatively dry climate is that the Ötztal is shielded from precipitation deriving from the north (Northern

Calcareous Alps) and the south (Alpine Main Range) (Kuhn *et al.* 1982). The mean annual temperature varies between 2.2 (Obergurgl) and 6.3 °C (Umhausen) (ZAMG 2013). The runoff regimes can be classified as glacio-nival (gauging station Brunau) and glacial (gauging stations Obergurgl and Vent) with highest runoff conditions in the period June–August and low runoff conditions in the winter period.

DATA AND METHODS

Field data

In this study, the following field data were used as input for HBV and HQsim:

- daily air temperature and precipitation;
- daily-observed discharge;
- digital terrain model (DTM), with $10 \times 10\ \mathrm{m}^2$ resolution;
- land cover data;
- soil maps (only for HQsim); and
- glacier cover data.

Daily air temperature and precipitation were extracted from the meteorological stations of the *Zentralanstalt für Meteorologie und Geodynamik*, *Tirol Wasserkraft AG*, Hydrographical Service Tyrol and the Commission of Glaciology, Bavarian Academy of Sciences for the period 1986–2012. Time series of observed daily discharge were obtained from the gauging stations Brunau (ÖA), Vent (VA) and Obergurgl (Ob) for the period 1983–2012. The DTM, land cover data, soil maps and glacial cover data were derived from the Airborne Laserscan recordings of 2006 (Land Tirol 2006), the CORINE land cover dataset (Bossard *et al.* 2000), the Hydrological Atlas of Austria (BMLFUW 2007), and the Austrian glacier inventories of 1997 (Lambrecht & Kuhn 2007) and 2006 (Abermann *et al.* 2012), respectively.

Hydrological modelling

Two hydrological models were used to simulate current and future daily discharge for the ÖA, VA and VA: HBV (Light) (Seibert & Vis 2012) and HQsim (Kleindienst 1996). HBV (Light) is a user-friendly version of the semi-distributed conceptual HBV-96 model of Bergström *et al.* (1992), which uses the concept of elevation vegetation units (EVUs). HQsim is a semi-distributed conceptual model based on the concept of hydrological response units (HRUs) and uses the BROOK model of Federer & Lash (1978) as foundation. More detailed information of the key characteristics and the contrasts between both models is given in Table 1.

HBV and HQsim were applied by using 250 m elevation zones and HRUs, respectively. The HRUs were delineated using elevation, aspect (derived from the DTM), land cover, and glacial extent (derived from the glacial inventories of 2006). Subsequently, daily temperature and precipitation values were calculated for each HRU. For the calculation of daily temperature, single time series of daily temperature data (considering a reference elevation of 0 m a.s.l.) and daily temperature gradients were composed for the entire catchment of the ÖA. These series were composed by a simple linear regression analysis using the daily temperature data of meteorological stations as input, and were subsequently used to calculate daily temperature for the mean elevation of each HRU. In order to calculate daily precipitation for each HRU, daily precipitation data were projected on a $5 \times 5\ \mathrm{km}^2$ grid, using inverse distance weighting as a methodological approach to interpolate precipitation data from meteorological stations to the grid points. Finally, the gridded precipitation data were weighted for each HRU, based on the areal weight of each HRU inside a grid cell. The type of precipitation depends on the temperature. Precipitation may occur as rain, snow or as a rain–snow mixture.

In HBV, elevation was used in combination with land cover and glacial extent to determine aspect-elevation area distributions for the different vegetation zones used in HBV (for this study the maximum number of three vegetation zones was applied, representing glacial cover, bare vegetated rock surfaces and vegetated areas (woodlands and meadows)). For the application of daily temperature in HBV, the former composed time series of daily temperature data (considering a reference elevation of 0 m a.s.l.) were used as input. The series of daily temperature gradients were however not applied in HBV, since only one value is required as temperature gradient in HBV. For the application of daily precipitation in HBV, single time series of

Table 1 | Key characteristics of HBV and HQsim

Hydrological model	HBV (Light)	HQsim
Model structure	Snow, glacier, soil, groundwater, and routing routine	Snow, glacier, vegetation, soil, groundwater, and routing modules
Spatial representation	EVUs	HRUs
Input variables	Temperature, precipitation, observed discharge, potential evapotranspiration	Temperature, precipitation, observed discharge, potential evapotranspiration
Potential evapotranspiration	Temperature-based approach (Hamon 1961)	Temperature-based approach (Hamon 1961)
Glacier melt, snow melt and accumulation	Degree-day approach with aspect and albedo correction (Konz & Seibert 2010)	Degree-day approach, distinguishing the effects of aspect, slope, and inclination of the sun (Hock 1999)
Glacier outflow	Glacier storage-outflow relationship (Stahl *et al.* 2008)	Integrated glacier module, consisting of three internal reservoirs representing, snow, firn and ice
Overland flow	Linear groundwater reservoir	Simulated for each HRU. Depending on fraction of area contributing area, which is a function of soil water content (Achleitner *et al.* 2012)
Subsurface flow	Linear groundwater reservoir	Simulated with Mualem van Genuchten approach (van Genuchten 1980)
Baseflow	Linear groundwater reservoir	Linear groundwater reservoir
Routing	Triangular weighting function	Approach of Rickenmann (1996)

daily precipitation data were composed from the gridded precipitation data for the catchments of the ÖA and the headwaters of the Venter and Ob separately. Dependent on temperature, precipitation may occur as rain or snow.

HBV and HQsim were calibrated and validated using manual calibration under a split-sample approach (Klemeš 1986). The models were both calibrated and validated for the same periods (see Table 2), although it has to be mentioned that for the calibration and validation of HBV a warming-up period (of 1 year) was needed in order to fill the reservoirs in the model. We chose to start the calibration in the late 1990s, because of the low data quality and availability in the 1980s and the beginning of the 1990s, making this period less feasible for calibration. For the VA, it was however not possible to start the calibration in the late 1990s since observed discharge time series were not available for the period 2003–2006. Therefore this period was deemed as unsuitable for the calibration of HBV and HQsim. Further, we chose to have two validation periods in order to identify differences between the model performances that are accompanied with the validation periods.

Table 2 | Calibration (Cal. P.) and validation periods (Val. P. I and II) (ÖA = Ötztaler Ache, GA = Gurgler Ache, and VA = Venter Ache)

		HBV	HQsim
ÖA	Cal. P.	1998–2007	1998–2007
	Val. P. I	1987–1997	1987–1997
	Val. P. II	2008–2012	2008–2012
GA	Cal. P.	1998–2007	1998–2007
	Val. P. I	1987–1997	1987–1997
	Val. P. II	2008–2012	2008–2012
VA	Cal. P.	1993–2002	1993–2002
	Val. P. I	1987–1992	1987–1992
	Val. P. II	2008–2012	2008–2012

Future climate forcing

To estimate the effects of climate change, time series of future climate variables were used as developed by the University of Natural Resources and Life Sciences, Vienna, Austria in cooperation with alpS Centre for Climate Change Adaptation (CCA), Innsbruck, Austria. To simulate future climate variables the output of three combinations of GCMs and RCMs were realised, used under CO_2 forcing following the SRES A1B scenario of the 4th IPCC assessment report:

- ARPEGE–ALADIN (Déqué *et al.* 1995; Farda *et al.* 2010);
- ECHAM5–RegCM3 (Giorgi *et al.* 1993; Roeckner *et al.* 2003);
- ECHAM5–REMO (Jacob & Podzun 1997; Roeckner *et al.* 2003).

These climate change simulations provided daily temperature and daily precipitation for the period 1985–2100. Error correction was applied by a per-month quantile mapping approach (Déqué 2007; Formayer & Haas 2010), thereby adjusting RCM output according to daily observed values of temperature and precipitation, and retaining the statistics of these observations for each month separately (12 quantile mappings). The observed values of temperature and precipitation were obtained from the E-OBS 1981–2010 dataset (Haylock *et al.* 2008) and the gridded precipitation dataset of Frei & Schär (1998), respectively. The error-corrected $25 \times 25\ \mathrm{km}^2$ RCM output was subsequently scaled down to the $1 \times 1\ \mathrm{km}^2$ grid of the Integrated Nowcasting through Comprehensive Analysis system (Haiden *et al.* 2011) using the localisation method of Pospichal *et al.* (2010), accounting for the complex topography of the Alps.

These projections were subsequently analysed in a so-called 'delta change approach' on a daily basis (Bosshard *et al.* 2011). The mean annual cycle of precipitation and temperature was calculated for the 30-year reference period 1985–2014 and the scenario periods 2010–2039 (near future), 2040–2069 (mid future), and 2070–2099 (far future). The mean annual cycle was smoothed, eliminating the high frequency part of the daily signal by using a low-pass filter according to Bosshard *et al.* (2011). The standard deviation (σ) of the extracted high frequency part of the climate signal was calculated in a moving window of 31 days to estimate the natural variability of temperature and precipitation in the 30-year periods (see Figure 2).

Absolute temperature and relative precipitation changes were calculated on a daily basis between the reference period and the scenario periods. This climate signal was used to alter the original input of meteorological data series of 1983–2012. Note that a shift of 2 years exists between the period of meteorological input and the reference period due to data availability. However, this small difference is neglected with respect to the overall variability in climate data.

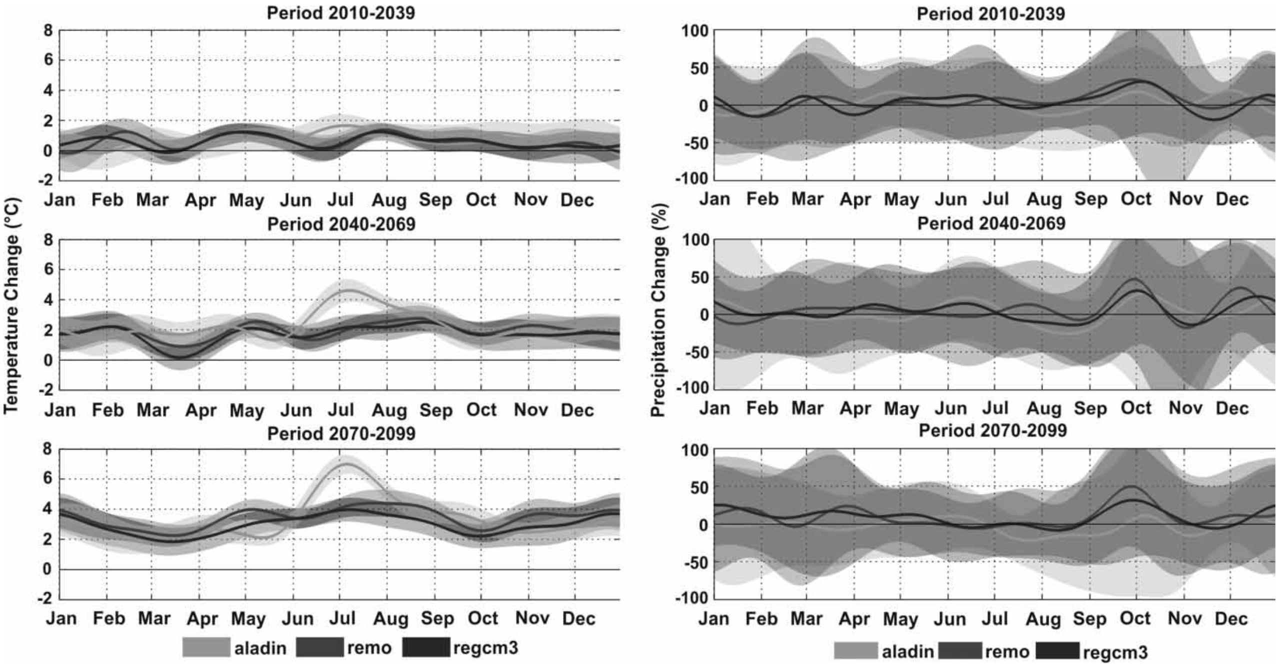

Figure 2 | Low-pass filtered signals and natural variabilities (±σ) of absolute temperature and relative precipitation changes for the near, mid, and far future.

The hydrological models HQsim and HBV were forced by delta change-modified time series related to projections that were resulting from each GCM-RCM combination. The mean of the outcomes, resulting from the three different simulations, was used for the analysis of changes in runoff characteristics. Highest temperature changes were observed from the ALADIN simulation for all three periods (see Figure 2). The realisations based on REMO and RegCM3 showed similar changes, most likely as they were forced by the same GCMs. The precipitation changes were rather small compared to the natural variability. The peak increase of precipitation in October is seen in all three realisations, but is also accompanied by a high variability.

Modelling change in glacier extent

In HBV and HQsim, glacier melt is simulated by using different approaches. In HBV, glacier melt is simulated using a degree-day approach with aspect and albedo correction (Konz & Seibert 2010), while in HQsim glacier melt is simulated by using a degree-day approach, which distinguishes the effect of aspect, slope and inclination of the sun (Hock 1999) based on the HRUs. Despite the ability to simulate glacier melt, none of these models is capable of simulating changes in glacial extent over time. Therefore future glacial extent was simulated separately with a glacier change model, able to simulate future ice thickness, glacier area and volume on a 50×50 m^2 grid as a result of changing climate conditions. In order to simulate future glacial extent, the following steps were conducted:

1. Spatially distributed elevation changes over a 9-year period (1997–2006) were obtained from the glacier inventories of 1997 (Lambrecht & Kuhn 2007) and 2006 (Abermann *et al.* 2012) and scaled to a mean annual surface elevation change.
2. Initial ice thickness distributions were inverted from the glacier surface topography following the ice thickness estimation method (ITEM) of Huss & Farinotti (2012), which is a method, based on glacier mass turnover and ice flow mechanisms. The 2006 DTM of Tyrol (Land Tirol 2006) and glacier outlines of the Austrian glacier inventory of 2006 were used as input. Subsequently, the glacier bed elevations were derived, subtracting the ice thicknesses from the 2006 glacier surface elevations.
3. Mean surface elevations were obtained for the period 2005–2105 with an interval period of 10 years (i.e. 2005, 2015, 2025, etc.), using the observed annual surface elevation change. Additionally a climate sensitivity of –0.89 m annual surface elevation change (i.e. specific mass balance of –0.8 m was converted by an assumed density of 900 kg m^{-3}; Kuhn & Batlogg 1998; Braithwaite & Zhang 2000) was added for each grid cell per 1 °C of temperature increase given in the climate scenarios.
4. New ice thickness distributions were calculated, using the estimated mean surface elevations and the former estimated glacier bed elevations. In case of lower surface elevations than the glacier bed elevations, ice thickness was set to zero. The remaining grid cells with a positive ice thickness constituted the future glacier area.

With respect to the uncertainties of the used ITEM, initial ice thickness was changed by ±20% to assess the resulting uncertainty in the glacier area (see Figure 3). Whereas glacier volume is expected to change first, caused by a strong reduction in mean ice thickness, glacier area is set to decrease with a temporal delay of 15–20 years. The temporal uncertainty range of total glacierized area will increase with time, whereas the uncertainty in area relative to the 2006 reference is highest between 2050 and 2060 and will decrease afterwards. The glacier area relative to the 2006 reference is

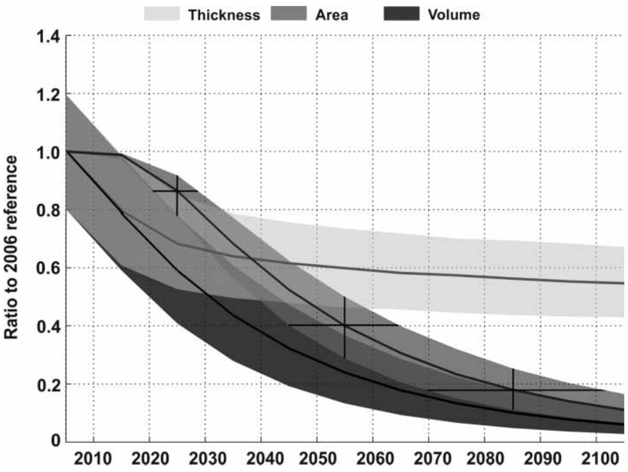

Figure 3 | Calculated changes of ice thickness, glacierized area, and glacier volume in relation to the 2006 extent of all glaciers in the Ötztal catchment. Shaded areas show the range of results based on an initial ice thickness variation of ±20%. Black crosses show the resulting uncertainty of glacier area in time and relative to the 2006 reference area at the central years of the climate periods used in this study.

shown in Figure 3. Depending on the applied GCM-RCM combination, about 10–20% of the present glacierized area is expected to exist at the end of the 21st century.

From the outcomes of the glacier change model, eventually projections of glacial extent were obtained for 2025, 2055, and 2085 and assumed to be constant throughout the scenario periods (i.e. 2010–2039, 2040–2069, and 2070–2099). Finally, HBV and HQsim were run for these periods with the glacial extent projections as input.

RESULTS

Calibration and validation

In Table 3, the calibration and validation periods are given for Brunau, Obergurgl, and Vent with respective model efficiency criteria according to Nash & Sutcliffe (1970).

For the calibration period, both models' performance was 'very good' (Moriasi *et al.* 2007) with Nash–Sutcliffe Efficiency (NSE) values of 0.86 or higher. In the validation periods, both models performed 'very good' as well. Nevertheless, there is a slight difference in performance between the two validation periods. In the second validation period both models perform slightly better than in the first validation period with NSE values of 0.84 or higher.

The level of performance differs from season to season, but also among the different models and locations. These differences in performance are observable in the percent bias (PBIAS) between observed and simulated discharge of the period 1987–2012 (see Figure 4). Based on the assumption that a model performs well if the PBIAS is less than ±15%

Table 3 | Calibration (Cal. P.), validation periods (Val. P. I and II), and respective NSE values (Br = Brunau, Ob = Obergurgl, and Ve = Vent)

			HBV	HQsim
Br	Cal. P.	1998–2007	0.87	0.89
	Val. P. I	1987–1997	0.85	0.85
	Val. P. II	2008–2012	0.90	0.89
Ob	Cal. P.	1998–2007	0.86	0.87
	Val. P. I	1987–1997	0.80	0.83
	Val. P. II	2008–2012	0.86	0.84
Ve	Cal. P.	1993–2002	0.87	0.87
	Val. P. I	1987–1992	0.85	0.86
	Val. P. II	2008–2012	0.90	0.87

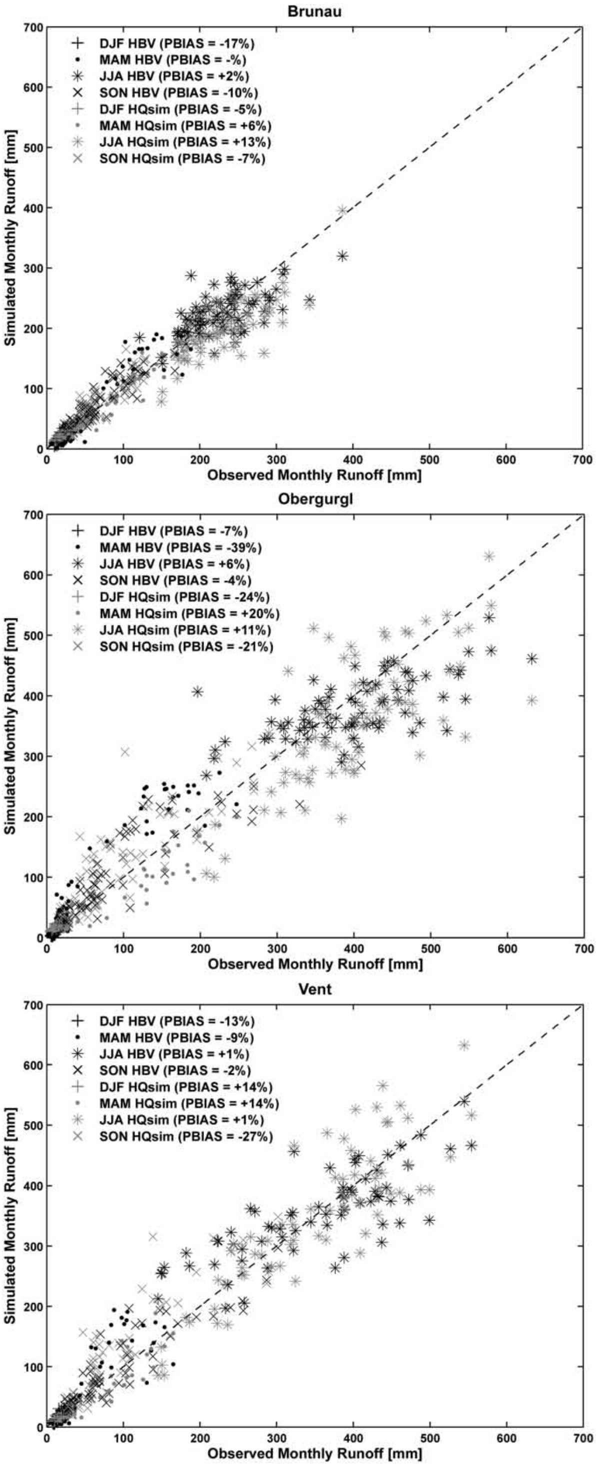

Figure 4 | Simulated vs. observed monthly discharge volumes for the period 1987–2012, including the PBIAS calculated over the seasons. Positive PBIAS values indicate an underestimation of simulated runoff and negative PBIAS values indicate an overestimation of simulated runoff (DJF = December, January, February, MAM = March, April, May, JJA = June, July, August, and SON = September, October, November).

(Moriasi *et al.* 2007), HBV performs well for the simulated spring, summer, and autumn runoff in Brunau, the simulated winter, summer, and autumn runoff in Obergurgl, and the simulated spring, summer, and autumn runoff in Vent, with the best performance for the simulated spring runoff in Brunau and the worst performance for the simulated spring runoff in Obergurgl. HQsim performs well for the simulated winter, summer, and autumn runoff in Brunau, the simulated summer runoff in Obergurgl, and the simulated winter, spring, and summer runoff in Vent, with the best performance for the simulated summer runoff in Vent and the worst performance for the simulated autumn runoff in Vent.

Change in future runoff

In Figure 5, runoff regime changes are projected for the near (2010–2039), mid (2040–2069), and far future (2070–2099). For Brunau, a glacial/glacio-nival regime is projected for the reference period with highest mean runoff values in July. The near future projections indicate that no significant changes will appear. Changes express themselves mainly in small absolute and relative changes that generally occur in April/May (see Appendix Tables A1 and A2, available with the online version of this paper). For the mid and far future, larger runoff changes are projected with relative increases up to 132% in April and relative decreases up to 51% in August. The combination of a runoff increase during spring and a runoff decrease during summer is expected to evolve the glacial/glacio-nival regime into a moderate nival regime with highest runoff conditions in May/June.

For Obergurgl and Vent, glacial runoff regimes are simulated for the reference period with highest mean monthly runoff values in July–August. These regimes are expected to persist in the near future, although annual and mean monthly runoff are projected to increase. For the mid and far future, the flow regimes will shift from a glacial regime

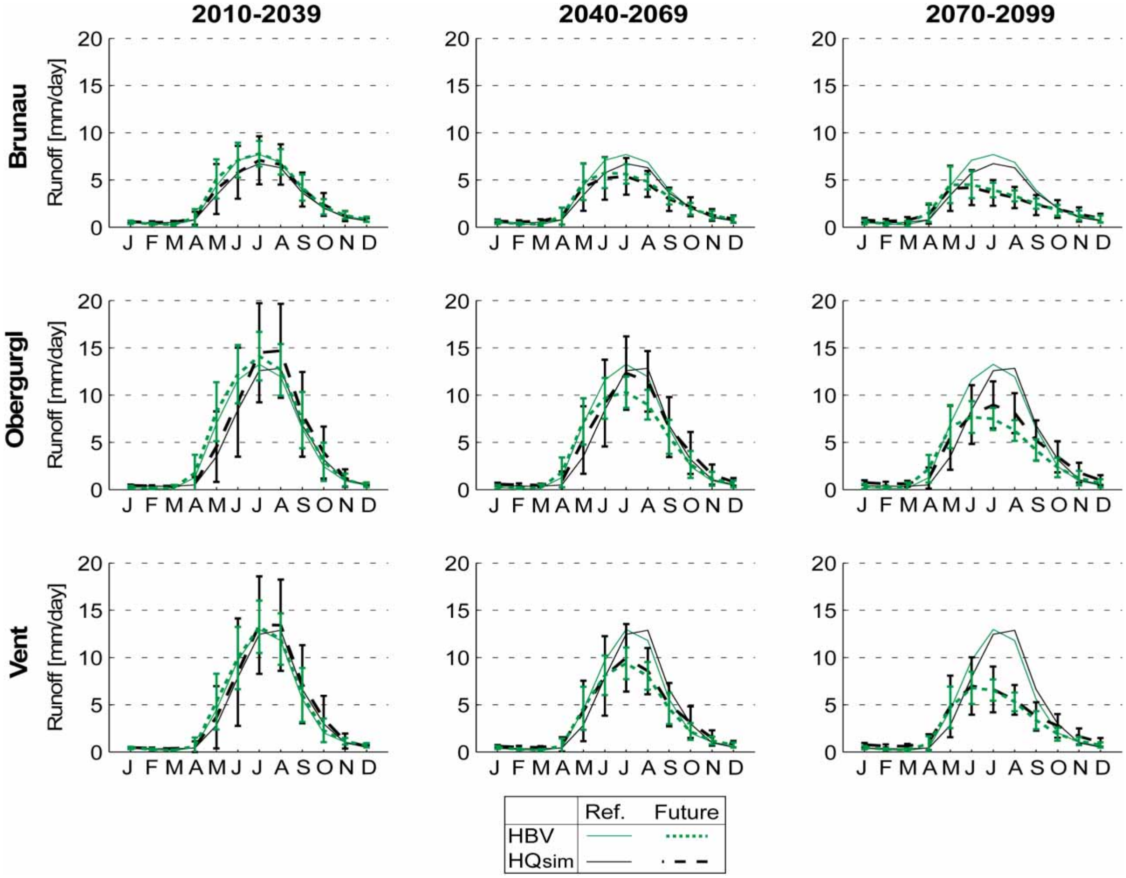

Figure 5 | Mean monthly runoff (mm/day) for reference and future periods. The error bars, which have been plotted for the future periods represent the variability (±σ) of the mean monthly runoff that has been projected by the hydrological models.

to a nivo-glacial/nival regime in Obergurgl with highest runoff conditions in June–July, and from a glacial regime to a nivo-glacial regime in Vent with highest runoff conditions in June. The relative changes accompanied with the regime shift in Obergurgl vary from relative increases up to 249% in April to relative decreases up to 46% in August, whereas annual runoff is projected to decrease up to 29%. In Vent, runoff changes are projected with relative increases up to 186% in May and relative decreases up 53% in August.

The simulated changes in runoff can be explained by several factors. In the near future the main factor responsible for runoff increases during summer and early autumn is likely to be an increase in glacial melt, which results from an increase in temperature. For the runoff increases during winter/spring, other factors may be responsible. Temperature increases result in (a) an earlier onset of snowmelt, leading to shorter snowpack durations, (b) a lower fraction of solid to total precipitation, and (c) a rise of the snowline by about 150 m for every 1 °C increase in temperature (Beniston 2003). The combination of lower fractions of solid precipitation and a rise in the snowline will lead to a decline in snow-covered area and to higher fractions of direct runoff. With a decline in snow-covered area, snow storage reduces, meaning that large volumes of precipitation cannot be stored any more. Normally, high fractions of snow-covered area ensure low runoff conditions during winter, but with a decreasing amount of snow storage, low runoff conditions cannot be sustained any more. Eventually the combination of shorter snowpack durations, higher direct runoff fractions, and declining snow-covered areas will result in runoff increases during the winter/spring period.

In the mid and far future, the earlier onset of snowmelt, lower fractions of solid precipitation, and a rise of the snowline are also likely to be the main drivers of runoff increases during winter/spring. For the summer runoff, reduction of glacial areas, a decrease in precipitation, and an increase in evapotranspiration are supposed to be the main drivers of decreases in runoff. The reason for the shift from summer runoff increases in the near future to summer runoff decreases in the mid and far future is likely to be that in the near future glacial thinning is the dominant melting process above glacial area reduction (see Figure 3), which means runoff regimes do not change and no decreases in runoff appear (Casassa *et al.* 2009). In the mid and far future, glacial area reduction is projected to be more dominant, which means runoff regimes will shift and summer runoff will decrease.

Seasonality of annual flood peaks

The changes of the seasonality under future climate scenarios were investigated by analysing the occurrence date of annual maximum series (AMS). For this purpose, rose diagrams were used, where the monthly frequency of annual maximum flood peaks was depicted for reference simulations and future scenarios. Figure 6 shows that the annual peaks of the reference simulations (i.e. HBV, HQsim) occur in the same months. Under reference conditions annual flood peaks occur from May to August for river gauging station Brunau and from June to September for gauges Obergurgl and Vent. For the near future (2010–2039) the peak occurrence is similar to the reference simulation for the three investigated time series (Figure 6, first column). In the mid future (2040–2069) flood peaks occur more often in early summer/late spring. The most pronounced changes are observed for the far future (2070–2099); under this scenario the modal month of flood (MMF) (i.e. the month with the largest number of events) shifts from July/August (i.e. reference simulation HBV and HQsim) to May for the station Brunau. For gauging station Obergurgl the variability of the occurrence date of annual flood peaks increases. For the station Vent the MMF shifts form July/August to June. Two general trends can be observed regarding the seasonality: (i) a shift of the MMF from July/August to May/June and (ii) an increased variability of the occurrence date of the annual flood peaks.

Low flow

Since summer runoff is expected to decrease in all catchments in the mid and far future, it is likely that future low flow frequency will increase at the same time. In order to investigate whether future low flow frequencies will increase or not, Flow Duration Curves (FDCs) (see Figure 7) were estimated from observed summer runoff and the simulated summer runoff of the mid and far future simulations of HBV and HQsim. For the FDCs, the 70- (Q_{70}) and

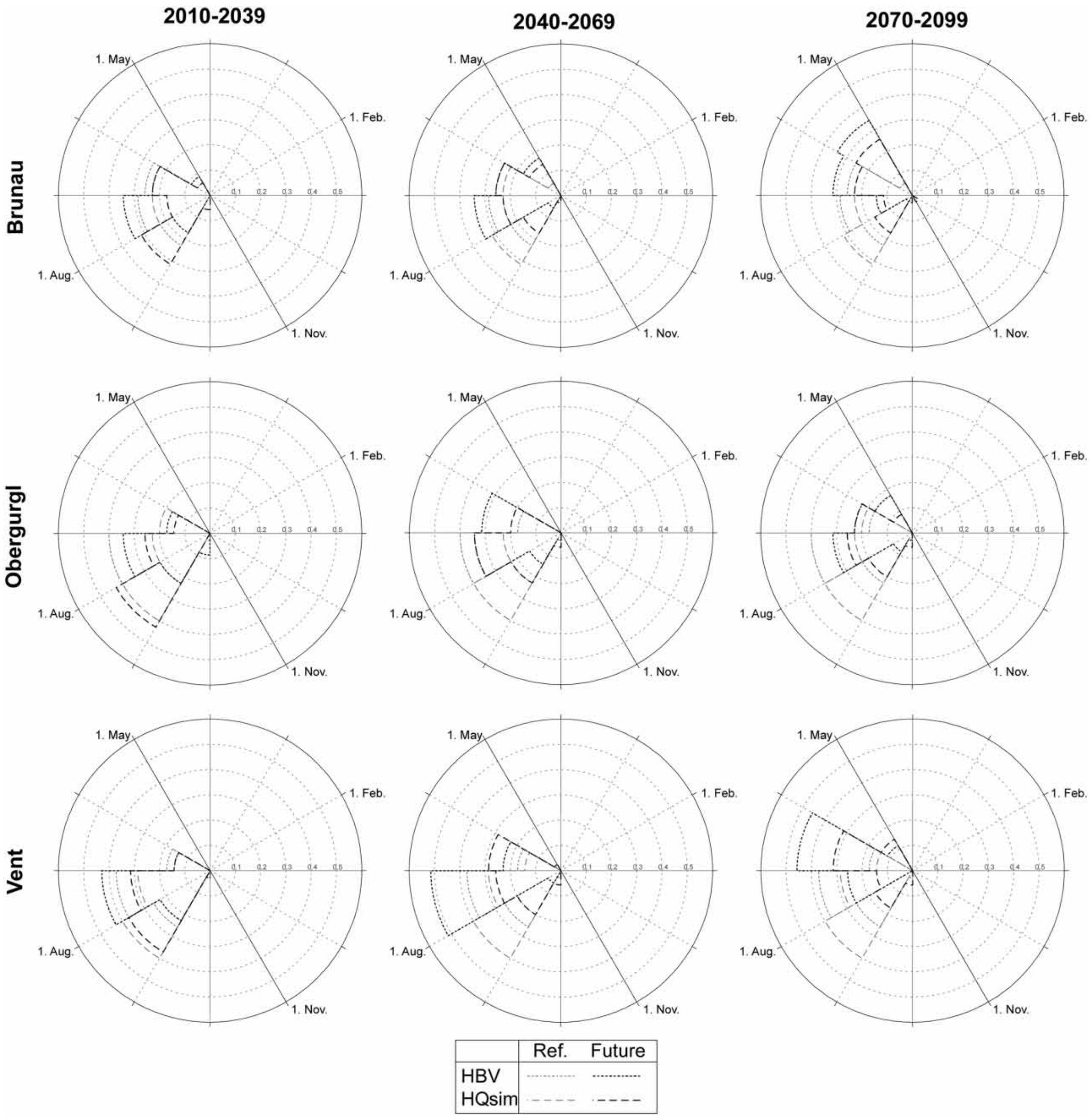

Figure 6 | Rose diagram of AMS considering the reference simulations (grey lines) and climate change scenarios (black lines) simulated with two different hydrological models. The rows represent three gauging stations and the column represents the future climate change.

95-percentile (Q_{95}) thresholds were used to analyse future low flow frequencies. These thresholds represent low flow indices, which have a common use in investigations to the low flow characteristics of perennial streams (WMO 2008). For the catchments in this study the Q_{70}/Q_{95} thresholds were approximately estimated as 5.9/3.5 mm/day for Brunau, 9.8/4.4 mm/day for Obergurgl, and 8.0/3.2 mm/day for Vent.

The Q_{70} and Q_{95} thresholds FDCs at Brunau show that low flow conditions will become more frequent in the mid and far future. An exception however is the mid future simulation of HBV with Q_{95} as reference. The FDC of this simulation indicates that low flow conditions will become less frequent. For the more glacierized catchments of Obergurgl and Vent, the same trend of less frequent low flow conditions is projected for the mid and far future simulations of HBV and HQsim, using Q_{95} as reference. However, the mid future HQsim simulation for Obergurgl shows no change in low flow regime. Likewise, using Q_{70} as reference, there will be no change either. All other mid

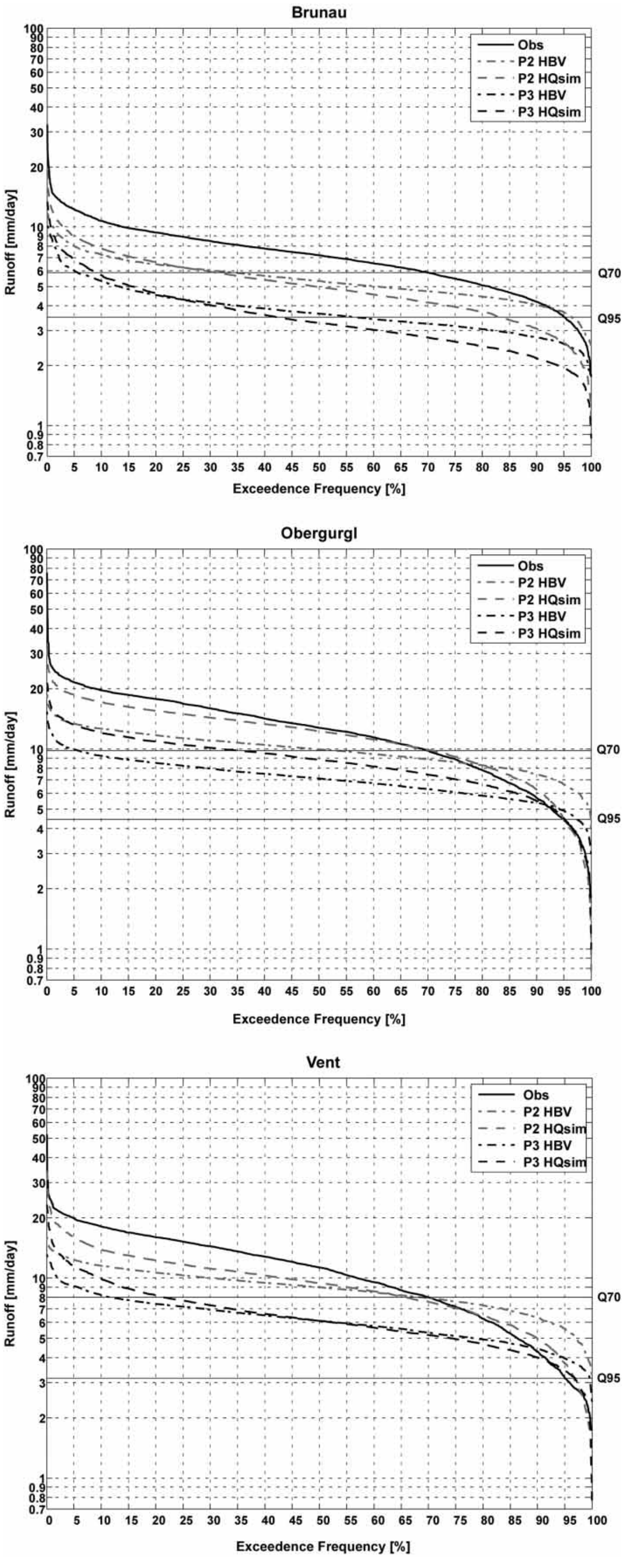

Figure 7 | FDCs of the period June–August for Brunau, Obergurgl and Vent (P2 = 2040–2069, and P3 = 2070–2099).

and far future simulations indicate an increase in low flow frequency. The increase and decrease in low flow frequencies for Q_{70} and Q_{95}, respectively, is likely to be caused by the influence of the remaining part of glaciers in the catchments of Obergurgl and Vent. Although the expectation is that glacier retreat will lead to an increase in low flow frequency, the remaining part of glaciers still might function as a buffer for the low flow extremes (i.e. Q_{95}). Since the influence of glaciers is higher in the catchments of Obergurgl and Vent, it may explain why, for the Q_{95} threshold, low flow frequency decreases in Obergurgl and Vent and increases in Brunau.

DISCUSSION

Two conceptual semi-distributed hydrological models, HBV and HQsim, were used to investigate the hydrologic response to future climate change. According to several studies (e.g. Jiang *et al.* 2007; Eregno *et al.* 2013), it is desirable to use more than one hydrological model to investigate the hydrological impact of future climate change since large differences may exist between the outcomes of different hydrological models. In this study, small differences between the outcomes of HBV and HQsim are found. Future runoff changes and changes in low flow conditions are predicted similarly, although some small differences exist in the runoff and low flow projections (i.e. FDCs) of Obergurgl (see Figures 5 and 7). Likewise, HQsim projects greater runoff variability for Brunau, Obergurgl, and Vent than HBV. Finally, differences between the HBV- and HQsim-projected changes of the seasonality of annual flood peaks (see Figure 6) are found. Whereas the shift of the MMF and the variability in the occurrence date of annual flood peaks are predicted similarly, differences exist in the occurrence of the MMF and the monthly frequency of annual flood peaks. Since both models have been forced by the same input data (with exception of the soil maps), climate change projections and glacier change projections, it is likely that the structural differences between HBV and HQsim are one of the main factors responsible for the variation between the outcomes of these models.

The outcomes of this study are generally in agreement with the outcomes of similar studies conducted in the

Ötztal and European Alps. For instance, Tecklenburg *et al.* (2012) showed a similar trend for the ÖA catchment with runoff increases in winter and spring, and runoff decreases in summer until 2099. It should however be mentioned that these outcomes were obtained under the assumption of complete loss of glaciers whereas in this study a loss of about 80–90% is projected for the end of the 21st century. In the same region, similar but slightly different results were obtained by Weber *et al.* (2010). They projected annual runoff increases for the period 2011–2020 and annual runoff decreases for the periods 2031–2040 and 2051–2060, while in this study annual runoff increases and decreases were generally projected for the periods 2010–2039 and 2040–2069, respectively. The main explanation for the differences between the outcomes is probably that in the study of Weber *et al.* (2010) a higher loss of glaciers has been projected for the first decades, resulting in an earlier appearance of annual runoff decreases towards the future.

Similar outcomes were also reported in other parts of the European Alps. For instance, Huss *et al.* (2014) projected for a catchment in the Swiss Alps annual runoff changes between –53 and +50% and August runoff changes between –89 and +22% for 2075. The outcomes of this study show comparable results with a projected 10–34% annual runoff decrease and a projected 36–53% runoff decrease in August for the period 2070–2099. Similar results were also obtained from another study implemented in the Swiss Alps (Addor *et al.* 2014) with lower summer flows, higher winter flows, and an earlier spring-summer peak discharge. The main difference is that in this study additional processes have been identified to drive these changes: lower summer flows are driven by both glacial area reduction and a decrease in summer precipitation, instead of a decrease in summer precipitation alone. Also, in this study higher winter flows are driven by a combination of decreases in glacial and snow storage, lower fractions of solid to total precipitation, and shorter snowpack durations. Previous studies attributed this mainly to lower fractions of solid to total precipitation. The projected changes in seasonality of annual flood peaks are comparable with outcomes of several other studies (e.g. Farinotti *et al.* 2012; Schneeberger *et al.* 2015), whereas outcomes related to low flow characteristics are deemed to be less reliable (see hereafter).

Despite the overall agreements with outcomes of other studies, still outcomes should be treated with care since the outcomes of this study are subject to several uncertainties that are accompanied with input data, climate projections, glacier change projections, and hydrological modelling. These uncertainties can be subdivided into two classes: aleatory and epistemic uncertainties. Aleatory uncertainties are the result of inherent variability related to variables such as temperature and precipitation (NRC 2000). Epistemic uncertainties are the result of incomplete knowledge due to model uncertainties and parameter uncertainties (Apel *et al.* 2004; Neuhold 2010).

Input data, such as daily precipitation and potential evapotranspiration, are mainly dominated by parameter uncertainties resulting from scarcity of data, measurement errors and parameter estimation methods. For instance, potential evapotranspiration has been estimated according to the temperature-based 'Hamon' approach, meaning that only variables such as daily temperature were used to estimate potential evapotranspiration. Since potential evapotranspiration highly depends on wind speed, global radiation, and relative humidity, it would mean that either potential evapotranspiration is overestimated on cloudy and humid days, or it is underestimated on windy days (Allen *et al.* 1998). Parameter uncertainties also dominate the parameterizations of the hydrological models HBV and HQsim. Since both models have been calibrated manually, parameters can be over-parameterized or inter-correlation can appear between parameters (Seibert 1997). Likewise, more than one parameter set can result in a good model performance, which complicates finding a unique parameter set.

Climate projections, glacier change projections and the hydrological modelling approaches are mainly associated with model uncertainties. For climate projections, these uncertainties emerge from downscaling, accuracy and the resolution of GCM and RCM outputs (Immerzeel *et al.* 2012). In addition, the delta change approach lacks in the representation of future changes to hydrological extreme events since the climate variability of the future climate scenarios rests on the climate variability of the present climate (Graham *et al.* 2007). This implies that for instance the number of wet and dry days does not change for the future climate scenarios, which produces an uncertainty in the outcomes related to the seasonality of annual flood peaks, and especially low flow characteristics. Since the outcomes related to low flow characteristics are more difficult to compare due to the limited amount of studies investigating this topic, the conjecture is that these outcomes are deemed to be less reliable.

Glacier change projections are mainly associated with model uncertainties that emerge from the simplified model assumptions used to model glacier changes. The modelling approach used for simulating glacier changes lacks for instance the possibility to assimilate simulated accumulation and ablation. Simplified model assumptions are also the main factor with regards to model uncertainties related to hydrological modelling approaches. For instance, both HBV and HQsim use simplified temperature-index approaches in which degree-day factors are assumed to remain constant over time. Nevertheless, degree-day factors vary in space and time (Hock 2005), which means uncertainties exist in relation to the ice- and snowmelt simulated by both models. To account for the temporal variability in degree-day factors, one may consider the use of physically based approaches including energy balance components in order to obtain a more sophisticated view on melt processes. The disadvantage is, however, that physically based approaches require more meteorological input variables (i.e. temperature, precipitation, incoming solar radiation, wind speed, and humidity, among others) than simplified temperature-index models (Jost *et al.* 2012). In addition, it is also found that simplified temperature-index models often outperform physically based energy-balance approaches on catchment scale (Hock 2003), which is another reason one may use simplified temperature-index approaches.

CONCLUSIONS AND OUTLOOK

The aim of this study was to investigate how glacierized catchments in the Ötztal Alps (Austria) will respond hydrologically to future climate change. Two conceptual semi-distributed hydrological models with different degrees of complexity were applied and forced using a combination of future climate simulations and outputs from a glacier change model. Eventually the outcomes of the models were analysed in terms of absolute and relative changes in mean runoff and runoff seasonality. Moreover, the change of occurrence time of annual flood peaks was analysed as well as the change in low flow frequency.

The outcomes indicate that in all catchments, the prevailing glacial melt dominated runoff regimes will shift to (more) snowmelt dominated runoff regimes towards the far future with the highest runoff occurring in May/June. These shifts are accompanied by relative spring runoff increases up to 132% in Brunau, up to 249% in Obergurgl, and up to 186% in Vent, and relative summer runoff decreases up to 51% in Brunau, up to 46% in Obergurgl, and up to 53% in Vent. Relative winter/spring runoff increases are likely to be caused by a combination of an earlier onset of snowmelt, a lower fraction of solid to total precipitation, and a rise of the snowline. Relative summer runoff decreases are likely to be caused by a combination of glacial area and volume reduction, a decrease in precipitation and an increase in evapotranspiration.

Accompanied with future runoff changes, annual flood peaks are expected to become less frequent in July–August and to become more frequent in May (Brunau/Obergurgl) and June (Obergurgl/ Vent). Low flow conditions are generally expected to become more frequent in Brunau in the mid and far future. In the glacierized catchments of Obergurgl and Vent low flow conditions are generally expected to become less frequent with regards to the Q_{95} threshold and to become more frequent with regards to the Q_{70} threshold.

Minor differences between the outcomes of the two hydrological models are found, which are mainly attributed to the structural differences between the two models.

The outcomes of this study aimed to contribute to a better understanding of how glacierized catchments respond hydrologically to future climate change. The outcomes might contribute to the development of adaptation strategies with respect to CCA and IWRM. Although the outcomes are sufficiently reliable to extract main trends, the outcomes are still subject to many uncertainties. Therefore improvements are needed in future research on the impact of climate change on the hydrology of glacierized catchments.

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