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Future high-mountain hydrology: a new parameterization of glacier retreat

M. Huss[1,2], G. Jouvet[3], D. Farinotti[2], and A. Bauder[2]

[1]Department of Geosciences, University of Fribourg, 1700 Fribourg, Switzerland
[2]Laboratory of Hydraulics, Hydrology and Glaciology (VAW), ETH Zurich, 8092 Zurich, Switzerland
[3]Institute of Analysis and Scientific Computing, EPF Lausanne, 1015 Lausanne, Switzerland

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Correspondence to: M. Huss (matthias.huss@unifr.ch)

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Abstract

Climate warming is expected to significantly affect the runoff regime of mountainous catchments. Simple methods for calculating future glacier change in hydrological models are required in order to efficiently project economic impacts of changes in the water cycle over the next decades. Models for temporal and spatial glacier evolution need to describe the climate forcing acting on the glacier and ice flow dynamics. Flow models, however, demand considerable computation power and field data input and are moreover not applicable on the regional scale. Here, we propose a simple parameterization for calculating the change in glacier surface elevation and area, which is mass conserving and suited for hydrological modelling. The Δh-parameterization is an empirical glacier-specific function derived from observations in the past that can easily be applied to large samples of glaciers. We validate the Δh-parameterization against results of a 3-D finite-element ice flow model. In case studies the evolution of two Alpine glaciers of different size over the period 2008–2100 is investigated using regional climate scenarios. The parameterization closely reproduces the distributed ice thickness change, as well as glacier area and length predicted by the ice flow model. This indicates that for the purpose of transient runoff forecasts, future glacier geometry change can be approximated using a simple parameterization instead of complex ice flow modelling. Furthermore, we analyse alpine glacier response to 21st century climate change and consequent shifts in the runoff regime of a highly glacierized catchment using the proposed methods.

1 Introduction

The retreat of mountain glaciers in response to ongoing climate warming is expected to have major impacts on the water resource management in alpine environments all over the world (e.g., Zierl and Bugmann, 2005; Horton et al., 2006; Hagg et al., 2006; Bradley, 2006; Stahl et al., 2008). Storage of fresh water in the seasonal snow cover and glacier ice is a key element in the water cycle on different temporal and spatial scales. It importantly affects issues of irrigation and hydropower production in mountainous regions and adjacent lowlands. In the long term the anticipated disappearance of mountain glaciers will lead to a shortage of water in the dry summer season (e.g., Zappa et al., 2003), and therefore have high economic impacts. There is a need for simple and widely applicable methods for calculating temporal and spatial changes in glacier coverage and ice volume in order to make reliable transient projections of future changes in the hydrology of alpine catchments. The assessment of glacier geometry change requires the description of (1) the surface mass balance reflecting the climatic forcing, and (2) the ice flow dynamics.

The climatic forcing acting on the glacier can be described using mass balance models of varying complexity that relate meteorological variables to accumulation and ablation rates at the glacier surface (e.g., Arnold et al., 1996; Klok and Oerlemans, 2002; Pellicciotti et al., 2005; Huss et al., 2008a). The ice dynamics of alpine glaciers have been assessed in many glaciological studies ranging from simple flowline models (e.g., Greuell, 1992; Oerlemans, 1997; Sugiyama et al., 2007) to complex 3-D ice flow models (Hubbard et al., 1998; Gudmundsson, 1999; Jouvet et al., 2008, 2009). Changes in Alpine glacier extent over the next decades have been calculated using combined models of mass balance and ice dynamics (Vieli et al., 1997; Wallinga and van de Wal, 1998; Schneeberger et al., 2003; Le Meur et al., 2007). Ice flow models, however, require considerable field data input and computational power and are, in general, not applicable for catchment or regional scale hydrological modelling.

This paper elaborates on a method to parameterize the change in ice-covered area, glacier length and ice thickness that occurs in response to climate warming. Whereas widely applicable methods to calculate snow and ice melt in hydrological models exist, the simulation of the distributed glacier surface elevation change in response to changing climate forcing and ice dynamics was not yet addressed in a simple way.

The Δh-parameterization, initially proposed by (Huss et al., 2008b), is a function relating the elevation of the glacier surface h to the surface elevation change Δh

(equivalent to ice thickness change) occurring over a given time interval. Typically, elevation changes are small in the accumulation area and largest near the terminus of mountain glaciers (Fig. 1) as could be shown by observations (e.g., Finsterwalder and Rentsch, 1977; Arendt et al., 2002; Bauder et al., 2007), based on theoretical considerations (Jóhannesson et al., 1989) and numerical modelling (e.g., Oerlemans, 1997). For application of the Δh-parameterization in practice, the glacier length (as shown on the abscissa of Fig. 1b) is approximated with the surface elevation, assuming these variables to be strongly correlated. The parameterization takes into account the conservation of mass and is thus well suited for transient hydrological modelling of temporal ice storage changes. For two glaciers in the Swiss Alps differing in size and geometry, we validate the performance of the Δh-parameterization in calculating future glacier geometry over the 21st century by comparing the results to a 3-D finite element ice flow model. The changes in glacier area and consequent shifts in the discharge regime are projected for the period 2008 to 2100 based on different climate scenarios.

2 Study site and field data

The two study sites are located in different regions of the Swiss Alps (Fig. 2). We focus on (i) Rhonegletscher, a medium-sized valley glacier with a length of about 8 km and an area of 15.9 km^2 in 2007, and (ii) Silvrettagletscher, a relatively small mountain glacier (2.8 km^2). For both glaciers, a variety of field data is available covering different temporal and spatial scales which makes them suitable for investigation of the proposed parameterization.

Ice volume changes for subdecadal to semicentennial intervals are available over the 20th century based on digital elevation models (DEMs) derived either from topographic maps (before 1960) or from aerial photographs (Bauder et al., 2007). Ice thickness was measured using radio-echo sounding in 2003 and 2008 on Rhonegletscher, and in 2007 on Silvrettagletscher. Bedrock maps were generated using on an advanced interpolation scheme accounting for the principles of ice flow dynamics (Farinotti et al., 2009a) which is applied between radio-echo sounding profiles.

Measurements of annual mass balance at stakes were carried out over several decades on both glaciers (Mercanton, 1916; Funk, 1985; Glaciological reports, 1881–2009). Additionally, snow probings in high spatial density were performed in six accumulation seasons on each glacier (unpublished data, VAW-ETHZ), providing information about the snow distribution pattern over the glacier surface. Daily discharge records at the BAFU gauging station at Gletsch from the catchment of Rhonegletscher (glacierization in 2007: 47%) are available for more than five decades.

Meteorological data (daily mean air temperature and precipitation sums) are recorded at several MeteoSwiss stations close to the glaciers. For an overview of the methods used to obtain continuous meteorological time series representative for the glacier sites over the 20th century refer to (Huss et al., 2008a).

3 Δh-parameterization

The Δh-parameterization describes the distribution of the surface elevation change in response to a change in climate. A glacier in a perfect state of equilibrium (not existing in reality) shows no ice thickness changes over time because all spatial differences in surface accumulation and ablation are balanced by the ice flow dynamics. A disequilibrium of mass balance and ice flow leads to distinct spatial patterns of the glacier surface elevation change. Its distribution depends on the size, the geometry, the ice flow regime and the spatial mass balance variability of the glacier. Therefore, the form of the Δh-parameterization varies between individual glaciers, but shows constant features for all mountain glaciers.

We discuss two possibilities for the derivation of the parameterization, the first one suited for glaciers with observations of surface elevation change in the past, the second one applicable to unmeasured glaciers.

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3.1 Parameterizations for individual glaciers

If at least two glacier surface DEMs are available, the Δh-parameterization is retrieved directly from observed surface elevation change patterns in the past. By comparing the elevation change between two DEMs in elevation bands with an arbitrary interval (here 10 m), a distribution of surface elevation h versus the elevation change Δh is obtained. The h–Δh function needs to be smoothed in order to exclude noise which would be amplified in the modelling. This applies in particular to the uppermost parts of the accumulation area, where the uncertainty in the DEMs is relatively high and the area covered by individual elevation bands is small (Bauder et al., 2007). The DEMs should be apart by more than one decade in order to eliminate effects of DEM uncertainty.

In general, the quality of the Δh versus h relation increases with the time span covered and the magnitude of changes occurring during this period. The observed distribution of elevation changes is, however, affected by long-term variations in glacier mass balance that are evident in the 20th century (e.g., Vincent, 2002; Huss et al., 2008a; Zemp et al., 2009). For example, the distribution of Δh over the glacier surface is inherently different for (1) periods of fast glacier wastage (e.g. since the 1990s), (2) during time intervals of positive mass balance (e.g. the 1970s) or (3) following such a period (e.g. the 1980s) due to the delayed response of ice flow to a change in climatic forcing. Over the next decades mostly negative mass balances are expected (e.g., Schneeberger et al., 2003; Huss et al., 2008b). Thus, it is proposed to derive the Δh vs. h function from observations in the past corresponding to case (1), i.e. periods between successive DEMs characterized by persistent glacier mass loss. The Δh vs. h function is normalized in order to obtain the dimensionless Δh-parameterization (Fig. 3a): the abscissa is normalized with the elevation range of the glacier according to $(h_{\max}-h)/(h_{\max}-h_{\min})$, where $h_{\max/\min}$ are maximum and minimum glacier surface elevation; and the ordinate is normalized with the maximum elevation change $\Delta h_{\max}$ as $\Delta h/\Delta h_{\max}$.

3.2 Parameterizations for unmeasured glaciers

As information about past glacier geometry changes is often unavailable, generalized Δh-parameterizations were retrieved from samples of different glacier size classes in the Swiss Alps in order to yield empirical functions applicable to unmeasured glaciers. For 34 glaciers for which repeated DEMs over the 20th century are available (Bauder et al., 2007; Huss et al., in press) glacier-specific Δh-parameterizations are derived (Fig. 3b). The functions were averaged in three size classes – large valley glaciers (area $A>20\,\mathrm{km}^2$), medium-sized valley glaciers ($5\,\mathrm{km}^2<A<20\,\mathrm{km}^2$) and small glaciers ($A<5\,\mathrm{km}^2$). For valley glaciers with a distinct canalisation of the ice flow in the ablation area, minor ice thickness changes occur over a large part of the elevation range (see Fig. 1). On small glaciers, in contrast, ice thickness changes are not restricted to regions near the glacier terminus and the curvature of the Δh-parameterizations is smaller (Fig. 3b). The parameterizations for the three size classes were approximated based on least squares using empirical functions of the form

$$\Delta h = (h_\mathrm{r}+a)^\gamma + b\cdot(h_\mathrm{r}+a)+c, \tag{1}$$

where Δh is the normalized surface elevation change and h_r the normalized elevation range. The exponent γ, prescribing the curvature of the Δh-function, decreases with glacier size (see numerical values in Fig. 3b).

3.3 Implementation

Once the Δh-parameterization is established, its application for the calculation of future glacier extent requires the following field data input, which can be obtained for every glacier from normally easily available data sets:

1. DEM and glacier outlines for model initialization,

2. the spatial distribution of surface mass balance calculated using a model driven by climate variables (e.g., Klok and Oerlemans, 2002; Machguth et al., 2006; Huss et al., 2008a), and

3. an estimate of the glacier bedrock topography. This information is required to update the glacier extent and determines the size of the ice reservoir. Ice thickness distribution and total ice volume can be calculated based on an inversion of surface topography (Farinotti et al., 2009a,b). More simple methods (e.g., Haeberli and Hoelzle, 1995; Bahr et al., 1997) can be applied to estimate the overall ice volume and, thus, to obtain a first guess of the mean ice thickness.

The Δh-parameterization is applied to update the 3-D glacier geometry at the end of each hydrological year. The lost or gained ice volume, calculated using a mass balance model, is converted into a distributed ice thickness change according to the parameterization. It is assumed that the redistribution of surface accumulation by ice flow takes place immediately.

Integration of the dimensionless Δh-function over the normalized elevation range h_r of the glacier, multiplied with the area A (in m^2) of each elevation band i and the ice density ρ_{ice} must equal the total annual change in glacier mass B_a:

$$B_a = f_s \cdot \rho_{ice} \cdot \sum_{i=0}^{i=h_r} A_i \cdot \Delta h_i. \tag{2}$$

B_a (in kg) is given by the mass balance computation and f_s (in m) is a factor that scales the magnitude of the dimensionless ice thickness change (ordinate in Fig. 3) and is chosen for each year such that Eq. (2) is satisfied. h_r refers to the annually updated glacier extent. An updated glacier surface elevation h_1 for the initial altitude h_0 of elevation band i is calculated as

$$h_1 = h_0 + f_s \cdot \Delta h_i. \tag{3}$$

Near the glacier terminus the annual surface lowering is restricted not to exceed that year's local surface mass balance in ice equivalent. This corresponds to non-dynamic downwasting of the glacier tongue, currently observed on many alpine valley glaciers (Paul et al., 2004). In this case, the parameterization is rescaled (Eq. 2) so that its integration yields the total annual volume change. The Δh-parameterization is not applied near the border of the glacier (i.e. where the ice thickness is smaller than 10 m). It is assumed that in these regions thinning due to ice dynamics is small. Ice thickness change is calculated based on the local mass balance in ice equivalent. Glacier extent is determined by updating the ice thickness distribution; the glacier disappears where ice thickness drops to zero.

4 Model description and application

4.1 Glacier evolution runoff model (GERM)

In this paper, the framework of glacier surface updating based on the Δh-parameterization is the glacio-hydrological model GERM. The model is designed to calculate the runoff from highly glacierized drainage basins and includes components for computing (1) precipitation and snow accumulation, (2) snow and ice melt based on the temperature-index approach, (3) evaporation, and (4) runoff routing. All components of GERM are described in (Huss et al., 2008b).

The model is forced by daily temperature and precipitation, and is calibrated and validated using different field data types. For Rhonegletscher and Silvrettagletscher the glacier module of GERM is tuned so that the results match the observed (i) changes in ice volume, (ii) in-situ point-based annual mass balance, and (iii) in-situ winter accumulation (Huss et al., 2008a). Runoff calculated by GERM for the Rhonegletscher catchment is validated against long-term daily discharge records. The glacio-hydrological model reproduces observed annual runoff volumes with an average deviation of 1.4% over the period 1957–2006 (Fig. 4a). The (Nash and Sutcliffe, 1970)-criterion is R^2=0.58 for annual and R^2=0.96 for monthly runoff. The model thus reasonably simulates the hydrological cycle (Fig. 4b) and is consistent with long-term ice volume changes and seasonal glacier mass balance variability.

4.2 Ice flow model

A three dimensional finite element ice flow model is used to simulate the flow dynamics of Rhonegletscher. The model is based on a Volume of Fluid (VOF) formulation (Scardovelli and Zaleski, 1999), has a high level of physical sophistication and solves the nonlinear Stokes equations. It has been successfully applied to different types of fluids (e.g., Maronnier et al., 2003) and was first employed by (Jouvet et al., 2008) to calculate glacier dynamics. Model application to Rhonegletscher is described in detail by (Jouvet et al., 2009).

Mass conservation along the ice-air interface yields a transport equation which can be used to determine the evolution of glacier geometry. Given the initial shape of the glacier, the ice flow velocity $\boldsymbol{u}$ is obtained by solving a 3-D nonlinear Stokes problem with a nonlinear sliding law along the ice-bedrock interface. Then, glacier geometry is updated each year by computing the volume fraction of ice φ, which satisfies the transport equation

$$\frac{\partial \varphi}{\partial t} + \boldsymbol{u} \cdot \nabla \varphi = b \delta_{\Gamma_\mathrm{A}}, \qquad (4)$$

where $b\delta_{\Gamma_\mathrm{A}}$ is a source term (i.e. surface mass balance) acting on the ice-air interface Γ_A. A decoupling algorithm allows the equations to be solved using different numerical techniques (Jouvet et al., 2008, 2009). The nonlinear Stokes problem is solved on a fixed, unstructured finite element mesh consisting of tetrahedrons whereas the transport equation is solved using a fixed, regular grid of smaller cells.

The ice flow model is implemented with the same scheme for calculation of glacier surface mass balance as GERM, using the parameters calibrated with field measurements. GERM and the ice flow model are driven using the identical meteorological time series in daily resolution.

For Rhone- and Silvrettagletscher ice flow model results are validated against repeated observations of glacier geometry. The model is initialized employing the first accurate glacier surface DEM available in 1874 (Rhone), and 1938 (Silvretta), respectively. Over the 20th century, changes in glacier area and surface elevation along a longitudinal profile are reproduced by the model for both glaciers (Fig. 5). Model performance is assessed by evaluating the root-mean-square (rms) error of the difference between simulated and observed glacier surface elevation at all grid cells for six DEMs on each glacier. We find an average rms error of 18 m for Rhonegletscher, and 11 m for Silvrettagletscher. The errors remain similar over the entire modelling period. These values are regarded as the a priori uncertainty in the 3-D ice flow model in the present configuration. Disagreement of modelled and measured surface elevation is attributed to (1) the description of ice dynamics in the model, (2) the uncertainty in the bedrock elevation (the deviations are largest in regions not covered by radio-echo sounding measurements), and (3) uncertainties in the calculated mass balance distribution.

4.3 Future climate forcing

Our assumptions on future climate are based on (Frei, 2007), who statistically evaluated the results of 16 regional climate models within the PRUDENCE project (Christensen and Christensen, 2007). Three scenarios for the seasonal change in air temperature and precipitation are defined according to (Huss et al., 2007). Scenario 2 represents the median (most probable), Scenario 1 a glacier-friendly evolution (cold-wet) and Scenario 3 is the most adversary to glacier existence (warm-dry) (Fig. 6). The three scenarios envelope a 95% confidence interval of expected future climate change in the Alps and thus cover the range of uncertainty in climate system evolution as given by different regional climate models. Expected changes in climate variables in 2050 are given for the three scenarios in Table 1. Daily meteorological time series for the period 2008 to 2100 are constructed by applying seasonal changes in air temperature and precipitation (Table 1) to detrended series recorded in the past.

5 Results

5.1 Validation of the Δh-parameterization

As the Δh-parameterization is derived from observed changes in glacier surface elevation over the 20th century a validation is not possible for this period. The parameterization aims at simplifying glacier retreat calculations for the next decades. Therefore, we compare the performance of the Δh-parameterization against the coupled surface mass balance and 3-D ice flow model that is run into the future using realistic climate change scenarios. Our validation does not imply that the predicted future glacier extent is “correct”, however it allows the investigation of the appropriateness of the glacier retreat parameterization versus the ice flow model. The latter is assumed to provide the best possible estimate of future 3-D evolution of glacier geometry.

The ice flow model and GERM, which is implemented with the Δh-parameterization for calculating the distributed ice thickness change, are forced using the same climatic input for the period 2008 to 2100. For both glaciers an up-to-date DEM (glacier geometry and outline) is available for 2007 serving as initialization for the future model runs. We apply the Δh-parameterization derived from the observations of glacier surface elevation change in the past for Rhonegletscher (Fig. 3a) and simulate Silvrettagletscher using the approximation (Eq. 1) derived for the sample of small alpine glaciers (Fig. 3b). Mass balance is calculated in daily resolution for every grid cell applying the parameters of the glacier module calibrated for the past. Model runs were performed for the Scenarios 1 to 3. Because the identical scheme for mass balance calculation is used to drive both the ice flow model and GERM, differences in simulated surface elevation and glacier extent are attributable to the description of ice flow dynamics only. The flow model is assumed to reproduce these in an optimal way and is regarded as the reference result.

According to our results, large Alpine valley glaciers, such as Rhonegletscher, will be likely to loose up to 90% of their ice volume until 2100. The spatial distribution of the ice-covered area as obtained from the ice flow model agrees with results of

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the Δh-parameterization and the distributed surface elevation change is captured over almost the entire 21st century (Fig. 7). Towards 2100 surface elevation near the glacier terminus is underestimated by the parameterization. This may partly be related to a mass balance-altitude feedback that tends to continuously amplify an initial difference in calculated surface elevation.

The rms error of surface elevation obtained using the parameterization in comparison to the ice flow model is around 20 m throughout the entire modelling period (Rhonegletscher) and is comparable for all three climate scenarios (Table 2). Good agreement is also found for Silvrettagletscher, for which no specific Δh-parameterization was derived (Fig. 3b). Average rms errors are between 10 and 20 m and are consistent as well for all scenarios (Table 2). Lower rms errors in comparison to Rhonegletscher are explained by smaller ice thicknesses. These results indicate that the Δh-parameterization is able to approximate glacier surface elevation changes as predicted by a sophisticated 3-D ice flow model for a wide range of possible future climate evolutions and for different glacier types. Misfits are in the same order as the a priori uncertainty in the ice flow model inferred for the 20th century.

In Fig. 8 the comparison of the glacier surface elevation calculated using the Δh-parameterization and the ice flow model is shown on a longitudinal profile. For Rhonegletscher the parameterization yields particularly satisfying results until 2050. The distribution of the surface elevation change on the central flow line is almost perfectly reproduced for all scenarios. Towards the end of the modelling period larger misfits occur in the ablation area. These are most pronounced for Scenario 3 (warm-dry). Scenario 1 (cold-wet) shows good agreement for the entire 21st century (Fig. 8). This is explained by the smallest changes in ice flow dynamics compared to the 20th century for which the Δh-parameterization was derived.

Future changes in area and length of Rhonegletscher are captured (Fig. 9). The parameterization yields average differences in ice-covered area given by the ice flow model of less than 3% throughout the entire modelling period. For the Scenario 2 (median) the mean misfit in glacier area is only 1.5%. Also glacier length is reproduced within less than 3% (Fig. 9). Towards 2100 larger errors are evident for Scenario 3.

The parameterization performs equally well for the smaller Silvrettagletscher. In general, it predicts slightly too fast glacier surface lowering in the ablation area and too little thinning in the accumulation area (Fig. 10). This is related to the fact that the Δh-parameterization was not derived specifically for Silvrettagletscher and thus ignores its particular characteristics. Nevertheless, ice-covered area and glacier length calculated using the parameterization and the ice flow model agree well (Fig. 11). The mean misfit of glacier area is smaller than 5% for all scenarios (excluding the time period with <20% of the initial glacier area) and even <1% for Scenario 2. Glacier length is reproduced within 10%. The complete disappearance of Silvrettagletscher during the 21st century is very likely. Whereas according to Scenario 2 no ice is left around 2070, the glacier survives in strongly reduced form only according to Scenario 1 (Fig. 11).

5.2 Future stream-flow runoff

Runoff from the drainage basin of Rhonegletscher is simulated for the 21st century using GERM implemented with the Δh-parameterization. In order to take into account year-to-year climate variability we perform multiple model runs using randomly disturbed meteorological series (Huss et al., 2008b). Due to the representation of glaciers as a dynamically changing storage component in the water cycle, the shift from an ice melt to a snow melt dominated runoff regime can be simulated transiently. Our results are in line with previous studies (Braun et al., 2000; Zierl and Bugmann, 2005; Stahl et al., 2008; Huss et al., 2008b) and indicate that this transition will take place during the next decades. During this time frame, water resource management will have to adapt to the major changes in the hydrological regime of high alpine catchments.

Over the next decades annual runoff from the Rhonegletscher catchment is expected to increase considerably (Fig. 12). For 2040 calculated runoff is between 23% and 36% higher than in 1961–1990, depending on the scenario. This is due to a rapid release of water from long-term glacial storage, because of increasing temperatures and consequently strong glacier retreat. Whereas annual runoff volume reaches a tipping point before 2100 in Scenario 2 (median) and 3 (warm-dry), the model results indicate steadily increasing runoff for Scenario 1 (cold-wet) due to relatively constant reduction of the glacier ice volume and enhanced precipitation at the same time (Fig. 12).

Our results show the gradual transition from a glacier melt to a snow melt dominated runoff hydrograph (Fig. 13). The transient increase in runoff over the next four decades is mainly concentrated in the summer months. Strong ice melt in combination with precipitation events occurring over the depleted accumulation area with significantly reduced storage capacity, also leads to an increased potential for destructive floods in this period.

After complete disappearance of the ice cover low-flow conditions in the summer months are anticipated that are enhanced by increased potential evaporation in a warmer climate. On the scale of the European Alps this is expected to have regional (Horton et al., 2006) to transnational impacts (Bradley, 2006; Junghans et al., 2010) on irrigation and agriculture, the biosphere and shipping traffic on major streams. Snow and ice melt peak discharge is shifted from early August to end of May. For the Rhonegletscher catchment, we find a decrease in August runoff by 55% for the year 2100 according to Scenario 2 compared to the period 1961–1990 (Fig. 13), and even by 94% for Scenario 3. Conversely, our results show a doubling of winter runoff (Scenario 2), and a more than fivefold increase for Scenario 3. Results of Scenario 1 indicate significantly smaller changes in the hydrograph.

6 Discussion

In order to investigate the suitability of alternative simple approaches to calculate the change in glacier surface area in response to future climate warming we validate two supplementary parameterizations against the ice flow model for Rhonegletscher. We consider (1) the “AAR-method”, and (2) “non-dynamic downwasting”.

In previous studies assessing the glacier retreat in the 21st century a simple method based on the accumulation area ratio (AAR) was applied (e.g., Horton et al., 2006;

Schaefli et al., 2007; Paul et al., 2007). It is assumed that the glacierized area A_{gl} is proportional to the multi-year mean accumulation area A_{acc}, which is calculated based on climate variables. A_{gl} is derived using the relation

$$A_{gl} = A_{acc}/\mathrm{AAR}_s, \tag{5}$$

where AAR_s is the accumulation area ratio required to yield a balanced mass budget. We assume AAR_s=0.6 (Schaefli et al., 2007; Paul et al., 2007). The accumulation area A_{acc} is calculated as the mean of the previous 10 years in order to average out year-to-year meteorological variability. An updated glacier area A_{gl} is determined annually using Eq. (5). In this approach it is implicitly assumed that the glacier is always in balance with the prevailing climate conditions, which is not justified for large ice masses in a dynamically changing climate. A major draw-back of the "AAR-method" is that it does not account for the conservation of mass. For transient hydrological modelling, in particular, this represents a serious problem as ice volume can disappear without contributing to discharge.

Given the mass balance and the ice thickness distribution, the change in glacier area can be calculated by rigorously assuming non-dynamic downwasting. Ice thickness change at each grid cell equals the annual mass balance in ice equivalent. This approach completely neglects a transport of mass from the accumulation to the ablation area. Thus, the lowering in the ablation area is expected to be too fast and surface elevation is supposed to increase at high altitudes. An advantage of this approach compared to the "AAR-method" is that ice volume is transiently modelled, i.e. mass is conserved.

Model runs using both supplementary parameterizations were performed for climate Scenarios 1–3 based on the identical meteorological input and the same scheme to calculate glacier mass balance as for the ice flow model. Table 3 shows that the rms error of surface elevation obtained with both supplementary parameterizations is significantly higher than for the Δh-parameterization (see Table 2 for comparison). The "AAR-method" yields a considerable underestimation of glacier surface elevation, and thus ice volume, for the entire modelling period. rms errors compared to the ice flow model are in the range of 60 to 120 m for Rhonegletscher (Table 3). For predicting glacier area change in a discrete time step of e.g. one century, or complete glacier disappearance the "AAR-method" is suitable.

Assuming no redistribution of snow and ice accumulation by ice flow leads to a monotonically increasing misfit relative to the ice flow model (Table 3). Whereas rms errors are lower than for the "AAR-method" in the first decades of the 21st century, "non-dynamic downwasting" performs worse with increasing length of the modelling period. This is explained by unhindered and continuous growth of the ice thickness in the accumulation area and too fast glacier recession in the ablation area.

Although misfits in calculated glacier surface elevation are comparable between the "AAR-method" and "non-dynamic downwasting" (Table 3), the differences in reproducing glacier area and length as simulated by the ice flow model are significant (Fig. 14). According to the "AAR-method" Rhonegletscher almost immediately looses its entire valley glacier tongue; averaged over the modelling period glacier area is underestimated by 44% and calculated glacier length is lower by 66% compared to the ice flow model (Scenario 2). Most Alpine glaciers are presently out of equilibrium, i.e. their size is too large for the current climate conditions. The "AAR-method" does not account for the time scale glaciers need to lose their excess ice mass and thus predicts too fast glacier retreat. The misfits are largest around 2050 when the glacier is far from equilibrium and become smaller as the ice-covered area decreases (Fig. 14).

Assuming "non-dynamic downwasting" a relatively good match with glacier area and length given by the ice flow model is achieved (Fig. 14), being only slightly worse than for the Δh-parameterization. "Non-dynamic downwasting" yields the best results for Scenario 3 that is based on extreme climate warming leading to rapid stagnation of ice flow and consequent disintegration of the glacier.

The testing of supplementary parameterizations for calculating future glacier retreat has shown that they yield results inferior to those of the Δh-parameterization, which is able to reproduce distributed glacier surface elevation change, as well as glacier area and length accurately based on the same field data input. The use of the "AAR-method" for transient projections of future glacier extent is discouraged as volume change time scales are neglected; the violation of mass conservation results in strong underestimation of runoff over the next decades (Huss et al., 2008b). "Non-dynamic downwasting" leads to an unrealistic distribution of glacier surface elevation, however, might be a suitable alternative to the Δh-parameterization in the case of small glaciers or very rapid climate change.

The major source of uncertainty for the prediction of future glacier area and consequent changes in the water balance and the runoff regime of high alpine drainage basins are the changes in the climate system, and how they act on the snow coverage and the glacier surface. State-of-the-art climate models indicate a wide range of possible climate trends in the future (IPCC, 2007). The spread is mainly due to unknown future emission of anthropogenic greenhouse gases. However, different climate models also exhibit diverging results when forcing them with the same CO_2 input (e.g., Christensen and Christensen, 2007). The use of ensembles, allowing a probability distribution of the climate model results to be determined is therefore highly important.

With climate warming several feedback mechanisms that are only partly incorporated in our mass balance model could contribute to a bias in the projections of glacier wastage and future runoff. Whereas we take into account positive feedbacks of increasing fraction of precipitation occurring in liquid form, and the prolongation of the melting season, additional positive backcoupling mechanisms as increasingly dark glacier tongues due to dust deposition (Oerlemans et al., 2009) and lakes forming in front of glacier termini, e.g. at Rhonegletscher (Farinotti et al., 2009a), are not considered. We do not account for feedbacks that locally reduce ice melt rates as well, such as increasingly debris-covered glacier tongues (Kellerer-Pirklbauer et al., 2008), and decreased direct radiation as the glacier lowers into deeply incised and shaded valley bottoms. Due to the various poorly understood processes that may compensate for each other, it is difficult to provide a joint uncertainty estimate of errors in future projections due to shortcomings of the glacier surface mass balance modelling procedure.

Investigation of the changes in climatic forcing at the elevation of the long-term equilibrium line of Alpine glaciers based on long-term measurement has shown that the degree-day factors of temperature-index models have changed significantly over the 20th century (Huss et al., 2009). Changes over short time periods are also evident from the analysis of energy balance measurements (Braithwaite, 1995; Carenzo et al., 2009). The use of constant parameters in empirical models calibrated in the past therefore adds to the uncertainty in simulated glacier extent over the 21st century. This uncertainty does, however, not compromise the validation of the Δh-parameterization against the ice flow model as both are driven by the same climate forcing and mass balance calculation scheme.

Our results show that the Δh-parameterization reproduces results given by the application of a complex ice flow model, and that the parameterization is thus suitable for the calculation of glacier retreat in response to future climate warming. However, as the Δh-parameterization represents a rigorous simplification of three dimensional glacier geometry changes due to ice dynamics, some restrictions are discussed.

The Δh-parameterization does not perform well in simulating glacier advance. In theory, the pattern of the altitudinal distribution of the ice thickness changes only differs by sign for glacier retreat and advance (Jóhannesson et al., 1989). However, this is only true after reaching a steady state. Alpine glaciers take one to several decades to reach a new equilibrium geometry after a step like change in climate (e.g., Hoelzle et al., 2003). The parameterization is applied at the end of every year, assuming an immediate transformation of the local mass change into a distributed surface elevation change over the entire glacier. As the Δh-parameterization is explicitly derived for periods of persistently negative mass balances, the transient glacier geometry change in the case of advance cannot be simulated accurately.

Changes in the shape of the Δh-parameterization over time are likely. With climate warming glaciers diminish in area which might lead to a lower curvature of the optimal Δh-parameterization, i.e. to a lower exponent γ in Eq. (1) (see also Fig. 3b). However, given the good performance of the Δh-parameterizations over a time interval of

90 years (see e.g. Figs. 8 and 10) the uncertainty induced by these factors is assumed to be acceptable.

7 Conclusions

In this study a simple parameterization for calculating the future change in ice-covered area, glacier volume and 3-D geometry is proposed and compared to results obtained from a state-of-the-art ice flow model. The evolution of Rhonegletscher and Silvretta-gletscher was simulated for the period 2008–2100 using three different climate change scenarios based on ensemble evaluation of 16 regional climate models. We find a dramatic retreat for both glaciers. Whereas the smaller Silvrettagletscher is likely to disappear around 2070, Rhonegletscher most probably still exists at the end of the 21st century, however, with a projected ice volume loss of more than 90% compared to today. Transient simulation of stream-flow runoff from a highly glacierized catchment quantitatively shows that glacier wastage will importantly impact on the hydrological regime.

The Δh-parameterization is able to reproduce glacier retreat over the 21st century given by a complex 3-D ice flow model and shows satisfying results for a wide range of scenarios of future climate change and different glacier types. Input data requirements are limited to (1) distributed glacier surface mass balance in annual resolution and (2) the initial ice thickness distribution. These data can be calculated based on often readily available data sets, such as glacier inventory data and land surface DEMs with a wide spatial coverage (e.g. Shuttle Radar Topographic Mission). The parameterization proposed in this paper is thus applicable to any mountain glacier. The Δh-parameterization is computationally cheap and therefore represents a viable alternative to complex ice flow modelling. It offers the possibility to calculate the evolution of large glacier samples in regional impact studies and to provide transient changes in glacier ice volume.

Climate change will have major impacts on alpine hydrology and the water resource management of mountainous regions. Glacier retreat and the release of freshwater from long-term glacial storage is expected to be a key element in projections of high alpine runoff over the next decades, and requires a description in hydrological modelling that meets the current level of glaciological research. As the application of ice flow models is normally not in the scope of regionally distributed hydrological models, this necessitates simple alternatives. Based on the good performance of the Δh-parameterization in reproducing (i) distributed glacier surface elevation, (ii) glacier area and (iii) length given by a 3-D ice flow model, we recommend this parameterization for the approximation of future glacier change for projections of stream-flow runoff from glacierized drainage basins over the 21st century.

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Table 1. Expected changes in air temperature and precipitation in 2050 relative to the period 1980–2000 (Frei, 2007) based on 16 regional climate models within the PRUDENCE projects (Christensen and Christensen, 2007) aggregated into three scenarios (Sc1–Sc3) according to (Huss et al., 2007).

	Temp. (°C)			Prec. (%)		
Season	Sc1	Sc2	Sc3	Sc1	Sc2	Sc3
Winter	+0.9	+1.8	+3.4	+21	+8	−1
Spring	+0.8	+1.8	+3.3	+10	−1	−11
Summer	+1.4	+2.7	+4.7	−7	−17	−31
Autumn	+1.1	+2.1	+3.5	−1	−6	−14

Table 2. Validation of surface elevation calculated using the Δh-parameterization against the ice flow model for three 30-year (Rhonegletscher) and 20-year periods (Silvrettagletscher), respectively, and three climate scenarios (Sc1–3). $\overline{\mathrm{rms}_\mathrm{d}}$ represents root-mean-square errors of the elevation difference at all grid cells averaged over the selected period.

	Period	Sc1	Sc2	Sc3
			$\overline{\mathrm{rms}_\mathrm{d}}$ (m)	
Rhone	2011–2040	15.9	13.6	14.5
	2041–2070	21.1	17.2	30.4
	2071–2100	22.6	27.8	23.2
Silvretta	2011–2030	7.6	6.9	7.3
	2031–2050	16.6	13.6	12.4
	2051–2070	24.5	16.1	6.7

Table 3. Validation of surface elevation calculated using supplementary simple parameterizations to calculate glacier retreat against the ice flow model for three 30-year periods and scenarios in the future (Rhonegletscher). The root-mean-square errors $\overline{\mathrm{rms}_d}$ of the difference in elevation at all grid cells averaged over the period considered is given for the "AAR-method" and "non-dynamic downwasting" in comparison to the ice flow model.

	Period	Sc1	Sc2	Sc3
			$\overline{\mathrm{rms}_d}$ (m)	
	2011–2040	60.6	92.5	103.0
AAR-method	2041–2070	89.1	114.1	88.9
	2071–2100	117.2	73.9	17.5
	2011–2040	33.9	30.9	27.4
no dynamics	2041–2070	88.7	66.1	46.8
	2071–2100	137.2	102.4	48.8

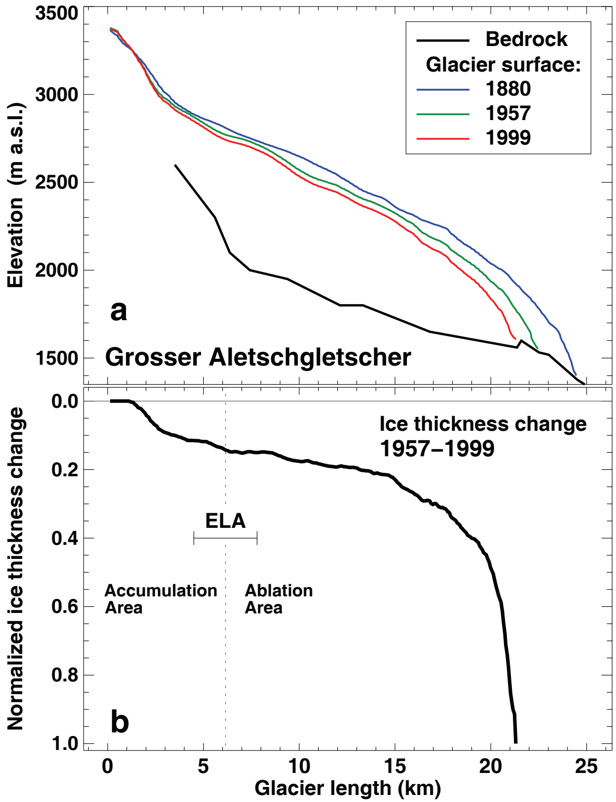

Fig. 1. (a) Observed long-term surface elevation changes in a longitudinal glacier profile for a large alpine valley glacier (Grosser Aletschgletscher). **(b)** Distribution of ice thickness change along the glacier in 1957–1999. Changes in ice thickness are small in the accumulation area and largest near the glacier terminus. The typical variability in the equilibrium line altitude (ELA) over the 20th century is shown.

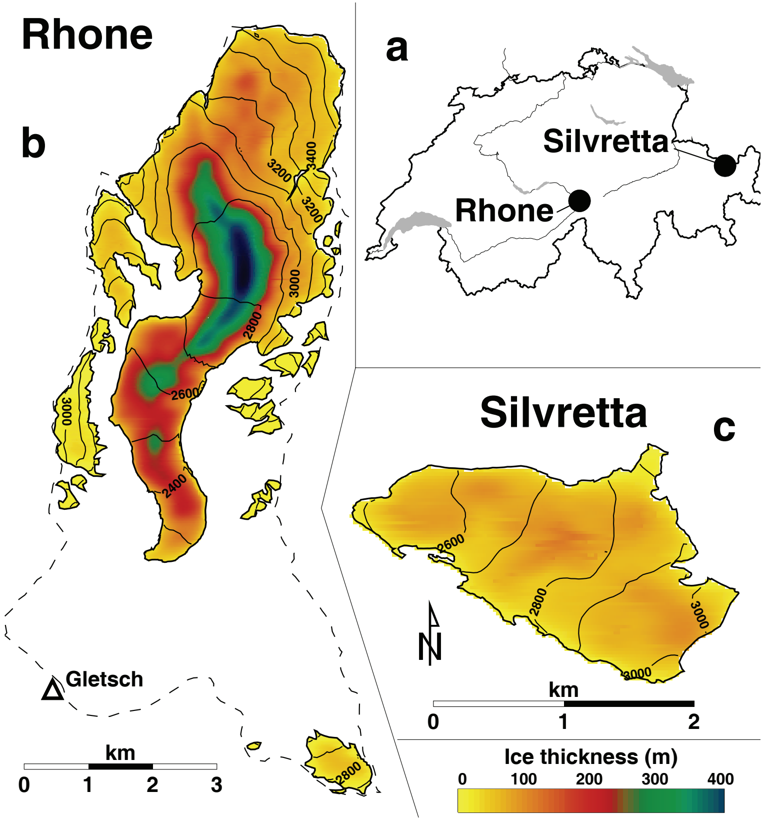

Fig. 2. Study site overview. **(a)** Location of the glaciers in Switzerland. **(b)** Hydrological drainage basin of Rhonegletscher (dashed). The gauging station at Gletsch is marked. The contour line interval is 100 m. The colours indicate ice thickness. **(c)** Map of Silvrettagletscher. Note that the scale differs from **(b)**.

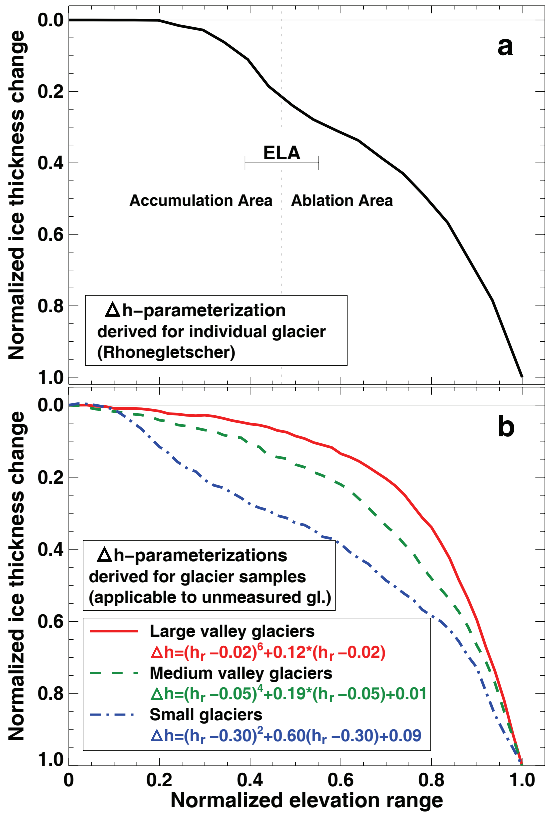

Fig. 3. **(a)** Δh-parameterization derived for Rhonegletscher from observed ice thickness changes in the 20th century. The typical variability in the equilibrium line altitude (ELA) is shown. **(b)** Empirical Δh-parameterizations for three glacier size classes applicable to unmeasured glaciers. Parameterizations are derived from digital elevation model comparison for 34 glaciers in Switzerland and were averaged over the respective size class. The equations refer to a numerical approximation (according to Eq. 1) of the line for each size class as displayed in **(b)**.

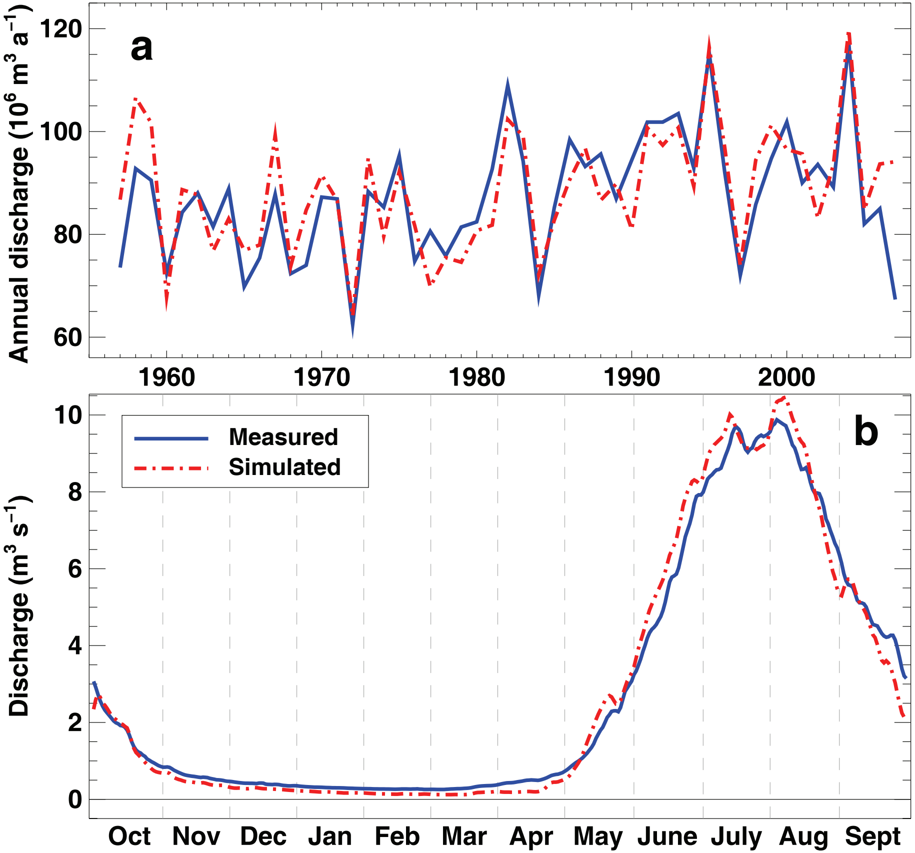

Fig. 4. Comparison of discharge from the Rhonegletscher catchment calculated using GERM to measurements at Gletsch. **(a)** Annual runoff volume, and **(b)** stacked daily runoff hydrographs for the period 1957–2006.

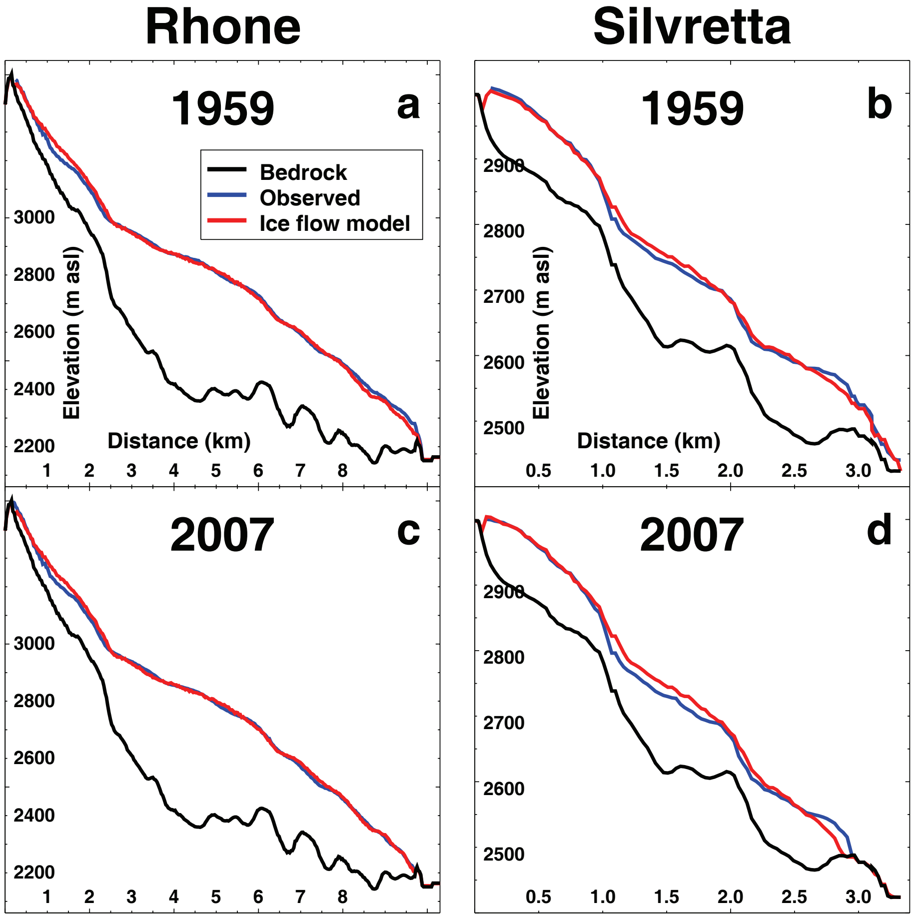

Fig. 5. Validation of the ice flow model over the 20th century using field data. Comparison of observed and calculated glacier surface on a longitudinal profile in 1959 and 2007. Model runs were initialized in 1874 (Rhone) and in 1938 (Silvretta).

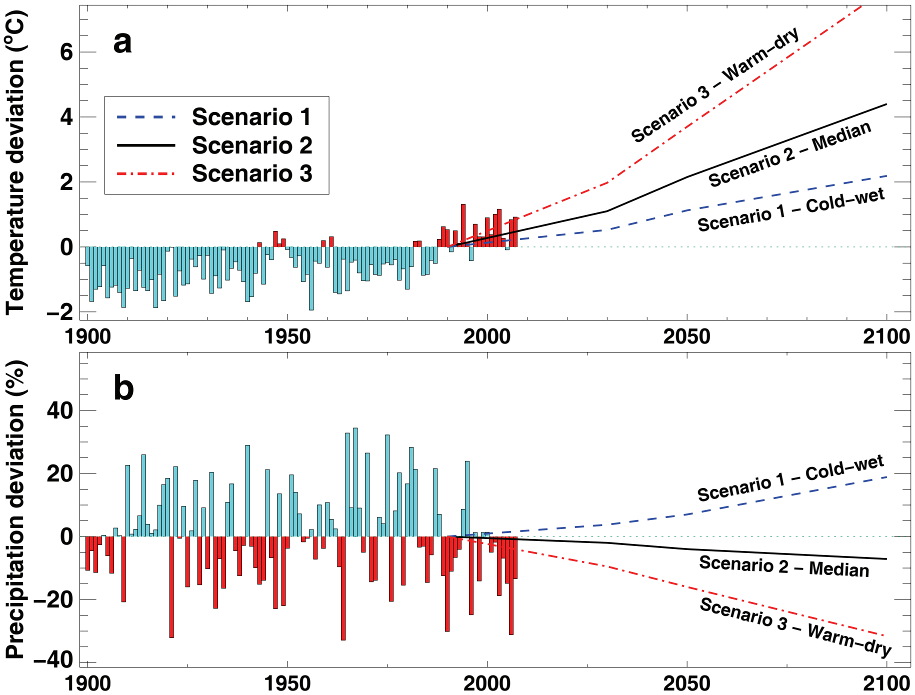

Fig. 6. Deviations of annual **(a)** mean air temperature and **(b)** precipitation sums from the the period 1980–2000. Measured data for the 20th century are displayed by bars, annual trends as assumed by Scenarios 1–3 (Table 1) are shown until 2100.

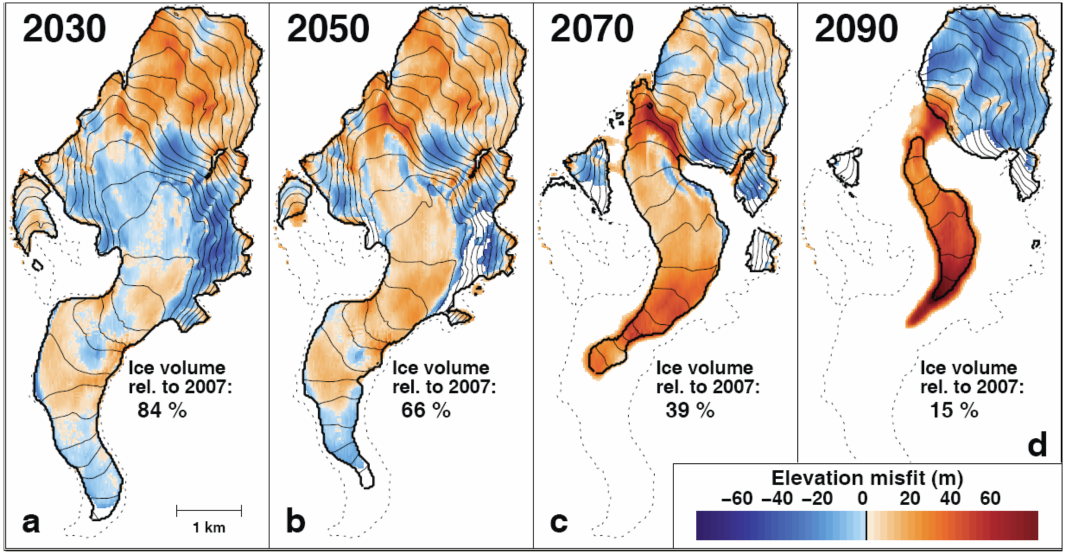

Fig. 7. Comparison of surface elevation and glacier extent calculated for Scenario 2 (median) using the ice flow model (M) and the Δh-parameterization (P) for Rhonegletscher. Coloured areas indicate ice coverage as calculated by the ice flow model. The colours refer to the difference in calculated surface elevation ($h_M - h_P$). Solid lines with contours show the glacier extent as predicted by the Δh-parameterization. The dotted line indicates the glacier outline in 2007. The percentage of ice volume relative to 2007 according to the parameterization is given.

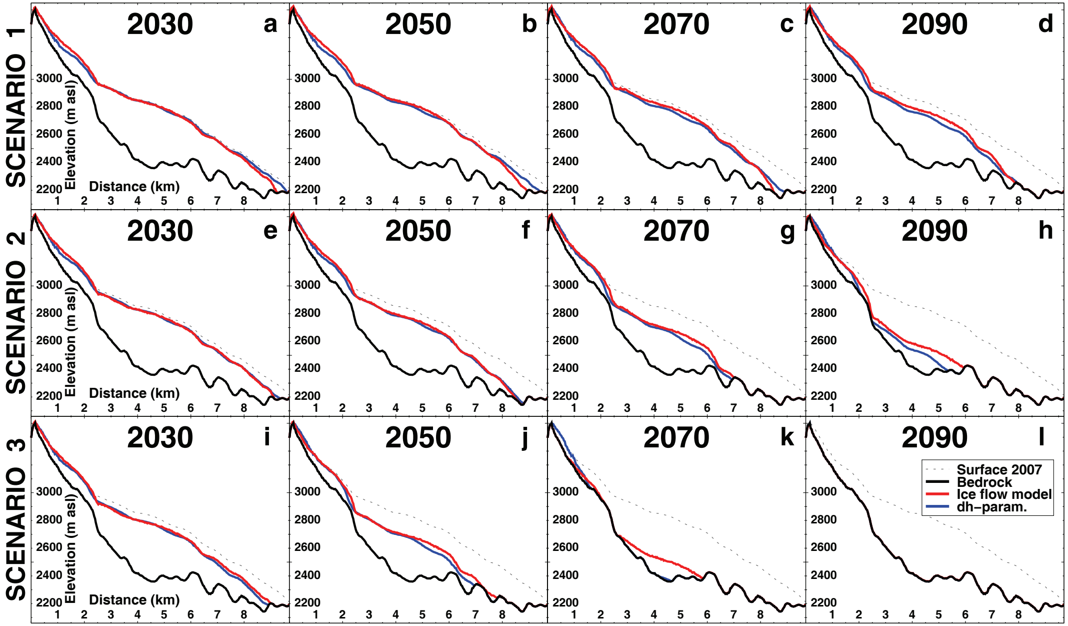

Fig. 8. Evolution of glacier surface elevation along a longitudinal profile calculated for Rhonegletscher using the 3-D ice flow model and the Δh-parameterization. Results for different climate change scenarios are shown.

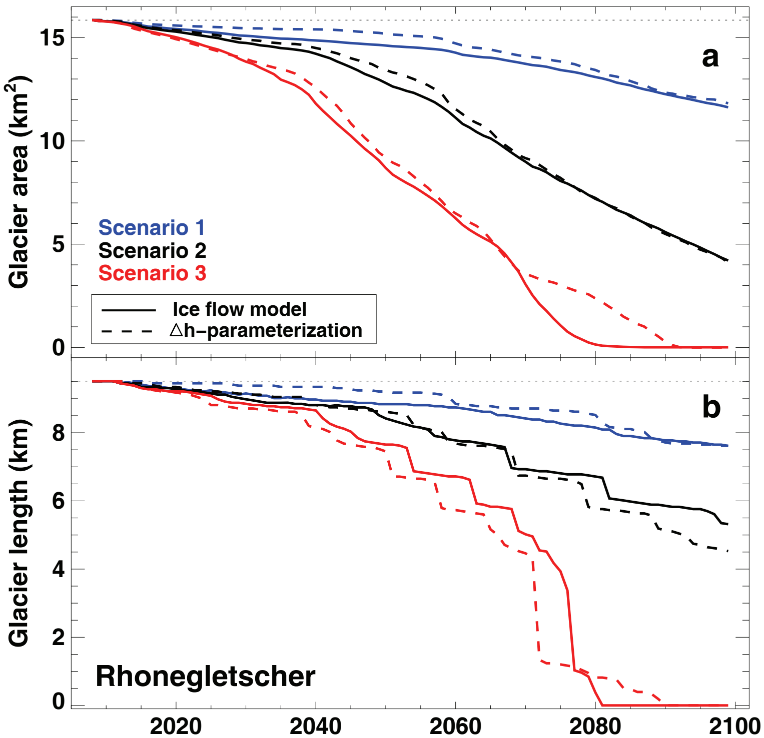

Fig. 9. Calculated **(a)** glacier area and **(b)** length based on the ice flow model and the Δh-parameterization according to the three climate scenarios (Rhonegletscher).

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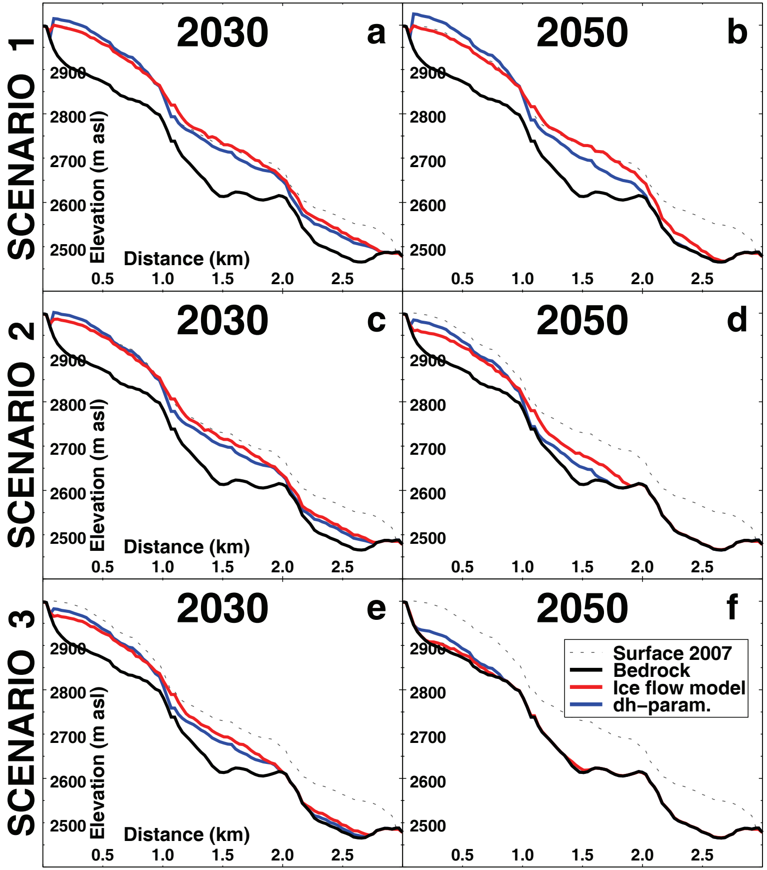

Fig. 10. Evolution of glacier surface elevation along a longitudinal profile calculated for Silvrettagletscher using the ice flow model and the Δh-parameterization. Results for different climate change scenarios are shown.

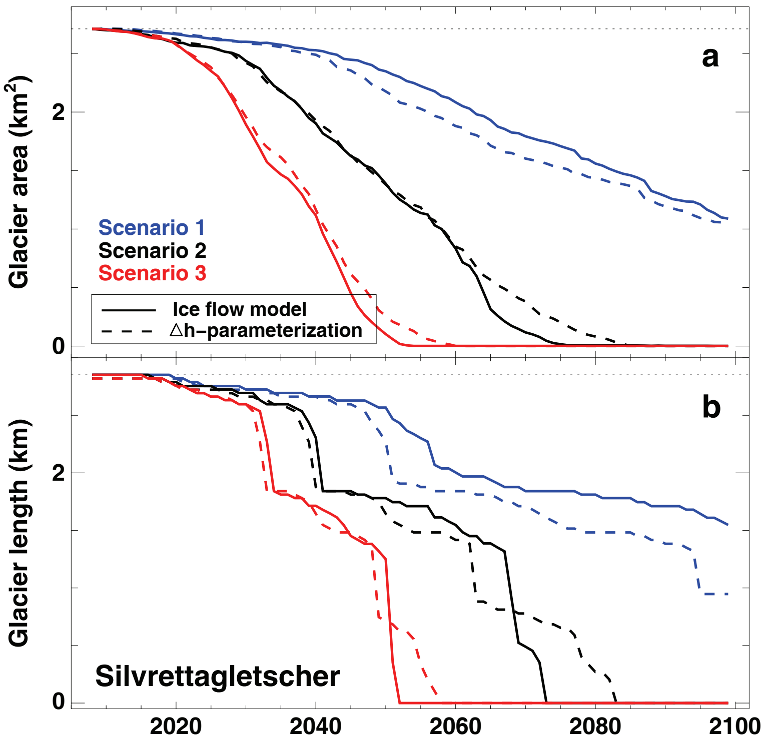

Fig. 11. Calculated **(a)** glacier area and **(b)** length based on the ice flow model and the Δh-parameterization according to the three climate scenarios (Silvrettagletscher).

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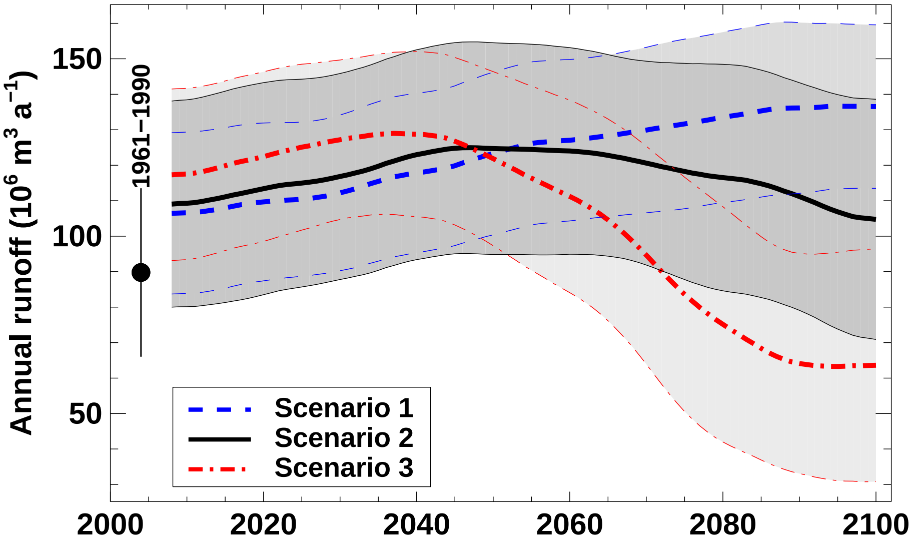

Fig. 12. Calculated annual runoff volume from the Rhonegletscher catchment based on three climate scenarios. Shaded areas indicate the range of variability (±2 standard deviations σ) obtained by performing multiple model runs with random meteorological variability around the expected average of each scenario (solid lines). The dot shows the measured mean annual runoff in the climatic normal period, ±2σ are indicated.

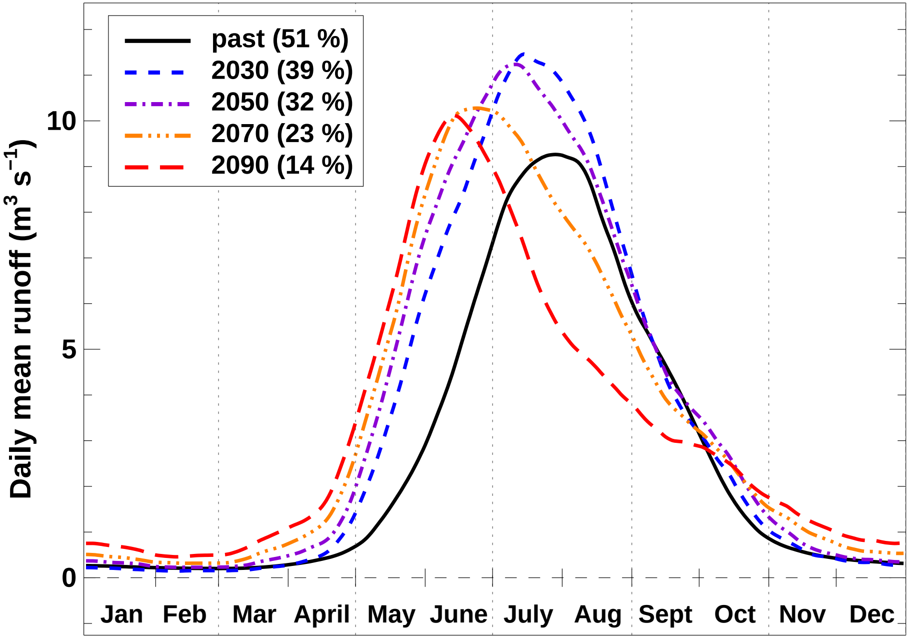

Fig. 13. Projected change in the hydrological regime of the Rhonegletscher catchment according to Scenario 2 (median). Measured discharge in the past refers to the 1961–1990 average. Numbers in brackets indicate the glacierization of the drainage basin.

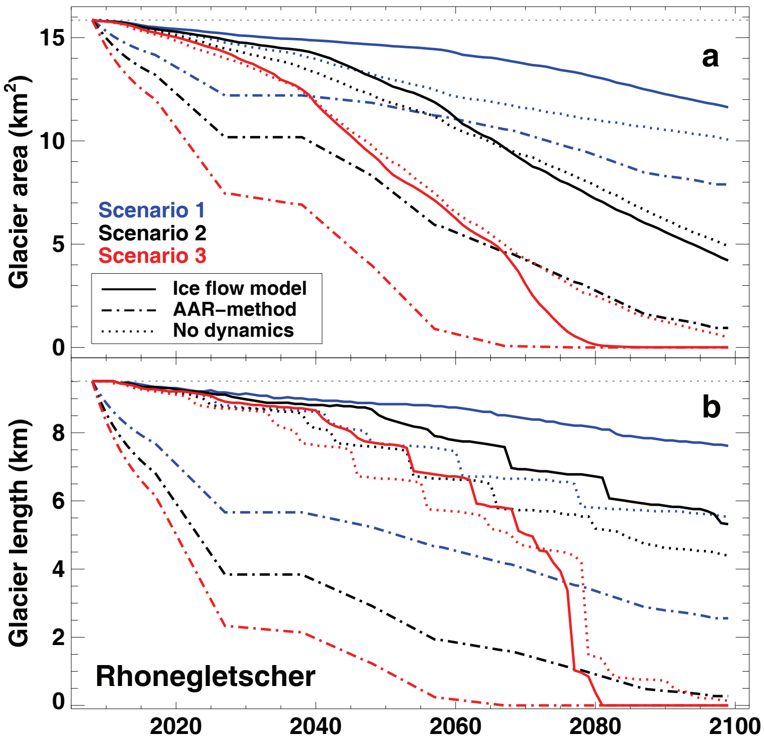

Fig. 14. Validation of simple alternative approaches for calculating future glacier change against the ice flow model. **(a)** Glacier area, and **(b)** length (Rhonegletscher).