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Extrapolating glacier mass balance to the mountain range scale: the European Alps 1900–2100

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Abstract

This study addresses the extrapolation of single glacier mass balance measurements to the mountain range scale and aims at deriving time series of area-averaged mass balance and ice volume change for all glaciers in the European Alps for the period 1900–2100. Long-term mass balance series for 50 Swiss glaciers based on a combination of field data and modelling, and WGMS data for glaciers in Austria, France and Italy are used. A complete glacier inventory is available for the year 2003. Mass balance extrapolation is performed based on (1) arithmetic averaging, (2) glacier hypsometry, and (3) multiple regression. Given a sufficient number of data series, multiple regression with variables describing glacier geometry performs best in reproducing observed spatial mass balance variability. Future mass changes are calculated by driving a combined model for mass balance and glacier geometry with GCM ensembles based on four emission scenarios. Mean glacier mass balance in the European Alps is $-0.32 \pm 0.04\,\mathrm{m\,w.e.\,a^{-1}}$ in 1900–2011, and $-1\,\mathrm{m\,w.e.\,a^{-1}}$ over the last decade. Total ice volume change since 1900 is $-100 \pm 13\,\mathrm{km^3}$; annual values vary between $-5.9\,\mathrm{km^3}$ (1947) and $+3.9\,\mathrm{km^3}$ (1977). Mean mass balances are expected to be around $-1.3\,\mathrm{m\,w.e.\,a^{-1}}$ by 2050. Model results indicate a glacier area reduction to 4–18 % relative to 2003 for the end of the 21st century.

1 Introduction

An accelerated mass loss of mountain glaciers and small ice caps all over the world is reported in response to current atmospheric warming (IPCC, 2007; WGMS, 2008; Cogley, 2009; Gardner et al., 2011). Negative glacier mass balances are an important component of current eustatic sea level rise (Kaser et al., 2006; Radić and Hock, 2011), and significantly affect the hydrology of streams fed by glacial melt water (e.g. Immerzeel et al., 2010). Knowledge about past and future changes in glacier mass balance at the mountain range scale is crucial for assessing global impacts of glacier wastage.

Mass balance measurements are only available for very few of the more than 100 000 mountain glaciers worldwide. Extrapolation of single glacier mass balance series to several thousand glaciers within a mountain range is not trivial and involves considerable uncertainties (e.g. Arendt et al., 2006). Differences in mass balance between neighbouring glaciers are more importantly controlled by glacier geometry than regional climate variability; mass balance response to similar changes in forcing can differ by up to a factor of four (Kuhn et al., 1985; Abermann et al., 2011b; Huss et al., 2012). Therefore, the surveyed mass balance glaciers might not be representative for larger areas. This fact needs to be accounted for in assessments of regional glacier mass change.

Temporal mass balance variations of individual series are similar at the scale of a mountain range (Letréguilly and Reynaud, 1990; Vincent et al., 2004) which is a prerequisite for the regionalization of mass balance. Many large-scale estimates of glacier mass loss are based on arithmetic averaging of the few available mass balance series (e.g. Kaser et al., 2006). The methodology suggested by Cogley (2005) applies a spatial interpolation algorithm that fits two-dimensional polynomials to the single glacier observations. Arendt et al. (2006) compare four different approaches for the regionalization of glacier mass change in the Chugach Mountains, Alaska. They find that extrapolation of observed 5-decade centerline surface elevation changes to the hypsometry of unmeasured glaciers yields results comparable to the averaging of glacier-wide balances, whereas mass change estimates based on volume-area scaling need to be considered with care.

Several studies have addressed glacier mass balance at the scale of the European Alps. Zemp et al. (2006) present glacier area and volume change estimates between 1850 and 2100 based on inventory data and the calculation of Equilibrium Line Altitudes (ELAs). A promising alternative to the extrapolation of single glacier mass balance measurements is numerical modelling of large glacier samples. Machguth et al.

(2009) compute mass balances of all Swiss glaciers between 1979–2003 based on regional climate model output. Results compare well with the observed mass change of selected glaciers but the strong variability in calculated 2-decade mean mass balance (between −2.9 and +0.7 m w.e. a^{-1}) indicates that modelling is not yet able to realistically capture all glaciers within a mountain range. This is mainly attributed to uncertain accumulation which is difficult to model purely based on meteorological data. Recently, the direct observation of regional glacier volume change over decadal periods by comparison of Digital Elevation Models (DEMs) for several 100 glaciers became possible (Paul and Haeberli, 2008; Abermann et al., 2011a). However, the DEM uncertainty remains a critical point, and sufficiently accurate terrain elevation data are not yet available at the scale of whole mountain ranges.

In this study mass balance and ice volume change series covering all glaciers in the European Alps are derived for the period 1900–2011 based on a comprehensive set of long-term mass balance data and glacier inventories (Huss et al., 2010a; WGMS, 2008; Paul et al., 2011). Furthermore, future mass balances are modelled for 2011–2100 using Global Circulation Model (GCM) ensembles based on four CO_2 emission scenarios used within the Intergovernmental Panel on Climate Change (IPCC). This paper also investigates and intercompares methodologies for the extrapolation of single glacier mass balance to the mountain range scale. Regionalization of mass balance is performed using (1) arithmetic averaging, (2) glacier hypsometry, and (3) multiple regression with variables describing glacier geometry (e.g. area, slope). Uncertainties in mass balance estimates for the entire European Alps are analyzed and the required field data basis for deriving mass balance series at the mountain range scale is discussed.

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2 Data

2.1 Mass balance data

Two types of glacier mass balance data are used: (1) long-term mass balance time series for the period 1900–2011 for 50 glaciers in the Swiss Alps (Huss et al., 2010a,b), and (2) mass balance series provided by the World Glacier Monitoring Service (WGMS, 2008, 2011) for 25 glaciers in Austria, France and Italy covering intervals of 3 to 61 yr. Given the aim of deriving mountain range scale mass balance series since 1900, data source (1) lends itself as the primary basis for mass balance extrapolation. Shorter WGMS series (2) that are scattered all across the European Alps are used for independent validation of extrapolated balances, and provide additional information on regional mass balance variability.

Mass balance series for 50 glaciers in all different regions of the Swiss Alps (Fig. 1) are based on a combination of various types of field measurements and detailed modelling of individual glaciers (Huss et al., 2010a,b). Ice volume changes for subdecadal to semi-centennial time periods are available from a set of 3 to 10 high-accuracy Digital Elevation Models (DEMs) per glacier covering the entire 20th century (Bauder et al., 2007). The DEMs were established by digitizing topographical maps and after 1960 by photogrammetrical analysis of aerial photographs. A distributed mass balance model (Hock, 1999; Huss et al., 2008a) is tuned specifically for each glacier to reproduce observed ice volume changes and to optimally match totally >10 000 in-situ point measurements of winter accumulation and annual mass balance (Huss et al., 2010a). The topographical information given by repeated DEMs allows the annual updating of surface elevation and glacier size. Thus, conventional mass balance that refers to the actual glacier geometry is evaluated (Huss et al., 2012). The 50 long-term series cover glacier sizes from 0.08 to 80 km^2, different exposures and glacier geometries, as well as various regional climate conditions and can thus be considered as a statistically representative sample of Alpine glacier coverage. In total, the data set includes 19 % of the glacierized area of the European Alps.

Additional mass balance data for glaciers in Austria, France and Italy provided by WGMS (2008) are based on the direct glaciological method. Series longer than 25 yr are available for 9 glaciers; shorter series (at least 3 yr) were used for another 16 glaciers (Fig. 1). Surveyed glaciers outside of Switzerland increase the total data coverage in the European Alps by another 4 %.

Annual mass balance series are complemented with published regional balances obtained from DEM comparison. By differencing the Shuttle Radar Topography Mission (SRTM) DEM from an older terrain model, Paul and Haeberli (2008) determined a cumulative mass balance of −11 m w.e. over the period 1985–2000 for about 1050 Swiss glaciers. Abermann et al. (2009) calculated glacier surface elevation changes based on two highly accurate Light Detection And Ranging (LiDAR) DEMs for the Oetztal Alps as −8.2 m (1997–2006). The same method was used by Abermann et al. (2011a) to compute cumulative glacier mass balance for the entire Austrian Alps for the period 1969–1998 (−9.4 m w.e.).

2.2 Glacier inventory

A complete and up-to-date glacier inventory is a prerequisite for glacier mass balance and volume change assessments at the mountain range scale. This study relies on a recent inventory of all glacierized surfaces in the European Alps derived by Paul et al. (2011) based on Landsat Thematic Mapper (TM) scenes from August/September 2003 (Fig. 1). Using threshold ratios between frequency bands of TM ice surfaces are mapped automatically (see e.g. Paul et al., 2004). This is complemented by manual digitizing of debris-covered glacier tongues and the separation of individual glaciers based on water divides. The confidence in the 2003 glacier inventory is relatively high as the images are cloud-free, and due to the extraordinarily hot summer all ice and firn surfaces are clearly exposed (Paul et al., 2011). According to this inventory, the total surface of all glaciers and ice patches in the European Alps was 2056 km^2 in 2003 (Paul et al., 2011). This area is distributed across Switzerland (50 %), Italy (19 %), Austria (18 %), France (13 %) and Germany (<1 %).

Vector outlines are available for all inventoried glaciers. By intersecting them with global terrain elevation data provided by the SRTM DEM from 2000 (version 4, Jarvis et al., 2008) topographical parameters (slope, aspect, area-elevation distribution, median elevation and range) for all individual glaciers were extracted. In addition, the Swiss glacier inventories for 1850 (Maisch et al., 2000) and 1973 (Müller et al., 1976) and the Austrian glacier inventories for 1969 and 1998 (Lambrecht and Kuhn, 2007) are used for inferring glacier area changes over the last century.

2.3 Future climate

Projections of glacier mass balance in the European Alps for the period 2011–2100 are based on the Coupled Model Intercomparison Project (CMIP5) coordinated by the World Climate Research Programme (see Taylor et al., 2011). Four Representative Concentration Pathways (RCPs) are defined for the 21st century (Meinshausen et al., 2011). A high emission scenario (RCP8.5) and a medium mitigation scenario (RCP4.5) are considered. Additionally, a peak-decline scenario (RCP2.6) with a rapid stabilization of CO_2 concentrations, and an intermediate scenario (RCP6.0) were used. For each RCP respective changes in climate are provided by a set of 7–11 GCMs. For the same GCMs also hindcasts for the 20th century are available.

Air temperature and precipitation as a mean over the entire perimeter of the European Alps (6–14° E, 45–48° N) were extracted for each GCM over 1961–2100. Changes in monthly temperature and precipitation relative to the period 1961–1990 were evaluated and superimposed on detrended daily meteorological station data of randomly chosen years (see also Huss et al., 2008b). Thus, for each of the 50 Swiss glaciers with mass balance data, 35 meteorological time series at daily resolution were established for 2011–2100 that refer to individual GCMs and the four RCPs. Relative to 1961–1990 annual average air temperature (ensemble mean of GCMs driven by the same RCP) is expected to increase by 2–5 °C until 2100, and annual precipitation totals remain almost constant (Fig. 2). The models indicate a general trend to above average warming and drier conditions in summer, and increased winter precipitation.

3 Methods

3.1 Extrapolating mass balance series

Single glacier mass balance series are extrapolated to all glacierized surfaces in the European Alps based on three different methods with varying data input requirements and complexities: (1) simple arithmetic averaging of measured mass balance, (2) evaluation of the glacier area-elevation distribution and attribution of observed mass balance in elevation bands to unmeasured glaciers, and (3) multiple regression of mass balance with variables describing glacier geometry (e.g. area, slope, median elevation etc.). Multiple regression is performed using three variables (henceforth termed M3), and eight variables (M8). These methods are described in detail in this section and results are intercompared. The fitting of the relations used for mass balance extrapolation is based on 38 of the 50 long-term Swiss series (Fig. 3a). 12 rather small glaciers in the south-eastern Swiss Alps (Huss et al., 2010b) were excluded here due to slightly lower mass balance data quality (last DEM earlier than 2000) and a regional overrepresentation of these glaciers (Fig. 1).

Extrapolation to the European Alps is carried out for 100-yr mean mass balances ($\overline{B_{100}}$), i.e. for each glacier g a value $\overline{B_{100,g}}$ in m water equivalent (w.e.) a^{-1} is obtained by applying one of the methods (1)–(3). Annual mass balance $B_{i,g}$ for year i is then calculated by

$$B_{i,g} = \overline{B_{100,g}} + \Delta\overline{B_{i,r}}, \tag{1}$$

where $\Delta\overline{B_{i,r}}$ is the annual mass balance anomaly in region r given by the difference between annual balance as a mean of all surveyed glaciers in that region $\overline{B_{i,r}^{\mathrm{obs}}}$ and the 100-yr mean $\overline{B_{100}^{\mathrm{obs}}}$ of all glaciers with mass balance observations:

$$\Delta\overline{B_{i,r}} = \overline{B_{i,r}^{\mathrm{obs}}} - \overline{B_{100}^{\mathrm{obs}}}. \tag{2}$$

Four regions accounting for specific mass balance variability are defined according to the drainage basins of the large streams Rhone, Rhine, Danube and Po as the main water divides often correspond to borders of specific climatic patterns. Calculation of $\Delta\overline{B}_{i,r}$ is based on the 50 long-term mass balance series, and is supported by data of 25 additional WGMS glaciers for the years covered by these series. Applying this method a mass balance time series with annual resolution for the period 1900–2011 is obtained for every glacier in the European Alps. Mean specific mass balance B_i^{Alps} in year i at the mountain range scale as a mean over n glaciers is computed as

$$B_i^{\mathrm{Alps}} = \sum_{g=1}^{n} (B_{i,g} \cdot A_{i,g}) \Big/ \sum_{g=1}^{n} A_{i,g}, \tag{3}$$

where $B_{i,g}$ is the annual mass balance and $A_{i,g}$ that year's area of glacier g.

In order to evaluate changes in ice volume and to solve Eq. (3), time series of glacier area change are necessary. However, repeated glacier inventory data are only available for very few points in time, and do not cover the entire study area. The aim is to derive annual area change series for each glacier in the European Alps based on as much observational evidence as possible.

All glaciers in Switzerland (representing half of the glacierized area of the Alps) are covered by three subsequent inventories (1850, 1973 and 2003, see Maisch et al., 2000; Müller et al., 1976; Paul et al., 2011). Area changes for individual glaciers in between these dates are interpolated to annual values proportional to mass balance variations:

$$A_{i,g} = A_{t1,g} - \left(\Delta A_{t1-t2,g} \cdot \sum_{j=t1}^{i} B_j \Big/ \sum_{j=t1}^{t2} B_j\right), \tag{4}$$

where $A_{i,g}$ is the area of glacier g in year i, $\Delta A_{t1-t2,g}$ is the area change between two inventories from the years t_1 and t_2, and B is the mean annual mass balance of four series extending back to the Little Ice Age (Huss et al., 2008a) cumulated over different periods.

Relative changes in glacier area over the 20th century strongly depend on glacier size (e.g. Paul et al., 2004). Whereas large glaciers generally lose low percentages of their area in a given period, the relative surface reduction of small glaciers is much higher. Based on this observation percental annual area changes relative to 2003 obtained for Swiss glaciers were extrapolated to all other glaciers not covered by repeated inventories based on seven size classes. An additional class accounts for glaciers that have disappeared between 1850 and 2003. Glacier area changes obtained from Eq. (4) were validated using the Austrian inventories 1969 and 1998 (Lambrecht and Kuhn, 2007). Whereas, for glaciers >0.5 km^2 estimated and observed area change in size classes agree within 1 %. The area loss of very small glaciers however seems to be overestimated by the 2003 glacier inventory for the entire Alps.

In order to evaluate the suitability and the uncertainties in the different extrapolation techniques all three methods were validated against different data sources: (i) comparison of inferred mass balance to the same 38 glaciers that were used to establish the regionalization relations does not allow an independent assessment of the extrapolation technique's performance but shows how well the observed differences in mass balance among the glaciers can be captured. Results are shown in Fig. 3a. (ii) Validation against 9 independent long-term WGMS mass balance series is shown in Fig. 3b. (iii) Extrapolated mass balances are compared to all available WGMS series (at least 3 yr) at the annual scale (Table 1). This also allows assessing how well year-to-year variability is captured. For validation data sources (i)–(iii) the root-mean-square (rms) of the difference between observed B^{obs} and extrapolated mass balance B^{ex}, and the bias $(\overline{B^{\text{ex}}} - \overline{B^{\text{obs}}})$ is evaluated. (iv) Validation against regional scale glacier elevation change assessments based on the geodetic method (Paul and Haeberli, 2008; Abermann et al., 2009; Abermann et al., 2011a) is performed by comparing mean extrapolated mass balance for the Swiss Alps (1985–2000), the Oetztal Alps (1997–2006), and the Austrian Alps (1969–1998) to elevation differences in repeated DEMs (Table 1).

For consistency, a density of 850 kg m^{-3} (see e.g. Huss et al., 2009; Zemp et al., 2010) was chosen to convert volume to mass change for all studies.

3.2 Arithmetic averaging

The averaging of observed mass balance is the most simple, but nevertheless a robust method for mass balance extrapolation and has been widely used for large-scale mass balance estimates (e.g. Cogley and Adams, 1998; Cogley, 2011; Kaser et al., 2006). The arithmetic average of mean specific mass balance of surveyed glaciers is applied to all unmeasured glaciers in a study region. The main advantage of this approach is its simplicity and its limited data requirements. Differences in glacier size, hypsometry, exposure and geographic location are, however, not accounted for and the mass balance of the few monitored glaciers is assumed to be representative for the entire mountain range.

100-yr mass balance of the 38 Swiss glaciers used for arithmetic averaging can be reproduced within an rms error of 0.133 m w.e. a^{-1} (Fig. 3a). Independent validation with 9 long-term WGMS glaciers outside of Switzerland (25-yr mean mass balance) shows an rms error of 0.428 m w.e. a^{-1} and a bias of 0.207 m w.e. a^{-1}, i.e. for this subset of glaciers extrapolated mass balance is not as negative as the measurements imply (Fig. 3b). This might however be related to extremely negative mass balances of Glacier de Saint Sorlin, Glacier de Sarennes (FR) and Ghiacciaio del Careser (IT) that are currently in a state of disintegration (e.g. Paul et al., 2007).

3.3 Glacier hypsometry

By considering the area-elevation distribution of individual glaciers, it might be possible to partly account for the effect of particular glacier geometries on mass balance. This concept is similar to extrapolating the mean of observed centerline surface elevation changes in altitude bands to unmeasured glaciers as proposed by Arendt et al. (2006). Here, 100-yr mean mass balance of the data sets presented by Huss et al.

(2010a,b) is averaged in 100 m elevation bands (excluding five glaciers with debris-covered tongues). This implicitly assumes that all glacierized surfaces located for example between 3000 and 3100 m a.s.l. exhibit the same mass balance everywhere throughout the mountain range. The strong regional differences in ELA (between 2600 and 3240 within the glacier sample) leading to balances in the same elevation band differing by up to 3 m w.e. a^{-1} is a major drawback of mass balance regionalization using glacier hypsometry. In order to account for this effect the averaged mass balance-elevation distribution is shifted so that the ELA in the observed mass balance profile corresponds to the median elevation (given by inventory data) of each glacier. This allows the correction of ELA differences and mimicks the extrapolation of observed mass balance gradients to the hypsometry of individual glaciers.

Mass balance variability is insufficiently captured using mass balance extrapolation based on glacier hypsometry. The rms error and the bias are larger compared to simple arithmetic averaging (Fig. 3). Therefore, the use of the glacier area-elevation distribution does not offer advantages in the extrapolation of single glacier mass balance to the mountain range scale in the case of the European Alps.

3.4 Multiple regression

The variability in long-term mean mass balance between adjacent glaciers can be significant although the glaciers are subject to similar changes in climate forcing (e.g. Kuhn et al., 1985; Abermann et al., 2011b, see also Fig. 3). The reasons for the different sensitivities of individual glaciers are still not fully understood. A relation to glacier response times (Jóhannesson et al., 1989) is evident, as larger glaciers require more time to retreat to a new equilibrium state at higher elevation after a change in climate, thus exhibiting more negative mass balances than smaller glaciers (e.g. Oerlemans, 2007). Although this effect only explains part of the differences, there is a clear link of mass balance variability with geometrical indices (Huss et al., 2012).

So far, no study has attempted mass balance extrapolation using multiple regression. This is certainly related to the extensive statistical basis that is required to reasonably apply this method. Homogenous mass balance data for several dozens of glaciers covering the entire range of characteristics must be available. Moreover, topographical parameters also need to be determined for all unmeasured glaciers.

Multiple regression relies on the following equation:

$$\overline{B_{100}} = a_1 \cdot x_1 + ... + a_n \cdot x_n + c, \tag{5}$$

where $\overline{B_{100}}$ is 100-yr mean mass balance calculated using the indicator variables $[x_1,...,x_n]$, the multiplicators $[a_1,...,a_n]$ and a constant c. Multiple regression of mass balance is performed with parameter combination M3 consisting of the most important variables, and M8 including additional variables with an important influence on mass balance. Table 2 provides an overview of the parameters used.

Glacier area (negatively correlated to mass balance), slope of the glacier tongue (positive) and median glacier elevation (positive) are able to explain 35 % of the variance in observed long-term glacier mass balance in the European Alps (Fig. 3a). Supplementary variables such as aspect, mean slope of the entire glacier, elevation range and geographic location considered for M8 increase the explained variance to 51 % but the parameters chosen for M3 remain most important (Table 2). According to multiple regression, large glaciers with a gently-sloping tongue and a low median elevation (i.e. relatively maritime climate) experience the most negative mass balances. South-exposed show less negative balances than north-exposed glaciers. Glaciers at the northern flank of the Alps show a tendency towards less negative mass balance, whereas balances slightly decrease towards the Eastern Alps. Mean slope of the entire glacier and elevation range only have a limited effect on the results (Table 2).

In comparison to arithmetic averaging and glacier hypsometry, M3 and M8 yield better results in explaining mass balance variability among the glaciers, and show a better with independent WGMS data in both the rms error and the bias (Fig. 3, Table 1). Multiple regression accounts for at least part of the differences due to glacier characteristics and thus is favourable for extrapolating mass balance from a non-representative sample of surveyed glaciers to the mountain range scale.

Validation of extrapolated mass balance against regional geodetic mass changes (Table 1) confirms that both arithmetic averaging and multiple regression are well suited for mass balance extrapolation to the entire European Alps. Observed decadal mass balances are mostly reproduced within 0.05 m w.e. a^{-1}. Systematic errors between glaciological and geodetic mass balances for monitored alpine glaciers can be substantially larger than this value (Huss et al., 2009; Zemp et al., 2010; Fischer, 2011). For the Swiss Alps 1985-2000 the extrapolation results in too little mass loss (Table 1). Direct validation of SRTM based elevation changes against repeated DEMs based on aerial photogrammetry (Bauder et al., 2007; Huss et al., 2010a) for 25 medium to large Swiss glaciers however indicates that Paul and Haeberli (2008) overestimate mass loss by about 0.14 m w.e. a^{-1}. This might be related to the partly considerable uncertainty in both DEMs used by Paul and Haeberli (2008) and agrees with findings by Gardelle et al. (2012) that the SRTM DEM underestimates actual surface elevation in the accumulation area of glaciers due to penetration of the radar waves into the firn. Thus, the positive bias in extrapolated mass balance (see Table 1) can be explained and is reduced to almost zero when accounting for the systematic error indicated by photogrammetrical DEMs.

Mass balance figures at the scale of the European Alps presented henceforth rely on multiple regression (M8). The choice of this method is supported by the favourable performance in comparison to various validation data, and the statistically representative and large glacier sample available for the European Alps.

3.5 Ice thickness and volume

The ice volume and thickness distribution of glaciers in the European Alps is crucial for modelling future mass balance and glacier area. These variables are inferred by applying an approach to invert glacier surface elevation to distributed ice thickness based on the principles of ice-flow dynamics (see Farinotti et al., 2009). For half of the 50 Swiss glaciers with long-term mass balance series direct ice thickness measurements are available (Farinotti et al., 2009) that are useful for validating calculated thickness and volume for these glaciers. The method for estimating ice thickness of all glaciers in the European Alps is based on a further development of the approach presented by Farinotti et al. (2009) and requires a DEM (provided by the SRTM) and glacier outlines (given by the 2003 inventory) as input. By estimating ice volume flux in a longitudinal glacier profile and solving Glen's ice flow law, ice thickness distribution on a regular grid is calculated for each individual glacier taking into account valley shape and basal shear stress variations (Huss et al., 2011). A total ice volume of 114 km^3, or a mean ice thickness of 55 m, for the European Alps in 2003 is computed.

This number compares well with traditional volume-area scaling (Bahr et al., 1997) which results in a volume of 128 km^3 based on the same data, and the approach presented by Haeberli and Hoelzle (1995) yielding 100 km^3 for the end of the 20th century. The ice volume found in the present study is significantly larger than the number obtained by Paul et al. (2004) (75 km^3), and slightly smaller than the ice volume estimate by Farinotti et al. (2009) upscaled to the European Alps (about 120 km^3). The latter is consistent with in-situ thickness observations on about two dozens of large glaciers in the Swiss Alps and is therefore considered to be relatively accurate.

3.6 Future glacier mass balance

The calculation of future glacier mass balance is based on a spatially distributed model (25 × 25 m grid) for snow accumulation, snow- and ice melt, and 3-D glacier geometry change (Huss et al., 2008b). For each of the 50 Swiss glaciers with mass balance data (Fig. 1) the model is driven by 35 time series of daily air temperature and precipitation generated based on the 4 RCPs and the respective GCM ensembles until the end of the 21st century. Initial surface geometry is taken from the last DEM available (between 1991 and 2008). Future mass balance is simulated using model parameters calibrated over multi-decadal periods in the past based on observed ice volume changes (Bauder et al., 2007). Figure 4 illustrates simulation results of future glacier change for the example of Gornergletscher, Switzerland.

Extrapolation of future glacier area and surface mass balance to the entire European Alps is based on the detailed modelling of 50 glaciers. Here, a rather simple extrapolation scheme is employed: the investigated glaciers are divided into seven size classes assuming them to be representative for their class in both their area change relative to the 2003 state and their mass balance. Due to the differences in dynamic response times between large and small glaciers, and consequently their different mass balance response to atmospheric warming, considering size classes for mass balance extrapolation over the 21st century is reasonable. The updating of single glacier ice volumes based on extrapolated mass balance and area allows determining the approximate date of disappearance of each glacier which considerably refines the future glacier area estimate based on size classes.

4 Results

Glacier mass balance in the European Alps over the 20th century is characterized by significant long-term variations (Fig. 5a). The mass budget was positive in the 1910s and close to balanced conditions between 1960 and the mid-1980s. Strongly negative mass balances are evident for the 1940s and the last two decades when the average annual balance approached $-1\,\mathrm{m\,w.e.\,a^{-1}}$ (Table 3). The mean mass balance in the European Alps over the period 1900–2011 is $-0.32\,\mathrm{m\,w.e.\,a^{-1}}$.

Alpine glacier area has decreased from about $3350\,\mathrm{km^2}$ by 1900 to presently less than $1900\,\mathrm{km^2}$ with a strong acceleration of area changes since the 1980s (Fig. 5b). This significant reduction in glacier area affects the rate of volume change. Although the most negative mass balance year was 2003 (-2.25 m w.e., $-5.1\,\mathrm{km^3}$ volume change) the annual ice volume loss in the European Alps was maximal in 1947 ($-5.9\,\mathrm{km^3}$). The most positive mass balance year 1977 resulted in a glacier volume change of $+3.9\,\mathrm{km^3}$. Since 1900 glaciers in the European Alps were subject to a cumulative ice volume change of $-100\,\mathrm{km^3}$ (Fig. 5c), which is equivalent to 0.25 mm of global sea level rise and roughly corresponds to the quantity of ice currently still present in central Europe.

Glaciers within the different nations of the Alps show some differences in extrapolated mean long-term mass balance (Table 4). Whereas glaciers in Switzerland and Italy show slightly less negative mass balance, especially glaciers in France have experienced strong mass losses which is in line with direct observations (see e.g. Thibert et al., 2008, Fig. 3b). Swiss glaciers have lost comparably low percentages of their area and volume throughout the 20th century (Table 4). This is explained by the distribution of large glaciers; two-thirds of glaciers $>10\,\mathrm{km}^2$ are located in Switzerland.

Future glacier mass balance at the scale of the European Alps is expected to show a slightly negative trend over the next decades for all scenarios (Fig. 5a). The model results indicate that mass balances are around $-1.29\,\mathrm{m\,w.e.\,a^{-1}}$ by 2050 (Table 3). Despite the significant atmospheric warming projected for all RCPs (Fig. 2a), future European glacier mass balances are expected to remain within the range of observed variability of the last decades. This is explained by the strong glacier area loss (Fig. 5b). Compared to 2003 54–60 % of the glacierized surfaces are expected to disappear during the next 40 yr (Table 3). This exerts a significant negative feedback on mass balance as glaciers retreat to higher elevations, and many smaller glaciers at low altitude vanish completely. Modelled mass balances according to the 4 RCPs diverge after 2050. The remaining glaciers tend towards a new equilibrium at significantly reduced size for RCP2.6 and RCP4.5. Assuming emission changes as in RCP8.5 triggers a continuous acceleration of glacier mass loss leading to down-wasting with average mass balances of less than $-2\,\mathrm{m\,w.e.\,a^{-1}}$ and an almost complete disintegration of the European glacier coverage by 2100 (Fig. 5a). Relative to the year 2003 the model results show that Alpine glacier area might be reduced to values of between 4 % (RCP8.5) and 18 % (RCP2.6). It is remarkable that also with the rapid decline in greenhouse gas emissions assumed for RCP2.6 (Meinshausen et al., 2011) more than 80 % of glacier surfaces in the Alps are expected to disappear.

Differences in future mass balance among the glacier size classes are considerable (Fig. 6). Whereas mass balance of glaciers currently <3 km^2 remain above -1 m w.e. a^{-1} for RCP6.0 throughout the century, the mass balance of larger glaciers shows a strong decrease beyond historical levels. These different behaviours are widely explained by the glaciers' dynamic response. Glaciers <3 km^2 are expected to be reduced to 10–40 % of their size by 2050 and therefore are relatively well adapted to climate forcing at that time. Very large glaciers in contrast show smaller percentages of area loss and remain comparably large due to their longer response time. Melting of the currently still several hundred meter thick ice of valley glaciers (Fig. 4) requires many decades and leads to progressively negative balances in response to rising air temperatures.

5 Uncertainty assessment

Estimating the uncertainty in mountain range scale mass balance involves three layers: (1) the uncertainty in observed mass balance data, (2) the uncertainties induced by the extrapolation scheme, and (3) a non-representative or too small glacier sample used for extrapolation. In this section, the quantification of error bars for the mountain range mass balance estimates thus proceeds from the local field data scale to the analysis of the benefits and drawbacks of the extrapolation methods. This allows identifying best practices for mass balance data regionalization depending on the observational evidence available.

The uncertainty in observed mass balance can be divided into a systematic error (bias) leading to too high/low long-term mean balances, and a stochastic error affecting year-to-year variability but not the long-term mean. 100-yr mass balances are mainly determined by observed ice volume changes (see Huss et al., 2008a). Therefore, the systematic bias in these is related to the accuracy of the repeated DEMs. Long-term mass balances of individual glaciers g are thus estimated to be subject to an uncertainty of $\sigma_g = \pm 0.07$ m w.e. a^{-1}, also including the uncertainty in the density assumption for converting volume to mass change (Huss et al., 2010a). As σ_g is assumed to be normally distributed among the $n = 38$ glaciers used for fitting the extrapolation relations, the systematic error due to mass balance data uncertainty is reduced to $\sigma_{\mathrm{syst,obs}}=\sigma_g/\sqrt{n} = 0.011\,\mathrm{m\,w.e.\,a^{-1}}$ according to the laws of error propagation.

The systematic uncertainty in mass balance due to the use of multiple regression (M8) for extrapolation is estimated by (i) combining results of the different validation approaches (Fig. 3, Table 1), and (ii) comparison of mountain range mass balance obtained from different regionalization techniques. M8 has an average bias of $0.06\,\mathrm{m\,w.e.\,a^{-1}}$ relative to annual mass balances based on the glaciological method (Table 1). This lies within the estimated uncertainty of $\pm 0.2\,\mathrm{m\,w.e.\,a^{-1}}$ in these (Dyurgerov, 2002) and could also be explained by a non-representative sample of monitored glaciers. Validation of M8 using geodetic mass changes (Table 1) shows a rather good agreement for different periods and regions with an error of about $0.02\,\mathrm{m\,w.e.\,a^{-1}}$. Note that the geodetic mass change found by Paul and Haeberli (2008) was corrected for its bias in comparison to photogrammetrical elevation changes. The 1900–2011 mass balance of the European Alps obtained using arithmetic averaging ($-0.33\,\mathrm{m\,w.e.\,a^{-1}}$), multiple regression M3 ($-0.29\,\mathrm{m\,w.e.\,a^{-1}}$) and M8 ($-0.32\,\mathrm{m\,w.e.\,a^{-1}}$) is similar indicating that the mass balance extrapolation based on the available data basis is relatively robust. Merging all of these evidences an overall systematic extrapolation uncertainty of $\sigma_{\mathrm{syst,ex}} = 0.04\,\mathrm{m\,w.e.\,a^{-1}}$ is estimated as an upper bound.

Thus, the total systematic uncertainty in long-term mass balance extrapolated to the European Alps using multiple regression M8 becomes

$$\sigma_{\mathrm{syst}} = \sqrt{\sigma^2_{\mathrm{syst,obs}} + \sigma^2_{\mathrm{syst,ex}}}, \qquad (6)$$

with $\sigma_{\mathrm{syst}} = \pm 0.041\,\mathrm{m\,w.e.\,a^{-1}}$ defining the error bar of the 20th century mountain range mass balance.

The year-to-year variability in extrapolated mass balance is primarily based on modelling using weather station data (Huss et al., 2010a), and is only partly supported by direct observations given by WGMS (2008) over the last decades. Thus, interannual variations are expected to be subject to significant uncertainties as local meteorological particularities of individual glaciers sites are difficult to capture. Furthermore, weather conditions, especially precipitation sums, show strong local to regional year-to-year variations within the European Alps. Although regional mass balance anomalies for each year are considered (Eq. 2), it seems to be impossible to reproduce all single glacier annual mass balances within a mountain range by extrapolation of measured data. The rms error for individual glaciers and years is about 0.5 m w.e. a^{-1} for all methods (Table 1). When the systematic error is removed this value reduces to 0.43 m w.e. a^{-1} which can be considered as the uncertainty in year-to-year mass balance variability. As this is a stochastic uncertainty, errors in individual years and glaciers will be averaged out over longer time spans and large glacier samples. Thus, this uncertainty does not affect the overall accuracy of the mountain range mass balance estimate but is significant when considering annual mass balance figures or time series of individual glaciers.

The sample size of surveyed glaciers is critical for determining the optimal method for mass balance data extrapolation. Only rarely the mass balance of more than a handful of glaciers is measured within a mountain range. This poses strict limitations on the applicability of more sophisticated methods for mass balance regionalization such as multiple regression. The effect of limited data availability on extrapolation uncertainty is tested by calculating the mass balance of the European Alps based on a glacier sample size increasing from 2 to 25 glaciers that are randomly drawn from the total 38-glacier sample (Fig. 3a). For each sample size mass balance extrapolation is repeated 1000 times with different random combinations of glaciers. The rms error of 100-yr mass balance relative to the 38-glacier sample, and the mean 1908–2008 mass balance of the European Alps is evaluated for arithmetic averaging and multiple regression (M3, M8). Extrapolation based on glacier hypsometry (Method 2) was not used in this experiment due to lower performance (see Fig. 3, Table 1).

When using arithmetic averaging for mass balance extrapolation, rms errors show an only moderate decrease for growing glacier samples. Arithmetic averaging yields rms errors smaller than M3 (M8) if less than 8 (15) mass balance series are available (Fig. 7a). For small glacier samples the performance of multiple regression is poor, or the method is even unfeasible. If more than 20 glaciers are available for fitting the multiple regression relation, M8 performs best. Figure 7b shows the mass balance uncertainty for the European Alps depending on glacier sample size. The range of possible solutions based on randomly selected series is considerable and emphasizes the need for carefully assessing the uncertainties in regional mass balance estimates. If, for example, only three time series were available documenting 20th century Alpine glacier mass changes, the 80 % confidence interval ranges from -0.41 to $-0.24\,\mathrm{m\,w.e.\,a^{-1}}$ for arithmetic averaging which is the only feasible method in that case (Fig. 7b). With growing sample size the uncertainty range narrows quickly for arithmetic averaging and multiple regression M3. For M8 the range of possible solutions is still relatively large with a sample size of 25 glaciers but decreases steadily for larger samples. The different extrapolation techniques converge to slightly different means (Fig. 7b).

Most of the earth's mountain ranges are only covered by very few mass balance observations (e.g. Kaser et al., 2006; WGMS, 2008). The results presented in Fig. 7 indicate that a significant uncertainty in mass balance estimates at the mountain range scale originates from a small and statistically non-representative coverage of surveyed glaciers, irrespective of the extrapolation method used. As a rule of thumb at least 5–10 series should be available to regionalize mass balance within acceptable bounds of uncertainty.

Mass balance series at the scale of the European Alps allow assessing the representativeness of existing long-term monitoring programs. In the Alps, nine series based on the glaciological method longer than four decades are available and are part of the WGMS 'reference' mass balance programmes (Zemp et al., 2009). Mean mass balance of these glaciers was compared to extrapolated mountain range balance. Vernagt and Sonnblick (AU) appear to be suitable index glaciers for Alpine mass balance. Silvretta

(CH) and Kesselwand (AU) show more positive balances compared to the mountain range average; Gries (CH), Hintereis (AU), Sarennes, Sorlin (FR), and Careser (IT) are below the mean – some of them significantly. Overall, the mass balance of the nine reference glaciers is 0.16 m w.e. a^{-1} more negative than the mountain range average. This indicates that European glacier mass loss might have been overestimated so far due to a non-representative sample of long-term monitoring series. This finding challenges the continued efforts for acquiring additional mass balance data on a larger set of glaciers in order to better capture spatial variability.

Future mass balances (Fig. 5a) are subject to a significant uncertainty that is however difficult to be quantified. First of all, GCMs with a spatial resolution of several 100 km are unable to realistically reproduce orographic processes in the Alpine mountain range (e.g. Schmidli et al., 2006). Therefore, changes in air temperature and precipitation predicted by GCMs might differ from regional variations in climate. However, for the 4 RCPs no comprehensive ensembles of regional climate models are available for the Alpine region so far. Furthermore, the use of these GCM outputs for impact studies all over the world will warrant comparability of the results in the frame of the IPCC.

Several additional uncertainties related to the impact modelling are important. For example, simulated glacier mass balances are affected by the model approach used for computing snow- and icemelt and glacier geometry change, as well as the initial ice thickness distribution. Parameters of mass balance models calibrated for past conditions might be subject to changes with the strong shifts in the climatic regime over the 21st century (e.g. van den Broeke et al., 2010). Moreover, insufficiently understood feedback effects, such as a decrease in glacier surface albedo (Oerlemans et al., 2009), the thickening of supraglacial debris (e.g. Jouvet et al., 2011), or the response of polythermal ice bodies at high elevation in the Alps (Hoelzle et al., 2011) might impact on modelled mass balances. Additional research is required to strengthen the process understanding for reducing these uncertainties. Due to the combined uncertainty of climate model input and the impact modelling, simulated future mass balance have to be interpreted with care and represent best estimates given the current state of knowledge.

6 Conclusions

Several methods were tested to extrapolate glacier surface mass balance from the single glacier to the mountain range scale. For the case of the European Alps where a sound observational data basis with several dozens of surveyed glaciers is available, multiple regression of mass balance with variables describing glacier geometry (e.g. area, slope, median elevation etc.) yields the best results and allows accounting for a non-representative distribution of mass balance measurements. Whereas, extrapolation based on observed mass balance in elevation bands and glacier hypsometry is not satisfactory in the case of the European Alps, simple arithmetic averaging that completely neglects glacier characteristics is a robust alternative particularly if only few (<10) mass balance series per mountain range are available. The uncertainty in mountain range scale mass balance assessments depends on the accuracy of observed mass balance series, the extrapolation scheme applied, and the number of mass balance monitoring series. By using all data documenting glacier mass change the mean 20th century mass balance of the European Alps can be computed within an error bar of ±0.04 m w.e. a^{-1}. Uncertainties however increase to ±0.1 m w.e. a^{-1} if less than 5 series are used for extrapolation.

Annual glacier mass balance for the period 1900–2011 were extrapolated to all glaciers in the European Alps based on Swiss long-term mass balance series. Results were validated against WGMS mass balances, and regional geodetic mass changes indicating a good agreement with independent data. The mean area-averaged mass balance is -0.32 ± 0.04 m w.e. a^{-1} for 1900–2011 corresponding to a total ice volume change of $-100 \pm 13\,\mathrm{km}^3$. Since 1900 about 45 % of the glacier surface, and roughly 50 % of the ice volume in the European Alps was lost. European glacier mass balance shows significant multidecadal variations with maximal annual ice volume losses in the 1940s and increasingly negative mass balances since the mid-1980s. According to climate change scenarios Alpine glaciers are expected to shrink to 4–18 % of their 2003 extent by the end of the 21st century, also with moderate atmospheric warming. Glacier mass balances are expected to decrease to $-1.29\,\mathrm{m\,w.e.\,a^{-1}}$ by 2050 simultaneous with a fast area loss. Afterwards, some scenarios indicate a gradual stabilization of Alpine mass balances at drastically reduced glacier size.

The extrapolation of single glacier mass balances to the mountain range scale involves significant uncertainties that need to be reduced for more accurate estimates of global sea-level rise due to mountain glacier mass loss, and better projections of future changes in the hydrology of glacierized basins. To this end, monitoring efforts documenting year-to-year mass balance variability must be strengthened, particularly in regions with poor data coverage (e.g. Cogley, 2011). Field monitoring can be supported but not be replaced by current remote sensing technology providing regional ice volume changes based on increasingly accurate DEMs acquired over subdecadal time scales.

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Table 1. Validation of annual mass balance extrapolated using (1) arithmetic averaging, (2) glacier hypsometry, and (3) multiple regression with three (M3) or eight variables (M8) against independent WGMS data and geodetic regional mass balances. The mean bias ($\overline{B^{\mathrm{ex}}} - \overline{B^{\mathrm{obs}}}$) and the rms error in mm w.e. a^{-1} for n = 790 annual mass balance observations based on the glaciological method are evaluated. Systematic errors in comparison to geodetic mass changes divided by the period length ($\overline{B^{\mathrm{ex}}} - \overline{B^{\mathrm{geod}}}$) are given in mm w.e. a^{-1} for 1985–2000 (Paul and Haeberli, 2008, Swiss Alps, PH2008), 1997–2006 (Abermann et al., 2009, Oetztal Alps, A2009), and 1969–1998 (Abermann et al., 2011a, Austrian Alps, A2011).

Method	bias	rmse	PH2008	A2009	A2011
1	97	508	89	2	0
2	245	569	132	119	121
3 (M3)	93	505	115	31	30
3 (M8)	59	497	136	6	−15

Table 2. The two parameter sets (M3, M8) used for the multiple regression analysis. The sign of the mass balance dependence on each variable is given. Explained variances r^2 are 35 % for M3 and 51 % for M8. The relative contribution R_{var} (in %) of each variable to the total explained variance of the parameter set (taken as 100 %) is evaluated by omitting one variable and comparing the reduction in r^2 with the original r^2.

M3	R_{var}	M8	R_{var}	Parameter x_n
–	19.5	–	25.0	Area (km^2)
+	47.0	+	20.2	Median gl. elevation (m a.s.l.)
+	33.5	+	23.1	Slope, lowermost 10 % (°)
		–	1.2	Slope, entire glacier (°)
		+	5.7	Aspect (°), dev. from N
		+	1.7	Elevation range (m)
		+	7.8	Northing (m)
		–	20.2	Easting (m)

Table 3. Decadal mean mass balances of glaciers in the European Alps for 1900–2010 and simulated future mass balance in 20-yr periods according to the 4 RCPs based on the GCM ensemble mean. Period averages of total Alpine glacier area are given.

Period	Scenario	$\overline{B}$ (m w.e. a^{-1})	Area (km^2)
1900–1910		−0.18	3272.6
1910–1920		+0.33	3241.3
1920–1930		−0.33	3182.9
1930–1940		−0.13	3095.1
1940–1950		−0.87	2976.8
1950–1960		−0.17	2808.4
1960–1970		−0.01	2748.0
1970–1980		+0.10	2731.5
1980–1990		−0.40	2686.0
1990–2000		−0.69	2330.2
2000–2010		−0.99	2034.1
2020–2040	RCP2.6	−1.31	1251.8
2040–2060	RCP2.6	−1.08	807.3
2060–2080	RCP2.6	−0.66	544.9
2080–2100	RCP2.6	−0.05	395.5
2020–2040	RCP4.5	−1.02	1380.4
2040–2060	RCP4.5	−1.19	936.3
2060–2080	RCP4.5	−1.04	570.8
2080–2100	RCP4.5	−0.68	349.4
2020–2040	RCP6.0	−1.00	1350.2
2040–2060	RCP6.0	−1.21	921.5
2060–2080	RCP6.0	−1.42	520.3
2080–2100	RCP6.0	−1.30	241.2
2020–2040	RCP8.5	−1.09	1348.4
2040–2060	RCP8.5	−1.66	829.2
2060–2080	RCP8.5	−2.09	349.0
2080–2100	RCP8.5	−2.16	125.7

Table 4. Key values of glacier change over the 20th century for Switzerland (CH), Italy (IT), Austria (AU) and France (FR). $\overline{B}$ is the mean 1900–2011 mass balance in m w.e. a^{-1}. Area A (in km^2) and estimated ice volume V (in km^3) are given for the year 2003, and area and volume changes (ΔA, ΔV) refer to the period 1900–2011. A_{2100} is the 4 RCP-average of modelled glacier area by 2100.

	$\overline{B}$	A_{2003}	V_{2003}	ΔA	ΔV	A_{2100}
CH	−0.29	1021.1	66.5	−622.9	−44.4	147.4
IT	−0.28	388.5	17.6	−339.7	−16.9	32.0
AU	−0.35	375.7	17.1	−315.9	−21.7	29.1
FR	−0.38	274.9	12.6	−208.0	−16.6	15.2

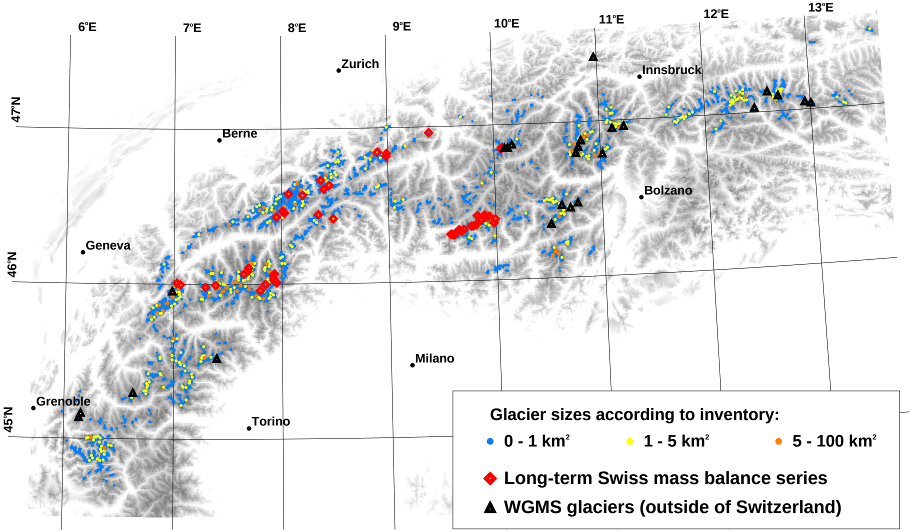

Fig. 1. Overview map of glacier coverage and glacier mass balance data in the European Alps. All inventoried glaciers according to Paul et al. (2011) are shown; the colour-coding indicates glacier size. Swiss glaciers with long-term mass balance series (Huss et al., 2010a,b) and additional mass balance glaciers obtained from WGMS (2008) are marked.

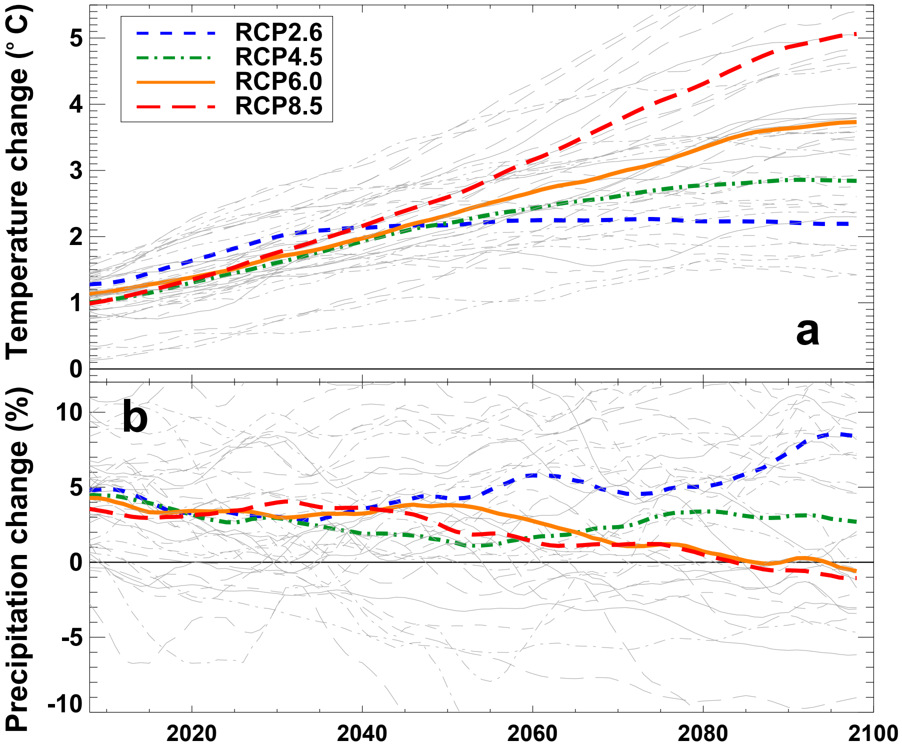

Fig. 2. Projected changes in **(a)** annual mean air temperature, and **(b)** annual precipitation sums relative to the period 1961–1990 for 35 GCMs (thin lines). Bold lines and colours indicate the average of GCM ensembles forced with the same RCP. All series are 20-yr low-pass filtered.

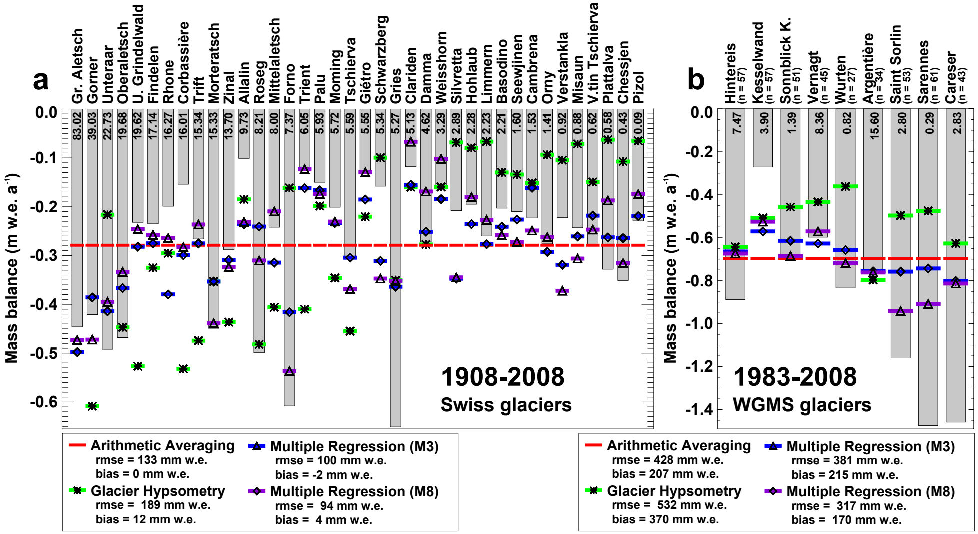

Fig. 3. Comparison of different methods for extrapolating glacier surface mass balance. **(a)** 100-yr mean mass balance (1908–2008) of 38 Swiss glaciers (Huss et al., 2010a,b) is shown with bars. Glacier area (2003) in km^2 is given. Mass balance extrapolated to these glaciers using arithmetic averaging (red lines), glacier hypsometry (asterisks), and multiple regression (triangles, diamonds) is shown. The rms error and the mean bias are given for each method. **(b)** Same as in **(a)** but for the 25-yr mean mass balance (1983–2008) of 9 glaciers provided by WGMS (2008). The total length of the series (*n*) and glacier area is given.

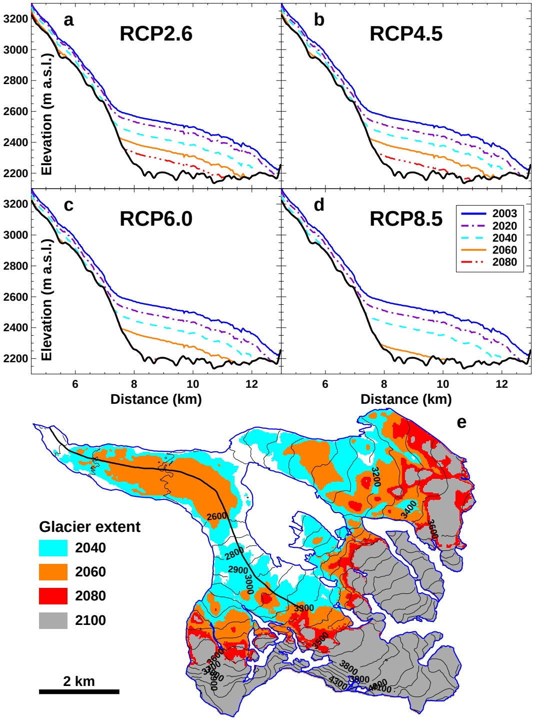

Fig. 4. Example of simulated future geometry changes of Gornergletscher, south-western Switzerland, the second largest glacier in the European Alps. **(a–d)** Modelled glacier surface elevation in longitudinal profiles (solid line in **e**) of the glacier tongue. Glacier change is simulated using the Beijing Climate Center (bcc-csm1-1) GCM driven by 4 RCPs. Results of bcc-csm1-1 correspond to the ensemble median. **(e)** Spatial changes in glacier size (RCP6.0). Contours refer to the glacier surface in 2003.

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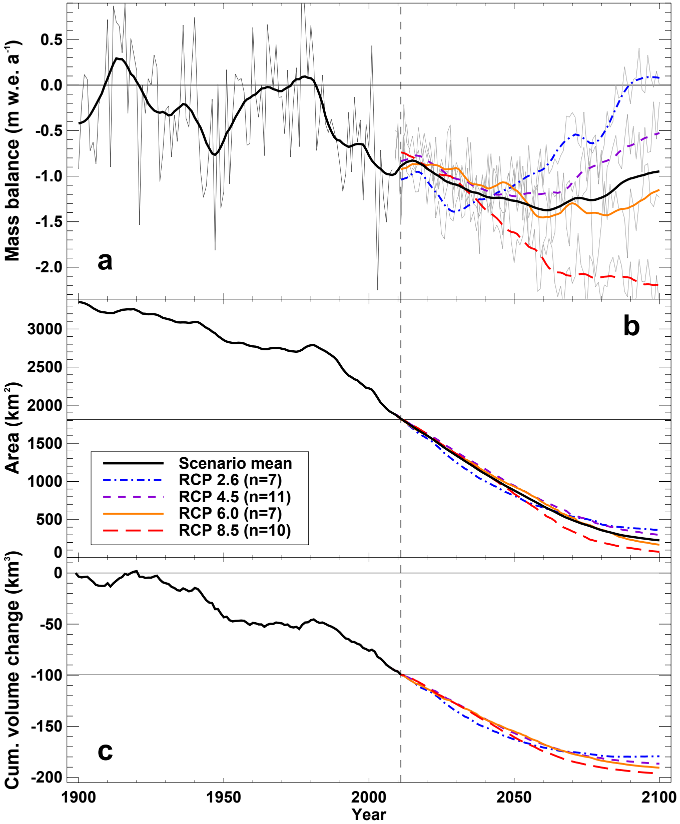

Fig. 5. Mass balance, area and ice volume change series extrapolated to all glaciers in the European Alps for 1900–2100. **(a)** Area-weighted average of mean specific annual mass balance (see Eq. 3). For 2011–2100 the ensemble mean mass balance of *n* GCMs according to the four RCPs is shown. Annual series (grey) are 11-yr low-pass filtered (bold). **(b)** Total glacierized area in the European Alps. **(c)** Cumulative ice volume changes assuming an ice density of 900 kg m^{-3}.

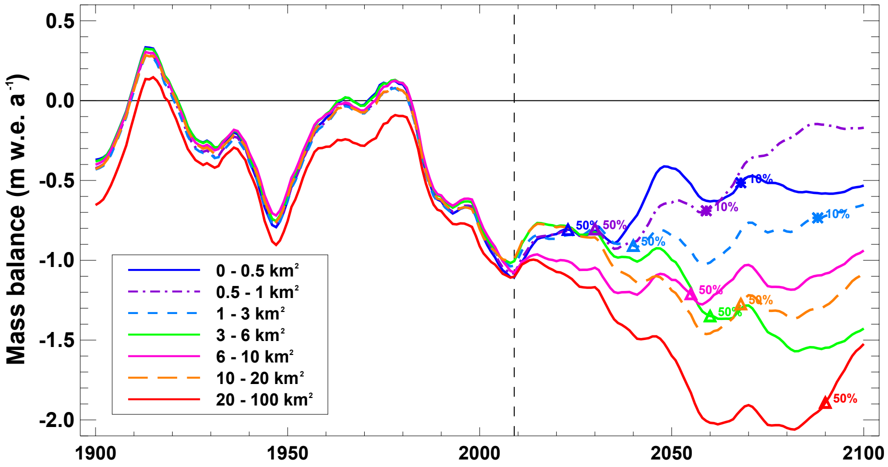

Fig. 6. Mass balance series (11-yr low pass filtered) of different glacier size classes (European Alps, 1900–2100). Attribution to size classes is relative to 2003. Future simulations refer to RCP6.0. Triangles (asterisks) indicate the date when area of the respective class has decreased to 50 % (10 %) of the 2003 extent.

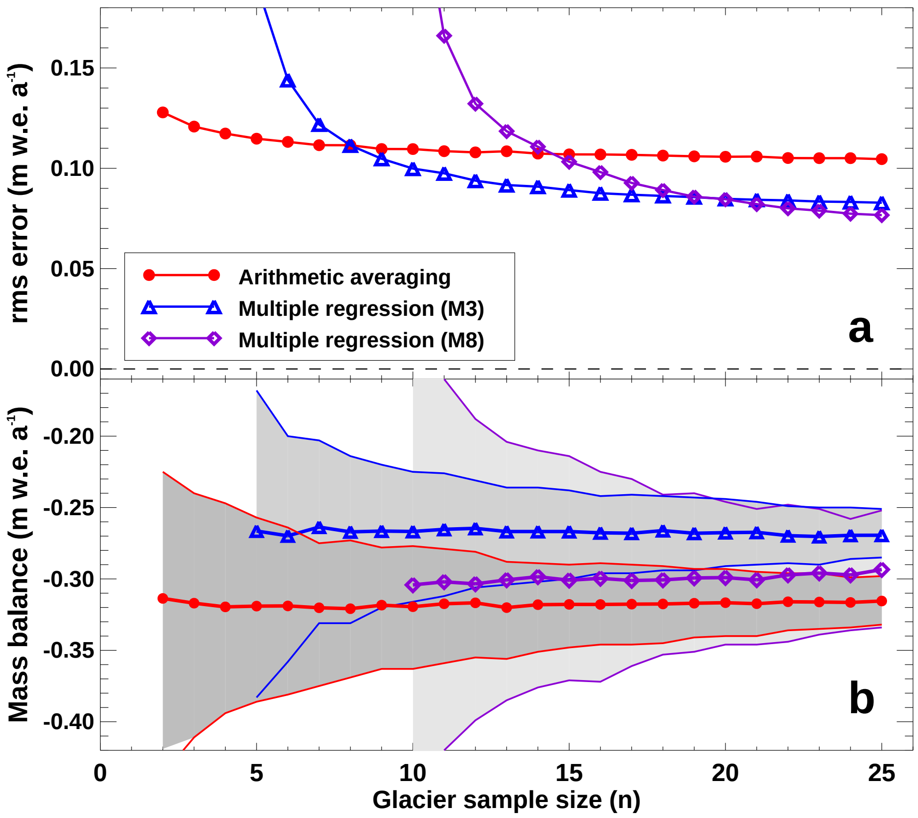

Fig. 7. Dependence of **(a)** the rms error and **(b)** the extrapolated mass balance for the European Alps (1908–2008) on glacier sample size. Arithmetic averaging and multiple regression (M3, M8) are used for mass balance regionalization. All results are based on n = 1000 randomly drawn glacier samples and the 80 % confidence interval for mountain range mass balance is given by the shaded area in **(b)**. Lines with symbols show the median result.