The Cryosphere, 6, 713–727, 2012
www.the-cryosphere.net/6/713/2012/
doi:10.5194/tc-6-713-2012

The Cryosphere

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

**M. Huss**[1,*]

[1]Department of Geosciences, University of Fribourg, 1700 Fribourg, Switzerland

[*]*Invited contribution by M. Huss, recipient of the EGU Young Scientist Outstanding Poster Paper (YSOPP) Award 2010.*

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

Received: 7 February 2012 – Published in The Cryosphere Discuss.: 15 March 2012
Revised: 4 June 2012 – Accepted: 12 June 2012 – Published: 6 July 2012

**Abstract.** This study addresses the extrapolation of in-situ 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 $-0.31 \pm 0.04\,\mathrm{m\,w.e.\,a^{-1}}$ in 1900–2011, and $-1\,\mathrm{m\,w.e.\,a^{-1}}$ over the last decade. Total ice volume change since 1900 is $-96 \pm 13\,\mathrm{km^3}$; 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 of 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 (WGMS, 2008; Cogley, 2009; Gardner et al., 2011). Negative glacier mass balances are an important component of 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 by 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 of larger areas. This fact needs to be accounted for in assessments of regional glacier mass change.

Temporal mass balance variations of individual series tend to be well correlated 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. Haeberli and Hoelzle (1995) find a mean mass balance of glaciers in the European Alps between 1850 and the mid-1970s of −0.2 to −0.3 m water equivalent (w.e.) $a^{-1}$ based on glacier inventory data. Zemp et al. (2006) present glacier area and volume change estimates in 1850–2100 using modelled equilibrium line altitudes (ELAs). Based on a regression model and homogenized climate data Schöner and Böhm (2007) derive mass balance time series since the Little Ice Age for glaciers in the European Alps. A promising alternative to the extrapolation of single-glacier mass balance measurements is numerical modelling of large samples of glaciers. 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 large difference 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 uncertainty in 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 hundred 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 by the Intergovernmental Panel on Climate Change (IPCC). This paper also investigates and intercompares methodologies for the extrapolation of mass balance series 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.

## 2 Data

### 2.1 Mass balance data

Two types of glacier mass balance information 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, information 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 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 sub-decadal to semi-centennial time periods are available from a set of 3 to 10 high-accuracy 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 more than 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 by interpolation. Thus, conventional mass balance, that is referred 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 area of the glaciers in the data set corresponds to 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 area 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

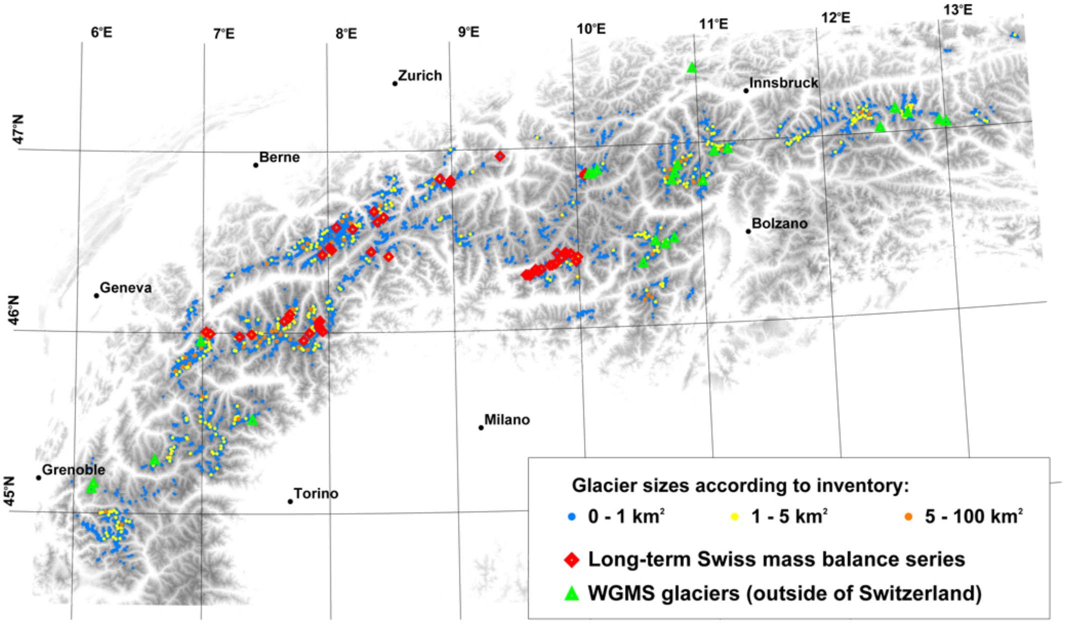

**Fig. 1.** Overview map of glacier coverage and glacier mass balance data in the European Alps. All inventoried glaciers according to Paul et al. (2011) are shown; the colour-coding indicates glacier size. Swiss glaciers with long-term mass balance series (Huss et al., 2010a,b) and additional mass balance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

changes based on two highly accurate light detection and ranging (LiDAR) DEMs for the Oetztal Alps, Austria, 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.). By comparison of photogrammetric and satellite-based DEMs, Berthier (2005) determined a mean thickness change of −12.1 m in 1979–2003 for glaciers in the Mont Blanc area, France.

### 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 wavelength 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 using them as a mask for 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) 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 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 averages within the perimeter of the European Alps (6–14° E, 45–48° N) were

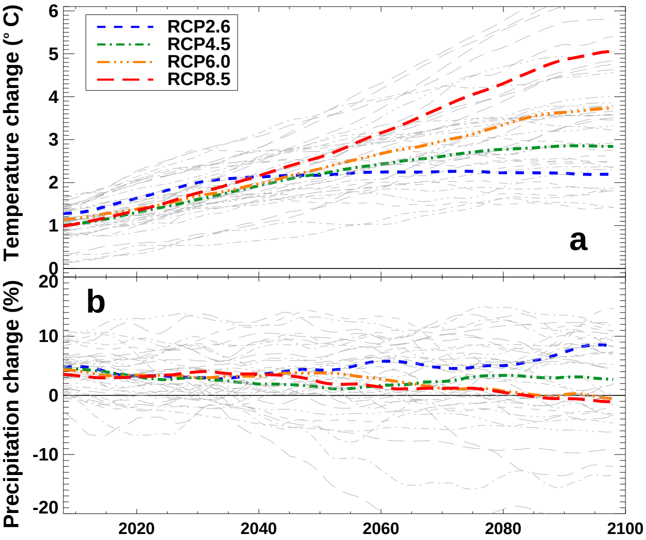

**Fig. 2.** Projected changes in **(a)** annual mean air temperature, and **(b)** annual precipitation sums relative to the period 1961–1990 for 35 GCMs (thin lines). Bold lines and colours indicate the average of GCM ensembles forced with the same RCP. All series are 20-yr low-pass filtered.

extracted for each GCM over 1961–2100. No additional variables, such as the radiation budget or cloudiness were considered. 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, 35 meteorological time series at daily resolution were established for 2011–2100. The combination of RCPs and individual GCMs yielded a total of 35 such series. 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 by 2100, and annual precipitation totals remain almost constant (Fig. 2). The models indicate a general trend to drier conditions and warming greater than the annual average in summer.

## 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 (area, slope, median elevation etc.). Multiple regression is performed using three variables (henceforth termed M3), and six variables (M6). 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 southeastern 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 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 for the study of specific mass balance variability are defined by the drainage basins of the large streams Rhone, Rhine, Danube and Po separating the European Alps into a west, north, east and south section. The main water divides often correspond to borders of specific climatic patterns (Auer et al., 2007). 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 $B_i^{\mathrm{Alps}}$ 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 four inventories (1850, 1973, 1998/1999 and 2003, see Maisch et al., 2000; Müller et al., 1976; Paul et al., 2004, 2011). Area changes for individual glaciers in between these dates are interpolated to

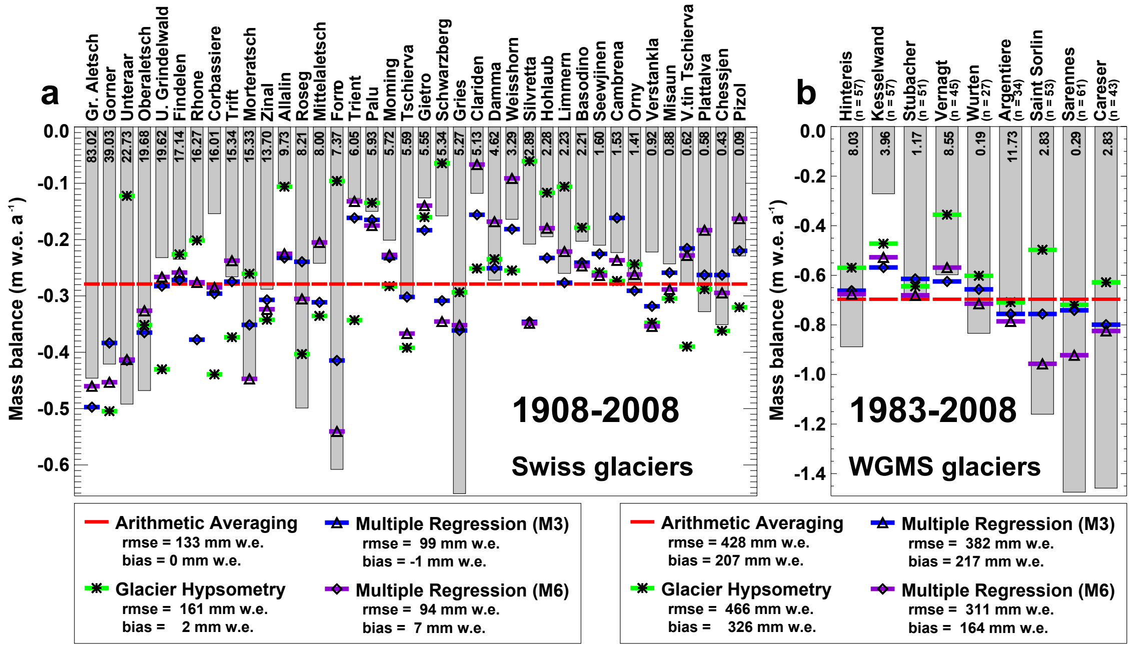

**Fig. 3.** Comparison of different methods for extrapolating glacier surface mass balance. **(a)** 100-yr mean mass balance (1908–2008) of 38 Swiss glaciers (Huss et al., 2010a,b) is shown with bars. Glacier area (by 2003) in km$^2$ is stated inside the bars. Mass balance extrapolated to these glaciers 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.

annual values proportional to mass balance variations:

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

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. Interpolating area changes using mass balance variations is a first order approximation; glacier area and length changes are a filtered and delayed response to the surface mass balance forcing.

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 percentage, annual area changes relative to 2003 obtained for Swiss glaciers were extrapolated to all other glaciers. Glaciers not covered by repeated inventories were grouped into 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). For glaciers $> 0.5\,\mathrm{km}^2$ 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 of and the uncertainties in the different extrapolation techniques, all three methods were validated against different data sources: (i) comparison of inferred mass balances to those of 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 reproduced. Results are shown in Fig. 3a. (ii) Validation against nine 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 $\overline{B^{\mathrm{ex}}} - \overline{B^{\mathrm{obs}}}$ between observed $B^{\mathrm{obs}}$ and extrapolated mass balance $B^{\mathrm{ex}}$, and the bias is evaluated. (iv) Validation against regional scale glacier elevation change assessments based on the geodetic method (Berthier, 2005; Paul and Haeberli, 2008; Abermann et al., 2009; Abermann et al., 2011a) is performed by comparing mean extrapolated mass balance for the Mont Blanc area (1979–2003), 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 mean density of $850\,\mathrm{kg\,m^{-3}}$ (see e.g. Huss et al., 2009;

**Table 1.** Validation of annual mass balance extrapolated using (1) arithmetic averaging, (2) glacier hypsometry, and (3) multiple regression with three (M3) or six variables (M6) against independent WGMS data and geodetic regional mass balances. The mean bias ($\overline{B^{\text{ex}}} - \overline{B^{\text{obs}}}$) 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 ($\overline{B^{\text{ex}}} - \overline{B^{\text{geod}}}$) are given in mm w.e. $a^{-1}$ for 1979–2003 (Berthier, 2005, Mont Blanc area, B2005), 1985–1999 (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 | B2005 | PH2008 | A2009 | A2011 |
|---|---|---|---|---|---|---|
| 1 | 97 | 508 | −79 | 89 | 2 | 0 |
| 2 | 158 | 539 | −373 | 80 | 71 | 20 |
| 3 (M3) | 93 | 505 | −80 | 115 | 31 | 30 |
| 3 (M6) | 57 | 495 | −94 | 144 | 26 | 2 |

Zemp et al., 2010) was chosen to convert volume change 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, 2005; Dyurgerov and Meier, 2005; Kaser et al., 2006, partly including area-weighting schemes). 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 in a first step. Five glaciers with debris-covered tongues were excluded as their locally reduced ablation at low elevation would induce non-representative average balance in these altitude bands. The averaging implies 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. However, the strong regional differences in long-term ELA given by the mass balance data set (between 2600 and 3240 m a.s.l. within the glacier sample) lead to balances in the same elevation band differing by up to 3 m w.e. $a^{-1}$ – an effect which must be accounted for. Thus, the mean mass balance-elevation distribution is shifted so that the ELA in the observed mass balance profile corresponds to the mean ELA of each glacier. This procedure allows the correction of ELA differences and mimics the extrapolation of observed mass balance gradients to the hypsometry of individual glaciers. Estimating long-term ELAs based on topographical information only is, however, uncertain and represents a major drawback of this method.

Mass balance variability is insufficiently captured using mass balance extrapolation based on glacier hypsometry. The rms error and the bias are larger than those for 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. This is counteracted by a faster loss in accumulation area of small glaciers, and therefore a more important albedo feedback on glacier melt. Although these effects only explain part of the differences, there is a clear link of mass balance variability with geometrical indices (Huss et al., 2012).

Already Lliboutry (1974) has proposed the calculation of mass balance using multiple regression. Schöner and Böhm (2007) apply a multiple regression model that uses both meteorological input data and information about median and minimum glacier elevation for reconstructing long-term glacier mass balance series in the European Alps. So far, no study has however addressed the differences in long-term mean mass balance among the glaciers using multiple regression with geometrical indices only. This is certainly related to the extensive statistical foundation 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 linear regression relies on the following equation:

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

where $\overline{B_{100}}$ is 100-yr mean mass balance calculated using the indicator variables $[x_1,...,x_n]$, the factors $[a_1,...,a_n]$ and a constant $c$. A number of parameters potentially describing mass balance variability was tested, and only those importantly contributing to the explained variance of the multiple regression were used. Multiple regression of mass balance is performed with parameter combination M3 consisting of the most important variables, and M6 including all variables with a significant influence on mass balance. Additional parameters, such as the average slope of the glacier, the elevation range and other variables describing glacier hypsometry, only marginally increase the correlation. Table 2 provides an overview of the variables finally used in the multiple regression. Indicator variables significantly correlated among each other are easting and northing, as well as median glacier elevation and northing. The limited statistical basis does not justify the fitting of non-linear models to the data.

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, and geographic location, considered for M6 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 glaciers exhibit 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 (Table 2).

In comparison to arithmetic averaging and glacier hypsometry, M3 and M6 yield better results in explaining mass balance variability among the glaciers, and show better agreement 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 to the mountain-range scale from an imperfectly representative sample of surveyed glaciers.

**Table 2.** The two parameter sets (M3, M6) 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 M6. The relative contribution $R_{\text{var}}$ (in %) of each variable to the total 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 | $R_{\text{var}}$ | M6 | $R_{\text{var}}$ | Parameter $x_n$ |
|---|---|---|---|---|
| – | 20.6 | – | 28.6 | Area (km$^2$) |
| + | 46.5 | + | 22.8 | Median gl. elevation (m a.s.l.) |
| + | 32.9 | + | 19.0 | Slope, lowermost 10 % (°) |
| | | – | 17.1 | Easting (m) |
| | | + | 8.0 | Northing (m) |
| | | + | 4.5 | Aspect (°), dev. from N |

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). Comparison of mass loss for the Mont Blanc area 1979–2003 indicates slightly too negative balances. According to Berthier (2005), the DEM of 1979, however, is subject to a significant bias at high elevation which is able to explain the misfit. For the Swiss Alps 1985–1999 the extrapolation results in too little mass loss (Table 1). Direct validation of SRTM-based elevation changes against volume changes obtained from repeated 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 in part to the 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) is reduced to almost zero by taking into account the systematic error indicated by photogrammetrical DEMs.

Mass balance figures at the scale of the European Alps presented henceforth rely on multiple regression (M6). 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 each glacier in the European Alps is crucial for modelling its future mass balance and area. These variables are inferred by applying an approach to invert distributed ice thickness from glacier surface elevation 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. The method for computing 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 glacier taking into account valley shape and basal shear stress variations (Huss and Farinotti, 2012). A total ice volume of 114 $\mathrm{km}^3$, 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 $\mathrm{km}^3$ based on the same data, and the approach presented by Haeberli and Hoelzle (1995), yielding 100 $\mathrm{km}^3$ 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 $\mathrm{km}^3$), and slightly smaller than the ice volume estimate by Farinotti et al. (2009) upscaled to the European Alps (about 120 $\mathrm{km}^3$). The latter is consistent with in-situ thickness observations on about two dozen 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). The model does neither include changes in supra-glacial debris coverage, nor positive feedbacks due to surface albedo decrease and proglacial lake formation. 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 four 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 Swiss glaciers. The extrapolation scheme employed is based on the results of multiple regression M6 but is extended for future conditions by considering glacier-size specific changes in mass balance and area. The investigated glaciers are divided into seven size classes which are assumed to be representative 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. Glacier-specific anomalies in $B_{100,g}$ obtained by M6 are superimposed on the mean size-class mass balance in order to calculate future mass balance of individual glaciers. 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.

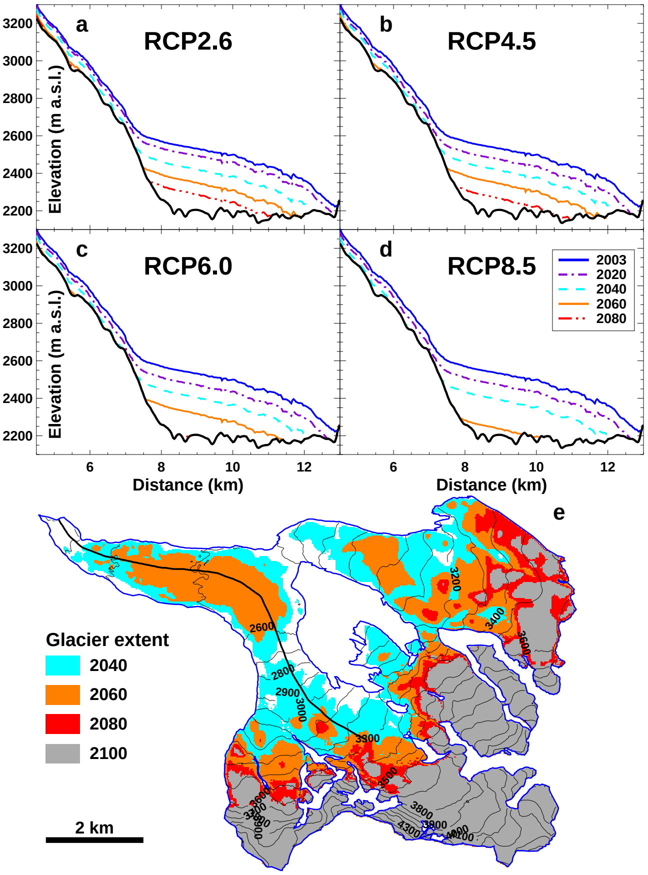

**Fig. 4.** Example of simulated future geometry changes of Gornergletscher, southwestern Switzerland, the second largest glacier in the European Alps. **(a–d)** Modelled glacier surface elevation in longitudinal profiles (solid line in **e**) of the glacier tongue. Glacier change is simulated using the Beijing Climate Center (bcc-csm1-1) GCM driven by four 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.

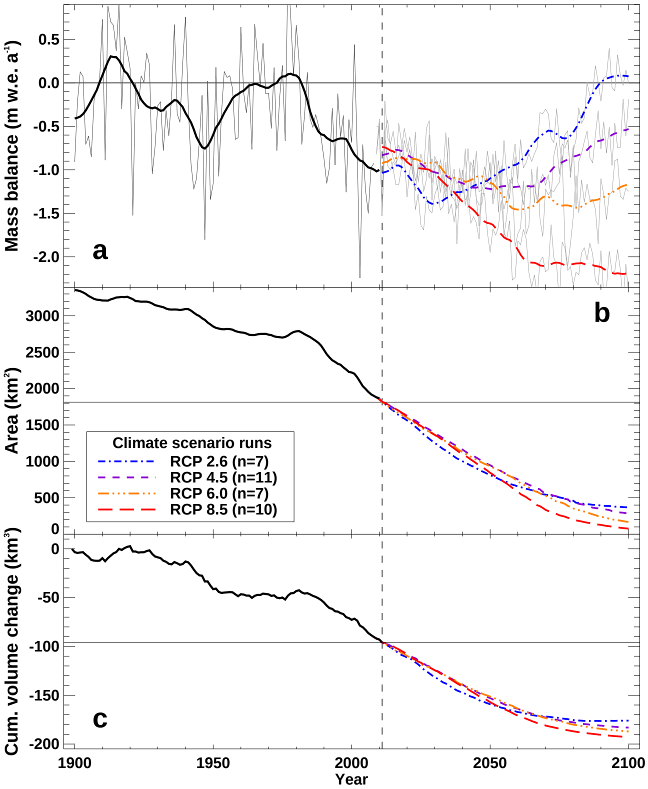

**Fig. 5.** Mass balance, area and ice volume change series extrapolated to all glaciers in the European Alps for 1900–2100. The dashed line indicates the onset of future modelling results (2011). **(a)** Area-weighted average of mean specific annual mass balance (see Eq. 3). For 2011–2100 the ensemble 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$^{-3}$.

**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 four 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 | | −0.17 | 3272.6 |
| 1910–1920 | | +0.34 | 3241.3 |
| 1920–1930 | | −0.32 | 3182.9 |
| 1930–1940 | | −0.12 | 3095.1 |
| 1940–1950 | | −0.86 | 2976.8 |
| 1950–1960 | | −0.17 | 2808.4 |
| 1960–1970 | | −0.00 | 2748.0 |
| 1970–1980 | | +0.11 | 2731.5 |
| 1980–1990 | | −0.40 | 2686.0 |
| 1990–2000 | | −0.68 | 2330.2 |
| 2000–2010 | | −0.99 | 2034.1 |
| 2020–2040 | RCP2.6 | −1.31 | 1251.8 |
| 2040–2060 | RCP2.6 | −1.08 | 809.5 |
| 2060–2080 | RCP2.6 | −0.67 | 547.6 |
| 2080–2100 | RCP2.6 | −0.06 | 395.5 |
| 2020–2040 | RCP4.5 | −1.03 | 1380.4 |
| 2040–2060 | RCP4.5 | −1.19 | 937.5 |
| 2060–2080 | RCP4.5 | −1.04 | 576.4 |
| 2080–2100 | RCP4.5 | −0.67 | 349.0 |
| 2020–2040 | RCP6.0 | −1.00 | 1350.2 |
| 2040–2060 | RCP6.0 | −1.21 | 922.5 |
| 2060–2080 | RCP6.0 | −1.42 | 521.7 |
| 2080–2100 | RCP6.0 | −1.28 | 244.2 |
| 2020–2040 | RCP8.5 | −1.09 | 1348.4 |
| 2040–2060 | RCP8.5 | −1.66 | 832.5 |
| 2060–2080 | RCP8.5 | −2.07 | 351.0 |
| 2080–2100 | RCP8.5 | −2.14 | 127.0 |

## 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 m w.e. a$^{-1}$ (Table 3). The mean mass balance in the European Alps over the period 1900–2011 is −0.31 m w.e. a$^{-1}$.

Alpine glacier area has decreased from about 3350 km$^2$ in 1900 to less than 1900 km$^2$ at present 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 (−2.24 m w.e., −5.1 km$^3$ volume change) the annual ice volume loss in the European Alps was greatest in 1947 (−5.9 km$^3$). The most positive mass balance year, 1977, resulted in a glacier volume change of +3.9 km$^3$. Since 1900, glaciers in the European Alps have experienced a cumulative ice volume change of −96 km$^3$ (Fig. 5c), which is equivalent to 0.24 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 are subject to 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 comparatively 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 $> 10$ km$^2$ are located in Switzerland.

Future glacier mass balance at the scale of the European Alps is expected to show a negative trend over the next

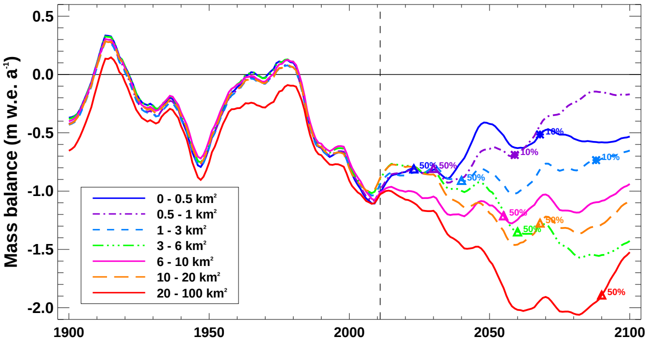

**Fig. 6.** Mass balance series (11-yr low pass filtered) of different glacier size classes (European Alps, 1900–2100). Attribution to size classes is relative to 2003. Future simulations refer to RCP6.0. Triangles (asterisks) indicate the date when area of the respective class has decreased to 50 %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

**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 ($\Delta A$, $\Delta V$) refer to the period 1900–2011. $A_{2100}$ is the four RCP-average of modelled glacier area by 2100.

| | $\overline{B}$ | $A_{2003}$ | $V_{2003}$ | $\Delta A$ | $\Delta V$ | $A_{2100}$ |
|---|---|---|---|---|---|---|
| CH | −0.28 | 1021.1 | 66.5 | −622.9 | −42.1 | 147.4 |
| IT | −0.27 | 388.5 | 17.6 | −339.7 | −16.4 | 32.0 |
| AU | −0.33 | 375.7 | 17.1 | −315.9 | −20.0 | 29.1 |
| FR | −0.40 | 274.9 | 12.6 | −208.0 | −17.5 | 15.2 |

decades for all scenarios (Fig. 5a). Until 2020 modelled mass balance is even slightly less negative compared to the observations of the early 21st century. This is explained by the GCM scenario runs that have not succeeded to reproduce the air temperatures of the very warm last decade and are lagging behind. The model results indicate that mass balances are around $-1.29$ 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 will 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. For large glaciers however also a positive back coupling effect due to surface lowering may become important. Modelled mass balances according to the four RCPs diverge after 2050. The remaining glaciers tend towards a new equilibrium at significantly reduced size for RCP2.6 and RCP4.5. The emission changes of RCP8.5 force a continuous acceleration of glacier mass loss leading to average mass balances of less than $-2$ 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 also that even 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 might disappear.

Mass balance shows considerable differences among the glacier size classes, and strongly diverge in the future (Fig. 6). Whereas mass balances 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 differences are explained by the glaciers' dynamic response and their increasing disequilibrium as we move on into the 21st century. 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 comparatively large due to their longer response time. Melting of valley glaciers, some of them are currently still several hundred meters thick (see e.g. Fig. 4), requires many decades and leads to progressively more negative balances in response to rising air temperatures.

Long-term Alpine mass balances were compared to global-scale glacier change assessments in order to judge their validity for the European Alps. For the period 1961–2000, Dyurgerov and Meier (2005) calculate a mountain-range mass balance for the Alps of $-0.11$ m w.e. a$^{-1}$ from the measurement series which is significantly less negative than the number obtained in the present study ($-0.25$ m w.e. a$^{-1}$). Jacob et al. (2012) find a mass loss for the European Alps corresponding to $-1.0 \pm 1.3$ m w.e. a$^{-1}$ for 2003–2010 based on the Gravity Recovery and Climate Experiment (GRACE). Although this number agrees relatively well with the extrapolated mountain-range balance for the same period ($-1.13$ m w.e. a$^{-1}$), the 95 % confidence interval of the GRACE-estimate is too large for allowing any conclusive and independent statements about the rate of European glacier mass loss. Future glacier volume projections were compared to the global modelling study by Radić and Hock (2011). Their ice volume loss for the European Alps by 2100 (median of 10 GCMs) is −76 % which is less than the −93 % (both relative to the year 2000) found in this study (Fig. 5). This is probably related to the larger area and volume that Radić and Hock (2011) used for initializing their model.

## 5 Uncertainty assessment

Estimating the uncertainty in mountain-range scale mass balance and volume change involves four layers: (1) the uncertainty in total glacier area of the European Alps, (2) the

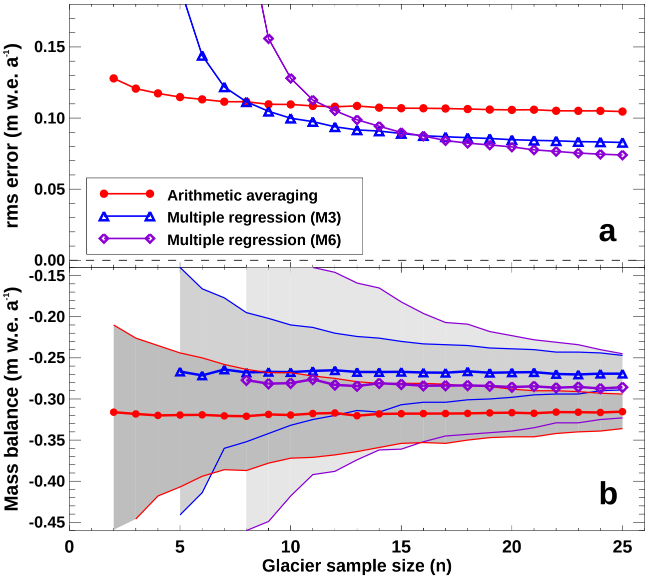

**Fig. 7.** Dependence of **(a)** the rms error and **(b)** the extrapolated mass balance for the European Alps (1908–2008) on glacier sample size. Arithmetic averaging and multiple regression (M3, M6) are used for mass balance regionalization. All results are based on $n = 1000$ randomly drawn glacier samples and the 90 % confidence interval for mountain-range mass balance is given by the shaded area in **(b)**. Lines with symbols show the median result.

uncertainty in observed mass balance data, (3) the uncertainties induced by the extrapolation scheme, and (4) 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 evolution of total glacier area in the European Alps throughout the 20th century was estimated by upscaling observed area changes between repeated Swiss glacier inventories to the entire mountain range and by interpolating them to the annual scale using mass balance variations. European glacier area inferred in this study (see Table 3) agrees well with previous estimates for 1973 (2900 km$^2$) and 1998/1999 (2270 km$^2$, Zemp et al., 2008). For the end of the Little Ice Age, Zemp et al. (2008) report a total area of 4470 km$^2$. Our area estimate for 1900 (3350 km$^2$) thus indicates that a considerable fraction of European glacier area and ice volume was lost already in the late 19th century which is supported by Lüthi et al. (2010).

The uncertainty in observed mass balance can be divided into an error term leading to too high/low long-term mean balances for the individual glacier, and a second term affecting year-to-year variability but not the long-term mean. 100-yr mass balances are mainly constrained by observed ice volume changes (see Huss et al., 2008a); their uncertainty is thus determined by the accuracy of the repeated DEMs. Long-term mass balances of individual glaciers $g$ are subject to an uncertainty of $\sigma_g = \pm 0.07$ m w.e. a$^{-1}$ (Huss et al., 2010a). This number was estimated by analyzing uncertainties originating from DEM differencing, and also includes the uncertainty due to the density assumption for converting volume change to mass change. As $\sigma_g$ is assumed to be independently distributed among the $n = 38$ glaciers used for fitting the extrapolation relations, the error due to mass balance data uncertainty is reduced to $\sigma_{\text{obs}}=\sigma_g/\sqrt{n} = \pm 0.011$ m w.e. a$^{-1}$ according to the laws of error propagation.

The uncertainty in mass balance due to the use of multiple regression (M6) 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. M6 has an average bias of 0.06 m w.e. a$^{-1}$ relative to annual mass balances measured by the glaciological method (Table 1). This lies within the estimated uncertainty of $\pm 0.2$ m w.e. a$^{-1}$ in these (Dyurgerov, 2002) and could also be explained by a non-representative sample of monitored glaciers. Validation of M6 using geodetic mass changes (Table 1) shows a rather good agreement for different periods and regions with an error of about $\pm 0.02$ m w.e. a$^{-1}$. Note that the bias in the geodetic mass changes of the studies by Berthier (2005) and Paul and Haeberli (2008) can widely be corrected as indicated by comparison to photogrammetrical elevation changes. The 1900–2011 mass balance of the European Alps obtained by arithmetic averaging ($-0.33$ m w.e. a$^{-1}$), multiple regression M3 ($-0.29$ m w.e. a$^{-1}$) and M6 ($-0.31$ m w.e. a$^{-1}$) is similar indicating that the mass balance extrapolation based on the available data basis is relatively robust. Merging evidence from all these sources, an overall extrapolation uncertainty of $\sigma_{\text{ex}} = \pm 0.04$ m w.e. a$^{-1}$ is estimated as an upper bound.

Thus, the total uncertainty in long-term mass balance extrapolated to the European Alps using multiple regression M6 becomes

$$\sigma_{\text{tot}} = \sqrt{\sigma_{\text{obs}}^2 + \sigma_{\text{ex}}^2}, \tag{6}$$

with $\sigma_{\text{tot}} = \pm 0.041$ 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 meteorological particularities of individual glaciers 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 balances or time series of individual glaciers.

The size of the sample of surveyed glaciers is critical for determining the optimal method for mass balance data extrapolation. Only rarely is the mass balance of more than a handful of glaciers measured within a mountain range. This imposes 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 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, are evaluated for arithmetic averaging and multiple regression (M3, M6). Extrapolation based on glacier hypsometry (Method 2) was not used in this experiment due to poorer 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 (M6), if fewer than 8 (13) 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 16 glaciers are available for fitting, the multiple regression relation, M6 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 90 % confidence interval ranges from −0.23 to −0.44 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 M6 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.

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. This is in line with the monitoring strategy proposed by Haeberli et al. (2000). For mountain ranges with fewer mass balance series, a combination with new remote sensing techniques providing a regional coverage might be a promising alternative.

Mass balance series at the scale of the European Alps allow assessing the representativeness of existing long-term monitoring programs, i.e. how well they agree with the mean balance of all Alpine glaciers (see Eq. 3). In the Alps, nine series (direct 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 (although data for Sonnblick are somewhat uncertain as balance is indirectly determined from accumulation area ratio since one decade). 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 0.15 m w.e. $a^{-1}$ more negative than the mountain-range average. When calculating Alpine mass balance by using the average of a moving sample including all available WGMS time series (between 8 and 28 since 1960) decadal means are between 0.07 and 0.13 m w.e. $a^{-1}$ more negative compared to the present study. This analysis indicates that European glacier mass loss might have been overestimated so far due to a non-representative sample of long-term monitoring series, and 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 quantify. First of all, GCMs with a spatial resolution of several 100 km are unable to 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 four RCPs no comprehensive ensembles of regional climate models are available for the Alpine region so far. 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. Additional uncertainty arises from the down-scaling of GCM data to the single-glacier scale and the potential changes in future climate variability.

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 ice melt and glacier geometry change. The considerable uncertainty in remaining ice volume also critically affects the timing of ultimate glacier disappearance in the European Alps. 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 and processes not included in the applied model approach, 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 (see 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 a small sample of series 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 (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 with an error of $\pm 0.04\,\mathrm{m\,w.e.\,a^{-1}}$. Uncertainties however increase to $\pm 0.1\,\mathrm{m\,w.e.\,a^{-1}}$ if fewer than 5 series are used for extrapolation.

Annual glacier mass balances 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 $-0.31 \pm 0.04\,\mathrm{m\,w.e.\,a^{-1}}$ for 1900–2011 corresponding to a total ice volume change of $-96 \pm 13\,\mathrm{km^3}$. Since 1900 about 45 % of the glacier surface, and roughly 50 % of the ice volume, in the European Alps has been 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, whereas others result in a run-away effect with mass balances lower than $-2\,\mathrm{m\,w.e.\,a^{-1}}$.

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. Field monitoring can be supported but not replaced by current remote sensing technology providing regional ice volume changes that are based on increasingly accurate DEMs acquired over sub-decadal time scales.

*Acknowledgements.* Mass balance data for all monitored glaciers in the European Alps were provided by the World Glacier Monitoring Service, Zurich. F. Paul is acknowledged for glacier inventory data of 2003. The World Climate Research Programme's Working Group on Coupled Modelling, which is responsible for CMIP, and the climate modelling groups are acknowledged for producing and making available their GCM output used for modelling future glacier mass balance. M. Hoelzle and M. Funk provided comments on an earlier version of the manuscript. Detailed reviews by M. Zemp and J. G. Cogley were helpful to finalize the paper.

Edited by: A. Kääb

## References

Abermann, J., Lambrecht, A., Fischer, A., and Kuhn, M.: Quantifying changes and trends in glacier area and volume in the Austrian Ötztal Alps (1969–1997–2006), The Cryosphere, 3, 205–215, doi:10.5194/tc-3-205-2009, 2009.

Abermann, J., Kuhn, M., and Fischer, A.: A reconstruction of annual mass balances of Austria's glaciers from 1969 to 1998, Ann. Glaciol., 52, 127–134, 2011a.

Abermann, J., Kuhn, M., and Fischer, A.: Climatic controls of glacier distribution and glacier changes in Austria, Ann. Glaciol., 52, 83–90, 2011b.

Arendt, A., Echelmeyer, K., Harrison, W., Lingle, C., Zirnheld, S., Valentine, V., Ritchie, B., and Druckenmiller, M.: Updated estimates of glacier volume changes in the western Chugach Mountains, Alaska, and a comparison of regional extrapolation methods, J. Geophys. Res., 111, F03019, doi:10.1029/2005JF000436, 2006.

Auer, I. and 31 others: HISTALP – historical instrumental climatological surface time series of the Greater Alpine Region, Int. J. Climatol., 27, 17–46, 2007.

Bahr, D. B., Meier, M. F., and Peckham, S. D.: The physical basis of glacier volume-area scaling, J. Geophys. Res., 102, 20355–20362, doi:10.1029/97JB01696, 1997.

Bauder, A., Funk, M., and Huss, M.: Ice volume changes of selected glaciers in the Swiss Alps since the end of the 19th century, Ann. Glaciol., 46, 145–149, 2007.

Berthier, E.: Dynamique et bilan de masse des glaciers de montagne (Alpes, Islande, Himalaya), Contribution de l'imagerie satellitaire, Ph.D. thesis, Université Paul Sabatier, available at: http://etienne.berthier.free.fr/download/Berthier_these_2005.pdf (last access: 5 July 2012), 2005 (in French).

Cogley, J. G.: Mass and energy balances of glaciers and ice sheets, in: Encyclopedia of Hydrological Sciences, edited by: Anderson, M. G., John Wiley, 2555–2573, 2005.

Cogley, J. G.: Geodetic and direct mass balance measurements: Comparison and joint analysis, Ann. Glaciol., 50, 96–100, 2009.

Dyurgerov, M. B.: Glacier mass balance and regime: data of measurements and analysis, Occasional Paper 55, Institute of Arctic and Alpine Research, University of Colorado, 89 pp., 2002.

Dyurgerov, M. B. and Meier, M. F.: Glaciers and the Changing Earth System: a 2004 Snapshot, Occasional Paper 58, Institute of Arctic and Alpine Research, University of Colorado, 117 pp., 2005.

Farinotti, D., Huss, M., Bauder, A., and Funk, M.: An estimate of the glacier ice volume in the the Swiss Alps, Global Planet. Change, 68, 225–231, 2009.

Fischer, A.: Comparison of direct and geodetic mass balances on a multi-annual time scale, The Cryosphere, 5, 107–124, doi:10.5194/tc-5-107-2011, 2011.

Gardelle, J., Berthier, E., and Arnaud, Y.: Impact of resolution and radar penetration on glacier elevation changes computed from DEM differencing, J. Glaciol., 58, 419–422, 2012.

Gardner, A. S., Moholdt, G., Wouters, B., Wolken, G. J., Burgess, D. O., Sharp, M. J., Cogley, J. G., Braun, C., and Labine, C.: Sharply increased mass loss from glaciers and ice caps in the Canadian Arctic Archipelago, Nature, 473, 357–360, doi:10.1038/nature10089, 2011.

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

Haeberli, W., Cihlar, J., and Barry, R. G.: Glacier monitoring within the Global Climate Observing System, Ann. Glaciol., 31, 241–246, 2000.

Hock, R.: A distributed temperature-index ice- and snowmelt model including potential direct solar radiation, J. Glaciol., 45, 101–111, 1999.

Hoelzle, M., Darms, G., Lüthi, M. P., and Suter, S.: Evidence of accelerated englacial warming in the Monte Rosa area, Switzerland/Italy, The Cryosphere, 5, 231–243, doi:10.5194/tc-5-231-2011, 2011.

Huss, M. and Farinotti, D.: A new approach for estimating ice thickness distribution of 90'000 mountain glaciers around the globe, Geophys. Res. Abstr., 14, EGU2012-4697, EGU General Assembly 2012, Vienna, Austria, 2012.

Huss, M., Bauder, A., Funk, M., and Hock, R.: Determination of the seasonal mass balance of four Alpine glaciers since 1865, J. Geophys. Res., 113, F01015, doi:10.1029/2007JF000803, 2008a.

Huss, M., Farinotti, D., Bauder, A., and Funk, M.: Modelling runoff from highly glacierized alpine drainage basins in a changing climate, Hydrol. Process., 22, 3888–3902, 2008b.

Huss, M., Bauder, A., and Funk, M.: Homogenization of long-term mass balance time series, Ann. Glaciol., 50, 198–206, 2009.

Huss, M., Hock, R., Bauder, A., and Funk, M.: 100-year mass changes in the Swiss Alps linked to the Atlantic Multidecadal Oscillation, Geophys. Res. Lett., 37, L10501, doi:10.1029/2010GL042616, 2010a.

Huss, M., Usselmann, S., Farinotti, D., and Bauder, A.: Glacier mass balance in the south-eastern Swiss Alps since 1900 and perspectives for the future, Erdkunde, 65, 119–140, 2010b.

Huss, M., Hock, R., Bauder, A., and Funk, M.: Conventional versus reference-surface mass balance, J. Glaciol., 58, 278–286, 2012.

Immerzeel, W. W., van Beek, L. P. H., and Bierkens, M. F. P.: Climate Change Will Affect the Asian Water Towers, Science, 328, 1382–1385, doi:10.1126/science.1183188, 2010.

Jacob, T., Wahr, J., Pfeffer, W. T., and Swenson, S.: Recent contributions of glaciers and ice caps to sea level rise, Nature, 482, 514–518, , 2012.

Jarvis, J., Reuter, H., Nelson, A., and Guevara, E.: Hole-filled SRTM for the globe Version 4, CGIAR-CSI SRTM 90 m Database, available at: http://srtm.csi.cgiar.org (last access: 5 July 2012), 2008.

Jóhannesson, T., Raymond, C., and Waddington, E.: Time-scale for adjustment of glaciers to changes in mass balance, J. Glaciol., 35, 355–369, 1989.

Jouvet, G., Huss, M., Funk, M., and Blatter, H.: Modelling the retreat of Grosser Aletschgletscher, Switzerland, in a changing climate, J. Glaciol., 57, 1033–1045, 2011.

Kaser, G., Cogley, J. G., Dyurgerov, M. B., Meier, M. F., and Ohmura, A.: Mass balance of glaciers and ice caps: Consensus estimates for 1961–2004, Geophys. Res. Lett., 33, L19501, doi:10.1029/2006GL027511, 2006.

Kuhn, M., Markel, G., Kaser, G., Nickus, U., Obleitner, F., and Schneider, H.: Fluctuations of climate and mass balances: different responses of two adjacent glaciers, Zeitschrift für Gletscherkunde und Glazialgeologie, 21, 409–416, 1985.

Lambrecht, A. and Kuhn, M.: Glacier changes in the Austrian Alps during the last three decades, derived from the new Austrian glacier inventory, Ann. Glaciol., 46, 177–184, 2007.

Letréguilly, A. and Reynaud, L.: Space and time distribution of glacier mass-balance in the northern hemisphere, Arctic Alpine Res., 22, 43–50, 1990.

Lliboutry, L.: Multivariate statistical analysis of glacier annual balances, J. Glaciol., 13, 371–392, 1974.

Lüthi, M. P., Bauder, A., and Funk, M.: Volume change reconstruction of Swiss glaciers from length change data, J. Geophys. Res., 115, F04022, doi:10.1029/2010JF0011695, 2010.

Machguth, H., Paul, F., Kotlarski, S., and Hoelzle, M.: Calculating distributed glacier mass balance for the Swiss Alps from regional climate model output: A methodical description and interpretation of the results, J. Geophys. Res., 114, D19106, doi:10.1029/2009JD011775, 2009.

Maisch, M., Wipf, A., Denneler, B., Battaglia, J., and Benz, C.: Die Gletscher der Schweizer Alpen, Zürich, 2nd Edn., 2000.

Meinshausen, M., Smith, S. J., Calvin, K., Daniel, J. S., Kainuma, M. L. T., Lamarque, J.-F., Matsumoto, K., Montzka, S. A., Raper, S. C. B., Riahi, K., Thomson, A., Velders, G. J. M., and van Vuuren, D. P.: The RCP greenhouse gas concentrations and their extensions from 1765 to 2300, Climatic Change, 109, 213–241, 2011.

Müller, F., Caflisch, T., and Müller, G.: Firn und Eis der Schweizer Alpen: Gletscherinventar, No. 57, Geographisches Institut der ETH Zürich, Zürich, 1976.

Oerlemans, J., Giessen, R. H., and van den Broeke, M. R.: Retreating alpine glaciers: increased melt rates due to accumulation of dust (Vadret da Morteratsch, Switzerland), J. Glaciol., 55, 729–736, 2009.

Paul, F. and Haeberli, W.: Spatial variability of glacier elevation changes in the Swiss Alps obtained from two digital elevation models, Geophys. Res. Lett., 35, L21502, doi:10.1029/2008GL034718, 2008.

Paul, F., Kääb, A., Maisch, M., Kellenberger, T., and Haeberli, W.: Rapid disintegration of Alpine glaciers observed with satellite data, Geophys. Res. Lett., 31, L21402, doi:10.1029/2004GL020816, 2004.

Paul, F., Kääb, A., and Haeberli, W.: Recent glacier changes in the Alps observed by satellite: Consequences for future monitoring strategies, Global Planet. Change, 56, 111–122, 2007.

Paul, F., Frey, H., and Bris, R. L.: A new glacier inventory for the European Alps from Landsat TM scenes of 2003: challenges and results, Ann. Glaciol., 52, 144–152, 2011.

Radić, V. and Hock, R.: Regionally differentiated contribution of mountain glaciers and ice caps to future sea-level rise, Nat. Geosci., 4, 91–94, doi:10.1038/ngeo1052, 2011.

Schmidli, J., Frei, C., and Vidale, P. L.: Downscaling from GCM precipitation: a benchmark for dynamical and statistical downscaling methods, Int. J. Climatol., 26, 679–689, doi:10.1002/joc.1287, 2006.

Schöner, W. and Böhm, R.: A statistical mass-balance model for reconstruction of LIA ice mass of glaciers in the European Alps, Ann. Glaciol., 46, 161–169, 2007.

Taylor, K. E., Stouffer, R. J., and Meehl, G. A.: A summary of the CMIP5 experiment design, available at: http://cmip-pcmdi.llnl.gov/cmip5/docs/Taylor_CMIP5_design.pdf (last access: 5 July 2012), 2011.

Thibert, E., Blanc, R., Vincent, C., and Eckert, N.: Glaciological and volumetric mass balance measurements error analysis over 51 years for the Sarennes glacier, French Alps, J. Glaciol., 54, 522–532, 2008.

van den Broeke, M., Bus, C., Ettema, J., and Smeets, P.: Temperature thresholds for degree-day modelling of Greenland ice sheet melt rates, Geophys. Res. Lett., 37, L18501, doi:10.1029/2010GL044123, 2010.

Vincent, C., Kappenberger, G., Valla, F., Bauder, A., Funk, M., and Meur, E. L.: Ice ablation as evidence of climate change in the Alps over the 20th century, J. Geophys. Res., 109, D10104, doi:10.1029/2003JD003857, 2004.

WGMS: Fluctuations of Glaciers, 2000–2005, Vol. IX, edited by: Haeberli, W., Zemp, M., Kääb, A., Paul, F. and Hoelzle, M., ICSU(FAGS)/IUGG(IACS)/UNEP/UNESCO/WMO, 2008.

WGMS: Glacier Mass Balance Bulletin No. 11 (2008–2009), edited by: Zemp, M., Nussbaumer, S. U., Gärtner-Roer, I., Hoelzle, M., Paul, F., and Haeberli, W., ICSU(WDS)/IUGG(IACS)/UNEP/UNESCO/WMO, 2011.

Zemp, M., Haeberli, W., Hoelzle, M., and Paul, F.: Alpine glaciers to disappear within decades?, Geophys. Res. Lett., 33, L13504, doi:10.1029/2006GL026319, 2006.

Zemp, M., Paul, F., Hoelzle, M., and Haeberli, W.: Glacier fluctuations in the European Alps 1850–2000: an overview and spatio-temporal analysis of available data, in: The darkening peaks: Glacial retreat in scientific and social context, edited by: Orlove, B., Wiegandt, E., and Luckman, B. H., University of California Press, 152–167, 2008.

Zemp, M., Hoelzle, M., and Haeberli, W.: Six decades of glacier mass-balance observations: a review of the worldwide monitoring network, Ann. Glaciol., 50, 101–111, 2009.

Zemp, M., Jansson, P., Holmlund, P., Gärtner-Roer, I., Koblet, T., Thee, P., and Haeberli, W.: Reanalysis of multi-temporal aerial images of Storglaciären, Sweden (1959–99) – Part 2: Comparison of glaciological and volumetric mass balances, The Cryosphere, 4, 345–357, doi:10.5194/tc-4-345-2010, 2010.