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Surface elevation and mass changes of all Swiss glaciers 1980–2010

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Surface elevation and mass changes of all Swiss glaciers

M. Fischer et al.

Abstract

Since the mid-1980s, glaciers in the European Alps have shown widespread and accelerating mass losses. This article presents glacier-specific changes in surface elevation, volume and mass balance for all glaciers in the Swiss Alps from 1980 to 2010. Together with glacier outlines from the 1973 inventory, the DHM25 Level 1 Digital Elevation Models (DEMs) for which the source data over glacierized areas was acquired from 1961 to 1991 are compared to the swissALTI^{3D} DEMs from 2008–2011 combined with the new Swiss Glacier Inventory SGI2010. Due to the significant differences in acquisition date of the source data used, resulting mass changes are temporally homogenized to directly compare individual glaciers or glacierized catchments. Along with an in-depth accuracy assessment, results are validated against volume changes from independent photogrammetrically derived DEMs of single glaciers. Observed volume changes are largest between 2700–2800 m a.s.l. and remarkable even above 3500 m a.s.l. The mean geodetic mass balance is -0.62 ± 0.03 m w.e. yr^{-1} for the entire Swiss Alps over the reference period 1980–2010. For the main hydrological catchments, it ranges from -0.52 to -1.07 m w.e. yr^{-1}. The overall volume loss calculated from the DEM differencing is -22.51 ± 0.97 km^3.

1 Introduction

Fluctuations of mountain glaciers are known as a sensitive indicator for climatic changes (e.g. IPCC, 2013). The currently observed atmospheric warming caused striking mass loss of mountain glaciers all over the world (e.g. Zemp et al., 2009; Radić and Hock, 2014), which significantly contributes to present sea-level rise (e.g. Marzeion et al., 2012; Gardner et al., 2013) and affects the runoff regimes of glacierized catchments in different regions around the globe (e.g. Kaser et al., 2010; Huss, 2011; Sorg et al., 2012).

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For glaciers of the entire European Alps, rapid mass loss and shrinkage is reported since the mid-1980s (e.g. Paul et al., 2011; Huss, 2012). Glacier area changes are documented by the comparison of consecutive inventories (e.g. Lambrecht and Kuhn, 2007; Diolaiuti et al., 2012). Mass balance data is available either from annual field measurements of individual glaciers using the direct glaciological method (e.g. WGMS, 2013), or from the comparison of the glacier surface topography of different years and a density assumption for converting volume to mass change (e.g. Abermann et al., 2009; Carturan et al., 2013). Together with the increasing number of digital elevation models (DEMs) available worldwide and the fact that also inaccessible areas and entire glacier systems can be measured, this so-called geodetic method has become a popular approach to derive surface elevation and mass changes for a large number of glaciers (e.g. Rignot et al., 2003; Larsen et al., 2007; Bolch et al., 2008; Berthier et al., 2010; Nuth et al., 2010; Gardelle et al., 2012a).

Paul and Haeberli (2008) analyzed the spatial variability of glacier elevation changes in the Swiss Alps between 1985 and 1999 by comparing the DHM25 Level 1 DEMs (25 m resolution) created from topographic maps by the Swiss Federal Office of Topography (swisstopo) with the medium-resolution (90 m) Shuttle Radar Topography Mission (SRTM) DEM. Several factors that might have an important influence on the accuracy of glacier elevation changes derived from DEM differencing have, however, not been conclusively assessed in their study: differences in the reference years of the surface elevation information used for individual regions, the problem of radar penetration into snow and ice (Dall et al., 2001; Gardelle et al., 2012b) and/or impacts of downscaling DEMs to higher resolution (Gardelle et al., 2012b; Carturan et al., 2013). Furthermore, applying the medium-resolution SRTM DEMs in high-mountain areas might cause problems (cf. Berthier et al., 2006). In number, these regions are generally dominated by very small glaciers, hereafter defined as being smaller than 0.5 km^2. Abermann et al. (2010) and Fischer et al. (2014) show that use of most accurate and high-resolution source data is of particular importance for change assessments of these smallest glacier size classes.

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Due to the recent compilation of more detailed source data, we are able to present an extended re-evaluation of glacier-specific changes in surface elevation, volume and geodetic mass balance for every single glacier in Switzerland. We compare the DHM25 Level 1 DEMs dating from 1961 to 1991 over glacierized areas with the swissALTI^{3D} DEMs from 2008–2011 and combine the former with the 1973 inventory (Müller et al., 1976) and the latter with the new Swiss Glacier Inventory SGI2010 (Fischer et al., 2014). For direct comparison between individual glaciers or glacierized catchments, we temporally homogenize resulting mass changes to a consistent period. This is necessary due to significant differences in acquisition date of the source data used. We discuss various sources of possible error accompanying studies of this type, perform an in-depth accuracy assessment of our results and validate them using independent volume changes from photogrammetrically derived DEMs. Furthermore, we comment on the controlling factors and the spatial variability of observed glacier mass changes.

2 Study region and datasets

2.1 Study region

The study area covers the entire Swiss Alps. In number, small, thin and rather steep ice patches and glacierets dominate (Haeberli and Hoelzle, 1995), but the majority of the ice volume is stored within only some few large valley glaciers (Farinotti et al., 2009). The total glacierized area mapped for 2010 is $944.3 \pm 24.1\,\text{km}^2$, corresponding to an area change of $-362.6\,\text{km}^2$ ($-27.7\,\%$, or $-0.75\,\%\,\text{yr}^{-1}$) since 1973 (Fischer et al., 2014). After a short period of mass gain between the late 1970s and the mid-1980s, the Swiss glaciers generally showed rapid mass loss until today (Huss et al., 2010a).

2.2 Digital elevation models and glacier outlines

The glacier surface topography at the time of the beginning of the observation period (hereafter referred to as t_1) is given by the DHM25 Level 1 DEMs from swisstopo, for which digitized contour lines and spot heights from the Swiss national topographic maps 1 : 25 000 were interpolated to a regular grid with 25 m grid spacing. The estimated vertical accuracy is reported to range between 3.7 and 8.2 m for rugged high-mountain topography depending on individual map sheets (Rickenbacher, 1999; swisstopo, 2000). For glacierized areas, the dating of these contour lines is not consistent with corresponding specifications given in the DHM25 Level 1 product information (cf. swisstopo, 2000). Therefore, we manually reconstructed the individual reference years of the surface topography at t_1 for every glacier by comparison of the DHM25 Level 1 contour lines with those from repeated updates of the 1 : 25 000 topographic maps of known reference years (http://s.geo.admin.ch/6f91341db). In addition to the obvious regional differences in t_1, there is a certain trend towards earlier t_1 for small glaciers, for which surface contour lines were less frequently updated (Fig. 1). Recent glacier surface topography, i.e. at the end of the observation period (hereafter referred to as t_2), is provided by the new 2 m resolution swissALTI^{3D} DEMs. For areas above 2000 m a.s.l., they were created by stereocorrelation of 2008–2011 SWISSIMAGE Level 2 aerial orthophotographs. For these areas, the vertical accuracy is ±1 to 3 m (swisstopo, 2013). Comparisons of the DHM25 Level 1 and the swissALTI^{3D} DEMs with available photogrammetrically derived DEMs of the same acquisition dates for t_1 and t_2 (Laboratory of Hydraulics, Hydrology and Glaciology (VAW), ETH Zurich, unpublished) show that for glacierized surface topography, the actual vertical accuracies of both the DHM25 Level 1 and the swissALTI^{3D} DEMs is likely much better in the glacier-wide mean (< ±1 m) than supposed by the values taken from literature.

The surface area of individual glaciers at t_1 is derived from the finalized digital version of the Swiss Glacier Inventory 1973 (SGI1973; Maisch et al., 2000; Paul, 2004), which was originally compiled by Müller et al. (1976) from stereophotogrammetry-based interpretation of aerial photographs acquired in early September 1973. The considerable time difference between the acquisition of the SGI1973 source data and individual DHM25 Level 1 DEMs used for t_1 (Fig. 1) is acceptable as only small area changes and an almost balanced mass budget of glaciers were reported for the European Alps between 1973 and the mid-1980s (Glaciological Reports, 1960-2013; Paul et al., 2004). For t_2, the glacier outlines originate from the latest Swiss Glacier Inventory SGI2010 derived by manual digitization from high-resolution (25 cm) aerial orthophotographs acquired between 2008–2011 (Fischer et al., 2014). Applying the SGI2010 and the swissALTI^{3D} DEMs as source data for t_2 is ideal because their acquisition date is mostly identical for individual glaciers.

2.3 Validation data

Time series of surface mass balance for glaciers of different type and size class covering the entire Swiss Alps over the last decades (Huss et al., 2010a, b) are used to validate the geodetic mass balances presented here. These series rely on ice volume changes derived from high-accuracy photogrammetrical DEMs for sub-decadal to multi-decadal time intervals (Bauder et al., 2007). By using a distributed mass balance modelling approach including comprehensive field data (winter accumulation, summer ablation and discharge measurements), annual mass balance series were calculated that agree with the observed geodetic mass changes.

3 Methods

3.1 Calculation of glacier volume change and average mass balance

Prior to the calculation of surface elevation changes, the swissALTI^{3D} DEMs were resampled to a grid cell size of 25 m (i.e. equal to the resolution of the DHM25 Level 1). Due to the identical coding scheme applied to both glacier inventories, elevation changes could be calculated for individual glacier entities as a next step by subtracting the DHM25 Level 1 DEMs from the swissALTI^{3D} DEMs (Fig. 2).

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The glacier-individual total volume change ΔV (m^3) for the respective survey period was calculated as follows:

$$\Delta V = \overline{\Delta z} \cdot A_{1973}, \quad (1)$$

where $\overline{\Delta z}$ is the average elevation change calculated from the difference between the swissALTI^{3D} and the DHM25 Level 1 DEMs within the perimeter covered by the glacier in 1973 (A_{1973}). Then, the area-averaged specific geodetic mass balance rate (m w.e. yr^{-1}) was calculated with:

$$\dot{B} = \frac{\Delta V \cdot f_{\Delta V}}{\overline{A} \cdot \Delta t}, \quad (2)$$

where $f_{\Delta V}$ is the density of volume change used to transform ΔV into a mass change, $\overline{A}$ the average area between 1973 and 2010 calculated as $(A_{1973} + A_{2010})/2$, and Δt the length of the observation period $(t_2 - t_1)$ in years. We hereafter refer to the area-averaged specific geodetic mass balcance rate as average mass balance. The conversion factor $f_{\Delta V}$ might vary from glacier to glacier, depending on the length of the observation period, the respective mass balance and the firn compaction history (Huss, 2013). Due to the fairly long observation periods, $f_{\Delta V}$ is set as a constant of 850 ± 60 kg m^{-3}, which is consistent with other studies (Sapiano et al., 1998; Fischer, 2011; Zemp et al., 2013).

The significant regional differences in the length of the observation periods (Fig. 1) imply that glacier-individual average mass balances $\dot{B}_g$ derived from the DEM differencing can not be directly compared to each other. In order to homogenize the glacier-individual observation periods to one comparable time interval we make use of the dataset by Huss (2012) providing annual mass balance variability extrapolated to the entire European Alps based on a combination of all available mass balance data covering our period of interest. The deviation of the glacier-individual average mass balance

$\dot{B}_g$ from the mountain-range mean (Huss, 2012) over the respective observation period $\overline{B_{t_2-t_1}}$ is used to temporally homogenize mass changes (Fig. 3). The annual mass balance $B_{i,g}$ for year i and any glacier g is thus calculated with:

$$B_{i,g} = B_{i,\mathrm{mr}} + \dot{B}_g - B_{t_2-t_1}, \quad (3)$$

where $B_{i,\mathrm{mr}}$ is the mean mountain-range mass balance for an individual year i from Huss (2012). Because 2010 is the reference year t_2 for most of the investigated glacier entities and the mean observation period is ≈ 30 yr (Fig. 1), the hydrological years 1980/81–2009/10 are defined as the reference observation period over the entire Swiss Alps over which resulting geodetic mass balance rates for individual glaciers are compared and analyzed.

3.2 Analysis of controls

Averaged over representative samples and observation periods, glacier area and elevation changes are usually in agreement with changes in air temperature and precipitation recorded over the investigated areas and time intervals (e.g. Abermann et al., 2009; VanLooy and Forster, 2011; Carturan et al., 2013). Within a mountain-range and despite similar climatic changes, the differences in long-term mass balance can however be significant between individual – and even adjacent – glaciers (e.g. Kuhn et al., 1985; Larsen et al., 2007; Huss et al., 2010a; Abermann et al., 2011). Different factors have been identified which can, however, only to a certain extent explain this variability. For instance, the glacier hypsometry, i.e. the distribution of glacier area and volume with altitude, plays an important role (Furbish and Andrews, 1984; Benn and Evans, 2010). Also, the characteristic glacier response time and dynamic adjustment to a certain climatic forcing varies with glacier size and affects the specific mass balance (Jóhannesson et al., 1989; Huss et al., 2012). Larger (and flatter) glaciers are expected to lag behind the current climatic forcing and to show more negative mass balances than smaller (and steeper) glaciers (Hoelzle et al., 2003). Very small glaciers

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situated in cirques, niches and below headwalls react faster to climatic changes (Kuhn, 1995), but their individual response to the latter is – in relative terms – even more variable than for larger glaciers (Carturan et al., 2012). Furthermore, local topographic and microclimatic factors are important for the behaviour and dynamics of mountain glaciers in general (e.g. Benn and Lehmkuhl, 2000; Oerlemans, 2010), and for very small glaciers in particular (e.g. DeBeer and Sharp, 2009; Hughes, 2009). These factors can be parameterized with geometrical indices which are related to the observed variability in long-term mass changes (Huss et al., 2012).

In order to identify the controlling factors and to better understand the spatial variability of the observed surface elevation and mass changes, a correlation analysis between the average mass balance over the reference period 1980–2010 and classes of mean area 1973–2010, median elevation, slope of the glacier terminus (mean slope over the lowermost 25 %), and dominant aspect, hereafter referred to as mean aspect, was performed. These four geometrical indices were shown to be able in explaining some of the variability in observed mass balances (e.g. Huss, 2012).

4 Accuracy assessment and validation

4.1 Uncertainty

The uncertainty in surface elevation, volume and mass changes presented in this study is mainly given by the uncertainty related to the two DEMs used. The latter, $\sigma_{\Delta z}$, is defined as:

$$\sigma_{\Delta z} = \pm\sqrt{\sigma^2_{\mathrm{DEM}_1} + \sigma^2_{\mathrm{DEM}_2}}. \tag{4}$$

The uncertainties in the DHM25 Level 1 DEMs, σ_{DEM_1}, and the swissALTI^{3D} DEMs, σ_{DEM_2}, are independent of each other and given by their vertical accuracies. Based on the values assigned by swisstopo (2000), the mean estimated vertical accuracies reported for each of the individual Swiss national topographic map 1 : 25 000 sheets are taken as σ_{DEM_1}. They are generally smaller than ±10 m in the central Alps and below ±5 m in the Prealps (swisstopo, 2000). For the swissALTI^{3D} DEMs above 2000 m a.s.l., the vertical accuracy is between ±1 to 3 m (swisstopo, 2013). Therefore, the average of ±2 m is assumed as a constant value for σ_{DEM_2}.

The glacier-individual uncertainty in volume change $\sigma_{\Delta V,g}$ is obtained by multiplying $\sigma_{\Delta z,g}$ with the initial glacier area A_{1973}. The uncertainty in the total volume change over the entire Swiss Alps is then derived by:

$$\sigma_{\Delta V,\mathrm{tot}} = \pm\sqrt{\sum_{g=1}^{n} \sigma^2_{\Delta V,g}} \tag{5}$$

and results in ±0.97 km^3. The uncertainty in the geodetic mass balance of individual glacier entities $\sigma_{\mathrm{geod},g}$ is calculated according to Huss et al. (2009) as:

$$\sigma_{\mathrm{geod},g} = \pm\sqrt{\Delta z_g^2 \cdot \sigma^2_{f_{\Delta V}} + f^2_{\Delta V} \cdot \sigma^2_{f_{\Delta z,g}}}, \tag{6}$$

with a mean density of the total volume change $f_{\Delta V} = 850\,\mathrm{kg\,m^{-3}}$ (cf. Sapiano et al., 1998; Huss, 2013) and a corresponding uncertainty $\sigma_{f_{\Delta V}} = \pm 60\,\mathrm{kg\,m^{-3}}$. The mean geodetic elevation change Δz is assumed to be uncorrelated to $f_{\Delta V}$. The resulting values for $\sigma_{\mathrm{geod},g}$ are then divided by the glacier-individual observation period (Δt) and range between ±0.07 and 0.42 m w.e. yr^{-1}. After the glacier-individual reconstruction of the t_1 values, we consider the accuracy of Δt as robust. Some uncertainty in t_2, and hence also in Δt, of maximum two years applies for only a few glaciers for which aerial orthophotographs used as source data for the creation of both the glacier outlines and DEMs at t_2 were acquired during two or more different survey years (glaciers overlapping two or more areas of t_2 in Fig. 1).

Finally, the uncertainty in the mean and area-weighted average mass balance of 1420 still existing glaciers in the entire Swiss Alps over the reference period 1980–2010 $\sigma_{\overline{B_{\mathrm{ref}}}}$ is derived with

$$\sigma_{\overline{B_{\mathrm{ref}}}} = \pm \frac{\sqrt{\sum_{g=1}^{n} (\sigma_{\mathrm{geod},g} \cdot \overline{A_g})^2}}{\sum_{g=1}^{n} \overline{A_g}}, \tag{7}$$

and results in ±0.03 m w.e. yr^{-1}.

4.2 DEM comparison over stable terrain

An analysis of possible elevation-, slope-, and aspect-dependent biases in DEM differencing is carried out by comparing both DEMs over stable terrain. The spatial distribution of surface elevation changes outside the glaciers is calculated within a mask around every entity (Fig. 4). The mean offset between both DEMs is -1.7 ± 5.5 (1σ) m. Thus, on average, the DHM25 Level 1 DEMs are slightly higher over stable terrain compared to the recent swissALTI^{3D} DEMs. The area-weighted mean standard deviation over all stable terrain close to glacierized areas of ±5.5 m agrees with the nominal uncertainty $\sigma_{\Delta z}$ assessed with literature-based uncertainty estimates. The stochastic uncertainty calculated as:

$$\sigma_{\Delta z,\mathrm{sto}} = \pm \frac{\sigma_{\Delta z}}{\sqrt{n}}, \tag{8}$$

with n the number of pixels for which DEM comparison over stable terrain is carried out, is ±0.7 m on average.

We find an almost linear but comparatively moderate increase of the elevation difference between both input DEMs with elevation (−0.7 m between 1500 and 2000 m a.s.l. to −2.5 m above 3500 m a.s.l. on average). The scatter of the bias also increases with elevation. No dependency is found when relating the mean offset to classes of slope.

However, the scatter significantly increases towards steep slopes. The bias is slightly dependent on aspect. While areas with a mean aspect NE and SW show the same mean offset as the overall value, positive values result for pixels with a mean aspect W–NW–N and negative values for pixels facing E–SE–S, i.e. exposed to the opposite direction (Fig. 4). This points to a slight shift in the elevation information included in the DHM25 Level 1 DEMs in NW–SE-direction. We assume this shift to originate from the creation of the DHM25 Level 1 source data and therefore calculate the influence of its correction via co-registration according to Nuth and Kääb (2011). Because the effect of this correction in average mass balance turns out to be in the order of $\pm 10^{-4}$ to 10^{-2} m w.e. yr^{-1} and is always smaller than the uncertainty in the derived average mass balance from 1980 to 2010 $\sigma_{\overline{B_{ref}}}$, i.e. smaller than ±0.03 m w.e. yr^{-1}, we consider the effect of the detected DEM shifts on calculated surface elevation, volume and mass changes as negligible.

4.3 Validation

For validation of average mass balances between 1980–2010 we choose 31 glaciers from the datasets of Huss et al. (2010a, b) for which volume changes based on the independent, photogrammetrically derived DEMs show closest temporal accord with our respective measured period.

For individual glaciers, mean mass balance from Huss et al. (2010a, b) partly differs significantly from our results over the same observation period. Nevertheless, these differences do not indicate a systematic error and the mean difference is almost zero (Fig. 5). Hence, when analysing individual glaciers, the uncertainty in the average geodetic mass balance and the temporally homogenized mass balance time series presented in this study has to be considered. Averaged over subsamples of glaciers or individual catchments though, the accuracy of the average geodetic mass balance is in the same order of magnitude as if derived with more precise source DEMs created, for instance, by photogrammetrical techniques.

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5 Results

5.1 Changes with altitude

Present-day area-altitude distribution was derived from the combination of the SGI2010 with the swissALTI^{3D} DEMs, for t_1 from the SGI1973 and the DHM25 Level 1 DEMs. Averaged over the entire Swiss Alps, observed area changes between 1973 and 2010 were largest between 2800 and 2900 m a.s.l. The most heavily glacierized altitudinal belt rose by approximately 200 m. (Fig. 6a). The overall volume loss for the entire Swiss Alps is $-22.51 \pm 0.97\,km^3$ for the measured period, whereof glaciers still present in 2010 account for $-22.37\,km^3$. Averaged within 100 m elevation bands, volume loss was strongest between 2700 and 2800 m a.s.l. Corresponding average elevation changes continuously decreased from largest changes at lowermost elevations (terminus of valley glaciers) towards zero in the accumulation area. No elevation bands with positive volume changes were detected (Fig. 6b). Both surface elevation and area changes were remarkable even above 3500 m a.s.l. (Fig. 6). The observed thinning at high altitudes and over the accumulation areas of glaciers emphasizes the current state of disequilibrium of glaciers in the Swiss Alps.

5.2 Average mass balance

For the entire Swiss Alps, the area-weighted average mass balance of 1420 still existing glaciers was $-0.62 \pm 0.03\,m\,w.e.\,yr^{-1}$ during our reference period 1980–2010. For the main hydrological catchments, it ranged between -0.52 and $-1.07\,m\,w.e.\,yr^{-1}$ (Fig. 7, Table 1). Catchments along the north side of the Alps (Aare b. Brugg, Reuss, Linth) showed nearly the same mass changes ($-0.63\,m\,w.e.\,yr^{-1}$ on average) as the average for entire Switzerland. In general, glaciers in the Valais Alps (Rhone, Doveria) lost comparatively less ($-0.59\,m\,w.e.\,yr^{-1}$) and glaciers south of the main Alpine crest (Maggia, Ticino, Maira, Poschiavino) and of the inner-Alpine Inn valley comparatively more ($-0.84\,m\,w.e.\,yr^{-1}$) mass than on average over the entire Swiss Alps. These

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differences might be attributed to regionally variable changes in the climatic forcing and/or topographic effects.

The close-ups of the eastern Bernese Alps/western Alps of central Switzerland (Fig. 8) and the central/eastern Valais Alps (Fig. 9) show a high spatial variability in the temporally homogenized geodetic mass balance 1980–2010. Individual glaciers showed strongly differing responses to a similar regional climate forcing. For most of the largest valley glaciers with flat termini (e.g. Unteraar- (UAR), Oberaletschgletscher (OAL), and Grosser Aletschgletscher (ALE) in Fig. 8, or Gornergletscher (GOR) and Glacier d'Otemma (OTE) in Fig. 9), mass changes were particularly high. In contrast, Fieschergletscher (FIE in Fig. 8) or Findelengletscher (FIN in Fig. 9) showed smaller mass loss. For small and very small glaciers, the scatter of resulting changes was maximal. Neighbouring glaciers sometimes exhibited a high local spatial variability in observed geodetic mass changes (e.g. glaciers in the vicinity of Grosser Aletsch- (ALE) and Unteraargletscher (UAR) in Fig. 8, or glaciers close to Glacier d'Otemma (OTE) or within the Weissmiesgruppe in Fig. 9), while for other regions the response was quite uniform (e.g. Rotondogruppe or Blüemlisalpgruppe in Fig. 8). Mass losses of the mostly medium-sized mountain and valley glaciers of the Mischabel- and Weisshorn-gruppe were also very uniform and comparatively moderate (Fig. 9). This is likely to a major part due to the continentality of these areas, influenced by one of the coldest and driest climate regimes in the entire Swiss Alps (e.g. Frei and Schär, 1998; Auer et al., 2007). The equilibrium line altitudes (ELAs) are highest for these glaciers (Maisch et al., 2000) and their sensitivity to changes in air temperature and precipitation lowest (cf. Oerlemans and Reichert, 2000). Kanderfirn (KAN in Fig. 8), a medium-sized valley glacier, is a good example to explain the probable influence of both glacier hypsometry and dynamic adjustment on its mass balance evolution. In 1973, Kanderfirn terminated on a rock threshold just above a steep slope. In 1850, it had a flat and rather thick tongue lying roughly 700 m lower than its 1973 terminus (Fischer, 2012). Before 1973, when Kanderfirn retreated back upwards the steep ice fall, mass changes were likely comparatively higher, as it is known to be the case for thin and steep mountain glaciers (cf. Bahr et al., 1998; Haeberli and Beniston, 1998). Then, having lost the majority of its lower-lying part, Kanderfirn showed comparatively less negative average mass budget within the observation period of this study.

5.3 Geometrical indices and long-term mass balance variability

For individual glaciers, the relation between the observed geodetic mass changes 1980–2010 and the explaining geometrical indices glacier area, median elevation, mean slope of the glacier terminus, and mean aspect was not straightforward. Both area and mean aspect did not reveal significant correlations with the geodetic mass balance ($r = -0.09$ for area, $r = 0.03$ for mean aspect, Fig. 10a and d). A weak correlation ($r = 0.22$) was found for median elevation (Fig. 10b), and a good one ($r = 0.42$) for mean slope over the lowermost 25 % of the glacier (Fig. 10c). Because parts of the significant scatter in Fig. 10a–c is likely caused by glacier-individual uncertainties and local effects, we also calculated the respective mean values for 5 %-quantiles of the data (triangles in Fig. 10a–c). Then, a more structured relation between the selected geometrical indices and long-term mass balance variability emerges. For average area, the correlation is negative (Fig. 10a). Larger glaciers tend to show more negative mass balance because of their longer response time (cf. Jóhannesson et al., 1989). The higher the median elevation of a glacier, the less negative the average mass budget tends to be (Fig. 10b). Median elevation is a proxy for the balanced-budget equilibrium line altitude (ELA_0) (Braithwaite et al., 2013), which in turn depends on continentality. The latter can be approximated as a function of mean annual air temperature and precipitation at the ELA_0 (Shumsky, 1964; Haeberli et al., 1989). Glaciers influenced by more maritime climatic conditions react more sensitively to changes in air temperature and precipitation than more continental glaciers do (Oerlemans and Reichert, 2000). The more gently-sloping the glacier tongue, the more negative the average mass budget (Fig. 10c). The flattest glacier termini are typically those of larger valley glaciers flowing down into narrow valley bottoms at low altitudes (cf. Maisch et al., 2000). There, the climatic conditions are in favour of higher melt rates (e.g. Bauder et al., 2007; Paul and Haeberli, 2008) and the effects of albedo and mass-balance vs. altitude act as self-reinforcing mechanisms (Haeberli et al., 2007; Oerlemans et al., 2009). Northeast-exposed glaciers lost most mass, southwest-exposed glaciers lost least (Fig. 10d). This is likely due to the different sensitivity to changes in air temperature increase for the respective classes of mean aspect (cf. Evans and Cox, 2005; Evans, 2006): because of the relatively higher influence of the shortwave radiation component, south-exposed glaciers generally react less sensitively to air temperature changes than north-exposed glaciers. Also, south-exposed glaciers are often smaller and therefore generally have a shorter response time and less negative mass balance.

6 Comparison to other studies for the European Alps

For the 1420 glaciers mapped in the SGI2010, the average mass balance of -0.62 ± 0.03 m w.e. yr^{-1} calculated over the reference period 1980–2010 is comparable to observed mass changes reported for other glacierized regions of the European Alps during the past years. Carturan et al. (2013) find an average mass budget of -0.69 ± 0.12 m w.e. yr^{-1} between the early 1980s and the mid-2000s for glaciers of the Ortles-Cevedale group on the southwestern border of South Tyrol, Italy. Applying the same methods as for temporal homogenization of mass changes derived from DEM differencing (cf. Sect. 3.1, Fig. 3), we calculate -0.65 m w.e. yr^{-1} for the Swiss Alps when averaged over the same time period as analyzed by Carturan et al. (2013). From area and volume changes reported by Abermann et al. (2009) for the Austrian Ötztal Alps between 1969–2006, we calculate a mean mass balance of -0.40 ± 0.05 m w.e. yr^{-1} averaged for 81 glaciers. The average mass balance for all Swiss glaciers is -0.39 m w.e. yr^{-1} from 1969–2006.

To derive surface elevation and mass changes for the entire Swiss Alps, Paul and Haeberli (2008) compared the DHM25 Level 1 DEMs to the SRTM DEM from February 2000 and combined the former with the SGI1973 and the latter with the SGI2000 created from medium-resolution (30 m) satellite imagery. They assumed t_1 = 1985 as

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constant and report an average mass balance of $-0.78\,\text{m w.e. yr}^{-1}$ between 1985 and 1999. Over the same reference period, we find an average mass balance of $-0.60\,\text{m w.e. yr}^{-1}$. Both the quality of the different source data used and methodologies applied can to some extent explain the considerable differences in derived average mass balance.

According to Jarvis et al. (2008), the vertical accuracy of the 90 m resolution SRTM DEM is ±30 m. Over glacierized areas in Switzerland, however, it is probably significantly higher (Paul, 2008). Nevertheless, the quality of the SRTM DEM is not comparable to the recently compiled 2 m swissALTI^{3D} DEMs. If the SRTM DEM is used, the impacts of the penetration of radar waves into snow and ice should be considered (Berthier et al., 2006; Gardelle et al., 2012b), as they can reach up to 10 m for the C-band of SRTM (Dall et al., 2001). This could explain the more negative surface elevation changes over accumulation areas observed by Paul and Haeberli (2008) who compared the SRTM DEM to photogrammetrically derived DEMs by Bauder et al. (2007). Moreover, the DEM preprocessing prior to differencing may cause additional uncertainty, for instance if source DEMs have to be downscaled to the same gird cell resolution (Carturan et al., 2013). For our study, the 2 m resolution swissALTI^{3D} DEMs were upscaled to 25 m, corresponding to the cell size of the DHM25 Level 1. Not only the quality of the source DEMs but also of the glacier outlines used is important. This especially applies if changes of small and very small glaciers have to be assessed. Fischer et al. (2014) show that the accuracy of glacier outlines derived from semi-automatic satellite remote sensing approaches using medium-resolution satellite imagery does not satisfy change assessments of glaciers $< 1.0\,\text{km}^2$.

Related to the methodological approaches used, the following aspects likely also cause part of the disagreement in calculated average mass balances between Paul and Haeberli (2008) and our study: assuming a density of the volumetric change of $900\,\text{kg m}^{-3}$ implies that only ice would have melted. Following Huss (2013), we apply a mean conversion factor of $850\,\text{kg m}^{-3}$ here. Also, the average mass balance for individual glaciers (Eq. 2) can be significantly biased if differences in the reference years of the source data are not considered. For Grosser Aletschgletscher, assuming t_1 as 1985 instead of 1980 changes the result by 0.14 m w.e. yr^{-1} (−0.87 instead of −0.73 m w.e. yr^{-1}). Defining t_1 as 1985 for all glaciers of Switzerland would change the mean geodetic mass balance by 0.03 m w.e. yr^{-1}. Hence, differences in the reference years of the source data account for 17 %, the different assumptions of the density of volume change for 24 %, and the quality of the source data used for 59 % of the disagreement in calculated average mass balances between the present study and Paul and Haeberli (2008).

7 Conclusions

In this article we presented glacier-specific changes in surface elevation, volume and geodetic mass balance for all glaciers of the Swiss Alps between 1980 and 2010. The DHM25 Level 1 DEMs acquired from 1961 to 1991 over glacierized areas were combined with the 1973 glacier inventory and then compared to the swissALTI^{3D} DEMs from 2008–2011 and glacier outlines from the new Swiss Glacier Inventory SGI2010. By making use of this recently compiled new source data of improved quality, we were able to reanalyze and extend the dataset of surface elevation changes in the Swiss Alps by Paul and Haeberli (2008). From the DEM differencing, we derive an overall volume loss of −22.51 ± 0.97 km^3 for the entire Swiss Alps for the measured period, whereof glaciers still present in 2010 account for −22.37 km^3. Observed ice volume changes were strongest between 2700–2800 m a.s.l. and remarkable even above 3500 m a.s.l. No elevation bands with positive volume changes were found. Results were validated against elevation changes from independent photogrammetrical DEMs. An in-depth accuracy assessment of volumetric and mass changes was performed for the analyzed glaciers. Elevation-, slope-, and aspect dependent errors were investigated from the comparison of both source DEMs over stable terrain outside the glaciers. Because of significant differences in the acquisition dates of individual DEMs, annual mountain-range mass balance variability (Huss, 2012) was used to temporally homogenize the geodetic mass changes to the comparable reference time interval 1980–2010. Over this period, the area-weighted mean geodetic mass balance is $-0.62 \pm 0.03\,\mathrm{m\,w.e.\,yr^{-1}}$ for the entire Swiss Alps. For the main hydrological catchments of Switzerland, mean balances range from -0.52 to $-1.07\,\mathrm{m\,w.e.\,yr^{-1}}$. For the study area, comparison of our results to previous studies revealed the manifold possible sources of uncertainty in deriving surface elevation and mass changes from DEM differencing.

To better understand the spatial variability of the observed surface elevation and mass changes, we investigated the relation of observed mass changes to topographic factors. Overall, as shown by several previous studies, the glacier hypsometry can partly explain the general pattern of different glacier responses to changes in climatic forcing. We found strongest correlations for the geometrical indices terminus slope (e.g. mean over lowermost 25 %) and median elevation.

The dataset presented in this article is useful for manifold future studies and applications. For instance, mass balance driven glacier evolution models of the entire Swiss Alps or approaches for the extrapolation of measured mass balance on single glaciers to whole catchments can be validated and improved. This would also imply a reduction in the uncertainty of future runoff projections from glacierized basins in Switzerland. Moreover, it is a valuable starting point for testing more sophisticated methods to explain the spatial variability in long-term mass balance in more detail.

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Table 1. Mean area-weighted geodetic mass balance 1980–2010 for the main hydrological catchments of Switzerland shown in Fig. 7, listed in alphabetic order.

Catchment	Glacierized Area (km^2) 1973	Glacierized Area (km^2) 2010	Glacierization (%) 1973	Glacierization (%) 2010	$\overline{B}_{ref}$ (m w.e. yr^{-1})
Alpenrhein	57.2	27.3	1.78	0.84	−0.69
Linth	23.3	16.0	1.09	0.75	−0.60
Reuss	102.5	75.7	3.03	2.23	−0.62
Aare b. Brugg	229.8	174.5	1.97	1.50	−0.64
Rhone	721.5	569.2	13.68	10.79	−0.59
Doveria	14.1	8.8	8.24	5.12	−0.52
Maggia	5.0	3.0	0.39	0.23	−0.83
Ticino	5.9	2.2	0.39	0.14	−0.67
Maira	20.4	13.0	10.76	6.86	−1.07
Poschiavino	9.5	6.9	5.60	4.06	−0.74
Inn	71.9	46.4	3.71	2.39	−0.81
All catchments	1261.2	942.8	3.89	3.04	−0.62

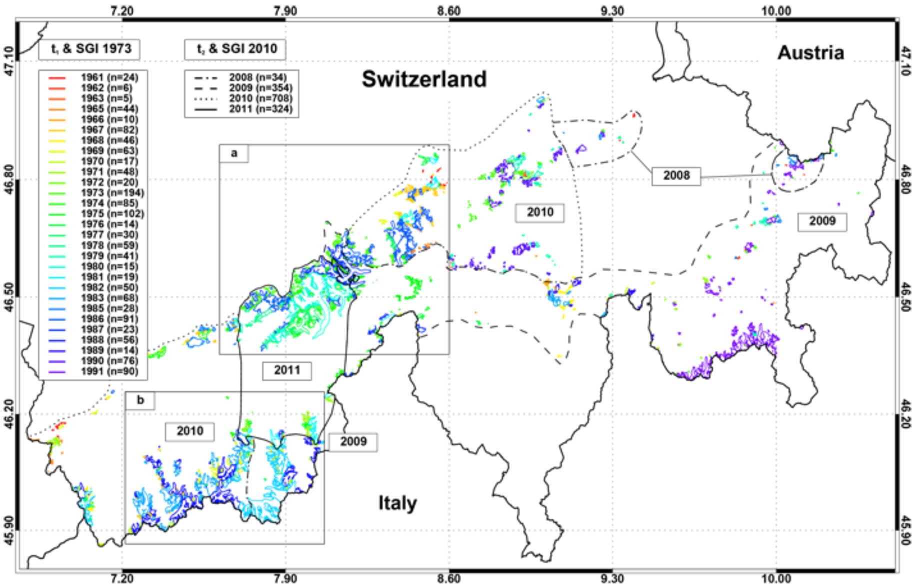

Figure 1. Glaciers in the Swiss Alps. Colours refer to the acquisition date of the elevation information (DHM25 Level 1) defining the beginning of the investigated period (t_1). Black lines delimit areas of equal acquisition dates of both glacier outlines and surface topography at the end of the investigated period (t_2). Two black rectangles show the perimeters of close-ups with resulting mean geodetic mass balance.

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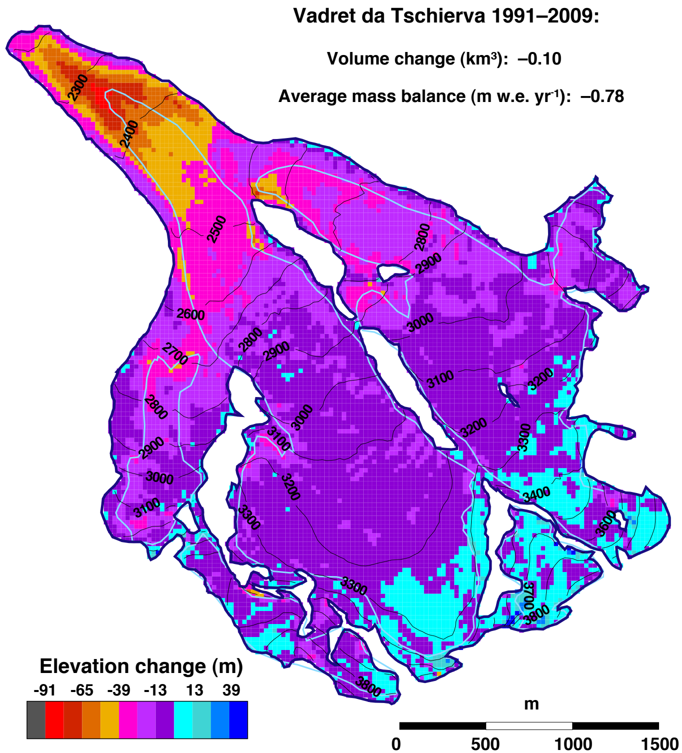

Figure 2. Spatial distribution of elevation changes for Vadret da Tschierva 1991–2009 within the digital glacier outlines from both the 1973 (dark blue) and the 2010 (light blue) inventories.

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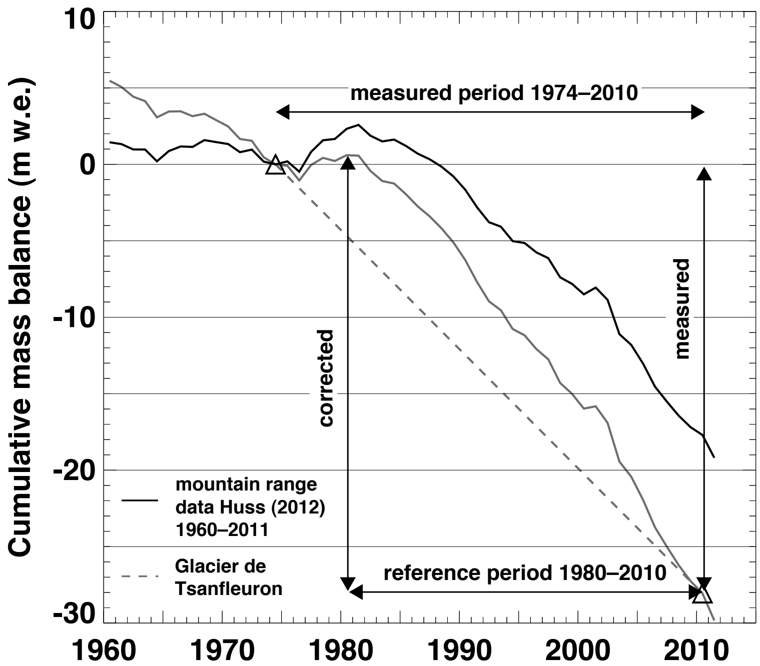

Figure 3. Temporal homogenization of cumulative average mass balance from DEM differencing for Glacier de Tsanfleuron (dark grey) based on cumulative mean annual mountain-range mass balance from Huss (2012).

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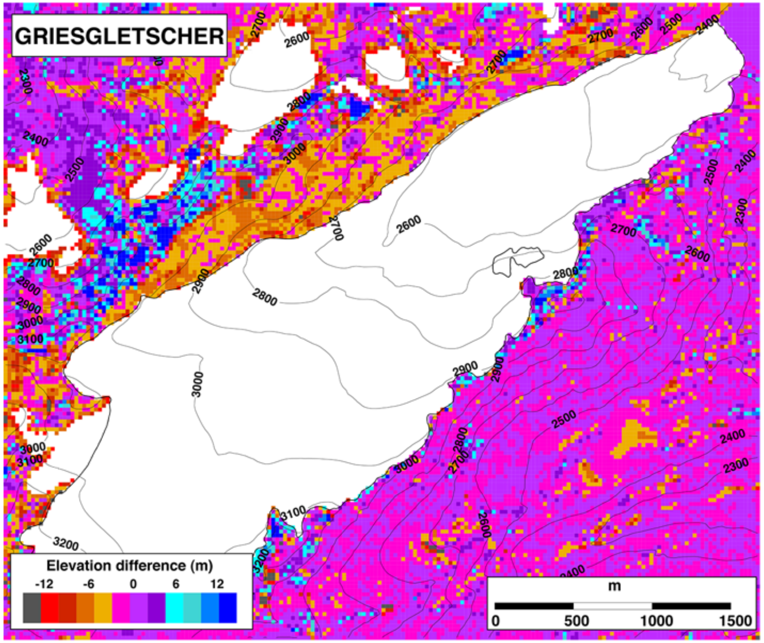

Figure 4. Comparison of input DEMs over stable terrain. The 1973 extents of Griesgletscher and adjacent smaller glaciers are masked out.

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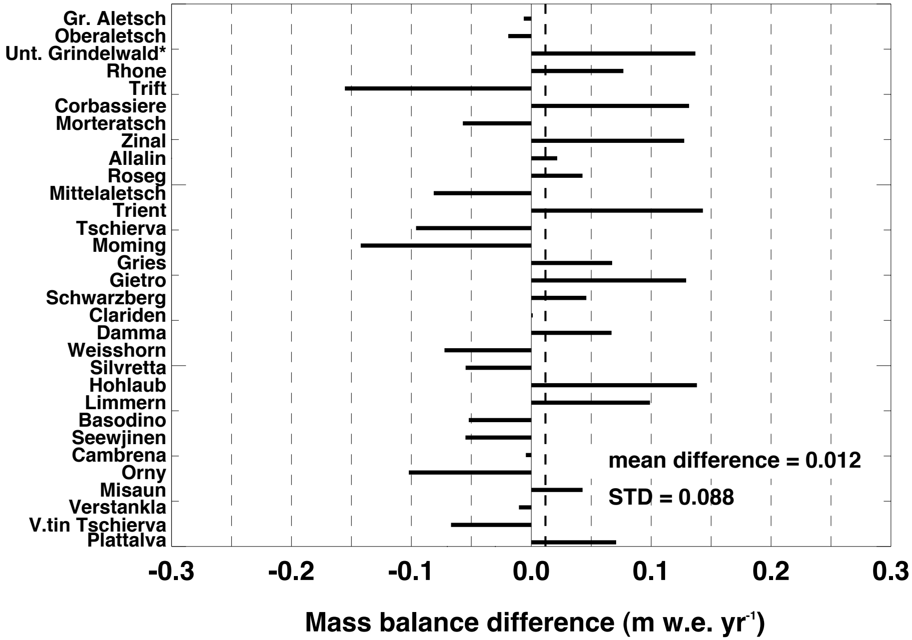

Figure 5. Validation of average geodetic mass balance with mass balance data from independent DEMs created by photogrammetry (Huss et al., 2010a, b). The mean difference is indicated with the bold dashed line. Individual glaciers are sorted according to their area.

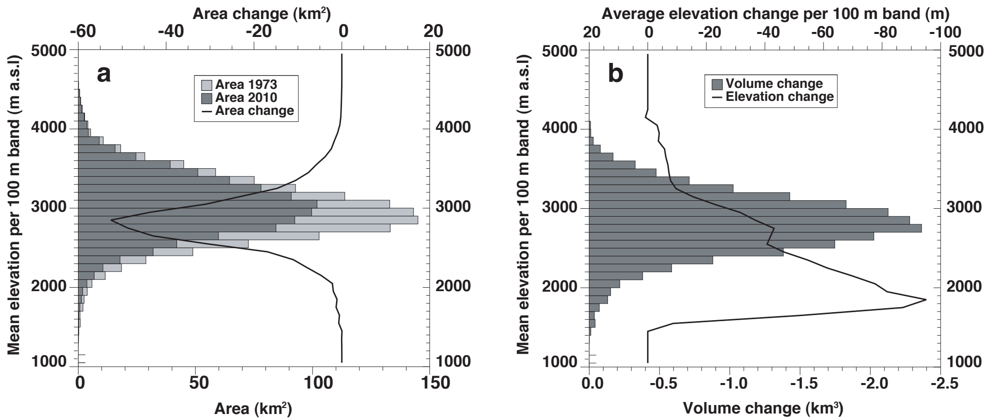

Figure 6. (a) Area-elevation distribution in 1973 and 2010 in 100 m elevation bands and corresponding area changes between the two inventories. **(b)** Elevation distribution of the observed volume loss within the measured period as well as resulting average elevation changes per 100 m elevation bands.

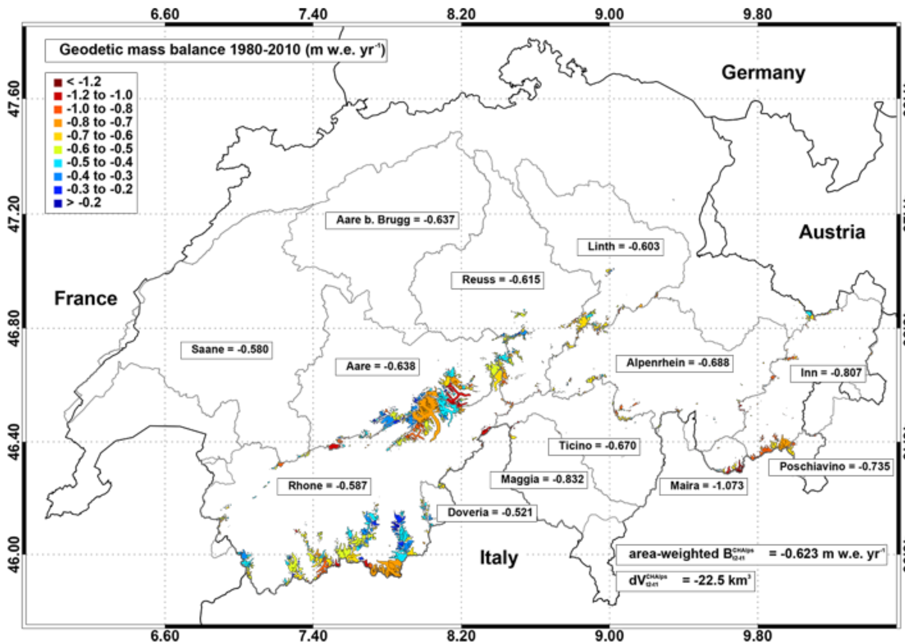

Figure 7. Mean area-weighted geodetic mass balance 1980–2010 for the main hydrological catchments and the entire Swiss Alps.

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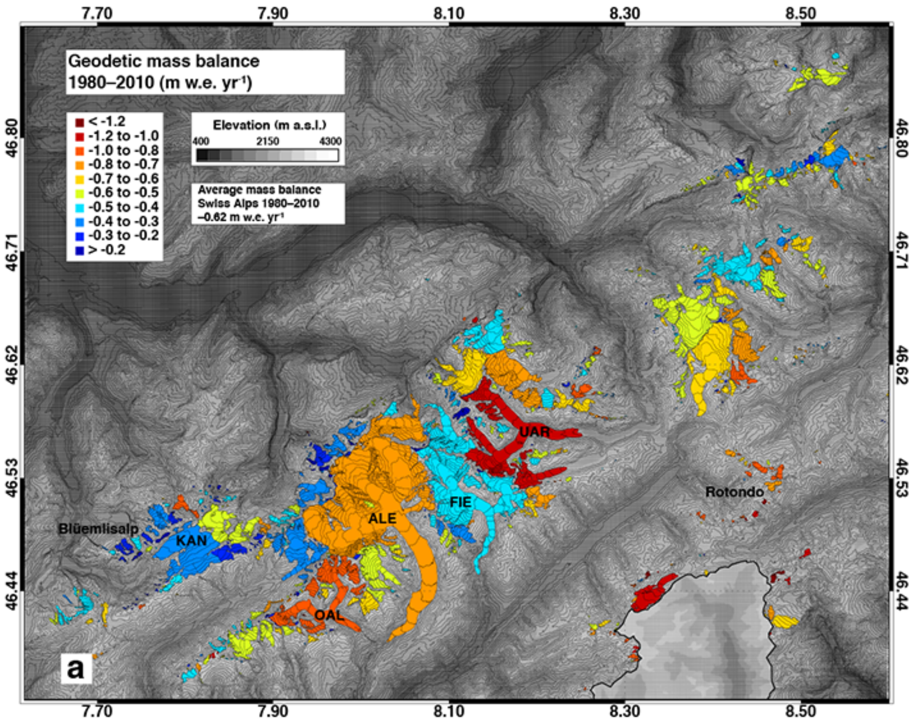

Figure 8. Spatial distribution of the temporally homogenized geodetic mass balance 1980–2010 for the eastern Bernese Alps/western Alps of central Switzerland. The SGI2010 outlines are taken to illustrate glacier surface area.

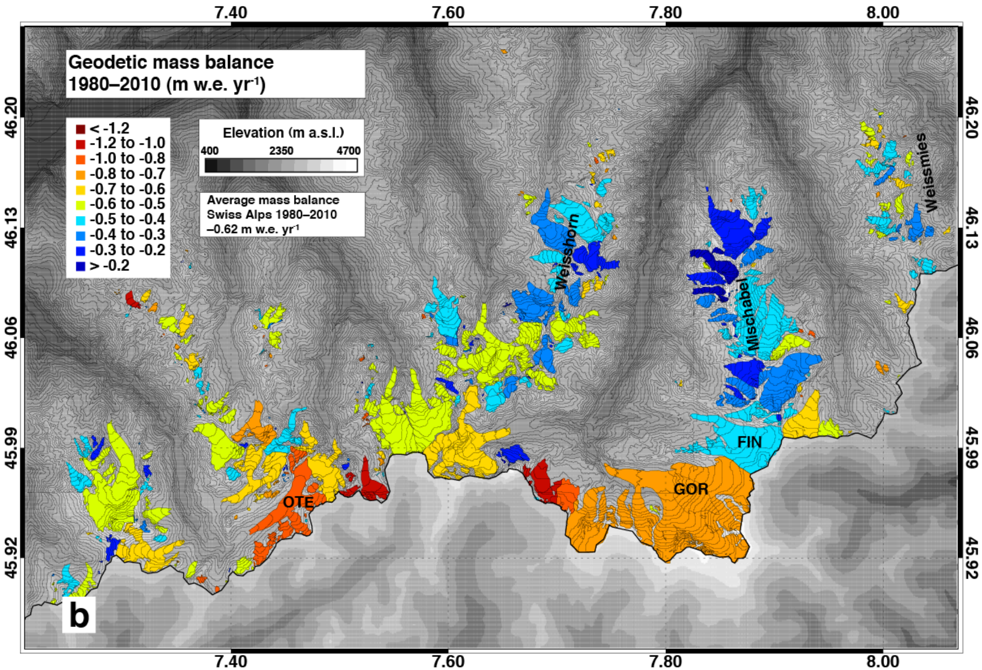

Figure 9. Spatial distribution of the temporally homogenized geodetic mass balance 1980–2010 for the central/eastern Valais Alps. The SGI2010 outlines are taken to illustrate glacier surface area.

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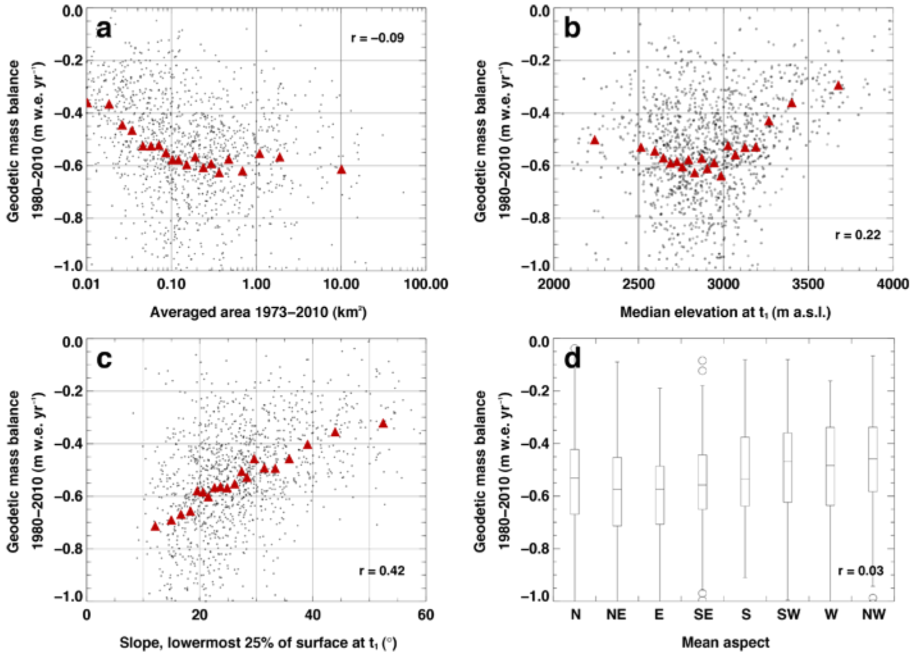

Figure 10. Observed relations between the variability of temporally homogenized geodetic mass balance 1980–2010 and several geometrical indices: **(a)** Average area 1973–2010, **(b)** median elevation at t_1, **(c)** surface slope averaged over the lowermost 25 % of the glacier, and **(d)** mean aspect. r is the linear correlation coefficient and purple triangles show mean values for 5 %-quantiles of the data.