Journal of Glaciology, Vol. 58, No. 208, 2012 doi: 10.3189/2012JoG11J216

Conventional versus reference-surface mass balance

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ABSTRACT. Glacier surface mass balance evaluated over the actual glacier geometry depends not only on climatic variations, but also on the dynamic adjustment of glacier geometry. Therefore, it has been proposed that reference-surface balances calculated over a constant glacier hypsometry are better suited for climatic interpretation. Here we present a comparison of 82 year modelled time series (1926–2008) of conventional and reference-surface balance for 36 Swiss glaciers. Over this time period the investigated glaciers have lost 22% of their area, and ice surface elevation close to the current glacier terminus has decreased by 78 m on average. Conventional balance in the last decade, at –0.91 m w.e. a^{-1}, is 0.14 m w.e. a^{-1} less negative than the reference-surface balance. About half of the negative (stabilizing) feedback on mass balance due to glacier terminus retreat is compensated by more negative mass balances due to surface lowering. Short-term climatic variability is clearly reflected in the conventional mass-balance series; however, the magnitude of the long-term negative trend is underestimated compared to that found in the reference-surface balance series. Both conventional and reference-surface specific balances show large spatial variability among the 36 glaciers.

1. INTRODUCTION

Glacier surface mass balance is often regarded as a good and direct indicator for climatic variations (e.g. Dyurgerov and Meier, 2000; Oerlemans and Reichert, 2000; Kaser and others, 2006; Cogley, 2009). A shift in climatic forcing is immediately reflected by a change in accumulation or ablation at any arbitrary location on the glacier surface (Ohmura and others, 2007). However, the glacier will adjust its size and geometry to a change in climatic forcing over longer time periods depending on its characteristic response time (Jóhannesson and others, 1989; Harrison and others, 2001). This dynamic adjustment affects the glacier-wide mass balances (Paul, 2010). Thus, they do not purely depend on climatic variations.

Glacier monitoring programs mostly report so-called conventional mass balances (Elsberg and others, 2001). These are evaluated over the concurrent extent and topography of the glacier (Zemp and others, 2009). Hence, conventional mass balances are the relevant quantity for hydrological applications, since they refer to the actual quantity of water released or stored by a glacier during a mass-balance year (Harrison and others, 2005). Conventional balances are, however, determined not only by climate, but also by changes in glacier surface area and hypsometry.

For investigating glacier–climate linkages, Elsberg and others (2001) introduced the reference-surface balance defined as the mass balance a glacier would have if its surface geometry remained fixed as it was at some reference date. Hence, the mass balance is not affected by any feedback from a changing glacier surface elevation and size and solely reflects the climate signal.

Although reference-surface mass balances are in principle better suited for climatic interpretations (Elsberg and others, 2001; Harrison and others, 2005, 2009), practical issues often hamper the applicability of this concept. Errors are involved when extrapolating measured point balances to the hypsometry and extent of the (older) reference surface that either no longer exists or has been buried. Uncertainties are expected to rise as the current geometry diverges from the reference surface, limiting the potential for climatic interpretations of such time series. Modelling reference-surface balances circumvents this problem, although results cannot be validated against in situ field observations as these refer to a different glacier hypsometry (Elsberg and others, 2001).

Conventional and reference-surface balances differ as a result of the dynamic adjustments of the glacier, i.e. the effects of glacier retreat/advance and glacier thinning/thickening. For simplicity, we phrase our discussion in terms of glacier retreat and thinning in this paper since this is the predominant pattern for the investigated glaciers in the study period. Glacier retreat resulting from negative mass balance exerts a negative, i.e. stabilizing, feedback on glacier mass change because loss of area at predominantly lower elevations will make the conventional mass balance less negative than it would have been without retreat under otherwise similar conditions. Thus, the glacier may approach an equilibrium with time even if climate conditions are not becoming more favourable.

Glacier thinning, in contrast, exerts a positive, i.e. self-amplifying, feedback: with decreasing surface elevation, the glacier is exposed to higher air temperatures, resulting in more negative conventional balances. The net effect of these two opposing feedbacks will depend on a number of factors related to climate, glacier geometry and characteristics (e.g. debris coverage).

These effects are visualized using two extreme cases in Figure 1. A step change in climate generates a negative mass balance. Case 1 assumes that the glacier terminus retreats but glacier surface elevation remains unaltered. Provided the change in forcing is sufficiently small, conventional mass balances will approach zero with time.

In case 2, the glacier thins, but its size remains unchanged. The conventional mass balance even becomes more negative than the reference-surface mass balance

(Fig. 1). Case 2 is not unrealistic; downwasting of alpine glacier tongues, particularly on those having a substantive debris coverage, has been widely observed during recent decades (Paul and others, 2007; Bolch and others, 2008). In most cases, however, the glacier's response will lie between these two end members.

Few studies have investigated the differences between conventional and reference-surface balances. Harrison and others (2009) investigated this issue to infer the dynamic health of two glaciers in Alaska (see also Van Beusekom and others, 2011) and to estimate their chances of survival under changed climate conditions. Gulkana Glacier showed significant differences between conventional and reference-surface mass balance after only a few decades. However, due to a longer response time, only small differences were found for Wolverine Glacier. Paul (2010) modelled the mass balance of 60 glaciers in the Swiss Alps over 1 year using the same climatic forcing, but hypsometry and glacier extent of either 1850 or 1973. Based on differences in modelled balances and the glaciers' sensitivity to air-temperature change, he concluded that 50–70% of the mass-balance response to a change in climate is 'hidden' in the geometric adjustment of the glacier. According to Paul (2010), annual mass balance modelled over the initial glacier surface at the end of the Little Ice Age would be about three times more negative than mass balance referred to a recent glacier geometry. The subject is also extensively discussed by Huss and others (2010) and Leclercq and others (2010a).

This paper presents the first application of the concept proposed by Elsberg and others (2001) to a large sample of glaciers within one mountain range, allowing the statistical analysis of the differences between conventional and reference-surface balances. We use 82 year time series of conventional and reference-surface mass balance (1926–2008) for 36 glaciers in the Swiss Alps obtained from mass-balance modelling aided by abundant in situ observations (Huss and others, 2010b). The objectives are to quantify the differences between conventional and reference-surface balances, to assess the value of conventional mass-balance series for climatic interpretation, and to estimate the importance of geometric adjustment, as well as the effects of glacier retreat and thinning alone in shaping conventional balances. Finally, we seek to explain the large spatial variability in specific annual mass balances, which is a prerequisite for extrapolating single glacier mass-balance series to the mountain range scale.

2. DATA

In this study, 36 glaciers from all parts of Switzerland are investigated (Fig. 2). The complete range of glacier sizes present in the European Alps is covered (<0.1 to 80 km^2; Table 1). Different glacier geometries are included in the dataset. The sites also include different exposures and regional climate conditions within the Alps. The glacier set corresponds to the 30 glaciers addressed by Huss and others (2010b), and is extended by 6 glaciers in the southeastern Swiss Alps for which high-quality topographical data are available (Huss and others, 2010c).

A comprehensive field dataset for the investigated glaciers is available covering large parts of the 20th century. Most importantly, for each of the 36 glaciers, a series of three to nine high-accuracy digital elevation models (DEMs) including mapping of the glacier outlines is available

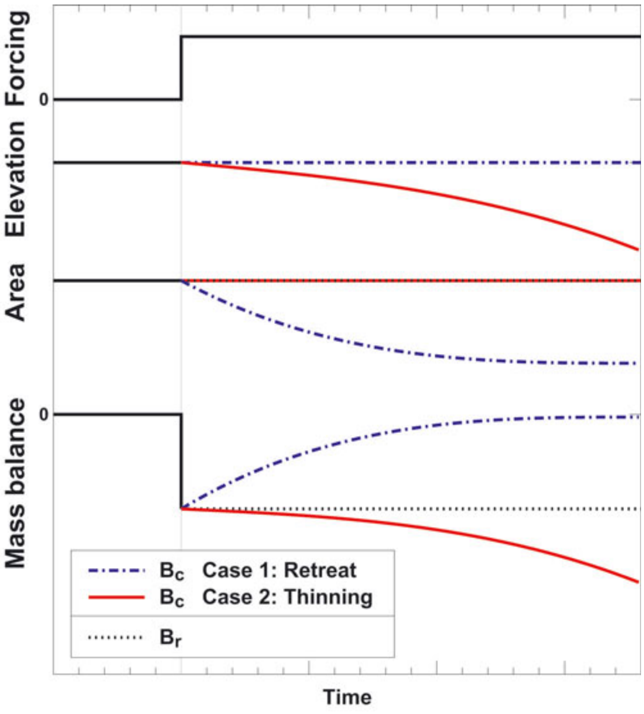

Fig. 1. Schematic response of a glacier in equilibrium to an idealized small step change in climate forcing that generates a negative mass balance. Two end members of the glacier's possible geometric response and associated conventional (B_c) and reference-surface (B_r) annual mass balances are shown: the glacier terminus retreats, but glacier surface elevation remains unaltered (dash-dotted lines); and the glacier thins, but its size is constant (solid lines). Note that B_r (dotted) is not affected by retreat or thinning, and hence remains unchanged after the change in forcing.

(Bauder and others, 2007). The first DEM was obtained by digitizing topographical maps (1 : 10 000 to 1 : 50 000 scale) based on terrestrial surveys. The maps date between 1926 and 1939 for most glaciers (Table 1). The estimated accuracy of the elevation information is ±2 m. After 1960, all DEMs are based on the photogrammetric evaluation of aerial photographs, and the uncertainty is assumed to be around ±0.5 m (Bauder and others, 2007). By comparison of subsequent DEMs, the ice-volume change over periods of years to a few decades can be calculated.

The total area of the 36 investigated glaciers decreased by 60 km^2, or 15%, from the first to the last DEM (1999–2008). The mean of all individual glacier area changes is –22%. Rates of area loss vary between 0.6% and 15% per decade, mainly depending on the size of the glacier (Table 1). Changes in hypsometry are most prominent close to the current glacier terminus. Glacier surface elevation in the first 100 m elevation band upward of the current glacier terminus has decreased by 78 m on average. Thinning of Grosser Aletschgletscher since 1926 exceeds 250 m. In contrast, for many smaller and/or steeper glaciers, changes in hypsometry near the terminus are small (<30 m).

Only for five glaciers were long-term mass-balance series based on the glaciological method reported to the World Glacier Monitoring Service (WGMS, 2008). However, >10 000 in situ measurements of ablation and accumulation originating from roughly two-thirds of the investigated glaciers were available for model calibration (Aellen, 1995; Huss and others, 2010b).

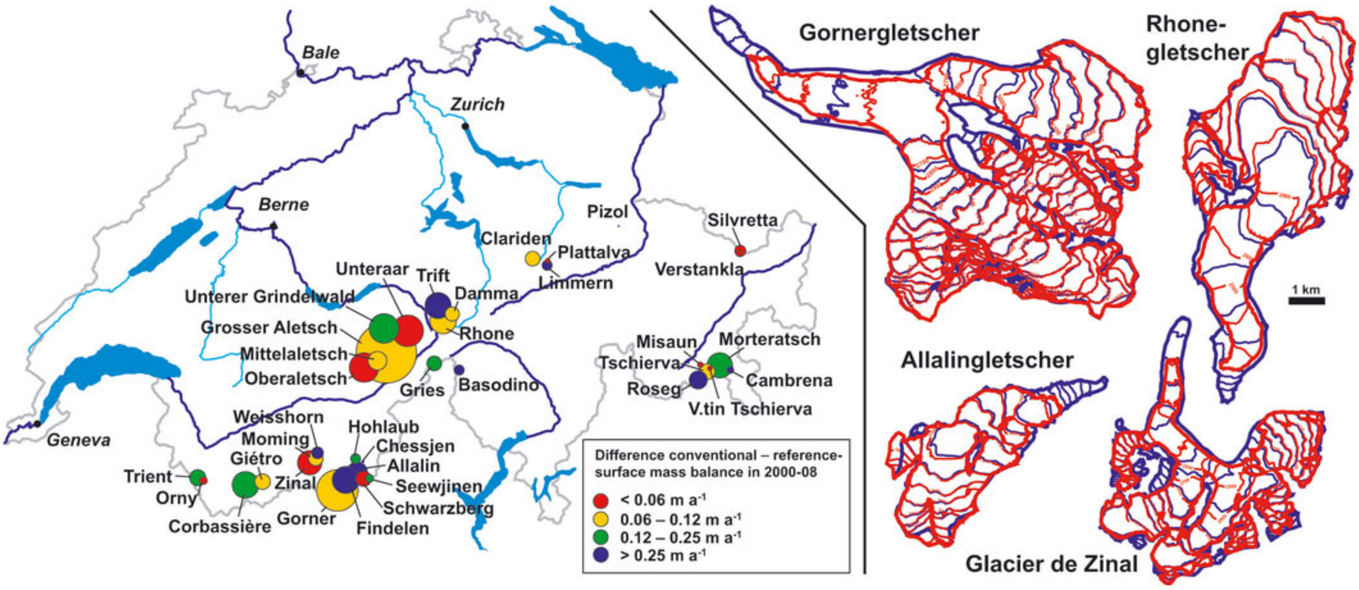

Fig. 2. Location of the study sites in the Swiss Alps, and detail maps of selected glaciers. The area of the circles is proportional to glacier size. The colour indicates the differences between conventional and reference-surface mass balance as a mean over the last decade. The topography and extent of four selected glaciers is shown for the first DEM (blue) and the last DEM (red). The contour interval is 100 m. All glaciers are displayed in the same scale.

3. METHODS

Time series of conventional mass balance for the 36 glaciers over the period 1926–2008 have been derived by Huss and others (2010b,c) using methods described by Huss and others (2008). An accumulation and temperature-index melt model including potential radiation distribution (Hock, 1999) is run in daily temporal resolution on a 25 m × 25 m grid using meteorological input (air temperature/precipitation) obtained from nearby weather stations. The model is tuned such that observed changes in ice volume in periods of years to several decades are matched, and that in situ observations of accumulation and ablation rates are reproduced as closely as possible. Annual mass balance is calculated over the annually updated glacier surface hypsometry and extent, which is obtained by linearly interpolating the terrain elevation between subsequent DEMs (Huss and others, 2008). The glacier-wide mass balance (conventional balance) is then computed as a mean over that year's total glacier surface area and refers to the hydrological year (1 October–30 September). The applied model has been shown to agree well with various types of field data (Huss and others, 2008).

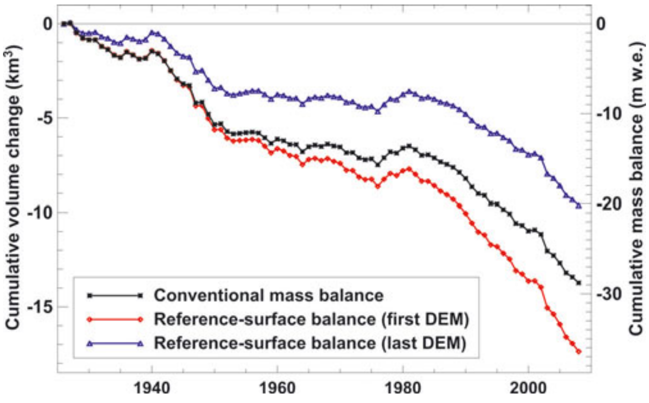

Fig. 3. Calculated cumulative ice volume change of the 36 investigated glaciers for conventional and reference-surface mass balance (first and last DEMs). The cumulative mean specific mass balance (right-hand-side axis) is relative to the reference-surface balance.

Adopting a modelling approach instead of relying solely on reported glacier-wide balances has two advantages: (1) A large number of mass-balance series over a consistent and long time period can be derived for further analysis by combining different types of inhomogeneous field data (e.g. ice-volume changes, sparse or temporally discontinuous point mass-balance measurements). (2) The modelled conventional balance is always evaluated over the actual (interpolated) glacier geometry (ice extent and surface elevation) while reported mass balances are often a mixture of conventional and reference-surface balances as the hypsometry is rarely updated annually.

Our methodology to calculate reference-surface mass balance is slightly different from that applied by Elsberg and others (2001) and Harrison and others (2009). They propose to extrapolate measured mass-balance profiles for individual years to the reference surface, whereas here we apply a grid-based mass-balance model. We rerun the same model as for the conventional balance using the same calibrated model parameters and climate forcing but keep the initial glacier hypsometry fixed in time.

4. RESULTS AND DISCUSSION

4.1. Conventional versus reference-surface balance

The 1926–2008 and 36-glacier mean of conventional mass balance is –0.36 m w.e. a^{-1}, and –0.45 m w.e. a^{-1} for the reference-surface balance (calculated over each glacier's first DEM; Table 1). Cumulated over 82 years, the conventional balance is 6.7 m w.e. less negative than the reference-surface balance (–36.6 m w.e.; Fig. 3). Both conventional and first-DEM reference-surface mass-balance time series

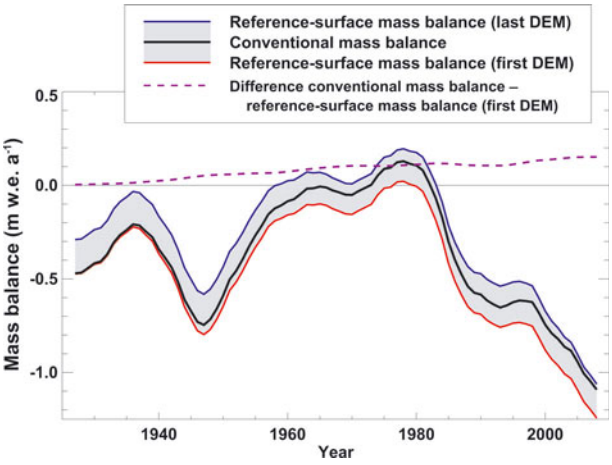

Fig. 4. Comparison of conventional and reference-surface mass-balance series over the 20th century. 36-glacier arithmetic averages of annual mass balance are low-pass filtered with an 11 year running mean. The dashed line refers to the difference $\Delta B_{\mathrm{c-r}}$ between conventional and reference-surface (first DEM) annual balances.

reveal distinct long-term variations. Mass balances were positive for two short periods in the 1910s and late 1970s, and particularly negative in the 1940s and in the period since the mid-1980s (Huss and others, 2010b).

The differences between 36-glacier averages of the conventional and the reference-surface annual mass balance derived from the glacier hypsometry of the first DEM, $\Delta B_{\mathrm{c-r}}$, gradually increase from 0 to 0.14 m w.e. a^{-1} (last decade's mean) over the 82 year period (Fig. 4), except for the 1980s when they remain relatively constant. This is explained by a short readvance of many Alpine glaciers due to several years of positive mass balance at the end of the 1970s (Glaciological reports, 1881–2009).

It is remarkable that reference-surface mass-balance variations evaluated over the hypsometry of the first and last DEMs are quasi-parallel. The difference in the glacier mass balance calculated with the identical forcing over two geometries fixed in time has an almost constant value irrespective of variations in the forcing.

An evaluation of the standard deviation in conventional and reference-surface mass-balance series for the period 1958–2008 shows that the differences are minor: one standard deviation of conventional mass balance is 0.65 m w.e. a^{-1}, whereas it is 0.66 m w.e. a^{-1} for reference-surface balance. Similar differences in variability are evident for the decadal timescale.

Based on these considerations we conclude, for our set of glaciers, that using conventional instead of reference-surface mass balance does not significantly hamper the study of climate variability (annual to decadal); it only affects the magnitude of the long-term trend in the mass-balance series.

Time series of conventional and reference-surface mass balances for selected glaciers with varying characteristics are presented in Figure 5. Allalingletscher, for example, exhibits a large difference between conventional and reference-surface mass-balance series. The mass-balance response is close to case 1 in Figure 1. The glacier had a steep tongue prior to the year 2000 (Table 2). The terminus of Allalingletscher is currently almost 700 m higher than it was 80 years ago, whereas surface elevation in the upper reaches of the glacier is little changed (Fig. 2).

Table 1. Investigated glaciers and field data basis. Glaciers are listed in descending order of surface area. The period covered by DEMs is given. The number of DEMs available for model calibration is shown in parentheses. ΔA is the relative glacier area change between the first and last DEMs. B_{c} is the mean specific conventional mass balance over the study period 1926–2008

Glacier	Period (n)	Area km^2	ΔA %	B_{c} m w.e. a^{-1}
Grosser Aletsch	1926–99 (4)	83.02	–9.6	–0.50
Gorner	1931–2003 (3)	39.03	–6.3	–0.51
Unteraar	1927–2003 (6)	22.73	–17.3	–0.64
Oberaletsch	1926–99 (3)	19.68	–17.3	–0.58
U. Grindelwald	1926–2004 (3)	19.55	–10.3	–0.31
Findelen	1931–2007 (3)	16.31	–17.8	–0.32
Corbassière	1935–2003 (3)	16.01	–4.0	–0.21
Rhone	1929–2007 (6)	15.94	–12.6	–0.31
Trift	1936–2003 (6)	15.34	–17.8	–0.39
Morteratsch	1935–2008 (4)	15.12	–19.7	–0.53
Zinal	1936–2006 (5)	13.41	–20.8	–0.37
Allalin	1932–2008 (9)	9.68	–5.7	–0.17
Mittelaletsch	1926–99 (3)	8.00	–17.2	–0.33
Roseg	1935–2008 (4)	7.57	–31.1	–0.56
Trient	1931–2005 (3)	5.87	–13.8	–0.18
Moming	1936–2006 (5)	5.45	–23.2	–0.20
Giétro	1934–2003 (6)	5.43	–7.1	–0.27
Tschierva	1935–2008 (4)	5.37	–29.5	–0.41
Schwarzberg	1946–2008 (8)	5.31	–10.1	–0.26
Clariden	1936–2003 (5)	5.13	–11.7	–0.20
Gries	1923–2007 (9)	4.97	–35.6	–0.70
Damma	1939–2007 (3)	4.60	–24.5	–0.36
Weisshorn	1936–2006 (5)	3.10	–30.6	–0.26
Silvretta	1938–2007 (7)	2.79	–21.6	–0.30
Limmern	1947–2000(5)	2.23	–17.2	–0.29
Basodino	1929–2002 (7)	2.21	–32.8	–0.32
Hohlaub	1946–2008 (8)	2.18	–24.9	–0.34
Seewjinen	1946–2008 (6)	1.47	–29.7	–0.31
Cambrena	1934–2008 (4)	1.37	–39.2	–0.34
Orny	1931–2005 (3)	1.36	–23.8	–0.31
Verstankla	1959–2003 (3)	0.92	–10.7	–0.32
Misaun	1936–2008 (4)	0.84	–28.3	–0.36
Plattalva	1947–2000 (5)	0.58	–23.5	–0.43
Tschierva	1935–2008 (4)	0.57	–33.5	–0.39
Chessjen	1946–2008 (6)	0.43	–46.8	–0.50
Pizol	1961–2006 (8)	0.08	–67.2	–0.33
Mean	**1936–2005 (5)**	**10.10**	**–22.0**	**–0.36**

Glacier de Zinal, along with other debris-covered glaciers (Unteraar, Oberaletsch), shows little difference between conventional and reference-surface balances (Fig. 5b). In some years the latter (calculated over the surface geometry of the first DEM) are less negative than the conventional balance. This is explained by the particular retreat characteristics of debris-covered glaciers. The glacier tongue shows a comparatively slow retreat due to the protecting effect of the debris cover; significant area and elevation changes occur at higher elevations. Thus, parts of the accumulation area are lost, making the conventional mass balance more negative than the reference-surface balance despite the lower-reaching glacier terminus at the beginning of the modelling period.

For Gornergletscher also, $\Delta B_{\mathrm{c-r}}$ remains small throughout the study period (Fig. 5c), but for different reasons. This large glacier with a wide, thick and gently sloping tongue

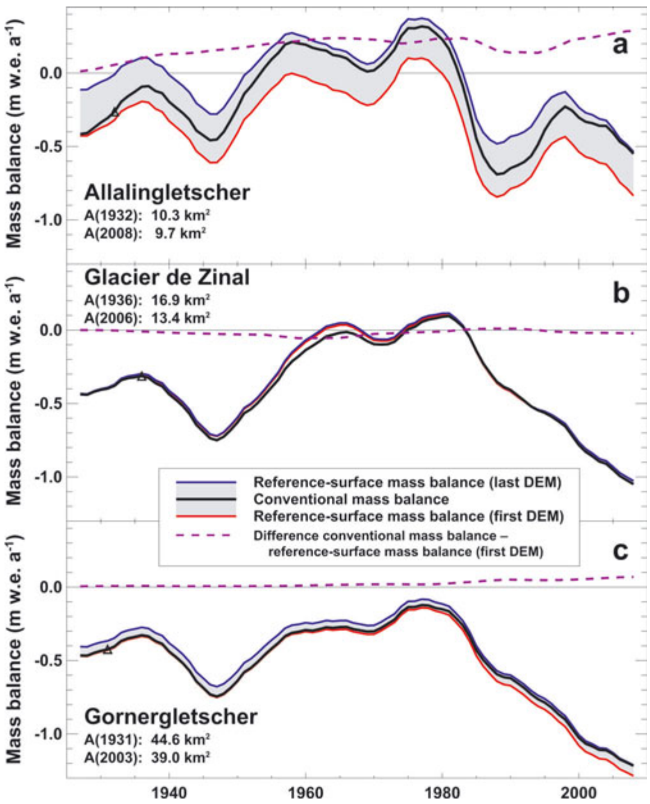

Fig. 5. Comparison of conventional and reference-surface mass-balance series for selected glaciers over the 20th century (see Fig. 2). Annual mass balance is low-pass filtered with an 11 year running mean. Curves for the reference-surface (first/last DEM) and the conventional balance are shown. The dashed line refers to $\Delta B_{\mathrm{c-r}}$. Glacier surface areas of the first DEM (indicated with a triangle) and the last DEM are given. (a) Allalingletscher, a glacier that is relatively well adapted to the current climatic conditions. (b) Glacier de Zinal, a glacier with a debris-covered tongue. (c) Gornergletscher, a large glacier that is out of equilibrium.

responded to atmospheric warming by a substantial surface lowering of its lower reaches in addition to glacier retreat (Fig. 2). Due to its long response time, it cannot reach balanced conditions in a timely way through retreat of the terminus to higher elevations. Hence, the opposing effects of glacier retreat and thinning largely compensate each other and the two balances are similar.

4.2. Importance of geometric adjustment

Quantifying the importance of geometric adjustment is not trivial and has so far been attempted in only a few studies. Paul (2010) modelled 1 year's specific mass balances of several glaciers over the geometries of 1850 and 1973 using the same climatic forcing. The difference between these balances corresponds to the effect that geometric adjustment exerted on the glacier's conventional mass balance. Then the mass-balance sensitivity of the glaciers (1850 geometry) to a 1°C temperature increase was simulated to quantify the effect that climate change alone would have had on the mass balance over the >100 year period. By taking the ratio of these numbers, it was concluded that only a third to a half of the expected mass-balance change due to air-temperature increase since 1850 is visible in conventional balances; hence 50–70% of the change is 'hidden' in the geometric adjustment (Paul, 2010). It is important to note that this result refers to average conditions in the period 1850–1973 and only the glaciers considered in that study.

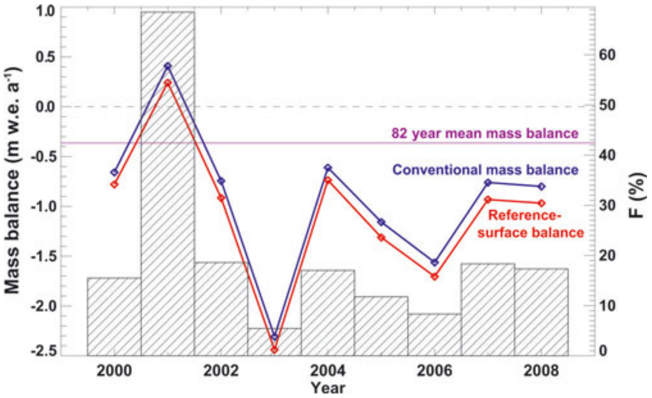

Fig. 6. Time series of 36-glacier average conventional (blue) and first-DEM reference-surface (red) annual mass balances for 2000–08. The right-hand-side axis and the bars refer to F (Eqn (1)).

Alternatively, this issue could be investigated using our conventional and reference-surface mass-balance time series. The fraction F of mass change that is due to geometric adjustment rather than climatic variability may be expressed as

$$F_i = \frac{|\Delta B_{\mathrm{c-r},\,i}|}{|B_{\mathrm{r},\,i}|}, \qquad (1)$$

where $\Delta B_{\mathrm{c-r},i}$ is the difference between conventional and reference-surface annual balance, and $B_{\mathrm{r},i}$ is the annual reference-surface balance, in year i.

Using Eqn (1) the importance of differences between conventional and reference-surface annual balances for 2000–08 is analyzed. F decreases as B_{r} diverges from zero, and is not defined in balanced conditions. For most years in 2000–08, F varies between 10% and 20% (Fig. 6). In 2003, which was characterized by an extremely hot summer, F decreased to 5% because $\Delta B_{\mathrm{c-r}}$ is small compared to the very negative mass balance.

This indicates that the percentage of mass balance that is due to geometric adjustment rather than climate variability is significantly lower for the period 1926–2008 than the value found by Paul (2010), and moreover strongly varies between individual years. Our analysis, however, also shows that expressing the difference between conventional and reference-surface mass balance as a percentage of that year's balance is delicate: glacier mass balance shows strong variations from year to year, as well as on the decadal scale, whereas $\Delta B_{\mathrm{c-r}}$ has no short-term variability but shows a steady long-term increase (Fig. 4).

For this reason, we caution against expressing differences between conventional and reference-surface mass balance as a percentage. The percentage of mass balance that is due to geometric adjustment rather than climate variability – obtained using Paul's (2010) approach or Eqn (1) – refers to the year (or any other time period) considered. It is not transferable to other years or periods, and thus cannot be generalized.

4.3. Retreat versus thinning

$\Delta B_{\mathrm{c-r}}$ depends on two effects that partly compensate each other: glacier terminus retreat and thinning (see Fig. 1). In order to quantify the relative impact of these two processes,

Table 2. Evaluation of glacier surface slope and mean specific annual mass balances averaged over the period 2000–08. $\overline{\alpha_0}$ is the mean surface slope averaged over the lowermost 10% of the glacier for the first DEM, and $\overline{\alpha_1}$ for the last DEM. $\overline{B_c}$ is the conventional balance, and $\overline{B_r}$ the reference-surface balance, calculated over the hypsometry of the first DEM, both averaged over the period 2000–08. $\overline{B_{nt}}$ is the mass balance the glacier would have had if retreat but no surface lowering had occurred over the 20th century. R indicates by how much the mass-balance change that would occur due to glacier terminus retreat alone is reduced by the effect of surface lowering. The mean signal is evaluated by calculating the 36-glacier arithmetic average

Glacier	$\overline{\alpha_0}$ °	$\overline{\alpha_1}$ °	$\overline{B_c}$ m w.e. a^{-1}	$\overline{B_r}$ m w.e. a^{-1}	$\overline{B_{nt}}$ m w.e. a^{-1}	R %
Grosser Aletsch	9	7	–0.93	–1.04	–0.71	67
Gorner	8	8	–1.13	–1.19	–0.99	68
Unteraar	9	12	–1.01	–0.98	–0.84	116
Oberaletsch	8	10	–1.35	–1.26	–1.18	197
U. Grindelwald	13	24	–0.58	–0.82	–0.44	37
Findelen	10	11	–1.05	–1.42	–1.00	12
Corbassière	12	10	–0.52	–0.65	–0.52	0
Rhone	14	8	–0.72	–0.82	–0.51	67
Trift	9	21	–0.84	–1.23	–0.76	16
Morteratsch	10	12	–1.13	–1.32	–0.96	46
Zinal	11	12	–0.94	–0.92	–0.76	111
Allalin	23	14	–0.35	–0.63	–0.35	0
Mittelaletsch	11	11	–1.02	–1.12	–1.00	11
Roseg	9	22	–1.07	–1.54	–0.85	31
Trient	27	27	–0.66	–0.89	–0.59	23
Moming	25	19	–0.88	–0.99	–0.82	32
Giétro	23	19	–0.65	–0.71	–0.39	81
Tschierva	13	14	–0.98	–1.05	–0.81	71
Schwarzberg	18	12	–0.68	–0.72	–0.58	71
Clariden	26	20	–0.47	–0.56	–0.25	71
Gries	10	9	–1.34	–1.47	–1.01	72
Damma	13	21	–1.19	–1.30	–0.96	66
Weisshorn	20	15	–0.77	–1.07	–0.65	27
Silvretta	14	10	–0.77	–0.82	–0.59	79
Limmern	20	20	–0.81	–1.07	–0.68	33
Basodino	23	26	–1.09	–1.46	–0.99	21
Hohlaub	24	14	–0.51	–0.69	–0.40	35
Seewjinen	21	22	–0.93	–1.05	–0.81	51
Cambrena	22	28	–1.06	–1.34	–0.77	50
Orny	17	15	–1.01	–1.05	–0.98	42
Verstankla	20	16	–0.99	–0.99	–0.84	100
Misaun	25	24	–1.08	–1.11	–0.90	86
Plattalva	20	21	–1.01	–1.06	–0.98	34
Tschierva	29	19	–1.23	–1.25	–1.01	91
Chessjen	14	17	–1.05	–1.32	–1.00	13
Pizol	9	18	–0.98	–1.26	–0.67	52
Mean	**16**	**16**	**–0.91**	**–1.06**	**–0.77**	**55**

we evaluate the mass balance the glacier would have had if only retreat, not thinning, had occurred. We reran the model and computed the mass balance, B_{nt}, of each glacier over the glacier extent of the last DEM, but the surface elevation of the first DEM. These balances are expected to be less negative than the corresponding reference-surface balances, B_r, as retreat but no thinning occurred. Figure 7 shows the surface geometry over which different mass balances are evaluated using the example of Rhonegletscher. $B_r - B_{nt}$ quantifies the mass-balance feedback due to glacier terminus retreat alone. The difference in conventional balance $B_c - B_{nt}$ quantifies the self-amplifying mass-balance feedback due to glacier thinning. The ratio of these two back-coupling effects, R, yields the fraction of the negative retreat feedback that is compensated for by the positive elevation feedback.

$$R = \frac{|B_c - B_{nt}|}{|B_r - B_{nt}|}. \qquad (2)$$

A value of R close to zero indicates that surface lowering is small and/or has a negligible effect on the mass balance compared to the effect exerted by glacier terminus retreat (case 1 in Fig. 1); a value of 100% means that the entire terminus retreat effect is compensated by lowering, and that $\Delta B_{c-r} = 0$, i.e. conventional balances are identical to reference-surface balances. Values exceeding 100% indicate that the mass-balance feedback due to thinning is larger than the retreat feedback (case 2 in Fig. 1).

We evaluate R according to Eqn (2) for mean balances over the period 2000–08 (Table 2). On average, roughly half the terminus retreat effect is compensated by the glacier-thinning effect. However, R shows a large variability among the glaciers, and ranges from 0 to 197%. For example, $R = 0$ for Allalingletscher, but for Gornergletscher more than two-thirds of the stabilizing effect on mass balance due to terminus retreat is compensated for by surface lowering (see also Fig. 5). Three glaciers have values exceeding 100%

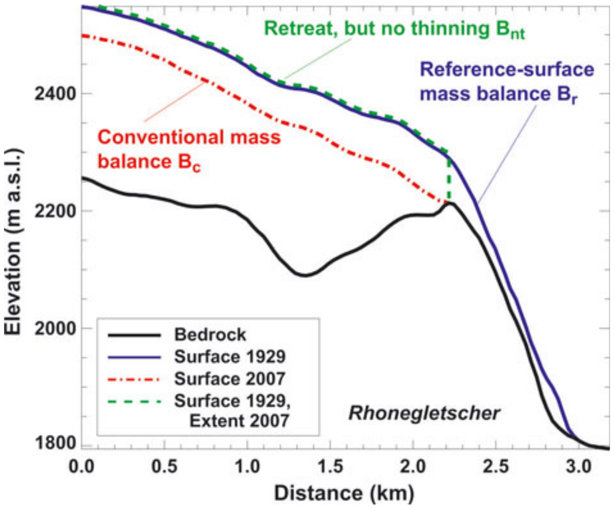

Fig. 7. Longitudinal profile of the tongue of Rhonegletscher (Fig. 2). Lines show the glacier surface in 1929, over which B_r is evaluated; the evolving 2007 surface (evaluation of B_c); and a hypothetical surface experiencing retreat but no thinning for the calculation of B_{nt}.

(Table 2); they have strongly debris-covered tongues, leading to particular dynamics of the geometry change (see Fig. 5b and corresponding descriptions).

4.4. Spatial variability in specific mass balance

Mean 82 year conventional mass balances differ strongly between the 36 glaciers analyzed (Table 1). The drivers of these differences of up to a factor of four between adjacent glaciers are still unclear despite similar climate conditions. Understanding differences in the sensitivity of conventional mass balance within a sample of glaciers to the warming trend observed over the last century is a prerequisite for extrapolating mass-balance series observed on individual glaciers to the mountain-range scale.

Differences in mean specific mass balance between individual glaciers are often explained by the dynamic response of glaciers to a change in climate forcing (Hoelzle and others, 2003): large, flat glaciers have longer response times (Jóhannesson and others, 1989), and thus are expected to exhibit more negative glacier-wide specific conventional mass balances than small, steep glaciers because a larger ice volume has to be melted close to the glacier terminus in order to allow a substantial retreat to a new steady state. Assuming two glaciers had initially similar mass balances, the differences in conventional balance between a large, flat glacier and a small, steep glacier will increase with time, at least at the beginning. In contrast, we expect the differences in reference-surface balances between these two glaciers to be much smaller, because these balances only depend on climate and not on glacier dynamics; the reference-surface balance is independent of glacier response times. Our data series, however, indicate that the spatial mass-balance variability among the 36 glaciers does not significantly decrease when considering reference-surface instead of conventional balances. Despite relatively similar changes in regional climate conditions, the glaciers have different climate sensitivities due to differences in their dynamic response and geometry.

This issue is further analyzed by statistically relating indicators for glacier geometry to mass balance. Since glacier surface slope and area are two variables known to be indicative for glacier dynamics (Oerlemans, 2007), as well as to describe glacier geometry, we correlated them against long-term means of both conventional and reference-surface mass balances. For this analysis we chose not to use the mean overall slope of the glacier, but only the slope averaged over the lowermost 10% of the glacier (according to the first DEM). This part of the surface corresponds to a large fraction of the area lost over the 20th century.

Conventional specific mass balances as a mean over the last 50 years (1958–2008) were correlated with glacier areas. This period was chosen because mass-balance series are well constrained with a high number of DEMs, and considerable differences between conventional and reference-surface mass balances have already been developed (Fig. 4). The correlation is significant according to the F test at the 0.1% level ($r = -0.41$, $n = 36$): the larger the glacier, the more negative its conventional mass balance (Fig. 8a). When considering the reference-surface balance instead, the effect of glacier size is reduced (Fig. 8c; $r = -0.28$) but still significant.

The correlation of mass balance with surface slope averaged over the entire glacier is significant, but the correlation coefficient is relatively small ($r = 0.30$). However, for the investigated glaciers, the slope of the tongue (lowermost 10% of the surface) correlates better than any other variable with the mean conventional mass balance ($r = 0.61$): the steeper the glacier tongue, the less negative its conventional mass balance (Fig. 8b). Interestingly, the correlation of the reference-surface balance and the slope of the glacier tongue remains significant and relatively high ($r = 0.55$; Fig. 8d). This indicates that only a small fraction of the differences in long-term means of specific mass balance between the investigated glaciers can be explained by differential dynamic adjustment of the glacier to new climatic conditions.

The correlation of ΔB_{c-r} and glacier area is not significant. This is also evident from Figure 2. Glacier area is a poor indicator for inferring the differences between conventional and reference-surface mass balance. Although larger glaciers tend to show relatively small ΔB_{c-r}, there are many exceptions (Fig. 8e). Again, the slope of the glacier tongue is better suited for estimating ΔB_{c-r}. Although the correlation is small ($r = 0.31$, $n = 33$), it is significant according to the F test: the steeper the glacier tongue, the larger the difference between conventional and reference-surface mass balance (Fig. 8f).

Values of R (Table 2; Eqn (2)), the percentage of the terminus retreat effect that is compensated by the surface lowering effect, were also correlated to glacier area and terminus slope. There is no evident statistical relation for either area or slope because of the large spread in the results that is probably due to the particular hypsometry of the individual glaciers.

The regression analysis has shown that the slope of the glacier tongue is a valid indicator for inferring differences in long-term specific mass balance between the glaciers, as well as for estimating the difference between conventional and reference-surface balances. Table 2 compiles terminus slopes obtained for both the glacier hypsometry at the beginning of the 20th century and today. Changes in slope may be used as a rough predictor of a glacier's future adaptation potential, i.e. how fast it can achieve a balanced mass budget after a change in forcing.

Several glaciers have shown a steepening of their glacier tongues over time. Triftgletscher and Vadret da Roseg, for

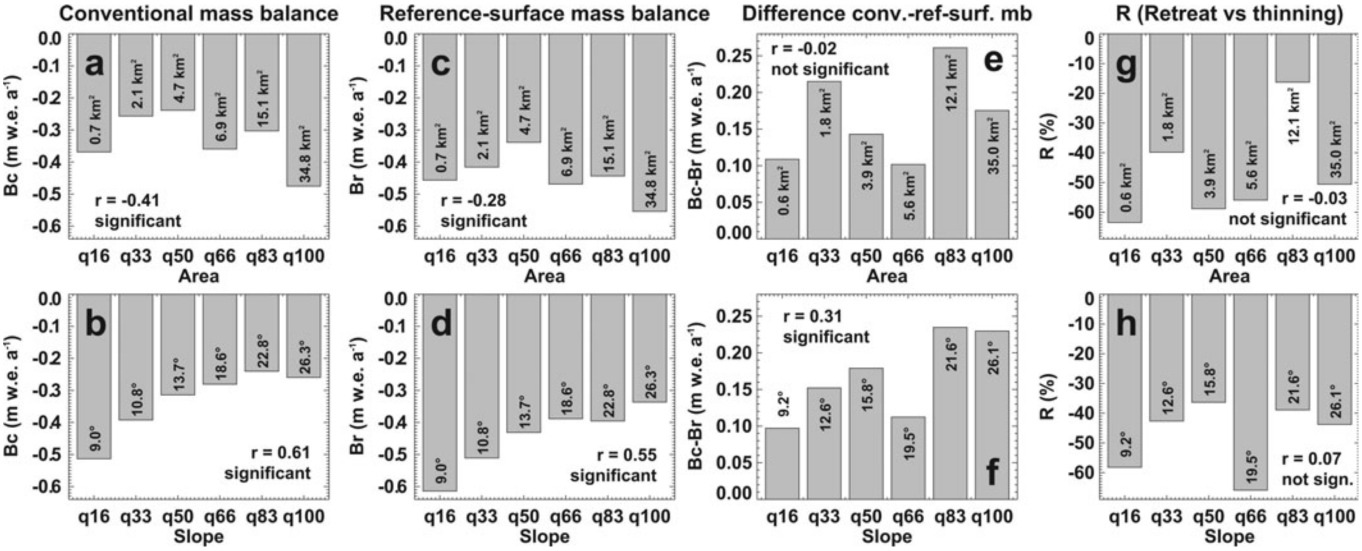

Fig. 8. (a–d) Relationship between the conventional and reference-surface (first DEM) mass balance, averaged over the period 1958–2008, and the glacier area and mean slope of the lowermost 10% of the glacier (first DEM). The linear correlation coefficient, r ($n = 36$), is given and the significance at the 0.1% level according to the F test is stated. Glaciers are sorted according to their area and slope and are divided into six classes including the same number of items (i.e. into six 16.6% quantiles). Bars show the mean mass balance in the classes, and the average area or slope of each class is given. (e–h) Same as (a–d), but for $\Delta B_{\mathrm{c-r}}$ over the period 2000–08, and R (Eqn (2) and Table 2). For the analysis in (e–h) the three strongly debris-covered glaciers (Unteraar, Oberaletsch, Zinal) are excluded, as they would distort the statistical analysis.

example, had gently sloping tongues at the beginning of the 20th century, but have now retreated into steeper terrain (Table 2). Conventional balances for both glaciers were more negative than for most others over the study period. This was favoured by their limited adaptation potential due to relatively gently sloping tongues. With the currently steeper glacier terminus slope, these glaciers might, however, be able to adapt more quickly to rising air temperature by faster retreat to higher elevations in future decades, thus managing to approach equilibrium conditions more easily than other large, flat glaciers such as Grosser Aletsch- or Gornergletscher (Table 2). Allalingletscher has the least negative specific balances throughout the last century, and is thus better adapted to current climate conditions than other glaciers. However, it has now lost its steep glacier tongue, and its terminus now lies in relatively flat terrain (Fig. 2); thus its future adaptation potential is also reduced.

5. CONCLUSION

This study presents the first evaluation of the differences between conventional and reference-surface mass balances based on a large sample of glaciers. Continuous 82 year time series have been derived for 36 glaciers in the Swiss Alps using a comprehensive field data basis and distributed modelling. The differences gradually increase over time between mass balances calculated over the continuously adapting actual glacier hypsometry and extent, and those calculated over a constant geometry. For the case of last century's glacier mass loss in the Swiss Alps, the opposing effects of glacier retreat and surface lowering combine to yield relatively small difference between conventional and reference-surface balances.

Although the magnitude of the long-term trend in glacier surface mass balance is significantly reduced when using conventional instead of reference-surface balances, the short-term to decadal-scale climatic variability is also clearly revealed in conventional balances. This is because the amplitude of year-to-year mass-balance variations is much higher than the monotonically increasing difference between conventional and reference-surface balance series (Fig. 4). The slope of the glacier tongue can be used as a rough indicator for the magnitude of this difference: steep glacier tongues are generally associated with a large $\Delta B_{\mathrm{c-r}}$.

Differences in long-term mean specific mass balance between glaciers within the same mountain range are often significant, although the glaciers experience similar changes in climatic forcing (Kuhn and others, 1985; Paul and Haeberli, 2008; Huss and others, 2010b). However, by no means all these differences can be attributed to the adjustment of glacier geometry and the glaciers' response time to a change in climatic forcing. Correlations between the slope of the glacier tongue and glacier area with long-term mean mass balance are also significant for reference-surface balances calculated over a static surface.

In agreement with Elsberg and others (2001) we recommend that for long-term glacier mass-balance studies both conventional and reference-surface mass balances should be evaluated using methods as described there or applied in this paper. This allows the unbiased interpretation of glacier mass balance in both the hydrological and the climatic context. Furthermore, differences between conventional and reference-surface balance are highly valuable for understanding the geometrical response and the present state of dynamic equilibrium of a glacier.

ACKNOWLEDGEMENTS

Weather data used for the modelling were provided by MeteoSwiss. Swisstopo was responsible for the aerial photograph surveys and H. Bösch carried out the photogrammetrical analysis for the establishment of DEMs. W. Harrison provided insightful comments. Careful reviews by G. Cogley and C. Vincent helped to improve the paper.

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MS received 13 October 2011 and accepted in revised form 7 December 2011