Online Supplement: Reply to the comment of Leclercq et al. on ”100-year mass changes in the Swiss Alps linked to the Atlantic Multidecadal Oscillation”

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Abstract. This Online Material presents one supplementary table, four supplementary figures and additional discussion of issues addressed in the main text.

1 Supplementary text

1.1 Examples of mass balance for individual glaciers

Here we illustrate the differences between conventional and reference-surface mass balances for selected glaciers with varying characteristics (Fig. S1). For most of the investigated glaciers, the differences between conventional and reference-surface balance increases from zero to 0.1 to 0.2 m w.e. a^{-1} throughout the 20th century (Fig. S1a).

Glaciers with steep tongues or small glaciers generally show larger differences between conventional and reference-surface mass balance, because they tend to retreat substantially in response to atmospheric warming thereby approaching a new equilibrium while the effect of surface lowering is of minor importance. For example Allalingletscher (Fig. S1b) had a steep tongue prior to the year 2000. The elevation of the glacier terminus is currently almost 700 m higher than it used to be 100 years ago, whereas surface elevation in the upper reaches of the glacier has only changed little. Therefore, the differences between conventional and reference-surface mass balance series are relatively small. The mass balance response is close to case 1 in Figure S1.

In contrast, large and flat glaciers tend to respond to atmospheric warming by a substantial surface lowering across the entire glacier and in addition to glacier retreat. Due to their long response time (Jóhannesson et al., 1989) they are unable to timely reach balanced conditions through retreat of the terminus to higher elevations. Therefore, the difference between conventional and reference-area mass balances remains small for these glaciers (Fig. S1d).

The tongue of Glacier de Zinal was strongly debris-covered throughout the entire 20th century. This glacier, along with other debris-covered glaciers (Unteraargletscher, Oberaletschgletscher) even shows opposite effects of mass balance reaction (Fig. S1c). Mass balance calculated over the surface geometry of the first DEM can be less negative than the conventional balance. This is explained by the slow retreat of the glacier terminus due to the debris cover and the importance of surface lowering all over the glacier surface (situation close to case 2 in Figure S1).

1.2 Discussion of Nemec et al. (2009) and Paul (2010)

When comparing cumulative series, the difference between conventional and reference-surface mass balance appears to be relatively high (Fig. S4). Based on the difference between cumulative mass balances simulated over the glacier geometries of 1865 and 1998 (Nemec et al., 2009), Leclercq et al. (2010) conclude that 50% of the mass change is ”hidden” in the geometric adjustment. Similar percentages are also found by Paul (2010). However, these numbers are only valid for years or periods with a mass balance corresponding to the long-term average. They are not applicable to periods of below-average mass loss (as for example the last decade of our study period), or periods of mass gain. Furthermore, we have shown that the differences between our conventional and reference-surface mass balances gradually increase from zero at the date of the first DEM (around 1930) to a maximum number during the last decade (see also Fig. S4). As the analysis performed by Nemec et al. (2009) and Paul (2010) refers to the period since the maximum of the Little Ice Age around 1850, their results are not comparable to ours.

We caution against generalizing differences between conventional and reference-surface mass balance obtained for individual glaciers and arbitrary time periods of different

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length. The magnitude of the difference strongly depends on the glacier surface geometry and the length of the period considered. Furthermore, our analysis shows that expressing the fraction of mass balance that is explained by geometric adjustment of the glacier as a percentage is delicate. Percentages refer to the individual glacier and to the time period considered and are not comparable to other glaciers or to other years/periods with deviating mean balances.

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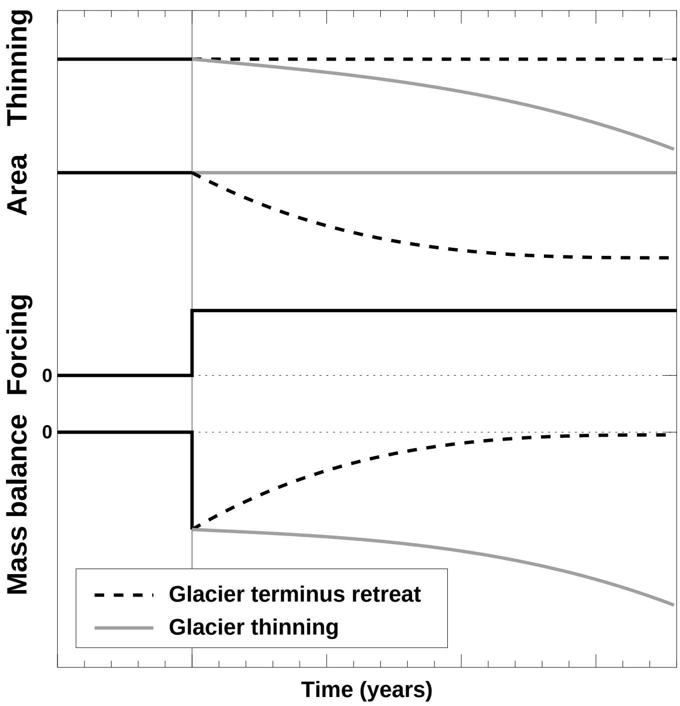
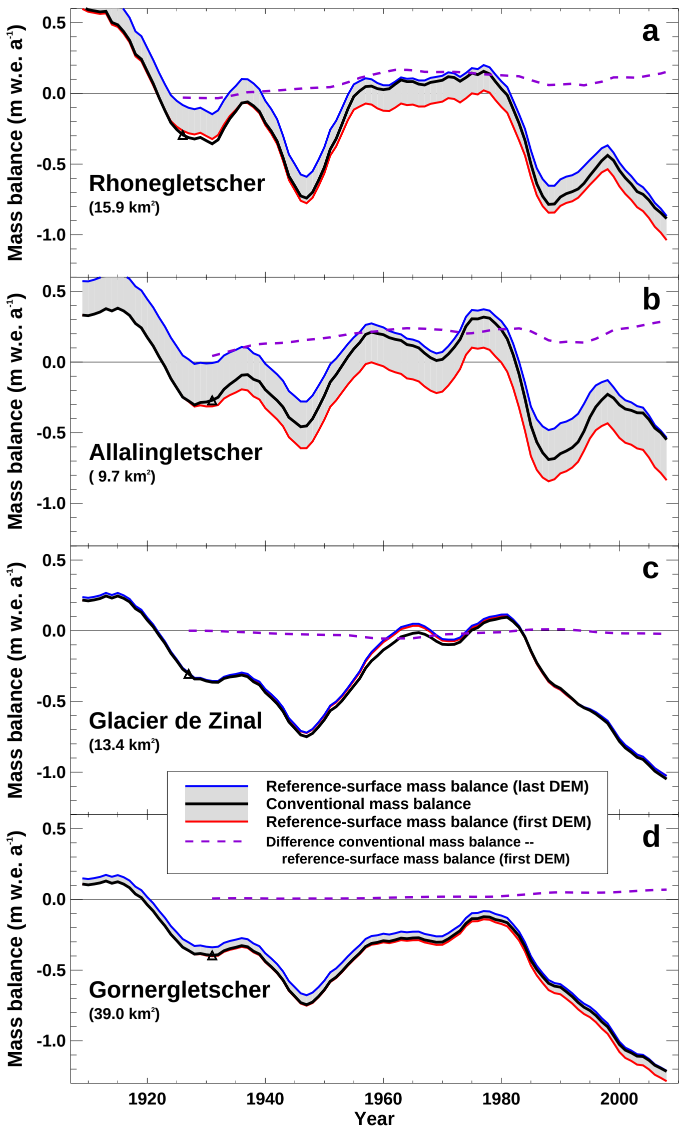
Supplementary Table S 1. Evaluation of specific annual mass balances averaged over the period 2000-2008 for the 30 glaciers presented in Huss et al. (2010). Glaciers are listed by descending current surface area. $\overline{b_{\rm c}}$ is the conventional mass balance, $\overline{b_{\rm r}}$ is the reference-surface mass balance calculated over the hypsometry of the first DEM, and $\overline{b_{\rm nt}}$ is the mass balance the glacier would have if retreat, but no surface lowering has occurred over the 20th century (mass balance calculated over glacier extent of the last DEM, but surface elevation of the first DEM). The difference $\overline{b_{\rm nt}}$-$\overline{b_{\rm r}}$ refers to the effect due to glacier terminus retreat alone (similar as in the estimate of Leclercq et al., 2010). The difference $\overline{b_{\rm c}}$-$\overline{b_{\rm nt}}$ shows the negative effect on mass balance due the glacier thinning. The last column $R_{\rm comp}$=($\overline{b_{\rm c}}$-$\overline{b_{\rm nt}}$)/($\overline{b_{\rm nt}}$-$\overline{b_{\rm r}}$) shows, by how much the mass balance change that would occur due to glacier terminus retreat alone ($\overline{b_{\rm nt}}$-$\overline{b_{\rm r}}$) is reduced by the effect of surface lowering (in percent). The total signal is evaluated by calculating the 30-glacier arithmetic average. When the combined effect of glacier terminus retreat and glacier thinning is included, the apparent decrease in the rate of glacier mass loss, if only accounting for the glacier retreat, is reduced by 46%.

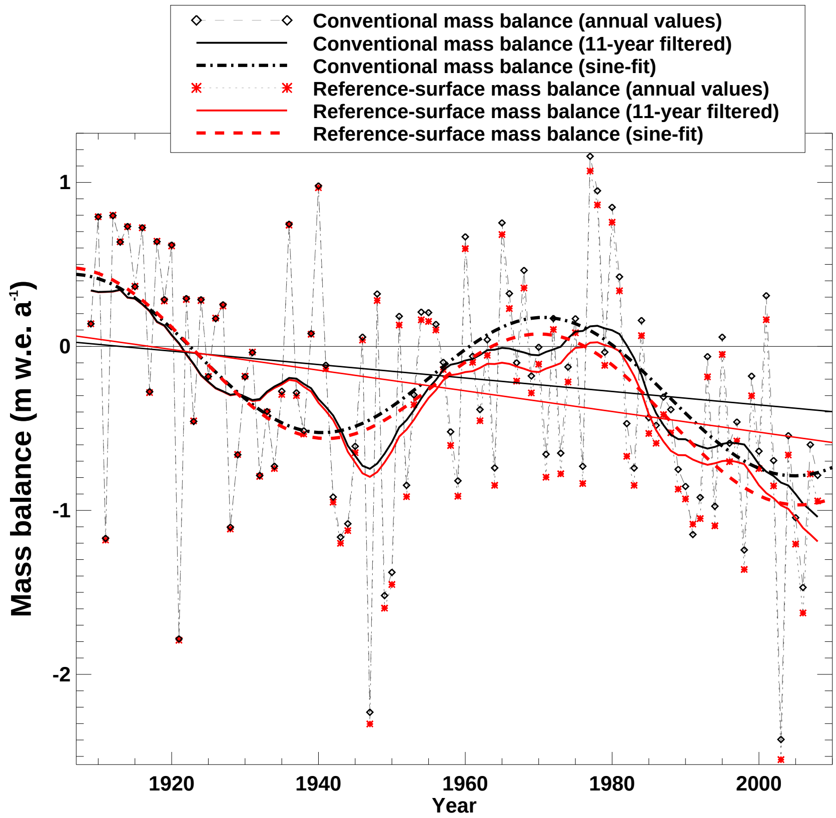
Glacier	$\overline{b_{\rm c}}$	$\overline{b_{\rm r}}$ (m w.e. a^{-1})	$\overline{b_{\rm nt}}$	$R_{\rm comp}$ (%)
Grosser Aletsch	–0.93	–1.04	–0.71	–67
Gorner	–1.13	–1.19	–0.99	–68
Unteraar	–1.01	–0.98	–0.84	–121
Oberaletsch	–1.35	–1.26	–1.18	–187
U. Grindelwald	–0.58	–0.82	–0.44	–37
Findelen	–1.05	–1.42	–1.00	–12
Corbassière	–0.52	–0.65	–0.52	0
Rhone	–0.72	–0.82	–0.51	–67
Trift	–0.84	–1.23	–0.76	–16
Zinal	–0.94	–0.92	–0.75	–112
Allalin	–0.35	–0.63	–0.35	0
Mittelaletsch	–1.02	–1.12	–1.00	–11
Trient	–0.66	–0.89	–0.59	–23
Giétro	–0.65	–0.71	–0.39	–81
Moming	–0.88	–0.99	–0.82	–32
Schwarzberg	–0.68	–0.72	–0.58	–71
Clariden	–0.47	–0.56	–0.25	–71
Gries	–1.34	–1.47	–1.01	–72
Damma	–1.19	–1.30	–0.96	–66
Weisshorn	–0.77	–1.07	–0.65	–27
Silvretta	–0.77	–0.82	–0.59	–79
Hohlaub	–0.51	–0.69	–0.40	–35
Limmern	–0.81	–1.07	–0.68	–33
Basodino	–1.09	–1.46	–0.99	–21
Seewjinen	–0.93	–1.05	–0.81	–51
Orny	–1.01	–1.05	–0.98	–42
Verstancla	–0.99	–0.99	–0.84	–100
Plattalva	–1.01	–1.06	–0.98	–34
Chessjen	–1.05	–1.32	–1.00	–13
Pizol	–0.98	–1.26	–0.67	–52
Total	–0.87	–1.01	–0.75	–46



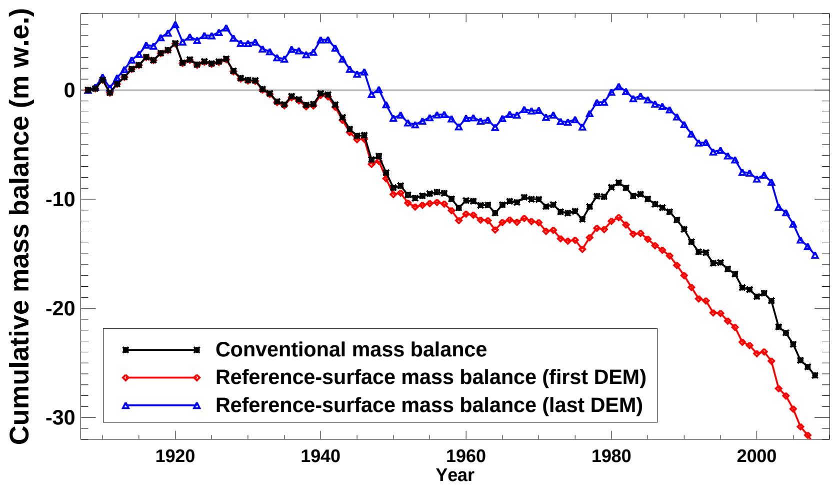
Supplementary Figure S 1. Schematic response of glacier mass balance to an idealized step change in climate that generates a negative mass balance (figure modified after Leclercq et al., 2010). Two end members of a glacier's possible geometric response are shown: (1) the glacier terminus retreats but glacier surface elevation remains unaltered (dashed), and (2) the glacier thins, but the glacier extent remains unchanged (solid). In the former case, the conventional glacier mass balance approaches equilibrium. As the glacier retreats, loss of low-lying areas of high melt are lost making the glacier-wide mass balance progressively less negative. In the latter case, the surface elevation decreases exposing the glacier to higher air temperature and enhanced melt leading to progressively more negative mass balances until the glacier has disappeared. In reality, the glacier's response will lie between these end members. Small and steep glaciers, however, tend to be closer to case (1). Large and flat glaciers are closer to case (2); downwasting of alpine glacier tongues has widely been observed during the last decades (e.g. Paul et al., 2007).



Supplementary Figure S 2. Comparison of conventional and reference-surface mass balance series for selected glaciers over the 20th century. Annual mass balance is low-pass filtered with an 11-year running mean. Curves for the reference-surface (first/last DEM) and the conventional mass balance are shown. The dashed line refers to the difference between the conventional and the reference-surface (first DEM) mass balance. Glacier surface area in 2008 is given, and the date of the first available DEM is indicated with a triangle. We show (a) Rhonegletscher as an example that exhibits a reaction representative for most of the data set, (b) Allalingletscher as a glacier that is well adapted to the current climatic conditions, (c) Glacier de Zinal as a glacier with a debris-covered tongue, and (d) Gornergletscher exemplary for a glacier that is out of equilibrium.



Supplementary Figure S 3. 30-glacier arithmetic mean of 100-year conventional and reference-surface mass balance. As in Huss et al. (2010) a sinusoidal fit to the annual data is shown. The amplitudes achieving the best fit are almost identical for both series. The sine-functions are superimposed on a steeper trend (shown with straight lines) when the reference-surface mass balance is used.



Supplementary Figure S 4. Cumulative time series of 30-glacier arithmetic average conventional and reference-surface mass balance over the 100-year period.