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The influence of changes in glacier extent and surface elevation on modeled mass balance

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Abstract

Glaciers are widely recognized as unique demonstration objects for climate change impacts, mostly due to the strong change of glacier length in response to small climatic changes. However, glacier mass balance as the direct response to the annual atmospheric conditions can be better interpreted in meteorological terms. When the climatic signal is deduced from long-term mass balance data, changes in glacier geometry (i.e. surface extent and elevation) must be considered as such adjustments form an essential part of the glacier reaction to new climatic conditions. In this study, a set of modeling experiments is performed to assess the influence of changes in glacier geometry on mass balance for constant climatic conditions. The calculations are based on a simplified distributed energy/mass balance model in combination with information on glacier extent and surface elevation for the years 1850 and 1973/1985 for a larger sample of glaciers in the Swiss Alps. The results reveal that about 50–70% of the glacier reaction to climate change (here a one degree increase in temperature) is "hidden" in the geometric adjustment, while only 30–50% can be measured as the long-term mean mass balance. Thereby, changes in glacier extent alone have an even stronger effect, but they are partly compensated for by a lowered surface elevation which gives on average a slightly more negative balance despite an increase of topographic shading. In view of several additional reinforcement feedbacks that are observed in periods of strong glacier decline, it seems that the climatic interpretation of mass balance data is also rather complex.

1 Background

Glacier changes are widely recognized as the best natural indicators of climatic change (e.g., Lemke et al., 2007) which is also a result of their systematic and globally coordinated monitoring for more than a century (WGMS, 2008). Today, this monitoring follows

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a tiered strategy within the global terrestrial network for glaciers (GTN-G) as part of the global climate/terrestrial observing systems (GCOS/GTOS) (Haeberli, 2006). The network includes the annual measurement of mass balance at about 60 glaciers and of length changes at about 600 glaciers (e.g. WGMS, 2008). While glacier mass balance can be interpreted as the direct and undelayed reaction to the annual atmospheric conditions, length changes are a delayed, enhanced and filtered signal which reflect atmospheric changes in an integrated way on much longer (i.e. climatic) time scales (e.g., Haeberli et al., 2007).

The high correlation of mass balance with atmospheric conditions (mainly temperature and precipitation) allows us to derive mass balance from meteorologic parameters (cf. Oerlemans, 2001). For this and other reasons it was (and still is) quite popular to extend the short record of mass balance time series back in time with data from climate stations (e.g., Letréguilly and Reynaud, 1990; Greuell, 1992; Huss et al., 2008; Vincent et al., 2004), upper air conditions from radiosonde measurements (e.g., Rasmussen and Conway, 2001), or other proxies (e.g., Linderholm and Jansson, 2007; Watson and Luckman, 2004). Indeed, such extended mass balance time series might no longer be independent proxies of climatic change and have thus to be treated separately from the measured data (Braithwaite, 2009). However, mean values of mass balance over longer time periods can also be determined independent of climatic data, e.g. from cumulative length changes (e.g., Haeberli and Hoelzle, 1995; Hoelzle et al., 2003).

For long-term extensions of mass balance time series it is important to consider the changes in glacier geometry (extent and surface elevation). Because nearly all measurements have been started for hydrological purposes, they refer to the most recent geometry of a glacier. As the geometric changes form an essential part of the dynamic reaction of a glacier to climatic change, the reported mass balance values only reflect a part of the climatic forcing (cf. Harrison et al., 2009) and measured cumulative values increasingly deviate from the related climate forcing. In order to use the mass changes for climate change studies, they have to be independent of climatic data and related to a fixed geometry, the so-called reference surface mass balance (cf. Elsberg et al., 2001; Cox and March, 2004).

While it is possible to directly convert a mean mass change (or ice melt) into the required change of the energy balance (Haeberli and Hoelzle, 1995), there is also an additional climatic interpretation of a long-term mass balance series. In principal, a glacier should reach a new steady-state (or balanced budget) by adjusting its surface properties after a glacier specific response time (e.g., Johannesson et al., 1989). Although this concept is more a theoretical one (due to the continuous climate forcing), a stationary glacier front of a "normal" glacier (i.e. without extensive debris cover or a calving terminus) is an indicator of a glacier that is in balance with the climatic conditions. In the European Alps, the periods 1850–1860, 1920–1930 and 1970–1980 could be related to such steady-state extents for small to medium-sized glaciers (WGMS, 2008).

For a given step change in one of the climatic parameters as for example a sudden temperature increase, glaciers should shrink and the balance related to the actual glacier surface should become less negative and progressively reach zero again (after full dynamic response). For an ongoing climatic forcing annual values will remain negative and for an accelerated forcing mass balance becomes increasingly more negative, maybe until a glacier disappears (Pelto, 2006; Harrison et al., 2009). The latter trend (increasingly negative mass balances over shrinking glacier areas) is currently observed in the Alps (Haeberli et al., 2007) as a response to a one degree temperature increase around 1985 (Beniston, 2005), but also in many other regions of the Northern Hemisphere (WGMS, 2008).

In part, this negative trend might already be enhanced by positive feedbacks which increase the energy available for melt. The latter can include a gradually decreased albedo of bare ice due to pollution (Oerlemans et al., 2009; Paul et al., 2005), enhanced down-wasting due to surface lowering (Raymond et al., 2005; Paul and Haeberli, 2008) and disintegration of glaciers (Carturan and Seppi, 2007; Paul et al., 2004). For many glaciers in the Alps down-wasting rather than retreat is the dominant reaction to the

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strongly increased temperatures after 1985 (Paul et al., 2007a; Paul and Haeberli, 2008). When a glacier front could not retreat to higher elevations (i.e. with lower temperatures), but large parts of the surface melt down and decrease in elevation, glacier melt is enhanced by a reinforcement feedback (Raymond et al., 2005; Fischer, 2010). In particular large glaciers with flat tongues at low elevations suffer from this feedback (e.g., Larsen et al., 2007; Schiefer et al., 2007; Paul and Haeberli, 2008). Thus, mass balance values reported from the Alps in the past decade do already include more than the response to climatic change and their interpretation is less clear than in previous periods (cf. also Fischer, 2010). Additionally, changes in glacier extent make the direct climatic interpretation of measured or reconstructed mass balance difficult (Harrison et al., 2009).

The aim of this study is to assess the influence of a changing glacier extent and surface elevation on modeled mass balance for a larger sample of different glaciers using data from two points in time. The experiments should reveal which part of the climate forcing is "visible" in the measured mass balance and which part is "hidden" in the geometric change. In order to investigate the maximum possible effect, reconstructed glacier extents from the Little Ice Age (LIA) and from the 1970s (outlines from the Swiss glacier inventory) were used. Both periods were characterized by nearly steady-state conditions which allows to tune the mass balance accordingly, e.g. to calculate mass balance sensitivities from a zero balance. Glacier surface elevation is taken from a reconstructed LIA DEM and a DEM from swisstopo representing the mid-1980's, both having a 25 m cell spacing. The mass balance is calculated with a distributed model of intermediate complexity (Machguth et al., 2006b; Paul et al., 2009) that allows calculations over large regions with several glaciers and sparse input data (here restricted to the daily variability of potential global radiation, temperature, and precipitation).

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2 Study region and input data

2.1 Study region

The selection of the study site is driven by the availability of the required input data and its representativeness for the anticipated effects. We have thus selected the region around Great Aletschglacier (Fig. 1), which is still the largest one in the Alps (area: 86 km^2, length 23 km). The region contains glaciers of all sizes, types and expositions, rugged high-mountain topography, and a steep precipitation gradient from the wet north to the drier south. For this region we have digital glacier outlines and 100 m equidistance elevation contour lines from around 1850 that have been digitized by Wipf (1999). Compared to other parts of the world, the Swiss topographic maps from the Little Ice Age (LIA) around 1850 are of a high (maybe unique) quality and have already been used for reconstruction of surface topography and geometric extent (Maisch et al., 2000). We further used digitized glacier outlines from the 1973 Swiss glacier inventory (Paul, 2007), and the DEM25 level 1 from swisstopo (25 m cell spacing) which was compiled in the mid-1980s. We assume that this is representative of the mid 1970s topography, as little change in glacier extent occurred between the mid 1970s and 1980s (Paul et al., 2004) and reported mass balance values indicate nearly steady-state conditions during that period (WGMS, 2007).

2.2 DEM reconstruction

The DEM from 1850 was reconstructed by combining 100 m contour lines with the glacier outlines from 1850 and the DEM25 within a Geographic Information System (GIS). The first step is a conversion of the DEM25 to contour lines with 25 m equidistance spacing and their replacement inside the 1850 glacier outlines with the 100 m contour lines from 1850. In a second step, these contours were interpolated within the GIS to a 50 m cell size DEM using the topogrid routine in Arc/Info (ESRI, 2004). Finally, the 50 m DEM was bilinearly interpolated to 25 m for smoothing and the final

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elevations inside the 1850 glacier outlines were replaced in the recent DEM25 with the interpolated ones. A shaded relief of the 1850 DEM clearly displays artefacts in flat regions of some glacier tongues close to the original contour lines, but often the elevation difference (5–30 m) is much smaller than the elevation change from the LIA to the mid 1970s (50–300 m). Towards the accumulation area however, the elevation changes decrease and the artefacts create more and more erroneous results (e.g. the 1985 surface can be higher than in 1850). In these regions, the interpolated 1850 DEM was reset to the DEM25. Glaciers smaller than 0.5 km^2 in 1850 were excluded from the statistical analysis.

2.3 Climatic data

The applied distributed mass balance model requires only limited inputs, but includes the most relevant processes governing mass balance variability in high mountain topography (Oerlemans, 2001; Paul et al., 2008): temperature (T), precipitation (P) and potential global radiation (R). The mean daily temperature values are generated by a cosine function from an annual mean and range following Oerlemans (1992). The mean annual values for 1850 were selected to give a mass balance that is close to zero in the mean for the entire region. A 1 °C higher temperature is used for some of the simulations with the 1970s glacier extent (Böhm et al., 2001).

The precipitation distribution (annual sums) is taken from the 2 km gridded climatology by Schwarb et al. (2001), which is based on the period 1971–1990 (Frei and Schär, 1998). These data are also used for the 1850 model run, as there is no evidence for a trend in precipitation totals since that time (Begert et al., 2005) and local precipitation gradients should not have changed too much. Moreover, we use precipitation as an additional, locally adapted tuning factor for each glacier, which allows us to be less accurate with the absolute values. In order to get a smoothed input data set, the 2 km precipitation grid was bilinearly resampled to the 25 m cells of the model domain (Fig. 2a).

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Global radiation has a high temporal and spatial variability. For this study the temporal variability due to cloud cover is neglected by assuming a constant cloud factor of 0.5 for each day of the year (cf. Paul et al., 2008). However, the spatial variability of the potential (i.e. cloud-free) global radiation is fully accounted for by calculating a mean daily value for each day of the year and the two DEMs from the computer code SRAD (Wilson and Gallant, 2000). In Fig. 2b the spatial distribution for the 1850 DEM and day 212 (31 July) is shown. All topographic factors (e.g. slope, aspect, sky view factor) are included and changes in global radiation receipt due to a changed glacier geometry is explicitly considered.

3 The mass balance model

The general approach of the applied surface energy and mass balance model is to include the most important variables for Alpine glaciers (T, P, R) with high precision, while others are parameterized more roughly (cf. Oerlemans, 2001). Details of the model used here were described by Paul et al. (2008) and a validation of model performance can be found in Machguth et al. (2006b) and Paul et al. (2009). We thus focus here on a short description of some of its basic characteristics. The model physics are based on the models developed by Oerlemans (1991, 1992) and Klok and Oerlemans (2002) with modifications to include a forcing by meteorological data in raster format. The model starts at day 274 (on October first of a year) with zero snow depth at all cells of the respective DEM and calculates cumulative mass balance for each cell at daily steps for a full hydrologic year (until 30 September).

Mean daily temperature is derived from a synthetic cosine curve (minimum 30 January) and is extrapolated to the elevation of each DEM cell by a constant lapse rate of 6.25 °C/km. Precipitation in the model occurs on each fifth day with 1/73 of the annual sum according to the interpolated climatology by Schwarb et al. (2001). This frequency is rather similar to the natural frequency of larger precipitation events. The mean daily potential global radiation is considered using the pre-calculated SRAD grids for each

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day of the year. Turbulent fluxes depend on temperature and humidity but not on wind speed. However, the exchange coefficient for the turbulent fluxes is allowed to increase down-glacier to mimic an increased surface roughness (Oerlemans, 1992). For this purpose a mean equilibrium line altitude (ELA) of 2900 m is used for the entire model domain. Some other meteorological parameters that are required in the model (e.g. air pressure, humidity) use constant climatologic mean values that are extrapolated to the DEM with their specific gradients (Machguth et al., 2006b; Paul et al., 2008). A snow albedo of 0.7 is used for freshly fallen snow (with an exponential ageing curve) and ice albedo is set to 0.3. Snow thickness (in m w.e.) and the spatio-temporal change of the snow line during the year is explicitly modeled. For a thin snow pack the albedo is reduced according to Klok and Oerlemans (2002) and the ice albedo is used when snow thickness is zero. Other studies have shown that such approaches of the energy balance calculation provide rather good results when compared to measurements or more complex approaches (Oerlemans, 2001; Hock et al., 2007). Net balances are derived in the GIS for each glacier from zone statistics using the respective glacier extents (1850 or 1973) as a zone and the obtained mass balance distribution (from the 1850/1985 DEM) as the values.

4 Experiments

To obtain comparable results, a rather synthetical set-up is used for the experiments. In principal, the analysis is based on two model runs (A and B) with the same climate forcing and the DEMs from 1850 (A) and the mid-1980s (B). The glacier extents from 1850 and 1973 are used to define the regions over which the mean mass balance for each glacier is calculated. Using the glacier-specific mean mass balance from the combination of the DEM 1850 and the extent from 1850 as a reference, three differences in mass balance are calculated:

- Experiment 1 (E1) results in the difference due to a change of the DEM (i.e. surface elevation) but keeps the 1850 extent,

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– E2 results in the difference from the change of the glacier extent (but maintaining 1850s topography), and

– E3 reveals the mass balance difference due to changes in both DEM and glacier extent.

These three experiments allow us to separately assess the change in mass balance due to surface lowering, decreased glacier extent and a combination of both adjustments. Due to glacier split after 1850, comparison (E3) is performed for (a) the 1973 extents, where all parts that belonged to the former 1850 extent are treated as one entity (E3a) and, (b) where all entities in 1973 are considered separately (E3b).

Additionally, mass balance sensitivities for a one degree increase in temperature are calculated for all glaciers and the two epochs (LIA and modern) based on model runs (A) and (B). These experiments (E4a and E4b) reveal how the mass balance sensitivity changes as a consequence of the new geometry. For this purpose, mean annual air temperature was increased by one degree for run (B) and precipitation amounts were tuned for each glacier to obtain a zero mass balance as a starting point. For the tuning, the precipitation sensitivity (change in mean mass balance due to a 10% lower precipitation) was calculated for each glacier and modeled mass balances were divided by this sensitivity to derive the related correction factors. The precipitation grid (Fig. 2b) was corrected with these glacier specific factors and new mass balances were calculated. After the second iteration mass balances were very close to zero (±0.02 m w.e.). The zero balance tuning is required to eliminate any influence from the initial balance on the calculated sensitivity. For example, a reduced sensitivity could be possible for a glacier that has already a negative balance with its ELA located in the steeper accumulation region. In this case, the size change of the ablation region is only small for a given ELA shift. The precipitation sensitivity was not re-calculated starting from a zero balance.

5 Results

For the images depicting differences in mass balance, mean values are first calculated for the respective glacier extents, then the two grids of mean mass balance are subtracted, and finally steps of half standard deviations of the mass balance differences are used for colour coding and visualization. Only glaciers larger than 0.5 km^2 are shown in the figures. The main purpose of these images is to illustrate the spatial variability of the values in the study region rather than to focus on values for individual glaciers. In Fig. 3a the mass balance distribution as obtained by the model is shown for the reference run (A) and the 1850 glacier extent. For better visibility the image is clipped with the glacier cover. The change in mass balance follows elevation closely, because the ice albedo has been fixed to 0.3 and the potential global radiation in the flat ablation regions of the larger glacier tongues has only a limited variability (Fig. 2b). In the accumulation region, the pattern of the precipitation distribution (Fig. 2a) takes over and governs the spatial variability. The modeled ablation at the terminus of -10 m w.e. a^{-1} at Great Aletschglacier (1450 m a.s.l.), and -12 m w.e. a^{-1} at both Grindelwald Glaciers (1200 m a.s.l.) are in agreement with other approaches using midpoint and minimum elevation together with a fixed mass balance gradient (Haeberli and Hoelzle, 1995). The modeled accumulation of 3.5 m w.e. near Jungfraujoch (3550 m a.s.l.) is rather high, but only found in small regions. They likely result from unconsidered processes in the mass balance model (e.g. wind drift) and too high precipitation values in the input data set for this region (Machguth et al., 2009).

The mean mass balance for each glacier without any tuning (run A) is depicted in Fig. 3b, using the above mentioned colour coding. While the arithmetic mean of all individual mass balance values is close to zero, there is a large spread of values between 1.8 and -1.8 m w.e. a^{-1} among the glaciers. In general, a distinct spatial pattern with more negative values in the west and east of the study region and balanced to positive values in the central part can be seen. In particular very small glaciers and those at the Northern Alpine rim have positive mass balances. For the latter this is

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obviously due to higher precipitation (Fig. 2a) and reduced global radiation (Fig. 2b). The very negative mass balance of Unteraarglacier (UAG in Fig. 3b) is most likely due to its low surface elevation. In reality, the glacier tongue is covered by a thick debris layer which might reduce ablation by a factor of two or more (Huss et al., 2007).

In Fig. 4a the results from experiment 1 (E1) are presented. In E1, glacier extent is constant (1850) while the DEM is changed. This reveals the change in mass balance due to the surface lowering alone. Such calculations are possible as the entire domain is covered by glacier ice in the model and mean mass balance does simply result from statistical calculations with the respective glacier zone. In principle, two opposite effects change mass balance in the two DEMs: On the one hand, the decrease in elevation results in higher temperatures which enhances melt and, on the other hand, the glacier surface can be subject to a stronger shading (better radiation protection) which reduces ablation (e.g., Arnold et al., 2006). As expected, the net effect is small as also visible in Fig. 4a. Differences in both directions occur (−0.17 to 0.12 m w.e. a^{-1}) and on average a small negative effect results (−0.05 m w.e.). This implies that the increase in temperature due to lowered elevations is the dominant effect and only few glaciers benefit from decreased radiation receipts due to enhanced shading. This has also been found in a recent study by Fischer (2010) for Hintereisferner in Austria.

In experiment 2 (E2) only the glacier extents are changed and the mass balance from the reference run (A) with the surface of the 1850 DEM is used. The resulting differences are depicted in Fig. 4b. The change in areal extent alone results in much more positive mass balances (up to +1.25 m w.e.) for all glaciers (+0.45 m w.e. in the mean) with a markedly different spatial pattern than for E1 (Fig. 4a). In particular, the flat and highly debris covered glacier tongues of Unteraar- and Oberaletschglacier, both with little change in radiation exposure after the areal change, and those glaciers on the northern slopes which only lost strongly shaded parts of their tongues, do not benefit much from the change in extent. Some glaciers also have a slightly more negative mean mass balance after their reduction in size which is basically due to their special topographic conditions.

In experiment 3 (E3a and E3b) both, the DEM and the glacier extent were changed. As expected, the mass balance change was somewhat smaller than with the change of the area alone (E2) as the surface elevation decrease (E1) generally enhances melt. In the mean, mass balances are about 0.36 m w.e. more positive (Fig. 5a) due to both changes. When the change is related to the 1973 glacier entities (E3b), several tributaries have a much more positive balance (up to 0.9 m w.e.) while others had more negative balances as they lost contact with higher accumulation areas (Fig. 5b).

The spatial variability of the mass balance sensitivity for experiment 4a (outlines and DEM from 1850) is presented in Fig. 6. All glaciers have a negative mass balance sensitivity, mostly between −0.35 and −0.87 m w.e. (mean −0.65 m w.e.) for a 1 °C increase in temperature. These values are in good agreement with other studies using different approaches for calculating sensitivity (e.g., Braithwaite and Zhang, 1999; Oerlemans and Fortuin, 1992). The pattern in Fig. 6 shows a surprising similarity to the pattern of the mass balance distribution in the reference run (A) without tuning (Fig. 3b). Indeed, a linear regression of mass balance and mass balance sensitivity gives a correlation coefficient of r=0.89 (Fig. 7a). This implies that the mass balance sensitivity (starting from a zero balance) can be obtained from an untuned reference run of the model. It is assumed that the similarity is a result of the area-elevation distribution (hypsography) of each glacier that might have a strong influence on both values (Furbish and Andrews, 1984).

The mass balance sensitivity was also calculated for the 1973 glacier extent and the recent DEM (E4b) to assess how the sensitivity has changed for the new geometry. Both sensitivities are compared in the scatter plot of Fig. 7b. Apart from eight glaciers that show virtually no change, the sensitivity for all glaciers decreased by about 0.05 to 0.15 m w.e. a^{-1}. To a certain extent this can be explained by the new position of the equilibrium line (EL), which is for the smaller extent higher up and thus closer to steeper terrain. In this region, the c. 150 m upward shift of the EL results in a comparably smaller change of the size of the ablation area than in flatter regions of a glacier.

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6 Discussion

6.1 Interpretation of the results

Mean measured or indirectly inferred annual mass balance for Alpine glaciers over the period 1850 to the mid 1970s (which represent two nearly steady-state extents) was about −0.2 to −0.3 m w.e. a^{-1} (Haeberli and Hoelzle, 1995; Bauder et al., 2007; Hoelzle et al., 2003; Haeberli et al., 2007; Steiner et al., 2005). Over the same time period, temperatures in the Alps increased by nearly 1 °C (Böhm et al., 2001). According to the sensitivity studies, such an increase would lead to a mean mass balance change of about −0.64 m w.e., which is about 2–3 times higher than measured. According to the experiments presented here, the changes in extent alone result in about 0.45 m w.e. more positive balances (on average), while the surface lowering alone has a smaller effect and accounts for about 0.05 m w.e. more negative balances (on average). Both changes combined cause about 0.36 m w.e. more positive balances, which is also the difference between the reconstructed balance and the theoretical one from the temperature sensitivity. The value for both changes is slightly different from the sum of the individual values as the changes do not scale linearly. As a general figure, the changes in glacier geometry were responsible for about 1/2 to 2/3 of the response to the temperature increase. The observed near steady-state mass balances of Alpine glaciers that occurred during the 1970s can thus be explained with the reconstructed mean mass balance combined with the compensation by geometric changes.

Due to the temperature increase of another degree in the 1980s, the current glacier geometries are again out of balance. The currently observed rapid glacier retreat in the Alps (Citterio et al., 2007; Lambrecht and Kuhn, 2007; Paul et al., 2004, 2007a) will thus continue. Assuming that no further temperature increase will occur, about 40% of the glacier area of the 1970s would have to disappear for a 150 m increase in ELA (Paul et al., 2007b; Zemp et al., 2006). Currently, about 25–30% of the former glacier area may already have disappeared, so about ten more years of retreat (at a rate of

−1% per year) can be expected for glaciers with a response times shorter than a few decades.

6.2 Implications for mass balance reconstructions

The model results have several implications: For proper determination of former mass balances an accurate reconstruction of glacier extent is much more important than that of the surface elevation. This is good news, as the reconstruction of former elevation contours is more error-prone and more uncertain than the determination of former glacier extent. Even where historic topographic maps are available, the elevation contour lines for glacier surfaces are often more hand drawn than measured. Hence, artefacts that might result from the spatial interpolation of a DEM from contour lines with a large equidistance (like an undulating surface) can be neglected. The results also demonstrate that the lowering of the surface elevation predominantly has a negative effect on the mass balance as also found in a recent study by Fischer (2010). In principle, somewhat higher surface temperatures at lower elevations and at the same time a slightly stronger shading in these regions could cancel each other out and for a few glaciers in this study the increased shading is even he dominant effect. This has a consequence for the currently observed down-wasting of many Alpine glaciers (Paul et al., 2007a; Paul and Haeberli, 2008): When their extent does not change too much (e.g. the glacier terminus rests in a stable position), the down-wasting is self-accelerating and able to melt down the ice without further climate change. The related processes were recently observed at the disintegrating tongue of Triftglacier and Gauliglacier and have now started at the tongue of Rhoneglacier (see www.swisseduc.ch). In these cases, the formation of lakes in overdeepened glacier beds accelerated glacier melt even further.

Another consequence is related to reconstructing mass balance back in time. When the actual glacier extent and surface elevation is considered for mass balance calculation (hydrologic balance), more negative mass balances result for a glacier under the same climatic forcing. The direct comparison of mass balances for glaciers with

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different extents is thus misleading. For such a comparison the geometric conditions must be the same. On the other hand, holding glacier extent constant in forward calculation of mass balance results in more negative balances than actually occur as glacier size is overestimated, while reconstructions will be more positive than in reality as glaciers were typically larger in the past. Such effects are currently only roughly considered in models that calculate future glacier changes (Radic and Hock, 2006). As Nemec et al. (2009) have shown in a transient model run (1865 to 2005) for Morteratsch Glacier, the mass balance for a fixed geometry was about 46% more negative than the hydrological one, which is in good agreement with the results obtained here.

The general decrease in the mass balance sensitivity for smaller glacier extents has to be considered for long forward integrations in coupled mass balance/flow models. However, it might be limited to the "classical" Alpine glacier type with increasingly steep backwalls towards higher elevations. In the case of ice caps/ice fields or other glacier types with a different hypsographic curve (more flat towards higher elevations), the sensitivity will likely increase (Furbish and Andrews, 1984).

6.3 Possible errors of the modelling

The applied mass balance model as well as the input data include simplifications that have an influence on the modeled mass balance in absolute terms. However, the main results of the study would not change much if a more complex model or a more accurate extrapolation of the glacier surface had been used as the *differences* in mass balance analysed here are much less influenced by such uncertainties. Moreover, a mass balance model that is based on the energy balance approach is less sensitive to small errors in the input data as some of the errors tend to cancel each other out. For example, regions where artefacts of the reconstructed DEM are present (e.g. a wave pattern) have in most cases two sides, one where mass balance is too negative and one where it is too positive compared to a "correct" surface. In the mean for an entire glacier, both local deviations compensate. However, near the glacier front extrapolation artefacts result in surfaces with a concave instead of a convex curvature and a related underestimation of the solar radiation receipts. This has to be considered when individual glaciers are analysed in detail, for example with mass balance profiles.

The mass balance model does not consider reduced melting for debris-covered glacier parts or redistribution of snow by wind and avalanches. As is obvious from Fig. 3a, several small glaciers located at high elevations have nearly no ablation area. This indicates that absolute precipitation amounts are too high and/or that snow redistribution is important (e.g., Machguth et al., 2006a; Paul et al., 2009). In the experiments performed here, this is compensated for by adjusting the precipitation until a zero mass balance is obtained for each glacier. Related high correction factors point to glaciers where these processes are important for mass balance (Paul et al., 2008).

7 Conclusions

The experiments presented in this study have shown that from a glaciers response to climate change (as given by its mass balance sensitivity) about 50–70% is "hidden" in its geometric adjustment and only 30–50% can be measured or reconstructed. Thereby, the decrease in areal extent (here from the LIA to 1973) results in a mass balance that is on average 0.45 m w.e. more positive, while the lowering of the surface gives on average 0.05 m w.e. more negative balances. However, for individual glaciers, the increased shading of a lowered glacier tongue can also result in a more positive balance. In total, the change in mass balance due to the geometric response combined with the measured/reconstructed balances result in adjusted glacier extents for the one degree higher temperatures of the 1970s, compared to 1850. The strong influence of glacier extent on mean mass balance has several implications: First, both the direct interpretation of mass balance values that refer to a variable geometry and the climatic interpretation of reconstructed/modelled past/future mass balance values is a very complex issue. Second, the same climatic forcing results in more negative mass balances for larger glacier extents and vice versa. Finally, mass balance sensitivities slightly decreased from the LIA to the 1970s glacier extents, for nearly all glaciers in the sample (by 0.06 m w.e. a^{-1} on average). This implies that in steep mountain topography shrinking glaciers are becoming less sensitive to climatic change and might thus be able to stabilize their extent. For icefields or icecaps this effect is likely opposite.

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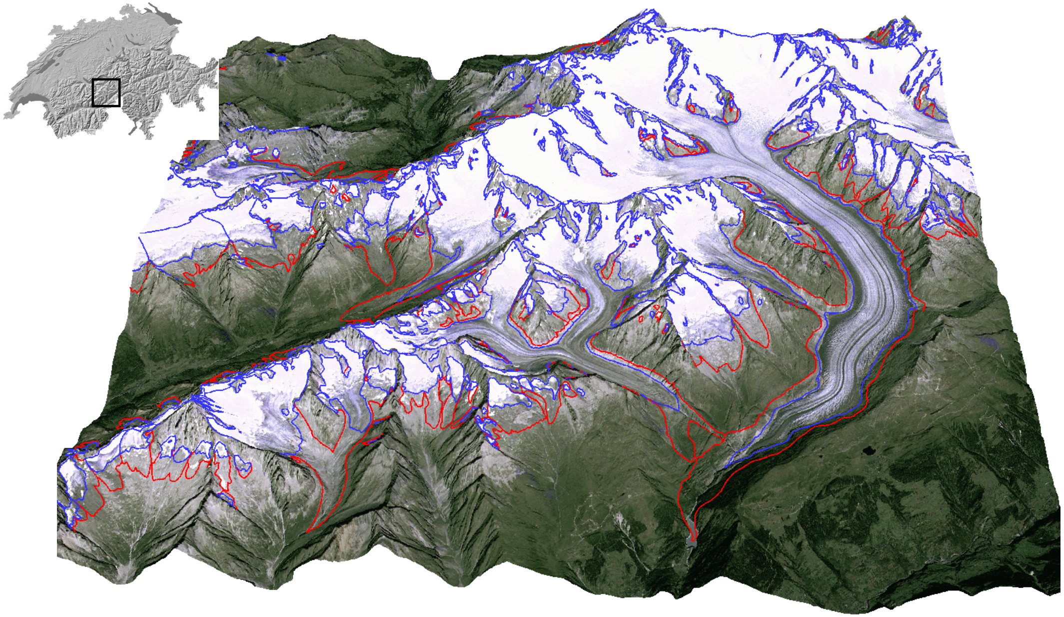

Fig. 1. The region around Great Aletschglacier in a synthetic oblique perspective view created from a pan- sharpened satellite image (Landsat TM with IRS-1C) and glacier outlines from 1850 (red) and 1973 (blue) draped over a DEM. The region covered is 40 km by 41 km in size.The inset map shows the location of the test site in Switzerland (black square). The DEM is reproduced by permission of swisstopo (BA100472).

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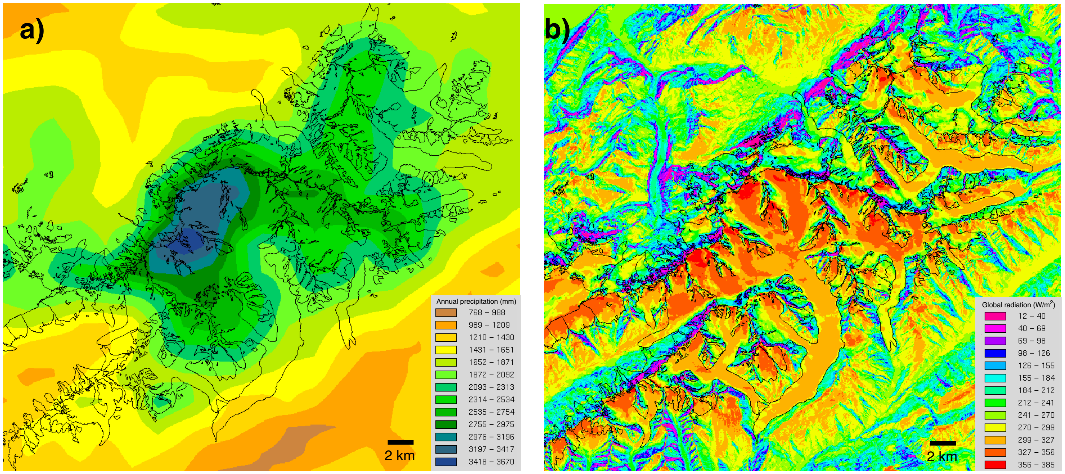

Fig. 2. **(a)** Mean annual precipitation from the Schwarb et al. (2001) climatology resampled from 2 km to 25 m cells with glacier outlines from 1850. **(b)** Mean daily potential global radiation as modeled by SRAD for day 212 of a year (31 July) using the reconstructed DEM from 1850.

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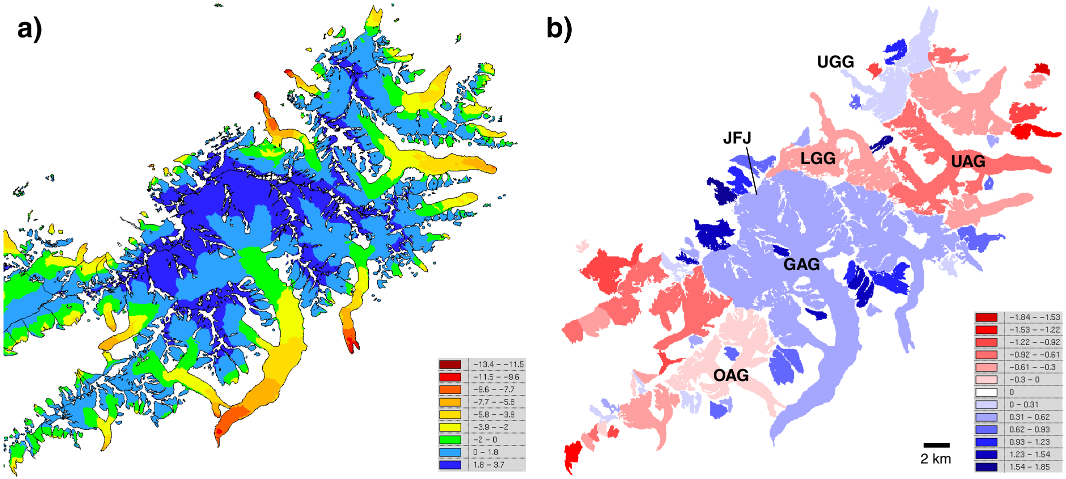

Fig. 3. (a) Mass balance distribution as obtained for the reference run using the DEM and outlines from 1850. **(b)** Resulting mean mass balance values for each glacier (colour coding in 1/2 standard deviations) for the same model run. Locations mentioned in the text are indicated (JFJ: Jungfraujoch, LGG/UGG: Lower/Upper Grindelwaldglacier, OAG: Oberaletschglacier, GAG: Great Aletschglacier, UAG: Unteraarglacier).

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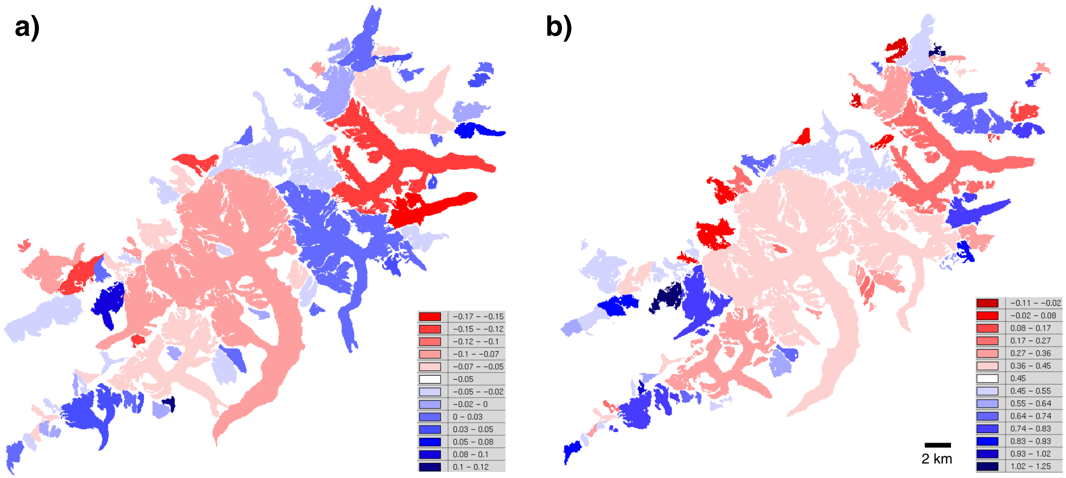

Fig. 4. **(a)** Change in mean mass balance due to a change of the DEM (experiment 1). **(b)** Change in mean mass balance due to a change of glacier extent (experiment 2).

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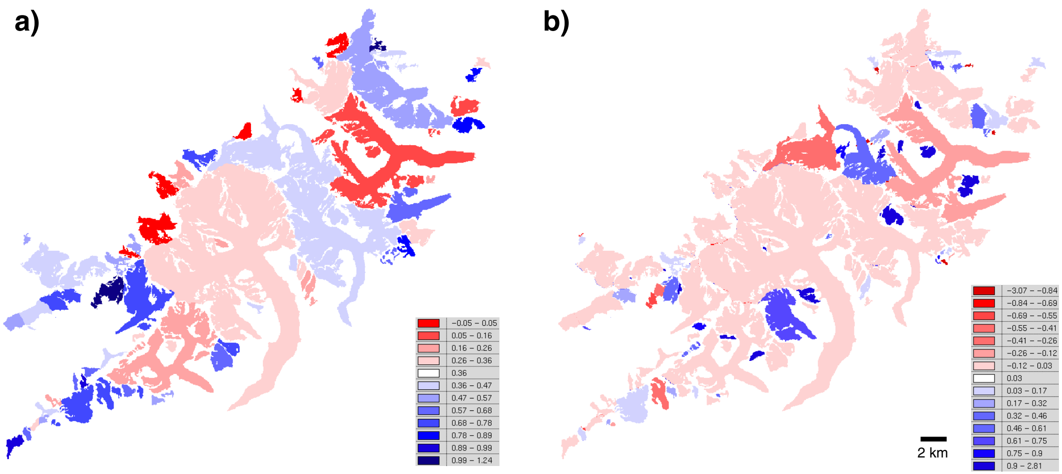

Fig. 5. **(a)** Change in mean mass balance due to a change of the DEM and glacier extent (experiment 3a). **(b)** As Fig. 5b, but here the change in mean mass balance considers glacier split (experiment 3b).

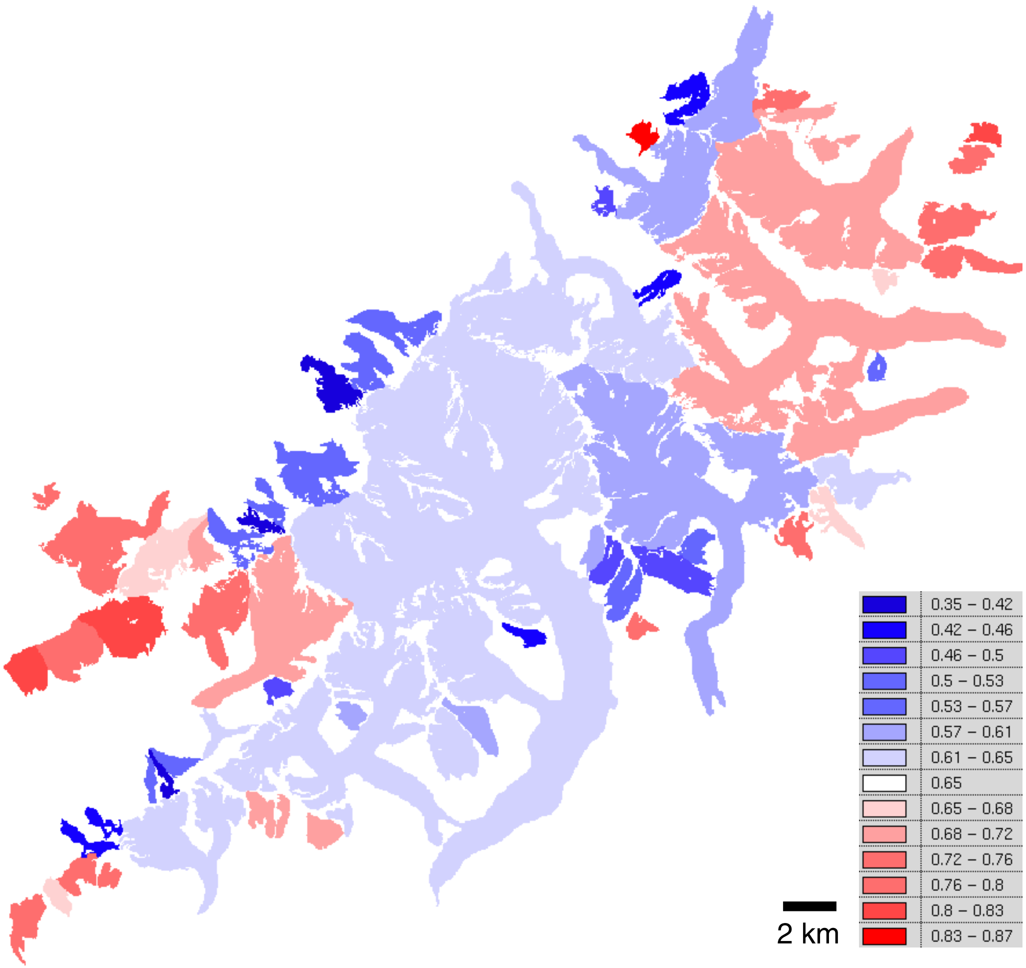

Fig. 6. Mass balance sensitivity for a one degree temperature increase based on the DEM and outlines from 1850 (experiment 4a).

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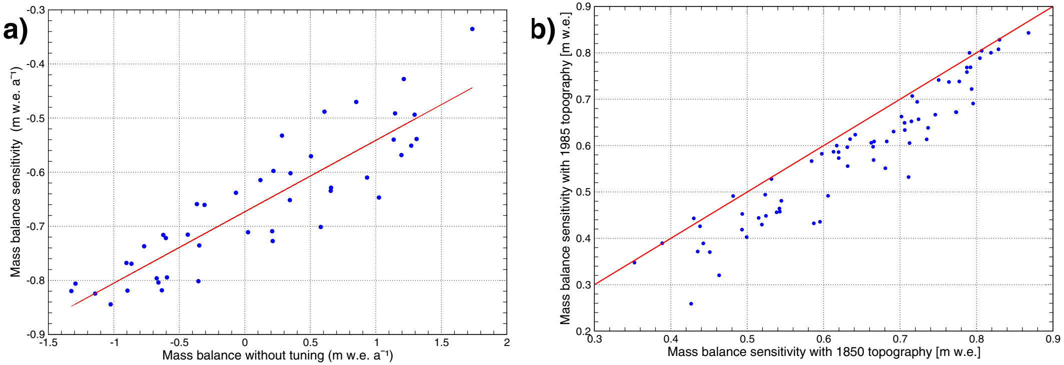

Fig. 7. **(a)** Comparison of the mean mass balance from the reference run without tuning with the mass balance sensitivity starting from a tuned zero balance. **(b)** Scatter plot comparing the mass balance sensitivity for the 1850 DEM and glacier extent with the sensitivity for the 1973 extent and the recent DEM (experiments 4a and 4b).

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