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Density assumptions for converting geodetic glacier volume change to mass change

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TCD

7, 219–244, 2013

Converting glacier volume change to mass change

M. Huss

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Abstract

The geodetic method is widely used for assessing changes in the mass balance of mountain glaciers. However, comparison of repeated digital elevation models only provides a glacier volume change that must be converted to a change in mass using a density assumption. This study investigates this conversion factor based on a firn compaction model applied to simplified glacier geometries with idealized climate forcing, and two glaciers with long-term mass balance series. It is shown that the “density” of geodetic volume change is not a constant factor and is systematically smaller than ice density in most cases. This is explained by the accretion/removal of low-density firn layers, and changes in the firn density profile with positive/negative mass balance. Assuming a value of $850 \pm 60 \text{ kg m}^{-3}$ to convert volume change to mass change is appropriate for a wide range of conditions. For short time intervals ($\leq 3 \text{ yr}$), periods with limited volume change, and/or changing mass balance gradients, the conversion factor can however vary from 0–2000 kg m^{-3} and beyond which requires caution when interpreting glacier mass changes based on geodetic surveys.

1 Introduction

Determination of glacier mass balance via the comparison of two terrain elevation models obtained from air- or space-borne observation is one of the most popular, and most accurate methods to monitor glacier mass change over periods of a few years to some decades (e.g. Rignot et al., 2003; Bamber and Rivera, 2007; Cogley, 2009; Nuth et al., 2010; Gardelle et al., 2012). Geodetic measurements of the glacier mass budget are powerful as large and inaccessible areas can be covered and the integrated changes of the whole glacier system are captured. However, the differencing of Digital Elevation Models (DEMs) provides a change in glacier volume instead of a mass change that is the relevant quantity for climate impact assessments (e.g. sea-level rise contribution, mountain hydrology). In glaciological studies, observable volume change ΔV is usually

TCD

7, 219–244, 2013

Converting glacier volume change to mass change

M. Huss

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



converted to a mass change ΔM by assuming a conversion factor $f_{\Delta V}$ as

$$\Delta M = f_{\Delta V} \cdot \Delta V. \quad (1)$$

The robustness of $f_{\Delta V}$ in time and space is crucial for the accuracy of geodetic mass balance determination, and has received little attention so far.

It can be shown that the factor $f_{\Delta V}$ is not constant in most cases, and is inherently difficult to determine. A temporal change in glacier mass M is given by the change in glacier volume V multiplied by its density ρ as

$$\frac{\partial M}{\partial t} = \frac{\partial(\rho V)}{\partial t}. \quad (2)$$

Integrated with time this yields

$$\Delta M = \Delta\rho V + \Delta V\rho, \quad (3)$$

where ρ is the bulk density of the glacier including its firn coverage, and $\Delta\rho$ is the change in average glacier density over the time interval considered. In practice, the exact individual quantification of $\Delta\rho$, ρ and V is however close to impossible. If we write Eq. (3) as

$$\Delta M = \left(\frac{\Delta\rho V}{\Delta V} + \rho \right) \cdot \Delta V = f_{\Delta V} \cdot \Delta V, \quad (4)$$

the terms $\Delta\rho$, ρ and V can be lumped into the conversion factor $f_{\Delta V}$ which allows direct calculation of mass change from volume change. Nevertheless, it is evident from this formulation that $f_{\Delta V}$ will not be a straight-forward constant.

Most studies make basic assumptions on the conversion factor between volume change and mass change and often rely on Sorge's law (Bader, 1954) that prescribes no changes in the vertical firn density profile over time. If Sorge's law holds, $\Delta\rho$ (Eq. 3) equals zero, and $f_{\Delta V}$ is about 900 kg m^{-3} , a number adopted in many previous assessments of geodetic mass balance (e.g. Cox and March, 2004; Bauder et al., 2007;

Converting glacier volume change to mass change

M. Huss

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**Converting glacier
volume change to
mass change**

M. Huss

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Schiefer et al., 2007; Paul and Haeberli, 2008; Cogley, 2009). A significant change in volume however directly implies either positive or negative mass balance, and hence a shift in the firn line, as well as a change in firn thickness and average density, thus directly contradicting Sorge's law. Based on a simple analysis of firn area changes, Sapiano et al. (1998) estimated the average "density" of volume change as 850 kg m^{-3} . Several recent studies have adopted this value in order to account for the effect of increasing or decreasing firn thickness on $f_{\Delta V}$ (Huss et al., 2009; Zemp et al., 2010; Fischer, 2010, 2011). Another approach is to use zonally variable conversion factors (Moholdt et al., 2010; Gardelle et al., 2012; Kaeaeab et al., 2012). The uncertainty range due to the density assumption is explored by either setting $f_{\Delta V} = 900 \text{ kg m}^{-3}$ for the entire glacier, or 900 kg m^{-3} in the ablation area, and 500 to 600 kg m^{-3} in the firn zone for converting volume changes to mass changes.

Based on a non-steady firn densification model for the percolation zone of the Greenland ice sheet, Reeh (2008) concludes that the "straight-forward translation of observed short-term ice sheet surface-elevation variations into mass changes may be completely misleading". This is explained by the transient adaptations of the firn density profile in response to temporally varying melt and accumulation rates. Helsen et al. (2008) show that surface elevation changes in the interior of Antarctica are mainly due to firn density variations and can not be interpreted as a mass change. These findings related to ice sheet mass balance are also relevant regarding mountain glaciers; surface elevation in the accumulation area, and hence glacier volume, is not coupled linearly to glacier mass.

Assessing the robustness of the conversion factor $f_{\Delta V}$ necessarily involves the application of a model that links the mass of a glacier to its volume by quantifying the terms of Eq. (3). In nature, particularly the direct measurement of mass change is prone to uncertainties, whereas volume change can be determined quite accurately using photogrammetry (e.g. Bauder et al., 2007; Nuth et al., 2010) or laser-scanning techniques (e.g. Abermann et al., 2010). Glacier mass change is normally estimated with the direct glaciological method by integrating surface-density corrected point measurements

over the glacier area. Several studies show, however, that systematic differences between the glaciological and the geodetic method are difficult to interpret as they might be explained by various poorly constrained sources of uncertainty (Zemp et al., 2010; Fischer, 2011). At the mountain-range scale, glacier mass change can also be directly measured with satellite-based observations using gravimetry (e.g. Jacob et al., 2012), but the uncertainties are still considerable and the spatial resolution is too low for providing mass variations of individual glaciers.

To date, no study has connected geodetically measured volume variations of mountain glaciers to their mass balance by taking into account firn compaction at a spatially distributed scale. In order to investigate the value and the temporal robustness of the conversion factor $f_{\Delta V}$ (Eq. 1), an empirical firn densification model coupled to idealized surface mass balance forcing is applied to a range of simplified glacier geometries. Further, the evolution of firn thickness and density since 1960 is simulated for two glaciers in the Swiss Alps based on long-term mass balance observations, and the changes in mass and volume are jointly discussed. This study provides recommendations for the “density” of volume change $f_{\Delta V}$ to be used in mass balance studies based on the geodetic method, and demonstrates in which cases the assumption of a straight-forward conversion factor fails.

2 Data and methods

2.1 Glacier geometry

$f_{\Delta V}$ is assessed at two stages: (1) for synthetic glacier geometries, and (2) in case studies with field data for the 50-yr time series of Gries- and Silvrettagletscher, Swiss Alps. This has the advantage that at stage 1, the response of glacier volume to a prescribed idealized mass balance forcing can be discussed under controlled conditions, depicting the dominant features, and at stage 2, these findings are put into the applied context of a glacier monitoring program.

Converting glacier volume change to mass change

M. Huss

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



A strongly simplified synthetic glacier geometry is defined at stage 1. The glacier is a slab with a constant slope of 15° , a constant width and a given elevation range that is varied between 300 m and 2000 m. For the whole modelling exercise, glacier geometry is assumed to remain constant, i.e. a dynamic response of ice flow is not accounted for.

Griesgletscher (4.97 km^2) and Silvrettagletscher (2.79 km^2 , both in 2007) are typical medium-sized alpine glaciers in the southern and eastern Swiss Alps (Fig. 1). A mass balance monitoring program is maintained since 1960 on both glaciers (Glaciological reports, 1960–2011). Annual mass balance is determined using the glaciological method. Eight (Gries) and six (Silvretta) DEMs are available over the last five decades, documenting changes in glacier area and volume (Bauder et al., 2007). Both mass balance series were homogenized by Huss et al. (2009) and systematic differences between the glaciological and geodetic method were corrected.

2.2 Firn densification

The processes of firn densification have been extensively studied for conditions below freezing level (e.g. Herron and Langway, 1980; Arthern and Wingham, 1998; Li and Zwally, 2004; Reeh, 2008; Ligtenberg et al., 2011). There are few modelling approaches however for temperate firn (e.g. Vimeux et al., 2009), and compaction rates can be higher by one order of magnitude compared to cold firn (Kawashima and Yamada, 1996; Cuffey and Paterson, 2010). The processes governing firn densification (pressure, aging) are active for both temperate and cold conditions thus allowing a similar description. For mountain glaciers, also refreezing of liquid water in the pore space can accelerate firn densification (Schneider and Jansson, 2004). Even in the case of temperate glaciers refreezing can be significant as winter temperatures tend to seasonally cool the uppermost firn layers below 0°C . Physical modelling of the refreezing rate requires the description of heat conduction and data on the surface temperature forcing (e.g. Reijmer and Hock, 2008; Ligtenberg et al., 2011).

Converting glacier volume change to mass change

M. Huss

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Here, the classical firn densification model by Herron and Langway (1980) developed for the Greenland ice sheet (HL-model) modified for the temperate firn of mountain glaciers is employed. The model is suitable for non-steady conditions as described by Reeh (2008), and calculates the density $\rho_{\text{firn}}(t_0, t)$ of the firn layer deposited at time t_0 after a time span of t yr as

$$\rho_{\text{firn}}(t_0, t) = \rho_{\text{ice}} - (\rho_{\text{ice}} - \rho_{\text{firn},0}) \cdot \exp(-c \cdot t) + r_t, \quad (5)$$

where ρ_{ice} is the density of ice, $\rho_{\text{firn},0}$ the density of new firn, and r_t accounts for densification due to refreezing of melt water. A value of $\rho_{\text{ice}} = 900 \text{ kg m}^{-3}$ is assumed as representative for alpine glaciers, and $\rho_{\text{firn},0}$ is set to 520 kg m^{-3} . According to Herron and Langway (1980), the parameter c is defined as

$$c = k_1 (b \cdot \rho_{\text{ice}} / \rho_w)^{1/2}, \quad (6)$$

with a term k_1 that is constant for temperate conditions and is used to tune simulated to observed firn densification (see below). b is the annual accumulation rate in m water equivalent (w.e.) and ρ_w the density of water. In order to keep the model simple (not requiring climate data input) and location-independent, firn densification due to refreezing is roughly approximated by assuming end-of-winter firn temperatures linearly decreasing from -5°C at the surface to 0°C at a depth of 5 m. For each layer, r is obtained by prescribing complete latent heat exchange; total refreezing r_t after t yr is calculated as $r_t = r_{t-1} + r$. After pore close-off at 830 kg m^{-3} , a linear densification rate with age of $10 \text{ kg m}^{-3} \text{ a}^{-1}$ is assumed until ice density is reached.

Density measurements from 13 mountain glacier firn cores were compiled for calibrating the firn compaction model. Firn cores reach depths of 10–22 m and are available for the European Alps (Ambach and Eisner, 1966; Oerter et al., 1982), Western Canada (Sharp, 1951), Central Asia (Kreutz et al., 2001; He et al., 2002), Patagonia (Matsuoka and Naruse, 1999; Shiraiwa et al., 2002), and Svalbard (Pälli et al., 2002). Most cores originate from temperate firn, but some glaciers are also polythermal. The

Converting glacier volume change to mass change

M. Huss

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



most detailed records that resolve the density of annual layers are provided by a 20 m deep firn pit on Kesselwandferner, Austria (Ambach and Eisner, 1966). All other firn density data were averaged in 1 m steps resulting in a representative density-depth relation supported by data from mountain glaciers in different regions. The standard deviation of observed density is 48–82 kg m⁻³ over depths of 1–18 m. The data of Kesselwandferner indicate slightly higher densities compared to the 12-core average profile but pore close-off is reached at the same depth (Fig. 2).

Application of the original HL-model for a location with mean annual accumulation rates equal to those observed by Ambach and Eisner (1966) results in significantly too slow firn compaction (Fig. 2). The modified model version includes a term for re-freezing r_f (Eq. 5), and the parameter $k_1 = 0.110 \text{ m}^{-0.5} \text{ a}^{-0.5}$ (Eq. 6) is optimized to match density profiles obtained from the firn cores. Densification rates with depth and age observed in different regions worldwide agree well with density calculated with the calibrated HL-model indicating that this empirical approach is able to capture firn compaction for a wide range of mountain glaciers (Fig. 2).

2.3 Mass balance forcing

In order to force the firn compaction model for the simplified glacier geometries, four experiments of idealized changes in surface mass balance were defined (Fig. 3). Each experiment consists of two scenarios, with a positive and a negative shift in Equilibrium Line Altitude (ELA), respectively. Before applying a change in mass balance, the model is run for a 50-yr spin-up phase with a balanced mass budget which allows convergence of the firn density profile to an equilibrium.

Surface mass balance distribution is prescribed by two linear elevation gradients db/dz . For the ablation area $db/dz = 0.008 \text{ a}^{-1}$ is assumed, and $db/dz = 0.004 \text{ a}^{-1}$ is chosen for the accumulation area. These values correspond to typically observed mass balance gradients on mid-latitude mountain glaciers (e.g. WGMS, 2008). In Experiment I, an immediate shift of the ELA by +100/–100 m is applied after model spin-up and is maintained for 50 yr. Experiment II prescribes a linear increase/decrease in

Converting glacier volume change to mass change

M. Huss

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



ELA by 5 m a^{-1} . For Experiment III, the step changes in mass balance are limited but the spatial distribution is changed. Whereas the first scenario assumes a 50 % increase in mass balance gradients both in the ablation and the accumulation area, the second scenario is characterized by reduced gradients. Experiment IV yields a shift in ELA (similar to Experiment I) but superimposes a natural year-to-year variability in mass balance (Fig. 3).

Surface mass balance forcing for the case studies on Gries- and Silvrettagletscher is provided by gridded maps of the annual mass balance distribution based on the extrapolation of the in-situ measurements for the period 1961–2007, and 1959–2007, respectively (Huss et al., 2009). The glacier geometry is updated annually taking into account surface lowering and glacier retreat based on direct observations. Both glaciers showed a balanced mass budget between the beginning of the measurements and the 1980s, and strong mass loss afterwards (Huss et al., 2009). Over the two-decadal period 1987–2007, the mean annual balance was $\overline{B}_{20} = -1.15 \text{ m w.e.}$ for Gries, and $\overline{B}_{20} = -0.66 \text{ m w.e.}$ for Silvretta with the ELA above the highest point of the accumulation area in several years causing a substantial degradation of the firn coverage (Fig. 1).

For both the synthetic glaciers and the case studies, mass change ΔM is calculated by integrating surface mass balance over the glacierized area. Volume change ΔV is obtained from the integration of firn layer thickness changes provided by the densification model over the entire firn column. For the ablation area, ice density is assumed to be constant at $\rho_{\text{ice}} = 900 \text{ kg m}^{-3}$. Thus, Eq. (1) can be solved and the conversion factor $f_{\Delta V}$ between volume change and mass change be calculated for arbitrary periods of one year to several decades.

Converting glacier volume change to mass change

M. Huss

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



3 Results

3.1 $f_{\Delta V}$ for idealized glaciers

For each of the four experiments (Fig. 3), the combined model for surface mass balance forcing and firn compaction is run, providing annual series of the change in glacier mass and volume. Figure 4 shows the conversion factor $f_{\Delta V}$ for observation periods of geodetic volume change that start with the step change in climate forcing and increase in length from 1 to 50 yr.

$f_{\Delta V}$ converges towards 900 kg m^{-3} after some decades for all experiments. When the firn density profile is allowed sufficient time to adapt, the cumulative volume loss in the ablation area (with ρ_{ice}) tends to dominate the changes in the firn area. For periods shorter than about two decades – a time interval which is typically covered by geodetic surveys – $f_{\Delta V}$ can, however, be significantly lower than 900 kg m^{-3} (Experiment I), both in the case of positive and negative volume change (Fig. 4a, Table 1). Firn layers with a density smaller than ρ_{ice} are added/removed which tends to make the glacier volume change larger than implied by the first order approximation of $f_{\Delta V} = \rho_{\text{ice}}$, irrespective of the sign of mass balance change. This is also evident from Eq. (4) providing details on the components of $f_{\Delta V}$. For example, a reduction in firn coverage associated with a negative volume change ($\Delta V < 0$) leads to an increase in bulk glacier density ($\Delta\rho > 0$), and thus a value of $f_{\Delta V}$ smaller than average glacier density ρ .

For a linearly increasing/decreasing mass balance (Experiment II), $f_{\Delta V}$ shows a similar evolution as for Experiment I with densities of volume change between 730 and 830 kg m^{-3} for observation period lengths of 2–20 yr (Table 1). The response of glacier volume shows some delay as no stabilization in climate forcing is prescribed (Fig. 3). It is remarkable that already with a minor change in mass balance, as in the first year after the spin-up phase ($\Delta\text{ELA} = 5 \text{ m}$), $f_{\Delta V}$ significantly diverges from 900 kg m^{-3} (Fig. 4b). This indicates that assuming validity of Sorge's law for estimating the factor to convert volume change to mass change is not even feasible for a small shift in mass balance forcing.

Converting glacier volume change to mass change

M. Huss

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Experiment III highlights a particular case that yields surprising results. If mass balance gradients both in the ablation and the accumulation area show a significant increase/decrease together with a relatively small change in glacier-wide mass balance, $f_{\Delta V}$ can assume values significantly larger than the density of water (Fig. 4c, Table 1). Absolute glacier volume changes are thus smaller than the associated mass changes in m^3 w.e. For the case of increasing gradients (Experiment III+), volume loss with ρ_{ice} is enhanced in the ablation zone, whereas the firn volume with a low average density grows in the accumulation area, partly compensating for the ice melt below the ELA. Strongly changing mass balance gradients are a rather particular response of glaciers to climate change, but may occur with rapidly rising air temperatures simultaneous to a precipitation increase as it has recently been observed in Arctic regions (e.g. Abdalati et al., 2005).

“Densities” of glacier volume change higher than 900 kg m^{-3} seem to be unphysical at first glance. However, the conversion factor $f_{\Delta V}$ does not necessarily correspond to the physical properties of a density (see also Eq. 4). For example, a glacier volume change ($\Delta V \neq 0$) can occur without any change in mass ($\Delta M = 0$) purely due to compaction of the firn layers. Conversely, mass balance can be negative ($\Delta M \neq 0$) with no change in total volume ($\Delta V = 0$) if melt increases in the ablation area, compensated in terms of volume by higher accumulation in the firn zone. According to Eq. (1) it is evident that in these special cases, $f_{\Delta V}$ can theoretically be located in the range $[0, \infty]$, but can even be negative if the signs of mass change and volume change are opposite.

Experiment IV is based on a variable mass balance forcing and thus most closely represents real conditions (Fig. 3). Average $f_{\Delta V}$ over 200 model runs of different random variability shows a similar evolution as for Experiment I. The conversion factor increases gradually from about 780 kg m^{-3} towards ice density with increasing observation period length (Table 1). For individual series of variable mass balance forcing, a strongly fluctuating signal is found however, in particular for observation period lengths of ≤ 3 yr (Fig. 4d). The interplay of years with positive and negative mass balance leads to a complex pattern of the firn densification dynamics in which anomalous

accumulation can impact on compaction rates for several years after deposition. If annual or multi-annual mass change is close to zero, already small changes in the firn density profile can induce diverging responses of glacier volume and mass, and hence a conversion factor $f_{\Delta V}$ that is highly variable and difficult to estimate.

The dependence of $f_{\Delta V}$ on glacier size was analyzed by running the model for glacier elevation ranges of 300–2000 m. In general, the conversion factor shows similar trends for small and large glaciers although some spread is evident (Fig. 4). Whereas for scenarios with negative glacier mass balance, the elevation range has little influence on $f_{\Delta V}$ (around $\pm 10 \text{ kg m}^{-3}$), the effect is more pronounced for an increase in ice volume. Glaciers with a limited elevation range in particular can show values of $f_{\Delta V}$ smaller by up to 70 kg m^{-3} compared to large glaciers. This is due to the higher percentage of the area of small glaciers that is affected by a given shift in the ELA. Elevation range is more influential for Experiment III; $f_{\Delta V}$ of small glaciers is below ρ_{ice} (Fig. 4c) because they do not reach a critical size of the accumulation area.

3.2 Application to long-term series

$f_{\Delta V}$ is computed based on a spatially distributed run of the firn compaction model using each year's observed mass balance distribution for Gries- and Silvrettagletscher after the spin-up phase. Calculated firn thickness locally reaches 20 m and shows a pattern related to the spatial variability of surface accumulation rates (Fig. 1). In response to a series of very negative mass balance years after the late 1980s (Glaciological reports, 1960–2011), the thickness of the firn coverage has strongly decreased on Silvretta, and it has almost disappeared on Gries.

Comparison of observed mass balance and calculated volume change for individual years indicates that the annual conversion factor shows a strong variability (Fig. 5a, b). While annual values of $f_{\Delta V}$ range between about -500 and 6500 kg m^{-3} for mass balances B_a of -0.2 to $+0.2 \text{ m w.e. a}^{-1}$, the spread in $f_{\Delta V}$ rapidly reduces with increasing magnitude of mass change being $790 \pm 75 \text{ kg m}^{-3}$ for $|B_a| > 1 \text{ m w.e. a}^{-1}$. The

Converting glacier volume change to mass change

M. Huss

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



observation of poorly constrained conversion factors for annual periods of a fluctuating signal corresponds to the results of Experiment IV (Fig. 4d), and indicates that determining glacier mass balance from short-term (i.e. one to a few years) geodetic surveys might be prone to errors due to an uncertain conversion of volume change to mass change.

$f_{\Delta V}$ was evaluated for periods of between 4 and 14 yr covered by DEMs that have been used for determining geodetic mass balances (Bauder et al., 2007; Huss et al., 2009). The results confirm the above findings. For periods with significant mass loss (i.e. all periods after the mid-1980s), $f_{\Delta V}$ is in the range 777–892 kg m⁻³ (Fig. 5c, d). With ongoing climate change, the firn coverage of small to medium-sized mountain glaciers might completely disappear, resulting in a $f_{\Delta V}$ converging to ice density. From the 1960s to the early 1980s, with mean mass balances close to zero, much more variable values are found for decadal periods. Reduced “densities” of volume change prevailing during these decades are explained by increased accumulation rates leading to the build-up of thick low-density firn layers, and thus relatively large volume changes compared to the almost balanced mass budget.

$f_{\Delta V}$ is 878 kg m⁻³ for Gries, and 866 kg m⁻³ for Silvretta for the entire 5-decadal observation period. Considering the components of $f_{\Delta V}$ (Eq. 4), these numbers seem to be reasonable given a bulk glacier density ρ of slightly below 900 kg m⁻³ (volume-weighted average of mean firn and ice densities), and the changes in glacier density $\Delta\rho$ and volume ΔV over time.

The suitability of using separate conversion factors for volume changes in the accumulation and the ablation area (e.g. Moholdt et al., 2010; Kaeab et al., 2012) was assessed by evaluating zonal surface elevation changes between two DEMs. Geodetic mass change was then calculated using a “density” of volume change of 600 kg m⁻³ in the firn area, and 900 kg m⁻³ below. Resulting changes in overall mass and volume were compared providing $f_{\Delta V, \text{zonal}}$ for all decadal periods (Fig. 5c, d). This relatively simple approach that avoids assuming a constant volume-mass conversion factor over time is able to reproduce some of the decadal variability in $f_{\Delta V}$ found with the firn

Converting glacier volume change to mass change

M. Huss

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



compaction model. It does, however, not take into account that changes in the firm density profile might not be revealed as variations in surface elevation, and hence does not capture the total effect.

4 Discussion

Although Figs. 4 and 5 suggest that values of $f_{\Delta V}$ may be erratic being beyond the physical ranges of snow or ice density, these results do not challenge the usefulness of the geodetic method but indicate that caution is required in some cases when interpreting the results. It has been shown that calculated conversion factors outside of a range of roughly $750\text{--}950\text{ kg m}^{-3}$ occur in connection with (i) short observation periods (1–3 yr), (ii) small volume changes, (iii) strong changes in the mass balance gradients, or a combination of these factors. In practice, (i) can be circumvented by conducting geodetic surveys over sufficiently long time periods. About 5–10 yr seem to be appropriate to significantly reduce the uncertainties inherent to DEM production, and the density assumption (see also Thibert et al., 2008; Huss et al., 2009; Zemp et al., 2010). For case (ii), highly variable $f_{\Delta V}$ result in relatively small absolute errors in calculated mass change as they occur in connection to an almost balanced mass budget (Fig. 5). Significant changes in mass balance gradients (iii) with a limited magnitude of glacier mass loss/gain (Fig. 3c) are related to a major shift in climatic conditions. This particular case needs to be carefully addressed if there are hints that these constraints are met. By accounting for the three above restrictions in the application of the geodetic method, problems arising from an uncertain conversion factor can be tackled and be reduced to an acceptable level.

Sensitivity tests were performed to investigate the robustness of calculated $f_{\Delta V}$ on simplifications in the modelling of glacier volume change. The model was run with idealized mass balance forcing for all experiments (Fig. 3) first using alternative glacier geometries, and second, by modifying the parameters and the formulation of the firm

Converting glacier volume change to mass change

M. Huss

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



compaction model. Differences in the computed conversion factor were then compared to the “reference” results (see Fig. 4, Table 1).

Two additional synthetic glaciers were defined for analyzing the dependence of $f_{\Delta V}$ on glacier geometry: (1) the glacier with a constant width has a slope of 8° below half of its elevation range, and is steep (35°) in its upper reaches; and (2) it is inclined by 35° in the ablation area, and 8° in the accumulation area. The area-elevation distribution of the glacier has a minor influence on $f_{\Delta V}$. Slightly higher average values were found for a glacier exhibiting a steep firn zone ($+2 \text{ kg m}^{-3}$, excluding Experiment III), and lower $f_{\Delta V}$ are present for the glacier geometry with a steep ablation area (-16 kg m^{-3}).

Assessing the performance and the suitability of the HL-model for mountain glaciers is difficult due to the paucity of direct field evidence (the parameters of Eq. (5) are poorly constrained). To test the impact of the approach to model firn compaction on calculated $f_{\Delta V}$, a simple linear firn density change with age was considered and calibrated with observations (Fig. 2). Assuming a constant densification rate of $35 \text{ kg m}^{-3} \text{ a}^{-1}$ yields results for $f_{\Delta V}$ that are lower by 8 kg m^{-3} on average (excluding Experiment III) compared to the reference. For example, $f_{\Delta V} = 836 \text{ kg m}^{-3}$ (Experiment I) is found for a 10-yr observation period (versus 844 kg m^{-3} for the calibrated HL-model).

The sensitivity of $f_{\Delta V}$ on the climate regime, i.e. the surface mass balance distribution and characteristic compaction rates, was analyzed (i) by reducing balance gradients by a factor 2, corresponding to more continental conditions, and (ii) by applying the uncalibrated HL-model (Fig. 2). The approach to model $f_{\Delta V}$ is relatively insensitive even to these major changes in firn compaction. For reduced mass balance gradients, the average conversion factor is 11 kg m^{-3} below the reference results (excluding Experiment III), the uncalibrated HL-model yields an average $f_{\Delta V}$ that is 21 kg m^{-3} lower. This reduction in the conversion factor is due to slower firn compaction, and hence a longer time lag in the response of the firn density profile to changed mass balance forcing.

The sensitivity tests indicate that calculated $f_{\Delta V}$ is robust regarding glacier geometry, the approach to model firn densification, and the climatic regime (continental/maritime) although the simplified setting of the experiments cannot account for all influential

Converting glacier volume change to mass change

M. Huss

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



processes present in nature. For example, densification due to refreezing is only modelled crudely. The conversion factor for most sensitivity tests is slightly below the reference results, but shows the same temporal trends and remains in the range of 700–900 kg m⁻³. Calculated average $f_{\Delta V}$ for Experiment III is higher, in contrast, for some sensitivity runs as they generally yield lower compaction rates thus exaggerating the firn volume response to a given mass balance forcing.

Besides the process of firn compaction that was explicitly modelled in this study, other effects can also influence the “density” of glacier volume change. Fischer (2011) describes the impact of opening and closure of crevasses on geodetic volume change in detail. If many crevasses are present, the bulk density of the entire ice body decreases. Changes in crevasse frequency over time might lead to a bias in the conversion of volume to mass. The importance of this effect also depends on the timing (snow coverage) and the spatial resolution of the geodetic survey. Although this process might affect $f_{\Delta V}$, its magnitude is difficult to quantify and needs to be addressed for each case individually.

5 Conclusions

The factor for converting glacier volume change to mass change is difficult to estimate and shows a considerable variability that affects the accuracy of the widely used geodetic method for the determination of glacier mass balance. Using an empirical firn compaction model adapted for mountain glaciers, the “density” of volume change was assessed for synthetic model glaciers with idealized climate forcing, and for two long-term glacier monitoring programs. The conversion factor $f_{\Delta V}$ is, in most cases, below the ice density which is used in numerous studies for calculating mass balance from geodetic volume change. The effect is relatively small yielding a typical overestimate of mass change of 1–10 %, but it is systematic, and thus needs to be accounted for. For observation periods of some years to several decades featuring significant changes in glacier volume, the density of volume change often lies in the range of 800–890 kg m⁻³,

Converting glacier volume change to mass change

M. Huss

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**Converting glacier
volume change to
mass change**M. Huss

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



both for positive and negative mass balances. For the particular case of strong changes in mass balance gradients together with limited mass gain/loss, $f_{\Delta V}$ can however also be systematically higher than the ice density. If short time intervals (1–3 yr) in a fluctuating mass balance signal are considered, and/or the volume changes over the observation period are small, $f_{\Delta V}$ can show an erratic behavior and may assume values of 0–2000 kg m⁻³ and beyond.

The findings of this study are in line with the simple assessment of $f_{\Delta V}$ by Sapiano et al. (1998) but highlights the strong variability, the underlying processes and the problems inherent to assuming a constant factor to convert geodetic volume change and mass change. For most cases, $f_{\Delta V} = 850 \pm 60$ kg m⁻³ is recommended. However, the conversion factor can strongly diverge from this mean value for particular conditions, and the density assumption might represent a significant component of uncertainty in geodetically determined mass balances.

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References

- Abdalati, W., Krabill, W., Frederick, E., Manizade, S., Martin, C., Sonntag, J., Swift, R., Thomas, R., Yungel, J., and Koerner, R.: Elevation changes of ice caps in the Canadian Arctic Archipelago, *J. Geophys. Res.*, 109, F04007, doi:10.1029/2003JF000045, 2005. 229
- Abermann, J., Fischer, A., Lambrecht, A., and Geist, T.: On the potential of very high-resolution repeat DEMs in glacial and periglacial environments, *The Cryosphere*, 4, 53–65, doi:10.5194/tc-4-53-2010, 2010. 222
- Ambach, W. and Eisner, H.: Analysis of a 20 m firn pit on the Kesselwandferner (Ötztal Alps), *J. Glaciol.*, 6, 223–231, 1966. 225, 226, 241
- Arthern, R. and Wingham, D.: The natural fluctuations of firn densification and their effect on the geodetic determination of ice sheet mass balance, *Climatic Change*, 40, 605–624, 1998. 224

Converting glacier volume change to mass change

M. Huss

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



- Bader, H.: Sorge's law of densification of snow on high polar glaciers, *J. Glaciol.*, 2, 319–323, 1954. 221
- Bamber, J. L. and Rivera, A.: A review of remote sensing methods for glacier mass balance determination, *Global Planet. Change*, 59, 138–148, 2007. 220
- 5 Bauder, A., Funk, M., and Huss, M.: Ice volume changes of selected glaciers in the Swiss Alps since the end of the 19th century, *Ann. Glaciol.*, 46, 145–149, 2007. 221, 222, 224, 231
- Cogley, J. G.: Geodetic and direct mass balance measurements: comparison and joint analysis, *Ann. Glaciol.*, 50, 96–100, 2009. 220, 222
- Cox, L. H. and March, L. S.: Comparison of geodetic and glaciological mass-balance techniques, Gulkana Glacier, Alaska, USA, *J. Glaciol.*, 50, 63–70, 2004. 221
- 10 Cuffey, K. M. and Paterson, W. S. B.: *The Physics of Glaciers*, 4. edn., Butterworth-Heinemann, Oxford, 704 pp., 2010. 224
- Fischer, A.: Glaciers and climate change: Interpretation of 50 years of direct mass balance of Hintereisferner, *Global Planet. Change*, 71, 13–26, 2010. 222
- 15 Fischer, A.: Comparison of direct and geodetic mass balances on a multi-annual time scale, *The Cryosphere*, 5, 107–124, doi:10.5194/tc-5-107-2011, 2011. 222, 223, 234
- Gardelle, J., Berthier, E., and Arnaud, Y.: Slight mass gain of Karakoram glaciers in the early twenty-first century, *Nat. Geosci.*, 5, 322–325, doi:10.1038/ngeo1450, 2012. 220, 222
- Glaciological reports: The Swiss Glaciers, 1958/59–2006/07, No. 80-128, Yearbooks of the Cryospheric Commission of the Swiss Academy of Sciences (SCNAT), Laboratory of Hy-
- 20 draulics, Hydrology and Glaciology (VAW) of ETH Zürich, 1960–2011. 224, 230
- He, Y., Yao, T., Theakstone, W., Cheng, G., Yang, M., and Chen, T.: Recent climatic significance of chemical signals in a shallow firn core from an alpine glacier in the South-Asia monsoon region, *J. Asian Earth Sci.*, 20, 289–296, 2002. 225
- 25 Helsen, M. M., van den Broeke, M. R., van de Wal, R. S. W., van de Berg, W. J., van Meijgaard, E., Davis, C. H., Li, Y., and Goodwin, I.: Elevation changes in Antarctica mainly determined by accumulation variability, *Science*, 320, 1626–1629, doi:10.1126/science.1153894, 2008. 222
- Herron, M. M. and Langway, C. C.: Firn densification: an empirical model, *J. Glaciol.*, 25, 373–385, 1980. 224, 225
- 30 Huss, M., Bauder, A., and Funk, M.: Homogenization of long-term mass balance time series, *Ann. Glaciol.*, 50, 198–206, 2009. 222, 224, 227, 231, 232

- Jacob, T., Wahr, J., Pfeffer, W. T., and Swenson, S.: Recent contributions of glaciers and ice caps to sea level rise, *Nature*, 482, 514–518, doi:10.1038/nature10847, 2012. 223
- Kaeaeab, A., Berthier, E., Nuth, C., Gardelle, J., and Arnaud, Y.: Contrasting patterns of early twenty-first-century glacier mass change in the Himalayas, *Nature*, 488, 495–498, doi:10.1038/nature11324, 2012. 222, 231
- Kawashima, K. and Yamada, T.: Experimental studies on the transformation from firn to ice in the wet-snow zone of temperate glaciers, *Ann. Glaciol.*, 24, 181–185, 1996. 224
- Kreutz, K. J., Aizen, V. B., Cecil, L. D., and Wake, C. P.: Oxygen isotopic and soluble ionic composition of a shallow firn core, Inilchek glacier, central Tien Shan, *J. Glaciol.*, 47, 548–554, 2001. 225
- Li, J. and Zwally, H. J.: Modeling the density variation in the shallow firn layer, *Ann. Glaciol.*, 38, 309–313, 2004. 224
- Ligtenberg, S. R. M., Helsen, M. M., and van den Broeke, M. R.: An improved semi-empirical model for the densification of Antarctic firn, *The Cryosphere*, 5, 809–819, doi:10.5194/tc-5-809-2011, 2011. 224
- Matsuoka, K. and Naruse, R.: Mass balance features derived from a firn core at Hielo Patagónico Norte, South America, *Arct., Antarct. Alp. Res.*, 31, 333–340, 1999. 225
- Moholdt, G., Nuth, C., Hagen, J. O., and Kohler, J.: Recent elevation changes of Svalbard glaciers derived from ICESat laser altimetry, *Remote Sens. Environ.*, 114, 2756–2767, 2010. 222, 231, 244
- Nuth, C., Moholdt, G., Kohler, J., Hagen, J. O., and Käab, A.: Svalbard glacier elevation changes and contribution to sea level rise, *J. Geophys. Res.*, 115, F01008, doi:10.1029/2008JF001223, 2010. 220, 222
- Oerter, H., Reinwarth, O., and Rufli, H.: Core drilling through a temperate Alpine glacier (Ver-nagtgferner, Oetzal Alps) in 1979, *Zeitschrift für Gletscherkunde und Glazialgeologie*, 18, 1–11, 1982. 225
- Pälli, A., Kohler, J. C., Isaksson, E., Moore, J. C., Pinglot, J. F., Pohjola, V. A., and Samuelsen, H.: Spatial and temporal variability of snow accumulation using ground-penetrating radar and ice cores on a Svalbard glacier, *J. Glaciol.*, 48, 417–424, 2002. 225
- Paul, F. and Haeberli, W.: Spatial variability of glacier elevation changes in the Swiss Alps obtained from two digital elevation models, *Geophys. Res. Lett.*, 35, L21502, doi:10.1029/2008GL034718, 2008. 222

Converting glacier volume change to mass change

M. Huss

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**Converting glacier
volume change to
mass change**

M. Huss

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



- Reeh, N.: A nonsteady-state firn-densification model for the percolation zone of a glacier, *J. Geophys. Res.*, 113, F03023, doi:10.1029/2007JF000746, 2008. 222, 224, 225
- Reijmer, C. H. and Hock, R.: Internal accumulation on Storglaciären, Sweden, in a multi-layer snow model coupled to a distributed energy- and mass-balance model, *J. Glaciol.*, 54, 61–72, 2008. 224
- 5 Rignot, E., Rivera, A., and Casassa, G.: Contribution of the Patagonia Icefields of South America to sea level rise, *Science*, 302, 434–437, doi:10.1126/science.1087393, 2003. 220
- Sapiano, J., Harrison, W. D., and Echelmeyer, K. A.: Elevation, volume and terminus changes of nine glaciers in North America, *J. Glaciol.*, 44, 119–135, 1998. 222, 235
- 10 Schiefer, E., Menounos, B., and Wheate, R.: Recent volume loss of British Columbian glaciers, Canada, *Geophys. Res. Lett.*, 34, L16503, doi:10.1029/2007GL030780, 2007. 222
- Schneider, T. and Jansson, P.: Internal accumulation in firn and its significance for the mass balance of Storglaciären, Sweden, *J. Glaciol.*, 50, 25–34, 2004. 224
- Sharp, R. P.: Features of the firn on Upper Seward Glacier St. Elias Mountains, Canada, *J. Geol.*, 59, 599–621, 1951. 225
- 15 Shiraiwa, T., Kohshima, S., Uemura, R., Yoshida, N., Matoba, S., Uetake, J., and Angelica Godoi, M.: High net accumulation rates at Campo de Hielo Patagónico Sur, South America, revealed by analysis of a 45.97 m long ice core, *Ann. Glaciol.*, 35, 84–90, 2002. 225
- Thibert, E., Blanc, R., Vincent, C., and Eckert, N.: Glaciological and volumetric mass balance measurements error analysis over 51 years for the Sarennes glacier, French Alps, *J. Glaciol.*, 54, 522–532, 2008. 232
- 20 Vimeux, F., Ginot, P., Schwikowski, M., Vuille, M., Hoffmann, G., Thompson, L. G., and Schotterer, U.: Climate variability during the last 1000 years inferred from Andean ice cores: a review of methodology and recent results, *Palaeogeogr. Palaeoclimatol.*, 281, 229–241, 2009. 224
- 25 WGMS: Fluctuations of Glaciers, 2000–2005, Vol. IX, ICSU(FAGS)/IUGG(IACS)/UNEP/UNESCO/WMO, World Glacier Monitoring Service, Zurich, Switzerland, 2008. 226
- Zemp, M., Jansson, P., Holmlund, P., Gärtner-Roer, I., Koblet, T., Thee, P., and Haeberli, W.: Reanalysis of multi-temporal aerial images of Storglaciären, Sweden (1959–99) – Part 2: Comparison of glaciological and volumetric mass balances, *The Cryosphere*, 4, 345–357, doi:10.5194/tc-4-345-2010, 2010. 222, 223, 232
- 30

Converting glacier volume change to mass change

M. Huss

Table 1. Calculated conversion factor $f_{\Delta V}$ (in kg m^{-3}) for all experiments (Fig. 3) and different lengths of the observation period (in years) after a change in mass balance. Scenarios with a positive (+) and a negative (–) shift in ELA are shown.

	2 a	5 a	10 a	20 a	40 a
Experiment I+	774	813	844	870	884
Experiment I–	739	785	824	858	878
Experiment II+	732	762	796	835	867
Experiment II–	730	756	787	820	848
Experiment III+	1680	1333	1112	995	945
Experiment III–	1543	1229	1065	975	935
Experiment IV+	808	816	844	870	885
Experiment IV–	755	792	829	860	879

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Converting glacier volume change to mass change

M. Huss

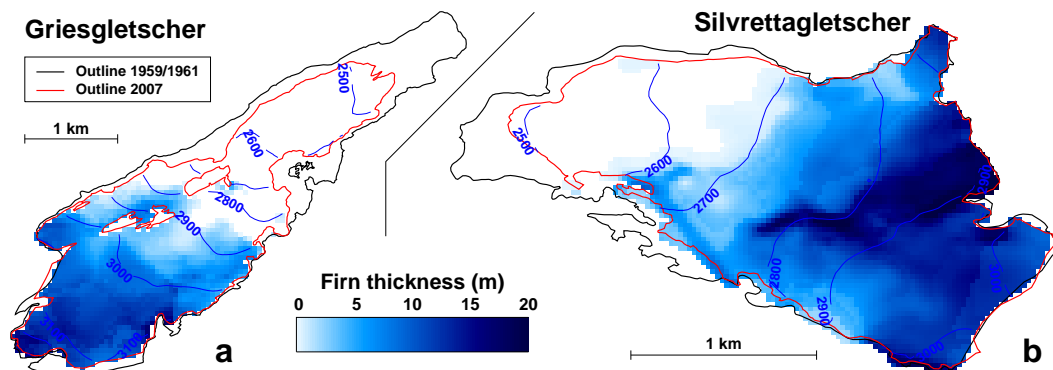


Fig. 1. Overview maps of (a) Griesgletscher and (b) Silvrettagletscher (enlarged by a factor 2), Swiss Alps, with glacier outlines around 1960 and in 2007, and modelled firn thickness (see below) in 1985 (down to pore close-off at 830 kg m^{-3}).

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Converting glacier volume change to mass change

M. Huss

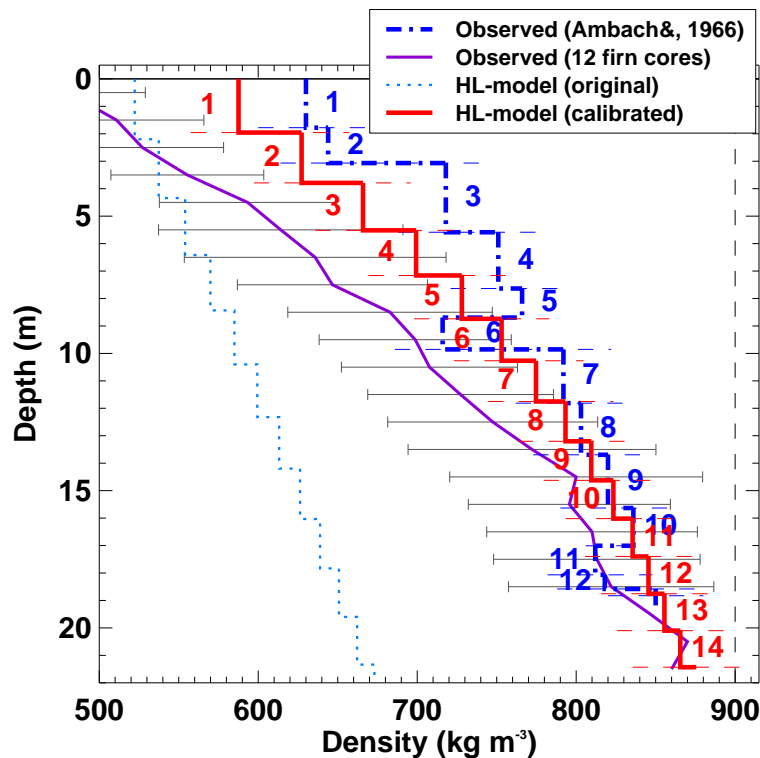


Fig. 2. Validation of calculated firn density (constant accumulation rate) against field measurements. Density of annual layers according to Ambach and Eisner (1966) and a mean density profile from 12 firn cores in different regions worldwide are shown (± 1 standard deviation given by grey bars). Numbers indicate the age of the firn layers in years.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Converting glacier volume change to mass change

M. Huss

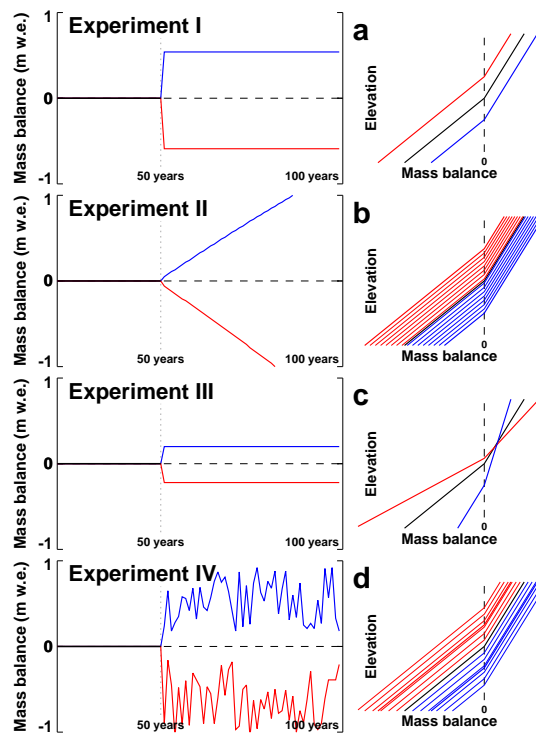


Fig. 3. Four experiments of surface mass balance forcing. Time series of glacier-wide mass balance (left), and mass balance distribution with elevation (right) are shown for each experiment. An experiment consists of two scenarios with a positive (red) and a negative (blue) shift in equilibrium line altitude.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Converting glacier volume change to mass change

M. Huss

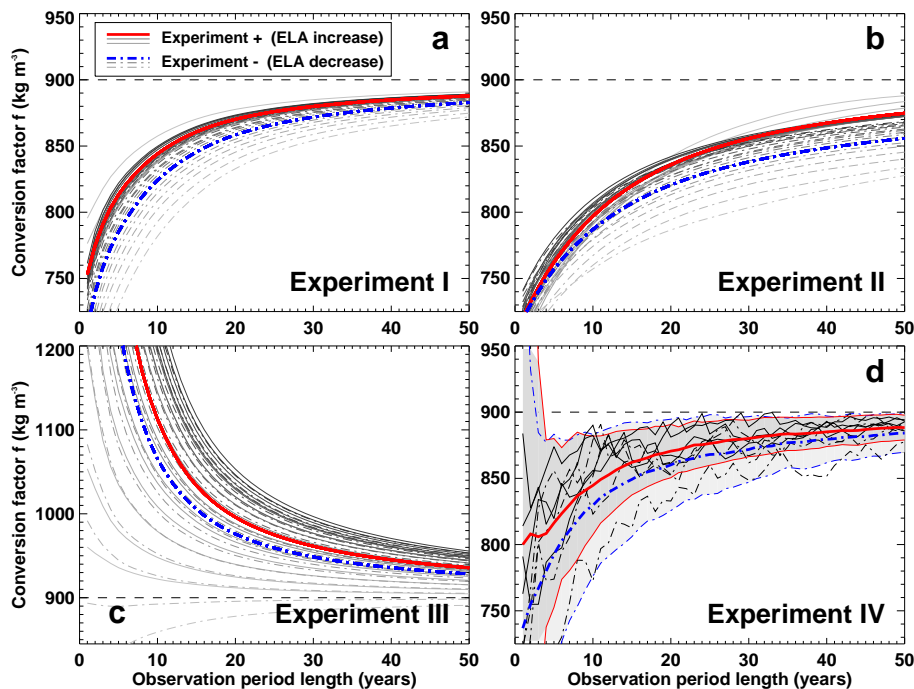


Fig. 4. Calculated conversion factor $f_{\Delta V}$ for observation period lengths increasing from 1 to 50 yr after a change in mass balance (Fig. 3). Thin lines refer to model runs using different glacier size (elevation ranges 300–2000 m), solid lines show the mean of all experiment simulations for a positive/negative shift in the ELA. In **(d)** the variability of 200 model runs is expressed as their average ± 2 standard deviations (shaded areas). Selected series of $f_{\Delta V}$ for individual model runs are shown.

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)
[◀](#)
[▶](#)
[◀](#)
[▶](#)
[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)

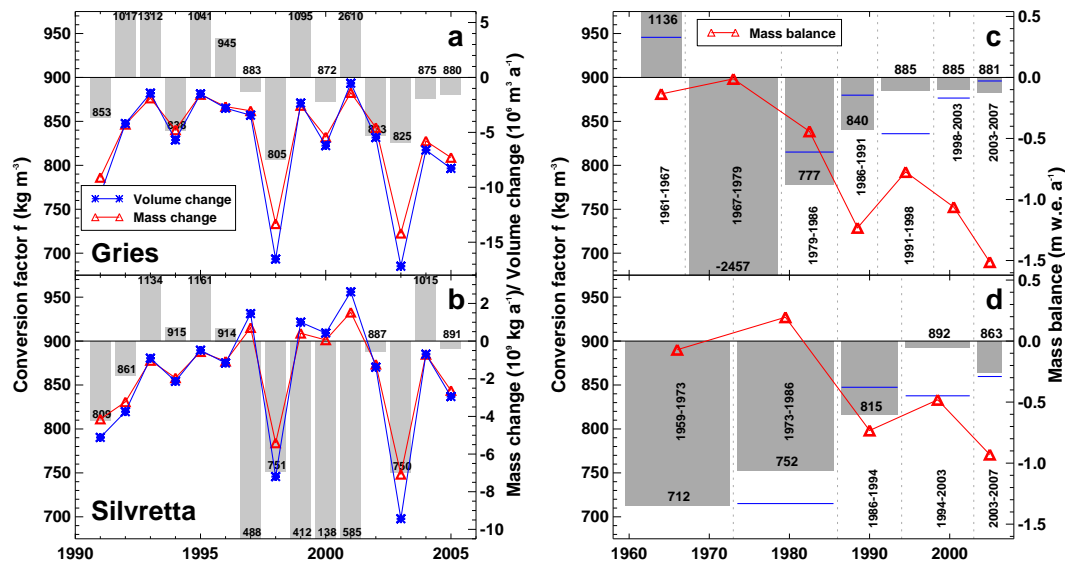



Fig. 5. Annual series of observed mass change and calculated volume change between 1990 and 2005 for **(a)** Griesgletscher and **(b)** Silvrettagletscher. The conversion factor $f_{\Delta V}$ for each year's volume change is shown by bars. Note that for bars beyond the plotted range, values are stated. **(c,d)** $f_{\Delta V}$ for Gries and Silvretta over period lengths of 4–14 yr corresponding to the dates of DEMs, and period mean mass balances. Blue lines show $f_{\Delta V, \text{zonal}}$ estimated assuming zonally separated “densities” of volume change (see e.g. Moholdt et al., 2010).

Converting glacier volume change to mass change

M. Huss

Title Page

Abstract Introduction

Conclusions References

Tables Figures

◀ ▶

◀ ▶

Back Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

