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Reanalysis of multi-temporal aerial images of Storglaciären, Sweden (1959–99) – Part 2: Comparison of glaciological and volumetric mass balances

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Abstract. Seasonal glaciological mass balances have been measured on Storglaciären without interruption since 1945/46. In addition, aerial surveys have been carried out on a decadal basis since the beginning of the observation program. Early studies had used the resulting aerial photographs to produce topographic glacier maps with which the in-situ observations could be verified. However, these maps as well as the derived volume changes are subject to errors which resulted in major differences between the derived volumetric and the glaciological mass balance. As a consequence, the original photographs were re-processed using uniform photogrammetric methods, which resulted in new volumetric mass balances for 1959–69, 1969–80, 1980–90, and 1990–99. We compared these new volumetric mass balances with mass balances obtained by standard glaciological methods including an uncertainty assessment considering all related previous studies. The absolute differences between volumetric and the glaciological mass balances are 0.8 m w.e. for the period of 1959–69 and 0.3 m w.e. or less for the other survey periods. These deviations are slightly reduced when considering corrections for systematic uncertainties due to differences in survey dates, reference areas, and internal ablation, whereas internal accumulation systematically increases the mismatch. However, the mean annual differences between glaciological and volumetric mass balance are less than the uncertainty of the in-situ stake reading and stochastic error bars of both data series overlap. Hence, no adjustment of the glaciological data series to the volumetric one is required.

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1 Introduction

Changes in glacier mass are a key element of glacier monitoring, providing important information for assessing climatic changes, water resources, and sea level changes (Kaser et al., 2006, Zemp et al., 2009). The available dataset of in-situ glacier mass balance measurements covers the past six decades (Sect. 2). The majority of these data series consists of just a few observation years. There are only 12 mass balance programs with continuous observations back to 1960 or earlier (Zemp et al., 2009), including Storglaciären with the longest record of glacier mass balance and one of the densest observation networks. The homogenization of these observations is gaining importance with increasing time length of the data series (e.g., Thibert et al., 2008; Huss et al., 2009; Fischer, 2010).

Annual glacier mass balance measurements based on the direct glaciological method (cf. Østrem and Brugman, 1991) are, hence, ideally combined with decadal volume-change assessments from geodetic surveys in order to assess random and systematic errors of both methods (Hoinkes, 1970; Haeberli, 1998, Fountain et al., 1999). Storglaciären has been surveyed by aerial photography about every decade (Holmlund, 1996). Maps had been constructed from these aerial photographs to determine the glacier area needed for mass balance calculations (Holmlund et al., 2005, Tarfala Research Station data) and to analyze the changes in surface topography (Holmlund, 1987, 1996). However, the comparison of volumetric mass balances derived from these digitized topography maps (of 1959, -69, -80, -90) with cumulative mass balance measurements shows major discrepancies, with maximum differences of half a meter per year (1969–80), as already noted by Albrecht et al. (2000).

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In order to overcome the problems related to the various existing maps and the methods used for deriving volume changes of Storglaciären, we re-processed dia-positives of the original aerial photographs of 1959, -69, -80, -90, and -99 based on a consistent photogrammetric processing for all survey years. Details on the study site, methodology, resulting digital elevation models (DEMs) and orthophotos, and derived changes in length, area, and volume are published in Koblet et al. (2010). In this paper, we compare the new volumetric mass balances with the glaciological mass balances for the periods of the aerial surveys. In addition, we summarize uncertainties related to both methods under consideration of all related previous studies and conclude with some recommendations for the mass balance monitoring program.

2 Historical background of mass balance measurement

Early observations of point mass balance date back to the end of the 19th and beginning of the 20th century, for example at Grosser Aletsch Gletscher (Aellen, 1996), Clariden Firn (Kasser et al., 1986; Müller and Kappenberger, 1991), Rhône Gletscher (Mercanton, 1916), and Silvretta Gletscher (Aellen 1996; Huss et al., 2008) in Switzerland. In the 1920s and 1930s, short-term observations (up to one year) were carried out at various glaciers in Nordic countries (e.g., Ahlmann 1929, 1935, 1939, 1942). After a detailed glacio-meteorological observation program at Kårsaglaciären, northern Sweden, in the early 1940s (Wallén 1948), Storglaciären in the Kebnekaise massif, northern Sweden, was chosen due to its relative accessibility and simple geometry for a long-term observation program (Schytt, 1947; Ahlmann, 1951). The mass balance work on Storglaciären started with winter-balance measurements in May 1946 (Karlén and Holmlund, 1996) and still continues today. In North America, early mass balance work started in the second half of the1940s as well (Meier, 1951; Pelto and Miller, 1990). Meanwhile, mass balance observations have been carried out on more than 300 glaciers worldwide (Cogley and Adams, 1998; Dyurgerov and Meier, 2005), of which about 230 data series are available from the World Glacier Monitoring Service (WGMS 2008).

3 Review of data and methods

A sound comparison of volumetric and glaciological mass balance data requires an uncertainty assessment of the major potential sources of error, such as in-situ and remote sensing methods applied, density assumptions, differences in survey dates and reference areas, internal ablation and accumulation, superimposed ice, and flux divergence. In this section, we aim at providing estimates for related uncertainties based on new data and/or earlier related studies.

3.1 Glaciological mass balances

Glacier surface mass balance at Storglaciären is measured following the direct glaciological method as described by Østrem and Brugman (1991). Measurements of winter and summer balances are carried out from late April to early May and around mid-September, respectively. Between 1945 and 1965, winter balance was measured by manual snow probing in fixed profiles across the glacier. Ablation was measured from a network of stakes along the same profiles. Since 1966, winter balance measurements have been made using a fixed system of probing points arranged in a 100×100 m grid covering the entire glacier (3 km^2; $\sim$100 data points km^{-2}). Snow density is determined from a varying number of pits or by core drillings. In recent years a depth-density function was fitted to the latter data and used to calculate density for each of the snow depth probings. Summer balance is measured from traditional stake readings. The observation network typically comprises 40–50 stakes distributed across the entire glacier ($\sim$15 stakes km^{-2}), and reaches up to 90 measurement points in some years. The stake network is less dense in crevassed and steep areas such as the headwalls of the glacier. Traditionally, the linear ablation gradient (cf. Haefeli, 1962) is used to extrapolate ablation in these areas. The number of stake and snow depth measurements has never been smaller than about half the modern values but have varied from year to year, especially before 1966 (Jansson and Pettersson, 2007).

Until 1993/94, the accumulation and ablation measurements were inter-/extrapolated manually by drawing contour lines. Areas between adjacent contour lines were integrated using a planimeter and assigning a constant balance value to each of these areas. Since 1994/95, the data have been interpolated on a 10 m resolution grid using the commercial PC software SURFER from Golden Software Inc. and more recently a MATLAB based toolbox implementing GSlib kriging (Deutch and Journel, 1998), applying the default parameter set of ordinary kriging (no nugget effect considered). Specific winter and summer balances are then obtained from averaging all grid cell values. In both the early and the new system, annual mass balance results from the sum of (negative) summer and (positive) winter balances.

Overviews on the Tarfala mass balance program and specifically on Storglaciären are given by Holmlund et al. (1996) and by Holmlund and Jansson (1999). The latter provide details on winter and summer balance measurement, whereas descriptions of inter-/extrapolation methods are found in Hock and Jensen (1999) and Jansson and Pettersson (2007). In the (old) official dataset as published by Holmlund and Jansson (1999), there are considerable time lags between the mass balance data and the reference area (from the most recent topographic map) used for calculating specific mass balances. This issue – inherent to all operational mass balance programs – is addressed by Holmlund

Table 1. Aerial and field survey dates, positive degree day sums (PDDS), related melt factors and resulting absolute melt corrections. The volumetric mass balance of 1969–80, for example, requires additional melt of 0.210 m w.e. in order to fit the field survey period. A corresponding correction for the beginning of the period is not required as there are no positive degree days recorded between the surveys. For more details see text.

aerial survey	field survey			PDDS		degree day	
date	end winter	end summer	summer balance [m w.e.]	summer survey [K d]	between surveys [K d]	factor [m w.e. K^{-1} d^{-1}]	correction [m w.e.]
23 Sep 1959	15 May 1959	15 Sep 1959	−1.80	501.5	7.3	0.0036	0.026
14 Sep 1969	15 May 1969	15 Sep 1969	−1.93	531.2	0.0	0.0036	0.000
18 Aug 1980	27 May 1980	21 Sep 1980	−2.16	607.5	59.2	0.0036	0.210
04 Sep 1990	24 May 1990	10 Sep 1990	−1.65	429.3	16.6	0.0038	0.064
09 Sep 1999	05 May 1999	15 Sep 1999	−1.52	434.0	27.2	0.0035	0.095

et al. (2005) by re-processing the data series (1945/46–2002/03) based on refined topographic maps. The authors do not re-evaluate the field data but digitize the old water equivalent contour maps, interpolate them onto a surface grid (20×20 m), and recalculate the seasonal and annual mass balances based on glacier areas (from the maps) corresponding to the years of the aerial surveys. Up until present, Holmlund et al. (2005) has been used as the new official dataset and was updated with Tarfala Research Station data, using the glacier area of the 1990 survey as reference for the calculation of specific mass balances since 1985/86.

3.2 Volumetric mass balances

Recurring aerial surveys have been carried out since the very beginning of the mass balance monitoring program at Storglaciären. The resulting vertical photographs had been used to produce several topographic glacier maps which are described in detail by Holmlund (1996). Based on these maps, early volume change assessments had been carried out challenged by inaccuracies in maps and methodologies (Holmlund, 1987, 1996; Albrecht et al., 2000). Koblet et al. (2010) re-analyze dia-positives of the original aerial photographs of 1959, -69, -80, -90, and -99 using a combination of analytical and digital photogrammetry. This results in a complete and consistent dataset of DEMs and orthophotos of the glacier. Based on this new dataset, the authors compute changes in length, area, and volume for the time periods between the aerial surveys. In this study, we now used these volume changes, including estimates for systematic and stochastic errors, for comparison with the glaciological mass balances.

3.3 Uncertainty assessments

3.3.1 Glaciological mass balance: field measurements and interpolation method

Jansson (1999) investigates uncertainties related to the in situ mass balance measurements at Storglaciären. Jansson empirically evaluates the influence of errors in stake reading and snow probing, snow density information, interpolation between observations, and extrapolation to areas not probed, as well as effects on reduced probing networks on the glacier mass balance results. Due to the dense observation network and the stochastic character of most of the errors related to point observations, the mean specific mass balance of Storglaciären is not very sensitive to errors in the investigated factors and can roughly be estimated to an overall uncertainty of ± 0.1 m w.e. a^{-1} (Jansson 1999). The re-analysis of the mass balance series by Holmlund et al. (2005) confirms this value for data after about 1960 and shows some larger errors in the early data. We, hence, set the overall stochastic uncertainty related to the field measurements to ± 0.2 m w.e. a^{-1} for the years 1959–65 and to ± 0.1 m w.e. a^{-1} for the years after 1965. Systematic errors related to the field measurements, such as the sinking of stakes in the accumulation area or the false determination of the last year's summer surface, might be an issue for individual survey years, but cannot be quantified due to the lack of corresponding information. Hock and Jensen (1999) demonstrate that different parameter settings of the kriging interpolation method have a strong influence on the spatial distribution pattern but little impact on the mean specific mass balances. They estimate the error (on the latter) introduced by the interpolation method to about ± 0.1 m w.e a^{-1}.

Table 2. Cumulative glaciological mass balances and related stochastic and systematic uncertainties with regard to field measurements (σ_{field}), interpolation methods (σ_{krig}), reference areas (σ_{ref}), internal ablation (σ_{intAbl}) and accumulation (σ_{intAcc}). Overall uncertainties are calculated based on the law of error propagation for the stochastic estimates ($\sigma_{\text{total.stoc}}$) and as sums for the systematic estimates ($\sigma_{\text{total.sys}}$); the latter including and excluding uncertainties for internal accumulation. All values are cumulated over the corresponding observation period with units in meter water equivalent (m w.e.). Note that the observation periods refer to the start and end year of the corresponding first and last field surveys, respectively, e.g., the period 1959–99 covers the hydrological years from 1959/60 to 1998/99.

observation period (# years)	cum. glac. mass balance	$\sigma_{\text{field.stoc}}$	$\sigma_{\text{krig.stoc}}$	$\sigma_{\text{ref.stoc}}$	$\sigma_{\text{ref.sys}}$	$\sigma_{\text{intAbl.sys}}$	$\sigma_{\text{intAcc.sys}}$	$\sigma_{\text{total.stoc}}$	$\sigma_{\text{total.sys}}$ excl. intAcc	$\sigma_{\text{total.sys}}$ incl. intAcc
1959–69 (10)	−3.110	±0.529	±0.316	±1.009	+0.048	−0.110	+0.484	±1.182	−0.062	+0.422
1969–80 (11)	−2.540	±0.332	±0.332	±0.984	+0.133	−0.121	+0.642	±1.090	+0.012	+0.654
1980–90 (10)	1.000	±0.316	±0.316	±0.378	−0.007	−0.110	+0.646	±0.585	−0.117	+0.529
1990–99 (9)	0.720	±0.300	±0.300	±0.059	−0.001	−0.099	+0.588	±0.428	−0.100	+0.488
1959–99 (40)	−3.930	±0.632	±0.632	±1.460	+0.173	−0.440	+2.360	±1.712	−0.267	+2.093

Table 3. Volumetric mass balances and related stochastic and systematic uncertainties with regard to density assumptions (σ_{density}), survey dates (σ_{survey}), and to the photogrammetric processing of the DEMs based on independent dGPS measurements (σ_{dGPS}). Overall uncertainties are calculated based on the law of error propagation for the stochastic estimates ($\sigma_{\text{total.stoc}}$) and as sums for the systematic estimates ($\sigma_{\text{total.sys}}$). All values are cumulated over the corresponding observation period with units in meter water equivalent (m w.e.). Note that the observation periods refer to the years of the corresponding aerial surveys.

observation period(# years)	volumetric mass balance	$\sigma_{\text{density.stoc}}$	$\sigma_{\text{dGPS.stoc}}$	$\sigma_{\text{dGPS.sys}}$	$\sigma_{\text{survey.sys}}$	$\sigma_{\text{total.stoc}}$	$\sigma_{\text{total.sys}}$
1959–69 (10)	−3.932	±0.274	±0.353	+0.292	−0.026	±0.447	+0.266
1969–80 (11)	−2.841	±0.198	±0.874	+0.765	−0.210	±0.896	+0.555
1980–90 (10)	1.299	±0.091	±0.867	−0.731	+0.146	±0.872	−0.585
1990–99 (9)	0.582	±0.041	±0.237	−0.421	−0.031	±0.241	−0.452
1959–99 (40)	−4.891	±0.350	±0.339	−0.095	−0.121	±0.487	−0.216

The uncertainties related to field measurements and interpolation method cumulated over the survey periods were calculated following the law of error propagation:

$$\sigma_{\text{field.stoc}} = \sqrt{\sum_{i=1}^{n} \sigma^2_{\text{field.stoc.i}}} \tag{1}$$

$$\sigma_{\text{krig.stoc}} = \sqrt{\sum_{i=1}^{n} \sigma^2_{\text{krig.stoc.i}}} \tag{2}$$

where $\sigma_{\text{field.stoc}}$ and $\sigma_{\text{krig.stoc}}$ are the uncertainties of field measurements and interpolation method, respectively, cumulated over n years of the survey periods. The resulting estimates for the stochastic errors of field measurements and interpolation method are given in Table 2.

3.3.2 Volumetric mass balances: photogrammetry

A sound quantitative assessment of the photogrammetry-related uncertainties is nicely demonstrated for Sarennes glacier, French Alps, by Thibert et al. (2008). Such a detailed analysis would be difficult to conduct in our case, as not all parameters are known for the early survey dates and because analogue and digital steps are combined in the photogrammetric processing (cf. Koblet et al., 2010).

As a consequence, Koblet et al. (2010) qualitatively evaluate the resulting DEMs and orthophotos and use two different approaches to assess the systematic and stochastic uncertainties of the volumetric mass balance derived from DEM-differencing. A set of 26 reference points located with a differential global-positioning system (dGPS) provides an independent validation of the digital elevation models (DEMs) and corresponding volume changes. The analysis of elevation differences in non-glacierized terrain allows investigating the significance of computed glacier thickness changes, the slope dependency of errors, and quantifying the integrative errors of the photogrammetry. Full details and equations are given in Koblet et al. (2010). In this study we used their results from the comparison with independent dGPS points as integrative estimates of stochastic and systematic uncertainties of the photogrammetric processing of the volume changes (Table 3).

3.3.3 Density assumptions

Density information is required in order to convert the change of a snow/firn/ice volume into a mass change. Most studies assume a constant density profile in the accumulation area and, hence, use glacier ice density for the conversion. This, however, may only be valid under steady-state conditions and for glaciers with a constant accumulation rate and no melting in that zone (Sorge 1935; Bader 1954). In reality, the density of the volume change is determined by the quantity of melted/newly formed snow, firn, and ice. Corresponding three-dimensional measurements are not available. We, hence, based our density assumptions on maximum and minimum estimates. Using the density of ice (917 kg m^{-3}) for the entire volume change will likely overestimate mass changes during periods of changing snow and firn layers and was thus regarded as a maximum estimate. As a minimum estimate we used a density of 800 kg m^{-3}, which is calculated as the zonal average of 700 (917) kg m^{-3} above (below) the balanced-budget equilibrium line altitude (ELA_0) of Storglaciären. ELA_0 and the corresponding accumulation area ratio (AAR_0) are derived from the linear regressions of ELA and AAR versus mass balance data (1946–2007) resulting in an ELA_0 at 1450 m a.s.l. and an AAR_0 of 45%. We hence used the (rounded) average of the two density assumptions (860 kg m^{-3}) for the conversion of the volumetric changes into water equivalent and the difference to maximum/minimum estimates (60 kg m^{-3}) as an uncertainty measure (Table 3, $\sigma_{\text{density.stoc}}$).

3.3.4 Survey dates

Comparison of glaciological with geodetic mass balance requires a correction because the field and aerial surveys are not carried out on the same date. The related error corresponds to the mass balance of that period and, hence, depends on the time span between the two surveys, the season, and the glacier mass turn over. The dates for the aerial surveys are based on information from Lantmäteriet and for 1980, -90, and -99, also labelled on the image frames. Exact dates of the winter and summer balance field work are available for 1980 and 1990 from the WGMS database. Corresponding meta-data for the surveys of the other years are not readily available. Assumptions for these other dates of mass balance field work are based on information from the Tarfala Station (Table 1).

For the mass balance correction we applied a classical degree-day model that relates glacier melt M, expressed in mm w.e., during a period of n time intervals, Δt, to the sum of positive air temperatures of each time interval, T^+, during the same period:

$$\sum_{i=1}^{n} M = \text{DDF} \sum_{i=1}^{n} T^+ \cdot \Delta t \tag{3}$$

The degree-day factor, DDF, is expressed in mm w.e. K^{-1} d^{-1} for Δt expressed in days and temperature in °C (Braithwaite, 1995; Hock, 2003). We used the daily air temperature series from the Tarfala meteorological station (1138 m a.s.l.; Grudd and Schneider, 1996), which are available since 1965, and a temperature lapse rate of 0.55 K 100 m^{-1}(Hock and Holmgren, 2005) to calculate positive degree-day sums at the balanced-budget equilibrium line altitude (ELA_0) of Storglaciären. The degree-day factor was calculated from summer balances and positive degree-day sums for every (aerial) survey year separately, with resulting values of 3.5, 3.6, and 3.8 mm K^{-1} d^{-1}. For 1959, positive degree-day sums were derived from averaging the cumulative positive degree-day profiles of the years 1969, -80, -90, and -99 as air temperature had only been measured during daytime in the summer months (JJA) prior to 1965. The largest difference between field and aerial surveys is found for 1980 with 34 days and a corresponding positive degree day sum of 59.2 K d resulting in an absolute melt correction of 0.21 m w.e. (see Table 1). For the uncertainty assessment in Sect. 3.3, the melt corrections for the beginning and the end of the survey periods are required in order to correct the volumetric mass balance to the dates of the field surveys (Table 3, $\sigma_{\text{survey.sys}}$). As such, the volumetric mass balance of the period from 18 August 1980 to 4 September 1990 needs to be corrected by +0.210 m w.e. and −0.064 m w.e., in order to fit the field survey period from 21 September 1980 to 10 September 1990.

The present approach does neglect the influence of snow fall events (and related albedo effects) during the summer period. This might lead to a systematic underestimation of the positive degree-day factor and to an overestimation of the melt correction in case of major snow fall events between the aerial and the field surveys. As there is no solid precipitation record available covering the entire period of interest, we used hourly temperature and precipitation data from 1989 to 2007 measured at the Tarfala Research Station to at least estimate the relevance of ignoring summer snow fall events. We used the summer data (15 May to 15 September) and skipped the years with more than 35 data gaps or implausible values (i.e., 1989, 1994, 1998, 2000, 2004). Solid precipitation was estimated from hourly precipitation at temperatures below 1.5 °C (Rohrer, 1989). Thereto, temperature at ELA_0 was calculated from the average of available sensors and a lapse rate of 0.55 K 100 m^{-1} (see above). Precipitation, measured with a Campbell tipping bucket rain gauge (0.16 mm per tip), was increased by 35% to account for the gauge undercatch error and then extrapolated assuming a 10% increase per 100 m elevation (Hieltala, 1989, Hock and Holmgren, 2005) to the ELA_0 of Storglaciären. However, a multiple linear regression model showed that solid precipitation does not significantly contribute to the summer mass balance whereas the positive degree-day sums explain a high percentage of its variance. Furthermore, there had been no major events of solid precipitation (i.e., daily sum >3 mm, cf. Fischer, 2010) during the days between the aerial and the field surveys in 1990 and in 1999 that would argue against a melt correction.

3.3.5 Reference areas

The calculation of "conventional" mass balances (Elsberg et al., 2001) actually requires an update of glacier extent (and elevation) for every survey year. However, the required information is only available after the decadal geodetic surveys and hence a lagged step-function of the real changes. Holmlund et al. (2005) address the time lag by recalculating the glaciological mass balance series on the basis of time periods with (constant) glacier extents centered on the years (1949, -59, -69, -80, -90) when the aerial photos were taken. However, they do not address the step change in reference area. The geodetic volume changes (1959–69, 1969–80, 1980–90, 1990–99) by Koblet et al. (2010) are calculated based on glacier extents on the orthophotos. Their outlines are congruent in the accumulation area for all years. In each period, the (larger) area of the first survey year is used as a reference extent. As a consequence, the reference area differs by up to 8% between the glaciological and the volumetric mass balances of a year (Koblet et al., 2010).

We assessed the related systematic uncertainty by correcting the glaciological mass balances to the reference areas of the aerial surveys. Thereto, the specific annual balances were multiplied by the glacier area of the glaciological dataset and divided by the extent in the volumetric dataset which was linearly interpolated between the aerial surveys in order to avoid step changes. As a result, the absolute values of the cumulated, glaciological mass balance decrease (Table 2, $\sigma_{\text{ref.sys}}$) due to the generally larger glacier areas as determined by Koblet et al. (2010).

The chosen approach does, however, not take into account that the relation between the specific mass balance and differences in glacier extent is not linear – local area differences at the glacier tongue (headwall) have a much more negative (positive) influence than those close to the ELA. The related possible error range can be estimated as the product of the above determined annual area differences ΔS and half the range of the annual mass balance within the glacier elevation boundaries M_{range}, resulting in the following stochastic uncertainty related to differences in reference areas:

$$\sigma_{\text{ref.stoc}} = \sqrt{\sum_{i=1}^{n} (0.5 \cdot \text{M}_{\text{range.i}} \cdot \Delta S_i)^2} \quad (4)$$

As the mass balance data for individual elevation boundaries are not readily available for all the years, we used an average mass balance range for all years (4.6 m w.e.; based on available data since 1971). The stochastic uncertainty was cumulated over the number of years n of the aerial survey periods according to the law of error propagation (Table 2, $\sigma_{\text{ref.stoc}}$).

3.3.6 Internal ablation and accumulation

Internal ablation due to ice motion, geothermal heat, and heat-conversion of gravitational potential energy loss from water flow through and under the glacier are other potential systematic biases not accounted for by standard measurements. The ice motion of the poly-thermal glacier (Pettersson et al., 2004) was considered to be small and corresponding internal ablation, thus, to be negligible (cf. Hooke et al., 1989 and Albrecht et al., 2000). The contribution of basal melting by geothermal heat was estimated according to Östling and Hooke (1986) as about 0.001 m w.e. a^{-1}. The internal melting by released potential energy in descending water was estimated on the order of 0.01 m w.e. a^{-1}, using an average drop of 200 m and a total annual discharge of $7\times10^6\,\text{m}^3$ (Holmlund, 1987). Finally, the total systematic uncertainty due to internal ablation (0.011 m w.e. a^{-1}) was cumulated over the number of years of the aerial survey periods (Table 2, $\sigma_{\text{intAbl.sys}}$).

Internal accumulation as described by Trabant and Mayo (1985) is usually not accounted for by traditional glaciological methods (Østrem and Brugman, 1991). Its influence on mass balance may be small in magnitude or even negligible on temperate glaciers, but if not accounted for can result in a systematic underestimation of the mass balance. As a consequence, internal accumulation needs to be considered for a poly-thermal glacier such as Storglaciären (Petterson et al., 2003). Based on data from 1997/98 and 1998/99, Schneider and Jansson (2004) estimate the internal accumulation due to re-freezing of percolating water in cold snow and firn as well as the freezing of water trapped by capillary action in snow and firn by the winter cold. They find that these two factors account for 30% and 70%, respectively, of the annual internal accumulation and that the significance of internal accumulation for the glacier mass balance depends on the areal extent of the accumulation area, the thickness of the active layer, and the winter temperature. Based on measured temperature profiles as well as physical characteristics and water content of firn, they obtaine values for internal accumulation of 0.04–0.06 m w.e. a^{-1}, or 3–5% of the winter balance of the entire glacier. Hence, we assumed the underestimation of the glaciological mass balance due to internal accumulation to 4% of the winter balances (Table 2, $\sigma_{\text{intAcc.sys}}$).

3.3.7 Superimposed ice

Superimposed ice accumulates on the current summer surface by refreezing of rain or melt-water produced during the current mass balance year. It forms above the previous year's surface and can be accounted for during standard stake readings (Østrem and Brugman, 1991). On Storglaciären, Schytt (1949) measured a maximum of about 0.1–0.2 m w.e. of superimposed ice formation in the ablation zone. The thickness can be substantial larger at the glacier margins and at the glacier terminus. The total amount of superimposed ice remaining at the end of the ablation season depends on the elevation of the snow line and is, hence, larger for positive balance years. We assumed the error of its determination to be covered with the uncertainty estimate for the field observations (Sect. 3.3.1).

3.3.8 Flux divergence

According to the principal of mass conservation, the mass balance should be balanced by the ice flux divergence and the thickness change, as long as integrated over the entire glacier (Paterson, 1994) and was not treated separately in this study. Note that any analysis dealing with mass balance at points or along profiles needs to consider the flux divergence.

3.3.9 Overall uncertainties

A direct comparison of glaciological and volumetric mass balances requires a correction for related uncertainties. Thereto, the glaciological mass balance were cumulated over the aerial survey periods and corrected for systematic errors due to uncertainties related to reference areas, internal ablation and accumulation (Table 2, $_{.sys}$). Besides the conversion from volume to mass balance (Sect. 3.3.3), the systematic corrections of the volumetric mass balances include the melt-correction due to differences in survey dates and elevation differences in the DEMs as derived from independent dGPS measurements (Table 3, $_{.sys}$). The systematic uncertainties are of positive and negative signs depending on whether they are to be added or subtracted from the glaciological/volumetric mass balance to fit the one based on the other method. Overall stochastic uncertainties are cumulated for the glaciological ($\sigma_{\text{glac.stoc}}$) and the volumetric ($\sigma_{\text{vol.stoc}}$) mass balances separately, both according to the law of error propagation:

$$\sigma_{\text{glac.stoc}} = \sqrt{\sigma^2_{\text{field.stoc}} + \sigma^2_{\text{krig.stoc}} + \sigma^2_{\text{ref.stoc}}} \quad (5)$$

$$\sigma_{\text{vol.stoc}} = \sqrt{\sigma^2_{\text{density.stoc}} + \sigma^2_{\text{dGPS.stoc}}} \quad (6)$$

where $\sigma_{\text{field.stoc}}$, $\sigma_{\text{krig.stoc}}$, and $\sigma_{\text{ref.stoc}}$ are the stochastic uncertainties related to the field measurements, interpolation method, and reference areas (Table 2, $_{.stoc}$) and where $\sigma_{\text{density.stoc}}$ and $\sigma_{\text{dGPS.stoc}}$ are the stochastic uncertainties related to density assumptions and to the DEMs (Table 3, $_{.stoc}$).

4 Results

The cumulative glaciological mass balances and related uncertainties are given in Table 2. The first two periods are negative followed by two periods of ice gain. The mass balance over the entire period covered is also negative. Annual stochastic uncertainties related to the field measurements ($\sigma_{\text{field.stoc}}$) were estimated to 0.2 and 0.1 m w.e. a^{-1} until and after the year 1965, respectively. Cumulated over the observation periods according to the law of error propagation, they result in errors of about $\pm$ 0.5 m w.e. for the first period, $\pm$ 0.3 m w.e. for the other decadal periods, and $\pm$ 0.6 m w.e. for the entire period from 1959–99. The annual stochastic uncertainties related to the interpolation methods ($\sigma_{\text{krig.stoc}}$) were estimated to $\pm$ 0.1 m w.e. a^{-1}, and hence result in the same cumulative errors as for field measurements, with exception of the first period. The correction of the glaciological mass balance to the reference areas and corresponding changes of the glacier in the new orthophotos lead to a systematic decrease of the absolute values of the glaciological mass balance ($\sigma_{\text{ref.sys}}$) of below 0.2 m w.e. and stochastic uncertainties ($\sigma_{\text{ref.stoc}}$) which are greatest in the first two periods with values of of below $\pm$ 1.0 m w.e. The overestimation of the mass balance due to ignoring the internal ablation ($\sigma_{\text{intAbl.sys}}$) was estimated to be small, with values of about -0.01 m w.e. a^{-1}. Cumulated over the aerial survey periods this leads to corrections for the decadal and the entire period of about -0.1 and -0.4 m w.e., respectively. The rough estimate of the internal accumulation ($\sigma_{\text{intAcc.sys}}$) shows an underestimation of the glaciological mass balance by between 0.5 and 0.7 m w.e. for the four decadal periods and by 2.4 m w.e. for the 40 years between the first and the last aerial survey. Overall systematic uncertainties ($\sigma_{\text{total.sys}}$) including internal accumulation are positive for all periods with decadal values of about 0.5 m w.e. When excluding corrections for internal accumulation, absolute decadal corrections are about 0.1 m w.e. or smaller and negative in all but the second period. Overall stochastic uncertainties ($\sigma_{\text{total.stoc}}$) are about $\pm$ 1.0 m w.e. in the first two decadal periods, roughly $\pm$ 0.5 m w.e. in the second two, and $\pm$ 1.7 m w.e. for the entire period of 1959–99.

The volumetric mass balances, based on Koblet et al. (2010) and an assumed density of 860 kg m^3, show the same trend in mass loss over the first two decades followed by two decades of mass regain. The mass balances and corresponding systematic and stochastic uncertainties are given in Table 3. The uncertainty related to the density assumption ($\sigma_{\text{density.stoc}}$) is below $\pm$ 0.4 m w.e. The comparison of the DEM with independent dGPS points provides a rough idea of the systematic and stochastic uncertainties related to the photogrammetry ($\sigma_{\text{dGPS.sys}}$ and $\sigma_{\text{dGPS.stoc}}$). Both show that the uncertainties of the volume changes related to the DEM of 1980 are about twice as large as the ones from the other periods. Systematic corrections of the volumetric mass balance to fit the field survey dates ($\sigma_{\text{survey.sys}}$) require additional melt in all but the third period (1980–90). Overall systematic uncertainties ($\sigma_{\text{total.sys}}$) are positive in the first two periods and negative in the others with absolute values between 0.2 and 0.6 m w.e. and with stochastic uncertainties ($\sigma_{\text{total.stoc}}$) between $\pm$ 0.2 and $\pm$ 0.9 m w.e. (Table 3.)

A summary of the above results is given in Fig. 2 which compares the cumulated official glaciological (Holmlund et al. (2005), Tarfala Research Station data) and the volumetric

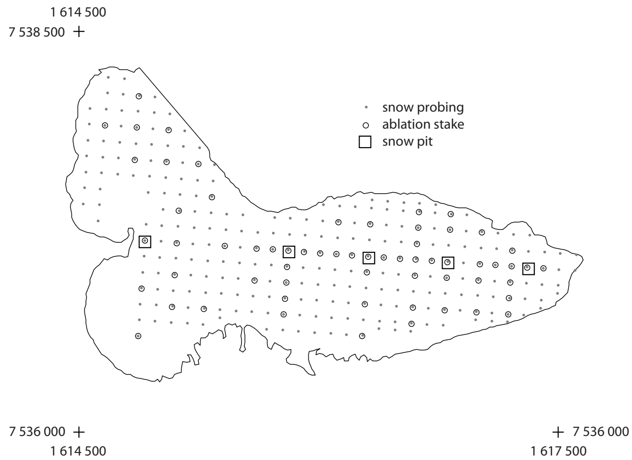

Fig. 1. Observation network on Storglaciären in 2006/07. Snow observations and ablation stakes are used for the determination of the winter and summer mass balance, respectively. Glacier outlines from the 1990 map (Holmlund, 1996). Map coordinates are in the Swedish coordinate system RT 90 2.5 gon V.

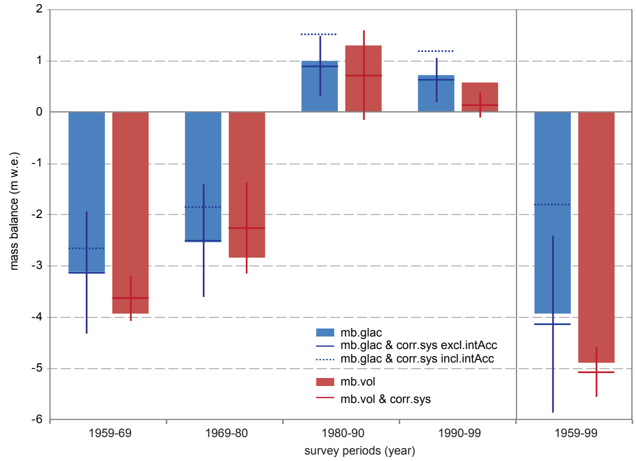

Fig. 2. Decadal glaciological and volumetric mass balances of Storglaciären. The "official" glaciological mass balances by Holmlund et al. (2005; blue bars) and the volumetric mass balances by Koblet et al. (2010; red bars) are shown for the periods of the aerial surveys. Corrections for systematic and stochastic uncertainties are indicated by horizontal and vertical lines, respectively. For the glaciological mass balances, the systematic uncertainties including corrections for internal accumulation (intAcc) are shown by dotted horizontal lines.

mass balances (Koblet et al., 2010). Corresponding overall systematic and stochastic errors are indicated by horizontal and vertical lines, respectively. Overall systematic corrections of the glaciological mass balance including internal accumulation are given separately (dotted horizontal line) as they offset clearly from the other results. The absolute values of the glaciological mass balance are smaller than the ones of the volumetric mass balance in all but the last period (1990–99). Systematic uncertainties are relatively small for the glaciological data and mostly negative when excluding internal accumulation. Including the latter, however, leads to clearly positive corrections. Stochastic uncertainties of the glaciological data are largest in the first two periods (about ± 1 m w.e.) mainly due to corrections related to reference areas. Absolute corrections for systematic uncertainties are 0.6 m w.e. or smaller and reduce the absolute volumetric mass balances in all but the overall time period (1959–99). Overall stochastic uncertainties are ± 0.9 m w.e. for the changes including the DEM of 1980 and half or less for the other periods.

5 Discussion

Based on the "official" glaciological mass balance series (Holmlund et al. (2005), Tarfala Research Station data), Storglaciären experienced a strong cumulative ice loss of about 13 m w.e. from the initiation of measurements in 1945 to the first half of the 1970s, followed by 15 years of small cumulative mass balance variations (Fig. 3). Between 1988 and 1995, the glacier increased its specific mass by some 4 m w.e. and subsequently lost 6 m w.e. from 1995–2007. The volumetric mass balances by Koblet et al. (2010) based on the available aerial photographs from 1959, -69, -80, -90, and -99 can only roughly trace these variations due to the decadal resolution. The cumulative changes (of the glaciological mass balance) between 1959 and 1999 account for just 4 m w.e. ice loss, of which 3 m w.e. were already lost by 1969. As a consequence, the decadal signal as derived from the photogrammetric surveys after 1969 is in the same order of magnitude or even smaller than the sub-decadal variations of the glaciological mass balances. The absolute glacier changes based on the photogrammetric surveys are larger than the corresponding changes from the glaciological in-situ measurements in three of the four decadal periods as well as over the entire observation period (1959–99).

The uncertainty assessment as described in Sects. 3 and 4 was an attempt to quantify the major sources of potential errors to be addressed in order to compare the glaciological with the volumetric mass balances. All estimates and assumptions taken to address stochastic and systematic uncertainties comprise additional sources of potential errors. The melt correction due to the different observation dates in 1959, for example, inherits the errors from the degree-day model (temperature data series, summer balance, melt factor, ELA_0-determination) as well as from the determination of the dates of the field survey and of the aerial survey (reporting), and neglects the effect of summer snow fall events. We waive the attempt to quantify all these potential errors of the uncertainty estimates since a corresponding overall value would represent a statistical exercise rather than a real-world uncertainty.

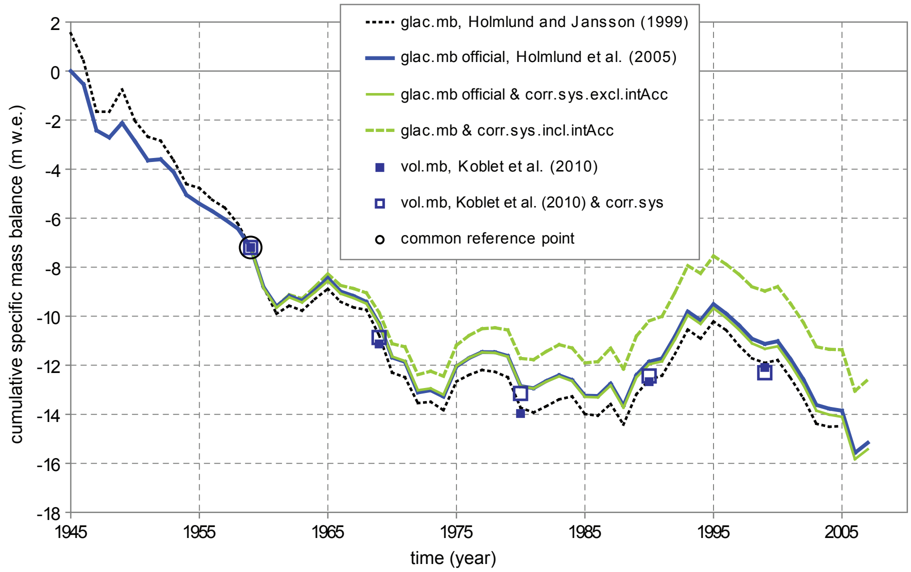

Fig. 3. Cumulative glaciological and volumetric mass balance series of Storglaciären. The official glaciological mass balance series (Holmlund et al. (2005), Tarfala Research Station data) is compared to the new volumetric mass balance data by Koblet et al. (2010; 1959-69-80-90-99). In addition, two glaciological mass balance series are shown which are based on the official one but corrected for directional uncertainties including/excluding internal accumulation (for details see text) as well as the old official series by Holmlund and Jansson (1999). In order to have a common reference point, all changes are relative to the value of 1959 of the "official" glaciological data series (Holmlund et al. (2005), Tarfala Research Station data; −7.2 m w.e.).

However, we applied the systematic uncertainties including corrections for reference areas, internal ablation, and internal accumulation to the official mass balance series (Holmlund et al. (2005), Tarfala Research Station data) in order to produce a "best estimate" glaciological mass balance series to compare with the volumetric changes by Koblet et al. (2010) which were converted to mass balance and corrected for systematic uncertainties in survey periods and photogrammetric processing. In principle, this should reduce the differences between the glaciological and the volumetric mass balance. In fact, this is true for most of the corrections and periods; but the systematic bias from the internal accumulation clearly increases the deviations in all periods. This effect becomes most prominent in Fig. 3, where the changes are cumulated with reference to the year of the first aerial survey (i.e., 1959).

The estimate of internal accumulation by Schneider and Jansson (2003; 0.04–0.06 m w.e. a^{-1}) is larger than earlier ones for Storglaciären by Östling and Hooke (1986; 0.02 m w.e. a^{-1}) and by Holmlund (1987; 0.03 m w.e. a^{-1}), which do both not consider refreezing capillarity water, but smaller than other estimates, e.g., for Alaskan glaciers by Trabant and Mayo (1985). Miller and Pelto (1999) note on Lemon Creek Glacier, Alaska, that a part of the observed internal accumulation could represent a redistribution rather than a net mass gain and that during warm winters there was no internal accumulation. However, Schneider and Jansson (2003) consider their results from 1997/98 and 1998/99 as representative for Storglaciären, at least with regard to winter temperatures and winter balances for the period 1965–99. Even if we assume that the findings by Schneider and Jansson (2003) are maximum estimates and set the average annual systematic error due to internal accumulation to half their absolute values, a systematic error of 0.82–1.23 m w.e. cumulates over the 40-year observation period. The systematic uncertainties of the volumetric mass balance as derived from independent dGPS measurements (cf. Koblet et al., 2010) do not provide an explanation for these differences and suggest that either the long-term effect of internal accumulation at Storglaciären is overestimated significantly, or another systematic error of the glaciological or the volumetric mass balance is not yet (correctly) accounted for.

At first glance, the comparison of the different data series as cumulative changes from 1959 might look unsatisfactory. The best agreements with the volumetric mass balances by Koblet et al. (2010) are the "old" glaciological series by Holmlund and Jansson (1999), followed by the official one (Holmlund et al. (2005), Tarfala Research Station data), and finally the "best estimates" (excl. and incl. internal accumulation) of the present study (Fig. 3). The systematic uncertainties applied to the volumetric mass balance by Koblet et al. (2010) cannot provide a final answer to these questions but show that the official glaciological series is within the range of uncertainty, whereas our "best estimate" is only within when ignoring internal accumulation. However, the mean annual deviations from the official glaciological mass balance series (Holmlund et al. (2005), Tarfala Research Station data) are below 0.1 m w.e. a^{-1} for all data series. This holds

Table 4. "Official" glaciological mass balance (Holmlund et al. (2005), Tarfala Research Station data) in comparison with other glaciological (glac.) and volumetric (vol.) mass balance (mb) series of Storglaciären. The table shows cumulative mass balances of the "official" glaciological data series for the observation periods and corresponding mean annual differences of the other series. Note that the observation periods refer to the start and end year of the corresponding first and last field surveys, respectively, e.g., the period 1959–99 covers the hydrological years from 1959/60 to 1998/99.

Obs. period	glac. mb by Holmlund et al. (2005), Tarfala Research Station data	glac. mb by Holmlund and Jansson (1999)	glac. mb this study, "best estimate", $\sigma_{\text{total.sys}}$ excl. intAcc	glac. mb this study, "best estimate", $\sigma_{\text{total.sys}}$ incl. intAcc	vol. mb by Koblet et al. (2010)	vol. mb by Koblet et al. (2010), $\sigma_{\text{total.sys}}$
(#) years	m w.e.	m w.e. a^{-1}	m w.e. a^{-1}	m w.e. a^{-1}	m w.e. a^{-1}	m w.e. a^{-1}
1959–69 (10)	−3.110	−0.047	−0.006	+0.042	−0.082	−0.056
1969–80 (11)	−2.540	−0.037	0.001	+0.059	−0.027	+0.023
1980–90 (10)	1.000	+0.014	−0.012	+0.053	+0.030	−0.029
1990–99 (9)	0.720	−0.003	−0.011	+0.054	−0.015	−0.066
1959–99 (40)	−3.930	−0.019	0.007	+0.052	−0.024	−0.029

for all the four observation periods as well as over the entire period of 1959–99 (Table 4). These mean annual deviations (Table 4) are then within or even smaller than the estimated uncertainty of a single stake or snow pit reading (cf. Thibert et al., 2008; Huss et al., 2009).

Over the past decades, it has become a standard procedure to check the (annual) glaciological with (decadal) volumetric mass balance methods, utilizing techniques such as topographic map comparison (e.g., Andreassen 1999; Conway et al. 1999; Kuhn et al. 1999; Hagg et al., 2004; Østrem and Haakensen, 1999), photogrammetry (e.g., Krimmel, 1999; Cox and March, 2005; Thibert et al., 2008; Haug et al., 2009; Huss et al., 2009; Fischer, 2010), global positioning systems (e.g., Hagen et al. 1999, Miller and Pelto 1999), or laser altimetry (e.g., Conway et al., 1999; Fischer, 2010; Echelmeyer et al., 1996; Sapiano et al., 1998; Geist and Stötter, 2007), the latter three references without direct comparison. It has become evident that a sound validation ideally is based on consistent data and procedures, and includes a sound assessment of stochastic and systematic uncertainties. In cases of major deviations between the results of the different methods, it is recommended that the (annual) glaciological data series be adjusted to the (decadal) volumetric changes (cf. Thibert et al., 2008; Huss et al., 2009). The decisive factor thereby is provided by the uncertainty assessment: if the stochastic error bars of the glaciological and volumetric mass balances, both corrected for systematic errors, do not overlap, an adjustment over the corresponding period is required. Large uncertainties in the volumetric mass balance might require a correction of the basic DEMs to a high-precision and high-resolution reference DEM (cf. Kääb, 2005) prior to the homogenization of the mass balances. In the case of Storglaciären, corresponding error bars do overlap in all periods (cf. Fig. 2) when ignoring systematic corrections for internal accumulation and, hence, an adjustment is not required. The inclusion of present systematic (over-) corrections for internal accumulation would, however, require such an adjustment for at least the overall period from 1959–99. Further research and the next aerial survey will have to re-address this issue.

6 Conclusions

Storglaciären has a continuous glacier mass balance record back to 1945/46 with a network density of about 100 observations per square kilometer for winter balance and 15 observations per square kilometer for summer balance. It is hence the longest glacier mass balance record with probably the greatest observation density available from the WGMS. As recommended by international monitoring standards, regular aerial surveys have been carried out on a decadal base since the beginning in order to validate the glaciological in-situ measurements with results from the geodetic method. For the first time, dia-positives of the original aerial photographs of 1959, -69, -80, -90, and -99 are used by Koblet et al. (2010) to directly produce volumetric changes based on uniform photogrammetric methods. In the present study we compared these volumetric with the official glaciological mass balances by Holmlund et al. (2005) including a sound analysis of potential uncertainties.

The volumetric mass balances are in good agreement with the glaciological data. The absolute differences between volumetric and the glaciological mass balances are 0.8 m w.e. in the first and 0.3 m w.e. or less in the other three decadal survey periods. These deviations can be reduced in most periods by applying corrections for systematic uncertainties such as differences in survey dates and reference areas or accounting for internal ablation. In contrast, accounting for internal accumulation based on the study by Schneider and Jansson (2004) systematically increases the mismatch. This suggests that either the effect of the internal accumulation is overestimated or that there is another systematic error not yet considered. However, the mean annual differences between such a "best estimate" glaciological mass balance, which corrects the official series by all directional uncertainties, and the volumetric mass balance, corrected for systematic uncertainties, are less than about 0.1 m w.e. a^{-1} and as such are within the order of magnitude of the stake and pit reading error.

From the present study we conclude that the new volumetric mass balances fit well overall with the glaciological ones and confirm the excellent quality of this data series. Excluding the systematic deviations due to the issue with the internal accumulation, there is an overlap of stochastic error bars of volumetric and glaciological mass balances and, hence, no need for an adjustment of the glaciological data series. Thanks to the very dense observation network of Storglaciären, the cumulative glaciological series fits well to the decadal volumetric data in spite of the low mass balance signal. Further investigations should, however, address the better quantification of systematic error sources, such as internal accumulation, as well as the issue of the (changing) reference areas used for mass balance calculations. The present study shows the importance of systematic and ideally uniform data processing as well as a sound uncertainty assessment in order to detect – and if necessary correct – systematic errors in the measurements. A next aerial survey is, therefore, overdue and should provide a new high-precision and high-resolution reference DEM.

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