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Comparison of glaciological and volumetric mass balance measurements at Storglaciären, Sweden

M. Zemp[1], P. Jansson[2], P. Homlund[2], I. Gärtner-Roer[1], T. Koblet[1], P. Thee[3], and W. Haeberli[1]

[1]Department of Geography, University of Zurich, Winterthurerstr. 190, 8057 Zürich, Switzerland
[2]Department of Physical Geography and Quaternary Geology, 106 91 Stockholm, Sweden
[3]Swiss Federal Institute for Forest, Snow and Landscape Research, Zürcherstr. 111, 8903 Birmensdorf, Switzerland

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Correspondence to: M. Zemp (michael.zemp@geo.uzh.ch)

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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 used the resulting aerial photographs to produce glaciological 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 1959–1969, 1969–1980, 1980–1990, and 1990–1999. We compare 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 0.9 m w.e. for the period of 1959–1969 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, hence, do not require an adjustment of the glaciological data series.

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).

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 were 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, 1969, 1980, 1990) with cumulative mass balance measurements shows major discrepancies, with maximum differences of half a meter per year (1969–1980), as already noted by Albrecht et al. (2000).

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, 1969, 1980, 1990, and 1999 based on a consistent photogrammetric processing for all survey years. Details on the study site, methodology, resulting digital elevation models (DEMs) and ortho-photos, 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 at various Nordic glaciers (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 accumulation and ablation, 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; ~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 (~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 subtracting summer from winter balance.

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 were 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 – was addressed by Holmlund et al. (2005) by re-processing the data series (1945/46–2002/03) based on refined topographic maps. The authors did not re-evaluate the field data but digitized the old water equivalent contour maps, interpolated them onto a surface grid (20×20 m), and recalculated 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 were used to produce several glaciological maps which are described in detail by Holmlund (1996). Based on these maps, early volume change assessments were carried out challenged by inaccuracies in maps and methodologies (Holmlund, 1987, 1996; Albrecht et al., 2000). Koblet et al. (2010) re-analyzed dia-positives of the original aerial photographs of 1959, 1969, 1980, 1990, and 1999 with standard photogrammetric techniques. This resulted in a complete and consistent dataset of DEMs and orthophotos of the glacier. Based on this new dataset, the authors computed changes in length, area, and volume for the time periods between the aerial surveys. We now use 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) investigated uncertainties related to the in situ mass balance measurements at Storglaciären. Jansson empirically evaluated the influence of errors in 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, the 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. 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. 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.

The combined uncertainty cumulated over the survey periods is calculated following the law of error propagation:

$$\sigma_{\text{glac}} = \sqrt{\left(\sqrt{\sum_{i=1}^{n} \sigma_{\text{field}}^2}\right)^2 + \left(\sqrt{\sum_{i=1}^{n} \sigma_{\text{krig}}^2}\right)^2} \qquad (1)$$

where σ_{field} and σ_{krig} 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 (i) and interpolation methods (ii) 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) use two different approaches to assess the systematic and stochastic uncertainties of the volumetric mass balance. 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, whereas an analysis of elevation differences in non-glacierized terrain allows quantifying the integrative errors of the photogrammetry. Note that the non-glacierized terrain is assumed not to change between the surveys. Full details and equations are given in Koblet et al. (2010). Table 3 summarizes the volumetric mass balances as well as estimates of stochastic (iii, iv) and systematic (E, F) uncertainties based on the two approaches.

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). Using the density of ice (917 kg m^{-3}) will likely overestimate mass changes during periods of changing snow/firn layers and is thus regarded as a maximum estimate. As a minimum estimate we use a density of $825\,\mathrm{kg\,m^{-3}}$, which is calculated as the zonal average of firn ($700\,\mathrm{kg\,m^{-3}}$), firn and ice ($800\,\mathrm{kg\,m^{-3}}$), and ice ($900\,\mathrm{kg\,m^{-3}}$) areas on Storglaciären based on a map created from aerial and terrestrial photographs taken in August 1998 and September 1999 by Schneider and Jansson (2004). We hence use the average of the two density assumptions ($871\,\mathrm{kg\,m^{-3}}$) for the conversion of the volumetric changes into water equivalent and the difference to maximum/minimum estimates ($46\,\mathrm{kg\,m^{-3}}$) as an uncertainty measure (Table 3, v).

3.3.4 Survey dates

Comparison of glaciological with geodetic mass balance requires a melt correction because the field and aerial surveys are not carried out on the same date. The corresponding error 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, 1990, and 1999, 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. Assumptions for the other dates of mass balance field work are based on our own data (Table 1).

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

$$\sum_{i=1}^{n} M = \mathrm{DDF} \sum_{i=1}^{n} T^{+} \cdot \Delta t \qquad (2)$$

The degree-day factor, DDF, is expressed in $\mathrm{mm\,d^{-1}\,K^{-1}}$ for Δt expressed in days and temperature in °C (Braithwaite, 1995; Hock, 2003). We use the daily air temperature series from the Tarfala meteorological station (1138 m a.s.l.; Grudd and Schneider, 1996) – available since 1965 – to calculate positive degree-day sums at the balanced-budget equilibrium line altitude (ELA_0) of Storglaciären. ELA_0 is derived from the linear regression of ELA versus mass balance data (1946–2007), which intersects zero balance at 1451 m a.s.l. The degree-day factor is 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 d^{-1} K^{-1}. For 1959, positive degree-day sums are derived from averaging the cumulative positive degree-day profiles of the years 1969, 1980, 1990, and 1999 as air temperature was only measured during daytime in the summer months (JJA) prior to 1965.

The differences between field and aerial surveys range between 1 and 34 days, resulting in a range of melt corrections between 0 and 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 adjust the glaciological mass balance to the dates of the aerial surveys (Table 2, A).

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 period. 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) addressed the time lag by recalculating the mass balance series on the basis of time periods with (constant) glacier extents centered on the years (1949, 1959, 1969, 1980, 1990) when the aerial photos were taken. The geodetic volume changes (1959–1969, 1969–1980, 1980–1990, 1990–1999) are calculated based on glacier extents by Koblet et al. (2010). Their outlines are congruent in the accumulation area for all years with extents of the glacier tongue based on the ortho-photos. In each period, the (larger) area of the first survey year was used as a reference extent. As a consequence, the reference area differs by up to 10% between the glaciological and the volumetric mass balances of a year (Koblet et al., 2010).

In order to get a rough estimate of the uncertainty of the glaciological mass balance to area differences and changes with time, the specific annual balances are multiplied by the glacier area of the "glaciological" dataset and divided by the extent in the "volumetric" dataset. Thereby, the latter area is 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, B) due to the generally larger glacier areas as determined by Koblet et al. (2010).

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) is considered to be small and corresponding internal ablation, thus, to be negligible (cf. Hooke et al., 1989; Albrecht et al., 2000). The contribution of basal melting by geothermal heat is estimated by Östling and Hooke (1986) as about 0.001 m w.e. The internal melting by released potential energy in descending water is estimated on the order of 0.01 m w.e., using an average drop of 200 m and a total annual discharge of 7×10^{6} m^{3} (Holmlund, 1987). The cumulative error over the survey periods is calculated following the law of error propagation (Table 2, C).

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 has to be considered for a poly-thermal glacier such as Storglaciären (Petterson et al., 2003). Schneider and Jansson (2004) estimate the internal accumulation due to re-freezing of percolating water in cold snow and firn and the freezing of water trapped by capillary action in snow and firn by the winter cold. Based on measured temperature profiles as well as physical characteristics and water content of firn, they obtained values for internal accumulation of 0.04–0.06 m w.e., or 3–5% of the annual accumulation of the entire glacier. Hence, we can now estimate the underestimation of the glaciological mass balance due to internal accumulation to 4% of the winter balances (Table 2, D).

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 (Schytt, 1949; Østrem and Brugman, 1991). In a typical year, Storglaciären gets about 0.1 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. The error of its determination is assumed 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.

4 Results

The glaciological mass balance is cumulated over the aerial survey periods for comparison with the volumetric mass balance. The periods discussed are 1959–1969, 1969–1980, 1980–1990, 1990–1999, and cover 10, 11, 10, and 9 mass balance years, respectively, as well as the full time range from the first to the last aerial survey (1959–1999) with 40 observation years. Also, the uncertainties as addressed in Sect. 3.3 are cumulated over these periods. The assessment of uncertainties includes estimates for both stochastic and systematic errors. Therefore the latter are of positive and negative signs depending on whether they are to be added or subtracted from the glaciological mass balance to fit the geodetic mass balance.

The cumulative glaciological mass balances of the first two periods are negative followed by two periods of ice gain. The mass balance over the entire period covered is also negative. Table 2 gives an overview of the cumulative mass balances between the survey periods and the related stochastic and systematic uncertainties. The general uncertainties for field measurements (i) and interpolation methods (ii) are both estimated at ±0.10 m w.e. a^{-1}. Based on the law of error propagation, these two uncertainties together cumulate to about ±0.45 and ±0.90 m w.e. for the individual survey periods and the entire time span, respectively. The differences in observation periods (A) as covered by the field and aerial surveys require mass balance corrections between 0.02 and 0.21 m w.e. In all but the third period (i.e., 1980–1990), additional melt was required to adjust the glaciological to the volumetric observation periods. The adjustment of the glaciological mass balance to the reference areas and corresponding changes based on the glacier extent in the new orthophotos (B) lead to the systematic decrease of the absolute values of the glaciological mass balance by between 0.01 and 0.17 m w.e. The overestimation of the mass balance due to ignoring the internal ablation (C) is estimated to be small, with values of about 0.01 m w.e. per year. Following the law of error propagation this results in corrections for the decadal and the entire survey periods of 0.03 and 0.06 m w.e., respectively. The rough estimate of the internal accumulation (D) shows an underestimation of the glaciological mass balance by between 0.48 and 0.65 m w.e. for the four decadal periods and by 2.36 m w.e. for the 40 years between the first and the last aerial survey.

The volumetric mass balances, based on Koblet et al. (2010) and an assumed density of 871 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 (v) varies between ±0.03 and 0.27 m w.e. The two approaches based on independent dGPS points (E, iii) and on an analysis of the DEM changes in non-glacierized terrain (F, iv) provide a rough idea of the systematic and stochastic uncertainties related to the volume changes. Both show systematic uncertainties of several decimetres and stochastic uncertainties of a few decimetres. They also 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.

5 Discussion

Based on the official glaciological mass balance series (Holmlund et al. (2005), Tarfala Research Station data), Storglaciären experienced a strong 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 periodic mass balance variations within a range of about 2 m w.e. Between 1988 and 1995, the glacier increased its 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, 1969, 1980, 1990, and 1999 can only roughly trace these variations 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 (1959–1999).

The uncertainty assessment as described in Sects. 3 and 4 is 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 (reporting) and of the aerial survey (shadow modelling). We waive the attempt to quantify all these potential errors since a corresponding overall value would represent a statistical exercise rather than a real-world uncertainty.

However, we apply the systematic uncertainties including corrections for (A) observation periods, (B) reference areas, (C) internal ablation, and (D) 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 mass balances by Koblet et al. (2010). In principle, this should reduce the differences between the glaciological and the volumetric mass balance. In fact, this is true when only the corrections (A), (B), and (C) are applied; but the systematic bias from the internal accumulation (D) even increases the deviations. This effect becomes most prominent in Fig. 2, where the changes are cumulated with reference to the year of the first aerial survey (i.e., 1959). Based on the comparison of the "best estimate" glaciological with the volumetric mass balance we conclude that either the systematic error introduced by the internal accumulation, as estimated from the study for the balance years 1997 and 1998 by Schneider and Jansson (2003), is overestimated significantly, one of the other directional uncertainties are underestimated, or another systematic error is not yet accounted for. The systematic uncertainties of the volumetric mass balance as derived from two different approaches (dGPS: E; non-glacierized terrain: F) do not provide an explanation for these differences.

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 estimate" (incl. all systematic corrections A, B, C, D) of the present study. The systematic uncertainties of the volumetric mass balance by Koblet et al. (2010; E, F) cannot provide a final answer to these questions but show that the "official" glaciological series is within the range of uncertainty, whereas the "best estimate" is not. However, the mean annual deviations from the "official" glaciological mass balance series (Holmlund et al. (2005), Tarfala Research Station data) are all below 0.1 m w.e. This holds for all the four observation periods as well as over the entire period of 1959–1999 (Table 4). The only two exceptions are the values for the first and third decade of the volumetric mass balance including the systematic corrections from the non-glacierized terrain (F). The mean annual deviations 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, which 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), global positioning systems (e.g., Hagen et al., 1999; Miller and Pelto, 1999), or laser altimetry (e.g., Conway et al., 1999; Echelmeyer et al., 1996; Sapiano et al., 1998; Geist and Stötter, 2007), the latter three 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). In the case of Storglaciären, the glaciological mass balance series agrees well with the new volumetric data by Koblet et al. (2010) and, hence, an adjustment is not required.

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, 1969, 1980, 1990, and 1999 were used by Koblet et al. (2010) to directly produce volumetric mass balances based on uniform photogrammetric methods. In the present study we compared these volumetric with the "official" glaciological mass balances 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 0.9 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 by applying corrections for systematic uncertainties in the glaciological mass balance 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 are less than 0.1 m w.e. and as such are within the order of magnitude of the stake 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.

There is, then, no need for an adjustment of the glaciological data series. Further investigations should 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. It is not surprising that the cumulative glaciological mass balance variations based on the very dense observation network of Storglaciären fit well with the decadal volumetric data. Nevertheless, 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.

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Table 1. Aerial and field survey dates, positive degree day sums (PDDS), and related melt corrections. For details see text.

aerial survey	field survey			PDDS		melt	
date	end winter	end summer	summer balance [m w.e.]	summer survey [K]	between surveys [K]	factor [m w.e. K^{-1}]	correction [m w.e.]
23 Sep 1959	15 Mai 1959	15 Sep 1959	1.80	501.5	7.3	0.0036	0.026
14 Sep 1969	15 Mai 1969	15 Sep 1969	1.93	531.2	0.0	0.0036	0.000
18 Aug 1980	27 Mai 1980	21 Sep 1980	2.16	607.5	59.2	0.0036	0.210
4 Sep 1990	24 Mai 1990	10 Sep 1990	1.65	429.3	16.6	0.0038	0.064
9 Sep 1999	5 Mai 1999	15 Sep 1999	1.52	434.0	27.2	0.0035	0.095

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Table 2. Glaciological mass balances and related stochastic and systematic (A–D) uncertainties. 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 1959–1999 covers the hydrological years from 1959/60 to 1998/99.

observation period	cumulative glac. mass balance	field measurements (i)	interpolation method (ii)	survey dates (A)	reference areas (B)	internal ablation (C)	internal accumulation (D)
1959–1969	−3.110	±0.316	±0.316	−0.026	+0.048	−0.032	+0.484
1969–1980	−2.540	±0.332	±0.332	−0.210	+0.133	−0.033	+0.642
1980–1990	1.000	±0.316	±0.316	+0.146	−0.007	−0.032	+0.646
1990–1999	0.720	±0.300	±0.300	−0.031	−0.001	−0.030	+0.588
1959–1999	−3.930	±0.632	±0.632	−0.119	+0.173	−0.063	+2.360

Table 3. Volumetric mass balances and related stochastic and systematic (E, F) uncertainties. 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	volumetric mass balance	dGPS systematic (E)	dGPS stochastic (iii)	non-glacierized systematic (F)	non-glacierized stochastic (iv)	density assumption (v)
1959–1969	−3.983	+0.300	±0.360	−0.650	±0.310	±0.210
1969–1980	−2.877	+0.780	±0.890	+0.380	±0.420	±0.152
1980–1990	1.315	−0.740	±0.880	+1.990	±0.340	±0.069
1990–1999	0.590	−0.430	±0.240	−0.700	±0.170	±0.031
1959–1999	−4.954	−0.100	±0.340	+0.760	±0.220	±0.268

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 1959–1999 covers the hydrological years from 1959/60 to 1998/99.

Time	glac.mb by Holmlund et al. (2005), Tarfala Research Station data	glac.mb by Holmlund and Jansson (1999)	glac.mb this study, ”best estimate”, corr. A/B/C	glac.mb this study, ”best estimate”, corr. A/B/C/D	vol.mb by Koblet et al. (2010)	vol.mb by Koblet et al. (2010), corr. E	vol.mb by Koblet et al. (2010), corr. F
obs. period	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}	m w.e. a^{-1}
1959–1969	−3.110	−0.047	−0.001	+0.048	−0.087	−0.057	−0.152
1969–1980	−2.540	−0.037	−0.010	+0.048	−0.031	+0.040	+0.004
1980–1990	1.000	+0.014	+0.011	+0.075	+0.032	−0.043	+0.231
1990–1999	0.720	−0.003	−0.007	+0.058	−0.014	−0.062	−0.092
1959–1999	−3.930	−0.019	0.000	+0.059	−0.026	−0.028	−0.007

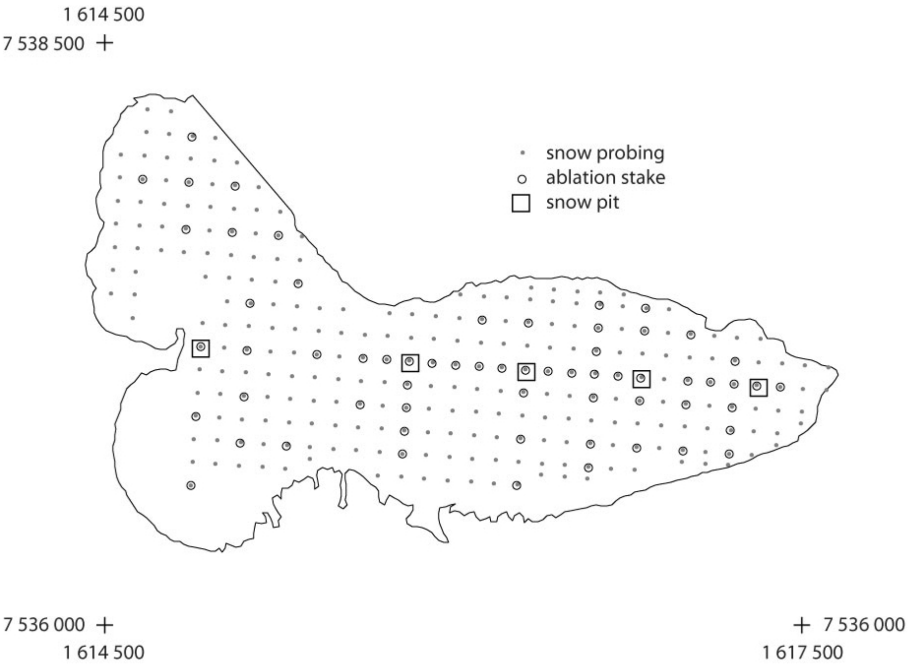

Fig. 1. Observation network on Storglaciären in 2006/07. Snow observations and ablation stakes are used for the determination of the winter and summer mass balance, respectively. Glacier outlines from the 1990 map (Holmlund, 1996). Map coordinates are in the Swedish coordinate system RT 90 2.5 gon V.

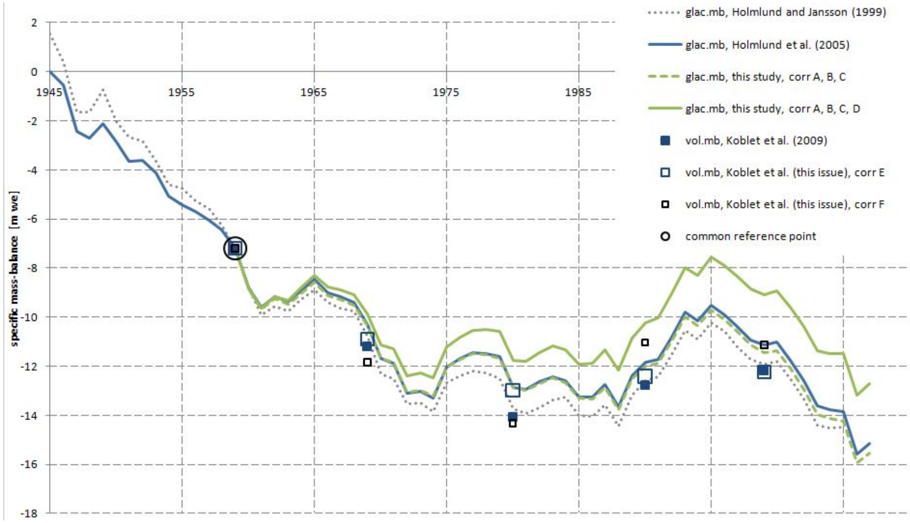

Fig. 2. Cumulative glaciological and volumetric mass balance series of Storglaciären. The "official" glaciological mass balance series (Holmlund et al. (2005), Tarfala Research Station data) is compared to the new volumetric mass balance data by Koblet et al. (2010; 1959–1969, 1969–1980, 1980–1990, 1990–1999). 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). Additional volumetric mass balances–all derived from digitized contour maps–are plotted based on Holmlund (1987; changes as calculated from maps and adjusted to the glaciological data by Holmlund and Jansson, 1999), and based on Holmlund (1996) and Albrecht et al. (2000). 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.).