Reanalysing of a mass balance record, Engabreen 1970-2014

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Preface

This report documents the results from Engabreen, and is part of a major reanalysis of mass balance measurements from ten glaciers in Norway with long time series. The time series are based on traditional glaciological observations using stakes, snow depth soundings and snow density measurements, as well as geodetic observations using aerial photogrammetry, laser scanning and maps.

This report is written by Hallgeir Elvehøy in collaboration with Liss Marie Andreassen, Bjarne Kjøllmoen and Rune V. Engeset. The entire renanalysis is documented in a scientific paper in The Cryosphere: www.the-cryosphere.net/10/1/2016/.

We would like to thank M. Zemp, J. Oerlemans, A. Kääb, M. Huss and C. Nuth for valuable input during the progress of the analysis.

Oslo, 29th February 2016

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Summary

Engabreen, a northern outlet glacier from western Svartisen (or Vestisen) in Nordland, is the most studied glacier in North-Norway, starting in 1892. It has been a part of the Norwegian mass balance monitoring program since 1970. The results showed a mass surplus from 1972 to 1977, near balance from 1977 to 1988, and a large mass surplus from 1988 to 2000. After 2000, the measurements reveal a slight deficit. In contrast to the large mass surplus shown by the annual measurements, geodetic mass balance calculations showed a slight mass deficit over the period 1968 to 2002. Consequently, an evaluation of the measurements and calculations was required.

The glaciological surface mass balance series from Engabreen was re-analysed based on comparison with geodetic mass balance. Digital Terrain Models (DTMs) from 1968, 2001 and 2008 were available. Glaciological and geodetic mass balance were compared for the periods 1969-2001 and 2001-2008. The DTMs and the surface mass balance measurements and calculations (1970-2014) were homogenized to ensure a uniform methodology for data processing and calculation from field data to the final balance values. The process involved digitising of analogue records and registering all point measurements of snow depths and stakes with positions and heights. The re-calculation was based on the “profile method” applying the appropriate DTM and the ice divide from 2008. In addition, the relevant uncertainties in both glaciological and geodetic mass balance results were assessed, and the internal and basal mass balance components were assessed to compensate for the generic difference between surface glaciological mass balance and total geodetic mass balance.

The homogenized glaciological mean annual balance for Engabreen over the periods 1969-2001 and 2001-2008 were $+0.69 \pm 0.28$ and $+0.02 \pm 0.28$ m w.e.a$^{-1}$, respectively. The corresponding geodetic mass balance were $-0.03 \pm 0.06$ and $-0.48 \pm 0.04$ m w.e.a$^{-1}$, respectively. The internal mass balance of Engabreen was quantified as $-0.15 \pm 0.05$ and $-0.08 \pm 0.03$ m w.e.a$^{-1}$ before and after 15th January 1993 when the sub-glacial river intakes at Engabreen started operating. The annual differences ($\Delta a= Ba_{\text{glac.}} - Ba_{\text{geod.}} + Ba_{\text{int.}}$) over 1969-2001 and 2001-2008 were -0.59 and -0.48 m w.e., respectively. The differences were found to be statistical significant at the 95 % confidence level. Hence, a calibration of both the periods 1969-2001(32 y) and 2001-2008 (7 y) was required. The periodic annual corrections were distributed equally over the years but split between winter and summer balances. The percentual distribution between winter and summer balance corrections was assessed according to the relative size of the two balance values.

The calibrated cumulative surface mass balance at Engabreen over 1969-2008 is $+0.4$ m w.e., while the original cumulative surface mass balance over the same period was $+22.2$ m we.
1 Introduction

1.1 Background

The Norwegian Water Resources and Energy Directorate (NVE) operate the Norwegian mass balance observation programme. The observations are both traditional field measurements, referred to as the glaciological method and geodetic surveys, referred to as the geodetic method (Cogley et al., 2011). The programme includes 10 long time series: 6 glaciers with time series longer than 50 years and another 4 glaciers with time series with more than 25 years of data (Fleig et al., 2013) as per end of 2015.

Glacier mass balance may be calculated by the glaciological (also called direct, traditional or conventional) method and by the geodetic (or cartographic) method. The glaciological mass balance method measures mass balance at point locations, and data are extrapolated over the entire glacier surface to obtain glacier-wide averages for the surface mass balance (Østrem and Brugman, 1991). The cumulative mass balance is the sum of the annual balances. In the geodetic method, the cumulative balance is calculated from glacier surface elevations measured in different years by differencing digital terrain models (DTMs) and by converting the volume change to mass balance using a density conversion procedure. In order to compare glaciological surface mass balance to geodetic mass balance, internal and basal mass balances have to be assessed. The geodetic method is often used as check on the accuracy of annual measurements by the glaciological method (e.g. Andreassen, 1999 and Zemp, 2010). In the joint paper from the workshop on “Measurement and Uncertainty Assessment of Glacier Mass Balance” at the Tarfala Research Station in northern Sweden it is recommended that mass balance series longer than 20 year should be re-analysed (Zemp et al., 2013). Reanalysis of mass balance records should be based on consistent data and procedures, and include assessment of both random and systematic uncertainties. If a comparison between the glaciological and the geodetic method of a long-term series show significant discrepancies or discrepancies larger than 0.2 m w.e.a⁻¹, a calibration of the surface mass balance series is advised (Zemp et al., 2013).

This report describes the re-analysis of the Engabreen surface mass balance time series. The geodetic and glaciological mass balance for the coincident period from autumn 1969 to autumn 2008 is compared. The comparison shows a major discrepancy of more than a half meter per year over 1969-2008, and consequently, a reanalysis of the surface mass balance time series is required. The output of the re-analysis is a homogenized glaciological mass balance time series with an uncertainty assessment, and a calibrated glaciological mass balance time series. Both time series will be published as elevation-distributed winter, summer and annual mass balances.

1.2 Engabreen

Engabreen (66°40′N, 13°50′E) is a northern outlet glacier from western Svartisen (or Vestisen) in Nordland, northern Norway. It is located in a mountainous area close to the ocean with peaks at 1400-1600 m a.s.l. Engabreen covers 37 km² and ranges in altitude from 89 to 1575 m a.s.l. (Fig. 1-1). Between 300 and 900 m a.s.l the glacier has a heavily crevassed icefall. The icefall aned the lower tongue below 300 m a.s.l. covers 7% of the glacier area. The glacier tongue experiences periodical melting throughout the winter due
to frequent occurrence of positive temperatures at sea level in the maritime climate. Consequently, the glacier tongue is often snow-free early in spring. The length of the glacier is about 11 km (measured from the ice divide west of Snøtind to the glacier terminus). The average slope on the plateau above 900 m a.s.l. is 4°, while the slope of the ice fall is 15°.

The mass balance measurements at Engabreen is a part of hydrological investigations financed by Statkraft AS to fulfill obligations in the concession related to regulation for hydro-power production in Svartisen Kraftverk.

1.3 Previous investigations


As background for planning of hydro-electric development in the Svartisen-Saltfjellet area, a hydrological monitoring program was initiated in the late 1960-ies, including river discharge, sediment transport (Bogen and Bønsnes, 2001) and mass balance at several glaciers (Andreassen et al, 2005). Several meteorological stations have been operated for energy balance studies (Messel,1985). Engabreen has been subject for continuous glaciological surface mass balance measurements since September 1969; the mass balance year 1969/1970 is the first year of the record (Tvede, 1971, Kjøllmoen, 2011). Both winter and summer balance terms have been calculated annually. The results show a mass surplus from 1972 to 1977, near balance from 1977 to 1988, and a heavy mass surplus from 1988 to 2000. After 2000, the measurements reveal a slight deficit. In contrast to the large mass surplus by the glaciological method, the geodetic mass balance showed a slight mass deficit over the period 1968 to 2002 (Haug et al, 2009).

1.4 Outline

This report is structured according to the scheme for reanalysing glacier mass balance series outlined in Zemp et al., (2013). In chapter 2 the observations, i.e. the maps/DTMs and original surface mass balance results, are presented. In chapter 3 the surface mass balance series and the geodetic surveys are homogenized and the geodetic mass balance is calculated. In chapter 4 the random errors and systematic biases are assessed. In chapter 5, the internal and basal balances are assessed to compensate for the generic difference between the glaciological surface mass balance and the geodetic mass balance, and then
the glaciological mass balance is validated against the geodetic mass balance, including internal and basal balances, and the need for a calibration of the surface mass balance is discussed. In chapter 6 the annual surface mass balance series are calibrated.

This report documents a part of the basis for a reanalysis of ten long-term mass balance series from Norwegian glaciers (Andreassen et al, 2016).

Figure 1-1 Map of Vestisen with Engabreen drainage divide in red.

2 Observations

2.1 Geodetic mass balance

Aerial photographs covering the entire glacier basin exist from 1945, 1968, 1985, 1998, 2002 and 2008. In addition, the glacier tongue was photographed 2 – 3 times per year between 1993 and 1997, and again in 2013 (several of the aerial photos are available as orthophotos at www.norgebilder.no). Detailed maps have been constructed from the photographs captured in 1968 and 1985. Due to insufficient horizontal overlap between two photo stripes the constructed map and DTM from 1985 is of inferior quality and are not used here. Engabreen was mapped using LIDAR in 2001, twice in 2002, in 2003 and in 2008. In 2013 only the tongue below ca 900 m a.s.l. was mapped. The map from 1968 and the DTMs from 2001 and 2008 have been used as basis for mass balance calculations and are described in more detail in the following.

The data processing was done using ArcMap 9.3/10.2 (ESRI) and Surfer 8 (Golden Software Inc.).

2.1.1 Mapping 25th August 1968

Vertical aerial photographs (scale 1:35000, flying height 5800 m a.s.l., Widerøes Flyveselskap AS, contract no 3205) were used to construct a map at scale 1:20 000 with
10 m contour lines on the glacier and 50 m contour lines outside the glacier (Fjellangers oppmåling AS). Some winter snow remained at the time of photography, and some new snow is visible in crevasses on the plateau. There are only two reference points within the map sheet (Helgelandsbukken and Snøtind). However, some spot elevations that coincide with NVE fix points are also plotted on the maps.

The map was analogue constructed in 1970 as a base map for the glacier investigations. The glacier boundary, contour lines and summit points were digitised by NVE in the end of the 1990s, and the points were then transformed from UTM ED50 to UTM EUREF89. The distance between points along contour lines varies. A 5x5 meter DTM was generated using TopoToRaster interpolation (ArcMap).

2.1.2 Mapping 24th September 2001

LIDAR data was captured by TopScan GmbH, Germany. Average point density was 0.7 points per m². LIDAR-data covering a control surface (Halsa football field 15 km NW of Engabreen) was mapped on the same flight showing elevation deviations of 0.00 ±0.09 meter. A 5x5 m DTM covering Engabreen and Engabrevatnet was constructed by Thomas Geist, Institute of Geography, University of Innsbruck, Austria (Geist et al., 2005).

The number of accepted return signals at the lowest part of the glacier was much lower than the average point density (0.033 points per m² between 400 and 600 m a.s.l., 0.0033 points per m² between 200 and 400 m a.s.l., and 0.0005 points per m² between 10 and 200 m a.s.l.). To fill the gaps on the lower glacier tongue, the LIDAR points from September 2001 and a 5x5m DTM from May 2002 were used. The elevation change between the two surveys at the 2001 points was calculated, and the points of elevation change were interpolated to a 5x5m grid. A new surface DTM for the lower glacier tongue (below ca
440 m a.s.l.) was calculated from the May 2002 DTM and the change grid, and combined with the original DTM from 2001. LIDAR-points from 2001 less than 20 meters from the glacier edge were excluded due to rugged topography.

The glacier outline was digitized from a difference map between the DTMs from 2001 and 2008, supported with intensity values from 24 September 2001, orthophotos from 23 June 2001 (www.norgebilder.no), and vertical aerial photos from August 2002.

2.1.3 Mapping 2nd September 2008

A large part of western Svartisen (Vestisen) was mapped using LIDAR on 2nd September 2008 (contract BNO08797, Blom Geomatics AS, Oslo, Norway). The point density varies between 2.6 and 6.0 points per square meter. A homogeneity check investigating elevation deviations between neighboring flight lines gave a total RMS-error of 0.175 m. The highest deviations were found in steep terrain, as expected. Based on the point elevation data a 5x5 m DTM covering Engabreen, Litlbreven and Storglombreen was constructed.

The glacier outline was mapped using a combination of laser intensity values, terrain relief and orthophotos constructed from vertical aerial photos from 24 August 2008 (www.norgebilder.no).
2.1.4 Density assessment

In order to convert the volume change of snow, firn and ice to a mass change, a density assessment is required. One approach is to assume the density profile in the accumulation area to be constant in time, and consider all changes to be a volume of glacier ice (Sorge’s law, Bader, 1954). Hence, the density of glacier ice, 900 to 917 kg m\(^{-3}\) (Cuffy and Paterson, 2010), has been used for the conversion (e.g. Andreassen 1999, Andreassen et al 2002, Haug et al. 2009). This assumption however, is valid only under steady-state conditions, whereas the amount of snow and firn may change between surveys. For glaciers melting down, a large part of the volume change can be the loss of firn. At Engabreen, changes have been both positive and negative. Without any measurements of firn densities and thickness, a reasonable estimate with an accuracy estimate gives the best approximation. Assuming a value of 850 ±60 kg m\(^{-3}\) to convert volume change to mass change is found to be appropriate for a wide range of conditions (Huss, 2013). Hence, this value was used for the conversion of the volumetric changes into mass change.

2.1.5 Adjustment for change between survey dates

Comparison of glaciological and geodetic mass balance requires an adjustment because the ground measurements and aerial surveys are acquired at different dates. The related difference depends on the time span between the ground and aerial surveys. Accordingly, increasing time span can result in an increasing difference. The season (summer/autumn) and the general mass turnover will also influence the difference. The adjustments where here assessed using stake measurements, www.senorge.no (Saloranta 2014a, 2014b) and a Positive Degree Day (PDD) model based on air temperature and precipitation measured at nearby climate stations Glomfjord (1968 and 2001) or Reipå (2008). Dates for ground measurements, aerial surveys and assessed annual minimum dates, and corresponding adjustments are shown as glacier wide averages in table 2-1.

The 1968 photos were captured more than a year ahead of the start of the mass balance measurements. The mass change for the period 25\(^{th}\) August 1968 to 21\(^{st}\) September 1969 was estimated using the PDD-model, and was found to vary from +1 m w.e. at 1350 m a.s.l. to -10 m w.e. at 300 m a.s.l. The glacier-wide adjustment was calculated as -0.3 ±0.5 m w.e. based on the altitudinal area distribution from 1968.

The 2001 LIDAR data were captured 17 days before the field survey. Stake measurements showed limited melting between 24\(^{th}\) September and 10\(^{th}\) October on the plateau. From www.senorge.no the annual minimum date was 24\(^{th}\) September above 1200 m a.s.l., but 21\(^{st}\) October on the lower plateau. At the glacier tongue, melting probably persisted until 5\(^{th}\) November. The glacier wide adjustment was assessed as -0.1 ±0.1 m w.e.

The 2008 LIDAR data were captured less than one month before the ground measurements. Melting at stakes between 2\(^{nd}\) September and 3\(^{rd}\) October at the plateau varied from 0.7 m of ice at E34 (960 m a.s.l.) to 0.05 m of snow at E101 (1310 m a.s.l.) and no change at E105 (1330 m a.s.l.). Some melting probably occurred between 3\(^{rd}\) October and 20\(^{th}\) October below ca 1200 m a.s.l. (www.senorge.no), but this melting is assessed to be neglible. At the glacier tongue melting probably persisted until 13\(^{th}\) November 2008. The glacier wide adjustment was assessed as -0.3 ±0.1 m w.e.
Table 2-1 Adjustments for change between mapping date and date for annual minimum.

<table>
<thead>
<tr>
<th>Year</th>
<th>Date Mapping</th>
<th>Date Field survey</th>
<th>Type of adjustment</th>
<th>Adjustment m w.e.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1970</td>
<td>25.08.1968</td>
<td>20.10.1969</td>
<td>Melting +annual balance 1969</td>
<td>-0.3 ±0.5</td>
</tr>
<tr>
<td>2001</td>
<td>24.09.2001</td>
<td>10.10.2001</td>
<td>Melting</td>
<td>-0.1 ±0.1</td>
</tr>
<tr>
<td>2008</td>
<td>02.09.2008</td>
<td>03.10.2008</td>
<td>Melting</td>
<td>-0.3 ±0.1</td>
</tr>
</tbody>
</table>

2.1.6 Glacier boundaries

Different approaches have been used to define the basin for the mass balance calculations. From 1970 until 2003, the glacier outline from 1968 and a surface drainage divide (i.e. drainage divide for a closed surface) defined the mass balance basin (38.02 km²). From 2004 until 2007, a sub-glacial drainage divide defined from hydraulic head calculations based on surface topography and ice thickness (Kennett et al, 1997) and the glacier outline from 2001 defined the mass balance basin (39.55 km²). From 2008, the glacier outline from 2008 and the surface drainage divide calculated from the 2008 DTM defined the mass balance basin (36.84 km²).

Here, the drainage basin for surface mass balance and geodetic mass balance was defined as a surface drainage basin (i.e. drainage divide for a closed surface) for glacier areas draining to lake Engabrevatnet where the river discharge is measured (159.3.0 Engabrevatnet), including Litlebreen and an area on the western side of the glacier tongue not supplying glacier ice to the glacier tongue (Elvehøy et al, 2009). For the geodetic volume change calculations, a combination of the glacier boundaries for both years in each period is used. The combined boundaries will surround the glacier areas for both years in each period.
2.2 Glaciological mass balance

The Norwegian Water Resources and Energy Directorate (NVE) have monitored glacier surface mass balance at Engabreen annually since 1970. Statkraft AS has financed the measurements. The extent of measurements has varied considerably over time, and different methods of calculation have been used. Measurements and calculations are in principle based on methods described in Østrem and Brugman (1991) and Andreassen et al (2005) and Kjøllmoen et al (2011). The measurements are reported in “Glaciological investigations in Norway”, which are annual reports published by NVE and available at www.nve.no/glacier. The 2010 measurements were reported in Kjøllmoen et al. (2011). Measurements from 2011 and later are due for publication in a multi-year report as soon as the re-analysis is finished.

2.2.1 Monitoring program

The mass balance measurements started in September 1969 (Tvede, 1971). The glaciological mass balance results are based on point measurements of winter and annual balance, calculation of point summer balances, and interpolation from point winter and summer balances to glacier-wide winter and summer balances. The winter balance is usually measured between mid-April and late May, while the annual balance is measured between mid-September and late October.

The monitoring programme has varied considerably over the measurement period. The number of stakes and their locations were intended to be kept stable for several years, but varied considerably from year to year due to time constraints and positioning difficulties. Due to spring warming the snow density on the lower plateau often are higher than on the upper plateau. To capture this difference the density measurements were performed at one lower and one higher location.

In the following, the period of measurements from 1970 to present is divided into four periods and described in more detail.

1970-81 - Extensive measurements on the plateau

The monitoring programme included about 20 stake locations on the glacier plateau, up to ten wires melted into the ice at the glacier tongue between 200 and 400 m a.s.l., two snow density pits on the plateau – one at higher (E121/E101) and one at lower elevation (E35/E14), and 200-500 snow depth soundings on the glacier plateau (Fig. 2-2). The stakes were positioned visually in the field, and then drawn on the maps. Stakes lost in winter were to some degree replaced in spring at the winter balance measurements. The stake positions were surveyed using triangulation from fix points at some occasions. The snow depth was sounded in 200-500 points on the glacier plateau. The sounding profile lines were defined by direct sighting between land marks or stake locations and compass berrings. Distances along profiles were measured by the snow mobile odometer. Hence, the location accuracy depended on the weather, the number of visible stakes, and the field workers local experience. The first winter measurements were normally performed around 1st December. Melting after 1st September was measured by comparing snow depth sounding and stake measurements at winter visits. This depended on that stakes could be found and that the summer surface could be located. Unfortunately, the available documentation has not been sufficient to verify that the autumn melting was included for all the years. In several of the first years, most of or all the stakes on the plateau were lost
during the winter. To secure some reference for the spring snow depth soundings, calendar masts which could stand up to 7-8 m high were introduced at locations E16 and E105 in 1976/77. These locations were then preferred for density measurements.

Personnel from the regular staff at NVE carried out winter maintenance, and spring and autumn measurements. Summer assistants maintained the stake network and operated a meteorological station from medio June until ultimo August. The stake network on the plateau and at the tongue was checked about weekly between 15th June and 1st September.

1982-98 – Index locations
After an evaluation of the spatial distribution of winter snow based on measurements from 1970 to 1978, four main stake locations on the plateau were selected as index locations (Fig 2-3). The snow depth was sounded in 40 to 300 points on the plateau along a few selected profiles. Snow density was measured at two locations (E16/E20 and E105). Location E20 was assessed more representative than E16, and consequently the lower density measurement was moved from 1983. Between 1982 and 1989, no stake measurements were carried out at the glacier tongue, and the winter and summer balances there were estimated from the average 1970-78 mass balance gradients. After 1989, one or two stake locations were maintained on the tongue in most years both for winter and summer balance calculations.

1999-2005 – Slightly extended monitoring programme
Between 1999 and 2005 the mass balance was measured typically at one stake location at the tongue and about nine locations on the plateau, two density pits were measured (E38 and E143), and about 150 snow depth soundings were conducted along ~30 km of profiles between 950 and 1460 m a.s.l. (Fig 2-4). Since 2001, one stake location (E34) at 960 m a.s.l. in a blue-ice area above the ice fall was maintained. Until 2001 the balance profile in the ice fall was interpolated between E38 (snow area at 1050 m a.s.l.) and E17 (blue-ice at 300 m a.s.l.). The introduction of stake location E34 resulted in a more negative annual balance profile.

2006-2014 – Reduced monitoring programme
The monitoring programme was reduced again for fieldwork to fit within one working day for two persons. One stake at the tongue and six stake locations at the plateau were maintained. The snow density was measured at one location (E5), and snow depth was measured at approximately 50 points along an 11 km profile between 1460 and 950 m a.s.l. along the stake line. (Fig 2-5).

2.2.2 Field measurements
The autumn survey consists mainly of stake readings, and preferably takes place at the annual minimum date, before the start of the next accumulation season. Then additional observations of snow line and firn line are possible. If the autumn measurements are performed after the annual minimum, the new snow depth to the summer surface is measured at the stakes by probing, coring or in a pit. If the autumn survey precedes the annual minimum, comparison of sounded snow depth and stake length change at the next visit can identify the additional melting (late autumn melting). Results from automated snow models (www.senorge.no) can help to identify such conditions. In practise, the autumn survey takes place when weather conditions are favourable.
At the glacier tongue, the melt season starts earlier in spring and last longer into the autumn than at the plateau. The low elevation, close proximity to the sea and frequent periods of above-zero temperatures during winter results in frequent melt-periods during the winter at the glacier tongue. Hence, the annual minimum date there is not obvious. Normally, the winter snow has melted at the time of the spring (snow) measurements, and up to 2 - 3 meters of ice melt can occur between autumn and spring survey dates.

In spring, snow depth is measured at a number of locations by probing to the summer surface from the previous year supported by the stake network. Until 2000, the snow depth soundings along profile lines were geo-referenced when plotted on maps based on stake positions and reference points, compass courses or direct sightings, and distance along profile lines either measured with snow mobile odometer or evenly distributed between end points. Consequently, the position accuracy of the snow depth measurements varies from ±1 m at recently triangulated stakes to ±100 m or more when soundings were conducted during low visibility. Since 2000, handheld global navigation satellite system (GNSS) instruments has been used for positioning, improving position accuracy to ±10 meter.

Snow density is measured either in a pit using a 0.5 m long steel tube containing 0.002 m³ of snow, or by using a coring auger, or a combination of the two. In 1976 and 1978-81, the snow density was measured partly during winter visits and then, at spring survey, down to the surface from the previous visit which was marked with red dye/dust. This procedure assumes no mass transport through the marked surface, i.e. no melting with drainage through the snow pack. Between 1989 and 1997 a standard function for density increase with depth based on previous measurements was used. Only the upper 2-3 meters of the snow pack was measured in a pit or by coring, and the deeper parts of the profile was assessed from the standard function.
Figure 2-2 Stake network, density pits and snow depth soundings in 1977.

Figure 2-3 Stake network, density pit and snow depth soundings in 1989.
Figure 2-4 Stake network, density pit and snow depth soundings in 2004.

Figure 2-5: Stake network, density pit and snow depth soundings in 2012.
2.2.3 Calculations

The surface mass balance is calculated using a stratigraphic method, i.e. calculating the annual mass change between two successive “summer surfaces” (surface minima) (Østrem and Brugman, 1991). The glacier wide winter and summer balances are calculated separately, and the glacier wide annual mass balance is calculated as the sum of the two.

Point winter balance is calculated at sounding and stake locations from measured snow depth converted to water equivalent values using a density conversion procedure.

From 1970 to 1988, the snow density and the water equivalent value was calculated for each snow sample in the pit or core, and the accumulated water equivalent was plotted against increasing snow depth in a diagram. From these diagrams, all measured snow depth was assigned a water equivalent value, manually. In 1976 and 1978-81, snow density was partially measured two or three times during the winter season. The total water equivalent value was calculated by addition, and an bulk density of the snow pack was calculated from the total snow depth in spring. An average density ($\rho_{av}$) of the snow pack was used for all point measurements of SD. Using the mean density as density conversion does not take into account that thicker snow packs have higher mean density then thinner snow packs due to compaction under over-lying snow.

Between 1989 and 1997, snow depth to water equivalent-profiles were assessed from measurements of snow density down to 2 to 3 m depth, and an empirical function based on density increase with depth from earlier measurements.

From 1998, the accumulated water equivalent was plotted against increasing snow depth and a mathematical trend line and function was calculated. Normally, a second order polynomial expressed as: $b_w = a*SD^2 + b*SD + c$ (a, b and c are coefficients) was used.

Until 2006, snow density used to be measured at two locations, one in the higher part (E101, E105, E121 or E143) and one in the lower part (E35, E38, E14, E16 or E20) of the plateau to capture differences normally caused by higher occurrence of melt early in spring at the lower part of the plateau. The boundary was set both from elevation (between 1200 and 1250 m a. s. l.) and geographically (around north 7395500).

In 1976 and 1978-81, the snow density was measured partly during winter visits and then, at spring survey, down to the surface from the previous visit which was marked with red dye/dust. This procedure assumes no mass transport through the marked surface, i.e. no melting with drainage through the snow pack.

Between 1989 and 1997, a standard function for density increase with depth based on previous measurements was used. The upper 2-3 meters were measured in a pit, and the deeper parts of the profile was estimated from a standard function. Since 1998, second order polynomial functions have been assigned to the “SD to SWE”-curves, and the functions were used to convert snow depth to snow water equivalents.

When two or more density measurements were performed, the different density conversion functions were used below and above a certain threshold – normally around 1200-1250 m a.s.l. which to some degree coincides with southern and northern part of the glacier (division at about UTM-North 7395000).
At the glacier tongue, the melt season starts earlier in spring and last longer into the autumn than at the plateau. The low elevation, close proximity to the sea and frequent periods of above-zero temperatures during winter results in frequent melt-periods during the winter at the glacier tongue. Hence, the annual minimum date there is not obvious. Normally, the winter snow has melted at the time of the spring (snow) measurements, and up to 2 - 3 meters of ice melt can occur between autumn and spring survey dates.

Point summer balance is calculated at stake locations from winter and annual balance at the stake locations. If stakes are lost during the winter, the summer balance is calculated from snow depth measurements in spring and stake measurements during summer. If stakes melt out during summer, the missing period is modelled using a PDD-model in combination with neighbouring stakes. Annual changes (ice melt, firn melt or snow accumulation) are converted to water equivalent values using a density of ice of 900 kg/m³, a firn density between 650 and 750 kg/m³ depending on the assumed age of the firn, and a standard density of remaining snow of 600 kg/m³. Some measurements of autumn snow density implies that particularly in years with a large mass surplus the standard density is too high.

From 1970 until 1988 maps of winter and summer balances with 0.5 m w.e. isolines were drawn from the measurements (Fig. 2-6). The calculation of the mass balance terms was based on the area between the isolines. The areas between adjacent isolines within each elevation bin (100 m) were integrated using a planimeter, assigned a value and the volume of winter or summer balance was calculated. Then altitudinal balance values $B_w(z)$, $B_s(z)$ and $B_a(z)$ were calculated. At the glacier tongue, the winter balance was set as 0 m w.e. below the temporary snow line altitude at spring measurements, typically between 300 and 600 m a.s.l., and the summer balance was set equal to the annual balance (Fig 2-7). After the monitoring programme was reduced in 1982, the average distribution of $B_w$ and $B_s$ from 1970-78 was used to draw the isolines in unmeasured areas.

Since 1989, the profile method has been used to define the mass balance curves $B_w(z)$, $B_s(z)$ and $B_a(z)$. Point measurements of winter and summer balance were plotted versus altitude, and representative values for each 100-m elevation bin were extracted from the scattered points. In the ice fall between the lower tongue and the plateau (400-900 m a.s.l.) the balance values were interpolated. Below ca 200 m altitude the balance values are extrapolated (Fig. 2-8).

The reported mass balances are surface mass balances. Internal mass balance and basal mass balance have been considered negligible for the annual results, and consequently the surface mass balance has been assumed to equal the total mass balance.
From 1970 to 1988 the spatial distribution of the mass balance was manually drawn for both winter and summer balance. This map is showing the summer balance of 1981 interpolated from the measurements (red numbers are summer balance in cm, calculated at stakes(stake number in black)).
Figure 2-7
Altitudinal distribution of winter, summer and annual balance in 1981.

Figure 2-8
Altitudinal distribution of winter, summer and annual balance in 1994.
2.2.4 Glaciological mass balance results 1969-2014

The original surface mass balance record (Fig. 2-9) shows that the glacier volume increased substantially between 1969 and 1977 (+8.4 m w.e.) and again between 1988 and 2000 (+14.0 m w.e.). Between 1977 and 1988 there were only small changes (+1.8 m w.e.). After 2000, the cumulative mass balance was negative (-4.2 m w.e.). Mean winter and summer balance including 2014 (45 years) was 2.88 and -2.44 m w.e.a⁻¹, respectively. The annual mass surplus was +0.44 m w.e.a⁻¹, and the cumulative glaciological mass balance was +20 m w.e.

Figure 2-9. The original mass balance record of Engabreen as reported in the series “Glaciological investigations in Norway”, and as accessible in the WGMS database.
3 Homogenization

3.1 Geodetic mass balance

The accuracy of the geodetic mass balance is primarily influenced by the quality of the raw data and by the process from raw data to mass balance results. The raw data acquisition and the data processing are quite different for 1968 and 2001/2008. The DTM based on LIDAR-data from 2008 was expected to be of better quality and is better documented. It was therefore selected as a reference with which the earlier maps/DTMs were compared. Hence, the DTM from 2008 is evaluated first. As 1969/70 was the first year with glaciological mass balance measurements, the geodetic mass balance was calculated for the periods 1969-2001, 2001-2008 and the total period 1969-2008. (Tab. 3-4).

3.1.1 Mapping 2008

The quality of the DTM was checked against several different data sets (Fig. 3-1). The DTM was compared to recorded lake level at Storglomvatnet (station 160.1.0) and Engabrevatnet (station 159.3.0). A narrow zone along the western shore of Storglomvatnet was considered. At the central part of this zone the point elevations were 579.60 ±0.05 m a.s.l., but higher in the northern and southern parts where point density was lower. Recorded lake level (daily average) was 579.66 m a.s.l. At Engabrevatnet (8 m a.s.l), an area in front of the proglacial river delta was mapped. Where point density was highest, the point elevations were 8.25 ±0.05 m a.s.l. with some outliers. The lake level scale is not referenced to mean sea level, but the daily mean lake level was 1.13 meter which is 0.08 m below median lake level.

![Figure 3-1: Validation of the 5x5 m DTM from 2nd September 2008. The DTM was compared to lake level, reference points on stable ground, and dGNSS profiles from the same day.](image-url)
Table 3-1. Validation of the 2008 DTM from comparison to reference points on bedrock. See Fig 3-1 for location.

<table>
<thead>
<tr>
<th>Reference point</th>
<th>H_ref</th>
<th>Recalc 2002?</th>
<th>H_DTM2008</th>
<th>Ref. above DTM</th>
</tr>
</thead>
<tbody>
<tr>
<td>ENG112 Skjæret</td>
<td>1354.62</td>
<td>Y</td>
<td>1352.45</td>
<td>2.17</td>
</tr>
<tr>
<td>ENG114 Ettind</td>
<td>1217.40</td>
<td>Y</td>
<td>1215.49</td>
<td>1.91</td>
</tr>
<tr>
<td>ENG108</td>
<td>1165.33</td>
<td>Y</td>
<td>1163.92</td>
<td>1.41</td>
</tr>
<tr>
<td>ENG119</td>
<td>1085.23</td>
<td>Y</td>
<td>1081.91</td>
<td>3.32</td>
</tr>
<tr>
<td>ENG111</td>
<td>1085.23</td>
<td>N</td>
<td>1081.91</td>
<td>3.32</td>
</tr>
<tr>
<td>ENG113</td>
<td>577.21</td>
<td>Y</td>
<td>576.85</td>
<td>0.36</td>
</tr>
<tr>
<td>ENG115</td>
<td>10.09</td>
<td>Y</td>
<td>9.56</td>
<td>0.53</td>
</tr>
<tr>
<td>ENG118</td>
<td>13.43</td>
<td>N</td>
<td>12.82</td>
<td>0.61</td>
</tr>
<tr>
<td>J15T26_Breitinden</td>
<td>1354.35</td>
<td>N</td>
<td>1353.91</td>
<td>0.44</td>
</tr>
<tr>
<td>J15T15_Snøtind</td>
<td>1594.18</td>
<td>N</td>
<td>1593.71</td>
<td>0.48</td>
</tr>
</tbody>
</table>

The 5 x 5 m DTM was compared with 437 point elevations measured with dGNSS on the glacier plateau on the same day as the LIDAR data collection (fig. 3-1). The dGNSS reference station was Holandsfjord, 5 km north of the surveyed area. Mean difference was -0.07 ±0.07 m (DTM above dGNSS), and max/min deviations were -0.30 /+0.19 meter. Then, the 5x5 m DTM was compared to 11 GCP’s around Engabreen (Tab 3-1). All the reference point elevations were higher than the DTM elevations. However, the reference points are often located in rugged terrain, and the reference point elevations may be referenced to top of a bolt or signal. Consequently, elevations from the DTM is expected to be lower than the reference elevations. Generally the evaluations show good accordance and indicate LIDAR data of sufficient quality.

3.1.2 Mapping 2001

The 2001 LIDAR data and DTM elevations was checked against several independent data sets. The deviation between the DTM and surface elevation measured with dGNSS at 9 stakes on the glacier plateau on the same day was -0.14 ±0.14 meter (Geist et al, 2005). At Engabrevatnet, LIDAR-points on dry land close to the shoreline (no reflections in the lake) was around 8.25 ±0.25 m a.s.l., which is comparable to 8.25 ±0.05 m a.s.l. in LIDAR-data on 2nd September 2008. The recorded lake level at 159.3.0 Engabrevatnet on 24th September 2001 was 1.15 m (local elevation), which was 0.02 m above the lake level on 2nd September 2008.

The quality of the 2001 DTM was also evaluated using a procedure described by Nuth et al (2011) comparing the 2001 and 2008 DTMs in non-glaciated areas. For 107420 grid cells well outside the 2001 glacier boundary the grid cell elevation in 2001 and 2008, and slope and aspect from the 2008 DTM were extracted. Using a selection of 46323 grid cells with slope between 0 and 30 degrees the evaluation showed no need for a horizontal
shift in the 2001 DTM. To evaluate the need for a vertical shift of the 2001 DTM, the standard error in mean elevation difference between 2001 DTM and the 2008 DTM was calculated using the formula

\[ \text{mean error(95\%)} = 1.96 \times \frac{\text{standard deviation}}{\sqrt{n}} \quad (1) \]

The mean error depends on the selection and the degree of freedom (n). The degree of freedom was set equal to the number of flight lines in the 2001 data set (31 flight lines, Geist et al, 2005). Using the sample of points with slope less than 30 degrees as representative for the glacier, the deviation between 2001 DTM and the 2008 DTM was \(-0.10 \pm 0.26\) meter, which is not significant (Table 3-3). The mean error (0.26 m) was used in the assessment of geodetic mass balance uncertainty (Ch 4). Even with the steepest slopes included, there was no indication of a significant vertical shift between the 2001 DTM and the 2008 DTM.

Table 3-2. Evaluation of vertical difference between DTM2001 and DTM2008 on stable ground. The data points were sorted according to slope. The mean error was calculated from equation 1.

<table>
<thead>
<tr>
<th></th>
<th>All</th>
<th>&lt;50deg</th>
<th>&lt;40deg</th>
<th>&lt;30deg</th>
<th>&lt;20deg</th>
</tr>
</thead>
<tbody>
<tr>
<td>points</td>
<td>107421</td>
<td>91362</td>
<td>73110</td>
<td>46323</td>
<td>22003</td>
</tr>
<tr>
<td>mean</td>
<td>0.55</td>
<td>0.26</td>
<td>0.08</td>
<td>-0.10</td>
<td>-0.09</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>1.88</td>
<td>1.16</td>
<td>0.95</td>
<td>0.73</td>
<td>0.56</td>
</tr>
<tr>
<td>Degree of freedom (n)</td>
<td>31</td>
<td>31</td>
<td>31</td>
<td>31</td>
<td>31</td>
</tr>
<tr>
<td>Mean error</td>
<td>0.66</td>
<td>0.41</td>
<td>0.34</td>
<td>0.26</td>
<td>0.20</td>
</tr>
</tbody>
</table>

3.1.3 Mapping 1968

The evaluated data set from 1968 consisted of the glacier outlines, point elevations digitized from 10 m contour lines on the glacier, and point elevations digitized from 50 m contour lines outside the glacier. At the time of photographing (25th August 1968) no independent surveying was done. The quality of the 1968 data was evaluated by comparing point elevations along the 50 m contour lines in non-glaciated areas with the 2008 DTM. The elevation points were mainly located in steep and rugged terrain, and the difference is not necessarily representative for the glacier surface. For 2319 point elevations outside the 1968 glacier boundary we extracted elevation, slope and aspect from the 2008 DTM. Using the procedure described by Nuth et al (2011), a horizontal shift of dE= +11.9 m and dN= -2.0 m was suggested and the 1968 data set was therefore shifted accordingly. The procedure was repeated using the shifted data set. The remaining (residual) shift was dE= +0.4 m and dN= +0.7 m.

To evaluate the need for a vertical shift of the 1968 dataset, the standard error between shifted elevation points and the 2008 DTM was calculated using formula (1). The degree of freedom, n, was set equal to the number of elevation contour lines outside the glacier boundaries (28). The elevation points were sorted according to slope (Tab 3-3). We used the sample of points with slope less than 30 degrees as representative for the glacier. Hence, the deviation between 1968 map and the 2008 DTM was \(-1.1 \pm 1.2\) meter, which is
not significant. The mean error (1.19 m) was used in the assessment of geodetic mass balance uncertainty (Ch 4).

Table 3-3. Evaluation of vertical difference between the 1968 map and DTM2008 on stable ground. The data points were sorted according to slope. The mean error was calculated from equation 1.

<table>
<thead>
<tr>
<th></th>
<th>All</th>
<th>&lt;50deg</th>
<th>40deg</th>
<th>&lt;30deg</th>
<th>&lt;20deg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Points</td>
<td>2319</td>
<td>1517</td>
<td>1012</td>
<td>526</td>
<td>184</td>
</tr>
<tr>
<td>Mean</td>
<td>-2.5</td>
<td>-2.0</td>
<td>-1.6</td>
<td>-1.1</td>
<td>-0.5</td>
</tr>
<tr>
<td>Stand.dev.</td>
<td>8.5</td>
<td>5.6</td>
<td>4.4</td>
<td>3.2</td>
<td>2.8</td>
</tr>
<tr>
<td>n</td>
<td>28</td>
<td>28</td>
<td>28</td>
<td>28</td>
<td>28</td>
</tr>
<tr>
<td>Mean error</td>
<td>3.2</td>
<td>2.1</td>
<td>1.6</td>
<td>1.2</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Figure 3-2
Distribution of 2319 non-glacial comparison points in the data sets from 1968 and 2008. Most of the data are representing steep slopes on both sides of the glacier tongue. The average elevation of the points (in 2008) was 741 m a.s.l.

The digitized elevation point data had to be transformed into a DTM to facilitate the volume change calculations. Interpolation based on point elevations from contour lines may produce unrealistic features. Based on an assumption of smoother interpolation of elevation change than of elevation, the 1968 DTM was calculated from a 1968-2008 elevation change raster and the 2008 DTM.
3.1.4 Elevation change 1968-2001

Based on a 5x5 m DTM from 24th September 2001 and point elevations along 10 meter contour lines on the 1968 map, the elevation change was calculated for each elevation point from 1968. A change raster was interpolated from the elevation change in the elevation points (Fig. 3-3). The volume change was calculated for an area defined by the glacier outline from 2001, nunatak outlines from 1968, and the surface drainage divide from 2008. Engabreen advanced considerably between 1968 and 2001, but Litlebreen retreated.

3.1.5 Elevation change 2001-2008

Based on 5x5 m DTMs from 24th September 2001 and 2nd September 2008 the elevation change is calculated for each grid cell (Fig. 3-4). The basin is defined by the glacier outline from 2001, nunatak outlines from 2008, and a surface drainage divide from 2008. Both Engabreen and Litlebreen retreated. An area of 0.95 km$^2$ (2.5%) showed elevation increase. The elevation increase is limited to a few locations where wind-blown snow seems to accumulate. In the ice fall some grid cells close to crevasses show elevation increase or decrease related to slightly changing position or size of crevasses. On the upper part of the glacier crevasses are less visible in 2008 than in 2001 due to more remaining snow and possibly smaller size. The largest elevation change (-80 m) was found close to the 2008 glacier terminus. Results are listed in table 3-4.
3.1.6 Elevation change 1968-2008

Based on a 5x5 m DTM from 2nd September 2008 and point elevations along 10 meter contour lines on the 1968 map, the elevation change was calculated for each elevation point from 1968. A change raster was interpolated from the elevation change in the elevation points. The volume change was calculated for an area defined by the glacier outline from 1968, nunatak outlines from 2008, and the surface drainage divide from 2008. Both Engabreen and Litlebreen retreated between 1968 and 2008.

3.1.7 Mass change

The geodetic mass balance was calculated for the periods coinciding with the glaciological mass balance measurements starting in the autumn 1969. That is 1969-2001 and 2001-2008, and the total period 1969-2008 (Tab 3-4). The volume change was calculated for the combined areas of the first and second DTM. The geodetic mass balance was calculated from elevation change multiplied with the density conversion factor (850 kg/m³), divided by the mean area for first and second DTM, and adjusted for melting between survey date and annual minimum. Between 1969 and 2001 (32 years) the mean annual geodetic mass balance at Engabreen was -0.03 m w.e.a⁻¹, which is close to equilibrium. Between 2001 and 2008 (7 years) the mean annual geodetic mass balance at Engabreen showed a mass deficit of -0.48 m w.e.a⁻¹.
### Table 3-4 Results

<table>
<thead>
<tr>
<th>Period</th>
<th>Area Year1</th>
<th>Area Year2</th>
<th>Mean elevation change</th>
<th>Density conversion factor</th>
<th>Mass change Year1</th>
<th>Mass change Year2</th>
<th>Date adjustment Year1</th>
<th>Date adjustment Year2</th>
<th>Geodetic mass balance Cumulative</th>
<th>Geodetic mass balance Annual</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>km²</td>
<td>km²</td>
<td>m</td>
<td>kg m⁻³</td>
<td>m w.e.</td>
<td>m w.e.</td>
<td>m w.e.</td>
<td>m w.e.</td>
<td>m w.e.</td>
<td>m w.e.</td>
</tr>
<tr>
<td>1969-2001</td>
<td>37.53</td>
<td>37.26</td>
<td>-1.3</td>
<td>850</td>
<td>-1.1</td>
<td>-0.3</td>
<td>-0.9</td>
<td>-0.1</td>
<td>-0.03</td>
<td>-0.03</td>
</tr>
<tr>
<td>2001-2008</td>
<td>37.26</td>
<td>36.84</td>
<td>-3.7</td>
<td>850</td>
<td>-3.1</td>
<td>-0.1</td>
<td>-3.3</td>
<td>-0.4</td>
<td>-0.48</td>
<td>-0.48</td>
</tr>
<tr>
<td>1969-2008</td>
<td>37.53</td>
<td>36.84</td>
<td>-5.0</td>
<td>850</td>
<td>-4.2</td>
<td>-0.3</td>
<td>-4.2</td>
<td>-0.3</td>
<td>-0.11</td>
<td>-0.11</td>
</tr>
</tbody>
</table>

### 3.2 Glaciological mass balance

As the methodology of the mass balance calculations has changed since the beginning in 1970 a homogenization of the series was necessary. Homogenizing was performed by re-calculation of the mass balance series to ensure as far as possible uniform methodology, data processing and interpretation from field data to the final balance values. Causes of inhomogeneity were the map source used for the mass balance calculations, variations in ice divide, the shift from contour line (balance maps) method to profile method including shift from calculation of accumulation and ablation to winter and summer balance at the tongue, and density conversion procedures. Based on available information, some errors in the calculations have been identified.

#### 3.2.1 Ice divide (1970-2014)

As Engabreen is a part of a plateau glacier (ice cap), the drainage basin has to be defined. The two main alternatives are 1) glaciological boundaries defining glacier areas contributing ice to the glacier tongue and 2) hydrological boundaries including all the glacier areas within a hydrological catchment (Elvehøy et al. 2009). Using glaciological drainage boundaries, the dynamic response of the glacier tongue (i.e. length change) can be directly related to the mass balance observations. The main drawback with this approach is that the boundaries will change as individual basins separates from the main ice body during glacier retreat. Using hydrological drainage boundaries, the mass balance observations in the main basin might not represent all the sub-basins, and the calculated mass balance might not represent the dynamics of the glacier tongue.

Here, the ice surface divide defined for the hydrological basin to the gauging station 159.3 Engabrevatnet is used. This area includes Littlebreen in the north, and an area on the western side of the icefall which are not contributing glacier ice to the glacier tongue (except some ice avalanching) (Fig 1-1). The ice divide for the glacier area draining to Engabrevatnet was manually interpreted in ArcMap from flow direction and flow accumulation calculated from DTM2008. The main difficulties were met where the ice divide is parallel to the ice flow, as in the northwestern slope from Snøtind and on the western side of the drainage basin. The 2008 ice divide was used for all three DTMs based on the assumption that this DTM was most accurate, and that changes in ice divide over the period of record were negligible. The elevation-area distributions for mass balance calculations were calculated by counting grid cells within 100 meter elevation bins, each grid cell representing 25 m².
3.2.2 Correct height-area distributions (1985-2003, 2005-2007)

The mass balance calculations were based on height-area distribution from three DTMs (1968, 2001 and 2008). The period between two mappings are divided in two, and each DTM was applied to half of the period before the mapping year and half of the period after the mapping year. The glaciological mass balance results were re-calculated using constant reference areas and corresponding altitude-area distributions for periods centered on the years when vertical photography and LIDAR campaigns were performed (1968, 2001 and 2008, split between 1984 and 1985, and between 2004 and 2005).

3.2.3 Density conversion (1970-1998)

Winter balance calculations are based on measurements of snow depth and snow density (described in chapter 2.2). The accumulated water equivalent was plotted against increasing snow depth and a mathematical trend line and function was calculated. A second order polynomial expressed as: 

$$ b_w = a*SD^2 + b*SD $$

(a and b are coefficients) was used. This procedure was adapted to data from 1970-2007 where feasible, i.e. if original snow density measurements or calculated snow depth to water equivalent plots were available. In 1976 and 1978-81, the snow density was measured in several steps, and a mean density was calculated and used for the calculation of the point winter balances. Between 1989 and 1996, snow density was measured only in the upper 2 to 4 meters of the snow pack. The density conversion procedure was homogenized for 32 out of 45 years

3.2.4 From contour line method to profile method (1970-1988)

From 1970 to 1988 the winter and summer balances were calculated by the contour line method using spatial interpolation. Many of the measurements prior to 1995 were only available in analogue format (forms, reports and maps). In order to digitize the point measurements, mass balance maps (snow depth, winter balance and summer balance) were scanned, and the maps were geo-referenced in ArcMap 10 (ESRI) using the printed grid (UTM-ED50) transformed from ED50 to EUREF89. The snow depth measurements and calculated point winter balances and summer balance at stakes were digitized and assigned positions and elevations from the relevant DTMs. Additional information on stake readings and density measurements were found in data reports. The annual reports (Glaciological investigations in Norway) gave further information regarding the annual results.

Homogenization of the mass balance calculation for the glacier tongue and ice fall, i.e. the area below 900 m a.s.l., includes to assess a consistent record for the glacier tongue based on measurements at location E17 around 300 m a.s.l., and to standardize the interpolation between the measurements on the plateau and the glacier tongue.

Melting at the glacier tongue at 300 m a.s.l. in un-measured periods were estimated using a PDD-model based on temperature records in Glomfjord and Reipå. The model was calibrated with summer measurements from 1973-76 (3 years), and validated with summer measurements from 1989-93 (4 years). The mass balance between model autumn minimum and model spring maximum (often in April) was set as 0 m w.e. In this way, the record consist of negative winter balances representing spring melt, and summer balances representing the measured melting between spring and autumn surveys plus estimated autumn melt. If winter melt was measured at stakes, the measured values was split between late autumn and early spring melt.
The point values of winter and summer balance were plotted versus altitude in a diagram, and balances curves were drawn manually from their distributions. To estimate the winter and summer balance in the icefall, a linear gradient between measurements at the lower tongue (E17 - 300 masl.) and the lower plateau (E38 at 1050 masl. until 2000, E34 at 960 masl. after 2000) has been used (Fig 2-8).

3.2.5 Results

The homogenizing of the mass balance series for Engabreen (1970-2014) was based on the “profile method” applying the appropriate DTM's and the ice divide from 2008. In addition the calculation principle was changed from balance maps to balance altitude profiles. The review of the historic data sets and the re-calculation process also revealed some errors in the original mass balance calculations. These errors were corrected in the re-calculations.

Between 1971 and 1976, many or all the stakes on the plateau were lost during winter. In these cases, the mass balance calculations relied on the soundings and corings. The evaluation of the measurements indicate the snow depth was over-estimated in the upper area. However, without proper verification, the original assessments were not altered. After 1977, when calender masts were put out in location E20 (1170 m a.s.l.) and E105 (1340 m a.s.l.), there were at least one point verification of the amount of snow in the upper areas in most years. Even in the snow-rich winters of 1989 and 1997, E20T was maintained and E105T re-appeared.

Late autumn melting means melting taking place between the autumn survey and the start of the accumulation season. This occurs more often at the lower part of the plateau (E34, E35, E38), and can be detected when stake length and sounded snow depth are measured at a winter or spring survey. Hence, detection of late autumn melting depends on stake maintenance. As a part of the homogenization process, documented late autumn melting in 1980, 1999, 2000 and 2010 was attributed to the proper year. Late autumn melting can be assessed from www.senorge.no, as in 1974 and 1975. However, this adjustment has not been performed.

The original and homogenized mass balance series for Engabreen are shown in table 3-4 and figure 3-6. The average changes are small, -0.02 and -0.01 m w.e.a\(^{-1}\), respectively for \(B_w\) and \(B_s\). However, individual years have changes up to 0.6 m w.e.a\(^{-1}\).

Homogenized results
1969-2001: +0.69 m w.e.a\(^{-1}\) (from +0.71 m w.e.a\(^{-1}\))
2001-2008: +0.02 m w.e.a\(^{-1}\) (from +0.06 m w.e.a\(^{-1}\))
1969-2008: +0.57 m w.e.a\(^{-1}\) (from +0.59 m w.e.a\(^{-1}\))
Figure 3-6 Original and homogenized mass balance series for Engabreen.
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<th>B.</th>
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<td>2008 38.74</td>
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4 Uncertainty assessment

Factors leading to random (stochastic) and systematic errors (bias) in the glaciological and geodetic methods are listed in Zemp et al (2013).

4.1 Geodetic mass balance

The main sources of uncertainty in the geodetic method are related to differences in DTM-orientation, to the representation of the glacier surface (from point density and precision), to the correction required because the field and aerial surveys were not carried out on the same date, and to the density conversion procedure. In the following, these elements are described.

4.1.1 Accuracy of DTMs orientation

The DTMs from 1968 and 2001 was checked against the DTM from 2008, and the 1968 DTM was co-registered (horizontally) to the 2008 DTM (ch 3.1.3). From comparison of single points on stable ground in the 1968 and 2001 data sets to the 2008 DTM, the accuracy in DTM elevation was calculated as ±1.19 and ±0.26 meter, respectively. The accuracy of the 2008 DTM was assessed as ±0.1 meter from comparison with simultaneous measurements (ch 3.1.1).

This term corresponds to uncertainty from co-registration in Zemp et al (2013), and is calculated using

\[ \sigma_{\text{coreg}} = \frac{1}{N} \left( (\sigma_{\text{DTM1}*p_{\text{ice}}}^2 + (\sigma_{\text{DTM2}*p_{\text{ice}}}^2)^{-2} \right) \]

as ±0.032 and ±0.032 m w.e. a\(^{-1}\) for the two periods, respectively. N is the number of years between DTM acquisitions.

4.1.2 DTMs representation of the glacier surface

The quality of the 1968 aerial photos was fairly good, but large, snow covered areas on the plateau implies a higher uncertainty. Assumed accuracy over glacier areas in a DTM produced from vertical aerial photos and available as digitized contour line maps is ±2 meter (Andreassen et al, 2012). This includes the production of original maps, digitalization of contour lines on paper maps, transformation between coordinate systems, and interpolation (ch 2.1.1). Assumed accuracy in the 2001 and 2008 DTMs produced from LIDAR point clouds is ±0.1 m (ch 3.1.1 and 3.1.2).

This term corresponds to uncertainty from autocorrelation in Zemp et al (2013), and is calculated as

\[ \sigma_{\text{auto.a}} = \frac{1}{N} (\sigma_{\text{DTM1}*p_{\text{ice}}} + (\sigma_{\text{DTM2}*p_{\text{ice}}}^2)^{-2} \right) \]

as ±0.053 and ±0.017 m w.e. a\(^{-1}\) for the two periods, respectively. N is the number of years between DTM acquisitions.

4.1.3 Survey dates

The adjustments for different survey dates are described in chapter 2.1.5. The associated uncertainties in the three DTMs are ±0.5 m w.e., ±0.1 m w.e. and ±0.1 m w.e., respectively, and the related uncertainty in geodetic mass balances is calculated as

\[ \sigma_{\text{sd.a}} = \frac{1}{N} ((\sigma_{\text{DTM1}*p_{\text{ice}}} + (\sigma_{\text{DTM2}*p_{\text{ice}}}^2)^{-2} \right) \]

as ±0.016 and ±0.014 m w.e. a\(^{-1}\), respectively. N is the number of years between DTM acquisitions.
4.1.4 Density conversion factor

The density conversion factor (described in chapter 2.1.4.) was 850 ±60 kg m\(^{-3}\) based on recommendations in Huss (2013). The uncertainty corresponds to ±0.002 and ±0.029 m w.e. a\(^{-1}\) for the two periods, respectively.

4.1.5 Quantification of uncertainty

The mean annual random error in the geodetic mass balance is estimated as

\[
\sigma_{\text{geod.total.a}} = \sqrt{\sigma_{\text{coreg}}^2 + \sigma_{\text{autocorr}}^2 + \sigma_{\text{dc}}^2 + \sigma_{\text{sd}}^2 + \sigma_{\text{ref}}^2}
\]

and integrates uncertainties related to the remaining elevation error after co-registration \((\sigma_{\text{coreg}})\), to the spatial autocorrelation in the elevation differences \((\sigma_{\text{autocorr}})\), to the density conversion \((\sigma_{\text{dc}})\) and to the difference in survey dates \((\sigma_{\text{sd}})\) and to changes in ice divide and glacier outlines \((\sigma_{\text{ref}})\) as root sum of squares (Zemp et al., 2013). The division is by the number of years (not by the square root of N) because the uncertainty over the period of record originates from the two geodetic surveys and is independent from the number of years in between.

The uncertainties for the geodetic mass balances were estimated to be 0.064 m w.e. a\(^{-1}\) for 1969-2001 and 0.050 m w.e. a\(^{-1}\) for 2001-2008. The first period has a low uncertainty due to the long period, while the second period has a low uncertainty due to the high accuracy of two LIDAR-based DTMs.

Table 4-1. Uncertainty sources for calculated geodetic mass balance (all terms in m w.e.a\(^{-1}\)).

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<th>DTM orientation (\sigma_{\text{coreg}})</th>
<th>Glacier surface (\sigma_{\text{autocorr}})</th>
<th>Survey dates (\sigma_{\text{sd}})</th>
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4.2 Glaciological mass balance

The accuracy of the glaciological mass balance measurements depends on several factors. The three main sources of random errors in the glaciological method are the field measurements at point locations, the spatial averaging of these results over the entire glacier, and the changes of glacier in area and elevation (Zemp et al., 2013). Janson (1999) discussed various topics related to accuracy of measurements and calculations at Storglaciären (3.2 km\(^2\)), and concluded that accuracies in total mass balance terms in the order of 0.1 m w.e.a\(^{-1}\) was achievable, but different choices for interpolation and averaging easily produced deviations in the order of 0.5 m w.e.a\(^{-1}\) for individual elevation bins when the monitoring network was of medium complexity. In the following, some elements influencing accuracy are discussed.
4.2.1 Field point measurements

4.2.1.1 Point measurements of snow depth and melting

Snow depth in spring can reach 10-12 meters in the upper areas. Probing through 10 m of snow is difficult if the snow pack is solid, and identifying the summer surface can be even more difficult. The summer surface often appears as a solid layer just below a layer of depth hoar, but after a cool summer combined with a large amount of remaining snow, this layer can be hard to distinguish. Then, stakes or masts where soundings can be referenced are important for the accuracy of the snow depth measurements. Problems with the identification of correct layer can vary from point to point, and might average out if the approximate snow depth is known (from stake measurements or corings). When probing to the summer surface, the probe might be inserted at an angle, and the snow depth will be over-estimated. Similarly, sloping stakes over-estimate snow-depth and melting if treated as vertical (not documented in the field). The slope of stakes has not been measured systematically, and neither has sloping stakes been corrected in a systematic way, but stakes that are too skew are often disregarded. The error will be larger as snow depth is deeper. This occurs randomly, but will occur more easily at larger snow depth. The effect on the results is difficult to estimate precisely, but slopes up to 15 degrees will not influence measurements significantly (over-estimates depth by up to 3.5%). The uncertainty in annual mass balance related to sounded snow depth was assessed as ±0.12 m w.e.a\(^{-1}\) from an assumed uncertainty in snow depth when conditions are favorable and difficult of 0.1 m and 0.5 m, respectively, a density conversion of 500 kg/m\(^3\), and an assumption that conditions are difficult in one out of three years.

Stakes might melt or sink into the ice or snow due to its own weight. This over-estimates snow depth and under-estimates melting (Østrem & Haakensen 1999, Østrem and Brugman, 1991). To avoid this stakes and masts should be supported at the base. Masts have been used at Engabreen since 1976 to improve our ability to maintain stakes in the accumulation area through winters with heavy accumulation. In the first years the masts were dug out late in summer and re-positioned relative to the summer surface. Later on, the masts were extended and can get very long (30+ m into firn). If the mast is fixed at a horizon, layers above will sink due to compaction. This under-estimates the annual balance. But masts not fixed might sink due to its own weight, and the annual balance will be over-estimated. However, even though these problems can influence single stakes in single years, the effect on a long term monitoring programme is limited. An additional stake measuring annual balance should be kept close to long masts. The uncertainty in annual mass balance related to stake measurements was assessed as ±0.10 m w.e.a\(^{-1}\).

4.2.1.2 Accuracy and variability of density point measurements

The operator-dependent variability in snow density measurements were assessed as 4% after several density measurements were performed simultaneously by different personnel at the same locations during exercises at Rembesdalskåka in March 2002 and April 2008. Consequently, if the mean density of 6 m snow is 500 kg/m\(^3\), the SWE is 3.00 ±0.12 m w.e. The differences between two locations at Rembesdalskåka in winter were rather small (10 kg/m\(^3\)), but at Engabreen in spring, when the surface melting has started in lower areas, the snow density can be in the order of 50 kg/m\(^3\) higher at lower elevations (Tab 4-2).
Table 4-2 Mean density (kg/m$^3$) to snow depth (m) at Engabreen and Storglombreen in 2000-2004. Elevation at locations are E143 (1400 m a.s.l.), S3 (1120 m a.s.l.), E38(1050 m a.s.l.) and E35 (1000 m a.s.l.).

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<th>Snow depth</th>
<th>Mean density to this snow depth</th>
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<td>E38</td>
<td>4.25</td>
<td>517</td>
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</table>

4.2.2 Spatial interpolation

Sounding profiles and stakes are located where access is safe and maintenance of stakes is easier, - typically in concave areas with more snow accumulation and less melting than in other areas (Fig 4-1). Convex areas where the snow blows off and crevassing is more extensive are avoided. The result is that we over-estimate the annual mass balance by over-estimating the snow accumulation and under-estimating the melting. An over-estimation of the annual balance on the plateau by 5% corresponds to 0.15 m w.e. in glacier-wide mass balance. On the other hand, ice falls where surface area is larger than the map area, and surface shape may enhance effects of turbulence, are avoided, too.
4.2.2.1 Varying point selection

The winter balance has been calculated from between 20 and 500 points, and the summer balance has been calculated from between 2 and 25 stake locations. To test the effect of a limited data set, corresponding points from years with few data points (1989 and 2012) were selected from the points in a year with a larger data set (1977). Comparison of figures 2-2, 2-3 and 2-5 shows some discrepancies in the profile lines between the years. This was solved by selecting some of the closest points even with distances up to 1 km. The resulting winter balances for 1977 using the point selections from 1977, 1989 and 2012 were 2.23, 2.37 and 2.22 m w.e., respectively. The summer balances for the selections from 1977, 1989 and 2012 were -1.34, -1.40 and -1.33 m w.e., respectively. In 2013, 107 snow depth points were sounded in a 500 x 500 m grid on the glacier plateau. A selection of 35 points close to the profile normally used since 2006 (Fig 2-5, 2012) was selected, and $B_w$ was calculated using the profile method. The difference between the two selections was 0.09 m w.e. (profile larger than grid). These examples indicate that changing point selections inflict uncertainty in the glacier wide annual mass balance in the order of ±0.05 m w.e.a$^{-1}$.

4.2.2.2 Representativity of density point measurements

The effect of using different density profiles is illustrated with results from Engabreen in 2002. That year, 162 snow depths were measured between 970 and 1465 m a.s.l., and two
density profiles were measured at 1050 (E38) and 1400 m a.s.l. (E143). In addition, a density profile was measured at Storglombreen at 1120 m a.s.l. (S3) (Table 4-2). The estimated 4% random error in density measurements results in a 4.5% random error in specific winter balance when calculated as +4% and -4% for individual measurements. Using the different density profiles as representative for the entire glacier resulted in a glacier-wide winter balance of 2.73 (E143), 3.06 (E138) and 2.97 (S3), while the original winter balance was 2.89 m w.e., indicating an influence from the choice of density location to the average winter balance in the order of 5% or ±0.15 m w.e.

4.2.2.3 Density of remaining snow and melted firn and ice

The density of remaining snow has been assessed as 600 kg/m$^3$. At E105 (1340 m a.s.l.) on 16th September 1994, mean density to summer surface at 2.05 meter depth was 585 kg/m$^3$. The mean density of remaining snow in the autumn at Ålfotbreen for nine years was 618 kg m$^{-3}$ (Kjøllmoen, 2016). This implies 600 ±20 kg/m$^3$ (±3.3%). The density of older firn is assessed between 650 and 750 kg/m$^3$ depending on the probable age of the firn. A reasonable accuracy is in the order of 50 kg/m$^3$ (±7%), but as the spatial and temporal contribution from melted firn to the cumulative mass balance is limited, the contribution to the overall accuracy is negligible. The density of melted ice is assessed as 900 ±20 kg/m$^3$ (accuracy 2%).

Uncertainty in annual mass balance related to the density of remaining snow and melted ice was calculated from the average altitudinal homogenized annual mass balance distribution as 0.046 m w.e.a$^{-1}$ using ±20 kg/m$^3$ above 1100 m a.s.l. and ±60 kg/m$^3$ below 1100 m a.s.l. (ELA for the average annual mass balance was 1080 m a.s.l.).

4.2.2.4 Interpolation in the ice fall

Spatial interpolation is based on the assumption of regular variation around measured points. In the icefall between 400 and 900 m a.s.l., the few measurements that exist indicate a higher melt rate than interpolated between E17 (300 m a.s.l.) and E34/E38 (960/1050 m a.s.l.). In 1971, measurements at 13 stakes between 175 and 550 m a.s.l., indicated a smaller elevation gradient at the lower part of the ice fall than the average gradient between 300 and 1050 m a.s.l. (Fig 3-5 upper). In 1989-90, a number of stakes were put out in the icefall between 200 and 900 m a.s.l. for velocity measurements. Some of the stakes around 600 m a.s.l. were monitored for more than a year, which made mass balance estimates possible. The amount of melting at 600 m a.s.l. were about the same as at 300 m a.s.l., indicating more or less uniform amounts of glacier melt below 700 m a.s.l. (Fig 3-5 lower).

Using the alternative summer balance profile in figure 3-5 (lower), the specific summer balance became about 0.15 m w.e. more negative than when using the standard profile. On the other hand, the amount of snow collected in crevasses due to wind transport is unknown. Since the affected area is limited to 6% of the total area, the effects on the glacier-wide balances are small. Since the data available from the ice fall is limited and only a small part of the glacier is affected (<10% of the area), the need for a consistent methodology favours a linear interpolation between E17 and the stakes at the glacier plateau. The contribution to the glacier wide uncertainty is assessed to be in the order of 0.1 m w.e.a$^{-1}$ (implying that the uncertainty in the icefall is in the order of 2 m w.e.a$^{-1}$).
Figure 3-5. Summer balance at stakes (red), winter balance at stakes on the glacier tongue below 900 m a.s.l., (blue), and winter and summer balance profiles in 1971 (upper) and 1990 (lower). Alternative profiles are shown with broken lines.
4.2.3 Reference area

The glacier surface is continuously changing, thus affecting the elevation of all measurements and the relationship between area and elevation used for spatial interpolation. The fact that DTMs are available at certain points in time only, introduce an uncertainty factor in the estimates of glaciological mass balance from reference glacier area-elevation functions. Larger changes and longer periods between mappings give higher uncertainties, while frequent sampling and smaller changes give smaller uncertainties. Effects of changes in ice divide, glacier boundaries and elevation distribution all leading to deviations between the true area-elevation distribution and the adapted distribution was assessed as leading to uncertainties of 0.014 and 0.011 m w.e.a\(^{-1}\), respectively, for 1969-2001 and 2001-2008.

4.2.4 Quantification of uncertainty

The total random error in glaciological mass balance cumulates the individual sources and years according to the law of error propagation assuming they are not correlated. Consequently, the annual random error is

\[ \sigma_{\text{glac.total.a}} = \frac{1}{\sqrt{N}} \times \sigma_{\text{glac.total.PoR}} \]

An error budget was estimated both from data and expert opinions from two glaciologist, one responsible for the observations and one fairly independent of the measurements, considering the main factors assumed to influence the uncertainty budget. All the terms were assessed as average for the periods 1969-2001 and 2001-2008.

The contributing factors are (in m w.e. a\(^{-1}\)):

<table>
<thead>
<tr>
<th>(\sigma_{\text{glac.point.a}})</th>
<th>0.195</th>
</tr>
</thead>
<tbody>
<tr>
<td>-probing to summer surface</td>
<td>0.117</td>
</tr>
<tr>
<td>-stakes and towers</td>
<td>0.100</td>
</tr>
<tr>
<td>-density snow</td>
<td>0.120</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>(\sigma_{\text{glac.spatial.a}})</th>
<th>0.193</th>
</tr>
</thead>
<tbody>
<tr>
<td>-density assumption for annual balance</td>
<td>0.046</td>
</tr>
<tr>
<td>-varying point selection</td>
<td>0.050</td>
</tr>
<tr>
<td>-spatial variation of snow density</td>
<td>0.150</td>
</tr>
<tr>
<td>-extrapolation in the ice fall</td>
<td>0.100</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>(\sigma_{\text{glac.ref.a}}) 1969-2001 / 2001-08</th>
<th>0.014/0.011</th>
</tr>
</thead>
<tbody>
<tr>
<td>-ice divide</td>
<td>0.010/0.010</td>
</tr>
<tr>
<td>-DTM</td>
<td>0.010/0.005</td>
</tr>
</tbody>
</table>

The uncertainty in the mean glaciological mass balance was estimated using the formula

\[ \sigma_{\text{glac.a}} = \sqrt{(\sigma_{\text{point.a}}^2 + \sigma_{\text{spatial.a}}^2 + \sigma_{\text{ref.area.a}}^2)} \]

as 0.275 m w.e. a\(^{-1}\) for both periods.
5 Validation

To account for the generic differences between geodetic and glaciological surface mass balance the internal and basal mass balance components and related uncertainties have to be calculated or assessed (Zemp et al. 2013). The comparison is valid for the period 1970-2008 (39 years).

5.1 Internal balance

Internal and basal accumulation and ablation processes are not included in the monitoring programme, and the contribution to the mass balance has to be assessed. Ablation inside and underneath the glacier due to heat of dissipation (and water supplied by rain) was calculated. Basal melting from geothermal heat flux and internal accumulation due to refreezing of melt water below the previous summer surface are believed to be less influential at Engabreen, and will to some degree cancel each other. Consequently, they were considered negligible.

Ablation due to heat of dissipation from water penetrating the glacier surface and leaving the glacier through the glacier river at the terminus was calculated for each elevation interval used in glaciological mass balance calculations following Oerlemans (2013). Ablation by dissipation of energy, $M$, was calculated by the formula

$$ M = \sum g \cdot \frac{p_h \cdot a_h \cdot (h - b_L)}{A \cdot L_m} $$

where $g$ is the acceleration of gravity, $h$ is mean elevation of elevation interval used in surface mass balance calculations, $p_h$ is precipitation at $h$, $a_h$ is glacier area of elevation interval $h$, $b_L$ is bed elevation at glacier snout, $A$ is total glacier area and $L_m$ is latent heat of fusion. Precipitation was defined as a linear function of elevation. Daily precipitation was extracted from data version 1.1.1 at [www.senorge.no](http://www.senorge.no) (Saloranta, 2014a and 2014b) at the highest elevation of the glacier, and the gradient was selected to give an annual precipitation 1.5 times the measured winter balance.

In January 1993, most of the subglacial rivers were diverted to a hydro power reservoir through sub-glacial river intakes at 620 m a.s.l.. Consequently, the annual internal ablation was smaller after 1992 than before (-0.15 and -0.08 m w.e. a⁻¹, respectively). The uncertainty was assumed to be one third of the calculated internal mass balance, which amounts to 0.05 m w.e. a⁻¹ for 1970-92 and 0.03 m w.e. a⁻¹ for 1993-2008.
5.2 Comparison of surface glaciological and geodetic mass balances

Only minor errors were identified in the homogenization process, even though some of the winter balances seems to be over-estimated due to over-estimated snow depth. The major sources of error seems to be the interpolation/extrapolation. The comparison of geodetic and surface glaciological mass balance follows the formula

\[
\text{Surface mass balance + internal ablation - geodetic mass balance} = \text{difference}
\]

Results from the glaciological and the geodetic mass balance calculations show distinct discrepancies (Tab. 5-1). The glaciological mass balance was 0.52 and 0.41 m w. e. a\(^{-1}\) too large, respectively.

Table 5-1. Results of the uncertainty. B is (glaciological, geodetic and internal) mass balance and \(\sigma\) is the estimated random error for the three balances. All mass balances and errors are in m w.e. a\(^{-1}\).

<table>
<thead>
<tr>
<th>Period</th>
<th>Yrs</th>
<th>B.glac.a</th>
<th>(\sigma).glac</th>
<th>B.geod.a</th>
<th>(\sigma).geod.</th>
<th>B.int.a</th>
<th>(\sigma).int</th>
<th>(\Delta)</th>
</tr>
</thead>
<tbody>
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<td>1969-2001</td>
<td>32</td>
<td>0.64</td>
<td>0.28</td>
<td>-0.03</td>
<td>0.06</td>
<td>-0.15</td>
<td>0.05</td>
<td>0.52</td>
</tr>
<tr>
<td>2001-2008</td>
<td>7</td>
<td>0.01</td>
<td>0.27</td>
<td>-0.48</td>
<td>0.04</td>
<td>-0.08</td>
<td>0.03</td>
<td>0.41</td>
</tr>
</tbody>
</table>

Following the analyses of Zemp et al (2013), both periods had a reduced discrepancy larger than 1.96, which indicate a very low probability to calibrate when calibration is not necessary (Tab 5-2). Thus the series were calibrated.

Table 5-2. Comparison of glaciological and geodetic mass balances. \(\Delta\) (in m w.e. a\(^{-1}\)) is the difference over the period of record between cumulative glaciological balance and geodetic balance, corrected for internal ablation. \(\delta\) (dimensionless) is the reduced discrepancy, where uncertainties are accounted for. \(\beta\) is the probability of accepting \(H_0\) although the results of both methods are different at the 95 % confidence level, while \(\varepsilon\) (in m w.e. a\(^{-1}\)) is the limit for detection of bias.

<table>
<thead>
<tr>
<th>Period of record</th>
<th>(\Delta)</th>
<th>(\delta)</th>
<th>H0 accepted</th>
<th>(\beta) for (\alpha=5%)</th>
<th>(\varepsilon).limit for (\alpha=5%)</th>
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</thead>
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<td>1969-2001</td>
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<td>no</td>
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<tr>
<td>2001-2008</td>
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<td>3.53</td>
<td>no</td>
<td>6</td>
<td>0.42</td>
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</table>
6 Calibrated surface mass balance

The annual glaciological surface mass balance for Engabreen needs to be calibrated with 0.52 m wea\(^{-1}\) (1969-2001) and 0.41 m wea\(^{-1}\) (2001-2008), respectively. There are several alternative procedures to distribute the total corrections between the terms and years. However, as long as the sources of bias are not established firmly and for the individual years, we chose to calibrate the annual balances equally, but distributing the annual correction between winter and summer balance terms according to the ratio between absolute values of winter and summer balance;

For year \(t\), the corrections \(B_{w\text{-corr}}(t)\) and \(B_{s\text{-corr}}(t)\) to the winter and summer balances \(B_w(t)\) and \(B_s(t)\) was calculated as

\[
B_{w\text{-corr}}(t) = B_{a\text{-corr}} \cdot B_w(t) / (B_p(t) - B_s(t)) \quad \text{and} \quad B_{s\text{-corr}}(t) = B_{a\text{-corr}} \cdot -B_s(t) / (B_p(t) - B_s(t))
\]

where \(B_{a\text{-corr}}\) is the periodic, annual correction. The balance curves were shifted correspondingly, and values for ELA and AAR were assigned from the calibrated, annual balance curves and the area-elevation-distributions (Example in Fig 6-1).

![Figure 6-1](image_url)

Homogenized (solid) and calibrated (dotted) mass balance curves from 1989, when Engabreen had a large (148%) winter balance and a small (82%) summer balance, compared to the 1971-2000 average.
Figure 6-2

The process of homogenization and calibration has altered the mean winter and summer balances for the 1971-2000 normal period from 3.04 and -2.20 m w.e. a⁻¹ to 2.76 and -2.44 m w.e. a⁻¹, respectively. The mean annual balance was reduced from +0.84 m w.e.a⁻¹ to +0.32 m w.e.a⁻¹. The calibrated cumulative mass balance curve (Fig 6-2) shows a mass increase from 1972 until 1977, mass deficit from 1977 to 1988, a new mass increase from 1988 to 1997, and a large mass deficit after 1997. This pattern corresponds to the length change observations at Engabreen.
<table>
<thead>
<tr>
<th>Year</th>
<th>$B_w$</th>
<th>$B_s$</th>
<th>$\Sigma B_a$</th>
<th>ELA</th>
<th>AAR</th>
<th>Area</th>
<th>$B_w$</th>
<th>$B_s$</th>
<th>$\Sigma B_a$</th>
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<td>2001</td>
<td>37,26</td>
<td>2,33</td>
<td>-1,88</td>
<td>0,45</td>
<td>1,87</td>
</tr>
<tr>
<td>1988</td>
<td>2,25</td>
<td>-3,47</td>
<td>-1,22</td>
<td>10,55</td>
<td>87</td>
<td>2001</td>
<td>37,26</td>
<td>2,05</td>
<td>-3,79</td>
<td>-1,74</td>
<td>0,13</td>
</tr>
<tr>
<td>1989</td>
<td>4,48</td>
<td>-1,82</td>
<td>2,66</td>
<td>13,21</td>
<td>926</td>
<td>2001</td>
<td>37,26</td>
<td>4,11</td>
<td>-1,97</td>
<td>2,14</td>
<td>2,27</td>
</tr>
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</table>
7 Conclusions

The glaciological surface mass balance series from Engabreen was re-analysed based on comparison with geodetic mass balance. The analysed glaciological mass balance series cover the period from 1969 to 2008. For this purpose, Digital Terrain Models (DTMs) from 1968, 2001 and 2008 were available. Glaciological and geodetic mass balance were compared for the periods 1969-2001 and 2001-2008.

In order to obtain comparable values the glaciological and the geodetic mass balances were first reviewed and homogenized. In addition, the relevant uncertainties were assessed. The homogenized glaciological mean annual balance for Engabreen over the periods 1969-2001 and 2001-2008 were +0.69 ±0.28 and +0.02 ±0.28 m w.e.a\(^{-1}\), respectively. The corresponding geodetic mass balance were -0.03 ±0.06 and -0.48 ±0.04 m w.e.a\(^{-1}\), respectively. The internal mass balance of Engabreen was quantified as -0.15 ±0.05 and -0.08 ±0.03 m w.e.a\(^{-1}\) before and after 15\(^{th}\) January 1993 when the sub-glacial river intakes at Engabreen started operating. The annual differences (Δa=Ba \text{glac.}−Ba \text{geod.}+Ba \text{int.}) over 1969-2001 and 2001-2008 were -0.59 and -0.48 m w.e., respectively.

The differences were tested for e, and the differences were found to be statistical significant at the 95 % confidence level. Hence, a calibration of both the periods 1969-2001(32 y) and 2001-2008 (7 y) was required.

The periodic annual corrections were distributed equally over the years but split between winter and summer balances. The percentual distribution between winter and summer balance corrections was assessed according to the relative size of the two balance values.

The calibrated cumulative surface mass balance at Engabreen over 1969-2008 is +0.4 m w.e., while the original cumulative surface mass balance over the same period was +22.2 m w.e.
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