# Geodetic mass balance of the western Svartisen ice cap, Norway, in the periods 1968–1985 and 1985–2002

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**ABSTRACT. The geodetic mass balance of the western Svartisen ice cap in northern Norway is determined, in this work, from photogrammetry on vertical aerial photographs taken in 1968, 1985 and 2002. The existing 1968 digital terrain model (DTM) was generated using analogue photogrammetry, and the 1985 and 2002 DTMs are newly generated using digital photogrammetry. The geodetic mass balance for 1968–85 is –2.6 $\pm$ 0.8 m w.e., and for 1985–2002 it is –2.0$\pm$ 1.6 m w.e. The area of western Svartisen decreased from 190 km$^2$ in 1968, to 187 km$^2$ in 1985 and to 184 km$^2$ in 2002. The outlet glacier Flatisen in the southeast retreated 1700 m over the two periods. The geodetic mass balance is also determined for Engabreen drainage basin, as –2.1 $\pm$ 0.9 m w.e. for the first period, and –0.3 $\pm$ 2.4 m w.e. for the second. The results for Engabreen are compared to traditional mass balances, and the large deviations cannot be explained from uncertainties determined for the geodetic method. The assessed errors contributing to the uncertainty in the geodetic mass balance are elevation errors, uncertainties from the applied melt correction, and the use of Sorge's law, assuming constant snow thickness and density.**

## INTRODUCTION

The geodetic mass balance is determined from glacier surface elevation data obtained from, for example, photogrammetry, laser scanning, global positioning system (GPS) or geodetic surveys. The change in ice volume over the period between measurements is found by subtracting the surface elevations. The volume change can be converted to water equivalents if the density of the glacier mass is known. Ablation adjustments should be conducted to correct for additional melt between the date of elevation measurements and the end of the balance year. Point elevation changes can only be calculated if the emergence velocity is known, because the elevation change of a glacier is the sum of both mass balance and ice flow (Paterson, 1994). A constant bedrock elevation is assumed in the geodetic method.

The traditional mass-balance method consists of annual field measurements on distributed points on the glacier (Østrem and Brugman, 1991). Stakes are drilled into the ice at representative sites, and accumulation and ablation are determined from stake readings. The density of the snow is measured in snow pits or from snow cores. Accumulation is often mapped more extensively by snow probing due to the complexity of the accumulation pattern. Contour maps of equal balances are determined and these are integrated for the whole glacier.

The geodetic and traditional methods of mass-balance determination each have their own advantages. The geodetic method is cheaper and less time-consuming, and it offers easy access to information on changes in glacier area, glacier slope and ice-divide migration. However, it gives no information on annual variations in accumulation or melting. Local annual climatic variations must thus be studied from traditional mass-balance data. The geodetic mass balance often extends further back in time than the traditional mass balance, and it is often possible to calculate the geodetic mass balance for glaciers not covered by a traditional mass-balance monitoring programme. Glaciers in Norway have been photographed from aircraft for many decades by the Norwegian Water Resources and Energy Directorate (NVE). These photographs make it possible to calculate the geodetic mass balance of some Norwegian glaciers over a timespan of more than 50 years (Andreassen, 1999; Østrem and Haakensen, 1999; Andreassen and others, 2002).

Sources of errors differ for the two methods. Systematic errors in the traditional method are the representativeness of the point measurements, stakes sinking in the firn area, snow probes deviating from the vertical, snow probes penetrating the summer surface, internal refreezing and internal ablation (Krimmel, 1999; Østrem and Haakensen, 1999; Cox and March, 2004). Systematic errors increase linearly with the number of years, hence the cumulative traditional mass-balance errors can increase considerably over time. Errors in the geodetic mass balance arise from elevation errors, ablation corrections and the assumption of constant snow thickness and density. However, the geodetic mass balance will not accumulate annual systematic errors, and can be used to check that the traditional mass balance is free of such errors (Krimmel, 1999; Cox and March, 2004).

Vertical aerial photographs have been collected for western Svartisen in 1968, 1985 and 2002. The ice cap is located between 66 and 67° N and between 13 and 14° E, from 10 to 1595 m a.s.l., in a maritime climate in northern Norway (Fig. 1)1. The ice cap is the second largest glacier on mainland Norway, with an area of 190 km$^2$. NVE has performed traditional mass-balance measurements on two of the outlet glaciers: Engabreen has been monitored annually since 1970, and Storglombreen was monitored from 1985 to 1988 and from 2000 to 2005. The front position of Engabreen has been monitored since 1903. The mass balance of Engabreen

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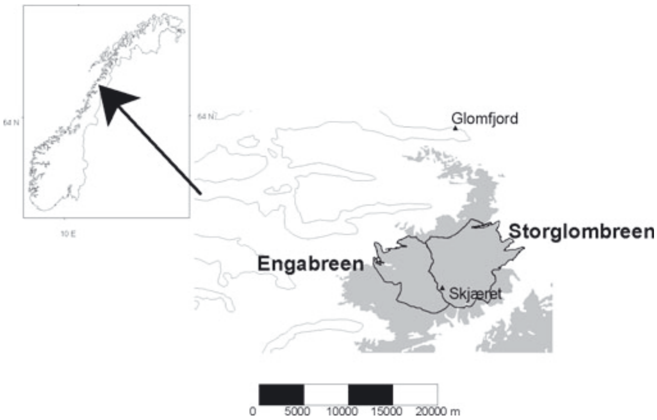


**Fig. 1.** The location of western Svartisen, Norway.

**Table 1.** Photograph and DTM information. Ablation adjustment intervals and number of positive degree-days between date of photography and end of ablation season at the plateau are also shown

| Photography date | Scale | No. of photographs | Grid size m | End of ablation season | Positive degree-days |
|---|---|---|---|---|---|
| 25 Aug 1968 | 1 : 35 000 | 19 | 25 | 11 Sep | 70 |
| 19 Aug 1985 | 1 : 35 000 | 19 | 10 | 29 Aug | 36 |
| 20 Aug 2002 | 1 : 15 000 | 30 | 20 | 13 Sep | 100 |

is highly sensitive to temperature changes, and the sensitivity is highest to a temperature increase during summer (Schuler and others, 2005).

The aim of this paper is to determine the geodetic mass balance of western Svartisen from photogrammetry applied to the vertical aerial photographs from 1968, 1985 and 2002. The geodetic mass balance for the Engabreen drainage basin is determined and compared to traditional mass-balance data reported by NVE. Uncertainties of the geodetic method are assessed and the results are discussed.

## METHODS

### Digital photogrammetry

Deriving digital terrain models (DTMs) using digital stereophotogrammetry is a well-established method described by, for example, Schenk (1999) and Kääb (2005). Overlapping stereo images are recorded. The recording geometry, as camera position and orientation angles, is estimated from ground-control points (GCPs) and tie points registered in the images. Identification of identical terrain features is conducted using cross-correlation calculations on subsections of the image pairs. This method requires contrast in the images. Snow and shadow areas typically have poor contrast and give inaccurate results. It can also be difficult to identify terrain features in steep areas, due to large geometrical distortions in the images. Quality control of the calculated elevations is conducted by visual inspection of the determined elevations in the stereoscopic viewing system on the screen. If the elevation looks incorrectly placed on the imaged terrain surface, the elevation is edited manually. In gridcells where no elevation can be measured, the elevation is determined from bilinear interpolation of surrounding points.

The accuracy of the determined recording geometry is crucial for the calculated elevations. It is an advantage that the GCPs are signalized on the ground using contrast colours so that they can be readily identified in the images. The GCPs and additional tie points should also be well distributed in the model.

The DTMs are constructed by stereophotogrammetry on vertical aerial photographs taken in 1968, 1985 and 2002 (Table 1) 1by Fjellanger Widerøe AS. The DTM from 1968 was constructed using analogue photogrammetry, while the two others are newly constructed using digital photogrammetry. The 1968 DTM was digitized earlier by the Norwegian Mapping Authority. A triangular irregular network (TIN) was constructed from the analogue contour map, and the DTM was interpolated from the TIN using bilinear interpolation. The DTM from 1985 is constructed by TerraTec AS, Oslo (formerly Fjellanger Widerøe AS), and the DTM from 2002 was constructed by the authors using SocketSet and Image Station software.

The coordinates of the points in the three DTMs do not coincide, both because of the grid size and the position of the grid nodes. The heights of the points in the 1985 DTM are interpolated to the positions of the points in the 1968 and 2002 DTMs using bilinear interpolation before the DTMs are differenced.

In the 1968 DTM the glacier front position and the elevation contours of the lower parts of Flatisen had been replaced with information from aerial photographs taken in 1993. This was done because Flatisen had retreated and thinned considerably during this period. A DTM with the 1968 heights for this area was not available.

The lake Storglomvatnet, north of Svartisen, is dammed by a power company. As three outlet glaciers terminate in this lake, their heights are influenced by the lake level in the reservoir. When the photographs were taken in 1968 the lake level was 510 m a.s.l., in 1985 it was 514 m a.s.l. and in 2002 580 m a.s.l.

### Geodetic mass balance

The geodetic mass balances for the two periods are computed for both the whole ice cap and for Engabreen drainage basin. We used the drainage divides determined by Kennett and others (1997). The boundaries for the Engabreen drainage basin are shown in Figure 21.

The DTMs are differenced using ESRI ArcInfo software. When a part of a drainage basin is not covered by the DTMs, the whole drainage basin is left out because the emergence velocity is not known. The different drainage basins can be seen in Figure 2. The 1968 DTM did not cover the entire Northern part drainage basin, so this part is left out in the first period. Because the Flatisen drainage basin contains many smaller outlet glaciers, one of these is excluded when differencing the 1985 and 1968 DTMs due to the updating of the glacier front position. We mapped a total of 88% in the first period. The 2002 DTM did not cover the entire Memorgebreen or Fonndalsbreen basins. These drainage basins are therefore excluded and we mapped a total of 91% in the second period. The elevations of the three outlet glaciers terminating in Storglomvatnet are influenced by the changing lake level in the reservoir. This affects the lowermost parts of the outlets, so that the elevation differences in

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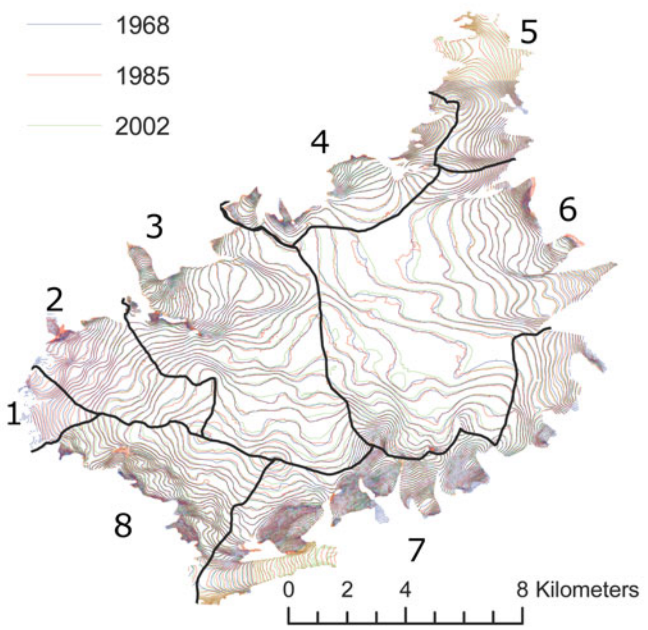


**Fig. 2.** Elevation contours for the three years. The contour interval is 20 m. The drainage basins are also shown: 1. Memorgebreen; 2. Fonndalsbreen; 3. Engabreen; 4. Dimdal–Frukosttindbreen; 5. Northern part; 6. Storglombreen; 7. Flatisvatnet; 8 . Nordfjordbreen.

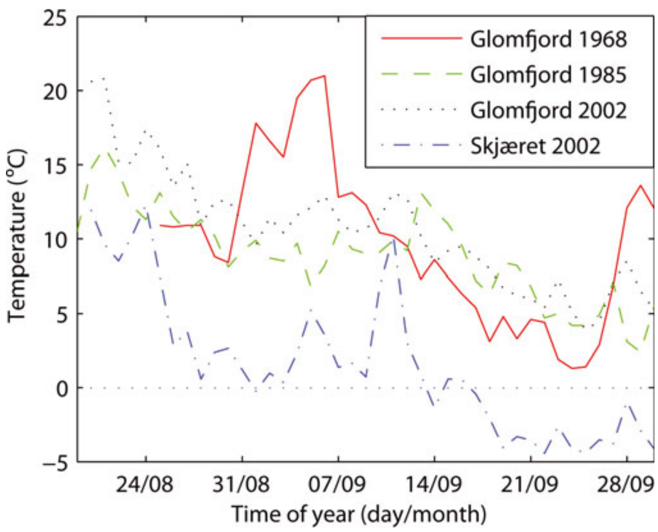


**Fig. 3.** Temperature at Glomfjord in 1968, 1985 and 2002 and temperature at Skjæret in 2002. Minor melt events may have occurred later than our estimated end of ablation season.

the second period did not stem from glacier thinning or thickening only. However, this only affected the first 100 m of the outlets, so excluding this area is assumed to be unnecessary.

In order to express the elevation changes as water equivalents, the thickness and density of the firn area at the time of photography should be known. However, as these data are not available, Sorge's law (Bader, 1954) is assumed. This states that the density is unchanged in an unchanging climate. By assuming this, the elevation change given in water equivalents can be found by multiplying the elevation change by the density of ice. A density of 900 kg m$^{-3}$ is commonly used (Andreassen, 1999; Krimmel, 1999; Cox and March, 2004), and is also used in this study.

The geodetic mass balances in both periods are adjusted for ablation. The sums of positive degree-days are calculated from temperature data between the date of photography and the end of the ablation season at the glacier plateau for each of the three years (Table 1). The end of the ablation season is determined from the weather station data from Skjæret. The temperature records from the nearest meteorological station, Glomfjord (39 m a.s.l.), provided by the Norwegian Meteorological Institute (met. no), are shown in Figure 31, together with NVE's temperature record for 2002 from Skjæret (1364 m a.s.l.), a nunatak at the glacier plateau. The locations of the meteorological stations are shown in Figure 1. The latter station has been operated by NVE since 1995. As temperature records from Skjæret in 1968 and 1985 are not available, the temperature at Skjæret is estimated using the temperature at Glomfjord and a temperature lapse rate between the stations (Schuler and others, 2005). Schuler and others (2005) determined an average lapse rate of $-0.0074\,°\mathrm{C\,m^{-1}}$ for the period 1999–2002. The sums of positive degree-days are compared, and the ablation adjustments are estimated based on the glacier melt rate calculated for Engabreen (Schuler and others, 2005). This melt rate takes into account the different albedo for snow and ice surfaces. In the period 1968–1985 the conducted ablation adjustment is 0.2 m w.e.; for the period 1985–2002 it is −0.3 m w.e.

End-of-balance-year adjusted point elevation changes are not adjusted for emergence velocity. According to Geist and others (2005), the emergence at Engabreen in the period 24 September 2001 to 28 May 2002 varied from −4 m at the glacier plateau to 7 m at the glacier tongue for the whole period (246 days). This gives emergence velocities ranging from $0.028\,\mathrm{m\,d^{-1}}$ at the tongue to $-0.016\,\mathrm{m\,d^{-1}}$ at the plateau. As the timespans were 6 days in the period 1968–85 and 1 day in the period 1985–2002, no corrections are made. It is assumed that the emergence velocity is the same for all three years, and that this assumption does not cause additional uncertainty. For point balances this is a reasonable assumption because the uncertainty from inaccurate elevations will be large.

## Error assessment

The relative elevation errors are important for the accuracy of the geodetic mass balance. The absolute errors of the three DTMs are of less importance for geodetic mass-balance determination, as they only indicate how accurate the DTMs are relative to a datum (Cox and March, 2004). Elevation differences over bedrock and spatial autocorrelation results have previously been used to assess the elevation uncertainty (Nuth and others, 2007). By differencing the DTMs over bedrock, the relative errors are estimated. The standard deviation of the elevation difference over bedrock gives the uncertainty of the point measurements. For assessing the spatial averaged uncertainty, the elevation differences are first detrended. Presence of spatial autocorrelation due to, for example, orientation errors is evaluated using semivariograms, and the results are used to evaluate spatial averaged uncertainty for the drainage areas. Details of the spatial analysis will be presented elsewhere. Only areas that are matched automatically in the 2002 DTM are used for determining the relative error. These areas exclude mountainsides steeper than 30° and shadow areas where few identical features are found in the stereo pairs. As steep mountainsides are excluded, relative elevation differences that may stem from

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**Table 2.** The root-mean-square errors given in ground coordinates for the GCPs in the newly constructed DTMs

| Year | X<br>m | Y<br>m | Z<br>m |
|---|---|---|---|
| 1985 | 0.098 | 0.101 | 0.068 |
| 2002 | 0.822 | 0.850 | 1.393 |

horizontal shifts of the elevation grids due to uncertainty in the absolute orientation are reduced. We choose a threshold of 30° because areas with a slope under this threshold are assumed to be most representative for the glacier area. Only 2% of the ice cap has a slope steeper than 30°. This 2% is not clustered, and the largest area is 0.1 km$^2$.

Ideally the three DTMs should have been constructed at the same time by the same constructor using the same software and the same well-signalized GCPs. If so, the DTMs would have had a more similar absolute orientation, and hence the relative difference between the DTMs over bedrock would be smaller. Some of the GCPs were used for orienting both the 1985 and the 2002 DTM, but the GCPs were, unfortunately, not well signalized in the 2002 photographs and the DTMs were constructed by different people. The quality of the absolute orientation thus differs for the two DTMs.

The melt rate used to estimate ablation corrections is calculated specifically for Engabreen. This means that the topography of Engabreen and its surrounding area, such as slope, aspect and effective horizon, is taken into account (Hock, 1999). Hence, errors are introduced by using the same melt rate for the whole of western Svartisen. The numbers of positive degree-days for the three years are calculated only for Skjæret. However, as the corrections are small, due to the relatively small differences in positive degree-days, this error will not be large. Based on this, an error of ±0.3 m w.e. is assumed.

Uncertainties introduced by assuming constant density can be due to both changes in the equilibrium-line altitude (ELA) and changes in the density of the firn layer. As no measurements of the density and thickness of the firn layer are available, the estimate of the uncertainty introduced by assuming constant density is based on information on the transient snowline altitude for the three years. Traditional mass-balance data are also investigated in order to reveal changes in the densification process of the firn layer. The densification process can change as the accumulation rate, the density of the newly accumulated snow and the temperature change (Arthern and Wingham, 1998; McConnell and others, 2000). The transient snowline in 1968 was ~1000 m a.s.l., in 1985 ~1400 m a.s.l. and in 2002 ~1250 m a.s.l. Modelling results of the mass balance from 1962 to 1968 show that all these years had positive mass balance (Andreassen and others, 2006). The traditional mass-balance data show that the years prior to 1985 had positive mass balances, while 1985 had a negative mass balance. In 2001 there was a large negative mass balance, when almost all the snow melted. The mass balance in 2002 was positive. This indicates that the firn in 1968 was new and relatively little densified, and that snow was present. In 1985 the firn was also new, but could have been more densified due to the negative mass balance in 1985. In 2002 the firn was dense, due to the very negative mass balance in 2001, but new snow was present. Based on this information, the uncertainty introduced by assuming constant density is ±0.6 m w.e. for 1968–85, and ±0.2 m w.e. for 1985–2002.

The grid size of the DTMs must be adequate to represent the topographic variations of the glacier surface. Andreassen (1999) tested how the geodetic mass balance varied when using grid sizes of 5, 10, 20, 50 and 100 m for Storbreen, Norway, and found that as long as the grid size was 5–20 m, the geodetic mass balance showed little variation. Storbreen glacier is a valley glacier with an area of 5.4 km$^2$ and an average slope of 14°. The three DTMs have different grid sizes, as shown in Table 1. Because the area of western Svartisen is 190 km$^2$ and the average slope is 8°, the grid sizes are assumed to represent the topographic variations of the ice-cap surface.

The flying height influences the accuracy of the determined elevations; flying lower gives a larger scale and a smaller standard error. The scales of the photographs listed in Table 1 show that the photographs from 2002 are likely to have the lowest errors.

Digitizing the analogue 1968 DTM introduces horizontal random errors, depending on the accuracy of the digitizer and the condition of the analogue manuscript (Andreassen and others, 2002). According to Kjekshus and others (2007), the standard deviation of this DTM is within 4–6 m.

In aerial photographs it is sometimes difficult to determine the glacier outline. Rocks and moraine material on top of the ice can make the glacier area erroneously defined, and also snow close to the glacier can make it difficult to draw the glacier outline. There is little moraine material on western Svartisen, so this is considered to be a minor problem. Snow is also considered to be a minor problem.

Flatisen terminates in the lake Flatisvatnet. Without estimates of the water depth, the actual volume change is difficult to obtain. This is considered to be a minor problem.

Elevation uncertainty, melt uncertainty and uncertainty from applying Sorge's law are uncorrelated errors. According to standard error propagation, the total error of the geodetic mass balance is the square root of the sum of each individual squared uncertainty.

## RESULTS

### Photogrammetry

The root-mean-square (rms) errors for the GCPs of the two DTMs constructed using digital photogrammetry, are shown in Table 21. The elevation contours for the three years are shown in Figure 2.

### Geodetic mass balance

The geodetic mass balance for the period 1968–85 is −2.6 m w.e. A total of 167 km$^2$ (88%) was mapped in this period. The westernmost and northernmost parts thinned considerably (Fig. 4)1. For Engabreen drainage basin, with an area of 40 km$^2$, the value is −2.1 m w.e.

The geodetic mass balance for the period 1985–2002 is −2.0 m w.e. A total of 170 km$^2$ (91%) was mapped in this period. Flatisen and the northernmost areas thinned considerably (Fig. 4). For Engabreen drainage basin the value is −0.3 m w.e.

In order to compare the geodetic mass balance in the two periods, it is also computed for the drainage basins covered

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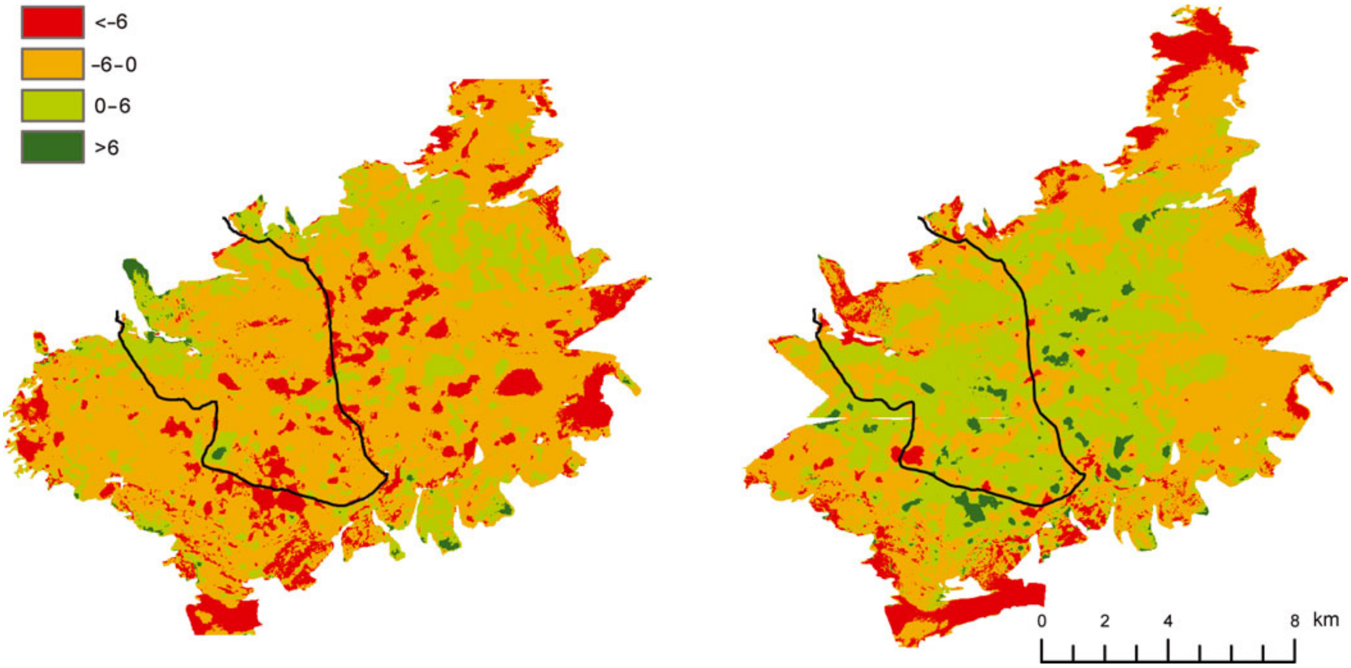


**Fig. 4.** Surface elevation change adjusted to the end of the balance year (in m w.e.) of western Svartisen in 1968–85 (left) and 1985–2002 (right). The black line marks the Engabreen drainage basin.

by all three DTMs. This area covers 80% of the ice cap and is 150 km$^2$. In the first period the geodetic mass balance for this area is −2.6 m w.e. and in the second it is −1.0 m w.e.

The ice-cap area decreased from 190 km$^2$ in 1968, to 187 km$^2$ in 1985 and to 184 km$^2$ in 2002. Between 1968 and 1985 Engabreen was the only outlet glacier that advanced. Between 1985 and 2002 Engabreen and two small outlet glaciers on the eastern side advanced slightly. Flatisen retreated 1700 m between 1968 and 2002.

Figure 5 1shows the surface elevation change for western Svartisen as a function of surface elevation for the two periods. In the period 1968–85, the positive elevation changes below 250 m a.s.l. can be fully attributed to the advance and thickening of Engabreen, as Engabreen is the only part of the ice cap that extends down to below 250 m a.s.l. Between 250 and 650 m a.s.l. the variation in the elevation changes reflects the thickening of Engabreen and the thinning and/or disappearance of the three outlet glaciers from Storglombreen and smaller outlets. Above 650 m a.s.l. the mean is below zero for all elevations. Unfortunately the elevation changes for Flatisen could not be obtained for the period 1968–85, due to the updating of the 1968 DTM mentioned earlier. In the period 1985–2002 the positive elevation changes below 100 m a.s.l. can be attributed to the advance of Engabreen. However, during this period no thickening of the Engabreen tongue could be observed. Between 350 and 550 m a.s.l. the retreat and thinning of Flatisen is the prevailing feature. The elevation changes are negative up to 1100 m a.s.l.

## Error assessment

The individual and geodetic mass-balance uncertainties are shown in Table 31. The uncertainties in the geodetic mass balance for the whole of western Svartisen and for Engabreen are estimated based on the error estimates and using standard propagation of individual uncertainties.

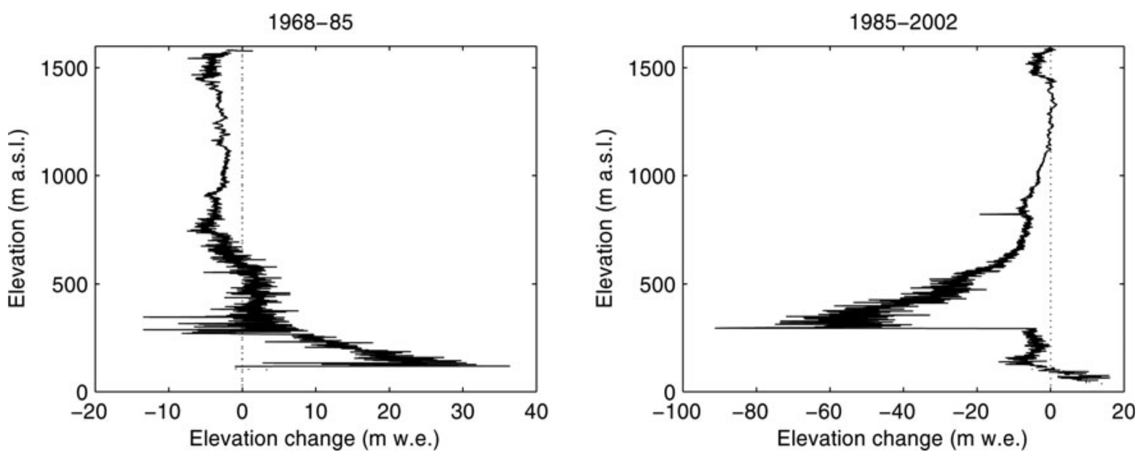


**Fig. 5.** Surface elevation change for western Svartisen as function of surface elevation in the two periods. The surface elevation change is adjusted to the end of the balance year. Note that the scale is different for the two periods.

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**Table 3.** Individual uncertainties and the geodetic mass-balance uncertainties for western Svartisen, Engabreen and single points

| Basin | Elevation uncertainty 1968–85 m w.e. | Ablation uncertainty 1968–85 m w.e. | Density uncertainty 1968–85 m w.e. | Mass-balance uncertainty 1968–85 m w.e. | Elevation uncertainty 1985–2002 m w.e. | Ablation uncertainty 1985–2002 m w.e. | Density uncertainty 1985–2002 m w.e. | Mass-balance uncertainty 1985–2002 m w.e. |
|---|---|---|---|---|---|---|---|---|
| Western Svartisen | 0.3 | 0.3 | 0.6 | 0.8 | 1.5 | 0.3 | 0.2 | 1.6 |
| Engabreen | 0.6 | 0.3 | 0.6 | 0.9 | 2.3 | 0.3 | 0.2 | 2.4 |
| Single points | 6.9 | — | — | — | 4.4 | — | — | — |

## DISCUSSION

### Photogrammetry

The georeferencing of the photographs affects the final result. All three DTMs were constructed at different times and by different constructors, hence they have different absolute orientation. This is unfavourable for the accuracy. The 1985 and the 2002 DTMs were constructed using some of the same GCPs, which were not signalized in the 2002 photographs. The large differences in rms errors of the 1985 and 2002 DTMs are because the 2002 GCPs were not signalized. The absolute orientation of the 1985 DTM is considerably better than expected. In this study, the unsignalized GCPs in the 2002 DTM caused a larger scale of autocorrelation in the bedrock differences, which made the elevation uncertainties large in the second period. In order to reduce this uncertainty in future studies the GCPs need to be well signalized.

Varying the grid size in the low-contrast area during matching can improve the results. This was not done in the present study, but should be done in future studies. When the grid size is increased, spatially infrequent features in the images may be identified and successfully matched. With a reduced grid size, spatially frequent features may be identified.

In order to avoid interpolation for a shift of the DTM to common point coordinates, the DTMs should be of the same grid size, with the gridpoints located at the same coordinates.

### Geodetic mass balance

The geodetic mass balances for the two periods for the drainage basins covered completely by all three DTMs are $-2.6 \pm 0.8$ m w.e. for the period 1968–85 and $-1.0 \pm 1.6$ m w.e. for the period 1985–2002. The mass balances are therefore not different in the two periods.

The results obtained in this study are not in agreement with the traditional mass-balance measurements of Engabreen that NVE has obtained annually since 1970. Kjøllmoen and others (2003) report a positive cumulative mass balance of 22 m w.e. from 1970 to 2002 for the Engabreen drainage basin. Using the same drainage divides, we find the geodetic mass balance for the 1968–85 to be $-2.1 \pm 0.9$ m w.e., and $-0.3 \pm 2.4$ m w.e. for the period 1985–2002. Other authors have also found the geodetic mass balance to be more negative than the traditional mass balance (Krimmel, 1999; Østrem and Haakensen, 1999). As Østrem and Haakensen (1999) point out, there are several sources of systematic errors in the traditional mass balance which can make the cumulative traditional mass balance too positive. Sinking of stakes in the firn area, snow probes deviating from the vertical, and snow probes penetrating the previous year's summer surface, are all possible sources of systematic errors. As Engabreen is an outlet glacier from an ice cap, the determination of drainage divides can also cause systematic errors which can make the cumulative traditional mass balance too positive (Elvehøy and others, in press).

In the period 1968–85 the positive elevation changes below 250 m a.s.l. exceed the uncertainty. The negative elevation changes at elevations between 650 and 1500 m a.s.l. also exceed the uncertainty. In the period 1985–2002 both the positive elevation changes below 100 m a.s.l. and the negative elevation changes found at elevations between 300 and 1050 m a.s.l. exceed the uncertainty.

The advances of Engabreen in both periods are in agreement with registrations of the front position (Kjøllmoen and others, 2003).

## CONCLUSION

DTMs constructed from aerial photographs were used to obtain the geodetic mass balance of the western Svartisen ice cap in the periods 1968–85 and 1985–2002. The geodetic mass balance in the period 1968–85 was $-2.6 \pm 0.8$ m w.e. A total of 167 km$^2$ (88%) of the ice cap was mapped. The geodetic mass balance in the period 1985–2002 was $-2.0 \pm 1.6$ m w.e. A total of 170 km$^2$ (91%) of the ice cap was mapped in this period. The area of the western Svartisen ice cap decreased from 190 km$^2$ in 1968, to 187 km$^2$ in 1985 and to 184 km$^2$ in 2002. The outlet glacier Flatisen, in the southeast, retreated significantly.

Obtaining the geodetic mass balance from aerial photographs is cheaper and less time-consuming than the traditional method. However, the absence of signalized GCPs reduces the accuracy. Additional inaccuracy is caused by the lack of field data regarding additional melting, and firn-density and firn-thickness measurements.

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## REFERENCES

Andreassen, L.M. 1999. Comparing traditional mass balance measurements with long-term volume change extracted from topographical maps: a case study of Storbreen glacier in Jotunheimen, Norway, for the period 1940–1997. *Geogr. Ann.*, **81A**(4), 467–476.

Andreassen, L.M., H. Elvehøy and B. Kjøllmoen. 2002. Using aerial photography to study glacier changes in Norway. *Ann. Glaciol.*, **34**, 343–348.

Andreassen, L.M., H. Elvehøy, T. Jóhannesson, J. Oerlemans, S. Beldring and M. van den Broeke. 2006. Modelling the climate sensitivity of Storbreen and Engabreen, Norway. *NVE Rapp*. 3-2006.

Arthern, R.J. and D.J. Wingham. 1998. The natural fluctuations of firn densification and their effect on the geodetic determination of ice sheet mass balance. *Climatic Change*, **40**(3–4), 605–624.

Bader, H. 1954. Sorge's Law of densification of snow on high polar glaciers. *J. Glaciol.*, **2**(15), 319–323.

Cox, L.H. and R.S. March. 2004. Comparison of geodetic and glaciological mass-balance techniques, Gulkana Glacier, Alaska, U.S.A. *J. Glaciol.*, **50**(170), 363–370.

Elvehøy, H., M. Jackson and L.M. Andreassen. In press. The influence of drainage boundaries on specific mass-balance results: a case study of Engabreen, Norway. *Ann. Glaciol.*

Geist, T., H. Elvehøy, M. Jackson and J. Stötter. 2005. Investigations on intra-annual elevation changes using multi-temporal airborne laser scanning data: case study Engabreen, Norway. *Ann. Glaciol.*, **42**, 195–201.

Hock, R. 1999. A distributed temperature-index ice- and snowmelt model including potential direct solar radiation. *J. Glaciol.*, **45**(149), 101–111.

Kääb, A. 2005. *Remote sensing of mountain glaciers and permafrost creep*. Zürich, Geographisches Institut der Universität Zürich. (Schriftenreihe Physische Geographie Glaziologie und Geomorphodynamik 48.)

Kennett, M., C. Rolstad, H. Elvehøy and E. Ruud. 1997. Calculation of drainage divides beneath the Svartisen ice-cap using GIS hydrologic tools. *Nor. Geogr. Tidsskr.*, **51**(1), 23–28.

Kjekshus, O.C., A. Edvardsen, S. Kristensen, S. Jaren, Ø. Olafsen and J. Tallhaug, 2007. *Forprosjekt – Opplegg for forvaltning, drift og vedlikehold av terrengdata*. Norge Digitalt.

Kjøllmoen, B., L.M. Andreassen, R.V. Engeset, H. Elvehøy and M. Jackson. 2003. Glaciological investigations in Norway in 2002. *NVE Rapp.* 3-2003.

Krimmel, R.M. 1999. Analysis of difference between direct and geodetic mass balance measurements at South Cascade Glacier, Washington. *Geogr. Ann.*, **81A**(4), 653–658.

McConnell, J.R. *and 7 others*. 2000. Changes in Greenland ice sheet elevation attributed primarily to snow accumulation variability. *Nature*, **406**(6798), 877–879.

Nuth, C., J. Kohler, H.F. Aas, O. Brandt and J.O. Hagen. 2007. Glacier geometry and elevation changes on Svalbard (1936–90): a baseline dataset. *Ann. Glaciol.*, **46**, 106–116.

Østrem, G. and M. Brugman. 1991. *Glacier mass-balance measurements. A manual for field and office work.* Saskatoon, Sask., Environment Canada. National Hydrology Research Institute. (NHRI Science Report 4.)

Østrem, G. and N. Haakensen. 1999. Map comparison or traditional mass-balance measurements: which method is better? *Geogr. Ann.*, **81A**(4), 703–711.

Paterson, W.S.B. 1994. *The physics of glaciers. Third edition.* Oxford, etc., Elsevier.

Schenk, T. 1999. *Digital photogrammetry.* Laurelville, OH, TerraScience.

Schuler, T.V. *and 6 others*. 2005. Distributed mass-balance and climate sensitivity modelling of Engabreen, Norway. *Ann. Glaciol.*, **42**, 395–401.