Glaciological investigations in Norway in 2003

The Norwegian Water Resources and Energy Directorate (NVE)

2004

Report No 4

Glaciological investigations in Norway in 2003

Published by:	Norwegian Water Resources and Energy Directorate
Editor:	Bjarne Kjøllmoen
Authors:	Liss M. Andreassen, Rune V. Engeset, Hallgeir Elvehøy, Miriam Jackson and Bjarne Kjøllmoen
Print:	Lobo Media
Number printed:	250
Frontpage photo:	Storgjuvbreen, a north-facing valley glacier situated in the northern part of Jotunheimen. Measurements from 1933 to 1961 showed a frontal retreat of 570 m over the 28 years period. Measurements of glacier length changes were restarted in 1997 and the glacier front has advanced about 30 m from 1997 to 2003. The photo is taken on 18th June 2003 by Miriam Jackson.
ISSN:	1502-3540
ISBN:	82-410-0514-8

Abstract:	Results of glaciological investigations performed at Norwegian glaciers in 2003 are presented in this report. The main part concerns mass balance investigations. Results from investigations of glacier monitoring are discussed in a separate chapter.

Subjects:	Glaciology, Mass balance, Front position, Glacier velocity, Volume changes

Norwegian Water Resources and Energy Directorate
Middelthuns gate 29
Post office box 5091 Majorstua
N-0301 OSLO
Norway

Telephone: +47 22 95 95 95
Telefaks: +47 22 95 90 00
Internet: www.nve.no

August 2004

Contents

Preface

This report is a new volume in the series "Glaciological investigations in Norway" which has been published since 1963.

The report is based on a number of reports on different investigations of Norwegian glaciers. Measurements of mass balance, front position change, glacier velocity, volume changes and other glaciological investigations are presented. Most of the investigations are ordered by external companies and have been published earlier as reports to the respective companies.

The report is published in English with a summary in Norwegian. The purpose of this report is to provide a joint presentation of the investigations and calculations made mainly by NVEs Section for Glaciers and Environmental Hydrology during 2003. The chapters are written by different authors with different objectives, but are presented in a uniform manner. The individual authors hold the professional responsibility for the contents of each chapter. The fieldwork and the calculations are mainly the result of co-operative work amongst the personnel at the Section for Glaciers and Environmental Hydrology.

Bjarne Kjøllmoen was editor and Miriam Jackson made many corrections and improvements.

Oslo, 11th August 2004

Kjell Repp
Director,
Hydrology Department

Sidsel Haug
Head of Section,
Section for Glaciers and Environmental Hydrology

Summary

Mass balance

Mass balance investigations were performed on fourteen glaciers in Norway in 2003. Ten of these glaciers are in southern Norway and four in northern Norway.

A dry winter season resulted in winter balances lower than average at thirteen of the fourteen measured glaciers. Rembesdalskåka at Hardangerjøkulen and Gråsubreen in Jotunheimen had the relative lowest winter balances with only 57 % of average. Winter balance greater than average was measured at only one glacier, Langfjordjøkelen in western Finnmark with 109 %.

A warm summer resulted in summer balances greater than average at all fourteen measured glaciers. In southern Norway the results were ranged from 136 % (Hansebreen) to 178 % (Gråsubreen) of average. The three glaciers in Jotunheimen had the greatest relative summer balance (165-178 %). In northern Norway, Engabreen had 132 % of average.

As a consequence of low winter balance and great summer balance the net balance was negative at all fourteen measured glaciers. The greatest deficit was measured at Hansebreen (−2.7 m w.eqv.) and Ålfotbreen (−2.5 m w.eqv.). For ten of the glaciers the equilibrium line altitude was *above* the glacier summit.

Front position

Front position measurements were performed for 25 Norwegian glaciers in 2003. Twenty-three of the glaciers are in southern Norway and two in northern Norway. Only Nigardsbreen, an eastern outlet from Jostedalsbreen, show an advance in front position (24 m) from autumn 2002 to autumn 2003. Since 1987 the cumulative advance for Nigardsbreen is about 270 metres. Three glacier outlets showed almost no change (< ±2 m). Seventeen glaciers showed a retreat of > 10 metres. Engabreen at Svartisen and Rembesdalskåka at Hardangerjøkulen had the greatest recession with 60 and 54 metres, respectively.

Sammendrag

Massebalanse

I 2003 ble det utført massebalansemålinger på 14 breer i Norge – ti i Sør-Norge og fire i Nord-Norge.

En nedbørfattig vinter i hele Sør-Norge og store deler av Nord-Norge førte til at vinterbalansen ble mindre enn gjennomsnittet på 13 av 14 målte breer. Rembesdalskåka på Hardangerjøkulen og Gråsubreen i Jotunheimen hadde relativt minst vinterbalanse med 57 % av normalt. Det var bare Langfjordjøkelen i Vest-Finnmark som fikk større vinterbalanse enn gjennomsnittet med 109 %.

Sommeren var varmere enn normalt over hele landet, og det førte til at sommerbalansen ble større enn normalt på alle målte breene. I Sør-Norge ble resultatene mellom 136 % (Hansebreen) og 178 % (Gråsubreen) av gjennomsnittet. Relativt størst ble sommerbalansen på de tre breene i Jotunheimen (165-178 %). I Nord-Norge hadde Engabreen 132 % av gjennomsnittet.

Med liten vinterbalanse og stor sommerbalanse ble det negativ nettobalanse på alle de 14 målte breene. Størst underskudd ble det på Hansebreen (–2,7 m) og Ålfotbreen (–2,5 m). På 10 av breene lå likevektslinjen *over* breens høyeste punkt.

Frontposisjon

Frontmålinger ble utført på 25 norske breer i 2003, 23 i Sør-Norge og 2 i Nord-Norge. Det var bare Nigardsbreen, en østlig utløper fra Jostedalsbreen, som hadde framstøt det siste året. Fra høsten 2002 til høsten 2003 var framgangen 24 meter. Siden framstøtet startet i 1987 har Nigardsbreen gått fram omkring 270 meter. Tre breutløpere viste liten endring (±2 m) i frontposisjon. Sytten breer hadde en tilbakegang på mer enn 10 meter. Engabreen, en nordvestlig utløper fra Svartisen, og Rembesdalskåka på Hardangerjøkulen hadde størst tilbakegang med hhv. 60 og 54 meter.

1. Glacier investigations in Norway in 2003

1.1 Mass balance

Studies of mass balance include measurements of accumulated snow (winter balance) during the winter season, and measurements of snow and ice removed by melting (summer balance) during the summer season. The difference between these two parameters gives the net balance. If the winter balance is greater than the summer balance, the net balance is positive and the glacier increases in volume. Alternatively, if the melting of snow and ice during the summer is larger than the winter balance, the net balance is negative and the ice volume decreases.

Method

The method used to measure mass balance is the same as used in previous years. Using experience gained from many years of measurements, the measurement network was simplified on individual glaciers at the beginning of the 1990s, without affecting the accuracy of the resulting balance calculations or the final results.

Winter balance

The winter balance is normally measured in April or May by probing to the previous year's summer surface along the same profile each year. Stake readings are used to verify the probings where possible. Since the stakes can disappear during particularly snow-rich winters, and since it is often difficult to distinguish the summer surface (S.S.) by probing alone, snow coring is also used to confirm the probing results. Snow density is measured in pits at one or two locations at different elevations on each glacier.

Summer and net balance

Summer and net balances are obtained from stake measurements, usually performed in September or October. Below the glacier's equilibrium line the net balance is always negative, meaning that more snow and ice melts during a given summer than accumulates during the winter. Above the equilibrium line, in the accumulation area, the net balance is always positive. Based on past experience, snow density of the remaining snow in the accumulation area is typically assumed to be 0.60 g/cm^3. After especially cold summers, or if there is more snow than usual remaining at the end of the summer, snow density is measured using snow-cores, or is assumed to be 0.65 g/cm^3. The density of melted firn is, depending on the age, assumed to be between 0.65 and 0.80 g/cm^3. The density of melted ice is taken as 0.90 g/cm^3.

Stratigraphic method

The mass balance is usually calculated using the so-called traditional stratigraphic method (Østrem and Brugman 1991), which means the balance between two successive "summer surfaces" (i.e. surface minima). Consequently, the measurements describe the state of the glacier *after* the end of melting and *before* fresh snow has fallen. In some occasions ablation *after* the final measurements in September/October can occur. Strictly speaking, this ablation should be included in this year's summer balance. However, measuring and calculating this additional ablation cannot be done until the following winter or spring. Thus, it is counted as a negative contribution to the next year's winter balance.

Accuracy

The accuracy of the mass balance measurements depends on several factors. The accuracy of the winter balance is influenced mainly by the accuracy of the point measurements (soundings, core drillings, stakes, towers and density pit) and how representative they are. The smoothness of the snow layer is also of importance. The accuracy of soundings and core drillings depends on the number of point measurements, the certainty of identifying the summer surface and the implementation of the measurements (e.g. if the probe penetrates vertically through the snow pack). Overall, the accuracy of winter balance decreases with increasing snow depth.

The accuracy of summer balance is dependent on the number of ablation stakes, the height distribution, how representative they are, and on the state of the stakes. Sources of error can be stakes sinking or tilting to one side.

The accuracy of the net balance is dependent on all the factors mentioned above.

As the mass balance is measured and calculated, it is very difficult to estimate the accuracy mathematically because it is difficult to quantify the accuracy of the individual factors. The determined values of accuracy are therefore based on a subjective estimate.

Mass balance program

In 2003 mass balance measurements were performed on 14 glaciers in Norway - 10 in southern Norway and 4 in northern Norway. In southern Norway, 6 of the glaciers have been measured for 41 consecutive years or more. They constitute a west-east profile extending from the maritime Ålfotbreen glacier with an average winter balance of 3.7 m water equivalent, to the continental Gråsubreen with an average winter balance of 0.8 m w.eqv. Storbreen in Jotunheimen has the longest series of all glaciers in Norway with 55 years of measurements, while Engabreen at Svartisen has the longest series (34 years) in northern Norway. In 2003, mass balance measurements were resumed on Gråfjellsbrea and Breidablikkbrea, two north-west facing glaciers on southern Folgefonna. These two glaciers were subjects for mass balance studies over the periods 1963-68 (Breidablikkbrea) and 1964-68 and 1974-75 (Gråfjellsbrea). The location of the glaciers investigated is shown in Figure 1-1.

In the following chapters mass balance studies performed on Norwegian glaciers in 2003 are reported. The numbers from the Norwegian Hydrological Unit System (REGINE) and from the World Glacier Monitoring Service (WGMS) are given for each glacier in Table 1-1.

The mass balance (winter, summer and net balance) is given both in volume (m^3 water) and specific water equivalents for each 50 or 100 m height interval. The results are shown in both tables and diagrams. All diagrams have the same ratio between units on the *x*- and *y*-axes in order to make comparison straightforward. Finally, histograms showing the complete mass balance results for each glacier are presented.

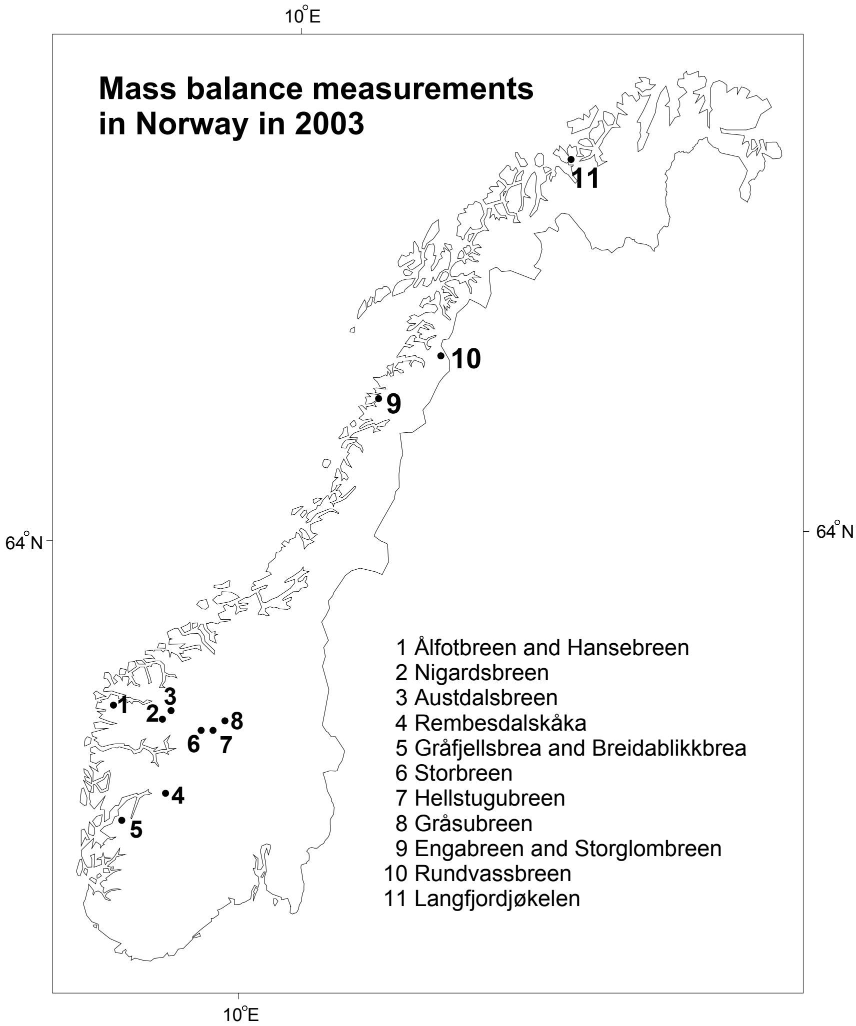


Figure 1-1
Location of the glaciers at which mass balance studies were performed in 2003.

Weather conditions and mass balance results

Wintry weather

The winter months October-December 2002 were cold and dry over the whole country. It was particularly dry in western Norway and Nordland county with 25-50 % of the normal amount of precipitation.

The period January-April was generally speaking warmer and drier than normal over the whole country. However, there was more precipitation than normal in western Norway in January (125-150 %) and in northern Norway in March (150-300 %). Also, in northern Norway it was considerably colder than normal in January. Winter 2002/2003 was snow poor in southern Norway, in the southern parts of Nordland county and in inner areas of Finnmark county. The eastern parts of Sogn and Fjordane county in western Norway had less than 50 % of normal winter precipitation. In northern Norway, Troms county and the western parts of Finnmark county had 100-150 % of normal precipitation.

Snow accumulation and winter balance

The dry winter season resulted in winter balances lower than average at thirteen of the fourteen measured glaciers. Rembesdalskåka at Hardangerjøkulen and Gråsubreen in Jotunheimen had the lowest relative winter balances, both with 57 % of average. In northern Norway, Engabreen at Svartisen was below average (82 %), while Langfjordjøkelen in western Finnmark was above average (109 %).

There was no indication of melting *after* the final measurements in autumn 2002 on any of the measured glaciers. Thus, the snow *accumulation* and the winter *balance* are equal.

Summer weather

Summer 2003 was considerably warmer than normal over the whole country. The mean temperature for the whole country during the summer season (May –September) was 1.8 ºC above normal, which is the fourth highest mean summer temperature measured since measurements began in 1866. July was particularly warm with 3-5 ºC higher temperature than normal in most parts of western Norway and in Nordland county. The coastal areas in Finnmark county were close to the average with 0-1 ºC warmer than normal.

Ablation and summer balance

The warm summer resulted in summer balances above average at all fourteen glaciers. In southern Norway the results were between 136 % (Hansebreen at Ålfotbreen ice cap) and 178 % (Gråsubreen in Jotunheimen) of average. The greatest relative summer balance was measured at the three glaciers in Jotunheimen. The summer balance for the two measured glaciers on southern Folgefonna was 182 % (Breidablikkbrea) and 183 % (Gråfjellsbrea) of average from the previous investigation periods in the 1960s and 1970s.

Net balance

Due to low winter balance and great summer balance the net balance was negative for all fourteen measured glaciers. The greatest deficit was measured at Hansebreen (–2.7 m water equivalent) and Ålfotbreen (–2.5 m w.eqv.). A deficit of the same size has occurred only one year at Ålfotbreen (1988) and two years at Hansebreen (1988 and 2001). For Rembesdalskåka the net balance was –1.8 m w.eqv., and there is only one year with a greater deficit, –1.9 m w.eqv. in 1969. Nigardsbreen at Jostedalsbreen ice cap had a negative net balance of –1.2 m w.eqv. An equal or greater deficit was measured in 1969 (–1.3 m w.eqv.) and in 1980 (–1.2 m w.eqv.). The net balance at Austdalsbreen, also part of Jostedalsbreen ice cap, was –2.3 m w.eqv. This is the most negative net balance measured since measurements began in 1988. The three glaciers in Jotunheimen had the second greatest deficit in the respective measuring periods. For ten of the glaciers the equilibrium line altitude was *above* the glacier summit.

The results from the mass balance measurements in Norway in 2003 are shown in Table 1-1. Winter (**b_w**,), summer (**b_s**) and net balance (**b_n**) are given in metres water equivalent (m w.eqv.) smoothly distributed over the entire glacier surface. The figures in the **% of average** column show the current results in percent of the average for the previous years (minimum eight years of measurements). The net balance results are compared with the mean net balance in the same way. **ELA** is the equilibrium line altitude (m a.s.l.) and **AAR** is the accumulation area ratio (%).

Glacier	*No. of WGMS*	*Period*	*Area* *(km^2)*	*Altitude* *(m a.s.l.)*	*b_w* *(m)*	*% of average*	*b_s* *(m)*	*% of average*	*b_n* *(m)*	*b_n middle*	*ELA*	*AAR %*
Ålfotbreen	*BL004*	1963-03	4.5	903-1382	2.52	67	-5.03	146	-2.51	0.29	>1382	0
Hansebreen	*BO002*	1986-03	3.1	930-1327	2.45	70	-5.12	136	-2.67	-0.26	>1327	0
Breidablikkbrea	*AJ001*	1963-68	3.9	1219-1660						-0.19		0
		2003-	3.6	1236-1659	2.08	-	-4.35	-	-2.27	-	>1659	
Gråfjellsbrea	*AK007*	1964-68 1974-75	9.4	1039-1660						0.20		0
		2003-	8.9	1051-1659	1.90	-	-4.07	-	-2.17	-	>1659	
Nigardsbreen	*A4014*	1962-03	47.8	320-1960	1.56	65	-2.72	139	-1.16	0.45	>1960	0
Austdalsbreen	*A4023*	1988-03	11.8	1200-1757	1.60	70	[1]-3.94	170	-2.34	-0.04	>1757	0
Rembesdalskåka	*AO001*	1963-03	17.1	1020-1865	1.33	63	-2.69	137	-1.36	0.16	>1860	0
Storbreen	*AD041*	1949-03	5.4	1390-2100	1.11	76	-2.68	173	-1.57	-0.20	2025	2
Hellstugubreen	*AD011*	1962-03	3.0	1465-2200	0.71	63	-2.23	165	-1.53	-0.26	>2200	0
Gråsubreen	*AB047*	1962-03	2.3	1830-2290	0.45	57	-1.84	178	-1.39	-0.25	>2290	0
Storglombreen	*C7013/* *C7014*	1985-88 2000-02	59.0 62.4	520-1580	2.18	[2]106	[3]-3.28	[2]119	-1.10	-0.75 [2]-0.70	>1580	0
Engabreen	*C4011*	1970-03	38.0	40-1594	2.41	82	-3.00	132	-0.60	0.67	1195	55
Rundvassbreen	[4]	2002-03	11.6	788-1537	1.88	-	-2.95	-	-1.07	[5]-0.07	1360	28
Langfjordjøkelen	*ET008*	1989-93 1996-03	3.7	280-1050	2.44	[6]109	-3.48	[6]118	-1.04	-0.10 [6]-0.65	>1050	0

[1]Contribution from calving amounts to 0.33 m for b_s
[2]Calculated for the measured periods 1985-88 and 2000-2002
[3]Contribution from calving amounts to 0.12 m for b_s
[4]WGMS number DI021 and DI022
[5]Mean value for the period 1961-98 estimated by map comparison
[6]Calculated for the measured periods 1989-93 and 1996-2002

Table 1-1
Review of the results from mass balance measurements performed in Norway in 2003. The glaciers in southern Norway are listed from west to east. Each glacier is reported in the number system of World Glacier Monitoring Service (WGMS). All ID's begin with N4A000, so only the last five characters are shown here.

Figure 1-2 gives a graphical presentation of the mass balance results in southern Norway for 2003. The west-east gradient is evident for both winter and summer balances.

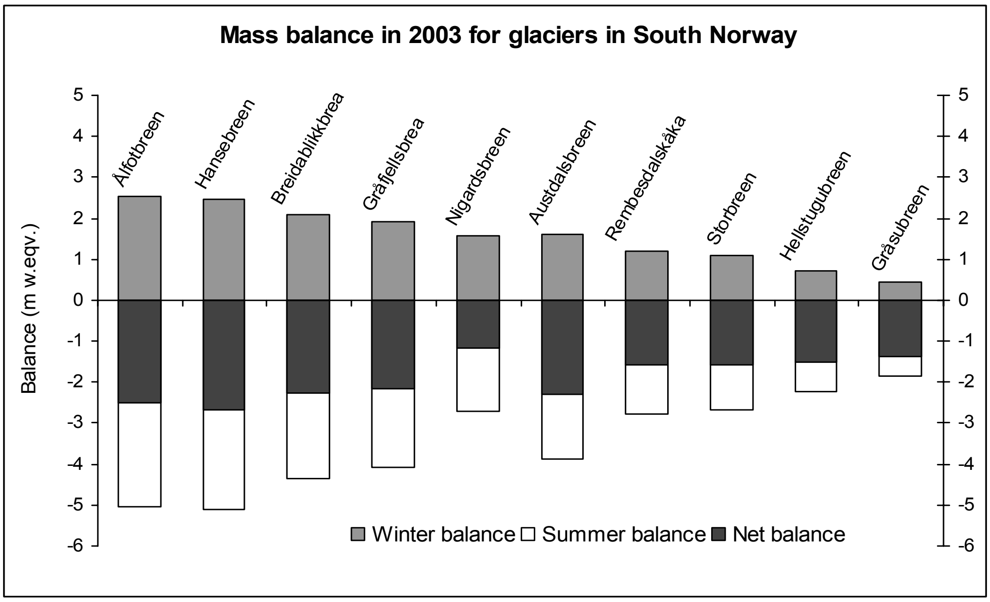


Figure 1-2
Mass balance 2003 in southern Norway. The glaciers are listed from west to east.

The cumulative net balance for some of the glaciers in southern Norway during the period 1963-2003 is shown in Figure 1-3. The maritime glaciers – Ålfotbreen, Nigardsbreen and Rembesdalskåka had a marked increase in volume during the period 1989-95. The surplus was mainly a result of several winters with heavy snowfall. However, over the last three years (2001-03) the net balance has become negative for these three glaciers. This volume decrease is due to a combination of winter seasons with little snow and warm summers. The continental glaciers in Jotunheimen – Storbreen and Gråsubreen show a distinct decrease in net balance over the whole period.

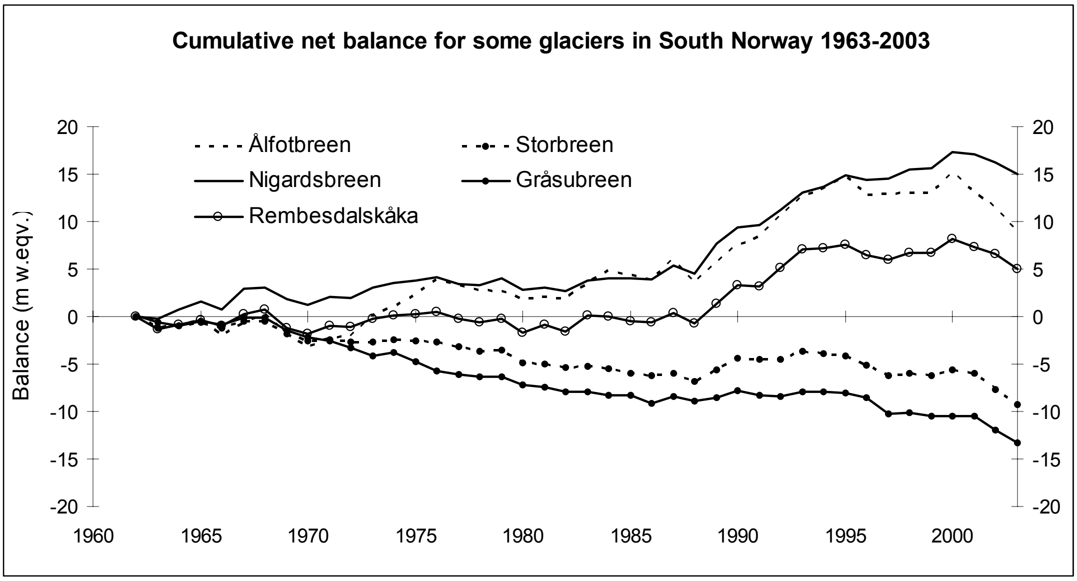


Figure 1-3
Cumulative net balance for Ålfotbreen, Nigardsbreen, Rembesdalskåka, Storbreen and Gråsubreen during the period 1963-2003.

1.2 Other investigations

Front position measurements were performed at 25 glaciers in Norway in 2003. Some of these have measurements going back to approximately 1900. The front position changes are described in a separate chapter (chap. 14).

Volume calculation of ice masses based on map comparison is performed for Ålfotbreen (chap. 2).

Glacier velocity has been studied at Austdalsbreen since 1987 (chap. 5).

Meteorological observations have been performed at Storbreen (chap. 7) and Engabreen (chap. 10).

Svartisen Subglacial Laboratory was initiated in 1992 and has since been used by researchers from several different countries (Jackson 2000). An overview of activities in the laboratory is given in chapter 10.

Due to avalanche risk Baklibreen is the subject of a monitoring program which continued in 2003 (chap. 14).

Based on regression analyses the net balances for 2003 are modelled for Tunsbergdalsbreen (chap. 4) and Svartisheibreen (chap. 10).

2. Ålfotbreen (Bjarne Kjøllmoen)

Ålfotbreen ice cap (61°45’N, 5°40’E) is 17 km^2, and is both the westernmost and the most maritime glacier in Norway. Mass balance studies have been carried out on two adjacent north-facing outlet glaciers - Ålfotbreen (4.5 km^2) and Hansebreen (3.1 km^2). The westernmost of these two has been the subject of mass balance investigations since 1963, and has always been reported as Ålfotbreen. On Hansebreen the investigations started in 1986. None of the outlet glaciers from the icecap are given names on the official maps. To distinguish the two different glaciers the last one has been given the name Hansebreen. Ålfotbreen, including its component parts and surroundings, is shown in Figure 2-1.

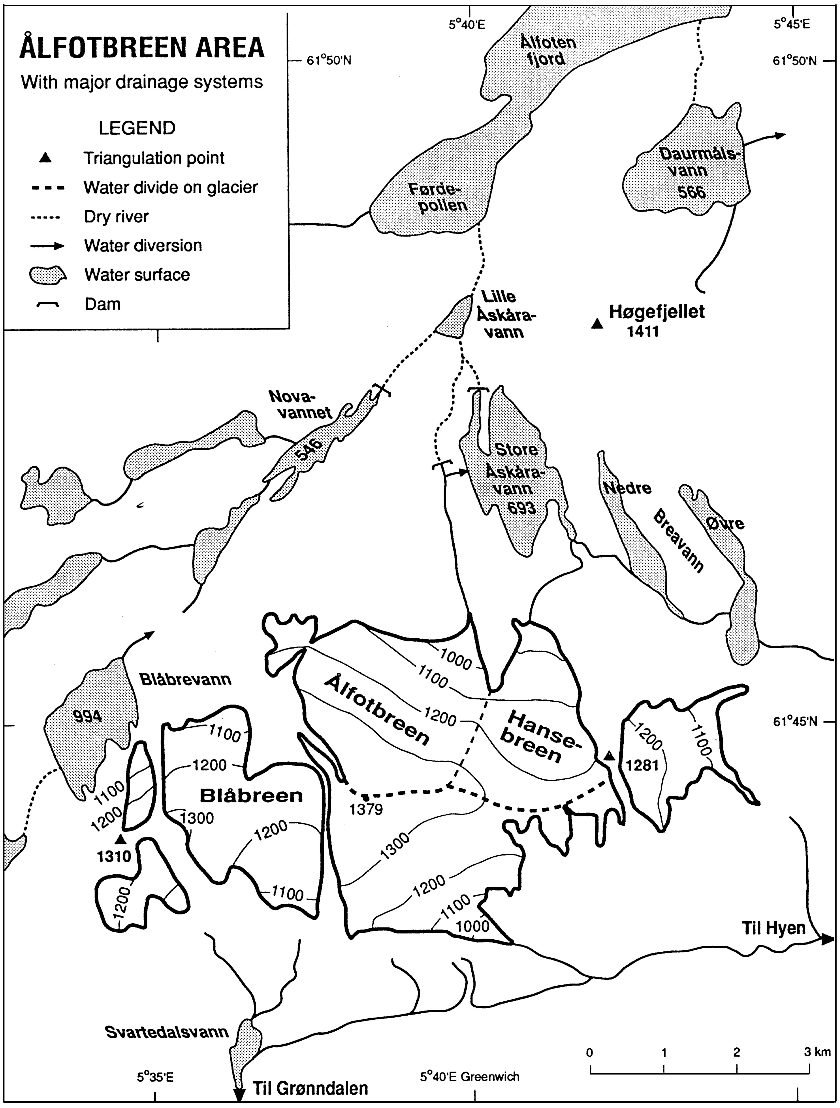


Figure 2-1
Ålfotbreen ice cap and surrounding area, showing the two north-facing glaciers Ålfotbreen and Hansebreen at which mass balance studies are performed.

2.1 Mass balance 2003

Fieldwork

Snow accumulation measurements were performed from 23rd to 25th of April. The calculation of winter balance at Ålfotbreen and Hansebreen is based on (Fig. 2-2):

- Uninterrupted measurements at tower T49 (1380 m a.s.l.), and measurements of one stake replacement and an older stake that appeared during the melt season at position 28 (1240 m a.s.l.) on Ålfotbreen. Uninterrupted measurements of stakes in positions 50 (1025 m a.s.l.) and 60 (1070 m a.s.l.), and measurements of stake replacements and older stakes in positions 80 (1125 m a.s.l.), 85 (1195 m a.s.l.) and 90 (1305 m a.s.l.) on Hansebreen.
- 129 snow depth soundings along a total of about 13 km of profiles on Ålfotbreen, and 77 snow depth soundings along about 9 km of profiles on Hansebreen. The snow depth varied between 4.5 and 5.5 m on both glaciers. The summer surface (SS) could easily be identified over the entire glacier.
- Snow density was measured down to the SS (3.9 m) at stake position 37.

The location of stakes, tower, density pit and sounding profiles are shown in Figure 2-2.

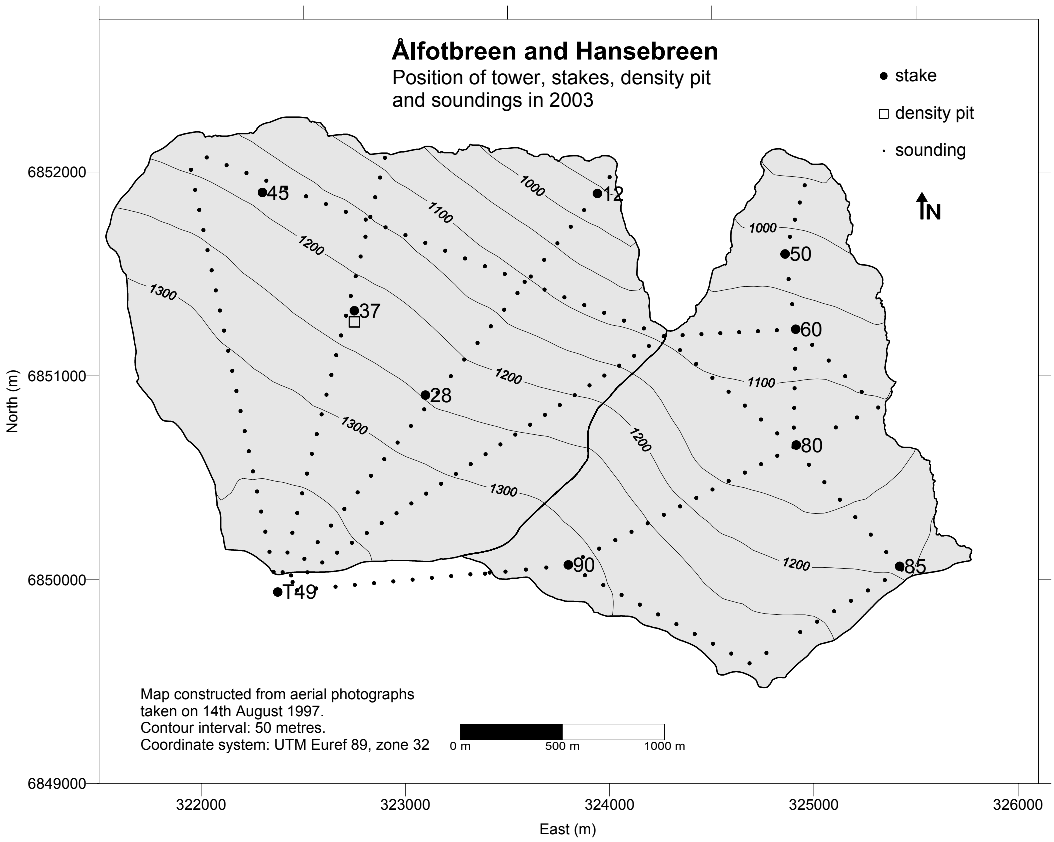


Figure 2-2
Location of stakes, soundings and density pit at Ålfotbreen and Hansebreen in 2003.

Ablation was measured on 20th October. The net balance was directly measured on stakes in five different positions on both glaciers. There was no snow remaining on the glacier from the winter season 2001/2002. At the time of the ablation measurements between 0.5 and 1 m of fresh snow had fallen. Hence it was impossible to determine the boundary between old firn and ice. At the summit of Ålfotbreen there had been net melting of 2.8 m firn since autumn 2002.

Results

The calculations are based on a glacier map from 1997.

Winter balance

The calculation of winter balance is based on point measurements of snow depth (stakes, tower and probings) and on measurement of snow density in one location. There was no melting after the final measurements in October 2002.

A density profile was modelled from the snow density measured at 1225 m a.s.l. The mean snow density of 3.9 m snow was 0.484 g/cm^3. The density model was assumed to be representative for both Ålfotbreen and Hansebreen, and all snow depths were converted to water equivalents using this model.

The calculation of winter balance was performed by plotting the point measurements (water equivalents) in a diagram. A curve was drawn based on a visual evaluation (Fig. 2-4), and a mean value for each 50 m height interval was estimated (Tab. 2-1).

Winter balance at Ålfotbreen in 2003 was 2.5 ±0.2 m w.eqv., corresponding to a volume of 11 ±1 mill. m^3 of water. The result is 67 % of the mean winter balance for 1963-2002, and 62 % of the mean for 1986-2002 (same period as Hansebreen).

The winter balance at Hansebreen was 2.4 ±0,2 m w.eqv., corresponding to a volume of 7 ±1 mill. m^3 of water. The result is 70 % of the mean value for the period of investigation.

The winter balance was also calculated using a gridding method based on the aerial distribution of the snow depth measurements (Fig. 2-3). Water equivalents for each cell in a 100 x 100 m grid were calculated and summarised. Using this method, which is a control of the traditional method, gave 2.5 m w.eqv. for both Ålfotbreen and Hansebreen.

Summer balance

The density of melted firn was estimated at between 0.70 and 0.85 g/cm^3, while the density of melted ice was estimated as 0.90 g/cm^3.

The summer balance at Ålfotbreen was measured and calculated directly at five stakes. The summer balance increased from −4.8 m w.eqv. at 1380 m elevation to −6.8 m at 965 m elevation. Based on estimated density and stake measurements the summer balance for Ålfotbreen was calculated as -5.0 ±0.3 m w.eqv., corresponding to -23 ±1 mill. m^3 of water. The result is 146 % of the mean value for 1963-2002, and 138 % of the mean value for 1986-2002. Since 1963 there are only two years (1988 and 2002) with a higher summer balance at Ålfotbreen.

The summer balance for Hansebreen was measured and calculated at five stakes and increased from −4.3 m w.eqv. at 1305 m elevation to −5.8 m at 1025 m elevation. Based on the five stakes and the estimated density the summer balance was calculated as −5.1 ±0.3 m w.eqv. or −16 ±1 mill. m^3 of water. The result is 136 % of the mean value. As with Ålfotbreen, a higher summer balance was measured only in 1988 and 2002.

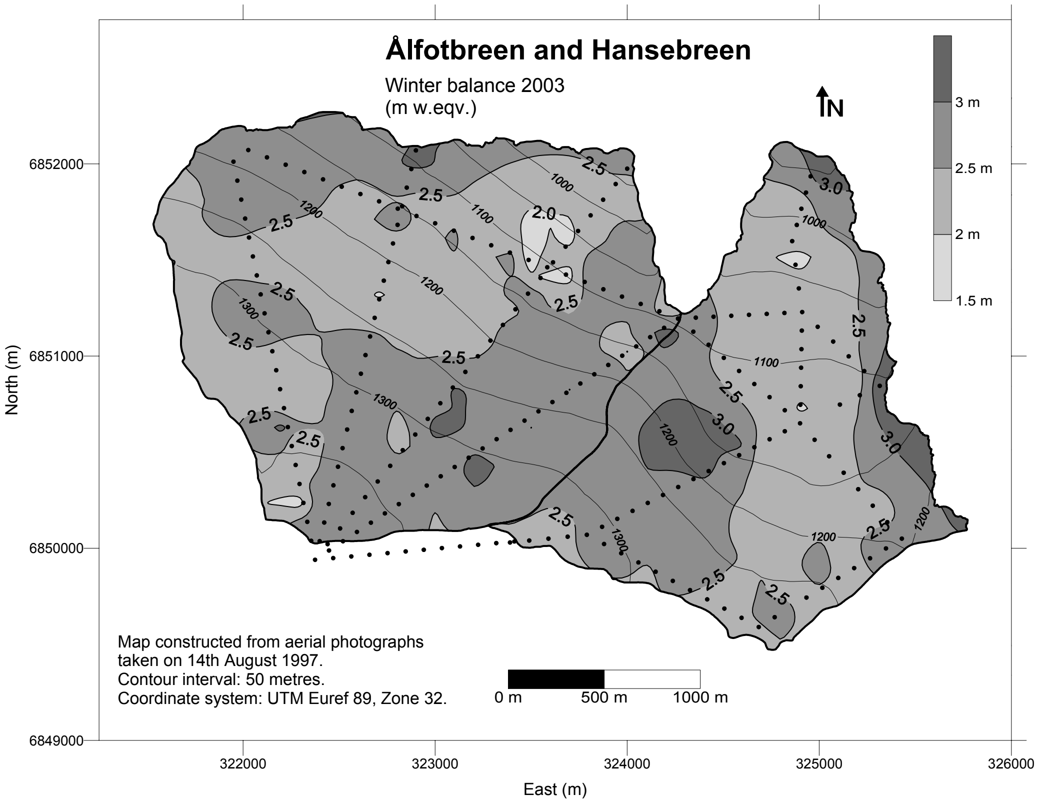


Figure 2-3
Winter balance at Ålfotbreen and Hansebreen in 2003 interpolated from 206 snow depth measurings (•).

Net balance

The net balance at Ålfotbreen for 2003 was calculated as −2.5 ±0.4 m w.eqv., or a volume loss of 11 ±2 mill. m^3 of water. The result is equal to the previous highest deficit recorded, in 1988. The mean net balance between 1963 and 2002 is +0.29 m w.eqv., and +0.42 m during 1986-2002 (comparable to Hansebreen).

The net balance at Hansebreen was calculated as −2.7 ±0.4 m w.eqv., or a deficit of 8 ±1 mill. m^3 of water. The result is equal to the highest deficit recorded in 1988 and 2001. The mean value for the period 1986-2002 is −0.26 m w.eqv.

As in 2001 and 2002 there was net ablation over the entire glacier surface. This means that the equilibrium line altitude lies *above* the highest summit (Fig. 2-4) on both glaciers. Consequently, the AAR is 0 %.

The mass balance results are shown in Table 2-1. The corresponding curves for specific and volume balance are shown in Figure 2-4. The historical mass balance results are presented in Figure 2-5.

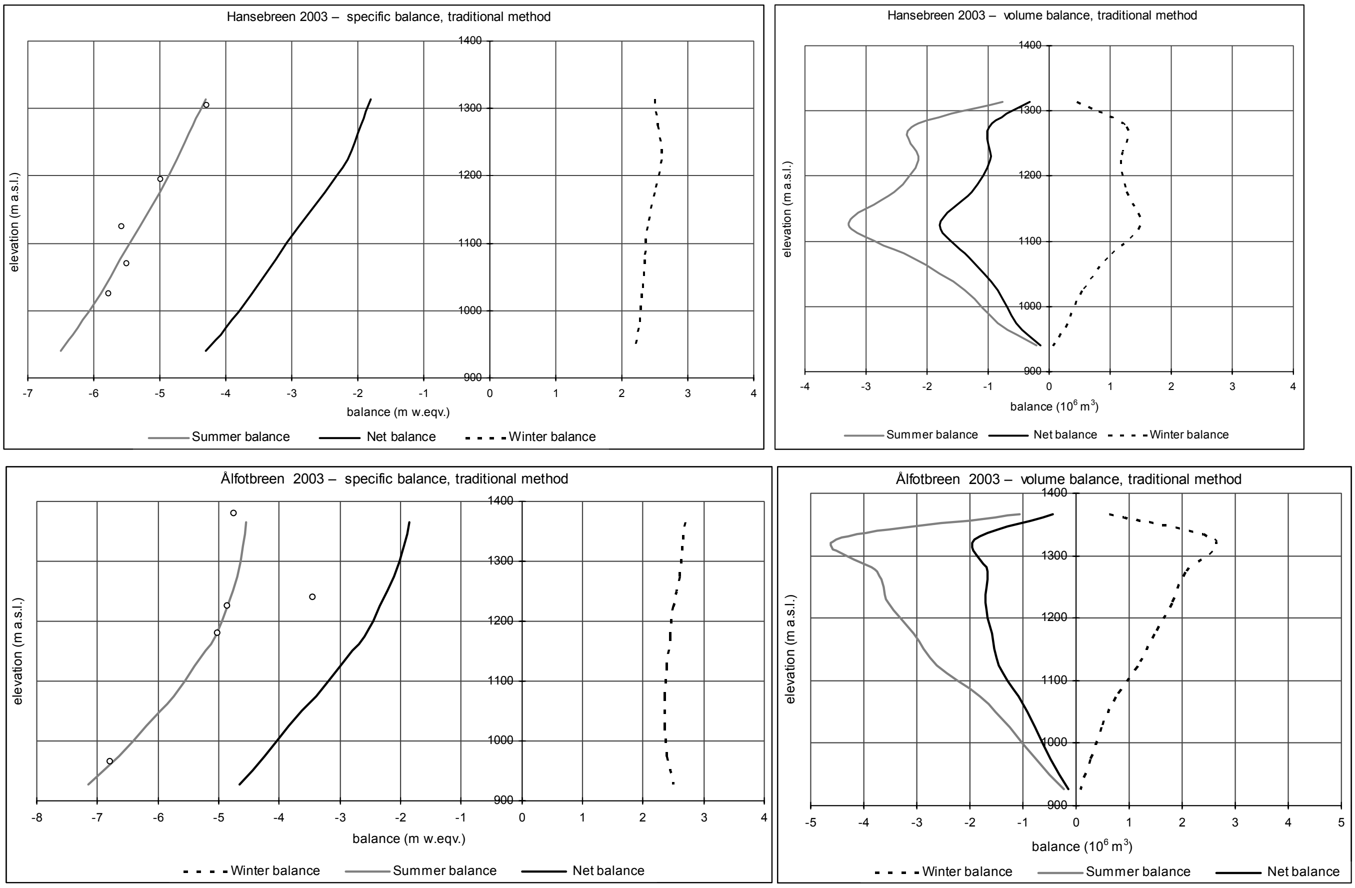


Figure 2-4
Mass balance diagram for Ålfotbreen (upper) and Hansebreen (lower) in 2003 showing altitudinal distribution of specific (left) and volumetric (right) winter, summer and net balance. Specific summer balance at each stake is shown (○).

The balance year 2002/2003 is the third successive year with negative net balance at both Ålfotbreen and Hansebreen. Since 1996 the cumulative net balance is −5.8 m w.eqv. at Ålfotbreen and −8.8 m w.eqv. at Hansebreen. During the period 1996-2003 only one year (2000) shows a significant positive net balance. Consequently, the last eight years are different compared with the period 1989-95 as the cumulative net balance then was +11.2 m w.eqv. at Ålfotbreen and +4.0 m eqv. at Hansebreen.

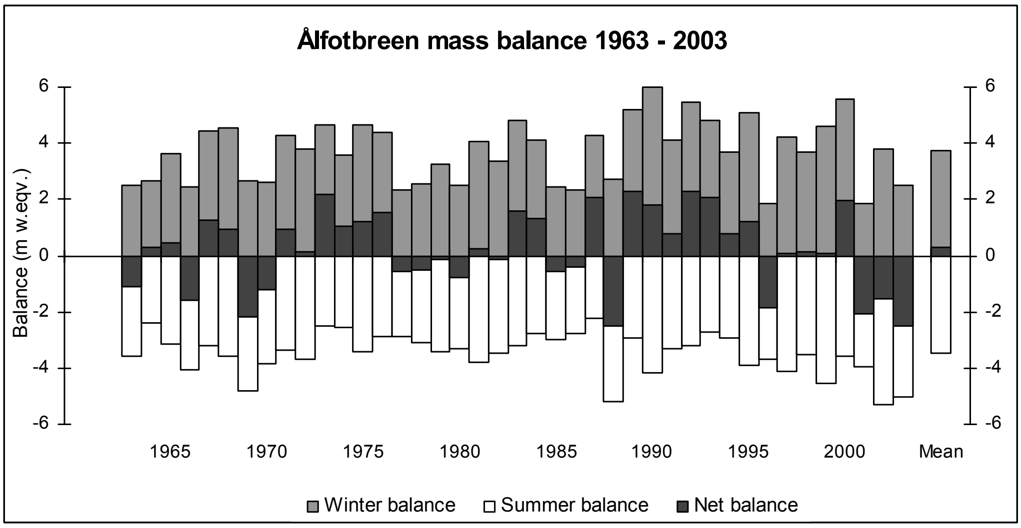
Mass balance Ålfotbreen 2002/03 – traditional method

Altitude (m a.s.l.)	Area (km^2)	Winter balance Measured 24th April 2003		Summer balance Measured 20th Oct 2003		Net balance Summer surfaces 2002 - 2003	
		Specific (m w.eq.)	Volume (10^6 m^3)	Specific (m w.eq.)	Volume (10^6 m^3)	Specific (m w.eq.)	Volume (10^6 m^3)
1350 - 1382	0.23	2.70	0.6	-4.55	-1.1	-1.85	-0.4
1300 - 1350	0.98	2.65	2.6	-4.60	-4.5	-1.95	-1.9
1250 - 1300	0.80	2.60	2.1	-4.70	-3.7	-2.10	-1.7
1200 - 1250	0.73	2.50	1.8	-4.85	-3.5	-2.35	-1.7
1150 - 1200	0.61	2.45	1.5	-5.05	-3.1	-2.60	-1.6
1100 - 1150	0.49	2.40	1.2	-5.40	-2.6	-3.00	-1.5
1050 - 1100	0.32	2.35	0.7	-5.75	-1.8	-3.40	-1.1
1000 - 1050	0.20	2.35	0.5	-6.20	-1.3	-3.85	-0.8
950 - 1000	0.11	2.40	0.3	-6.65	-0.8	-4.25	-0.5
903 - 950	0.03	2.50	0.1	-7.15	-0.2	-4.65	-0.1
903 - 1382	**4.50**	**2.52**	**11.3**	**-5.03**	**-22.6**	**-2.50**	**-11.2**

Mass balance Hansebreen2002/03 – traditional method

Altitude (m a.s.l.)	Area (km^2)	Winter balance Measured 23rd April 2003		Summer balance Measured 20th Oct 2003		Net balance Summer surface 2002 - 2003	
		Specific (m w.eq.)	Volume (10^6 m^3)	Specific (m w.eq.)	Volume (10^6 m^3)	Specific (m w.eq.)	Volume (10^6 m^3)
1300 - 1327	0.18	2.50	0.44	-4.30	-0.76	-1.80	-0.32
1250 - 1300	0.50	2.55	1.28	-4.50	-2.25	-1.95	-0.98
1200 - 1250	0.45	2.60	1.18	-4.75	-2.15	-2.15	-0.97
1150 - 1200	0.51	2.50	1.27	-5.00	-2.53	-2.50	-1.27
1100 - 1150	0.62	2.40	1.49	-5.30	-3.29	-2.90	-1.80
1050 - 1100	0.40	2.35	0.95	-5.60	-2.26	-3.25	-1.31
1000 - 1050	0.23	2.30	0.54	-5.90	-1.38	-3.60	-0.84
950 - 1000	0.13	2.25	0.30	-6.25	-0.83	-4.00	-0.53
930 - 950	0.03	2.20	0.07	-6.50	-0.21	-4.30	-0.14
930 - 1327	**3.06**	**2.45**	**7.5**	**-5.12**	**-15.7**	**-2.67**	**-8.2**

Table 2-1
Winter, summer and net balances for Ålfotbreen (upper) and Hansebreen (lower) in 2003. The mean values for Ålfotbreen during the period 1963-2002 are 3.74 m (bw), −3.45 m (bs) and +0.29 m w.eqv. (bn). The corresponding values for Hansebreen during the period 1986-2002 are 3.52 m, −3.78 m and −0.26 m w.eqv.



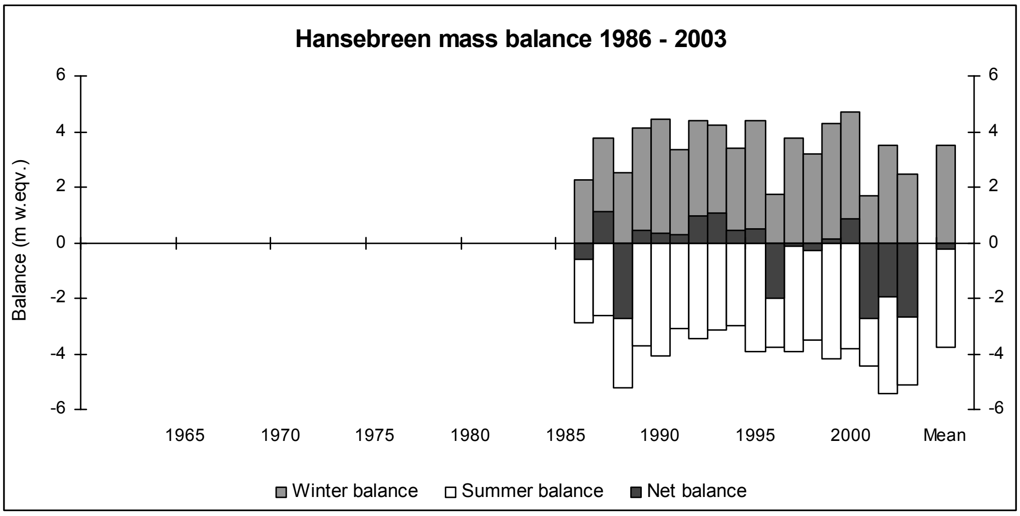


Figure 2-5
Mass balance at Ålfotbreen (upper) during the period 1963-2003 and Hansebreen (lower) during the period 1986-2003.

2.2 Volume change 1988-1997

Methods

Calculating the volume change of ice masses over a period of time is possible using various methods. The volume change for Ålfotbreen over the period 1988-1997 is calculated using the photogrammetric (also called cartographic) method. This method includes air photography, scanning of air photos, adjustment of stereo models, creation of X, Y and Z data, and generating Digital Elevation Models (DEMs). The total volume change can be calculated by comparison of the DEMs from 1988 and 1997, respectively.

The data processing involves generation of DEMs from the X, Y and Z data sets using a grid-based graphics program. The surface elevation changes are calculated by subtracting the DEMs on a cell-by-cell basis. The result is a regular grid with elevation differences. For comparison with volume change calculations derived from other methods, the elevation difference are converted to the difference in water equivalents by multiplying the grid with the density of ice, usually 900 kg/m^3. The volume change values are also modified for the additional melting that occurred between the date of photography and the end of the melting season. The melting is calculated using a model based on daily input data of precipitation and air temperature.

Data material

Aerial photographs

Vertical aerial photographs of Ålfotbreen were taken on 7th September 1988 and 14th August 1997 (Tab. 2-2). Both photo sets were taken by the Norwegian mapping company Fjellanger Widerøe AS (FW) and the scale was 1:30 000.

	Vertical air photograph			Derived data set		
Year	Contract No.	Date	Scale	XYZ Data type	Contour interval	Grid Size
1988	FW 9678	7th Sept. 1988	1:30 000	Contour lines	10 m	
1997	FW 12177	14th Aug. 1997	1:30 000	Regular grid		10 m

Table 2-2
Vertical air photographs and derived data sets from Ålfotbreen 1988 and 1997.

Winter 1988 was fairly dry and the summer was unusually warm in southern Norway. Little snow and much ablation resulted in a considerable negative net balance on several glaciers. At Ålfotbreen there was no snow remaining on the glacier surface and no fresh snow had fallen at the time of photography. Thus, the 1988 photographs are of excellent quality and are well-suited for this purpose.

The second half of winter 1997 was snow-rich and snowfalls probably occurred in both May and June. The summer season (May-September) 1997 was the warmest in 50 years in southern Norway. Due to the additional snow accumulation in May and June the measured summer *balance* was less than the real summer *ablation*. Ålfotbreen was approximately in balance that year, and most of the glacier surface was covered by snow from the previous winter. Hence the 1997 photographs are not of such good quality as the 1988 photos.

Co-ordinate system and Ground Control Points

The co-ordinate system applied for construction of the 1988 data set was the Norwegian national system NGO 1948, Axis 1. The 1997 data set was created in the global system UTM, Zone 32 in the EUREF 89 geodetic datum. To ensure comparable data sets the 1988 data was transformed into the UTM system.

Adjustment of the stereo models requires reliable Ground Control Points (GCP) in the surrounding area. A proper GCP has to be visible and distinct in the air photographs, and the X, Y and Z co-ordinates have to be well-qualified. The 1988 stereo model was established using GCPs, whilst the 1997 model was adjusted using six GCPs. Three of the GCPs were used for both models. The GCPs are shown in Figure 2-6.

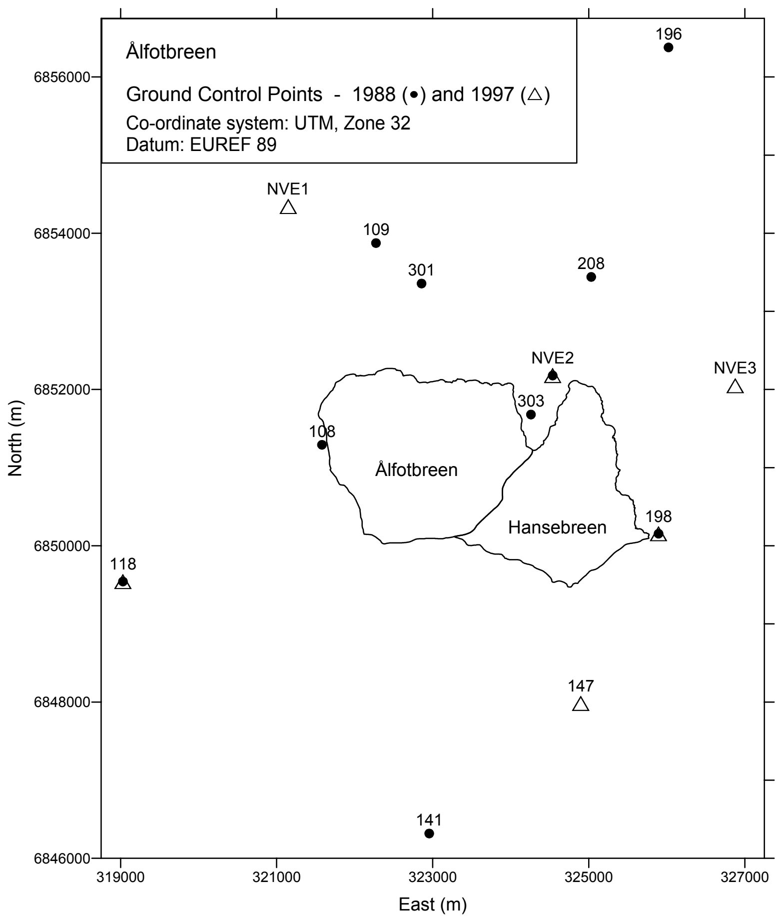


Figure 2-6
Ground control points (GCP) used for establishing the stereo models 1988 and 1997.

X, Y and Z data set

X, Y and Z data from 1988 were reconstructed from analogue air photographs (diapositives) using an analytical stereo plotter. The data set was created as points on contour lines with 10 m equidistance.

Data from 1997 were derived from digitised air photos using a digital photogrammetric workstation. The data set was generated as a regular grid with cell size 10 m.

Data processing

Generation of a Digital Elevation Model requires regularly gridded points. The 1988 and 1997 data sets were converted to grid files using the grid-based graphic program Surfer (Golden Software, Inc., 1999). The choice of grid method and grid size are both dependent on the input data characteristics and will influence the interpolation procedures. The selected gridding methods used were *Kriging* and *Inverse Distance to a Power*. Both gridding methods were tested using four different grid sizes – 10, 25, 50 and 100 metres.

Grid files were created separately for Ålfotbreen and Hansebreen. The ice margin in the outer edges and the drainage divide between Ålfotbreen and Hansebreen were somewhat different for 1988 and 1997. The 1997 ice margin was generally outside the 1988 margin. Thus, the calculated glacier area was delimited by the 1997 boundary line.

The volume change was calculated by extracting the 1988 and 1997 grids, converting to water equivalent by multiplying by 0.9 and modified for additional melting. The end of melting season was determined as 10th October for both years.

Results

The additional melting for Ålfotbreen was calculated as 0.8 m w.eqv. over the period 8th September to 10th October 1988, and 2.1 m w.eqv. between 15th August and 10th October 1997. The corresponding values for Hansebreen are 0.8 m w.eqv. and 2.2 m w.eqv.

The volume calculation shows that between 7th September 1988 and 14th October 1997 Ålfotbreen had a specific net surplus of 5.8 m w.eqv. Adjusting for the additional melting, the result is +4.5 m w.eqv., or a volume increase of 20×10^6 m^3 (Fig. 2-7).

The calculation for Hansebreen shows a surplus of 3.2 m w.eqv. Adjusted for additional melting the surplus was 1.9 m w.eqv., or a volume increase of 6 x 10^6 m^3 water.

More than 90 % of the glacier area increased in volume, while the remainder lost volume. The largest mass increase was at the lower part of Ålfotbreen with more than 10 m thickening. The lower part of Hansebreen was the only area where a surface sinking (0-5 m) had occurred. However, some small isolated patches around the ice margin can also indicate ice thinning.

The cumulative net balance over the same period measured by the conventional method is +9.4 m w.eqv. for Ålfotbreen and +1.8 m w.eqv. Hence, the volumetric calculation for

Hansebreen shows good accordance to the measured value, while the result for Ålfotbreen is rather different from the measured value. There is no obvious explanation of the divergent results for Ålfotbreen. The years 1989, 1990, 1992, 1993 and 1995 were all snow-rich. The snow estimation was complicated for these years and may have resulted in an overestimation of the winter balance.

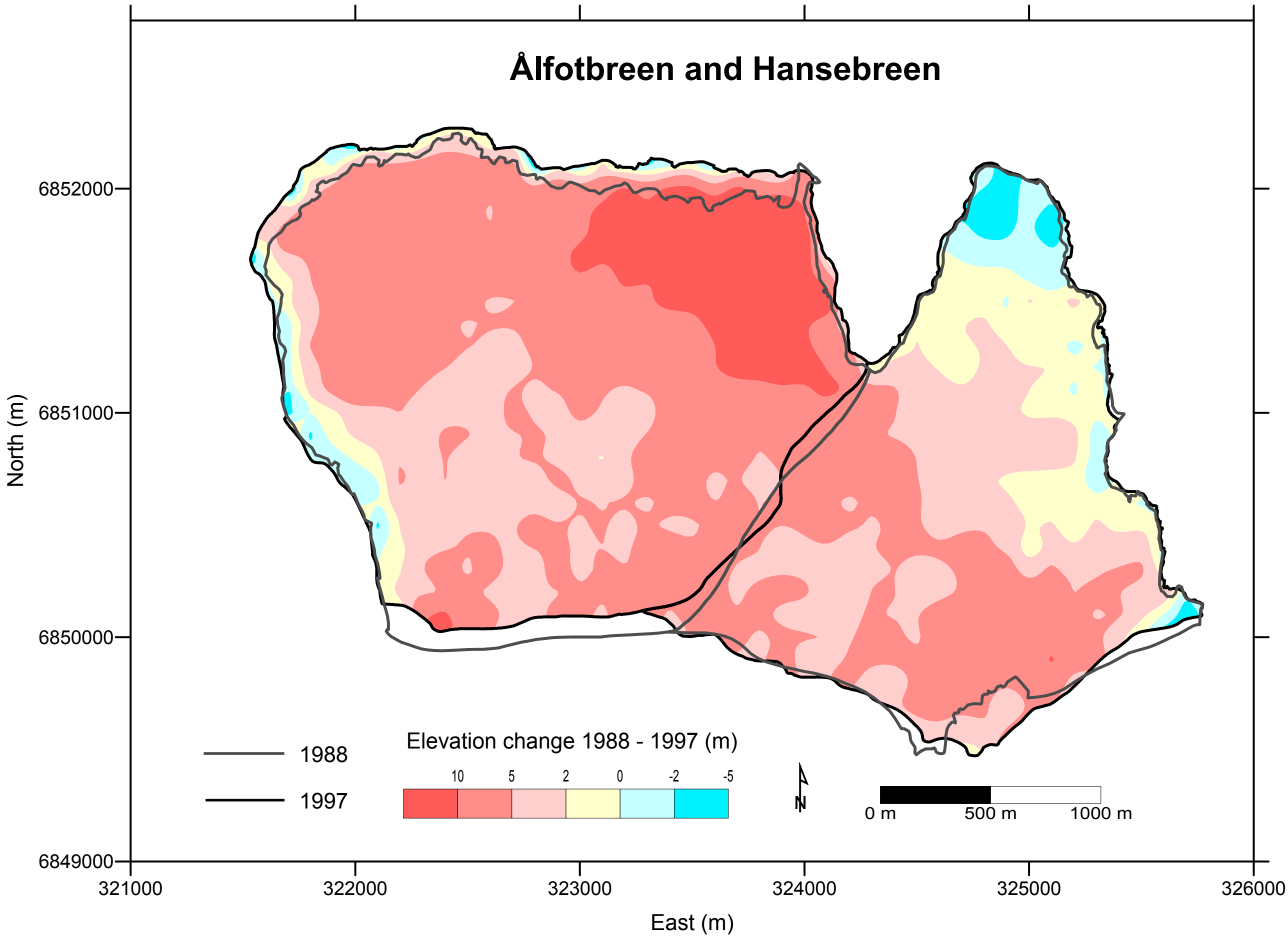


Figure 2-7
Elevation change of Ålfotbreen and Hansebreen between 7th September 1988 and 14th August 1997.

Accuracy

The accuracy of the final result is affected by several factors. The quality of the Ground Control Points will influence the XYZ data processing, and it is important to ensure some common GCPs for the two DEMs. Generating XYZ data over snow-covered areas based on air photographs is difficult due to the poor contrast, and the accuracy will be lower in those areas. Data transformations and interpolation routines providing regular grid models will impair the accuracy. The overlay operation and volume calculation will also introduce errors. Also, the estimation of ablation between time of photography and, the end of melting is an uncertain factor.

Based on these sources of errors the uncertainty of the result is estimated to be ±2.0 m w.eqv.

3. Folgefonna (Bjarne Kjøllmoen)

Folgefonna is situated in the south-western part of Norway between Hardangerfjorden to the west and the mountain plateau Hardangervidda to the east. It is divided into three separate ice caps - Northern, Middle and Southern Folgefonna. In 2003 mass balance measurements began on two adjacent westward-facing outlet glaciers of Southern Folgefonna (60°4'N, 6°24'E) – Breidablikkbrea (3.6 km^2) and Gråfjellsbrea (8.9 km^2). Southern Folgefonna is the third largest (168 km^2 in 1981) ice cap in Norway.

Mass balance measurements have been carried out at Breidablikkbrea during 1963-68 and at Gråfjellsbrea over the periods 1964-68 and 1974-75. The historical results are presented in Figure 3-5.

Parts of Folgefonna including Breidablikkbrea and Gråfjellsbrea are shown in Figure 3-1.

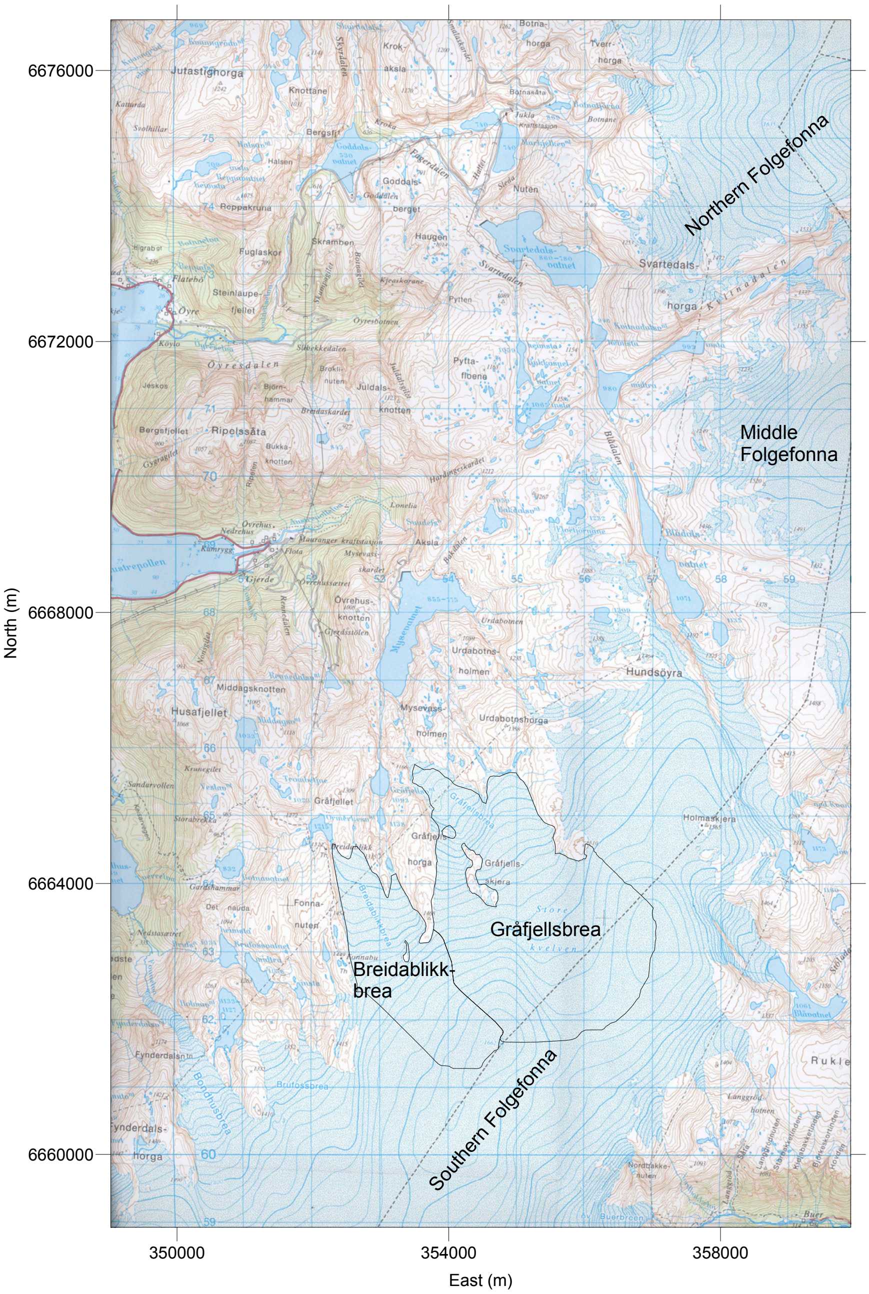


Figure 3-1
Parts of the Northern, Middle and Southern Folgefonna ice caps showing the two westward-facing glaciers Breidablikk-brea and Gråfjells-brea at which mass balance studies began in 2003.

3.1 Mass balance 2003

Fieldwork

Snow accumulation measurements were performed on 30th and 31st of May. The calculation of winter balance (Fig. 3-2) at Breidablikkbrea and Gråfjellsbrea is based on:

- Uninterrupted measurements of stakes in all five positions at each glacier. Stake position 60 is located on the border between Breidablikkbrea and Gråfjellsbrea and is included in the calculations for both glaciers.
- 56 snow depth soundings along a total of about 9 km of profiles at Breidablikkbrea, and 104 snow depth soundings along about 16 km of profiles at Gråfjellsbrea. The summer surface (SS) could easily be identified over the entire glacier. Above 1500 m altitude the snow depth varied between 3 and 4 m on both glaciers. However, some soundings in the uppermost areas showed snow depths of more than 4 m. Below 1500 m altitude the snow depth was more variable – from less than 1 m to more than 4 m.
- Snow density was measured down to the SS (3.1 m) at stake position 25 (1485 m a.s.l.) at Gråfjellsbrea.

The location of stakes, density pit and sounding profiles are shown in Figure 3-2.

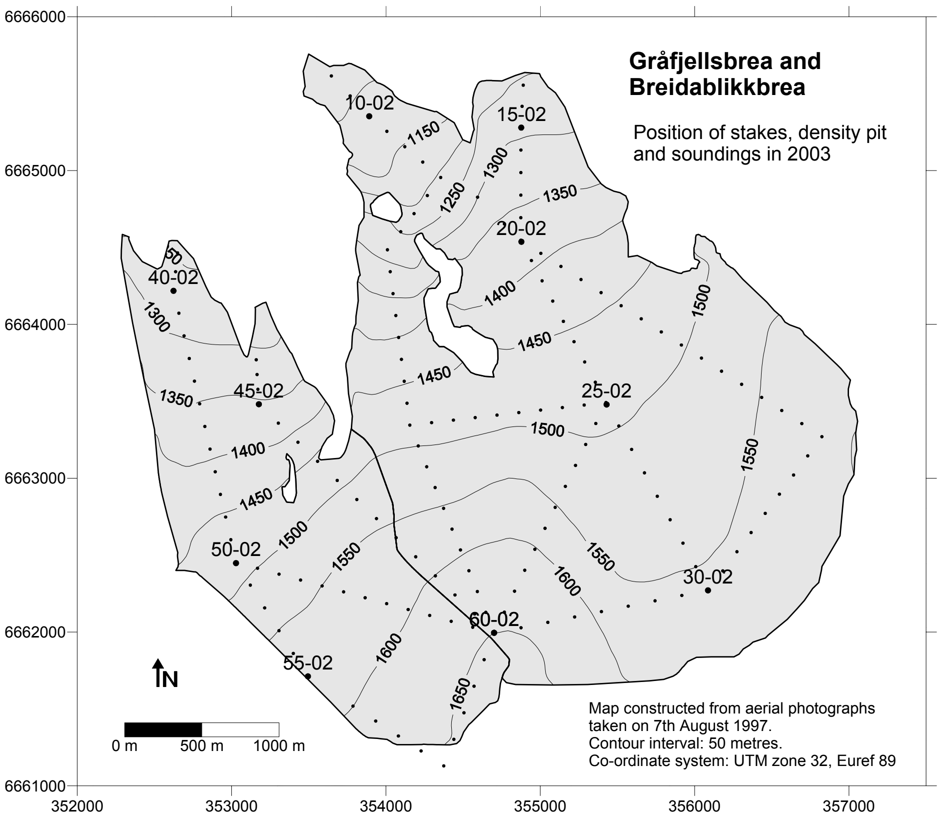


Figure 3-2
Location of stakes, soundings and density pit at Breidablikkbrea and Gråfjellsbrea in 2003.

Ablation was measured on 20th September. The net balance was measured at stakes in five different positions on each glacier. There was no snow remaining on the glacier surface from the winter season 2001/2002. At the time of the ablation measurements no fresh snow had fallen. At the summit of the glacier, in position 60 (1645 m a.s.l.), the measurements showed net melting of 2.2 m firn since autumn 2002.

Results

The calculations are based on a glacier map from 1997. The area distribution may be changed for each glacier after drainage boundaries have been re-surveyed.

Winter balance

The calculation of winter balance is based on point measurements of snow depth (stakes and probings) and on measurement of snow density in one representative location. There was no melting after the final measurements in October 2002.

A density profile was modelled from the snow density measured at 1485 m a.s.l. The mean snow density of 3.1 m snow was 0.558 g/cm^3. The density model was assumed to be representative for both Breidablikkbrea and Gråfjellsbrea, and all snow depths were converted to water equivalents using this model.

The calculation of winter balance was performed by plotting the point measurements (water equivalents) in a diagram. A curve was drawn based on visual evaluation (Fig. 3-4) and a mean value for each 50 m height interval was estimated (Tab. 3-1).

Winter balance at Breidablikkbrea in 2003 was 2.1 ±0.2 m w.eqv., corresponding to a volume of 8 ±1 mill. m^3 of water. The result is 94 % of the average for the study period 1963-68.

The winter balance at Gråfjellsbrea was 1.9 ±0.2 m w.eqv., corresponding to a volume of 17 ±1 mill. m^3 of water. The result is 77 % of the average for 1964-68.

As verification, the winter balance was also calculated using a gridding method based on the aerial distribution of the snow depth measurements (Fig. 3-3). Water equivalents for each cell in a 100 x 100 m grid were calculated and summarised. Using this method gave 1.9 m w.eqv. for Breidablikkbrea and 1.8 m w.eqv. for Gråfjellsbrea.

Summer balance

The density of melted firn was estimated at between 0.70 and 0.75 g/cm^3, while the density of melted ice was estimated as 0.90 g/cm^3.

The summer balance at Breidablikkbrea was measured and calculated at five stakes, and increased from −3.7 m w.eqv. at 1645 m altitude to −5.1 m at 1345 m altitude. Based on estimated density and stake measurements the summer balance was calculated as −4.3 ±0.3 m w.eqv., corresponding to −16 ±1 mill. m^3 of water. The result is 182 % of the mean value for 1963-68.

The summer balance for Gråfjellsbrea was measured and calculated at five stakes and increased from −3.7 m w.eqv. at 1645 m altitude to −5.1 m at 1100 m altitude. Based on the five stakes and the estimated density the summer balance was calculated as −4.1 ±0.3 m w.eqv. or −36 ±1 mill. m^3 of water. The result is 172 % of the mean value for 1964-68.

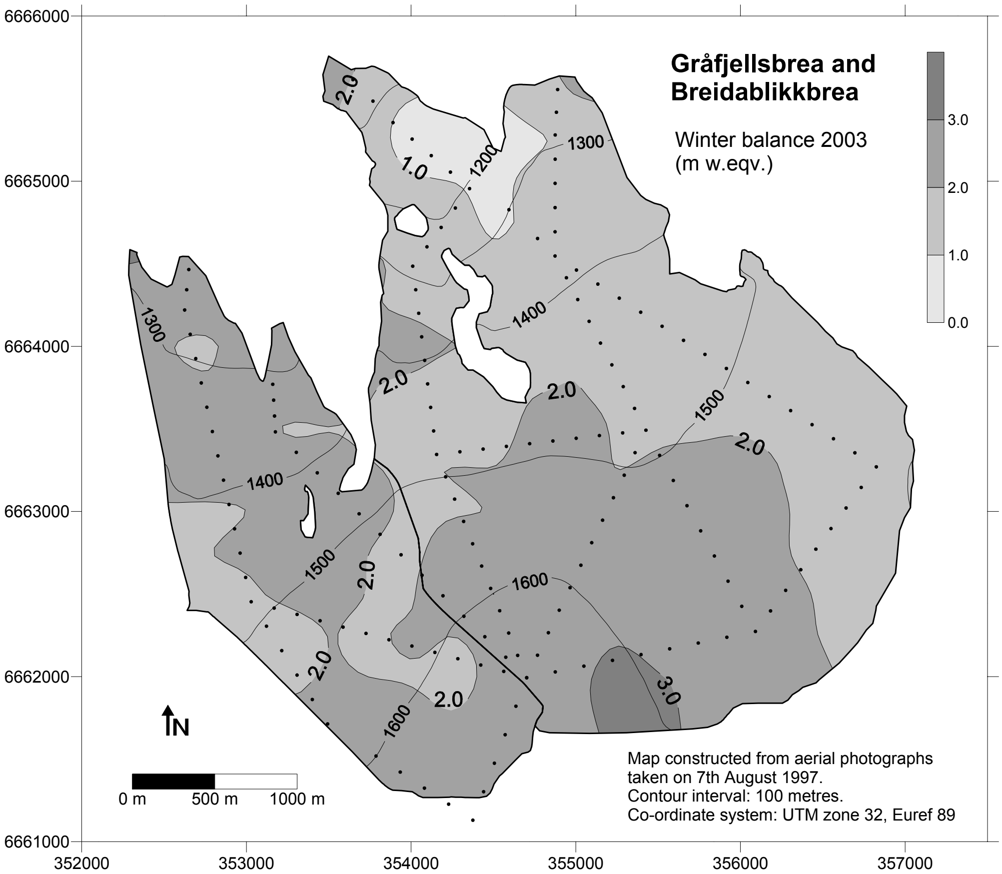


Figure 3-3
Winter balance at Breidablikkbrea and Gråfjellsbrea in 2003 interpolated from 160 snow depth measurements (•).

Net balance

The net balance at Breidablikkbrea for 2003 was calculated as −2.3 ±0.4 m w.eqv., or a volume loss of 8 ±1 mill. m^3 of water. The mean net balance for 1963-68 was −0.19 m w.eqv.

The net balance at Gråfjellsbrea was calculated as −2.2 ±0.4 m w.eqv., or a deficit of 19 ±4 mill. m^3 of water. The mean value for the period 1964-68 was +0.12 m w.eqv.

As shown in Figure 3-4, the equilibrium line altitude lies *above* the highest summit (1659 m a.s.l.) on both glaciers. Consequently, the AAR is 0 %.

The mass balance results are shown in Table 3-1. The corresponding curves for specific and volume balance are shown in Figure 3-4. The historical mass balance results are presented in Figure 3-5.

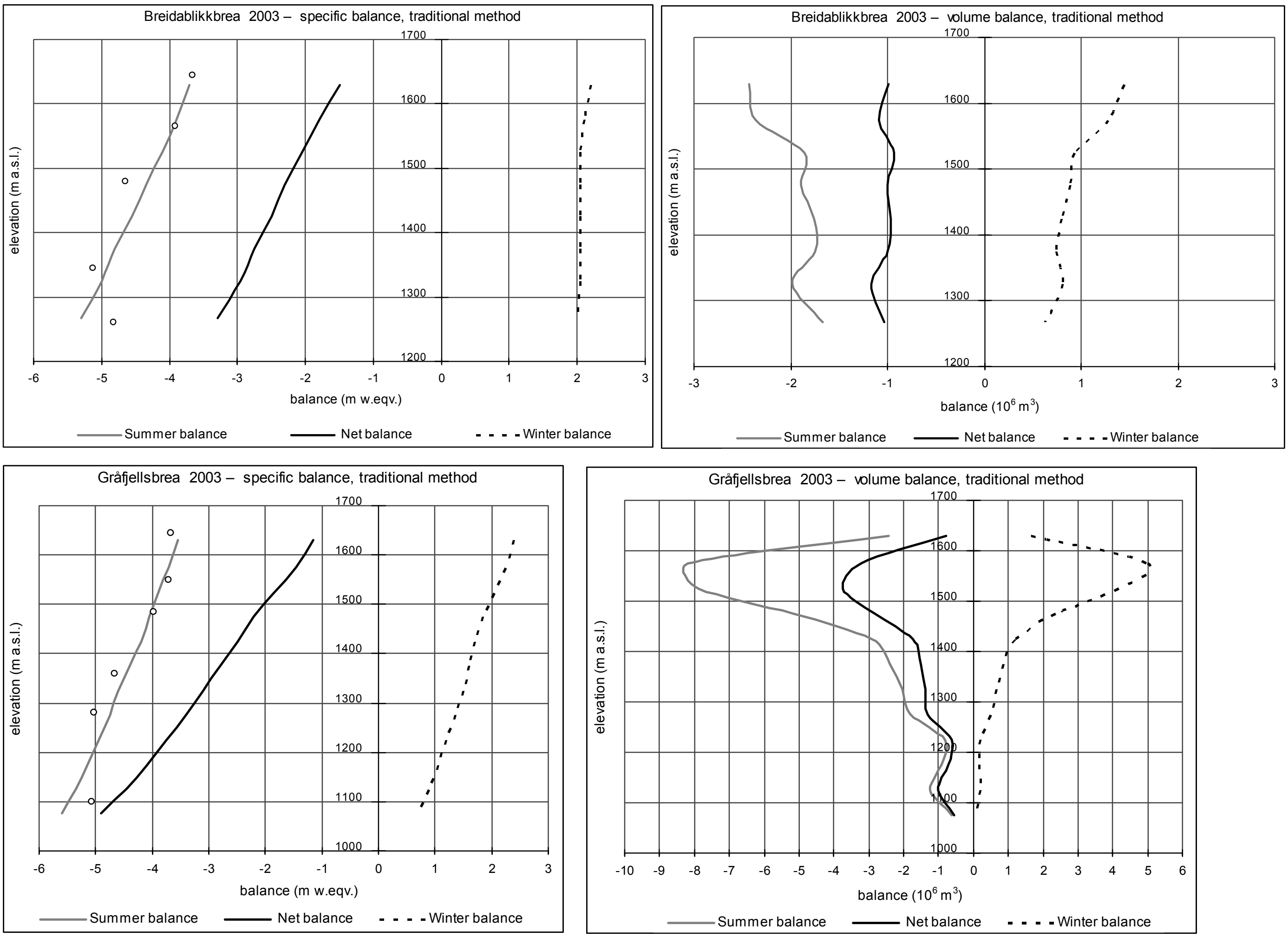


Figure 3-4
Mass balance diagram for Breidablikkbrea (upper) and Gråfjellsbrea (lower) in 2003 showing altitudinal distribution of specific (left) and volumetric (right) winter, summer and net balance. Specific summer balance at each stake is shown (o).

Mass balance Breidablikkbrea 2002/03 – traditional method

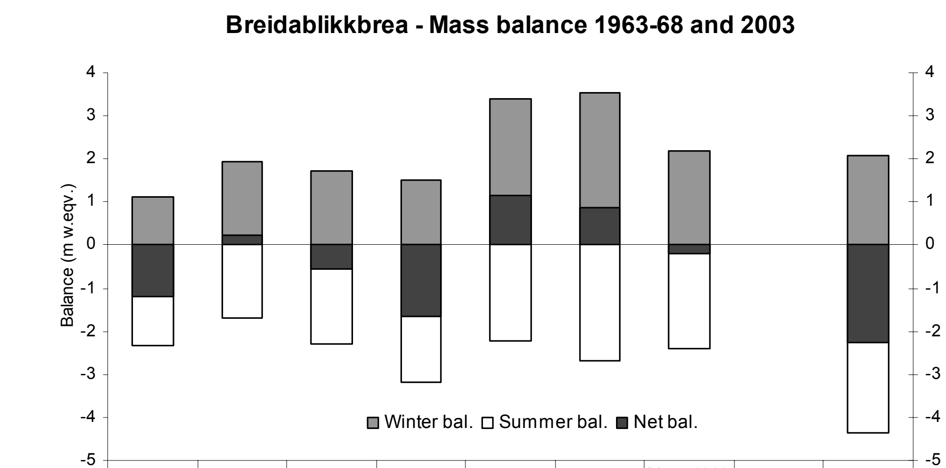
Altitude (m a.s.l.)	Area (km^2)	Winter balance, Measured 31st May 2003: Specific (m w.eq.)	Winter balance: Volume (10^6 m^3)	Summer balance, Measured 20th Sept 2003: Specific (m w.eq.)	Summer balance: Volume (10^6 m^3)	Net balance, Summer surfaces 2002 - 2003: Specific (m w.eq.)	Net balance: Volume (10^6 m^3)
1600 - 1659	0.66	2.20	1.4	-3.70	-2.4	-1.50	-1.0
1550 - 1600	0.61	2.10	1.3	-3.90	-2.4	-1.80	-1.1
1500 - 1550	0.45	2.05	0.9	-4.10	-1.9	-2.05	-0.9
1450 - 1500	0.43	2.05	0.9	-4.35	-1.9	-2.30	-1.0
1400 - 1450	0.39	2.05	0.8	-4.55	-1.8	-2.50	-1.0
1350 - 1400	0.36	2.05	0.7	-4.80	-1.7	-2.75	-1.0
1300 - 1350	0.40	2.05	0.8	-5.00	-2.0	-2.95	-1.2
1236 - 1300	0.31	2.00	0.6	-5.30	-1.7	-3.30	-1.0
1236 - 1659	**3.61**	**2.08**	**7.5**	**-4.35**	**-15.7**	**-2.26**	**-8.2**

Mass balance Gråfjellsbrea 2002/03 – traditional method

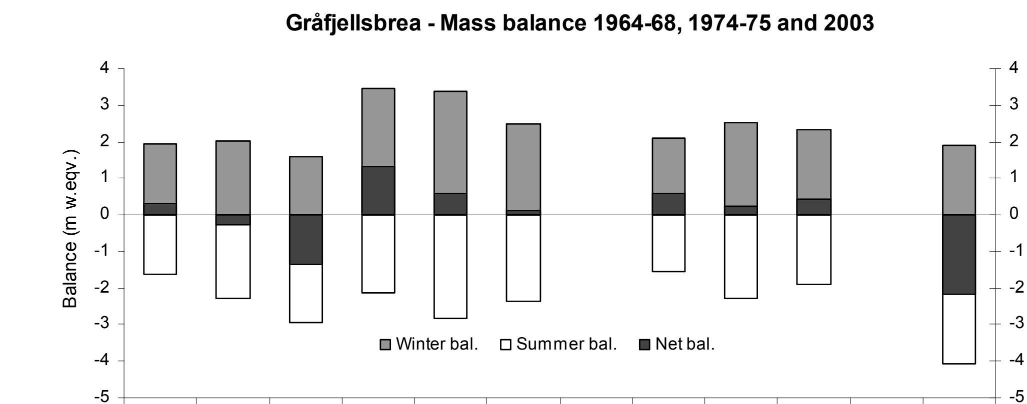
Altitude (m a.s.l.)	Area (km^2)	Winter balance, Measured 31st May 2003: Specific (m w.eq.)	Winter balance: Volume (10^6 m^3)	Summer balance, Measured 20th Sept 2003: Specific (m w.eq.)	Summer balance: Volume (10^6 m^3)	Net balance, Summer surfaces 2002 - 2003: Specific (m w.eq.)	Net balance: Volume (10^6 m^3)
1600 - 1659	0.68	2.40	1.6	-3.55	-2.4	-1.15	-0.8
1550 - 1600	2.21	2.25	5.0	-3.70	-8.2	-1.45	-3.2
1500 - 1550	2.03	2.05	4.2	-3.90	-7.9	-1.85	-3.7
1450 - 1500	1.28	1.85	2.4	-4.05	-5.2	-2.20	-2.8
1400 - 1450	0.70	1.70	1.2	-4.20	-2.9	-2.50	-1.7
1350 - 1400	0.54	1.60	0.9	-4.40	-2.4	-2.80	-1.5
1300 - 1350	0.44	1.50	0.7	-4.60	-2.0	-3.10	-1.4
1250 - 1300	0.38	1.35	0.5	-4.75	-1.8	-3.40	-1.3
1200 - 1250	0.16	1.20	0.2	-4.95	-0.8	-3.75	-0.6
1150 - 1200	0.18	1.05	0.2	-5.15	-0.9	-4.10	-0.7
1100 - 1150	0.23	0.90	0.2	-5.35	-1.2	-4.45	-1.0
1051 - 1100	0.11	0.70	0.1	-5.60	-0.6	-4.90	-0.5
1051 - 1659	**8.94**	**1.90**	**17.0**	**-4.07**	**-36.4**	**-2.17**	**-19.4**

Table 2-1
Winter, summer and net balances for Breidablikkbrea (upper) and Gråfjellsbrea (lower) in 2003.

The mass balance was measured at Breidablikkbrea over the period 1963-68 and at Gråfjellsbrea in 1964-68 and 1974-75. The historical mass balance results are presented in Figure 3-5.



	1963	1964	1965	1966	1967	1968	Mean 1963-68		2003
Winter bal.	1.11	1.92	1.72	1.52	3.40	3.55	2.20		2.08
Summer bal.	-2.32	-1.68	-2.28	-3.17	-2.23	-2.68	-2.39		-4.35
Net bal.	-1.21	0.24	-0.56	-1.65	1.17	0.87	-0.19		-2.27



	1964	1965	1966	1967	1968	Mean 1964-68		1974	1975	Mean 1974-75		2003
Winter bal.	1.94	2.01	1.58	3.46	3.39	2.48		2.11	2.53	2.32		1.90
Summer bal.	-1.62	-2.29	-2.93	-2.14	-2.82	-2.36		-1.53	-2.28	-1.91		-4.07
Net bal.	0.32	-0.28	-1.35	1.32	0.57	0.12		0.58	0.25	0.42		-2.17

Figure 3-5
Winter, summer and net balance at Breidablikkbrea over the period 1963-68 and 2003 (upper figure), and at Gråfjellsbrea during the periods 1964-68, 1974-75 and 2003 (lower figure).

4. Nigardsbreen (Bjarne Kjøllmoen)

Nigardsbreen (61°42'N, 7°08'E) is one of the largest and most well-known outlet glaciers from Jostedalsbreen. It has an area of 47.8 km^2 (measured in 1984) and flows south-east from the centre of the ice cap. Nigardsbreen accounts for approximately 10 % of the total area of Jostedalsbreen, and extends from 1960 m a.s.l. down to approximately 320 m a.s.l.

Glaciological investigations in 2003 include mass balance and front position change. Some observations of the ice-dammed lake Brimkjelen at Tunsbergdalsbreen have also been performed. Nigardsbreen has been the subject of mass balance investigations since 1962.

Figure 4-1
The glacier snout of Nigardsbreen photographed on 6th August 2003. Photo: Bjarne Kjøllmoen.

4.1 Mass balance 2003

Fieldwork

Snow accumulation measurements were performed on 1st June and the calculation of winter balance (Fig. 4-2) is based on:

- Uninterrupted measurements of towers and stakes in nine different positions. It was also possible to make use of measurements of substitute stakes drilled in June 2003 and older stakes that appeared during the melt season in two more positions. Stake readings did not show any indications of melting *after* the final measurements in October 2002.
- Core samples at positions 56 (3.9 m snow and 54 (3.0 m snow).
- 142 snow depth soundings along approximately 28 km of profiles between 1610 and 1960 m a.s.l. Identifying the summer surface (SS) was simple over the whole glacier.

The snow depth was slightly over 4 m at higher elevation. Between 1600 and 1750 m a.s.l. the snow depth varied between 3 and 4 m.

- Snow density was measured down to SS (3.9 m) at position 56.

Location of stakes, towers, density pit, core samples and sounding profiles are shown in Figure 4-2.

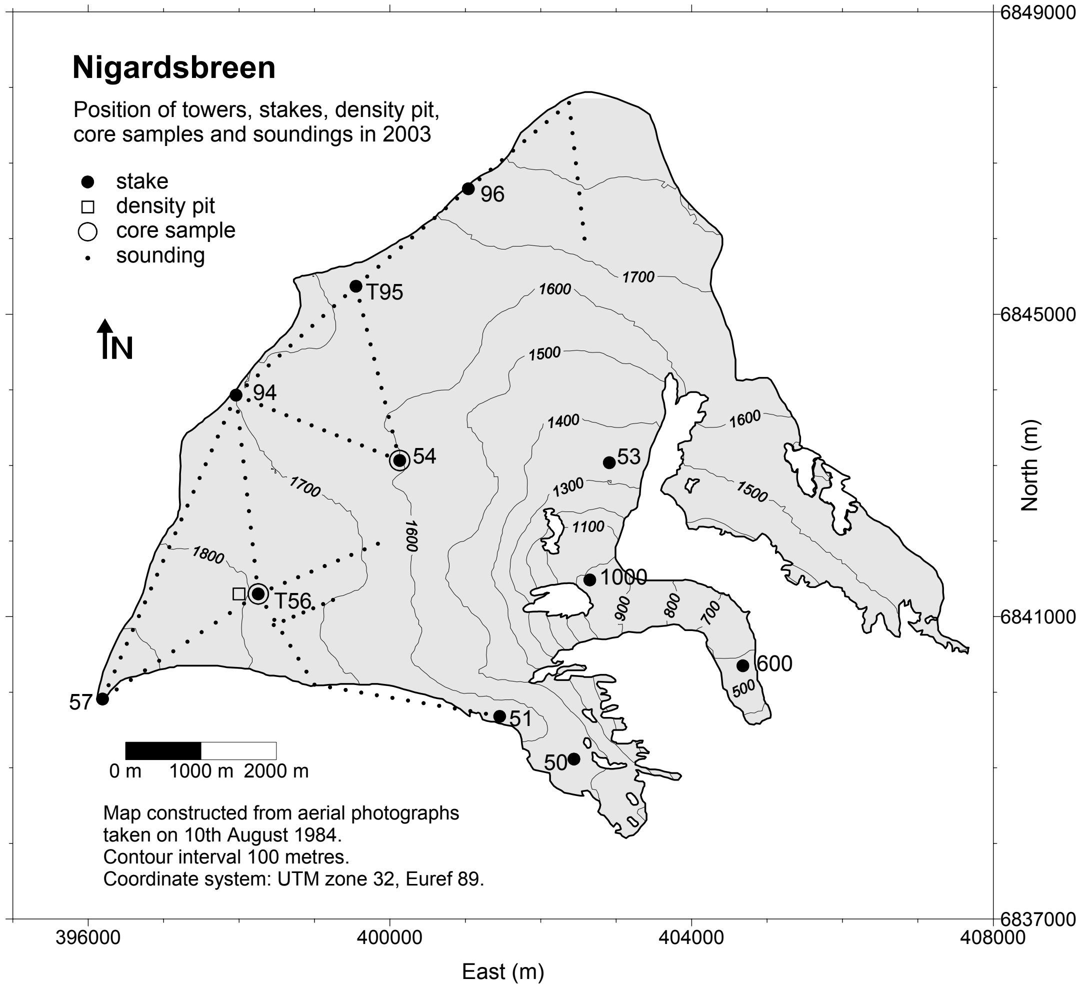


Figure 4-2
Location of towers and stakes, density pits, core samples and sounding profiles at Nigardsbreen in 2003.

The final ablation measurements were carried out on 20th September. Measurements were made at thirteen stakes and two towers in eleven different positions. Since snow measurements on 1st June the stakes on the plateau had increased in length by about 4.5 m. Hence there was no snow remaining from winter 2003, even in the uppermost areas. In addition about 0.5 m of firn had ablated in the accumulation area. On the glacier tongue the net melting between autumn 2002 and autumn 2003 was 8.5 m of ice at 600 m altitude. At the time of measurements about 5 cm of fresh snow had fallen in areas above 1600 m elevation.

Results

The calculations are based on a glacier map from 1984.

Winter balance

The calculation of winter balance is based on point measurements of snow depth (stakes and towers, probings and core drillings) and on measurement of snow density at one representative location.

There was no melting after the final measurements on 7th October 2002. Consequently, winter *accumulation* and winter *balance* are equal.

A density profile was modelled from the snow density measured at position 56 (3.9 m snow). Using this model gave a snow density of 0.474 g/cm^3 (1800 m a.s.l.). The model was used for all snow depth measurements.

The winter balance calculation was performed by plotting measurements (water equivalents) in a diagram. A curve was drawn based on visual evaluation (Fig. 4-3), and a mean value for each 100 m height interval estimated (Tab. 4-1). The elevations above 1600 m a.s.l. were well represented with point measurements. Below this altitude the curve pattern was based on only a few probings at 1320, 985 and 600 m altitude.

This gives a winter balance of 1.6 ±0.2 m w.eqv., corresponding to a water volume of 74 ±10 mill. m^3. The result is 65 % of the average for 1962-2002. Only two years, 1996 and 1977, have shown a lower winter balance on Nigardsbreen.

The winter balance was also calculated using a gridding method based on the aerial distribution of the snow depth measurements (Fig. 4-3). In areas with insufficient measurements some (12) simulated points were extracted. These point values were modelled based on measurements from the period 1975-81, years with extensive measurements. Water equivalents for each cell in a 100 x 100 m grid were calculated and summarised. The result based on this method, which is a control of the traditional method, also showed a winter balance of 1.6 m w.eqv.

Summer balance

When calculating the summer balance the density of 1 year old ablated firn was estimated as 0.65 g/cm^3. The density of ablated firn older than 1 year was estimated at between 0.7 and 0.8 g/cm^3, and, the density of melted ice was determined as 0.90 g/cm^3.

The summer balance was calculated at nine stakes and towers, and increased from −2.0 m w.eqv. at the glacier summit (1960 m a.s.l.) to −7.4 m down on the tongue (615 m a.s.l.). Based on estimated density and stake measurements the summer balance was calculated to be −2.7 ±0.3 m w.eqv., which is −130 ±15 mill. m^3 of water. The result is 139 % of the average for 1962-2002.

Net balance

The net balance was calculated at stakes and towers in 11 positions. At stake 1000 the measurements were supplemented with estimated data from previous years.

The net balance for 2003 was calculated as −1.2 m ±0.3 m w.eqv., which is equal to a deficit of −56 ±15 mill.m^3 water. The mean value for the period 1962-2002 is +0.45 m w.eqv. (Fig. 4-5), while the average over 1996-2002 is +0.20 m w.eqv. Only two years have shown an equal or greater deficit on Nigardsbreen, −1.2 m w.eqv. in 1988 and −1.3 m w.eqv. in 1969.

As a consequence of net ablation over the whole glacier area the Equilibrium Line Altitude (ELA) was *above* the glacier summit (>1960m a.s.l.). Accordingly, the Accumulation Area Ratio (AAR) was 0 %. Since 1962 the AAR has never been lower than 3 % (1969).

The mass balance in 2003 for Nigardsbreen is shown in Table 4-1 and the corresponding curves are shown in Figure 4-4. The historical mass balance results are presented in Figure 4-5.

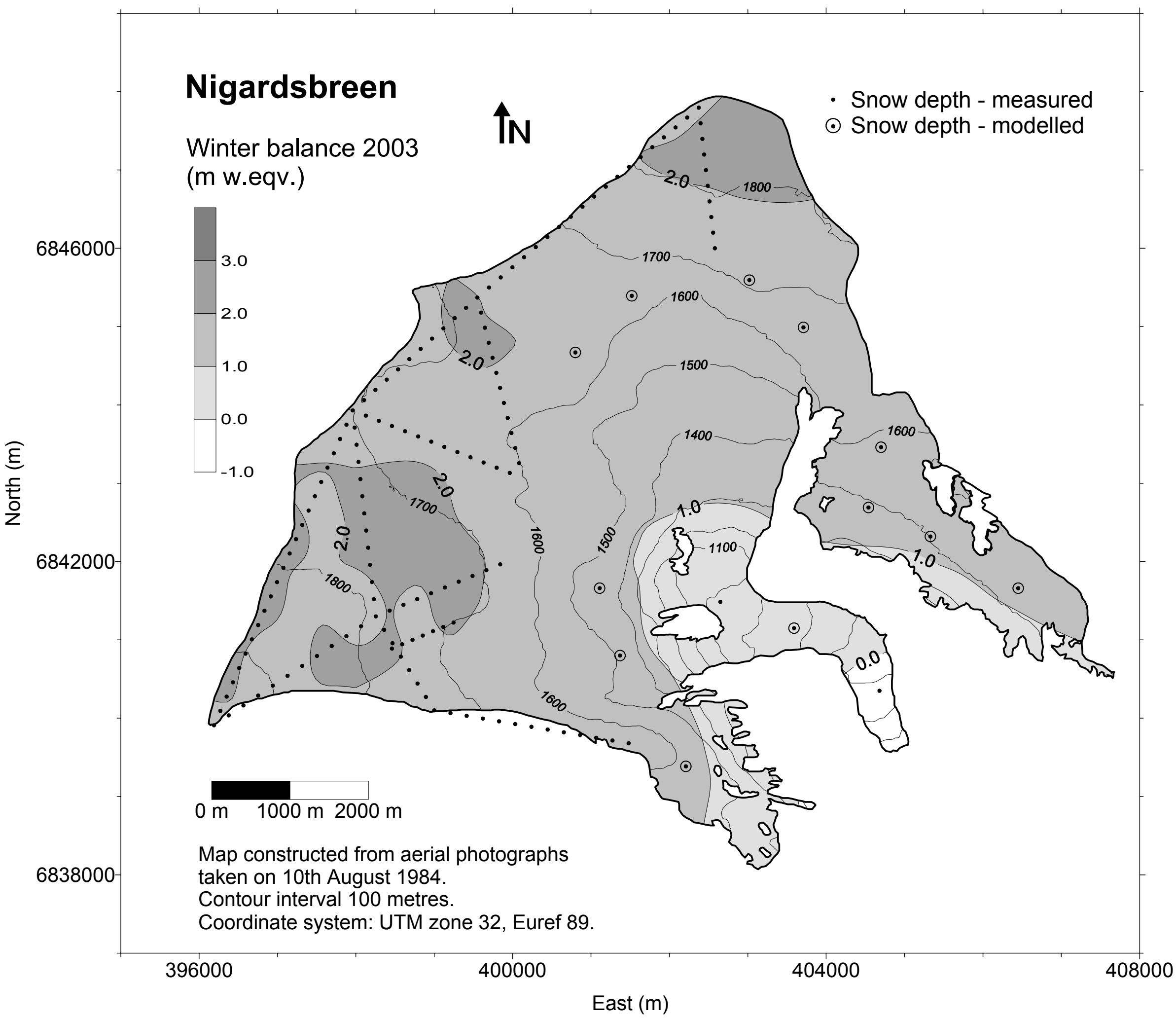


Figure 4-3
Winter balance at Nigardsbreen in 2003 interpolated from 142 measurements (•) of snow depth. In areas with few or no measurements twelve extrapolated points (◉) are added.

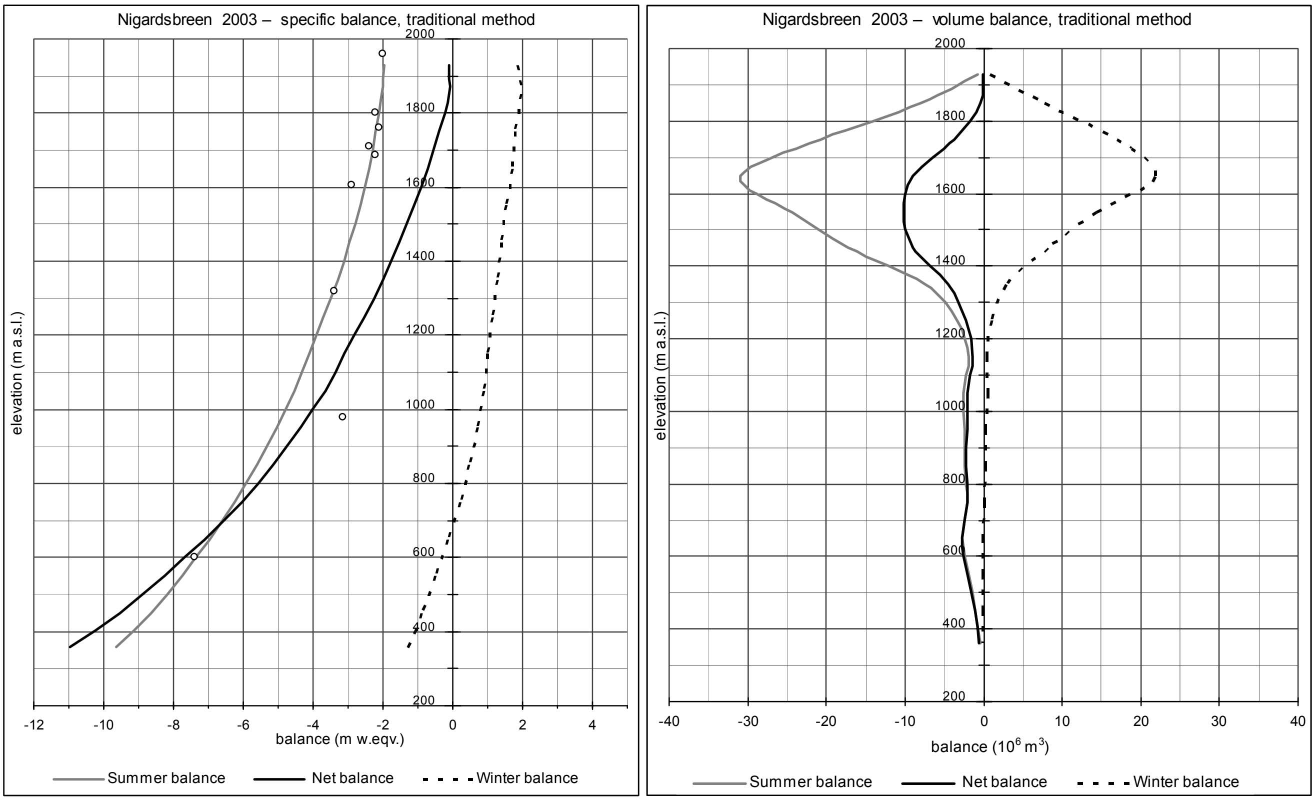


Figure 4-4
Mass balance diagram showing specific balance (left) and volume balance (right) for Nigardsbreen in 2003. Specific summer balance at nine stakes are shown as dots (o). As the net balance curve does not intersect the y-axis, the ELA lies above the glacier summit at 1960 m a.s.l. Thus the AAR was 0 %.

Mass balance Nigardsbreen 2002/03 – traditional method

Altitude (m a.s.l.)	Area (km^2)	Winter balance, Measured 1st June 2003: Specific (m w.eq.)	Winter balance: Volume (10^6 m^3)	Summer balance, Measured 20th Sept 2003: Specific (m w.eq.)	Summer balance: Volume (10^6 m^3)	Net balance, Summer surface 2002 - 2003: Specific (m w.eq.)	Net balance: Volume (10^6 m^3)
1900 - 1960	0.38	1.85	0.7	-1.95	-0.7	-0.10	0.0
1800 - 1900	3.92	1.95	7.6	-2.05	-8.0	-0.10	-0.4
1700 - 1800	9.39	1.80	16.9	-2.20	-20.7	-0.40	-3.8
1600 - 1700	12.88	1.70	21.9	-2.40	-30.9	-0.70	-9.0
1500 - 1600	9.18	1.55	14.2	-2.65	-24.3	-1.10	-10.1
1400 - 1500	5.82	1.40	8.1	-2.95	-17.2	-1.55	-9.0
1300 - 1400	2.28	1.30	3.0	-3.30	-7.5	-2.00	-4.6
1200 - 1300	0.90	1.15	1.0	-3.70	-3.3	-2.55	-2.3
1100 - 1200	0.45	1.00	0.5	-4.10	-1.8	-3.10	-1.4
1000 - 1100	0.58	0.90	0.5	-4.55	-2.6	-3.65	-2.1
900 - 1000	0.47	0.70	0.3	-5.05	-2.4	-4.35	-2.0
800 - 900	0.44	0.45	0.2	-5.60	-2.5	-5.15	-2.3
700 - 800	0.33	0.20	0.1	-6.25	-2.1	-6.05	-2.0
600 - 700	0.39	-0.15	-0.1	-6.95	-2.7	-7.10	-2.8
500 - 600	0.24	-0.50	-0.1	-7.75	-1.9	-8.25	-2.0
400 - 500	0.12	-0.90	-0.1	-8.65	-1.0	-9.55	-1.1
320 - 400	0.05	-1.30	-0.1	-9.65	-0.5	-10.95	-0.5
320 - 1960	**47.82**	**1.56**	**74.7**	**-2.72**	**-130.2**	**-1.16**	**-55.4**

Table 4-1
Winter, summer and net balance for Nigardsbreen in 2003. Mean values for the period 1962-2002 are 2.40 (b_s), -1.95 m (b_s) and +0.45 m (b_n) water equivalent.

The balance year 2002/2003 is the third successive year with negative net balance at Nigardsbreen. During the 7-year period 1989-1995 the cumulative net balance was more than 10 m w.eqv. surplus. Over the last 8 years (1996-2003) the cumulative net balance is slightly positive with 0.2 m w.eqv. In this last period only two years show a significant positive net balance, 1998 and 2000. However, during the entire period of investigations (1962-2003) the cumulative net balance is more than 17 m w.eqv.

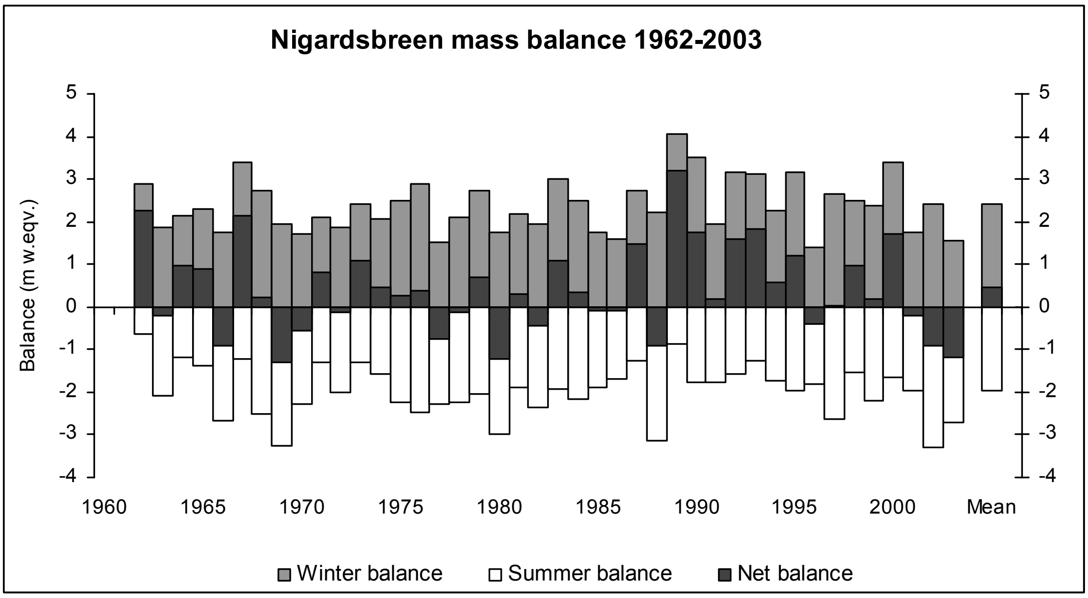


Figure 4-5
Annual mass balance at Nigardsbreen during the period 1962-2003.

4.2 Tunsbergdalsbreen

Mass balance

From 1966 to 1972 mass balance measurements were made simultaneously at both Tunsbergdalsbreen (50.1 km^2, 1964) and Nigardsbreen. A linear regression analysis of the results from these seven years gives an equation that can be used to calculate the annual net balance of Tunsbergdalsbreen.

$$bn_T = 0.987 \cdot bn_N - 0.283$$

bn_T = net balance at Tunsbergdalsbreen, and bn_N = net balance at Nigardsbreen.

For 2003 the net balance at Tunsbergdalsbreen was estimated as -1.43 ±0.45 m w.eqv., corresponding to a deficit of about 72 ±20 mill. m^3 of water. Since 1962 the estimated accumulated net balance is about +5.1 m w.eqv.

Based on the measurements during 1966-72 a correlation between the equilibrium line altitude (ELA) for Nigardsbreen and Tunsbergdalsbreen was established. The analysis indicates that the ELA at Tunsbergdalsbreen in autumn 2003 was about 1850 m a.s.l.

Brimkjelen

About 3 km above the western side of the glacier snout lies an ice-dammed lake called Brimkjelen. Due to glacier recession during the last century, the area and volume of the lake has decreased considerably. The last estimate of the volume was about 2 million m^3 in 1982.

From 1984 to 1997 no systematic observations were made of the lake. Annual observations were resumed in autumn 1997 and continued in 2003 by photography on 20th September (Fig. 4-6). The lake was empty at this time and there was no indication that there had been water in the lake over the past year.

Figure 4-6
Brimkjelen photographed on 20th September 2003. The glacier lake was empty at the time of observation. Photo: Miriam Jackson.

5. Austdalsbreen (Hallgeir Elvehøy)

Austdalsbreen (61°45'N, 7°20'E) is an eastern outlet of the northern part of Jostedalsbreen, ranging in altitude from 1200 to 1760 m a.s.l. The glacier calves into the regulated lake Austdalsvatnet. Glaciological investigations started at Austdalsbreen in 1986 in connection with the construction of a hydroelectric power plant for which Lake Austdalsvatnet is a reservoir.

The glaciological investigations in 2003 included mass balance, front position change and glacier velocity. Mass balance has been measured at Austdalsbreen since 1988.

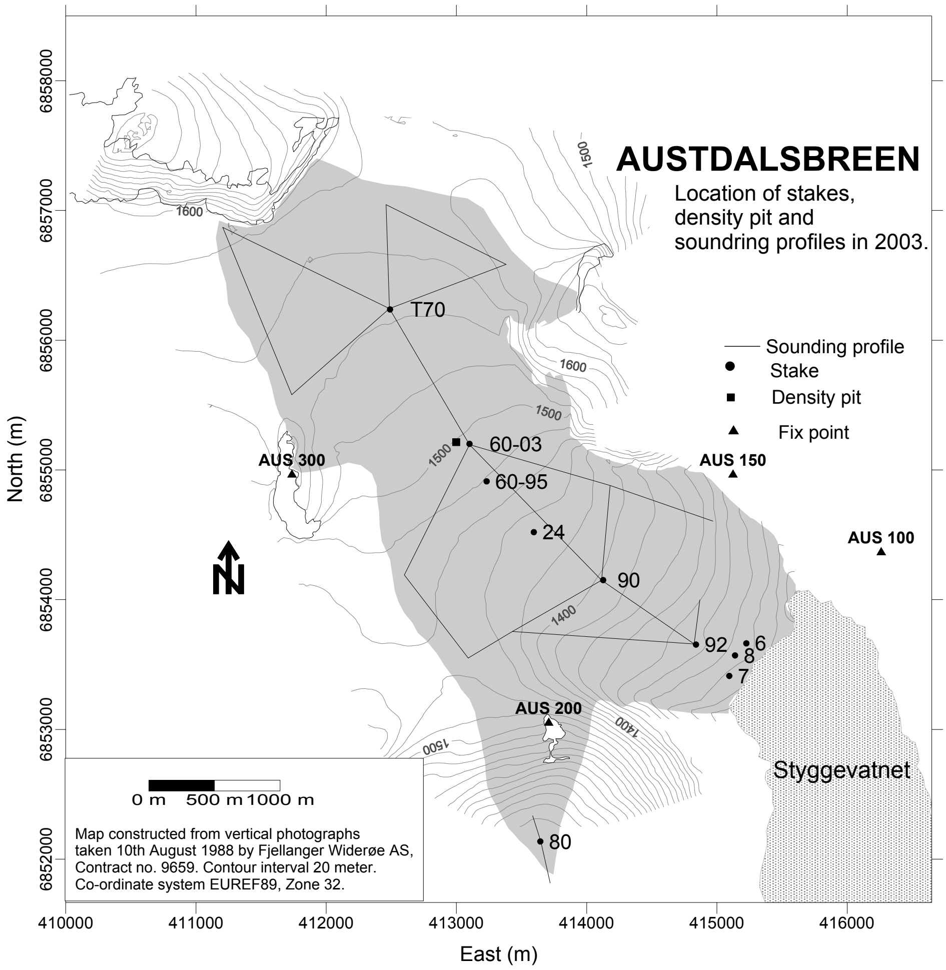


Figure 5-1
Location of stakes, density pit and sounding profiles at Austdalsbreen in 2003.

5.1 Mass balance 2003

Fieldwork

Winter accumulation was measured on 2nd June. The calculation of winter balance was based on the following data (Fig. 5-1):

- Snow depth at stakes 92, 90, 24, 60-95 and T70 was 1.60, 1.65, 2.65, 2.75 and 3.40 m respectively. Stakes 6, 7 and 8 were not measured.
- Snow depth by coring at stake 80 (1730 m a.s.l.) showed snow depth of 2.6 metres.
- 93 snow depth measurements along 18 km of profiles. At Austdalsnuten above 1700 m a.s.l. the snow depth was 2.5 m. Between 1425 and 1600 m a.s.l. most of the soundings showed snow depth of 3.0 and 3.6 m. Between 1300 and 1425 m a.s.l. the snow was 2.5 to 3.5 m deep. Below 1300 m a.s.l. the snow depth was not measured. The summer surface from 2002 (SS) was easy to detect in all areas.
- Snow density down to SS at 3.05 m depth at stake 60-03 (1495 m a.s.l.). Mean snow density was 0.52 g/cm^3.
- On 26th June the transient snow line altitude was 1275 m a.s.l. At stake 6 (1250 m a.s.l.), 1.05 m of ice had melted. At stake 92 (1300 m a.s.l), 1.05 m of snow from a snow depth of 1.60 m had melted by 26th June.

By 8th August, all the winter snow at Austdalsbreen had melted.

Summer ablation and net balance measurements were carried out 20th September. The transient snow line altitude (TSL) was higher than the top of the glacier (>1760 m a.s.l.). There was no new snow on the glacier The firn line altitude was 1440 m a.s.l. At stake 80 (1730 m a.s.l.), 2.05 m of firn had melted away. At stakes between 1440 and 1600 m a.s.l. (60 and T70) 2.45 to 1.3 m of firn had melted away. At stakes between 1300 and 1440 m a.s.l. (92, 90 and 24) 2.35 to 4.10 m of ice had melted away. At the lowermost stakes (6, 7 and 8), 6.0 to 6.65 m of ice had melted away in addition to the winter snow cover.

Results

The mass balance was calculated according to the stratigraphic method (see chap.1). The calculations are based on a map from 10th August 1988 reduced for the areas below the highest regulated lake level (below 1200 m a.s.l., 0.11 km^2).

Winter balance

There are no observations indicating melting after the stake measurements on 7th October 2002.

The winter balance was calculated from snow depth and snow density measurements on 2nd June. A function correlating snow depth with water equivalent was calculated based on snow density measurements at stake 60-03 (1495 m a.s.l.). The mean density of 4 m of snow in this profile was 0.51 g/cm^3. This function was then used to convert all snow depth measurements to water equivalent.

Snow depth water equivalent values were plotted against altitude. By averaging values within 50 m altitude intervals and visual evaluation, an altitudinal winter balance curve was drawn. Between 1600 and 1700 m a.s.l. no snow depths were measured, so the curve was interpolated in this area. Below 1300 m a.s.l. the snow depth varies greatly due to an irregular topography and crevasses which trap a large portion of the drifting snow. Even though the stake readings (on 26th June) indicate that there was no snow at the stakes on 2nd June, the crevasses would have contained a substantial amount of snow. This gives only a slight decrease in winter balance below 1300 m a.s.l. From the winter balance curve a mean value for each 50 m altitude interval was determined. The winter balance was 1.6 ±0.2 m w.eqv. or 19 ±2 million m^3 water. This is 70 % of the 1988 – 2002 average (2.28 m w.eqv.). The winter balance was even lower in 1996 (53%) and 2001(46%).

The winter balance was also calculated using a gridding method based on the spatial distribution of the snow depth measurements (Fig. 5-2). Five extra points estimated from nearest measurements and terrain properties were included to support the interpolation routine. Water equivalents for each cell in a 25 x 25 m grid were calculated and summarised. The result based on this method, which is a control of the traditional method, also showed a winter balance of 1.6 m w.eqv.

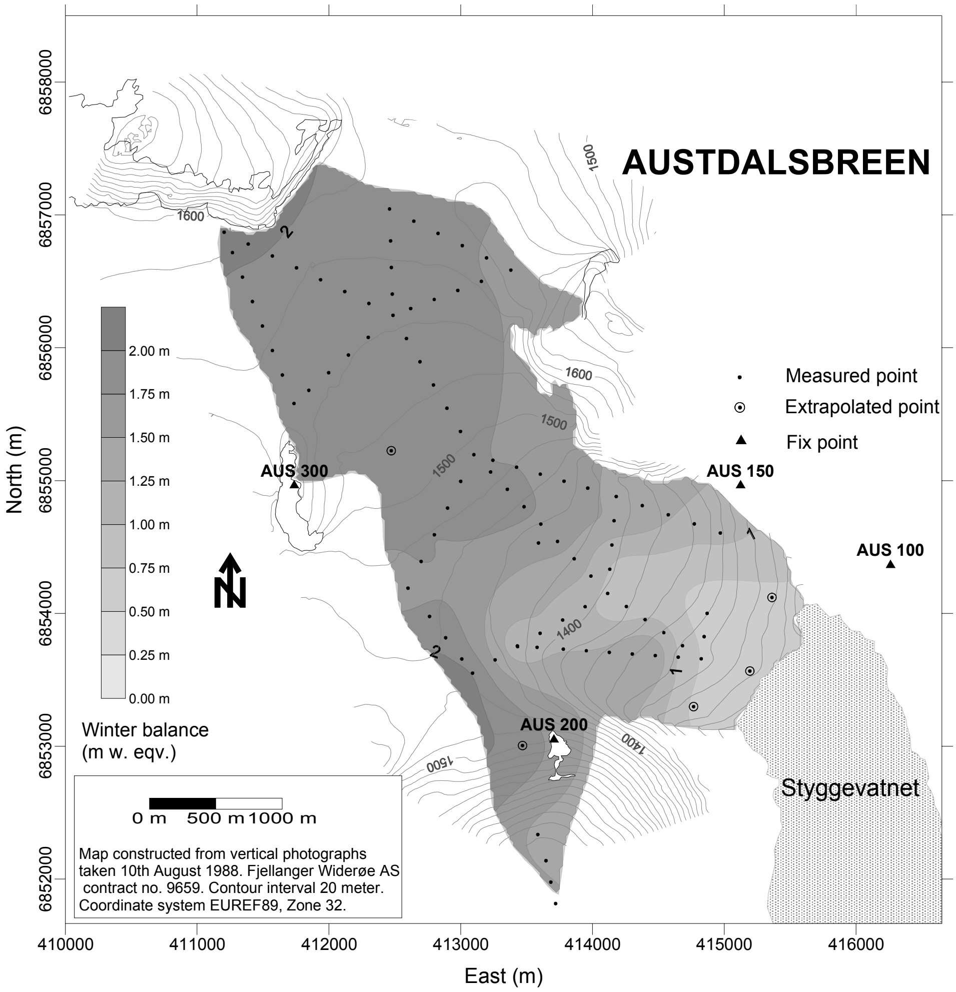


Figure 5-2
Winter accumulation at Austdalsbreen in 2003 from 93 water equivalent values calculated from snow depth soundings. Five estimated point values were added to aid the interpolation in areas without measurements.

Summer balance

The summer balance was calculated directly for seven stake positions between 1250 and 1730 m a.s.l.. The density of firn (mainly from the winter 1999-2000) was set to 0.7 g/cm^3. A summer balance curve was drawn from these values (Fig. 5-3).

Calving from the glacier terminus was calculated as the annual volume of ice (in water equivalent) transported through a cross section close to the terminus, and adjusted for the volume change related to the annual front position change. This volume is calculated as:

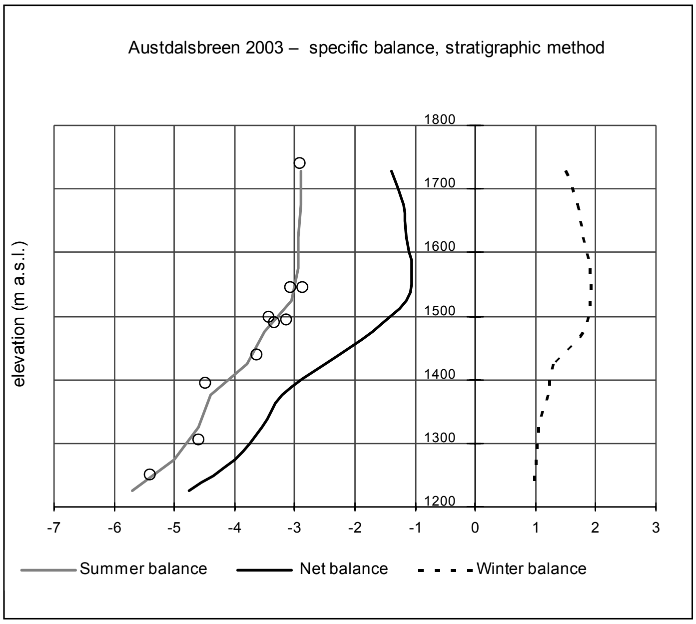
$$Q_k = \rho_{ice} * (u_{ice} - u_f) * W * H$$

where ρ_{ice} is 0.9 g/cm^3, u_{ice} is annual glacier velocity (55 ±10 m/a (chapter 5.3), u_f is front position change averaged across the terminus (-30 ±5 m/a, chapter 5.2), W is terminus width (1100 ±50 m), and H is mean ice thickness at the terminus (47 ±5 m) based on surface altitude surveyed October 2002 and September 2003, and a bottom topography map compiled from radar ice thickness measurements (1986), hot water drilling (1987) and lake depth surveying (1988 and 1989). The resulting calving volume was 4.0 ±0.5 million m^3 water or 0.33 ±0.04 m w.eqv. averaged across the glacier area (11.8 km^2).

The summer balance, including calving, was calculated as -3.9±0.3 m w.eqv., which corresponds to -47±3 million m^3 of water. The calving volume was 9 % of the summer balance. The result is 170 % of the 1988-2002 average (-2.32 m w.eqv.). The summer balances of 2002 and 2003 are the largest summer balances measured at Austdalsbreen.

Net balance

The net balance at Austdalsbreen was calculated as -2.3 ±0.3 m w.eqv., corresponding to -28 ±3 mill. m^3 water. This is the largest mass deficit at Austdalsbreen since the measurements started. The 1988-2002 average is -0.04 m w.eqv. The entire glacier was below the equilibrium line altitude (ELA) for the third consecutive year. Consequently, the Accumulation Area Ratio (AAR) was 0 % for 2003. The altitudinal distribution of winter-, summer- and net balances are shown in Figure 5-3 and Table 5-1. Results from 1988-2003 are shown in Figure 5-4.



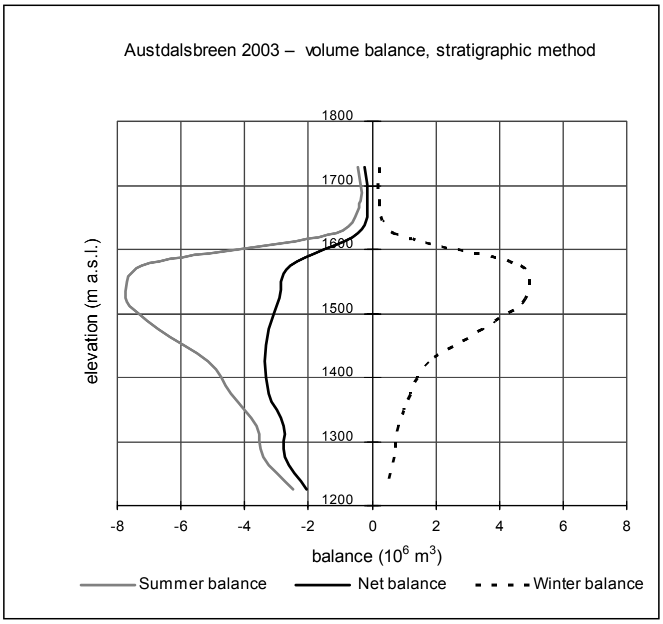


Figure 5-3
Altitudinal distribution of winter-, summer- and net balance shown as specific balance (left) and volume balance (right) at Austdalsbreen in 2003. Specific summer balance at ten stakes in seven locations is shown (o).

Mass balance Austdalsbreen 2002/03 – stratigraphic method

Altitude (m a.s.l.)	Area (km^2)	Winter balance Measured 2nd Jun 2003		Summer balance Measured 20th Sep 2003		Net balance Summer surface 2002 - 2003	
		Specific (m w.eqv.)	Volume (10^6 m^3)	Specific (m w.eqv.)	Volume (10^6 m^3)	Specific (m w.eqv.)	Volume (10^6 m^3)
1700 - 1757	0.16	1.50	0.24	-2.90	-0.46	-1.40	-0.22
1650 - 1700	0.13	1.70	0.22	-2.90	-0.37	-1.20	-0.15
1600 - 1650	0.38	1.80	0.68	-2.95	-1.11	-1.15	-0.43
1550 - 1600	2.45	1.90	4.65	-2.95	-7.22	-1.05	-2.57
1500 - 1550	2.54	1.90	4.82	-3.05	-7.74	-1.15	-2.92
1450 - 1500	1.92	1.80	3.46	-3.50	-6.73	-1.70	-3.27
1400 - 1450	1.36	1.30	1.76	-3.80	-5.15	-2.50	-3.39
1350 - 1400	1.01	1.20	1.21	-4.40	-4.44	-3.20	-3.23
1300 - 1350	0.79	1.05	0.83	-4.60	-3.62	-3.55	-2.79
1250 - 1300	0.69	1.00	0.69	-5.00	-3.44	-4.00	-2.75
1200 - 1250	0.44	0.95	0.41	-5.70	-2.48	-4.75	-2.07
Calving					-4.0		-4.0
1200 - 1757	**11.84**	**1.60**	**19.0**	**-3.94**	**-46.7**	**-2.34**	**-27.7**

Table 5-1
Altitudinal distribution of winter-, summer- and net balances at Austdalsbreen in 2003.

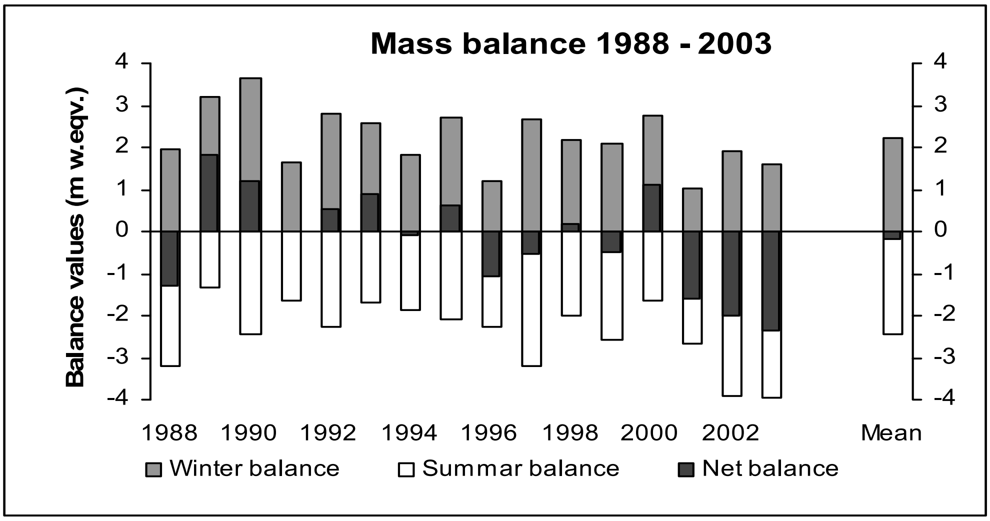


Figure 5-4
Winter-, summer and net balances at Austdalsbreen during the period 1988-2003.

5.2 Front position change

Six points along the terminus were surveyed on 20th September 2003. Between 7th October 2002 and 20th September 2003 the mean front position change was -30 ±5 m (Fig. 5-5). Since 1988 the glacier terminus has retreated approximately 390 metres, while the glacier area is reduced by 0.4 km^2. The lower part of Austdalsbreen is shown in Figure 5-5.

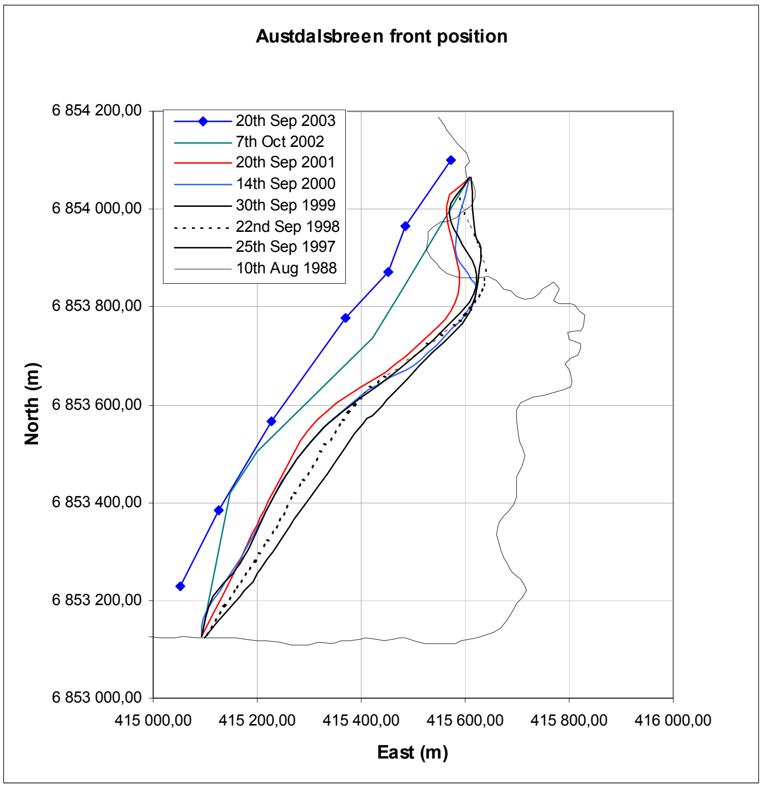


Figure 5-5
Surveyed front position of Austdalsbreen in 1988, 1997, 1998, 1999, 2000, 2001, 2002 and 2003. Mean front position retreat between 7th October 2002 and 20th September 2003 was -30 m.

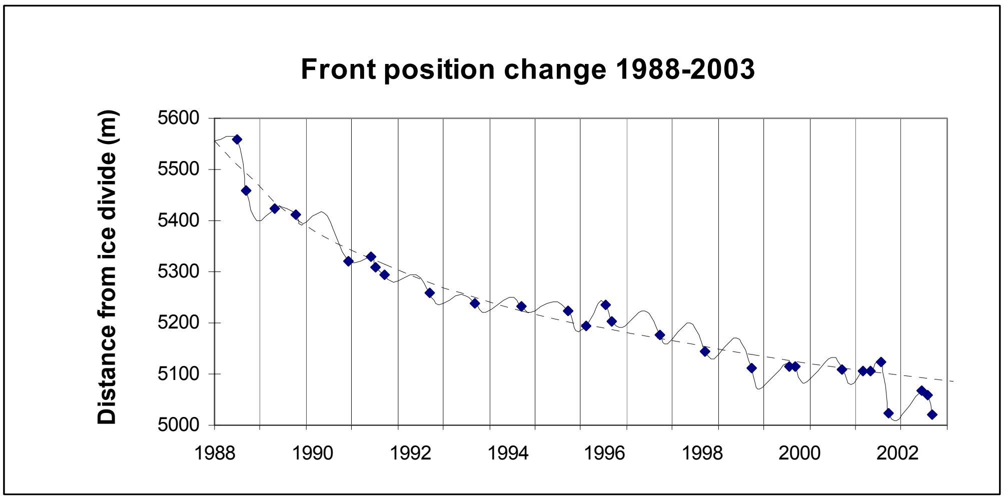


Figure 5-6
Surveyed front position change along a central flow line, shown as change in glacier length along this flow line (dots). The solid line indicates annual variation in front position. The glacier front advances from December to July when the lake is frozen, and retreats during July-December due to calving. In 1988 the level of lake Austdalsvatnet was regulated as a reservoir for the first time. The broken line shows predicted front position change based on expected annual lake level variations due to regulation and an annual net balance of -0.47 m w.eqv. (Laumann & Wold, 1992).

Due to large variations in calving, the variation in front position throughout the year is large compared with the net change from year to year. Figure 5-6 illustrates how the front position at a central flow line has varied over the last 16 years. As a consequence of lake regulation it was expected that the glacier terminus would retreat. Modelling resulted in a prediction for future front position change shown as a broken line in Figure 5-6. Mean annual net balance has been -0.19 m w.eqv., while the model input used -0.47m w.eqv. The last two years the retreat has been slightly larger than prescribed. This corresponds to a highly negative mass balance during the last three years.

5.3 Glacier velocity

Glacier velocities are calculated from repeated surveys of stakes on the lower part of the glacier. The stake network was surveyed on 7th October, 26th June and 20th September, and annual velocities were calculated for six stake positions. Above 1300 m a.s.l. the stake velocities were slightly lower in 2003 than in 2002. At the stakes close to the terminus the velocities increased from 40-50 m/a in 2002 (which was fairly low) to 50-60 m/a in 2003. The results are compared with results from 1988-2002 in Figure 5-7.

To calculate the calving volume (chapter 5.1), the glacier velocity averaged across the front width and thickness was estimated. The surface centre line velocity was calculated from measurements at stake 6, 7 and 8 (66 m/a, 69 m/a and 54 m/a), distance from stake to terminus (October and September), and a typical strain rate from previous years (0.01 a^{-1}). The cross-sectional averaged glacier velocity is estimated to be 70 % of the centre line surface velocity based on earlier measurements and estimates of the amount of glacier sliding at the bed. This results in a terminus cross-sectional averaged glacier velocity of 55 ±10 m/a.

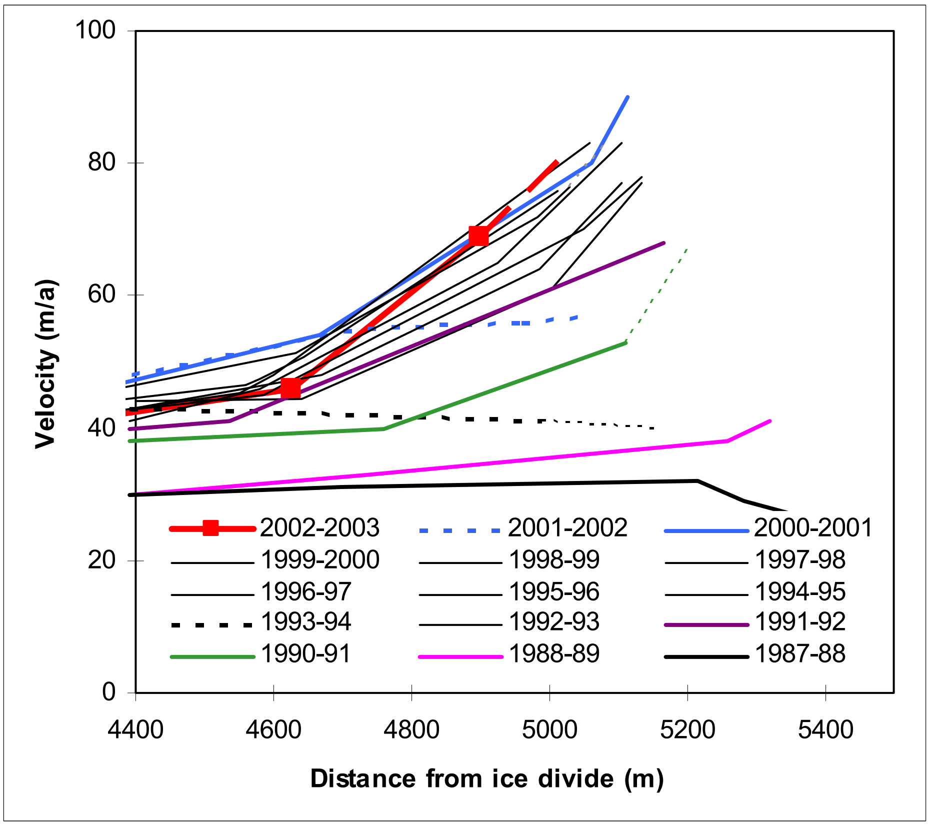


Figure 5-7
Glacier velocity (in m/a, measured each September) along a central flow line interpolated between averaged stake positions at the lower part of the glacier. Between the lowest stake and the terminus the velocity is extrapolated (broken line). The distance 4600 m from ice divide corresponds approximately to stake 92 (Fig. 5-1). Between 1988 and 2003 the terminus retreated 450 metres along the flow line.

6. Hardangerjøkulen (Hallgeir Elvehøy)

Hardangerjøkulen (60°32'N, 7°22'E) is the sixth largest (73 km^2) glacier in Norway. The glacier is situated on the main water divide between Hardangerfjorden and Hallingdalen valley. In 1963 the Norwegian Polar Institute began mass balance measurements on the south-western outlet glacier Rembesdalskåka (17 km^2), which drains towards Simadalen valley and Hardangerfjorden. This valley has been ravaged by jøkulhlaups (outburst floods) from the glacierdammed lake Demmevatnet, the most recent occurring in 1937 and 1938. Since 1985, the Norwegian Water Resources and Energy Directorate (NVE) has been responsible for the mass balance investigations at Rembesdalskåka. The investigated basin covers the altitudinal range between 1020 and 1865 m a.s.l.

Front position measurements were started at Midtdalsbreen by the University of Bergen in 1982. Statkraft re-initiated front position measurements at Rembesdalskåka in 1995. Front position change has been measured in several periods during the 20th century. These measurements are described in chapter 14.

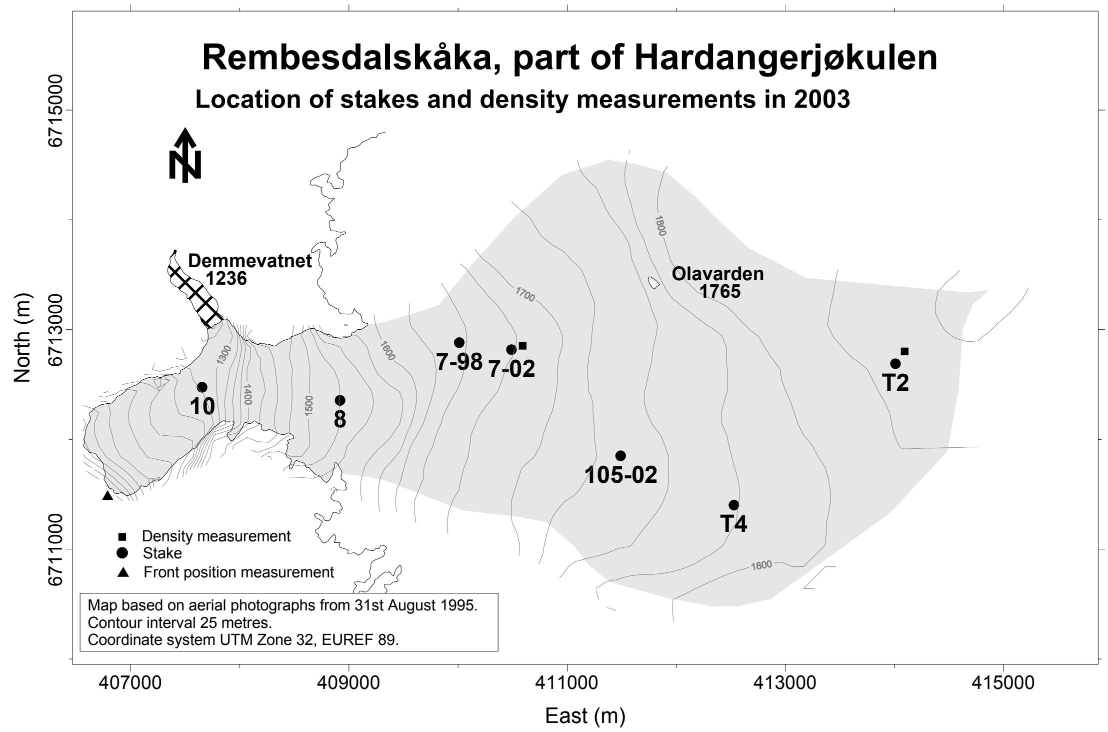


Figure 6-1
Location of stakes and density measurements at Rembesdalskåka, the south western outlet of Hardangerjøkulen, in 2003. The reference point for front position measurements is shown also.

6.1 Mass balance at Rembesdalskåka in 2003

Fieldwork

Due to adverse weather conditions the extent of the winter balance measurements was reduced from 70 – 80 point measurements at stakes and along sounding profiles, to snow depth measurements at the seven stakes only. The winter balance was measured on 16th June. The calculation of winter balance is based on the following data (Fig. 6-1):

- Snow depth measurements at stakes 10 (1275 m a.s.l.), 8 (1525 m a.s.l.), 7-98 (1645 m a.s.l.), 7-02 (1675 m a.s.l.), 105-02 (1725 m a.s.l.), T4 (1770 m a.s.l.) and T2 (1830 m a.s.l.) showing snow depths of 0.40, 0.00, 1.95, 2.43, 2.75, 3.25 and 3.05 m respectively. Comparison of stake measurements and snow depth soundings at stake 10 showed late autumn melting of 0.35 m of ice. At stake 8, 0.3 m of ice had melted before 16th June.
- Snow density down to 1 m depth at stakes 7-02 (1675 m a.s.l.) and T2 (1830 m a.s.l.) on 26th June. Mean snow density was 0.53 and 0.51 g/cm^3, respectively. The snow depth at that time was 1.93 and 3.05 m. At stake 7-02 the snow depth had decreased by 0.3 m since 16th June. At stake T2 there was no change.

Summer ablation and net balance was measured on 14th October. There was fresh snow on the glacier. Measurements at the stakes showed that the new snow was up to 1 m deep. The stake readings showed that all the winter snow had melted over the summer. The net balance was measured at seven locations between 1275 and 1830 m a.s.l. At stakes T2 (1830 m a.s.l.), T4 (1775 m a.s.l.), 105-02 (1730 m a.s.l.) and 7-02 (1675 m a.s.l.), 1.1, 1.3, 1.3, and 1.65 m firn had melted away in addition to the winter snow. The firn was 1 to 3 years old at stake T2, and 3 to 6 years old at stake 7-02. At stakes 7-98 (1640 m a.s.l.), 8 (1525 m a.s.l.) and 10 (1275 m a.s.l.) 2.85, 3.1 and 5.2 m of ice, respectively, melted during the summer.

Results

The mass balance is calculated according to a stratigraphic method relating the net balance to the difference between two successive "summer surfaces", excluding snow accumulation before the date of net balance measurements but also excluding ablation after net balance measurements. The calculations are based on a map from 1995.

Winter balance

The winter balance was calculated from snow depth measurements taken on 16th June 2003.

The snow density measurements from 26th June are compared with density measurements at Folgefonna (31st May – 1485 m a.s.l., Chapter 3), Nigardsbreen at Jostedalsbreen (1st June – 1800 m a.s.l., Chapter 4) and Austdalsbreen at Jostedalsbreen (2nd June – 1495 m a.s.l., Chapter 5). The density of the top metre of snow at Hardangerjøkulen was similar to the density at Folgefonna and Austdalsbreen, while the density at Nigardsbreen was significantly lower. Therefore, the density profile measured at Folgefonna is used to estimate the water equivalent value of the snow pack at Hardangerjøkulen on 16th June. From this model the mean density of 3 metres of snow is 0.56 g/cm^3.

The calculated water equivalent values were plotted against altitude. From these points, an altitudinal winter balance curve was drawn (Fig. 5-2).

From the winter balance curve a mean value for each 50 m elevation interval was determined. The winter balance was 1.3 ±0.4 m w.eqv. or 23 ±6 mill. m^3 water. This is 63 % of the 1963 – 2002 average of 2.13 m w.eqv., and 61 % of the 1998 - 2002 average of 2.17 m w.eqv.

Summer balance

The summer balance was calculated at seven stake positions between 1275 and 1830 m a.s.l. The density of the melted firn at stakes T2, T4, 105-02 and 7-02 was set as 0.7 g/cm^3. The density of the ice at stake 7-98 was set as 0.8 g/cm^3 because the stake is located close to the firn line where the surface ice has not been subjected to high pressure. The density of the ice at stakes 8 and 10 is set as 0.9 g/cm^3. From these seven point values the summer balance curve in Figure 6-2 was drawn.

The summer balance was calculated as -2.7 ±0.2 m w.eqv., corresponding to -46 ±3 mill. m^3 of water. This is 137 % of the 1963-2002 average, which is –1.96 m w.eqv., and 131 % of the 1998-2002 average of –2.05 m w.eqv.

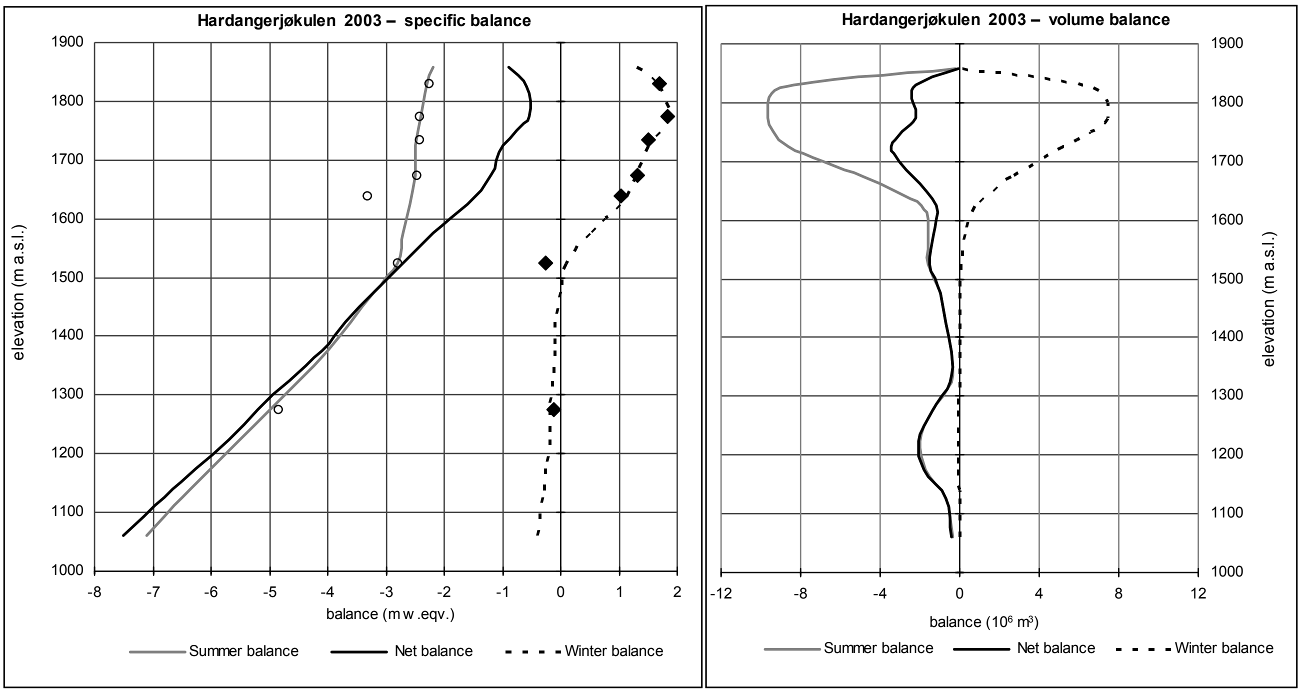


Figure 6-2
Altitudinal distribution of winter-, summer- and net balance shown as specific balance (left) and volume balance (right) at Rembesdalskåka, Hardangerjøkulen in 2003. Specific winter and summer balance at seven locations are shown (♦ and o).

Mass balance Hardangerjøkulen 2002/03 – traditional method							
		Winter balance		Summer balance		Net balance	
		Measured 16th Jun 2003		Measured 14th Oct 2003		Summer surface 2002 - 2003	
Altitude (m a.s.l.)	Area (km²)	Specific (m w.eqv.)	Volume (10⁶ m³)	Specific (m w.eqv.)	Volume (10⁶ m³)	Specific (m w.eqv.)	Volume (10⁶ m³)
1850 - 1865	0,09	1,30	0,1	-2,20	-0,2	-0,90	-0,1
1800 - 1850	3,93	1,70	6,7	-2,30	-9,0	-0,60	-2,4
1750 - 1800	4,03	1,85	7,5	-2,40	-9,7	-0,55	-2,2
1700 - 1750	3,46	1,50	5,2	-2,50	-8,6	-1,00	-3,5
1650 - 1700	1,94	1,30	2,5	-2,50	-4,8	-1,20	-2,3
1600 - 1650	0,75	1,00	0,7	-2,60	-1,9	-1,60	-1,2
1550 - 1600	0,59	0,50	0,3	-2,70	-1,6	-2,20	-1,3
1500 - 1550	0,57	0,10	0,1	-2,80	-1,6	-2,70	-1,5
1450 - 1500	0,29	0,00	0,0	-3,20	-0,9	-3,20	-0,9
1400 - 1450	0,19	-0,10	0,0	-3,60	-0,7	-3,70	-0,7
1350 - 1400	0,10	-0,10	0,0	-4,00	-0,4	-4,10	-0,4
1300 - 1350	0,10	-0,15	0,0	-4,50	-0,4	-4,65	-0,5
1250 - 1300	0,27	-0,20	-0,1	-5,00	-1,4	-5,20	-1,4
1200 - 1250	0,36	-0,20	-0,1	-5,50	-2,0	-5,70	-2,1
1150 - 1200	0,28	-0,25	-0,1	-6,00	-1,7	-6,25	-1,8
1100 - 1150	0,11	-0,30	0,0	-6,50	-0,7	-6,80	-0,7
1020 - 1100	0,05	-0,40	0,0	-7,10	-0,4	-7,50	-0,4
1020 - 1865	17,1	1,33	22,8	-2,69	-46,1	-1,36	-23,3

Table 6-1
Altitudinal distribution of winter-, summer- and net balances at Rembesdalskåka, Hardangerjøkulen in 2003.

Net balance

The net balance at Rembesdalskåka was calculated as -1.4 ±0.3 m w.eqv. or -23 ±5 mill. m^3 water. The 1963-2002 average is +0.16 m w.eqv., and the 1998-2002 average is +0.12 m. Since all the winter snow had melted during the summer, the ELA for 2003 was above the highest point of the glacier. Consequently, the accumulation area ratio (AAR) was 0 %. The altitudinal distribution of winter-, summer- and net balances is shown in Figure 6-2 and Table 6-1. Results from 1963-2003 are shown in Figure 6-3.

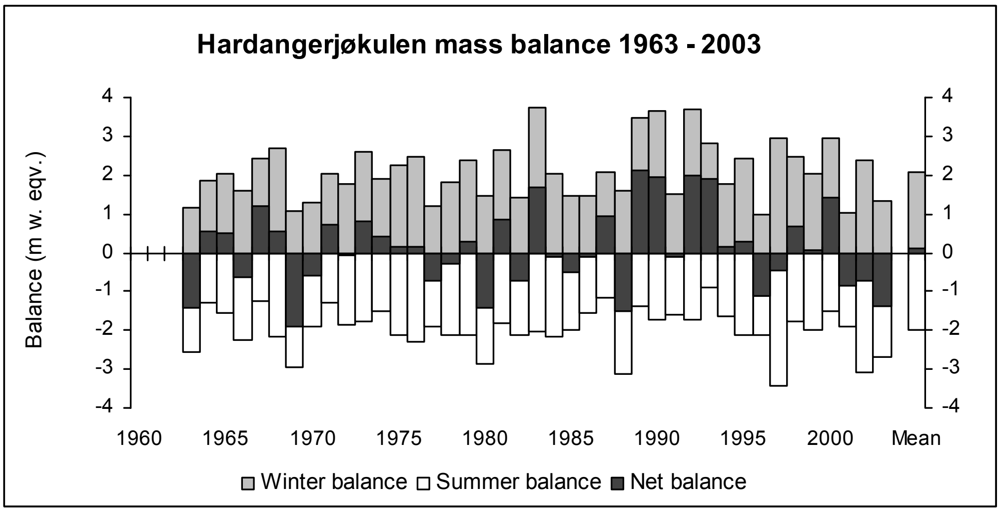


Figure 6-3
Winter-, summer- and net balances at Hardangerjøkulen during the period 1963-2003. Mean values for the period are b_w=2.10 m, b_s=-1.98 m and b_n=+0.12 m water equivalent.

7. Storbreen (Liss M. Andreassen)

Storbreen (61°34' N, 8°8' E) is situated in the Leirdalen valley in the central part of Jotunheimen, a mountainous area in central southern Norway (Fig. 7-1). The glacier has a total area of 5.4 km^2 and ranges in altitude from 1390 to 2090 m a.s.l. (Fig. 7-2). Mass balance measurements were initiated in 1949 and have been carried out continuously since then. Since September 2001 an automatic weather station (AWS) has been running on the glacier and some results from the first two years are presented in chapter 7.2.

Figure 7-1
Location map showing Storbreen and other glaciers (shaded) in the Jotunheimen mountain area. Mass balance measurements are carried out on Storbreen and Hellstugubreen in the central part and on Gråsubreen in the eastern part.

7.1 Mass balance 2003

Fieldwork

Accumulation measurements were performed on 15th May. Stakes were visible at 9 different locations. Snow depth was measured at 128 points along 13 km of profiles, covering almost the whole altitudinal range of the glacier (Fig. 7-2). The probing conditions were good, and the summer surface from the previous year was easy to identify. Snow depth varied between 0.5 and 3.9 m, with a mean of 2.5 m.

Snow density was measured at stake 4 (1730 m a.s.l., Fig. 7-2) by sampling in a 2.7 m deep pit. Ablation measurements were performed on 28th September. Ablation or net balance was measured at 8 stake locations.

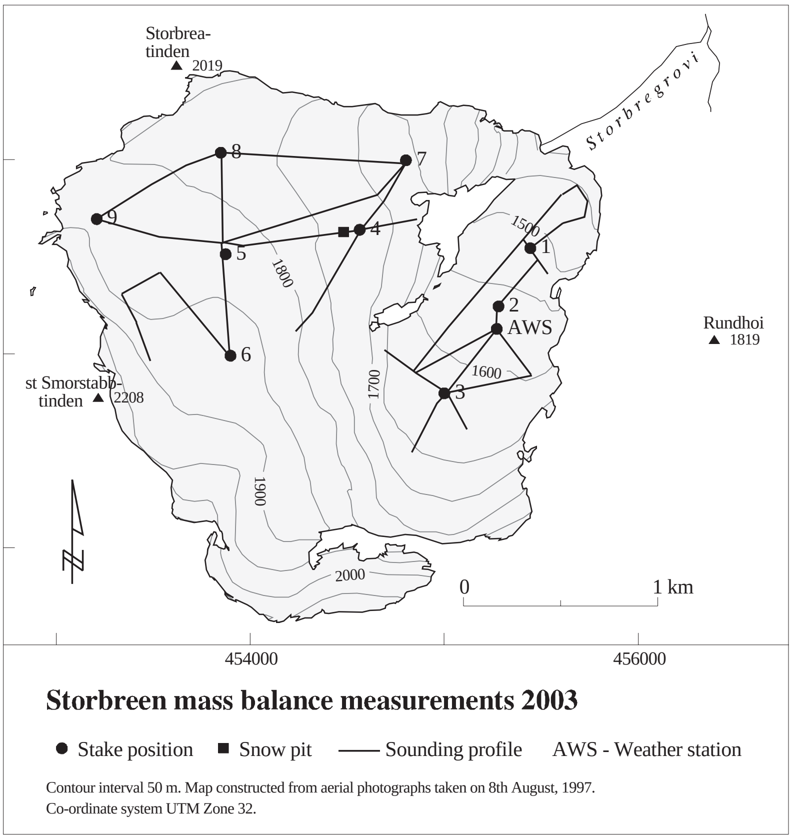


Figure 7-2
Map of Storbreen showing the location of stakes, snow pit, sounding profiles and weather station (AWS) in 2003.

Results

The mass balance results are shown in Table 7-1 and Figure 7-3.

Winter balance

Winter accumulation was calculated from soundings and the snow density measurements. The mean measured snow density was 0.40 g/cm^3. The density profile was considered to be representative for the rest of the glacier. The winter accumulation was calculated as the mean of the soundings within each 50-metre height interval. There was no additional melting after the ablation measurements the previous year.

The specific winter balance was thus calculated to be 1.11 ± 0.2 m w.eqv. This is 77 % of the mean for the period 1949-2002.

Summer balance

Summer balance was calculated directly from stakes at eight locations. There was no remaining snow at any of the stakes. The density of the melted firn was assumed to be 0.7 g/cm^3. The density of the melted ice was assumed to be 0.9 g/cm^3. The summer balance was calculated to be -2.68 ± 0.3 m w.eqv, which is 160 % of the mean for the period 1949-2002. This is the third most negative summer balance measured, only in 2002 and 1997 has there been recorded higher ablation at Storbreen.

Net balance

The net balance of Storbreen in 2003 was -1.6 ± 0.3 m w.eqv., which is equivalent to a volume of -8.4 ± 0.16 10^6 m^3 of water. This is the second largest deficit measured at Storbreen; only 2002 was more negative. Except for a few isolated patches all the snow from the previous winter melted away. The ELA was estimated to be 2025 m a.s.l. and the accumulation area ratio (AAR) 2 %. The total deficit of the glacier since 1949 amounts to -14.1 m w.eqv., giving a mean annual net balance of -0.26 m w.eqv. for the 56 years of measurements (Fig. 7-5). Figure 1-3 (p. 12) shows the cumulative balance of Storbreen and four other glaciers since 1963.

Mass balance Storbreen 2002/03 – traditional method

		Winter balance		Summer balance		Net balance	
		Measured 15th May		Measured 28th Sep		Summer surfaces 2002 - 2003	
Altitude (m a.s.l.)	Area (km^2)	Specific (m w.eq.)	Volume (10^6 m^3)	Specific (m w.eq.)	Volume (10^6 m^3)	Specific (m w.eq.)	Volume (10^6 m^3)
2050 - 2100	0.04	1.75	0.07	-1.50	-0.06	0.25	0.01
2000 - 2050	0.15	1.65	0.25	-1.65	-0.25	0.00	0.00
1950 - 2000	0.23	1.60	0.37	-1.80	-0.41	-0.20	-0.05
1900 - 1950	0.36	1.50	0.54	-1.95	-0.70	-0.45	-0.16
1850 - 1900	0.57	1.45	0.83	-2.15	-1.23	-0.70	-0.40
1800 - 1850	0.92	0.89	0.82	-2.40	-2.21	-1.51	-1.39
1750 - 1800	0.75	1.03	0.78	-2.65	-1.99	-1.62	-1.21
1700 - 1750	0.64	0.89	0.57	-2.80	-1.79	-1.91	-1.22
1650 - 1700	0.40	1.25	0.50	-3.00	-1.20	-1.75	-0.70
1600 - 1650	0.49	1.12	0.55	-3.25	-1.59	-2.13	-1.04
1550 - 1600	0.35	0.96	0.34	-3.45	-1.21	-2.49	-0.87
1500 - 1550	0.21	0.79	0.17	-3.60	-0.76	-2.81	-0.59
1450 - 1500	0.18	0.68	0.12	-3.80	-0.68	-3.12	-0.56
1390 - 1450	0.06	0.68	0.04	-4.00	-0.24	-3.32	-0.20
1390 - 2100	**5.35**	**1.11**	**5.94**	**-2.68**	**-14.32**	**-1.57**	**-8.38**

Table 7-1
The distribution of winter, summer and net balance in 50 m altitude intervals for Storbreen in 2003.

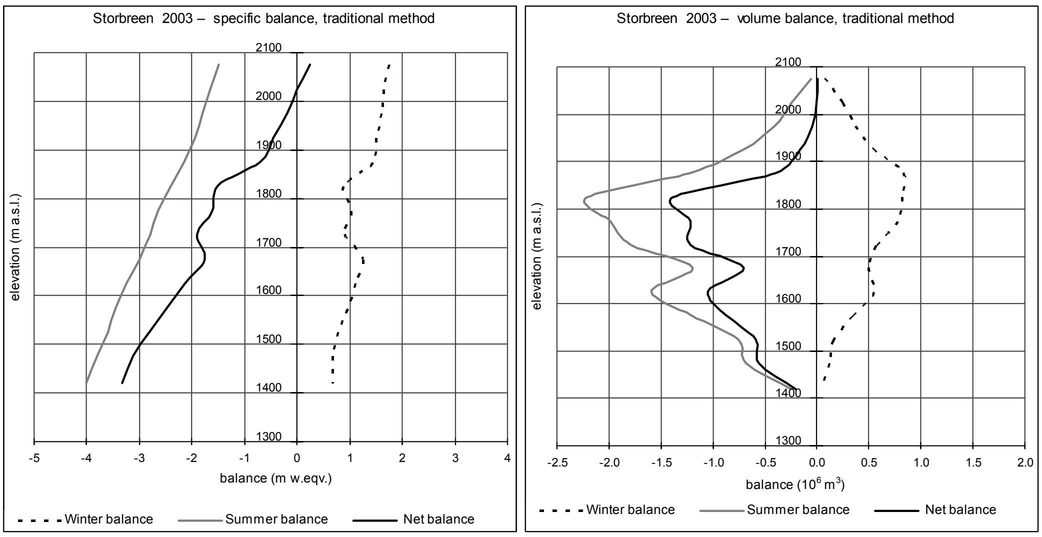


Figure 7-3
Mass balance diagram for Storbreen 2003, showing specific balance on the left and volume balance on the right.

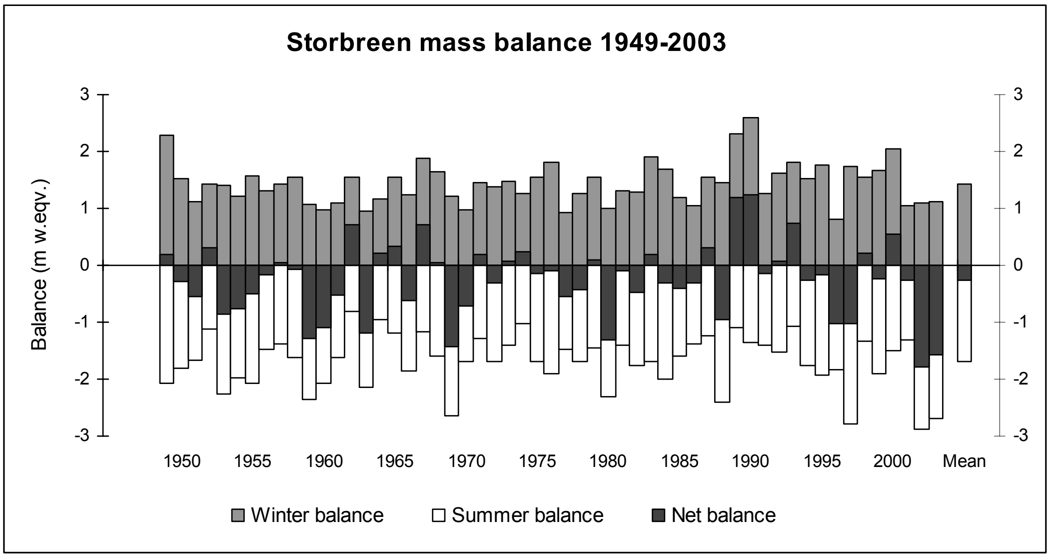


Figure 7-4
Winter, summer and net balance at Storbreen for the period 1949-2003.

7.2 Meteorological measurements

Since September 2001 an automatic weather station (AWS) has been operating in the ablation zone of Storbreen, at about 1580 m asl. (Fig. 7-2 and Fig. 7-5). Some of the results from the first two years are presented here. The station records air temperature, wind speed, wind direction, radiation and height above the surface every 30-minutes. The station was put up by the Institute of Marine and Atmospheric Research (IMAU), University of Utrecht (e-mail: j.oerlemans@phys.uu.nl) and is operated by IMAU, in co-operation with NVE. The results from the AWS will be used to monitor the local climate of Storbreen and to calibrate an energy-balance model for Storbreen.

Figure 7-5
The automatic weather station (AWS) at Storbreen, July 2003. Photo: Liss M. Andreassen.

Results

Air temperature

Air temperature was measured at two levels, at 2 m and at 6 m above the surface. The sensor at the lowest level was buried by snow during the first winter. The data from the highest level is shown in Figure 7-6. The annual mean temperature was −1.0 °C in 2001/2002 and –2.0 °C in 2002/2003. The lowest diurnal value recorded during the observation period was -18.3 °C (3rd January 2003), while the highest diurnal value was 12.3 °C (16th July 2003).

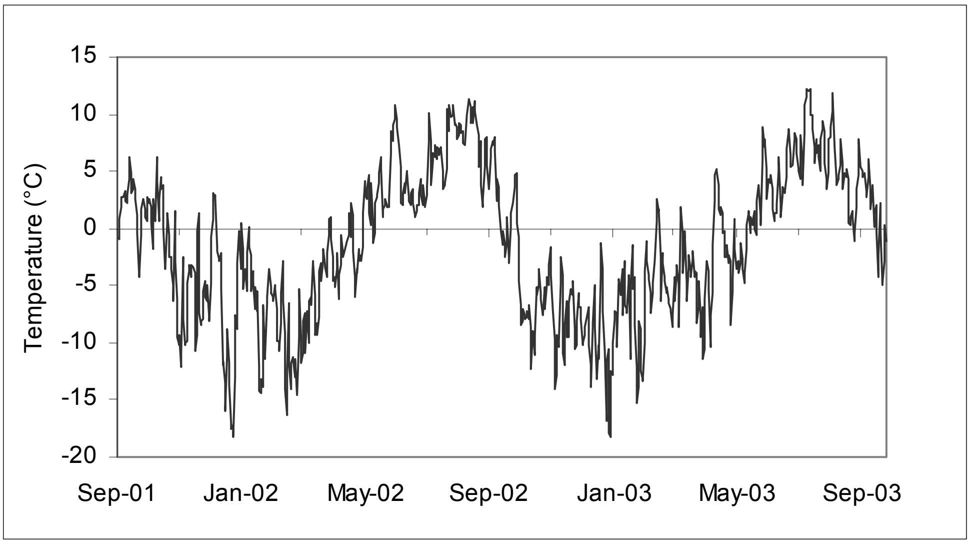


Figure 7-6
Daily mean temperature measured 6 m above the glacier surface of Storbreen from 6th September 2001 to 1st October 2003.

Wind

Wind was also measured at two levels, at 2 and at 6 m. The sensor at the lowest level was covered by snow in February 2002 and no reliable data were obtained afterwards, so only the values from the upper sensor at 6 m covered both years. The mean wind speed at 6 m height was 3.8 m/s in 2001/2001 and 3.4 m/s in 2002/2003. The mean wind speed was about 0.5 m/s lower at the 2 m level for the 5 month-period when both sensors were operating.

The mean wind direction at 6 m level was about 190 degrees in both observation years (Fig. 7-7). The dominant wind direction is down slope, towards the glacier tongue.

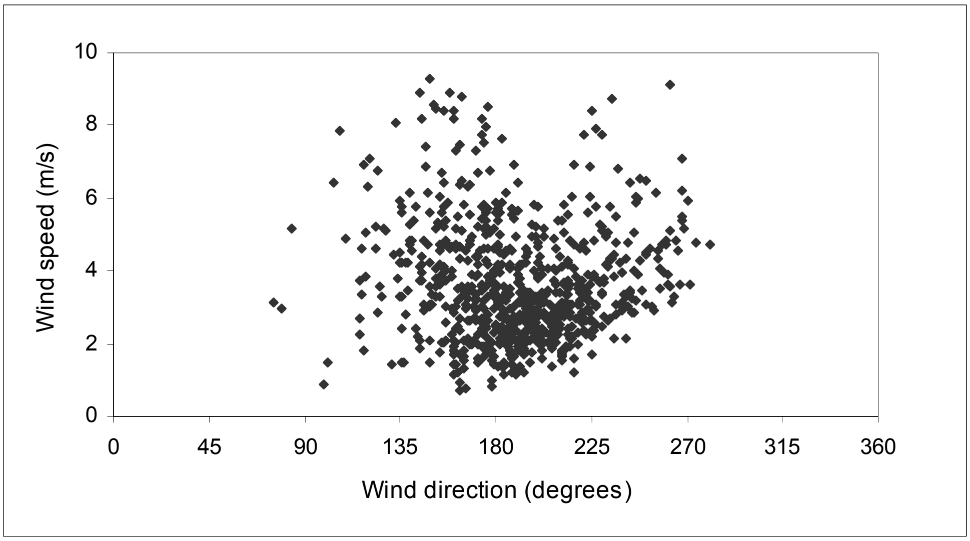


Figure 7-7
Daily mean wind speed versus daily mean wind direction at 6 m level at Storbreen from 6th September 2001 to 1st October 2003. The dominant wind direction is down slope the glacier.

Radiation

The AWS measures shortwave (solar) radiation by two pyranometers and infrared radiation by two pyrgometers. Figure 7-8 shows the incoming and outgoing shortwave radiation measured in the observation period. The annual cycles in solar radiation are clearly seen. Note the large difference in albedo (ratio of reflected to incoming radiation) between spring and fall.

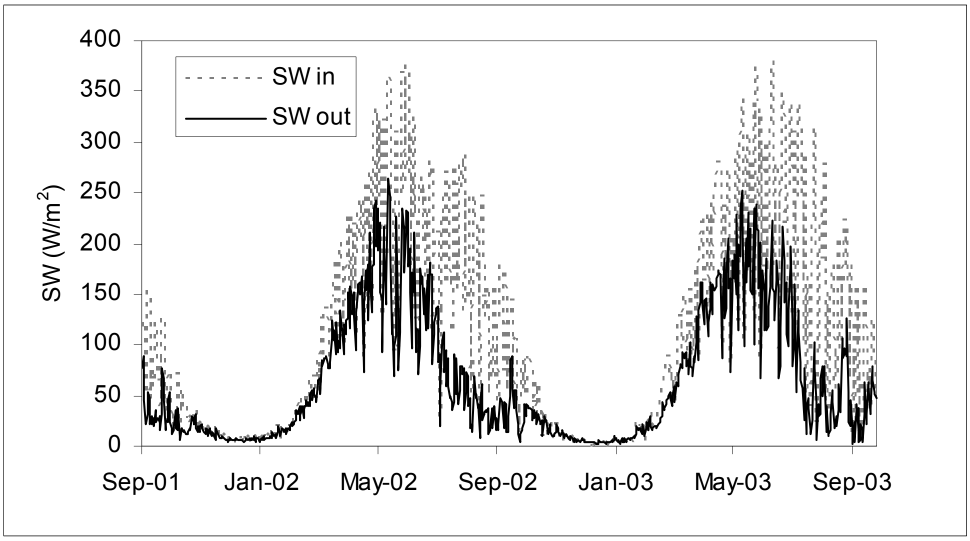


Figure 7-8
Daily mean incoming (SW in) and reflected (SW out) shortwave radiation for Storbreen from 6th September 2001 to 1st October 2003.

8. Hellstugubreen (Liss M. Andreassen)

Hellstugubreen (61º34`N, 8º 26`E) is a north-facing valley glacier situated in central Jotunheimen (Fig. 7-1). It ranges in elevation from 1480 to 2210 m a.s.l. and has an area of 3.0 km^2 (Fig. 8-1). Mass balance investigations have been carried out annually since 1962, and 2003 is the 42nd year of continuous measurements.

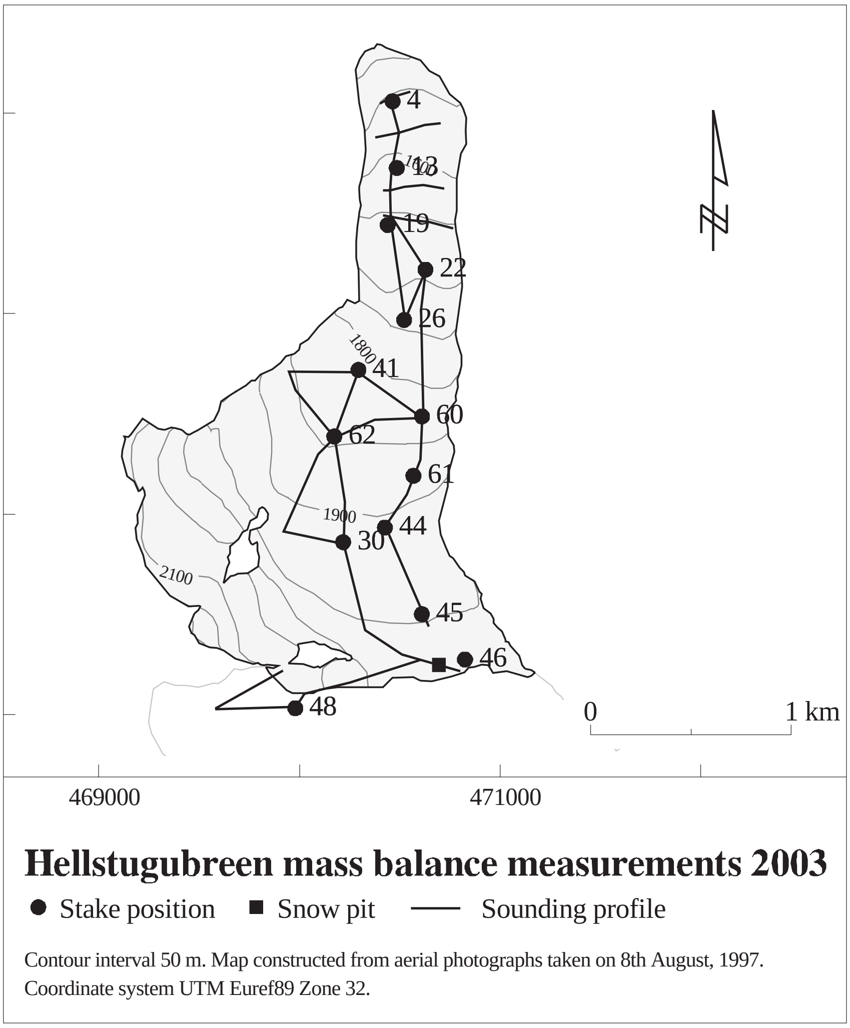


Figure 8-3
Map of Hellstugubreen showing location of stakes, sounding profiles and snow pit in 2003. Figure 7-1 shows a location map of the study glaciers in Jotunheimen.

8.1 Mass balance 2003

Fieldwork

Accumulation measurements were carried out on 16th May. Stakes at 15 locations were visible. Snow depth was measured at 105 points along 10.5 km of profiles covering most of the glacier (Fig. 8-1). The probing conditions were good, and the summer surface from the previous year was easy to identify over the whole glacier. The snow depth varied between 0.5 and 2.9 metres, with a mean depth of 1.9 m. The snow density was measured by sampling in a pit at 1960 m a.s.l. The total snow depth was 2.2 m. Ablation measurements were carried out on 10th September at stakes in all locations, except one (stake 48) which was measured on 28th September (Figure 8-2). The location of stakes, density pit and sounding profiles are shown in Figure 8-1.

Figure 8-2
Measurements at stake 48 at Hellstugubreen on 28th September 2003. The glacier hut is visible in the background (on the horizon). Photo: Liss M. Andreassen.

Results

The mass balance results are presented in Table 8-1 and Figure 8-3.

Winter balance

The winter balance was calculated from soundings and one snow density measurement, which was considered to be representative for the whole glacier. The density was 0.37 g/cm^3. The winter accumulation was calculated as the mean of the soundings within each 50-metre height interval. The additional melt after the previous year's ablation measurement was insignificant this year and was not accounted for, in contrast to the two previous years. The winter balance was 0.71 ± 0.2 m w.eqv. This is only 63 % of the mean for the period 1962-2002, the fourth lowest winter balance measured at the glacier.

Summer balance

The summer balance was calculated from stakes at 13 locations. There was no snow left from the winter at any of the stakes at the end of the season. The density of the melted firn was estimated to be between 0.70 and 0.75 g/cm^3 depending on the age of the firn. The density of the melted ice was assumed to be 0.9 g/cm^3 as usual. The summer balance was calculated to be -2.2 ± 0.3 m w.eqv., which is 158 % of the mean value for the entire observation period. This is the fourth highest ablation measured at Hellstugubreen.

Net balance

Winter precipitation far below normal and high melting resulted in the second most negative net balance measured at Hellstugubreen, exceeded only by that measured in 1997. The net balance of Hellstugubreen in 2003 was -1.5 ± 0.3 m w.eqv., which amounts to a lost volume of -4.4 ± 0.09 mill. m^3 water. The equilibrium line altitude (ELA) was not observed due to fresh snow covering the glacier in late September, but was assumed to be above 2200 m a.s.l. giving an accumulation area ratio (AAR) of 0 % (Fig. 8-3). Since 1962 Hellstugubreen has had a cumulative mass loss of 13.6 m w.eqv., the equivalent of -0.32 m w.eqv. per year (Fig. 8-4).

Mass balance Hellstugubreen 2002/03 – traditional method

		Winter balance		Summer balance		Net balance	
		Measured 16th May 2003		Measured 10th Sep 2003		Summer surfaces 2002 - 2003	
Altitude (m a.s.l.)	Area (km^2)	Specific (m w.eq.)	Volume (10^6 m^3)	Specific (m w.eq.)	Volume (10^6 m^3)	Specific (m w.eq.)	Volume (10^6 m^3)
2100 - 2200	0.02	0.72	0.01	-1.30	-0.03	-0.58	-0.01
2050 - 2100	0.25	0.79	0.20	-1.40	-0.35	-0.61	-0.15
2000 - 2050	0.17	0.92	0.16	-1.50	-0.26	-0.58	-0.10
1950 - 2000	0.35	0.83	0.29	-1.70	-0.60	-0.87	-0.30
1900 - 1950	0.60	0.73	0.44	-1.90	-1.14	-1.17	-0.70
1850 - 1900	0.35	0.72	0.25	-2.10	-0.74	-1.38	-0.49
1800 - 1850	0.33	0.82	0.27	-2.30	-0.75	-1.48	-0.48
1750 - 1800	0.14	0.62	0.09	-2.50	-0.35	-1.88	-0.26
1700 - 1750	0.10	0.68	0.07	-2.70	-0.26	-2.02	-0.20
1650 - 1700	0.16	0.74	0.12	-2.95	-0.48	-2.21	-0.36
1600 - 1650	0.13	0.60	0.08	-3.30	-0.43	-2.70	-0.35
1550 - 1600	0.17	0.33	0.06	-3.60	-0.62	-3.27	-0.57
1500 - 1550	0.09	0.13	0.01	-3.80	-0.35	-3.67	-0.34
1465 - 1500	0.03	0.10	0.00	-4.00	-0.11	-3.90	-0.11
1465 - 2200	**2.90**	**0.71**	**2.05**	**-2.23**	**-6.47**	**-1.53**	**-4.43**

Table 8-2
The distribution of winter, summer and net balance in 50 m altitude intervals for Hellstugubreen in 2003.

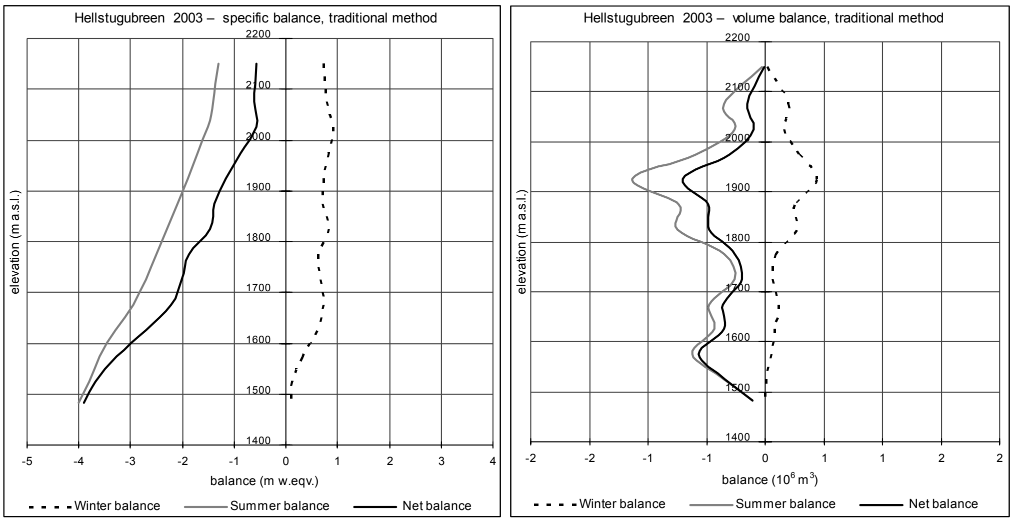


Figure 8-3
Mass balance diagram for Hellstugubreen 2003, showing specific balance on the left and volume balance on the right.

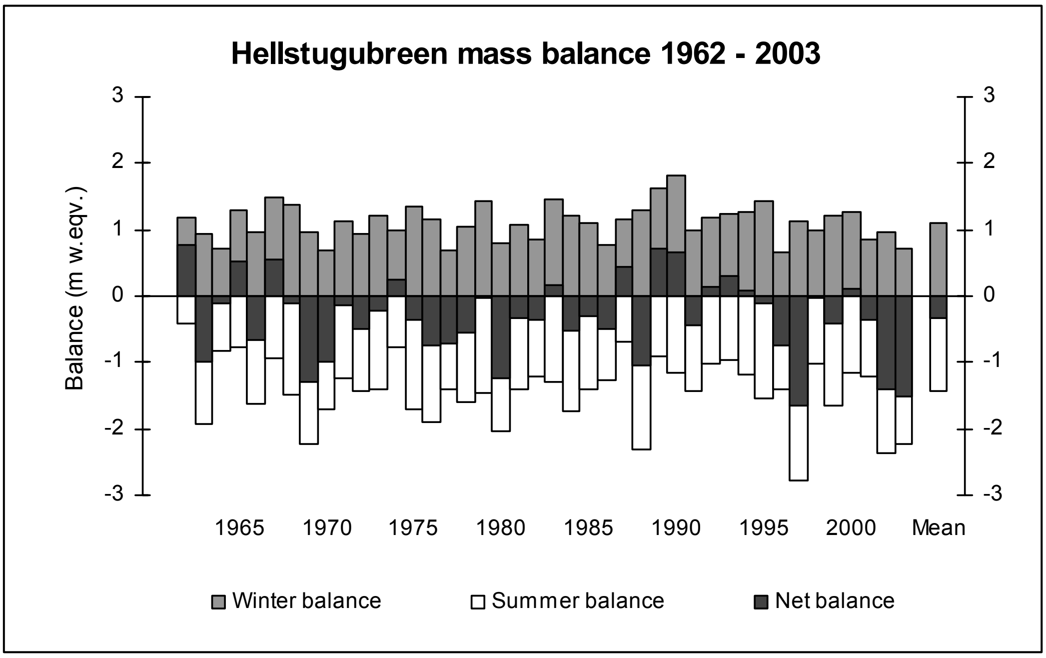


Figure 8-4
Winter, summer and net balance at Hellstugubreen for the period 1962-2003.

9. Gråsubreen (Liss M. Andreassen)

Gråsubreen (61°39' N, 8°37'E) is located in the eastern part of the Jotunheimen mountain area in southern Norway (Fig. 7-1). The glacier covers an area of 2.2 km^2 and ranges in elevation from 1830 to 2290 m a.s.l. (Fig. 9-1). Annual mass balance measurements began in 1962 and have continued annually since then.

Gråsubreen is a polythermal glacier. Superimposed ice occurs in the central parts of the glacier where snowdrift causes a relatively thin snow pack, and superimposed ice may be responsible for up to 8 % of the total accumulation in these areas.

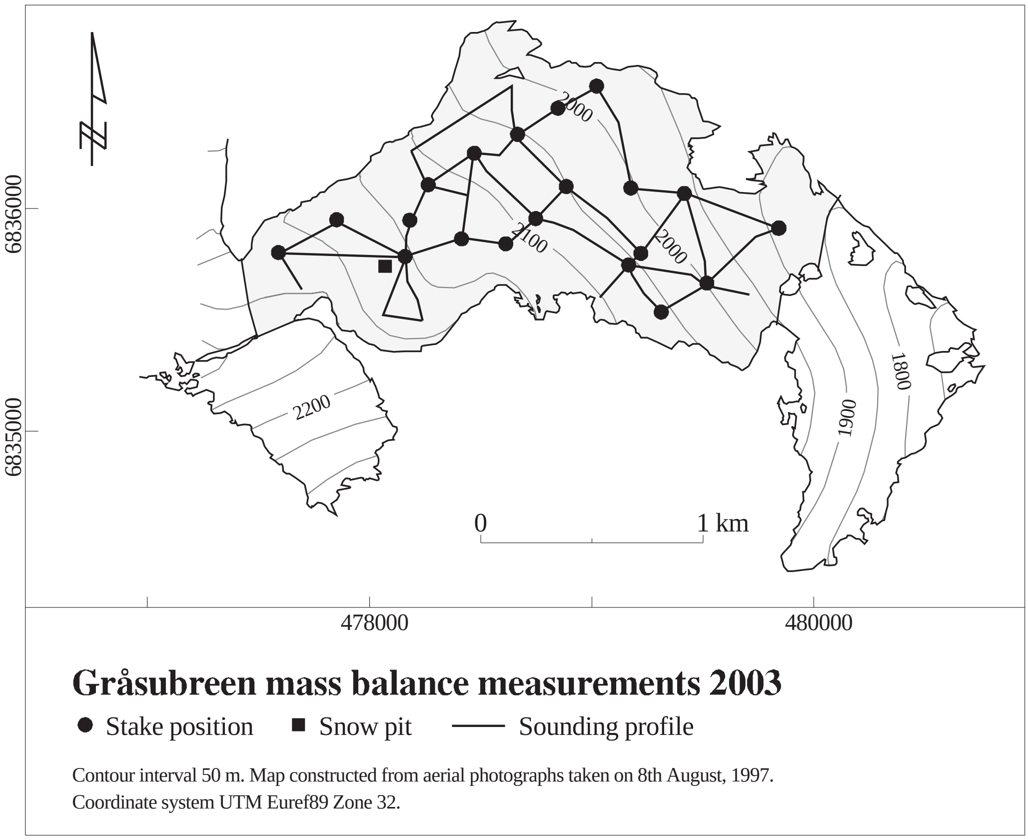


Figure 9-4
Map of Gråsubreen (shaded in grey) showing the location of stakes, snow pit and sounding profiles in 2003. A location map of Gråsubreen and other glaciers in Jotunheimen is shown in Figure 7-1.

9.1 Mass balance 2003

Fieldwork

Accumulation measurements were carried out on 18th May. Stakes in 19 locations were measured. A total of 101 snow depth measurements were made along 11.1 km of profiles, covering most of the glacier (Fig. 9-1). The probing conditions were good, and the previous year's summer surface was easy to identify over the entire glacier. Snow depth varied between 0.4 and 2.4 m, with a mean of 1.2 m.

The snow density was measured at 2180 m a.s.l. in a pit dug through the winter snow pack (1.8 m snow). Ablation measurements were carried out on 27th September, when stakes in all locations were measured (Fig. 9-1). A fresh layer of 5-25 cm of snow covered the surface. Field work carried out on 5th August revealed that most of the winter snow had already melted away from the glacier at this time (Fig. 9-2).

Figure 9-5
View of the upper part of Gråsubreen looking west towards Glittertind, the second highest peak in Norway. The picture was taken on 5th August 2003 and most of the winter snow had already melted away. Photo: Liss M. Andreassen.

Results

The mass balance results are presented in Table 9-1 and Figure 9-3.

Winter balance

Winter accumulation was calculated from the soundings and the snow density measurement, which was considered representative for the whole glacier. The mean measured snow density was low, only 0.33 g/cm^3. The winter accumulation was calculated as the mean of the soundings within each 50-meter height interval. This gave a winter balance of 0.45 ± 0.2 m w.eqv., which is 58 % of the mean for the period 1962-2002.

The stake recordings showed neither significant additional melting after the previous year's ablation measurements, nor any significant formation of superimposed ice. Therefore, winter balance was not adjusted for these factors.

Summer balance

Summer balance was calculated from direct measurements of stakes in 16 locations. There was no remaining snow left at any of the stakes. The density of the melted ice and firn was estimated to be 0.90 and 0.75 g/cm^3 respectively. The resulting summer balance was -1.84 ± 0.3 m w.eqv. This is 174 % of the mean for the period 1962-2002. This is the fifth largest summer balance recorded at Gråsubreen during the observation period.

Net balance

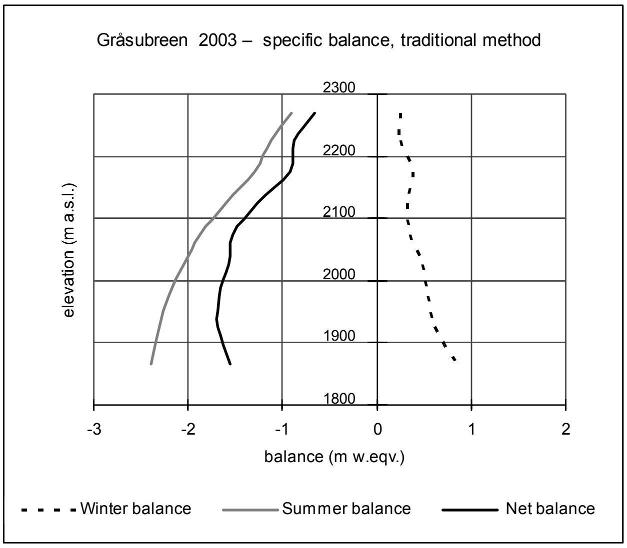
Gråsubreen had a pronounced mass loss in 2003 with a net balance of -1.4 ± 0.3 m w.eqv, the same as in 2002 and the second largest net deficit during the observation period, only 1997 had a larger deficit than 2002 and 2003. The equilibrium line altitude (ELA) at the end of the season was not observed due to fresh snow covering the glacier, but was assumed to be above the maximum altitude of the glacier, thus the accumulation area ratio (AAR) was 0 % (Fig. 9-3).

Since 1962 Gråsubreen has had a cumulative mass loss of 12.7 m w.eqv., or - 0.30 m w.eqv. per year. Most of this mass loss occurred in the 1970s and 1980s, however, the glacier has had a pronounced deficit over the past two years (Fig 9-4). Figure 1-3 (p. 12) shows the cumulative balance of Gråsubreen and four other glaciers since 1963.

Mass balance Gråsubreen 2002/03 – traditional method

		Winter balance Measured 18th May 2003		Summer balance Measured 27th Sep		Net balance Summer surfaces 2002 - 2003	
Altitude (m a.s.l.)	Area (km^2)	Specific (m w.eq.)	Volume (10^6 m^3)	Specific (m w.eq.)	Volume (10^6 m^3)	Specific (m w.eq.)	Volume (10^6 m^3)
2250 - 2290	0.04	0.25	0.01	-0.90	-0.04	-0.66	-0.03
2200 - 2250	0.17	0.25	0.04	-1.12	-0.19	-0.87	-0.14
2150 - 2200	0.26	0.38	0.10	-1.30	-0.34	-0.92	-0.24
2100 - 2150	0.34	0.33	0.11	-1.60	-0.54	-1.27	-0.43
2050 - 2100	0.37	0.36	0.13	-1.88	-0.70	-1.52	-0.57
2000 - 2050	0.42	0.48	0.20	-2.05	-0.86	-1.57	-0.66
1950 - 2000	0.36	0.54	0.19	-2.20	-0.79	-1.66	-0.60
1900 - 1950	0.14	0.62	0.09	-2.30	-0.33	-1.68	-0.24
1830 - 1900	0.15	0.85	0.13	-2.40	-0.37	-1.55	-0.24
1830 - 2290	**2.25**	**0.45**	**1.00**	**-1.84**	**-4.15**	**-1.39**	**-3.14**

Table 9-1
The distribution of winter, summer and net balance in 50 m altitude intervals for Gråsubreen in 2003.



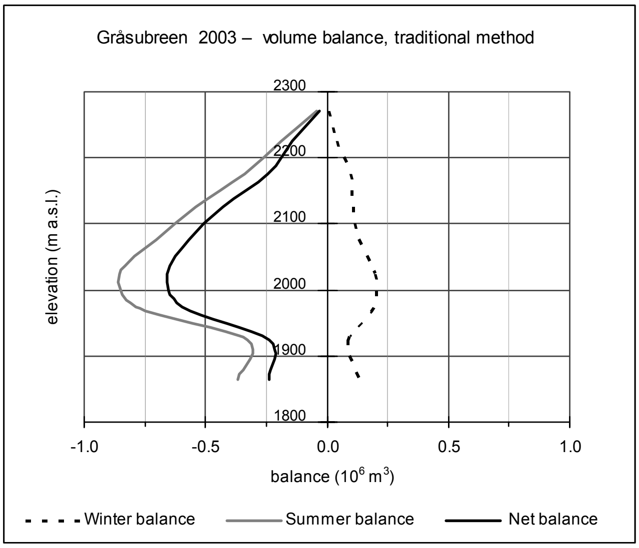


Figure 9-3
Mass balance diagram for Gråsubreen 2003, showing specific balance on the left and volume balance on the right.

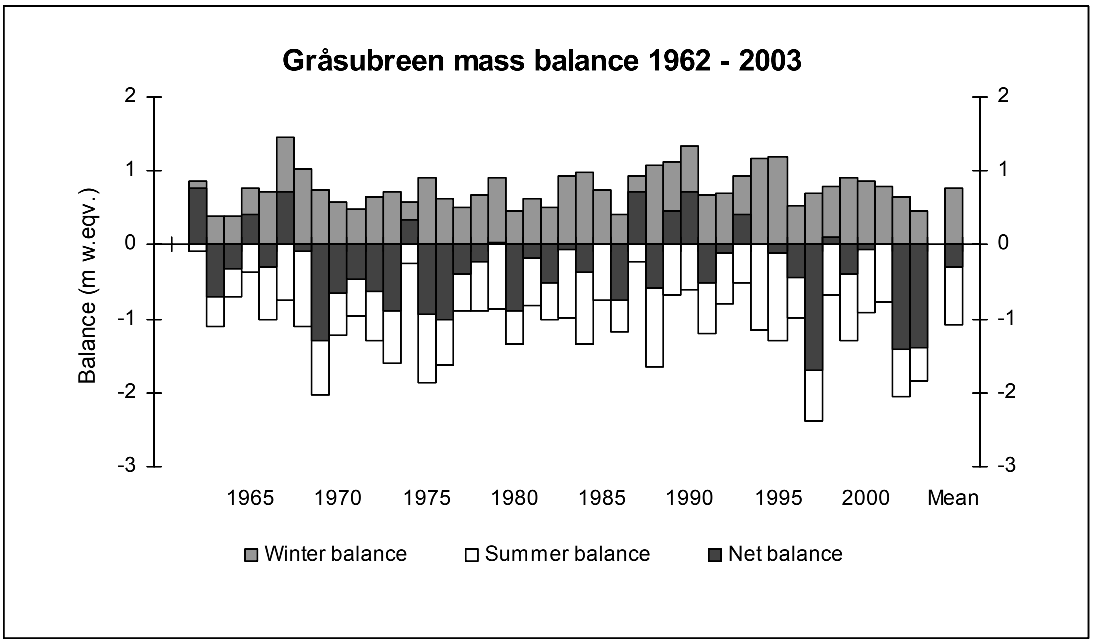


Figure 9-4
Winter, summer and net balance at Gråsubreen during the period 1962-2003.

10. Engabreen (Hallgeir Elvehøy)

Engabreen (66°40'N, 13°45'E) is a 38 km^2 north-western outlet from the western Svartisen ice cap. It covers an altitude range from 1575 m a.s.l. (at Snøtind) down to 7 m a.s.l. (at Engabrevatnet), as shown in Figure 10-1. Mass balance measurements have been performed annually since 1970.

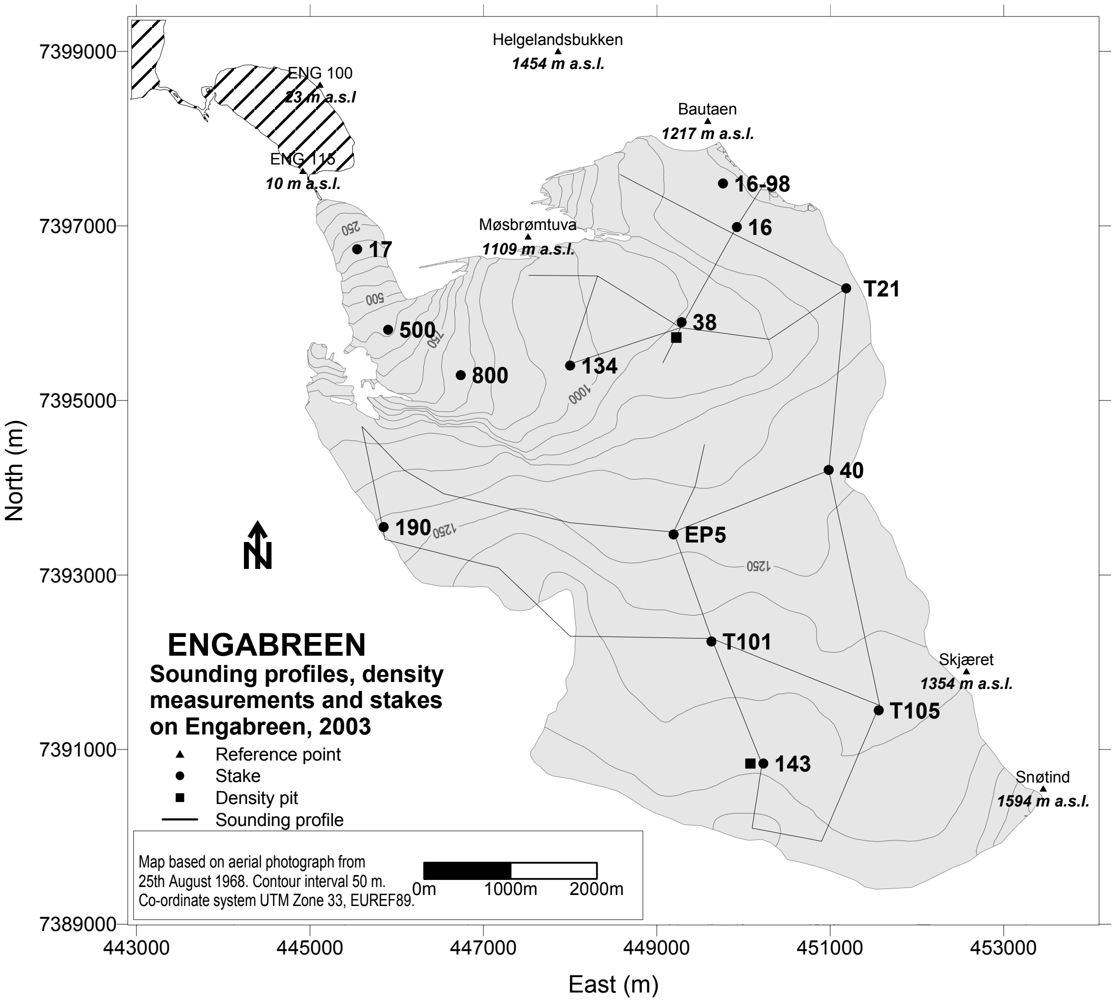


Figure 10-1
Location of stakes, density pits and sounding profiles on Engabreen in 2003.

10.1 Mass balance 2003

Fieldwork

Snow accumulation measurements were carried out between 20th and 23rd May. The locations of stakes and towers, density pits, core samples and sounding profiles are shown in Figure 10-1. The calculation of winter balance is based on:

- Direct measurements of snow depth at eleven stakes between 300 and 1340 m a.s.l. At stake 17 and 500, all the winter snow and 0.75m and 0.40 m of ice, respectively, had melted.
- The transient snow line altitude at 600 m a.s.l.
- Snow density measured to a depth of 4.35 m at stake 38, and to 5.95 m depth at stake 143. Mean snow density was 0.56 g/cm^3 and 0.50 g/cm^3, respectively.
- 161 snow depth soundings along 32 km of profiles. The snow depth was between 4.5 and 6.0 m above 1200 m a.s.l., and between 3.0 and 4.5 m between 950 and 1200 m a.s.l.

The net balance measurements were carried out on 28th September. There was up to 0.96 m of new snow on the glacier. From stake measurements the transient snow line altitude was about 1200 m a.s.l.

The net balance was observed at 10 positions between 300 and 1400 m a.s.l. At the glacier tongue (300 m a.s.l.), 11 m of ice had melted during the summer. At 960 m a.s.l. all the winter snow and 3.5 m of ice had melted. At 1050 m a.s.l. all the winter snow and 1 m of firn had melted away. Around 1200 m a.s.l., 4.5 to 5.0 m snow and some firn at certain stakes had melted away. Above 1200 m a.s.l. approximately 4.5 to 5.0 m of snow had melted away, and up to 1.5 m of snow remained at the stakes.

Results

The mass balance is calculated using the stratigraphic method, which reports the balance between two successive "summer surfaces", excluding snow accumulation before the date of net balance measurements but also excluding ablation after net balance measurements. The late autumn melting is normally restricted to the lower parts of the glacier. It is insignificant compared with winter accumulation and summer ablation, and it is usually difficult to determine accurately. The extent of late autumn melting is considered to be insignificant based on comparison of stake readings and snow depth soundings.

The calculations were performed using a map from 1968 and drainage divides calculated from bottom topography and ice thickness (Kennett & Elvehøy, 1995).

Winter balance

The calculation of winter balance was based on point measurements of snow depth (stake readings and snow depth soundings) and on snow density measurements (Fig. 10-1). Water equivalent profiles were modelled from the snow density measured at stake 38 and 143. Using these models, the mean snow density for 5 m of snow was calculated as 0.56 g/cm^3 at stake 38 and 0.49 g/cm^3 at stake 143. The models based on the density profiles at stake 38 and 143 were then used to calculate the water equivalent value of the snow depth measurements below and above 1225 m a.s.l., respectively.

Point values of the snow water equivalent (SWE) were plotted against altitude in a diagram, and a curve was drawn based on visual evaluation. Below 950 m a.s.l. the winter balance curve was interpolated based on the observed snow depth around stakes 34 and 800, the transient snow line altitude, and the observed negative winter balance at stakes 500 and 17 (Fig. 10-3). Based on this altitudinal distribution curve, the winter balance was calculated as 2.4 ±0.2 m w.eqv., which corresponds to a volume of 92 ±8 million m^3 of water. This is 82 % of the mean value for the period from 1970-2002 (2.95 m w.eqv.), and 102 % of the mean value for the 5-year period 1998-2002.

The winter balance is also calculated from the spatial distribution of the snow depth measurements using gridding methods (Fig. 10-2). The result based on this method was 2.35 m w.eqv., which is in close agreement with the result from the altitudinal distribution curve.

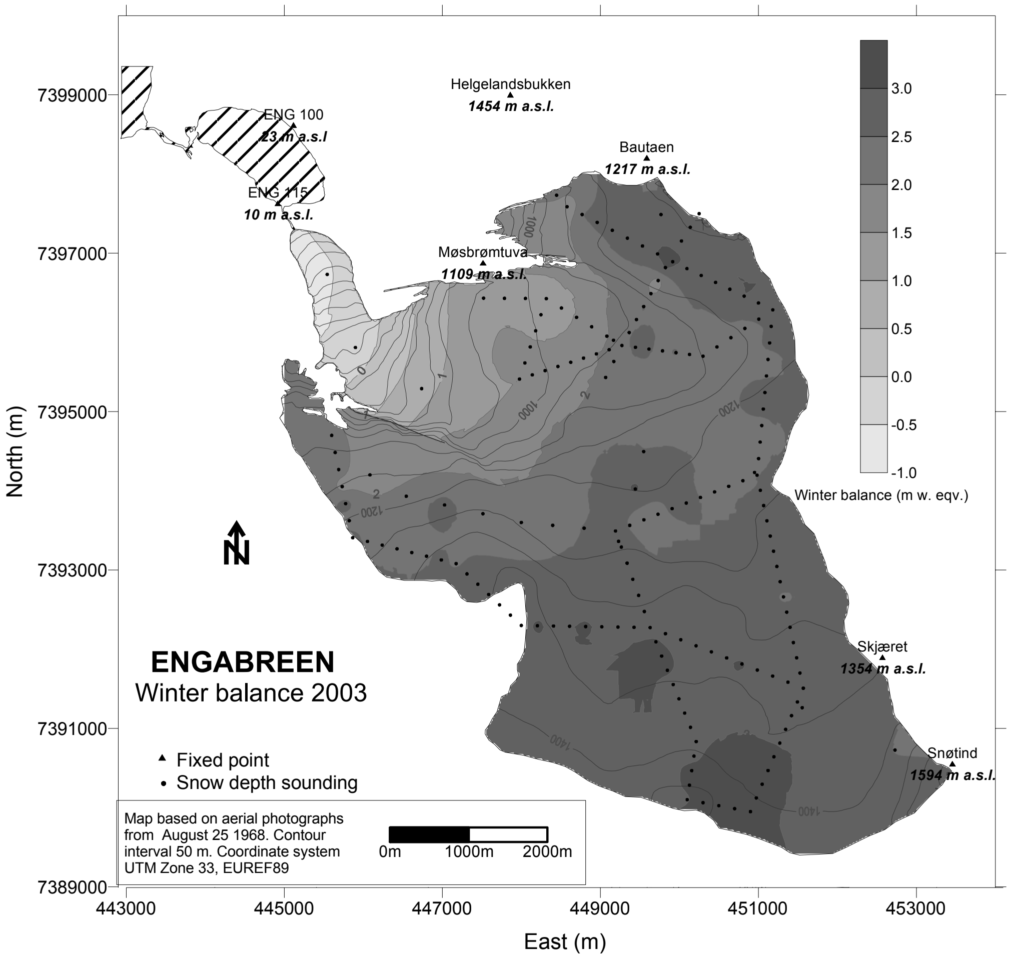


Figure 10-2
Winter balance at Engabreen in 2003 calculated from 174 point observations of snow depth and two point observations of ice melting.

Summer balance

The summer balance was measured and calculated directly at eleven locations between 300 and 1400 m a.s.l. An altitudinal distribution curve was drawn based on the measurements (Fig. 10-3). The summer balance was calculated as −3.0 ± 0.2 m w.eqv., which equals a volume of −114 ± 8 million m^3 water (Tab. 10-1). This is 132 % of the average for the period 1970-2002 (−2.28 m w.eqv.), and 122 % of the average for the 5-

year period 1998-2002. In 2002, the summer balance was −3.5 m w.eqv., while the highest summer balance measured at Engabreen was −4,1 m w.eqv. in 1988.

Net balance

The net balance of Engabreen for 2003 was calculated as –0.6 ±0.3 m w.eqv., which corresponds to a volume loss of 20 ±10 mill. m^3 water. The mean value for the period 1970-2002 is +0.63 m w.eqv., and −0.09 m w.eqv for 1998-2002. The equilibrium line altitude (ELA) was determined as 1195 m a.s.l. from the net balance curve in Figure 10-3. This gives an accumulation area ratio (AAR) of 55 %. The mass balance results are shown in Figure 10-3 and Table 10-1. The results from 2003 are compared with mass balance results for the period 1970 - 2002 in Figure 10-5.

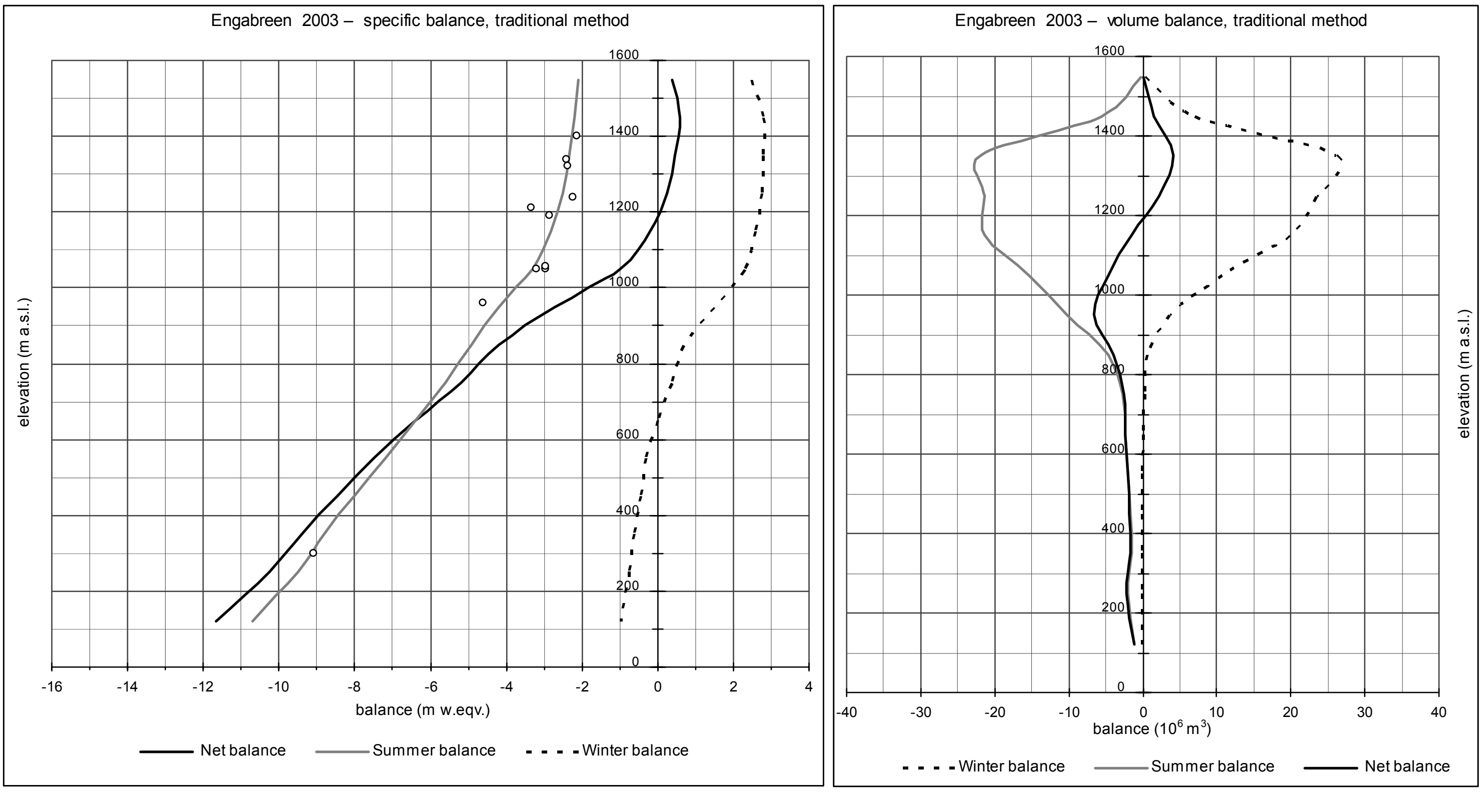


Figure 10-3
Mass balance diagram showing specific balance (left) and volume balance (right) for Engabreen in 2003. Summer balance at stakes and towers is shown as circles (○).

Figure 10-4
The terminus of Engabreen on 20th May 2003. The large boulder in the river was deposited there in 1998 at the culmination of the most recent advance. Photo: Hallgeir Elvehøy.

Mass balance Engabreen 2002/03 – traditional method

Altitude (m a.s.l.)	Area (km^2)	Winter balance, Measured 20th May 2003: Specific (m w.eqv.)	Winter balance, Measured 20th May 2003: Volume (10^6 m^3)	Summer balance, Measured 28th Sep 2003: Specific (m w.eqv.)	Summer balance, Measured 28th Sep 2003: Volume (10^6 m^3)	Net balance, Summer surface 2002 - 2003: Specific (m w.eqv.)	Net balance, Summer surface 2002 - 2003: Volume (10^6 m^3)
1500 - 1594	0,12	2,50	0,3	-2,10	-0,3	0,40	0,0
1400 - 1500	2,51	2,80	7,0	-2,20	-5,5	0,60	1,5
1300 - 1400	9,35	2,80	26,2	-2,35	-22,0	0,45	4,2
1200 - 1300	8,55	2,75	23,5	-2,50	-21,4	0,25	2,1
1100 - 1200	7,60	2,60	19,8	-2,80	-21,3	-0,20	-1,5
1000 - 1100	4,66	2,30	10,7	-3,30	-15,4	-1,00	-4,7
900 - 1000	2,46	1,50	3,7	-4,20	-10,3	-2,70	-6,6
800 - 900	0,94	0,70	0,7	-4,90	-4,6	-4,20	-3,9
700 - 800	0,50	0,40	0,2	-5,60	-2,8	-5,20	-2,6
600 - 700	0,37	0,00	0,0	-6,40	-2,4	-6,40	-2,4
500 - 600	0,27	-0,30	-0,1	-7,20	-1,9	-7,50	-2,0
400 - 500	0,21	-0,45	-0,1	-8,00	-1,7	-8,45	-1,8
300 - 400	0,17	-0,60	-0,1	-8,80	-1,5	-9,40	-1,6
200 - 300	0,22	-0,75	-0,2	-9,50	-2,1	-10,25	-2,3
40 - 200	0,10	-0,95	-0,1	-10,70	-1,1	-11,65	-1,2
40 - 1594	38,0	2,41	91,5	-3,00	-114,2	-0,60	-22,7

Table 10-1
Specific and volume winter, summer, and net balance calculated for 100 m elevation intervals at Engabreen in 2003.

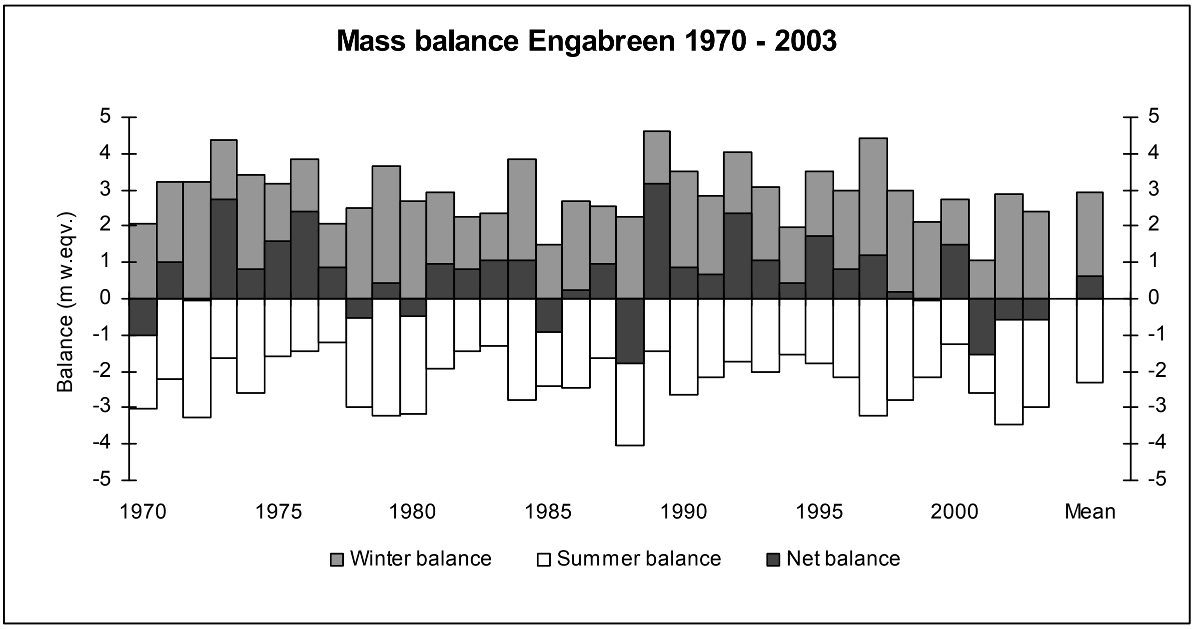


Figure 10-5
Mass balance at Engabreen during the period 1970-2003. The accumulated surplus amounts to 21 m water equivalent.

10.2 Meteorological measurements

A meteorological station recording air temperature, global radiation, precipitation, wind speed and wind direction is located on the nunatak Skjæret (1364 m a.s.l.) close to the drainage divide between Engabreen and Storglombreen (Fig. 10-1). The station has recorded data since 1995 with some data gaps. The nearest meteorological station is Glomfjord (39 m a.s.l.) 19 km north of Skjæret. This station has been operated by the Norwegian Meteorological Institute (DNMI) since 1916.

In 2003, the station at Skjæret has undergone both technical and operational problems. Therefore, the station has recorded only 47 days of observations, mainly from January. At Glomfjord the mean annual temperature in 2003 was 118 % of the 1961-90 average. The summer temperature (15th May - 15th September) was 1.5 ºC lower than in 2002, but 1.8 and 1.3 ºC higher than in 2000 and 2001, respectively. The temperature record from Glomfjord and the discharge record from the glacier river in Svartisen Subglacial Observatory (station 159.13, 600 m a.s.l., not shown here) show that some melting took place in the first few days after 26th Sep 2002, but the record from Skjæret indicates that there was no melting on the plateau. Both temperature and discharge records indicate that melting started on the plateau around 12th May, 10 days before the winter balance measurements, but the amount of water released from the glacier was limited. After the net balance measurements on 28th September 2003 there were several periods of melting recorded at the subglacial discharge station. However, there was 0.2 to 0.9 m of new snow on the glacier on 28th September (above 950 m a.s.l.), implying that late autumn melting did not affected the summer balance for most of Engabreen. At the glacier tongue melting normally occurs periodically throughout the winter.

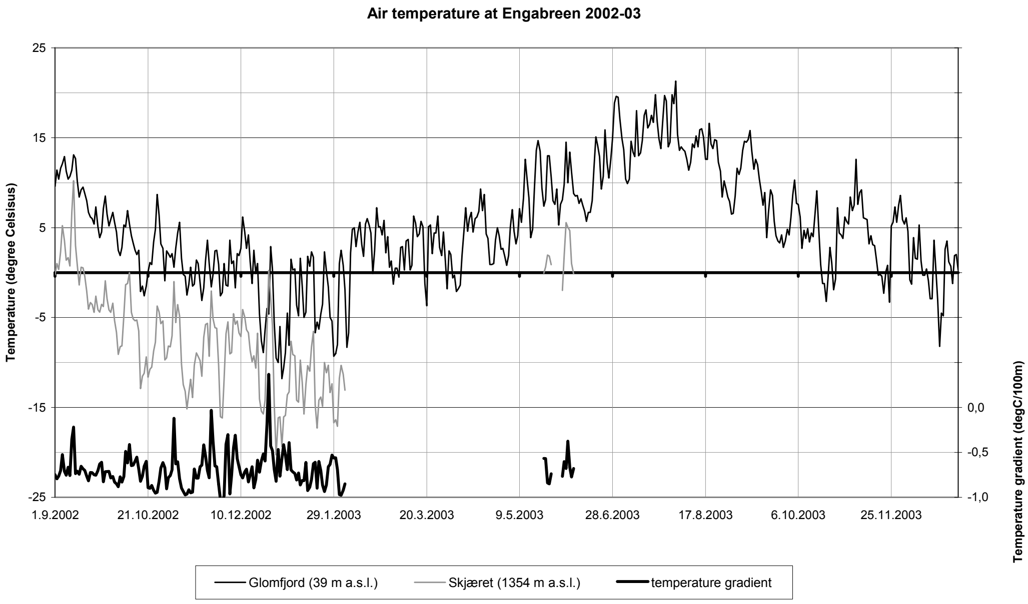


Figure 10-6
Daily mean air temperature at Skjæret (159.20.0) and Glomfjord (80700) between 1st September 2002 and 31st December 2003, and daily temperature gradient between Glomfjord and Skjæret.

10.3 Svartisen subglacial laboratory

Svartisen Subglacial Laboratory is a unique facility situated under Engabreen. It allows direct access to the bed of the glacier for the purposes of measuring sub-glacial parameters and performing experiments on the ice. Further general information about the laboratory is available in report number 14 in NVE's document series for 2000, entitled 'Svartisen Subglacial Laboratory' (Jackson, 2000).

Pressure measurements

Six load cells were installed at the bed of the glacier in December 1992 in order to measure variations in subglacial pressure. Four of these were still operating in 2003. A further two load cells were installed in November 1997 and were also still operating in 2003 (Figure 10-7). The load cells are Geonor P-105 Earth Pressure Cells. Readings are recorded from the load cells at 15 minute intervals (more frequently when experiments are being performed). The load cells did not record data for the first seven weeks of 2003 due to a technical problem, but were then operational from 18th February to the end of the year. A seventh load cell was installed in November 2003. Records from this load cell are not given here.

Pressure sensor records for 18th February to 12th May 2003 are shown in Figure 10-8. The first few weeks are typical for the winter period with very little load cell activity. An event occurs on about 18th March which is clearly visible at all the load cells. The pressure initially drops and then rises again – slowly and only back to the original level at load cells 2 and 6, but quickly and at first to a pressure 1 bar higher than before at the other four load cells. There was also a discernible increase in the measured subglacial discharge, which peaked late on 18th March. This event is probably due to meltwater at the glacier caused by warmer weather over the preceding six days and several days of precipitation. Most of the remaining period is fairly quiet in terms of pressure activity. However, load cells 97-1 and 97-2 are fairly active, especially 97-2 after 10th April. The behaviour of these two cells in these period is unusual – neither correlated nor anti-correlated despite their proximity to each other, and precipitation and subglacial discharge don't show anything that would explain this behaviour.

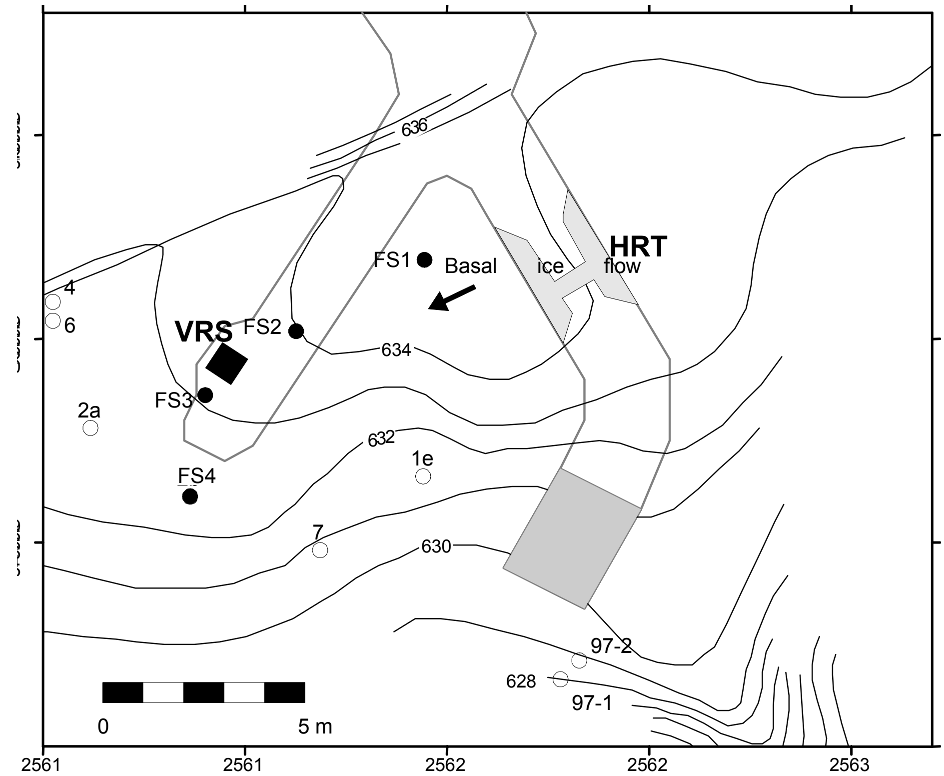


Figure 10-7
Tunnel system showing locations horizontal research tunnel (HRT) and vertical research shaft(VRS), load cells 1e, 2a, 4, 6, 7 (no longer working), 97-1 and 97-2 and boreholes, marked FS.

Data for the period from 12th May to 15th May are not shown, as there was experimental work in progress during this period leading to very noisy data, and the experimental results will be reported elsewhere.

Pressure sensor records for the spring – early summer period from 16th May to 29th July, are shown in Figure 10-9. Records of subglacial discharge show that this increased sharply on 18th May, although there were a couple of smaller peaks in dishcarge before then. The records for the load cells 4 and 6 are correlated, and show several sharp drops and subsequent peaks which are almost all related to increases in subglacial discharge, usually occurring a day or two after the peak in discharge. Towards the end of June and early July there were several successive days without precipitation, and the diurnal signal

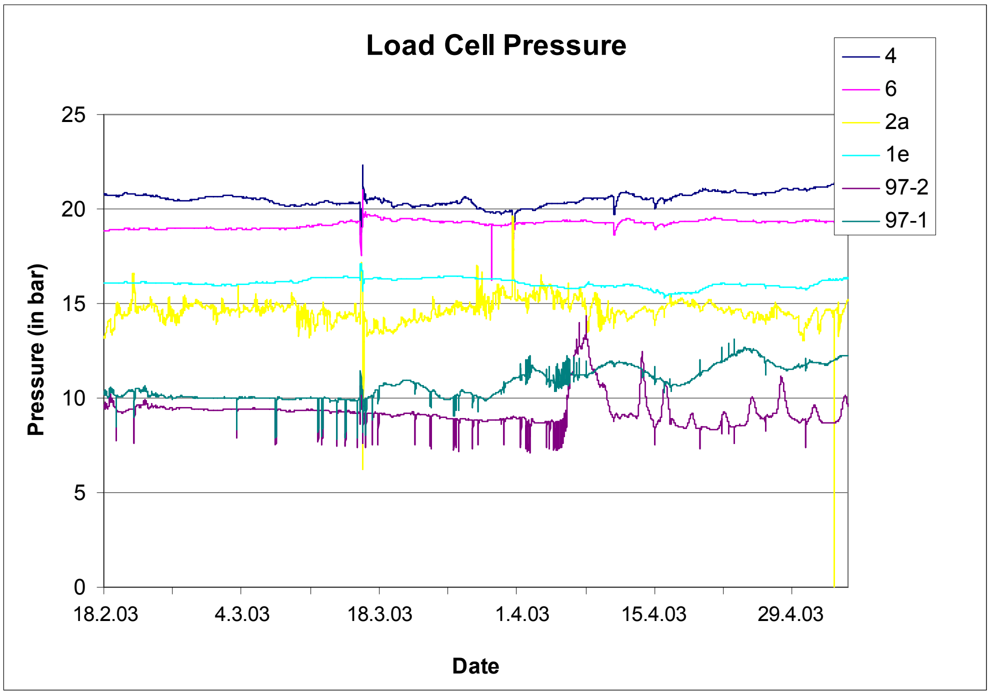


Figure 10-8
Data logger records for the period February to early May.

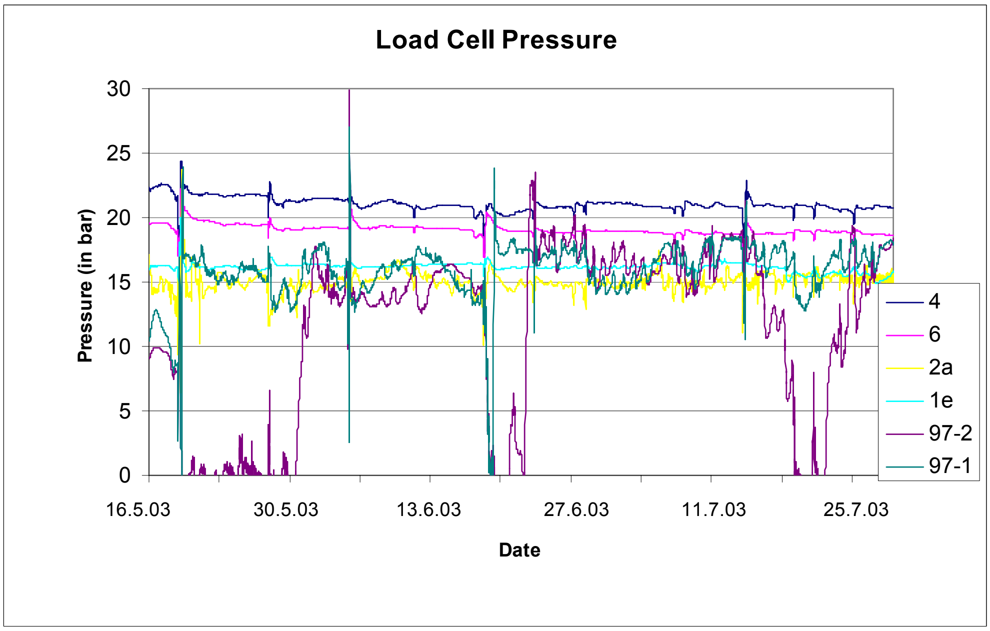


Figure 10-9
Data logger records for the period mid-May to July.

in water input to the glacier is most clearly seen in the load cell records for 1e, 97-1 and 97-2. There are several examples of anti-correlation for the pressure records for 97-1 and 97-2. This has been observed previously in a period following experimental work.

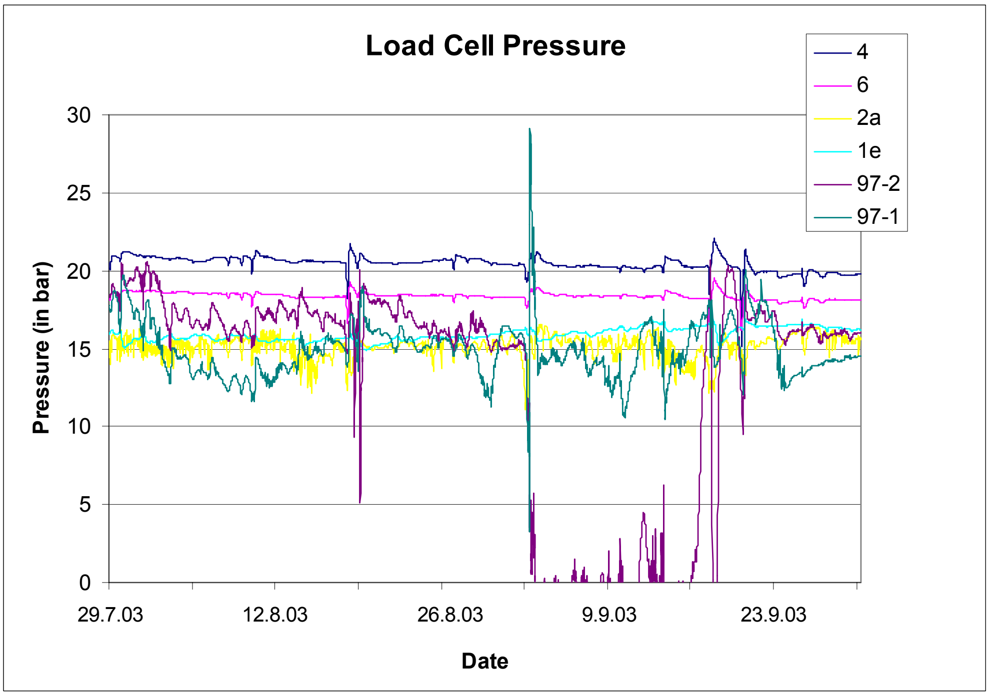


Figure 10-10
Data logger records for the period late-July to September.

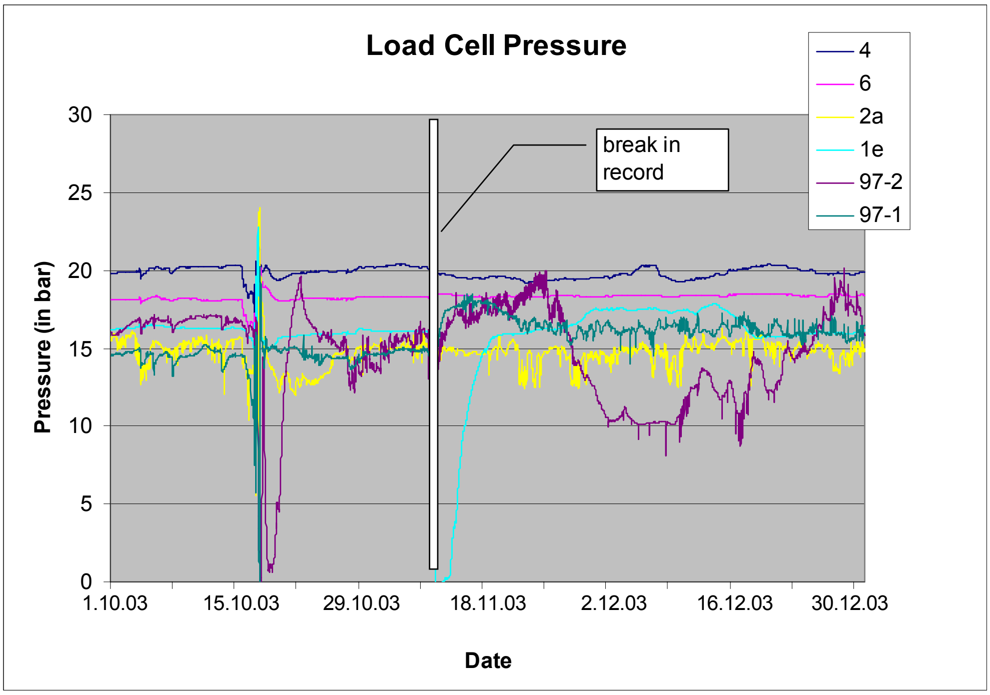


Figure 10-11
Data logger records for the period October to December.

Pressure sensor records for the rest of the summer period and into early autumn, from 29th July to 30th September, are shown in Figure 10-10. Load cell records for 4 and 6 are quiet compared with typical summer signals, whereas records for the other four are noisier than usual, especially 97-1 and 97-2. Recorded subglacial discharge was very low in the second half of August, but showed a sudden increase on about 2nd September. This is reflected in all the records almost immediately. Negative values for cell 97-2 show there has been probably been some drift in the calibration for this load cell.

Pressure sensor records for the autumn/winter period to the end of the year, from 1st October to 31st December, are shown in Figure 10-11. There is a break in the record from the evening of 6th November to midday on 13th November. During this time pump tests were taking place in the tunnel (see below) and a tunnel was melted out so that the records are very noisy. An event on 17th October is reflected in all the records and is related to a sudden increase in subglacial discharge. There was also another event on 6th November, although we see only the beginning of this here. This event was due to unseasonably warm temperatures, as well as some precipitation over the previous three days, which caused another rapid increase in subglacial discharge. The noisy records after the break between 6th and 13th November are due to the ice closing in again on the load cells.

Research projects

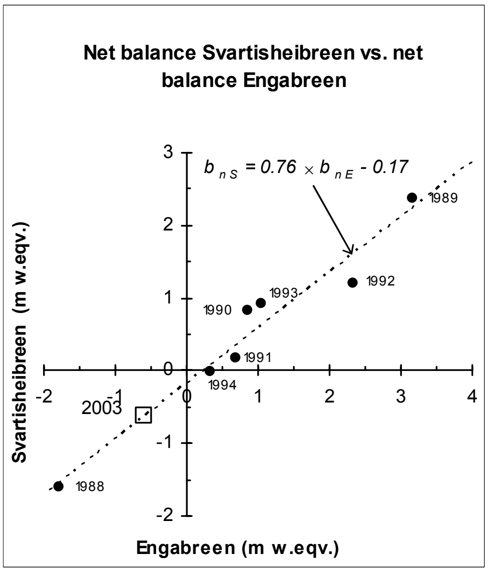
Two major research projects took place in the subglacial laboratory in 2003. The first was the final fieldwork for the doctoral work of University of Oslo student, Gaute Lappegard. He performed several high-pressure pump experiments in the laboratory and measured basal ice velocities on two occasions, in May and November. Also, a horizontal tunnel was melted out in November, one load cell was replaced and the subglacial topography was mapped.

The second project involved a group of American researchers led by Neal Iverson of Iowa State University and Denis Cohen of Yale University. This was a short visit to replace a couple of load cells in the friction panel that weren't functioning.

10.4 Svartisheibreen

Svartisheibreen (5.5 km^2, 774 – 1530 m a.s.l., 66°35'N, 13°45'E) is located 10 km south-west of Engabreen. The glacier has been monitored since 1987 in connection with a planned hydropower development. The monitoring program included mass balance (1988 – 1994), bed topography, glacier velocity, volume change, and lake level recording in the proglacial lake Heiavatnet. The lake has been subject to jøkulhlaups at least three times between 1991 and 1999. The glacier was not visited during 2003.

The net balance of Svartisheibreen in 2003 was modelled from a linear regression model between net balance at Engabreen and net balance at Svartisheibreen. Using this model, the specific net balance of Svartisheibreen was -0.6 m w.eqv., which corresponds to a mass loss of 3 mill. m^3 water (Fig 10-12). The cumulative net balance at Svartisheibreen since 1969 equals +10 m w.eqv. The cumulative net balance at Engabreen in the same period is +21 m w.eqv.



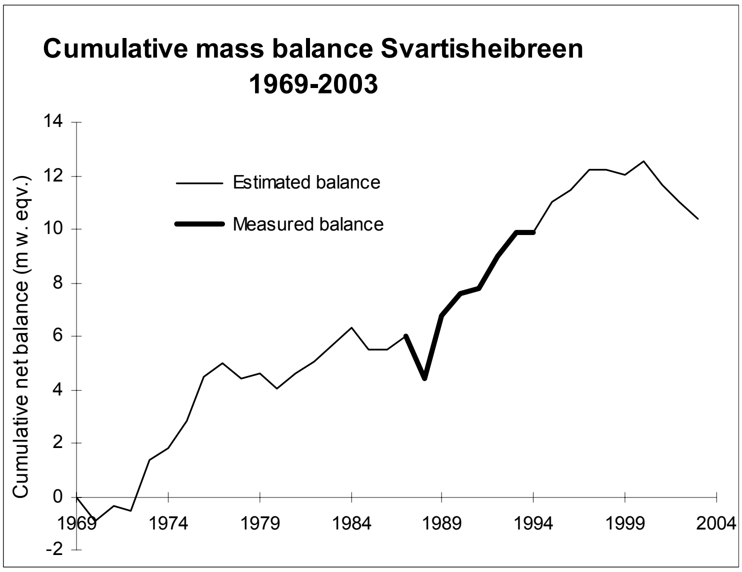


Figure 10-12
Net balance at Svartisheibreen modelled from measured net balance at Engabreen and Svartisheibreen in 1988-94 (left), and cumulative specific net balance at Svartisheibreen for the period 1969-2003 (right).

11. Storglombreen (Hallgeir Elvehøy)

Storglombreen (66°41'N, 14°00'E) is the largest outlet from the Svartisen icecap. It covers an area of 62.4 km^2 and drains the western Svartisen ice cap to Lake Storglomvatnet (Fig. 11-1). Most of its area is located between 900 and 1300 m a.s.l. Three outlets calve into the lake. Mass balance measurements were carried out during the four years from 1985 to 1988, and recommenced in 2000. Front position changes are monitored also.

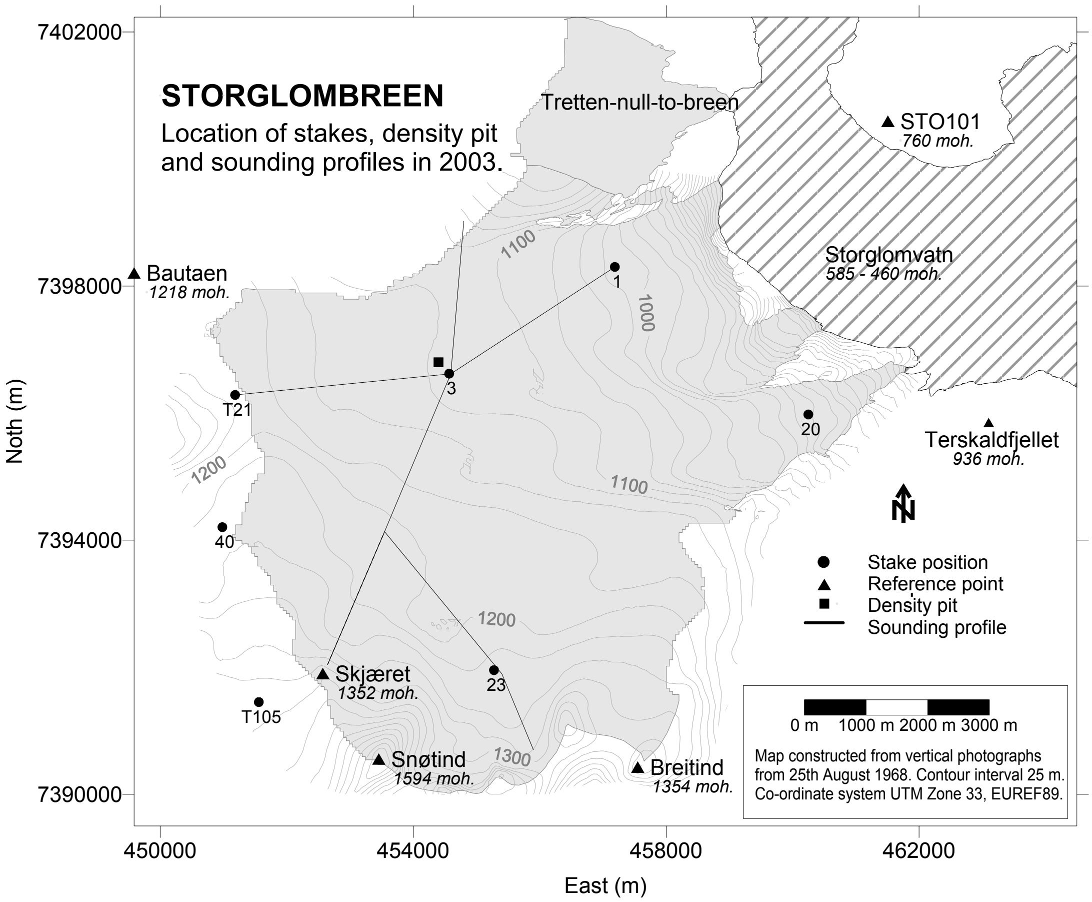


Figure 11-1
Location of stakes, density pit and sounding profiles at Storglombreen in 2003. Three stakes on Engabreen located close to Storglombreen were also used in the calculations.

Based on an extensive monitoring program from 1985 to 1988, a simplified observation network for mass balance measurements has been established. A linear regression between mean water equivalent for all snow depths along the selected profiles (corresponding to the profiles in Fig.11-1), and specific winter balance for the entire glacier from winter balance maps was established. A linear regression between summer balance at stake 3 and specific summer balance (without calving) for the entire glacier was also established (Kjøllmoen, 2001).

11.1 Mass balance 2003

Fieldwork

Snow accumulation measurements were carried out 20th May. The location of stakes, density pit and sounding profiles are shown in Figure 11-1. The calculation of the winter balance was based on:

- Snow depth at stakes 1, 3, T21, 23 and 40, which was 3.00, 4.30, 4.95, 4.80 and 5.05 m, respectively.
- Snow depth at stake 20 measured on 1st June. Snow melting and compaction between 20th May and 1st June were estimated to have reduced the snow depth at the stake from 0.85 m to 0.35 m as measured.
- Snow density measured to a depth of 4.3 m at stake 3. Mean snow density was 0.55 g/cm^3.
- 88 snow depth soundings along 18 km of profiles between 1016 and 1315 m a.s.l. In addition, one point measurement close to the drainage divide between Engabreen and Storglombreen at 1410 m a.s.l was used. Most observations showed between 4 and 5 m of snow. The summer surface was generally well defined.

Net balance measurements were carried out on 28th September. At that time up to 0.5 m of new snow had fallen on the glacier. All the winter snow had melted at the stakes on Storglombreen. At Engabreen some winter snow remained at stakes 40 and T105, indicating that some winter snow may have remained in small areas on the north-east slopes of Snøtinden. Stake 20 melted out between 1st June and 29th July. Based on measurements at stake 134 at Engabreen and stake 1 at Storglombreen, the amount of melting was estimated as 0.35 m of snow and 2.7 m of ice in this period.

During the summer, 0.85 m snow and 5.00 m ice melted at stake 20, and at stake 1, 3.00 m of snow and 2.30 m of ice had melted. At the plateau, 4 - 5 m of snow and 0.15 (stake 3) and 0.70 m firn (stake 23) had melted.

Results

The calculations were based on a map from 1968 and drainage divides calculated from bottom topography and ice thickness (Kennett et al. 1997). The mass balance was also calculated using the regression equations established from the observation period 1985-1988.

Winter balance

The winter balance was calculated from point measurements of snow depth (stakes and soundings) and measurements of snow density at stake 3. The snow density measurements were used to model a water equivalent profile. According to this model, the mean snow density for the upper 5 m of snow was 0.53 g/cm^3. This model was used to convert all snow depth observations to water equivalent values.

The total winter balance was calculated from the altitudinal distribution of the snow depth soundings. Point values of the snow water equivalent were plotted against altitude, and a representative curve was drawn based on the mean value in each 100 m elevation interval. As snow depth was observed only between 900 and 1300 m a.s.l., the mean balance curve for the period 1985-1988 was used as a basis for the curve below 900 m a.s.l. and above 1300 m a.s.l. Using this method the total winter balance was calculated as 140 ±10 million m^3 water, which corresponds to 2.2 ±0.3 m w.eqv.

The winter balance was also calculated using the regression equation defined from measurements and results in 1985-88. The mean water equivalent for 93 snow depth measurements along the profiles shown in Figure 11-1 was 2.4 m. This corresponds to a specific winter balance of 2.1 m, which is close to the result above.

The altitudinal winter balance distribution is shown in Figure 11-2 and Table 11-1. The mean winter balance for 1985-88 and 2000-02 (7 years) is 2.05 m w.eqv.

Summer balance

The summer balance was measured and calculated at four locations on Storglombreen (20, 1, 3 and 23), and two locations on Engabreen (40 and T105) located very close to the ice divide (Fig. 11-1). The summer balance curve was drawn from these six point values and the mean balance curve for the period 1985-1988 (Figure 11-2).

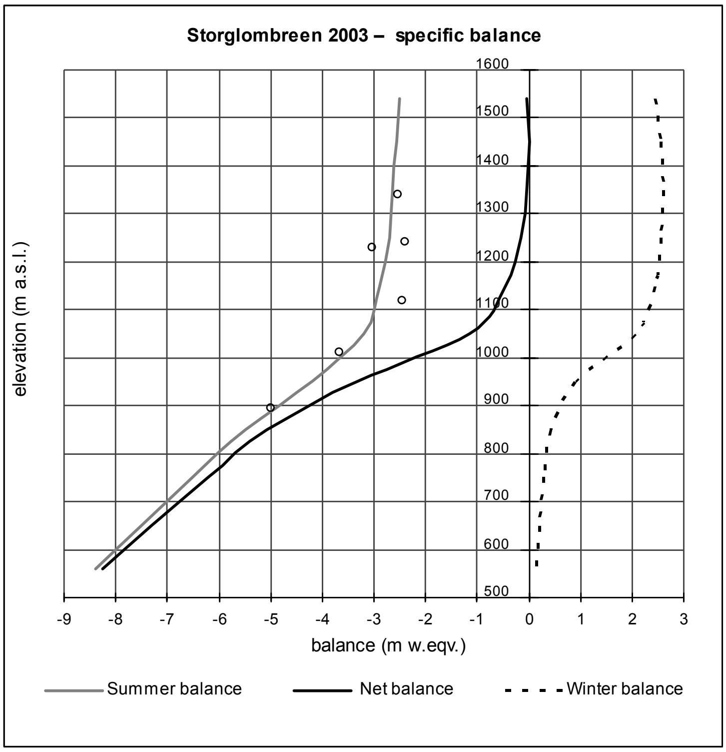
The contribution from calving and ice avalanches was estimated as -7 million m^3 water, as it was in 1985-1988. This contribution was estimated from a terminus length of 1.6 km, a mean terminus height of 50 m and a glacier velocity of 100 m/a. The total summer balance, including the calving contribution, was -200 ±20 million m^3 water, which is equal to a specific balance of –3.3 ±0.3 m w.eqv. The mean summer balance for the seven mass balance years (1985-1988 and 2000-2002) measured previously is –2.75 m w.eqv. The calculated summer balance is 119 % of the 8-year average.

The summer balance was also calculated using a regression model. The summer balance at stake 3 was −2.4 m w.eqv., corresponding to a specific summer balance including calving of 3.0 m w.eqv., which is close to the result above.

Net balance

The net balance of Storglombreen for 2003 was −1.1 ±0.4 m w.eqv., which corresponds to a mass loss of 70 ±30 million m^3 water. The mean value for 1985-1988 and 2000-02 is −0.68 m w.eqv. Since it is most likely that all of the winter snow melted during the summer, the equilibrium line altitude (ELA) was undefined, and the accumulation area ratio (AAR) was 0 %.

The mass balance results are shown in Table 11-1 and Figure 11-2. The results from 2003 are compared with mass balance results for the period 1985-1988 and 2000-02 in Figure 11-3.



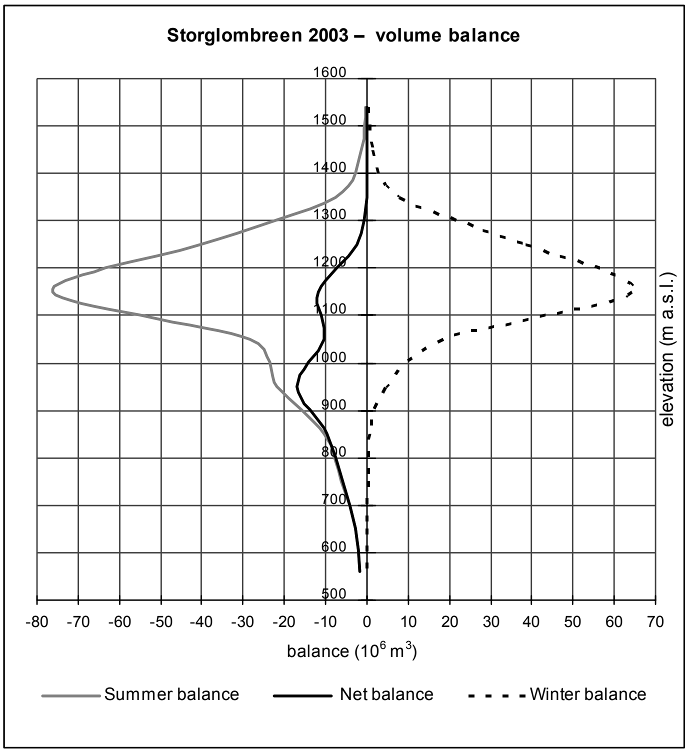


Figure 11-2
Winter-, summer and net balance for Storglombreen in 2003, showing specific balance (left) and volume balance (right). Summer balance at stakes is shown as circles (°).

Mass balance Storglombreen 2002/03 – traditional method

Altitude (m a.s.l.)	Area (km^2)	Winter balance Measured 20th May 2003		Summer balance Measured 28th Sep 2003		Net balance Summer surface 2002 - 2003	
		Specific (m w.eqv.)	Volume (10^6 m^3)	Specific (m w.eqv.)	Volume (10^6 m^3)	Specific (m w.eqv.)	Volume (10^6 m^3)
1500 - 1580	0.18	2.45	0.44	-2.50	-0.45	-0.05	-0.01
1400 - 1500	0.58	2.55	1.47	-2.55	-1.47	0.00	0.00
1300 - 1400	2.89	2.60	7.50	-2.65	-7.65	-0.05	-0.14
1200 - 1300	15.02	2.55	38.30	-2.70	-40.56	-0.15	-2.25
1100 - 1200	26.23	2.45	64.27	-2.90	-76.08	-0.45	-11.81
1000 - 1100	8.91	2.05	18.26	-3.20	-28.51	-1.15	-10.25
900 - 1000	5.16	0.90	4.65	-4.20	-21.69	-3.30	-17.04
800 - 900	1.91	0.44	0.84	-5.50	-10.49	-5.06	-9.65
700 - 800	0.95	0.29	0.27	-6.50	-6.16	-6.21	-5.88
600 - 700	0.38	0.20	0.08	-7.50	-2.83	-7.30	-2.76
520 - 600	0.22	0.15	0.03	-8.40	-1.88	-8.25	-1.85
Calving					-7.2		-7.2
520 - 1580	62.4	2.18	136.1	-3.28	-205.0	-1.10	-68.8

Table 10-1
Specific and volume winter, summer, and net balance calculated for 100 m elevation intervals for Storglombreen in 2003.

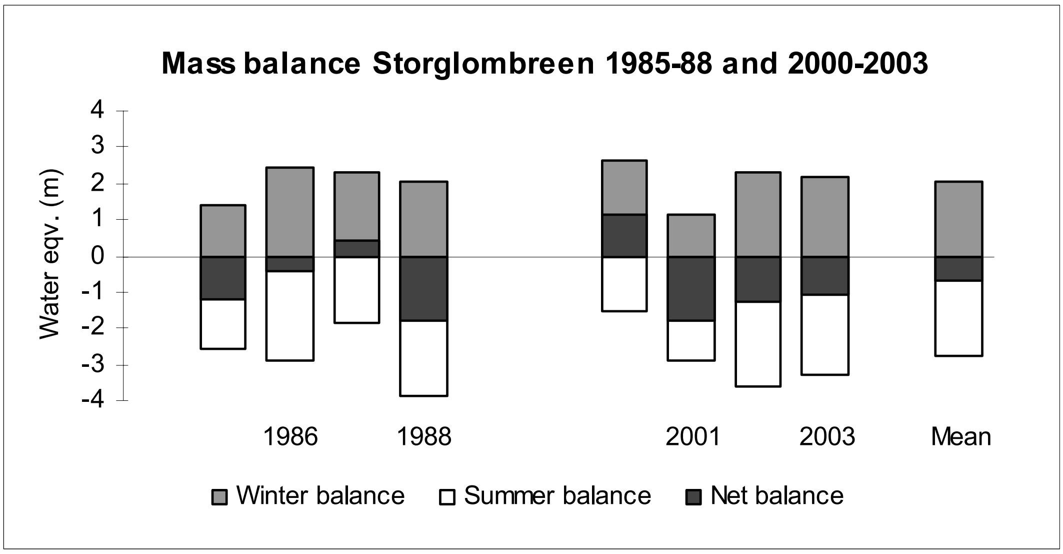


Figure 11-3
Mass balance at Storglombreen during the period 1985-1988 and 2000-2003.

11.2 Front position change

Storglombreen has three distinct termini that calve into Storglomvatnet (Fig. 11-1). Observations of front position changes began in 2000, and will continue in order to document changes associated with changes in the water level of the reservoir. The calving terminus of the glacier Tretten-null-to-breen is observed also (Fig. 11-1).

The termini were surveyed on 28th September from STO101 using Terskaldfjellet as a reference point (Fig. 11-4). A Geodimeter total station and eight reflectors located in the helicopter window were used. The terminus was positioned by observing the reflectors as the helicopter touched the ice edge, if possible, along the front perimeter. The accuracy of this method depends on the geometry of the glacier front and the flight conditions, and such measurements may therefore be relatively uncertain. Horizontal uncertainty of individual points is estimated to be less than ±2 m, while vertical uncertainty is much less when the helicopter touches the ground. Figure 11-4 shows the observations, and the observed terminus position in 1985 and 1968. At the time of the field visit, the lake level was 583 m a.s.l., close to the highest level at 585 m a.s.l.

Tretten-null-to-breen

The 150 m long terminus was defined by measuring three points. The terminus had retreated approximately 20 m between 2002 and 2003.

North Storglombreen

The 400 m long terminus was defined by measuring three points. No change was detected between 2002 and 2003.

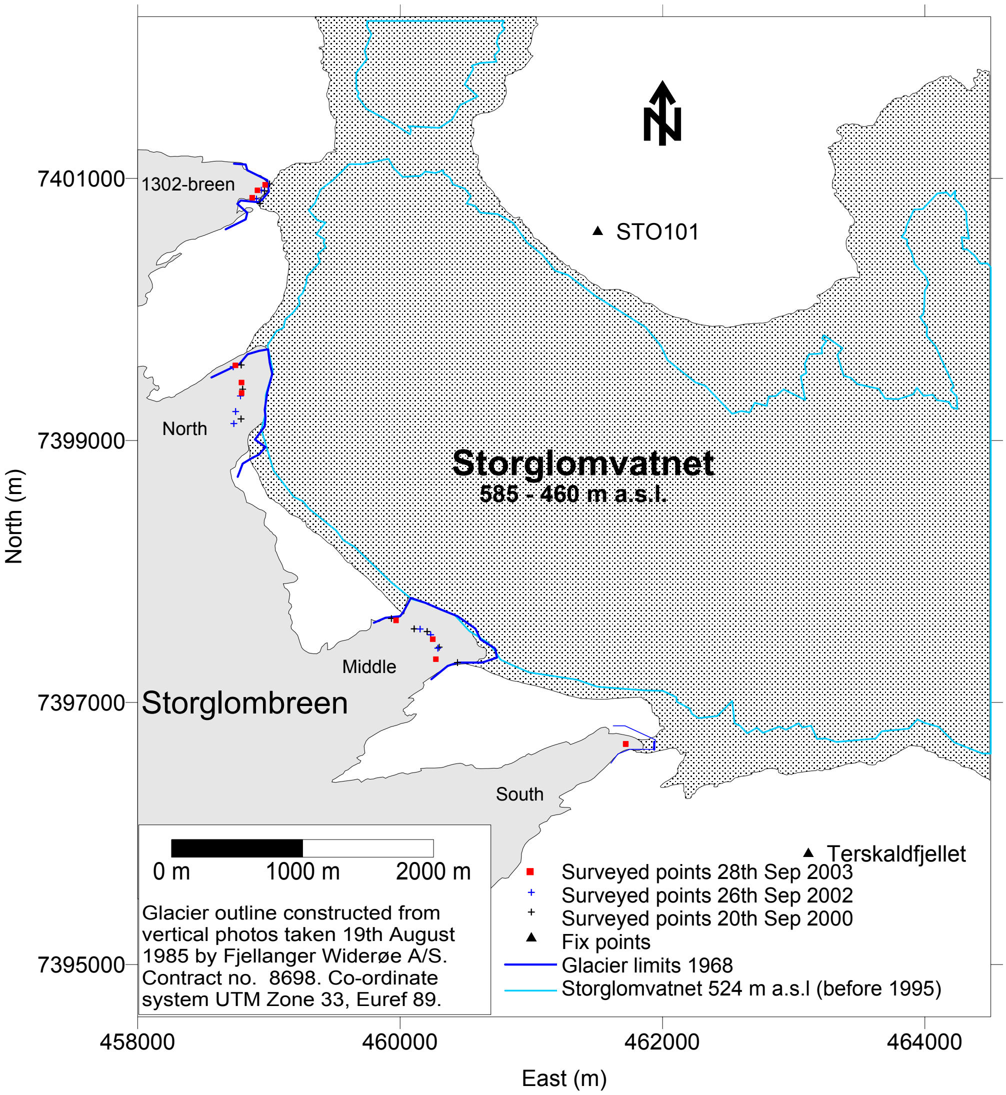


Figure 11-4
Front position changes of the termini that calve into the Storglomvatnet reservoir.

Middle Storglombreen

The terminus in the lake was defined by measuring two points. No significant change was detected.

South Storglombreen

This glacier tongue is not visible from STO101. The glacier terminated in the lake. Comparison to photographs from 2002 implies that no significant change has taken place. The front position was measured using hand-held GPS.

12. Rundvassbreen (Rune V. Engeset)

Rundvassbreen (Fig. 12-1) is a 11.6 km^2 northeastern outlet glacier of the icecap Blåmannsisen (67°20'N, 16°05'E) which, at 87 km^2, is the fifth largest glacier in Norway. Rundvassbreen extends from 1536 m elevation down to 788 m a.s.l. Rundvassbreen is the glacier outlet that drains past the lake Øvre Messingmalmvatn, from which a jøkulhlaup in September 2001 drained about 40 million cubic metres of water under the glacier. This event led to a detailed study of the glacier and jøkulhlaup by the hydropower company Elkem Energi Siso AS. An observation programme was begun in 2001 and includes mass balance, lake level change of Øvre Messingmalmvatn and ice surface movement (Engeset 2002 and Engeset 2003). The mass balance observations and results are described in this chapter.

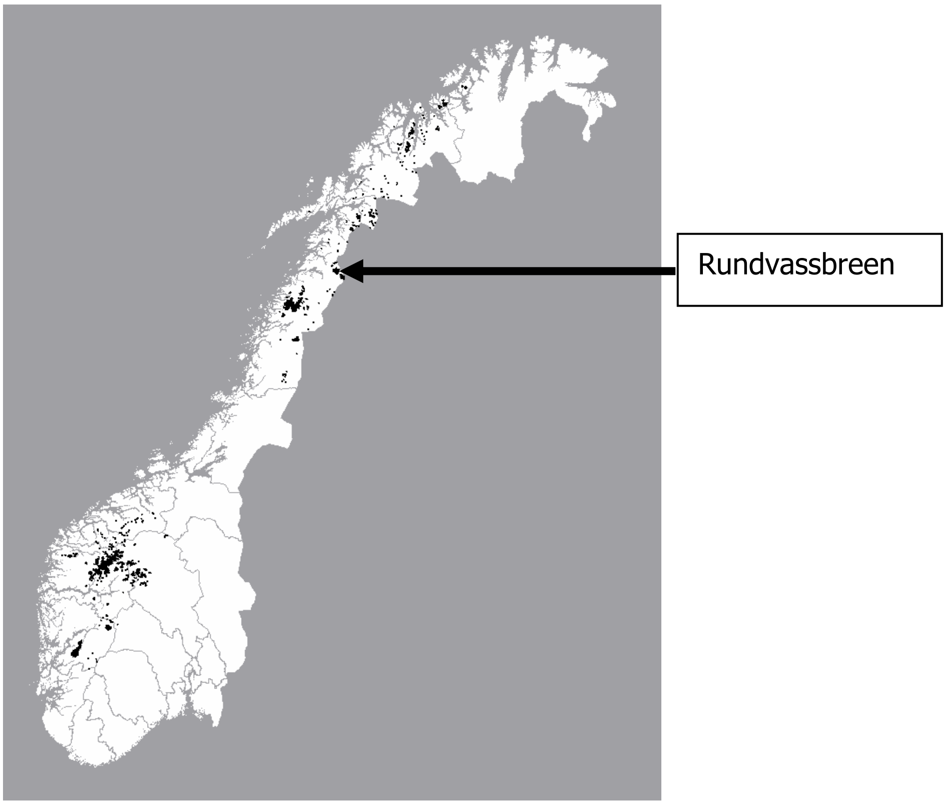


Figure 12-1
Location map.

12.1 Mass balance 2003

Fieldwork

Snow accumulation measurements were carried out on 19th May. The calculation of winter balance is based on (Fig. 12-2):

- Measurement of snow depth at 5 of the 7 stakes, the two stakes at the highest elevations were still under snow at this time. Stakes are located at the following elevations: 966 (stake 10), 1112 (stake 20), 1174 (stake 30), 1275 (stake 40), 1333 (stake 50), 1395 (stake 60), and 1525 (stake 70) m a.s.l.

- Snow depth measured at 171 locations spaced every 150 m along a 27 km profile. Identification of the summer surface was relatively easy, albeit more difficult between 1450 and 1525 m a.s.l. Snow depth was about 4-6 m above 1300 m a.s.l. (about 1 m less than the previous winter). Below this elevation the snow depth was between 1 and 5 m, but considerably uneven.
- Snow density cores were obtained at stake 50 (1330 m a.s.l.) and stake BMIP5 (1111 m a.s.l. located in the ice barrier area). A snow density cylinder was used to 1.5 m depth and cores retrieved at greater depths down to 4.2 m (stake 50) and 3.0 m (stake BMIP5). A relatively high density of about 500 kg/m^3 was observed from the top to the summer surface.

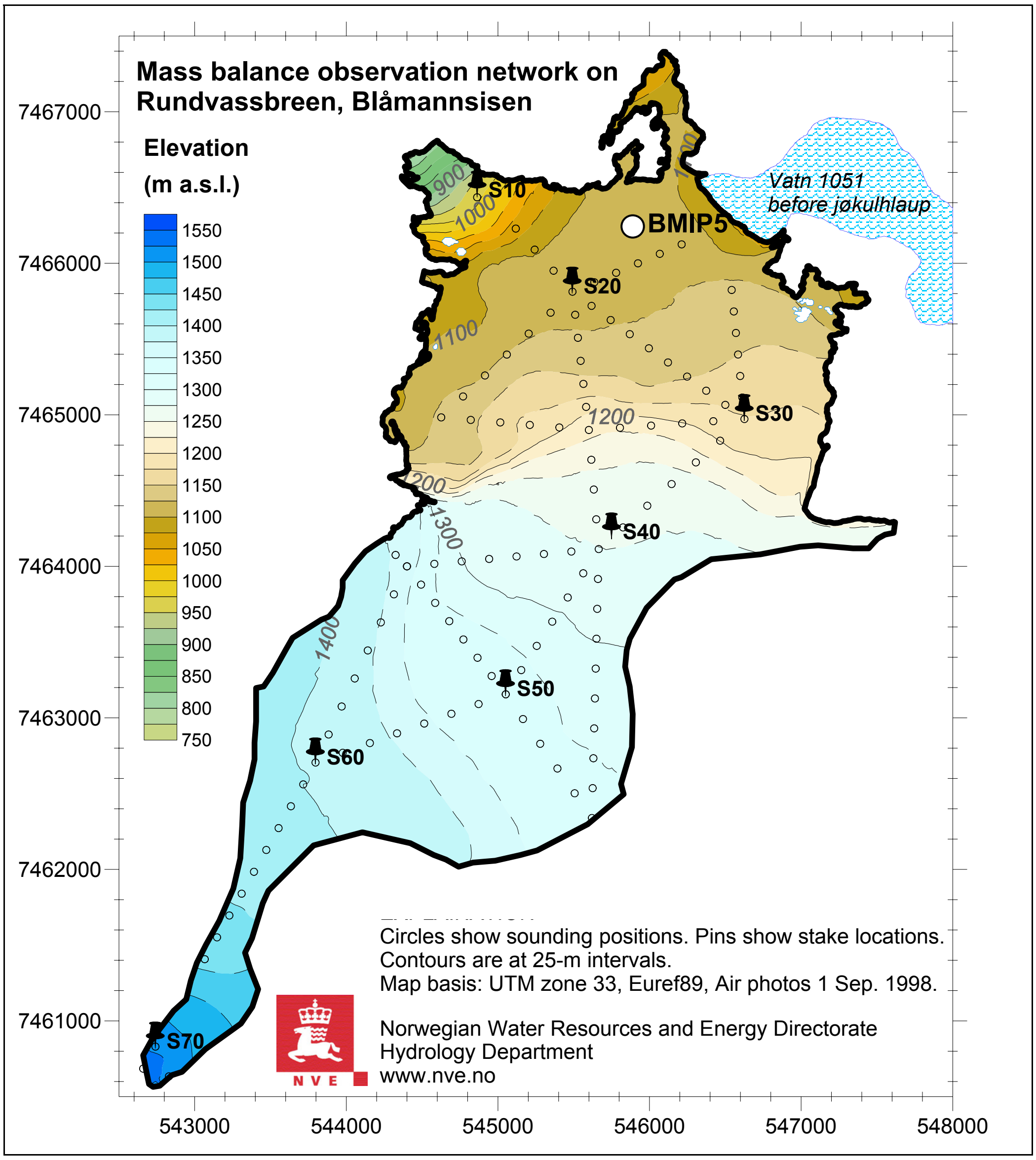


Figure 12-2
Location of stakes/cores, density pit and sounding profiles at Rundvassbreen in 2003.

Ablation measurements were carried out on 29th September. Between 1 and 1.3 m of fresh snow was found on top of the summer surface, thus the firn and snow limits were not visible. Stake readings suggest that the snow limit at the end of the ablation season was located between stake 50 and stake 60, probably at about 1350 m a.s.l, which is 50 m higher than the previous year.

Results

Winter balance

The calculation of winter balance is based on point measurements of snow depth (171 soundings and 7 stakes) and snow density at two locations.

Snow water equivalent (SWE) was calculated by the fitting of two functions between observed depth and density:

Above 1200 m a.s.l.: SWE = 0.489 x snowdepth + 1.017
Below 1200 m a.s.l.: SWE = -0.032 x snowdepth^2 + 0.624 x snowdepth - 0.013

The winter balance calculation was performed by plotting measurements (water equivalent) on a diagram. A curve was drawn based on visual evaluation, and a mean value for each 50 m height interval was estimated (Tab. 12-1). This gives a *winter balance* of 1.9 m w.eqv., corresponding to a water volume of 22 mill. m^3, which is 90 % of the previous year's winter balance.

Simulation of the glacier mass balance (Engeset 2002) for the period 1962-2001 (40 years) gave an annual mean of 1.73 m w.eqv. (winter balance), −1.83 (summer balance) and −0.10 (net balance). The 2003 winter balance is 110 % of simulated annual mean for 1962-2001.

Summer balance

In calculating the summer balance the density of the remaining snow was estimated as 600 kg/m^{-3}, and the density of melted ice as 900 kg/m^{-3}.

The summer balance was calculated at 7 stakes and estimated for each 50-m elevation interval. Based on estimated density and stake measurements the *summer balance* was calculated to be −2.9 m w.eqv., which is −34 mill. m^3 of water. This is 94 % of the value for 2002, and 164 % of the simulated annual mean for 1962-2001.

Net balance

The *net balance* was calculated as −1.07 m w.eqv., which equals a deficit of 12 mill. m^3 water.

The diagram in Figure 12-5 indicates that the equilibrium line altitude (ELA) was 1360 m a.s.l. Accordingly, the Accumulation Area Ratio (AAR) was 28 %.

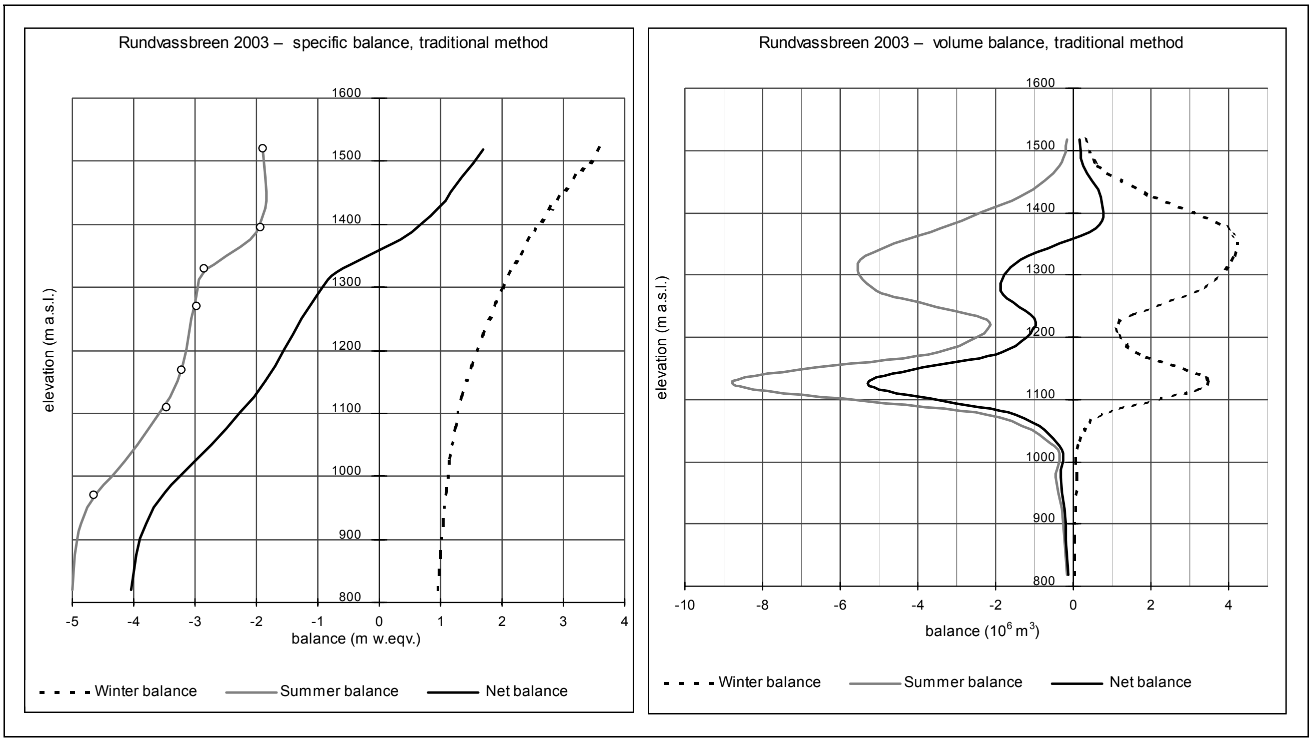


Figure 12-5
Specific balance (left) and volume balance (right) for Rundvassbreen 2003.

Mass balance Rundvassbreen2002/03 – traditional method

Altitude (m a.s.l.)	Area (km^2)	Winter balance, Measured 19th May 2003: Specific (m w.eq.)	Winter balance: Volume (10^6 m^3)	Summer balance, Measured 29th Sep 2003: Specific (m w.eq.)	Summer balance: Volume (10^6 m^3)	Net balance, Summer surfaces 2002 - 2003: Specific (m w.eq.)	Net balance: Volume (10^6 m^3)
1500 - 1537	0.09	3.60	0.3	-1.90	-0.2	1.70	0.1
1450 - 1500	0.20	3.20	0.6	-1.85	-0.4	1.35	0.3
1400 - 1450	0.75	2.80	2.1	-1.85	-1.4	0.95	0.7
1350 - 1400	1.62	2.45	4.0	-2.10	-3.4	0.35	0.6
1300 - 1350	1.92	2.15	4.1	-2.85	-5.5	-0.70	-1.3
1250 - 1300	1.69	1.90	3.2	-3.00	-5.1	-1.10	-1.9
1200 - 1250	0.70	1.70	1.2	-3.10	-2.2	-1.40	-1.0
1150 - 1200	1.09	1.50	1.6	-3.20	-3.5	-1.70	-1.9
1100 - 1150	2.58	1.35	3.5	-3.40	-8.8	-2.05	-5.3
1050 - 1100	0.59	1.25	0.7	-3.75	-2.2	-2.50	-1.5
1000 - 1050	0.12	1.15	0.1	-4.15	-0.5	-3.00	-0.4
950 - 1000	0.10	1.10	0.1	-4.60	-0.4	-3.50	-0.3
900 - 950	0.06	1.05	0.1	-4.85	-0.3	-3.80	-0.2
850 - 900	0.05	1.00	0.0	-4.95	-0.2	-3.95	-0.2
788 - 850	0.03	0.95	0.0	-5.00	-0.1	-4.05	-0.1
788-1537	**11.6**	**1.88**	**21.8**	**-2.95**	**-34.1**	**-1.07**	**-12.3**

Table 12-1
Winter, summer and net balance for Rundvassbreen in 2003.

13. Langfjordjøkelen (Bjarne Kjøllmoen)

Langfjordjøkelen (70º10'N, 21º45'E) is a plateau glacier situated on the border of Troms and Finnmark counties, approximately 60 km northwest of the city Alta. It has an area of about 8.4 km^2 (1994), and of this 3.7 km^2 drains eastward (Fig. 13-1). The investigations are performed on this east facing part, ranging from 280 to 1050 m a.s.l.

The glaciological investigations in 2003 include mass balance and change in front position. Langfjordjøkelen has been the subject of mass balance measurements since 1989 with the exception of 1994 and 1995.

Figure 13-1
The mass balance measurements are performed on the east-facing outlet (3.7 km^2). The photo was taken on 7th September 2003. Photo: Nils Haakensen.

13.1 Mass balance 2003

Fieldwork

Snow accumulation was measured on 24th May and the calculation of winter balance is based on (Fig. 14-2):

- Measurements of substitute stakes drilled in May 2003 and older stakes that appeared during the melt season in positions 10 (500 m a.s.l.), 20 (665 m a.s.l.), 30 (885 m a.s.l.) and 40 (1050 m a.s.l.).
- Core samples at positions 10, 20, 30 and 40.

- 64 snow depth soundings along about 11 km of profiles between 335 and 1045 m a.s.l. Above 900 m altitude the summer surface (SS) was quite distinct. Below 900 m level the SS was more difficult to define. The snow depth varied from 2-3 m at the glacier snout to about 5 m above 900 m altitude.
- Snow density was measured down to 4.2 m depth (SS) at 885 m altitude (stake position 30).

Location of stakes, density pit and sounding profiles are shown in Figure 13-2.

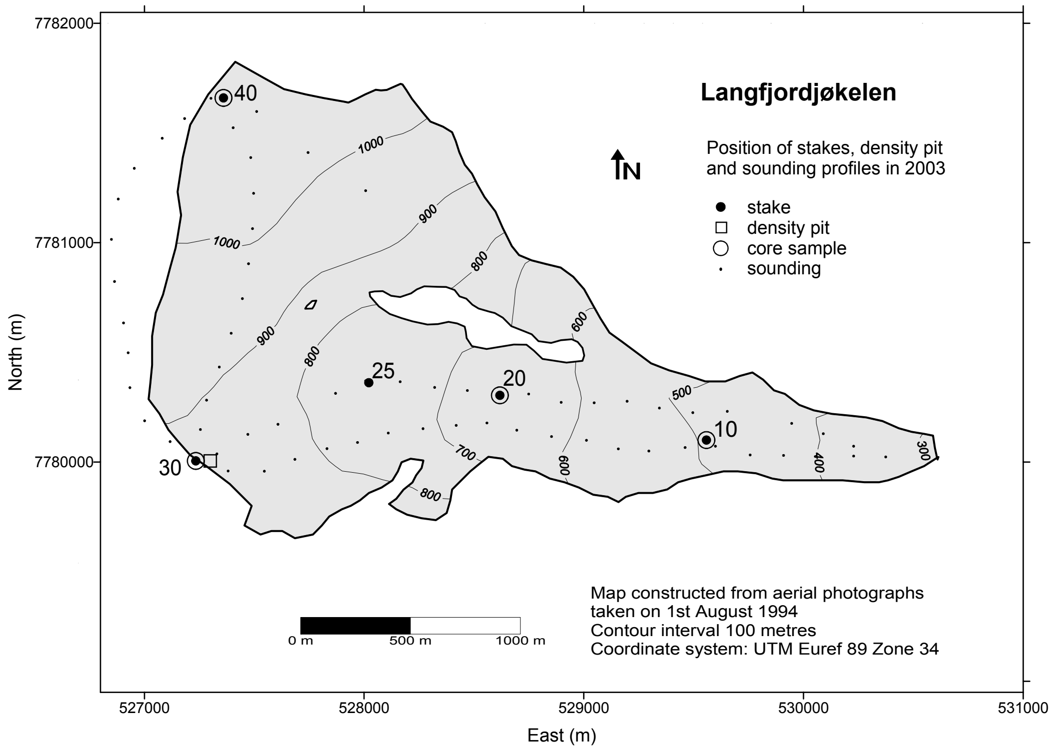


Figure 13-2
Locations of stakes, soundings and density pit at Langfjordjøkelen in 2003.

Ablation was measured on 2nd October. The net balance was measured directly at six stakes in all five locations between 500 and 1050 m a.s.l. There was no snow remaining on the glacier from winter 2002/2003 at this time, and between 25 (500 m a.s.l.) and 80 cm (1050 m a.s.l.) of fresh snow had fallen.

Results

The calculations are based on a glacier map from 1994.

Winter balance

The calculations of winter balance are based on several point measurements of snow depth (stakes, core samples and probings) and on one snow density measurement.

A density profile was modelled from the snow density measurement at 885 m altitude. The mean density of 4.2 m snow was 0.525 g/cm^3. The density model was used to convert all measured snow depths to water equivalents.

The winter balance calculations were performed by plotting the measurements (water equivalents) in a diagram. A curve was drawn based on visual evaluation (Fig. 13-4) and a mean value for each 100 m height interval was estimated (Tab. 13-1).

The winter balance was calculated as 2.4 ±0.2 m w.eqv., corresponding to a water volume of 9 ±1 mill. m^3. The result is 109 % of the mean value for the periods 1989-1993 and 1996-2002.

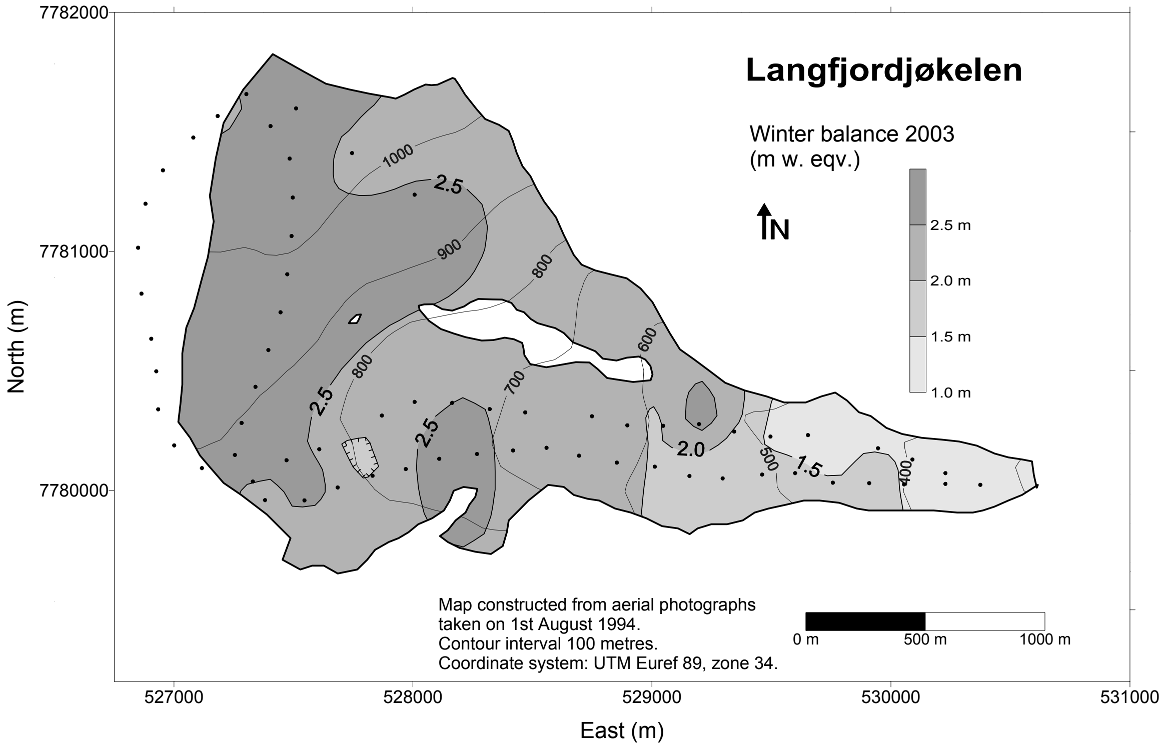


Figure 13-3
Winter balance at Langfjordjøkelen in 2003 interpolated from 64 snow depth measurements (•).

The winter balance was also calculated using a gridding method based on the aerial distribution of the snow depth measurements (Fig. 13-3). Water equivalents for each cell in a 100 x 100 m grid were calculated and summarised. The winter balance based on this method, which is a control of the traditional method, was also 2.4 m w.eqv.

Summer balance

The density of melted firn was estimated as 0.65 g/cm^3, while the density of melted ice was calculated as 0.90 g/cm^3.

The summer balance was measured and calculated at four stake positions, and increased from −2.9 m w.eqv. at position 40 (1050 m a.s.l.) to −4.4 m w.eqv. at position 10 (500 m a.s.l.). Based on estimated density and stake measurements, the summer balance was calculated to be −3.5 ±0.3 m w.eqv., which is −13 ±1 mill. m^3 of water. The result is 119 % of the average for the periods 1989-1993 and 1996-2002. This is the third greatest summer loss since the measurements started in 1989.

Net balance

Hence, the net balance at Langfjordjøkelen for 2003 was −1.04 ±0.3 m w.eqv., which equals a volume loss of −4 ±1 mill. m^3 of water (Tab. 13-1). The mean value for the measurement periods 1989-93 and 1996-2002 is −0.72 m w.eqv. (Fig. 13-5), while the average over the last 5-year period 1998-2002 is −1.5 m w.eqv.

Figure 13-4 indicates that the equilibrium line altitude (ELA) was above the glacier summit (1050 m a.s.l.). Accordingly, the Accumulation Area Ratio (AAR) was 0 %.

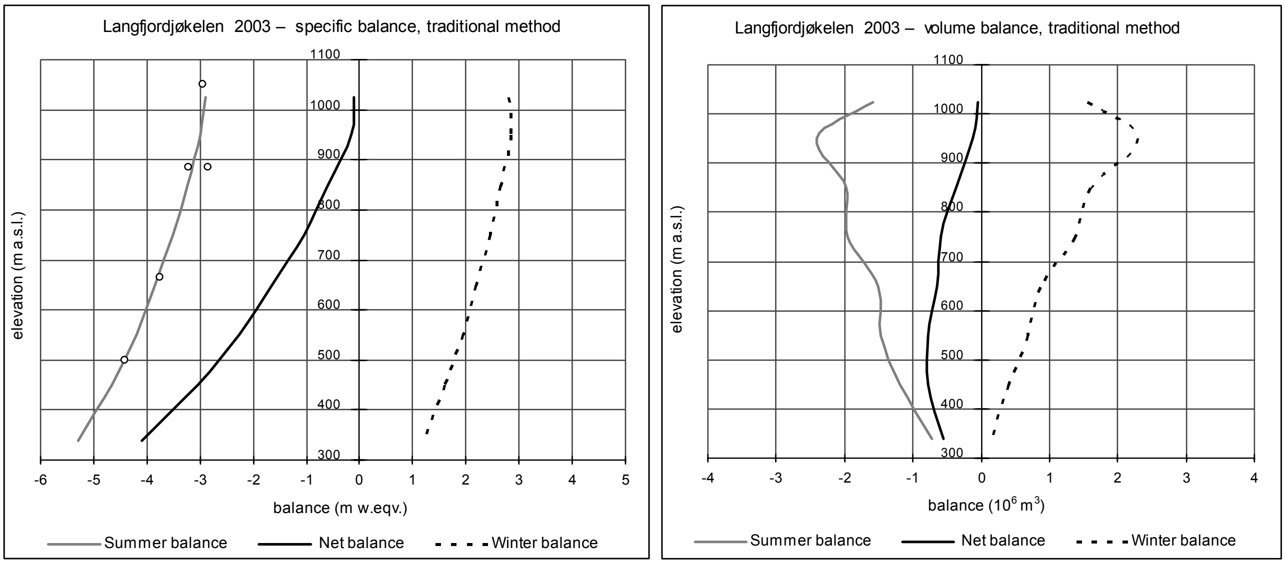


Figure 13-4
Mass balance diagram showing specific balance (left) and volume balance (right) for Langfjordjøkelen in 2003. Summer balance for stakes at three different sites is shown (o).

Mass balance Langfjordjøkelen 2002/03 – traditional method

Altitude (m a.s.l.)	Area (km^2)	Winter balance Measured 24th May 2003		Summer balance Measured 2nd Oct 2003		Net balance Summer surface 2002 - 2003	
		Specific (m w.eq.)	Volume (10^6 m^3)	Specific (m w.eq.)	Volume (10^6 m^3)	Specific (m w.eq.)	Volume (10^6 m^3)
1000 - 1050	0.55	2.80	1.5	-2.90	-1.6	-0.10	-0.1
900 - 1000	0.81	2.85	2.3	-3.00	-2.4	-0.15	-0.1
800 - 900	0.61	2.65	1.6	-3.25	-2.0	-0.60	-0.4
700 - 800	0.56	2.45	1.4	-3.50	-2.0	-1.05	-0.6
600 - 700	0.39	2.20	0.9	-3.85	-1.5	-1.65	-0.7
500 - 600	0.35	1.95	0.7	-4.20	-1.5	-2.25	-0.8
400 - 500	0.25	1.60	0.4	-4.65	-1.2	-3.05	-0.8
280 - 400	0.14	1.20	0.2	-5.30	-0.7	-4.10	-0.6
280 - 1050	**3.65**	**2.44**	**8.9**	**-3.51**	**-12.8**	**-1.07**	**-3.9**

Table 13-1
Winter, summer and net balance for Langfjordjøkelen in 2003. Mean values for the periods 1989-93 and 1996-2003 are b_w = 2,23 m, b_s = −2,95 m and b_n = −0,72 m w.eqv.

The balance year 2002/2003 is the seventh successive year with significant negative net balance at Langfjordjøkelen. Since measurements began in 1989 the cumulative net balance is about −10 m w.eqv. Most of this mass loss has occurred over the last seven years (1997-2003).

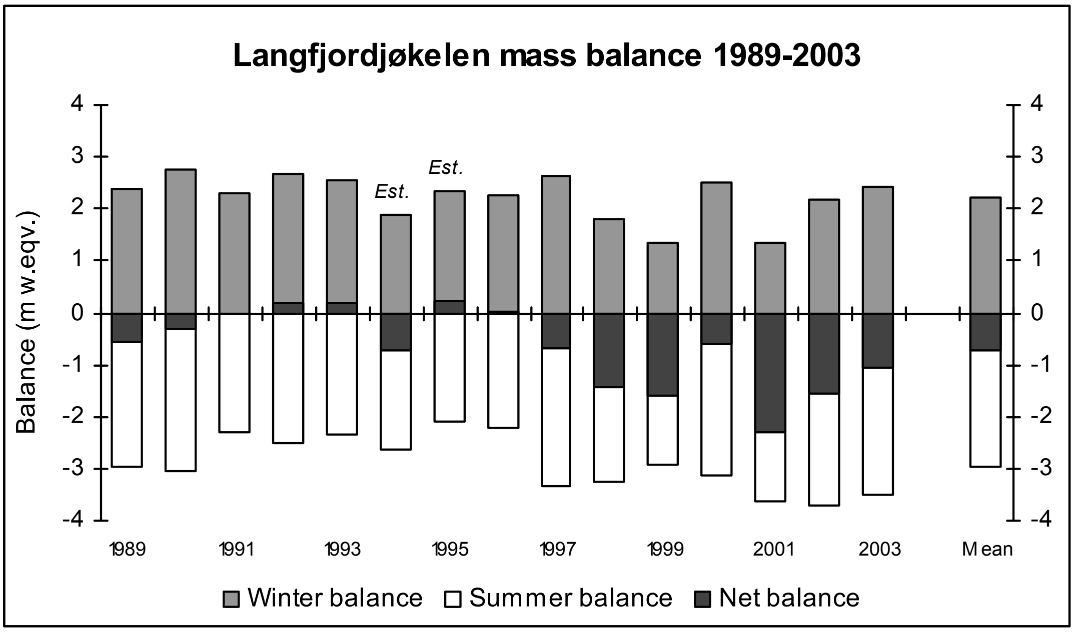


Figure 13-5
Mass balance at Langfjordjøkelen during the period 1989-2003. The total accumulated deficit over 1989-2003 is about 10 m water equivalents (includes modelled values for 1994 and 1995).

14. Glacier monitoring

(Hallgeir Elvehøy and Miriam Jackson)

14.1 Glacier length change

Observations of glacier length change have been made of Norwegian glaciers since the 1880s, but continuous measurements started around 1900.

In 2003, glacier length change was measured for 25 glaciers, 23 in southern Norway and 2 in northern Norway (Fig. 14-1).

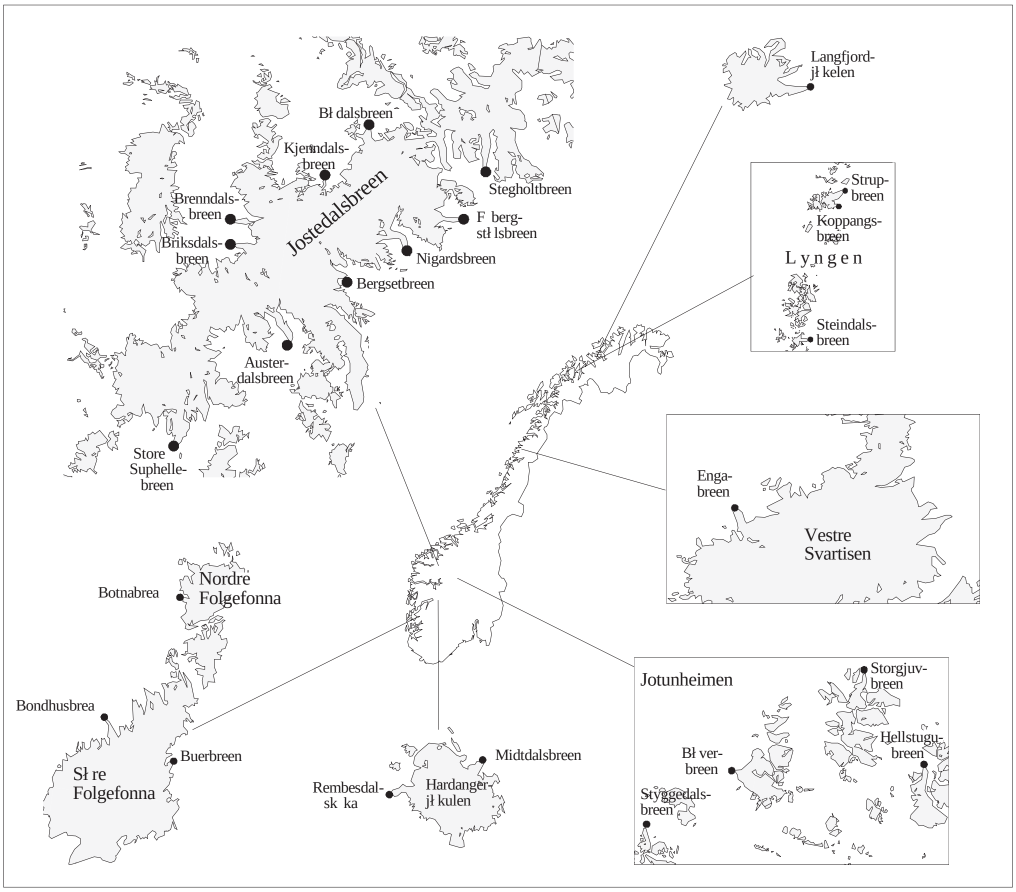


Figure 14-1
Location map showing glaciers where front position measurements were performed in 2003. Notice that the different glacier areas are not to the same scale.

Methods

The distance to the glacier terminus is measured from one or several established cairns or painted marks on rocks in defined directions, normally in September or October each year. Change in distance gives a rough estimate of the length change of the glacier. These measurements have a fairly high degree of uncertainty to what extent the measurement is representative for the entire glacier tongue. Nevertheless, the measurements give valuable information about glacier fluctuations and regional tendencies and variations when longer time periods are considered.

Results 2003

The front position changes from autumn 2002 to autumn 2003 at the observed glaciers are shown in Table 14-1. The main trend in Norway was glacier retreat. Nigardsbreen (Fig. 4-1), an eastern outlet glacier from the Jostedalsbreen ice cap, was the only monitored glacier which advanced (+24 m).

Minor or no changes (between −2 and +2 m) were observed at 3 glaciers, while the remaining 21 glaciers had negative length changes in this period. In fact, 17 of the 25 glaciers showed a net reduction in glacier length amounting to more than 10 m. At Engabreen (Fig. 10-4) and Rembesdalskåka, the observed retreat was 60 m and 54 m, respectively (Fig. 14-3).

Area	Glacier	Change (m)	Measured by
Jostedalsbreen	Austerdalsbreen	0	NVE
	Bergsetbreen	-19	NVE
	Brenndalsbreen	-30	University of Trier
	Briksdalsbreen	-38	NVE
	Bødalsbreen	-20	University of Trier
	Fåbergstølsbreen	-16	NVE
	Kjenndalsbreen	-26	University of Trier
	Nigardsbreen	24	NVE
	Stegholtbreen	-21	NVE
	Store Supphellebre	-30	Norsk Bremuseum
Folgefonna	Bondhusbrea	-21	Statkraft
	Botnabrea	-8	Statkraft
	Breidablikkbrea	-6	NVE
	Buerbreen	-38	NVE
	Gråfjellsbrea	-6	NVE
Hardangerjøkulen	Midtdalsbreen	-24	University of Bergen
	Rembesdalskåka	-54	NVE
Jotunheimen	Bøverbreen	-9	University of Trier
	Hellstugubreen	-10	NVE
	Leirbreen*	-70	NVE
	Storbreen**	-19	NVE
	Storgjuvbreen	0	University of Trier
	Styggedalsbreen	-1	NVE
Svartisen	Engabreen	-60	NVE
Finnmark	Langfjordjøkelen	-37	NVE

Table 14-1
Net glacier length change between autumn 2002 and autumn 2003 for 25 glaciers in Norway. See Figure 14-1 for location. *Change for two years (2001-2003). Measured at the glacier river outlet. **Change for two years (2001-2003).

Changes since 1980

In the 1980s, most of the observed glaciers were in a state of retreat (Fig. 14-2). In the 1990s, the number of monitored glaciers increased as a response to public and scientific interest in glacier fluctuations in general and the on-going advance at many outlet glaciers from coastal ice caps such as Nigardsbreen, Briksdalsbreen and Engabreen (Fig. 14-3). At the same time many continental glaciers such as Hellstugubreen were slowly retreating. After 2000, the latest advance ended for most glaciers.

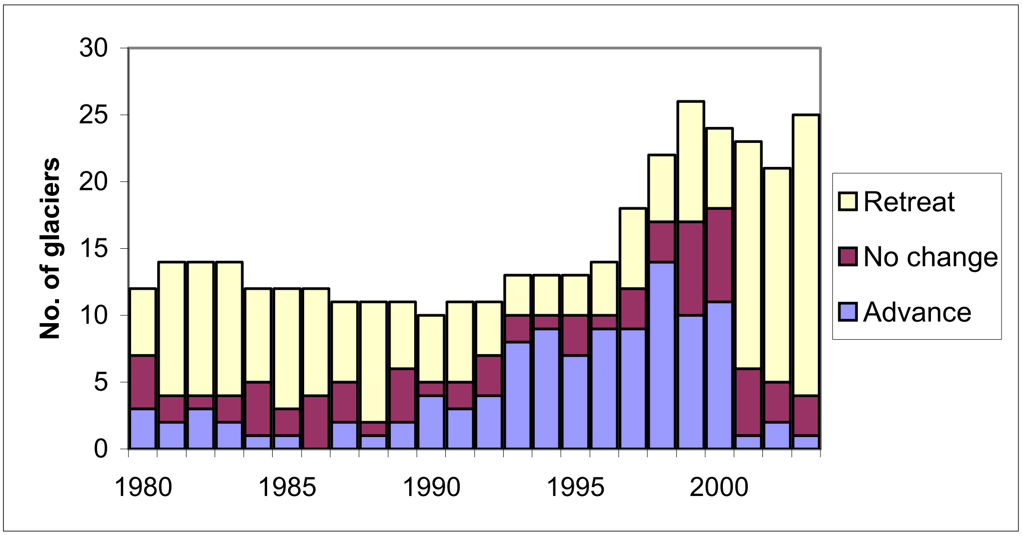


Figure 14-2
Diagram showing number of glaciers each year which have retreated (more than 2 m), show no change (between ±2 m change) or have advanced (more than 2 m advance) since 1980.

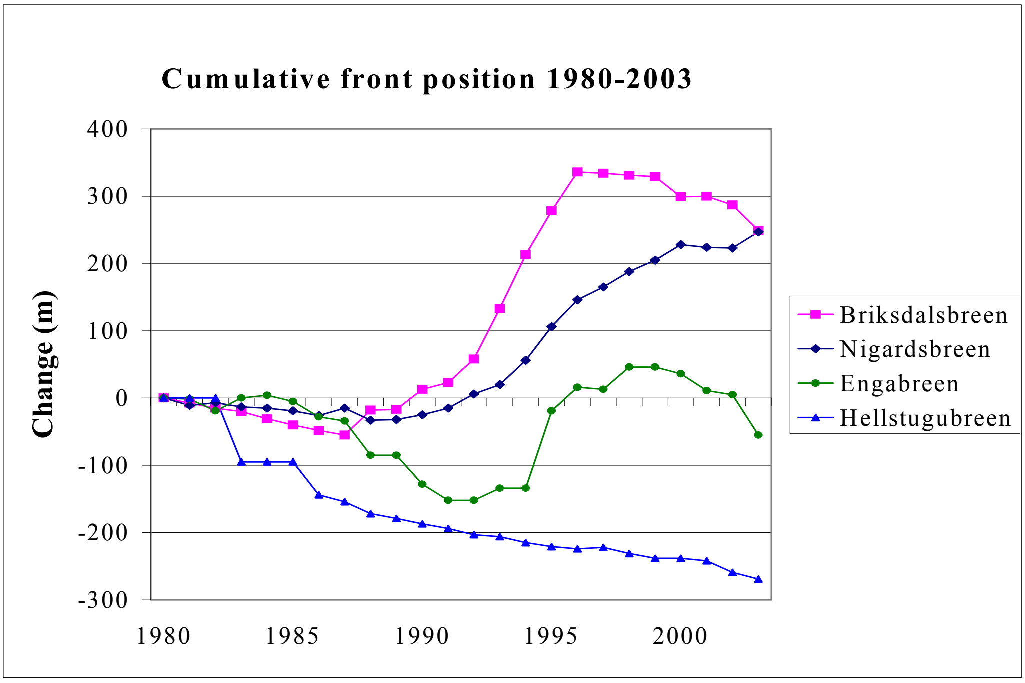


Figure 14-3
Cumulative glacier length change since 1980 for selected glaciers. See Figure 14-1 for locations.

14.2 Monitoring of Baklibreen

Baklibreen (61°40′N, 7°05′E) is an outlet glacier of Jostedalsbreen. It has an area of 3 km^2 and covers an elevation range from 1950 m a.s.l. to about 1200 m a.s.l. An ice fall occurred from the glacier in the summer of 1986. The ice fell a total of 600-700 m and killed three tourists walking along the footpath below. The ice that fell is thought to have covered an area of 4000 m and to have had a total volume of 200 000 m^3. An observation programme was set up in 1987 to study the risk of future icefalls, and was in operation until 1999. A more limited monitoring programme has been in existence since 2000 and since 2001 this has been carried out as part of the European Union 5th Framework Glaciorisk project.

Figure 14-4
Baklibreen, September 2003. Photos: Miriam Jackson.

Photographs taken in 2003 are shown in Figure 14-4. These suggest continued ice loss from the front compared with photographs from previous years. A comparison of aerial photographs from 1964 and 1984 show that ice thickness decreased significantly over most of the glacier over this period. A comparison of glacier surface measurements done in 1989 with the 1984 aerial photographs show little change in this period. The biggest increase took place in the period between 1989 and 1994 when ice thickness increased between 10 m and 20 m on the surveyed part of the glacier (area below 1300 m a.s.l.). A slight increase was measured between 1994 and 1996, and little change was registered between 1996 and 1999. More detailed information on these measurements is available in Kjøllmoen (ed.) (2000).

Survey points on the glacier in 2002 and 2003 are shown in Figure 14-5. Measurements on Baklibreen since 1993 have been made from a survey point established on a nearby prominent rock outcrop, and sightings are then made with a GDM to different points on the glacier. These points are visited by helicopter, and prisms are used for sighting. For points that are coincidental for both years, there is a change in elevation of between 3 and 8 m, with the 2003 points having the lower elevation. This continues the lowering trend of the glacier surface that has been observed over the last few years. For those survey points that are not exactly coincident in both years, an interpolated elevation was used. The 2002 survey was performed on 8th October, and the 2003 survey was performed on 20th September.

Continued surface lowering of Baklibreen suggest that a large icefall, such as occurred in 1986, is less likely to occur. However, smaller icefalls can occur. The continued frontal retreat of neighbouring glacier Bergsetbreen also means that there is increased danger of people being in the danger zone of an ice fall. Bergsetbreen advanced 360 m from the mid 1980s to 1997, and the footpath under Baklibreen became inaccessible. However, Bergsetbreen has retreated 49 m since 2000, and the footpath may once again become a popular path for walkers and climbers.

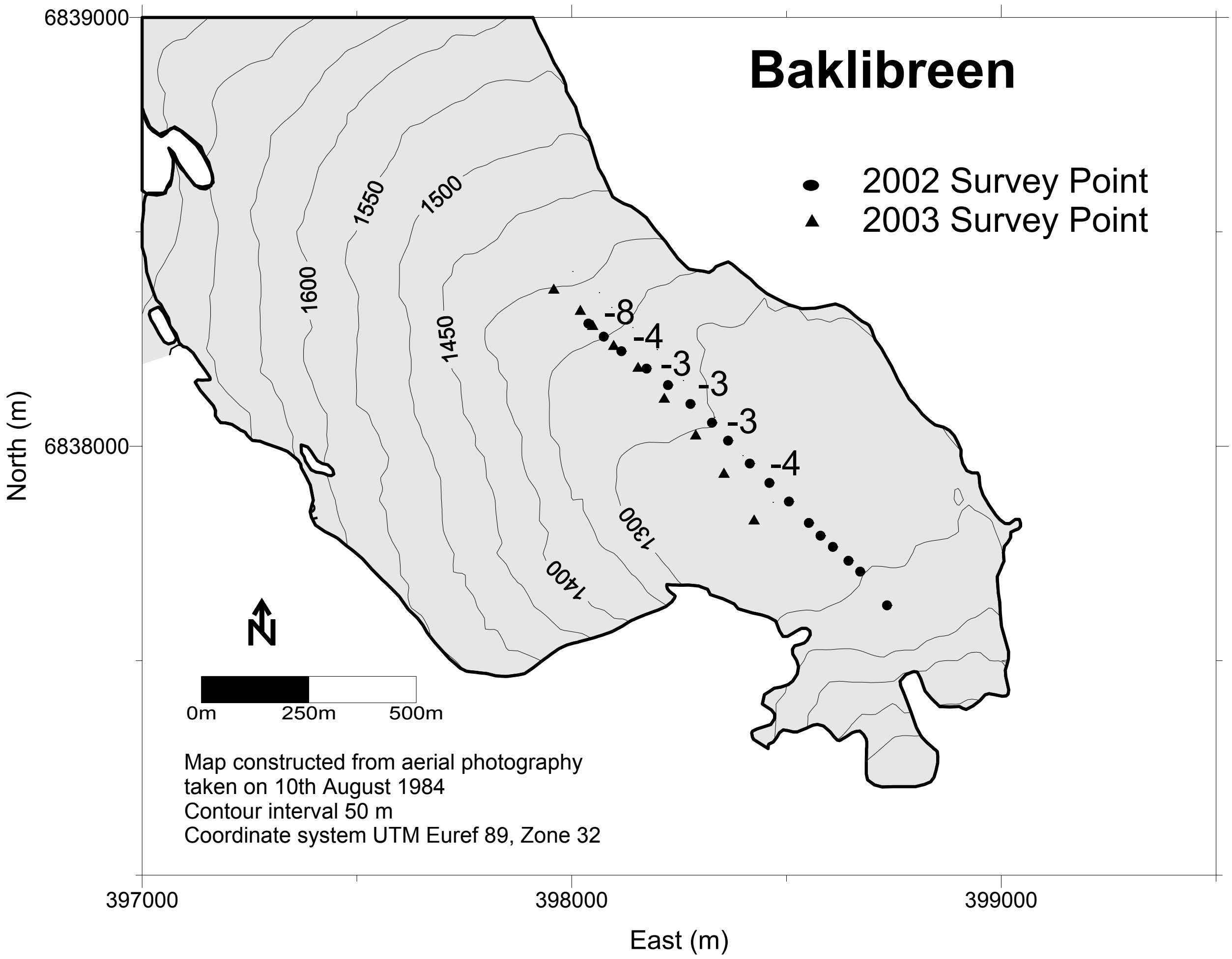


Figure 14-5
Map of Baklibreen showing survey points on the glacier in 2002 and 2003. Numbers to right of survey points are elevation change from 2002 to 2003 in metres.

15. References

Engeset, R.V.
2002: Jøkulhlaup ved Blåmannsisen. Jøkulhlaupet 2001 og fremtidige jøkulhlaup. *NVE Oppdragsrapport 9 2002*, 47 pp.

Engeset, R.V.
2003: Mot nytt jøkulhlaup ved Blåmannsisen. Undersøkelser 2003. *NVE Oppdragsrapport 11 2003*, 16 pp.

Golden Software, Inc.
1999: Surfer 7. User's Guide.

Jackson, M.
2000: Svartisen Subglacial Laboratory. *NVE Document 14 2000*, 27 pp.

Kennett, M & H. Elvehøy
1995: Bestemmelse av dreneringsgrensene for inntak til Svartisen Kraftverk. *NVE Rapport 22 1995*, 18 pp. (kap. 10-1)

Kennett, M., T. Laumann & B. Kjøllmoen
1997: Predicted response of the calving glacier Svartisheibreen, Norway, and outbursts from it, to future changes in climate and lake level. *Annals of Glaciology, 24*, p. 16-20. (kap 10-4)

Kennett, M., C. Rolstad, H. Elvehøy & E. Ruud
1997: Calculation of drainage divides beneath the Svartisen ice-cap using GIS hydrologic tools. *Norsk Geografisk Tidsskrift, Vol. 51*, p 23-28.

Kjøllmoen, B. (ed.)
2000: Glasiologiske undersøkelser i Norge 1999. *NVE Rapport 2 2000*. 140 pp.

Kjøllmoen, B. (ed.)
2001: Glaciological investigations in Norway in 2000. *NVE Report 2 2001*, 122 pp.

Kjøllmoen, B & M. Kennett
1995: Breundersøkelser på Svartisheibreen 1988-94. *NVE Rapport 17 1995*, 35 pp.

Laumann, T & B. Wold
1992: Reactions of a calving glacier to large changes in water level. *Annals of Glaciology, 16*, p. 158-162.

Østrem, G. & M. Brugman
1991: Glacier mass-balance measurements. A manual for field and office work. National Hydrology Research Institute, *Scientific Report, No. 4.* Environment Canada, N.H.R.I., Saskatoon and Norwegian Water Resources and Energy Directorate, Oslo, 224 pp.

Appendix A

Publications published in 2003

Engeset, R.
Mot nytt jøkulhlaup ved Blåmannsisen? Undersøkelser 2003. *NVE Oppdragsrapport 11 2003*, 16 p.

Kjøllmoen, B (Ed.)
Glaciological investigations in Norway in 2001. *NVE Report 1 2003*, 102 p.

Kjøllmoen, B (Ed.)
Glaciological investigations in Norway in 2002. *NVE Report 3 2003*, 92 p.

Kjøllmoen, B & R.V. Engeset
Glasiologiske undersøkelser på Harbardsbreen 1996-2001. Sluttrapport. *NVE Oppdragsrapport 1 2003*, 33 p.

This series is published by Norwegian Water Resources and Energy Directorate (NVE)

Published in the Report series 2004

No. 1 Jens Erik Rindal, Thomas Skaugen: Simulation of precipitation and temperature for generating long synthetic discharge series for use in spring flood scenarios. (22 pp.)

No. 2 Jens Erik Rindal, Thomas Skaugen: Manual for generating synthetic series of precipitation and temperature for use in spring flood scenarios. (22 pp.)

No. 3 Suldal Pilot River Basin. Provisional Article 5 Report pursuant to the Water Framework Directive (52 pp.)

No. 4 Bjarne Kjøllmoen (Ed.): Glaciological investigations in Norway in 2003 (98 pp.)