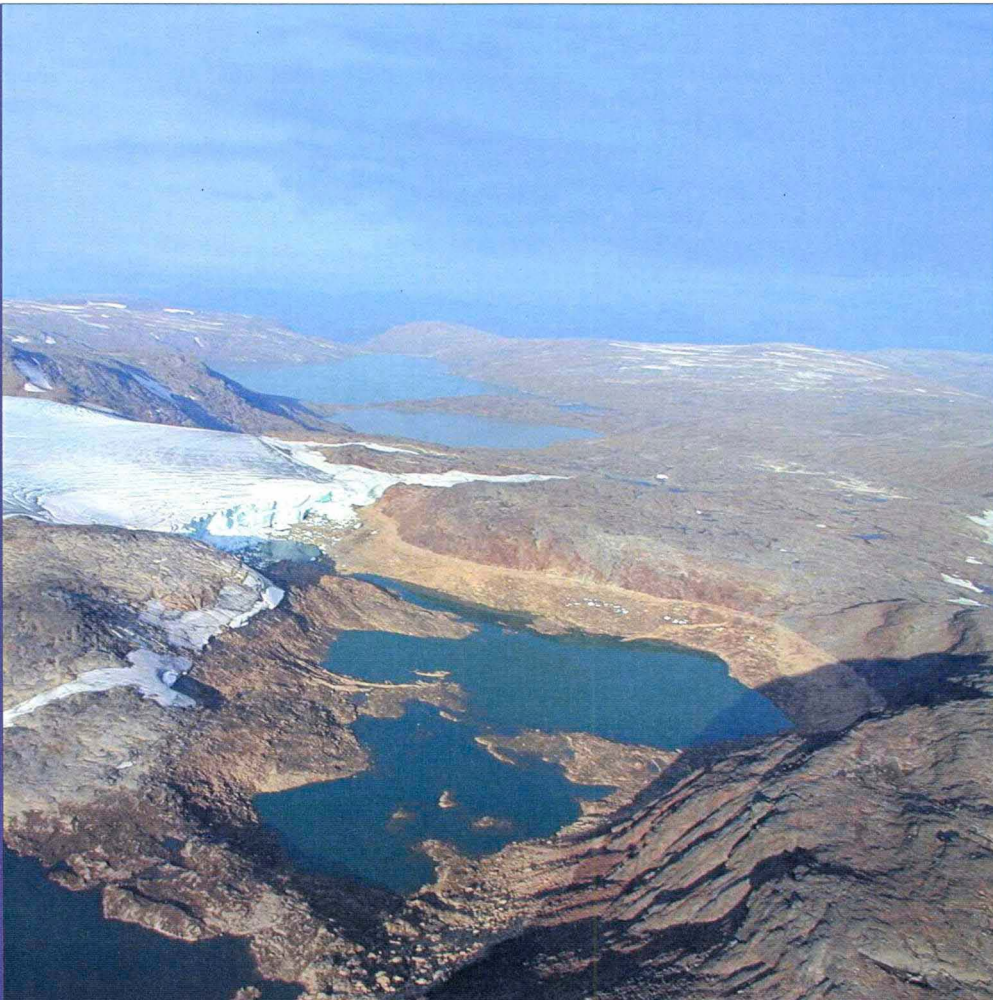




Glaciological investigations in Norway in 2001

Bjarne Kjøllmoen (Ed.)

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Report No 1

Glaciological Investigations in Norway in 2001

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- Frontpage photo: Part of Rundvassbreen, a northern outlet of Blåmannsisen in North Norway. In September 2001 there was an outburst from the glacier-dammed lake in front of the glacier. The photo is taken on 18th September 2001 by Hans-Martin Hjemaas, Elkem ASA.
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- Abstract: Results of glaciological investigations performed at Norwegian glaciers in 2001 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, Ice movement

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February 2003

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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, and other glaciological investigations are presented. Most of the investigations are ordered by external employers and published earlier as reports to these.

The report is published in English with a minor summary in Norwegian. The purpose of this report is to provide a joint presentation of the investigations and calculations made mainly by NVEs Glacier and Snow section during 2001. Even though the chapters are written by different authors with different objectives, a uniform pattern is the aim. The authors had the professional responsibility for the content of each chapter. The fieldwork and the calculations are mainly a result of co-operative work amongst the employees at the Glacier and Snow section.

Bjarne Kjølmoen was editor and Laila P. Høivik made many corrections and improvements.

Oslo, February 2003



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Summary

Mass balance investigations were performed on thirteen glaciers in Norway in the year 2001. Ten of these glaciers are in southern Norway and three in northern Norway.

The winter balance was lower than average for almost all the study glaciers in Norway. On Gråsubreen in Jotunheimen it was about average (102 %). Engabreen in northern Norway the winter balance was only 35 % of the average 1970-2000. However, notice that melting *after* the final measurements 2000 occurred at several glaciers. This melting was not measured and calculated until spring 2001. Thus, this melting is included as a *negative* contribution to the 2001 winter balance. This means that the *winter balance* 2001 is somewhat lower than the *winter accumulation*, and the winter balance values are not quite comparable with previous years for these glaciers. For more details, see each chapter.

The summer balance was larger than average on the glaciers in western and northern Norway. Hansebreen and Austdalsbreen had the largest comparative summer balance, with 122 % of the average. The glaciers in Jotunheimen had summer balances somewhat smaller than average.

The final results show a negative net balance for twelve of thirteen glaciers. The greatest deficit was measured at Hansebreen (-2.7 m w.eqv.) and Langfjordjøkelen (-2.3 m w.eqv.). The result for Langfjordjøkelen is the greatest deficit measured since the measurements began in 1989. Gråsubreen was exactly in balance. For seven of the glaciers the equilibrium line was above the glacier summit.

Front position measurements were performed for 24 Norwegian glaciers in 2001. Twenty one of the glaciers are in southern Norway and three in northern Norway. The results show a retreat in front position for most of the measured glaciers from autumn 2000 to autumn 2001. At Jostedalsbreen the front position of the outlet Kjenndalsbreen retreated markedly with nearly 50 metres. Briksdalsbreen was about steady state. A marked frontal retreat was also measured at the outlet Rembesdalskåka from Hardangerjøkelen (46 m). Measurements from Folgefonna and Jotunheimen show minor recessions. In northern Norway Engabreen (Svartisen) and Langfjordjøkelen (in western Finnmark) had both significant frontal retreats of 25 metres.

Sammendrag

I 2001 ble det utført massebalansemålinger på 13 breer i Norge – 10 i Sør-Norge og tre i Nord-Norge.

Vinterbalansen ble mindre enn middelverdiene på alle de undersøkte breene i landet med unntak av Gråsubreen (102 %). Engabreen hadde bare 35 % av gjennomsnittet 1970-2000. Det man imidlertid skal være oppmerksom på er at det på de fleste breene forekom noe smelting *etter* de avsluttende målingene høsten 2000. Denne smeltingen ble målt og beregnet om våren 2001, og er derfor medregnet som et negativt bidrag til vinterbalansen 2001. Det betyr at *vinterbalansen* 2001 er noe mindre enn den reelle *vinterakkumulasjonen*, og tallene er dermed ikke helt sammenlignbare med tidligere år for de fleste breene. For flere detaljer, se under hvert enkelt kapittel.

Sommerbalansen ble jevnt over større enn gjennomsnittet på breene på Vestlandet og i Nord-Norge. Relativt størst ble sommerbalansen på Hansebreen og Austdalsbreen med 122 % av middelverdiene. På breene i Jotunheimen ble sommerbalansen litt mindre enn normalt.

Sluttresultatet viser at det ble negativ nettobalanse på 12 av 13 målte breer. Størst underskudd ble det på Hansebreen (-2,7 m vannekv.) og Langfjordjøkelen (-2,3 m vannekv.). Siden målingene startet i 1989 har det ikke vært målt større underskudd på Langfjordjøkelen. Gråsubreen var akkurat i likevekt. På sju av de målte breene lå likevektslinjen *over* breens høyeste punkt.

Frontmålinger ble utført på 24 norske breer i 2001, 21 i Sør-Norge og 3 i Nord-Norge. Resultatene viser tilbakegang på de fleste breutløperne i hele landet fra høsten 2000 til høsten 2001. På Jostedalsbreen hadde utløperen Kjenndalsbreen den mest markerte tilbakegang med nærmere 50 meter. Frontposisjonen på Briksdalsbreen var omtrent uforandret. Det ble også målt en markert tilbakegang på 46 m på Rembesdalskåka, en av utløperne fra Hardangerjøkulen. Målinger fra Folgefonna og Jotunheimen viser bare mindre tilbakegang. I Nord-Norge hadde fronten på Engabreen i Nordland og Langfjordjøkelen i Vest-Finnmark begge en signifikant tilbakegang med 25 meter.

1. Glacier investigations in Norway in 2001

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.

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 balances are obtained from stake measurements, usually carried out 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 older firm is assumed to be between 0.65 and 0.75 g/cm^3 . The density of melted ice is set to 0.90 g/cm^3 .

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* 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.

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 evenness of the snow layer is also of importance. The accuracy of soundings and core drillings is dependent 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 increases with increasing snow depth.

The accuracy of summer balance is primarily dependent on the number of stakes at which melting is measured. Further, it depends on the representativity of the stakes and on the state of the stakes. Common sources of error are stakes sinking, and 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 2001 mass balance measurements were performed on 13 glaciers in Norway - 10 in southern Norway and 3 in northern Norway. In southern Norway, 6 of the glaciers have been measured for 39 consecutive years or more. They constitute a west-east profile reaching from the very maritime Ålfotbreen glacier with an average winter balance of 3.8 m water equivalent, to the very 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 53 years of measurements, while Engabreen has the longest series (32 years) in northern Norway. The location of the glaciers investigated is shown in Figure 1-1.

In the following chapters mass balance studies performed on Norwegian glaciers in 2001 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 given 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.

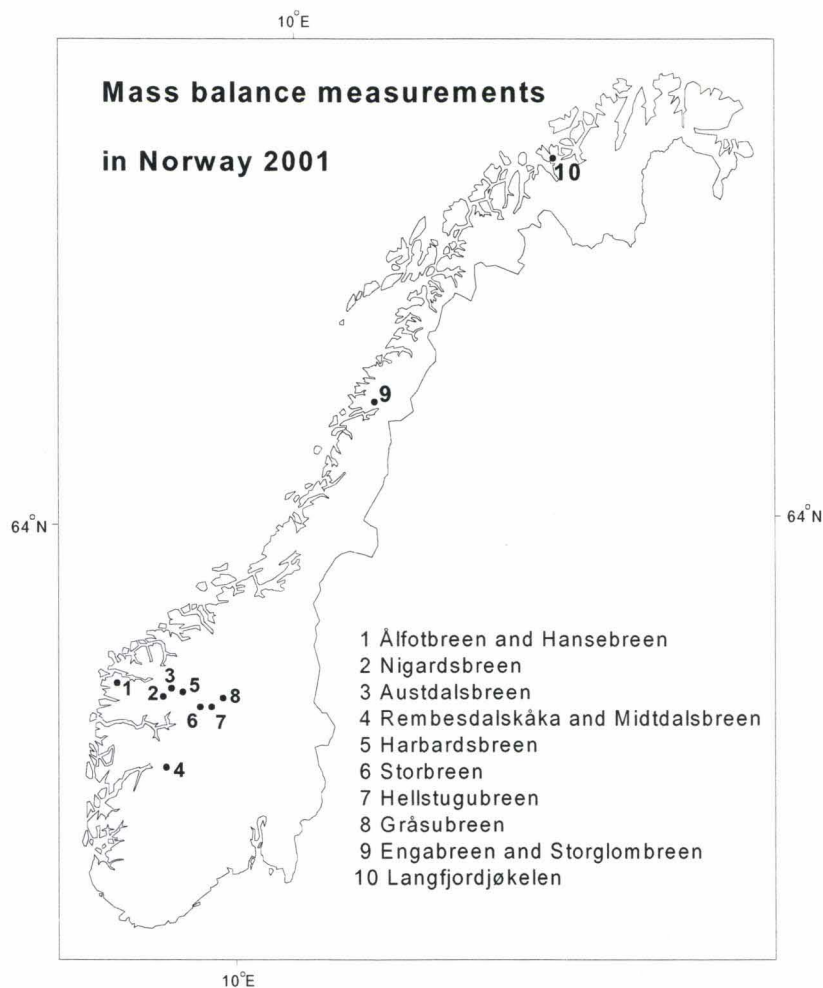


Figure 1-1
Location of the glaciers at which mass balance studies were performed in 2001.

Weather conditions and mass balance results

The autumn 2000 was characterized by unusually mild weather all over the country. The monthly temperatures for October and November were 2-5 °C higher than normal (the normal period is 1961-1990). October 2000 was the second warmest October month since 1866, warmest was in 1961. The weather was also extremely dry during these months, particularly in northern Norway, and western Norway as far south as county Rogaland. This combination of warm and dry weather resulted in a belated start for the snow accumulation on glaciers all over the country. December was also dry along most of the coast and in the western mountain regions. The winter months after the turn of the year continued in the same manner. In some glacier areas in

western Norway and in Nordland county the precipitation was as low as 25-50 % of normal in January and March. In February and April however, the precipitation was about average in western Norway and even higher than average in northern Norway. The winter 2000/2001 as a whole was dry in Nordland and in western Norway, particularly north of Sognefjorden. In Finnmark the snow conditions varied, but in general there was little snow in the western coastal areas.

For the glaciers in western Norway winter balance was between 1.0 and 1.9 m water equivalents (m w.eqv.). In Jotunheimen the results amounted to between 0.8 m and 1.1 m w.eqv. In northern Norway the winter balance for Engabreen was as low as 1.0 m w.eqv., while Langfjordjøkelen in western Finnmark had 1.4 m w.eqv. However, notice that melting *after* the final measurements 2000 occurred at several glaciers. This melting was not measured and calculated until spring 2001. This melting is therefore included as a *negative* contribution to the 2001 winter balance. This means that the *winter balance* 2001 is somewhat lower than the *winter accumulation*, and the winter balance values are not quite comparable with the previous years' for most of the glaciers. This melting amounts to 0.5 m w.eqv. for Engabreen, 0.4 m for Storglombreen, 0.2 m for Austdalsbreen and Rembesdalskåka, and 0.1 m for Nigardsbreen, Harbardsbreen, Storbreen, Hellstugubreen, Gråsubreen and Langfjordjøkelen. At Ålfotbreen and Hansebreen there was no melting after the final measurements in the autumn 2000.

Except for June the summer temperature in 2001 was somewhat higher than normal in most of the country. Consequently the summer balance was larger than average for the glaciers in western and northern Norway. The relatively greatest summer balance was at Hansebreen and Austdalsbreen, with 122 % of the mean values. At the glaciers in Jotunheimen the summer balance was lower than average.

The final results show negative net balance for twelve of thirteen glaciers. Hansebreen (-2.7 m w.eqv.) and Langfjordjøkelen (-2.3 m w.eqv.) had the greatest deficit. The result at Langfjordjøkelen is the greatest deficit measured since measurements began in 1989. Gråsubreen was exactly in balance. For 7 of the glaciers the equilibrium line was above the glacier summit.

The results from the mass balance measurements in Norway in 2001 are shown in Table 1-1. Winter (b_w), summer (b_s) and net balance (b_n) are given in metre water equivalents (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 8 years of measurements). The net balance results are compared with the mean net balance in the same way. **ELA** is the equilibrium line altitude.

Figure 1-2 gives a graphical presentation of the mass balance results in southern Norway for 2001. The west-east gradient is evident for both winter and summer balances.

Glacier	Number code WGMS REGINE	Period	Area (km ²)	b_w (m)	% of average	b_s (m)	% of average	b_n (m)	b_n middle	ELA
Ålfotbreen	36204 086.6C1B	1963-01	4.5	1.86	49	-3.95	116	-2.09	0.40	>1382
Hansebreen	36206 086.6E	1986-01	3.1	1.71	47	-4.43	122	-2.72	0.02	>1327
Nigardsbreen	31014 076.EZ	1962-01	47.8	1.75	72	-1.97	103	-0.22	0.50	1560
Austdalsbreen	37323 076.H	1988-01	11.8	1.04	43	-2.66 ¹⁾	122	-1.62	0.23	>1757
Rembesdalskåka	22303 050.4C1Z	1963-01	17.1	1.03	48	-1.88	97	-0.85	0.21	1760
Midtdalsbreen	04302 012.CZCK2	2000-01	6.7	1.26	-	-1.90	-	-0.64	0.06 ²⁾	1785
Harbardsbreen	30704 075.DC	1997-01	13.2	0.88	-	-1.99	-	-1.11	-0.28 ³⁾	>1960
Storbreen	00541 002.DHBBZ	1949-01	5.4	1.05	72	-1.32	79	-0.27	-0.22	1855
Hellstugubreen	00511 002.DHBAZ	1962-01	3.0	0.85	76	-1.21	89	-0.36	-0.27	1910
Gråsubreen	00547 002.DGDC	1962-01	2.3	0.80	102	-0.78	75	0.02	-0.26	2070
Storglombreen	67313/ 160.C 67314	1985-88 2000-01	59.0 62.4	1.15	-	-2.91	-	-1.76	-	>1580
Engabreen	67011 159.81	1970-01	38.0	1.05	35	-2.58	116	-1.53	0.78	>1594
Langfjordjokelen	85008 211.33Z	1989-93 1996-01	3.7 3.7	1.36	-	-3.64	-	-2.28	-0.10 -0.86	>1050

¹⁾ Contribution from calving amounts to 0.25 m for b_s .

²⁾ Mean value for the period 1961-1995 estimated by map comparison.

³⁾ Mean value for the period 1966-1996 estimated by map comparison.

Table 1-1

Review of the results from mass balance measurements performed in Norway in 2001. The glaciers in southern Norway are listed from west to east. Each glacier is reported in two different number systems. The first column denotes the numbers used in the reports to the World Glacier Monitoring Service (WGMS), while the second column gives numbers from the Norwegian Hydrological Unit System (REGINE).

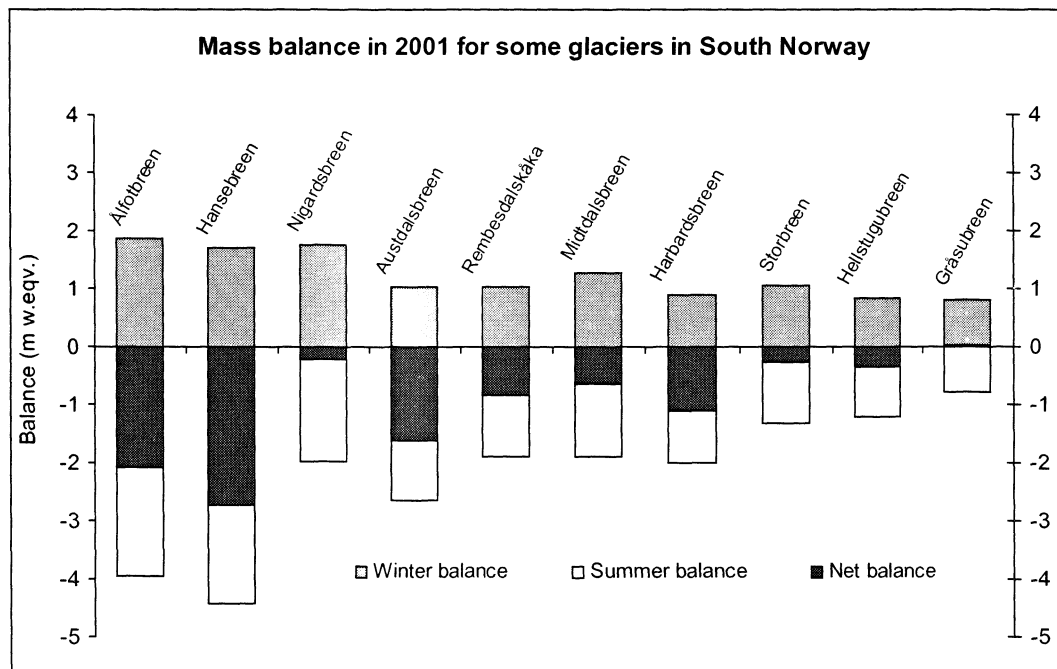


Figure 1-2

Mass balance 2001 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 1963-2001 is shown in Figure 1-3. The maritime glaciers – Ålfotbreen, Nigardsbreen and Hardangerjøkulen – have increased in volume, while Storbreen and Gråsubreen in Jotunheimen show a distinct decrease in net balance. The considerable surplus for the maritime glaciers is mainly a result of some winters with high snowfall between 1989 and 1995.

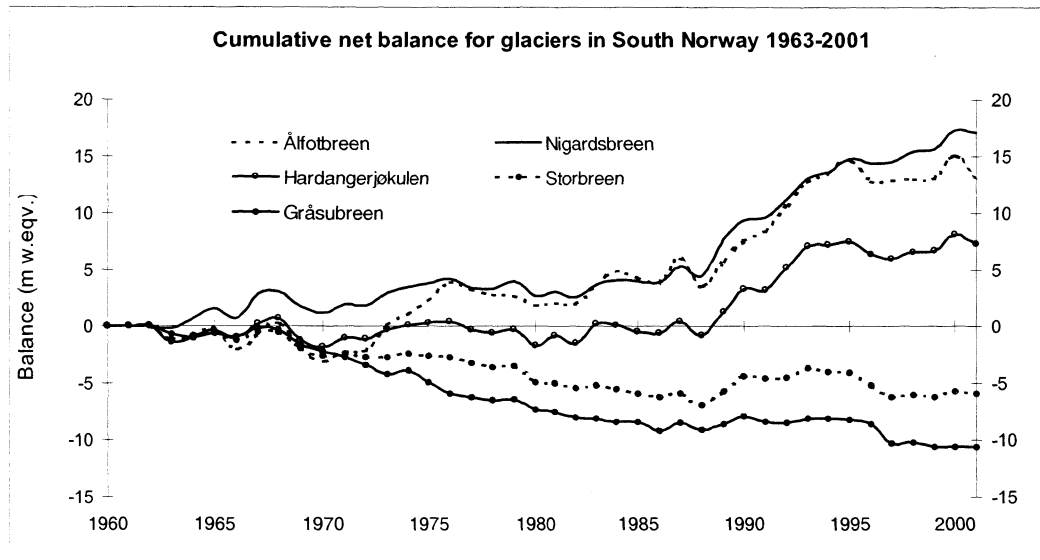


Figure 1-3
Cumulative net balance for Ålfotbreen, Nigardsbreen, Hardangerjøkulen, Storbreen and Gråsubreen during the period 1963-2001. Ålfotbreen and Nigardsbreen have a considerable surplus, most of this was acquired between 1989 and 1995.

1.2 Other investigations

Front position measurements were performed at 24 glaciers in Norway in 2001. Some of these have measurements going back to ca. 1900. As well as being presented in a separate chapter (chap. 15), the front position changes are described for each glacier in its respective chapter.

An ice-dammed lake at Harbardsbreen has been observed since the early 1990's. The observations were continued in 2001 with photographs taken in February, May, August and September (chap. 6).

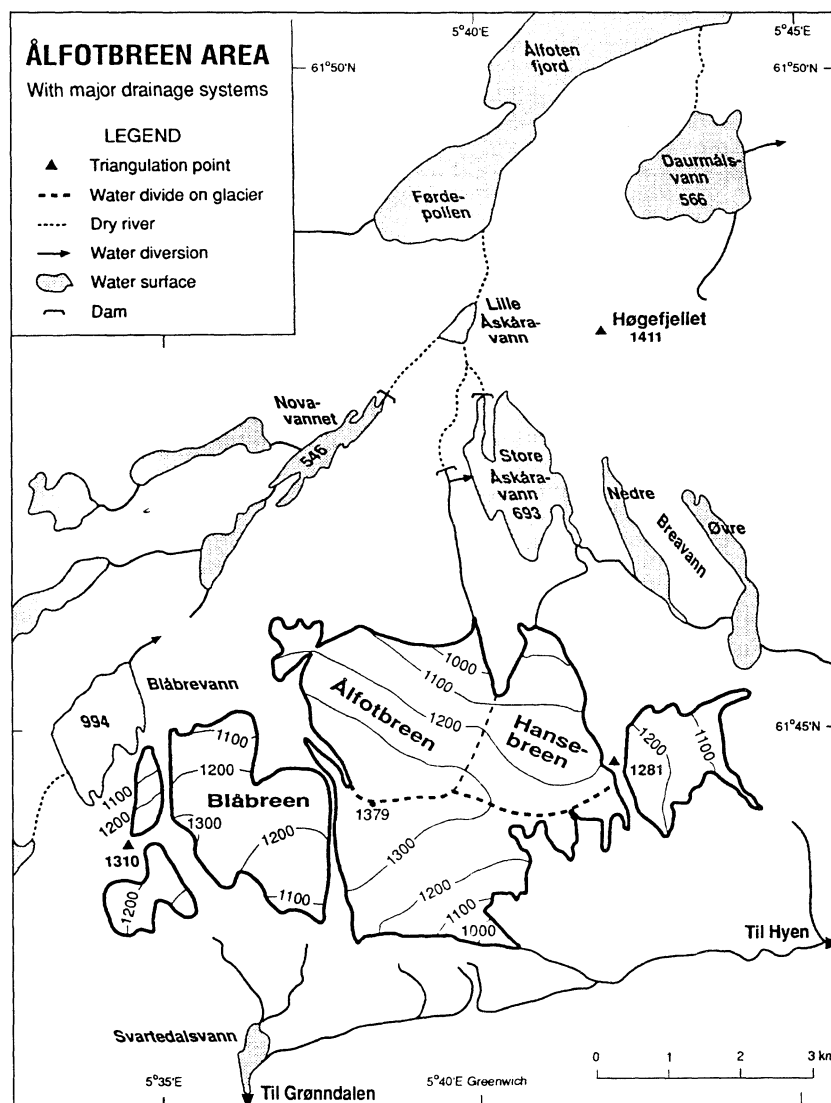
A number of measurements were performed at Svartisheibreen during the period 1988-94 (Kjøllmoen & Kennett 1995). Mass balance, ice movement, front position change, surface elevation and water level in a small lake in front of the glacier terminus (Heiavatnet) were measured. Annual observations of water level in Heiavatnet, equilibrium line altitude and changes in ice thickness on the snout have been performed since 1995 and were continued in 2001 (chap. 10).

Meteorological observations were performed at Nigardsbreen, Engabreen, Harbardsbreen and Langfjordjøkelen.

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 11.

2. Ålfotbreen (Bjarne Kjølmoen)

Ålfotbreen ice cap (61°45'N, 5°40'E) is 17 km², 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 km²) and Hansebreen (3.1 km²). The westernmost of these 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 its surroundings is



shown in Figure 2-1.

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

2.1 Mass balance 2001

Fieldwork

Snow accumulation measurements were performed 27th and 28th April. Calculation of winter balance at Ålfotbreen and Hansebreen is based on (Fig. 2-2):

- Direct measurements of tower T49 and ten stakes in 8 different positions at Ålfotbreen, and of 4 stakes in 2 different positions at Hansebreen.
- 74 snow depth soundings along a total of about 12 km of profiles at Ålfotbreen, and 41 snow depth soundings along about 9 km of profiles at Hansebreen. The snow depth varied between 3 and 6 m at both glaciers. The summer surface (SS) could be easily identified over the entire glacier.
- Snow density was measured down to SS (4.1 m) ca. 400 m west of stake position 37 (1250 m a.s.l.).

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

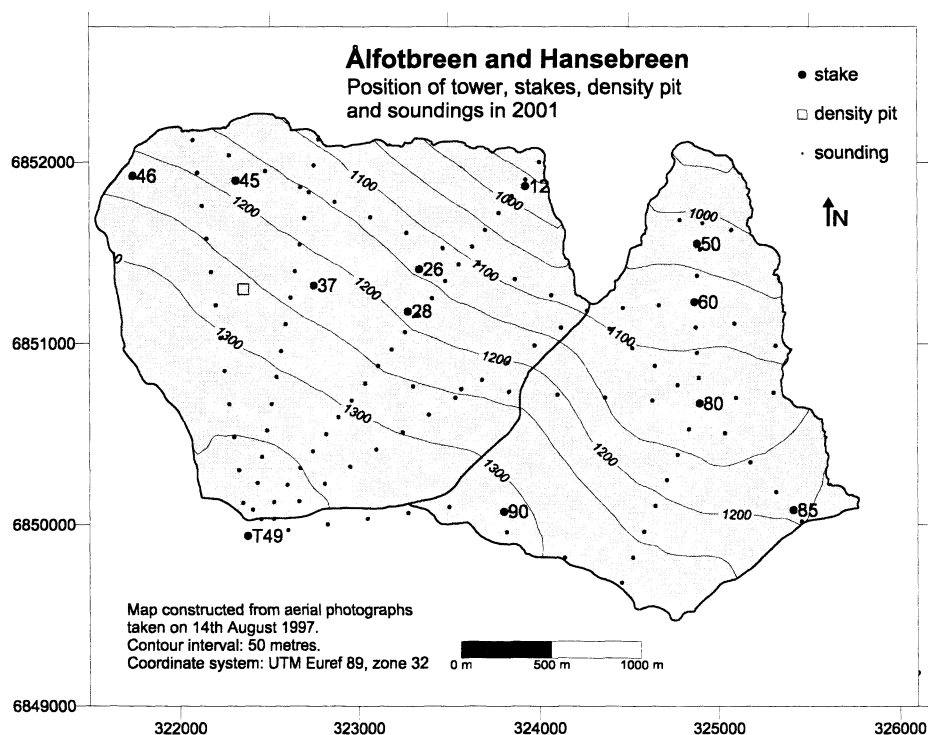


Figure 2-2
Location of stakes, soundings and density pit at Ålfotbreen and Hansebreen in 2001.

Ablation was measured on 18th October. The net balance was directly measured on stakes in 5 different positions between 1180 and 1380 m a.s.l. at Ålfotbreen, and at 4 stake positions between 1030 and 1305 m a.s.l. at Hansebreen. There was no snow remaining on the glacier surface from the winter 2000/2001. The summer melting in

2001 was considerable and in addition to all the snow, about 3 m of firn had melted at 1380 m altitude. At the time of ablation measurements no fresh snow had fallen.

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 2000.

A density profile was modelled from the snow density measured at 1250 m a.s.l. The mean snow density of 4.1 m snow was 0.44 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 2001 was $1.9 \pm 0.2 \text{ m w.eqv.}$, corresponding to a volume of $8 \pm 1 \text{ mill. m}^3$ of water. The result is 49 % of the mean winter balance for 1963-2000, and 44 % of the mean for 1986-2000 (for comparison with Hansebreen). This is the second lowest winter balance since the measurements started in 1963, the lowest being 1.8 m in 1996.

The winter balance at Hansebreen was $1.7 \pm 0.2 \text{ m w.eqv.}$, corresponding to a volume of $5 \pm 1 \text{ mill. m}^3$ of water. The result is 47 % of the mean value for the period of investigation. This is the lowest winter balance ever measured at Hansebreen, and is the same as in 1996.

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 summarized. Using this method, which is a control of the traditional method, gave exactly the same results as above.

Summer balance

The density of melted firn was estimated between 0.65 and 0.75 g/cm^3 , while the density of melted ice was estimated to 0.90 g/cm^3 .

The summer balance at Ålfotbreen was measured and calculated directly at 5 stakes. For another stake (12-01) the measurements were supplemented with correlation to other stake measurements in the same area. The summer balance increased from about -3.5 m w.eqv. in the upper parts of the glacier to -5.5 m at the tongue. Based on estimated density and stake measurements the summer balance for Ålfotbreen was calculated as $-4.0 \pm 0.3 \text{ m w.eqv.}$, corresponding to $-18 \pm 1 \text{ mill. m}^3$ of water. The result is 116 % of the average between 1963 and 2000, and 112 % of the average between 1986 and 2000.

The summer balance for Hansbreen was measured and calculated at four stakes and increased from -4 m w.eqv. in the upper parts, to approx. -5 m in the lower parts. Based on these four stakes the summer balance was calculated to -4.4 ± 0.3 m w.eqv. or -14 ± 1 mill. m^3 of water. The result is 122 % of the mean value over 1986-2000. Only one year has shown a greater summer loss from Hansbreen, 1988 with -5.2 m.

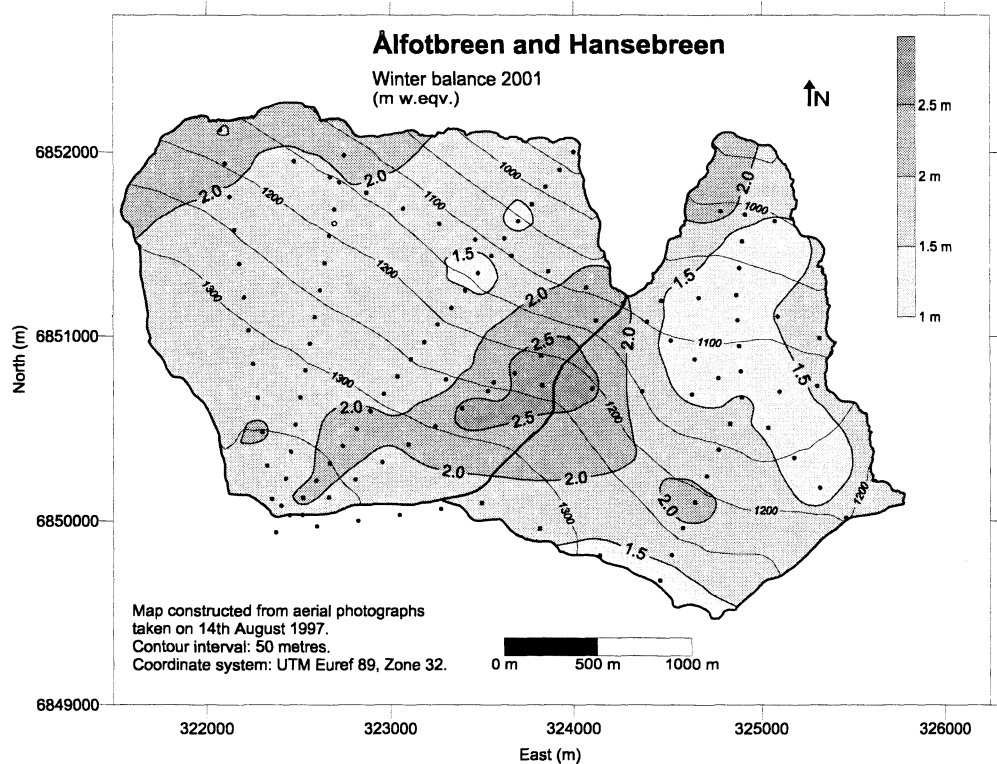


Figure 2-3
Winter balance at Ålfotbreen and Hansbreen in 2001 interpolated from 115 snow depth measurements (•).

Net balance

The net balance at Ålfotbreen for 2001 was calculated as -2.1 ± 0.4 m w.eqv., or a volume loss of 9 ± 2 mill. m^3 of water. Since the measurements began, two years have had a greater deficit, 1969 and 1988. The mean net balance was $+0.40$ m w.eqv. during 1963-2000, and $+0.72$ m during 1986-2000.

The net balance at Hansbreen was calculated as -2.7 ± 0.4 m w.eqv., or a deficit of 8 ± 1 mill. m^3 of water. This is the greatest deficit ever measured at Hansbreen, and is equal to the result in 1988. The mean value for the period 1986-2000 ($+0.02$ m) shows that the glacier has been close to balance for the last fourteen years.

With net ablation over the entire glacier surface the equilibrium line altitude lies *above* the highest summit (Fig. 2-4) at 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.

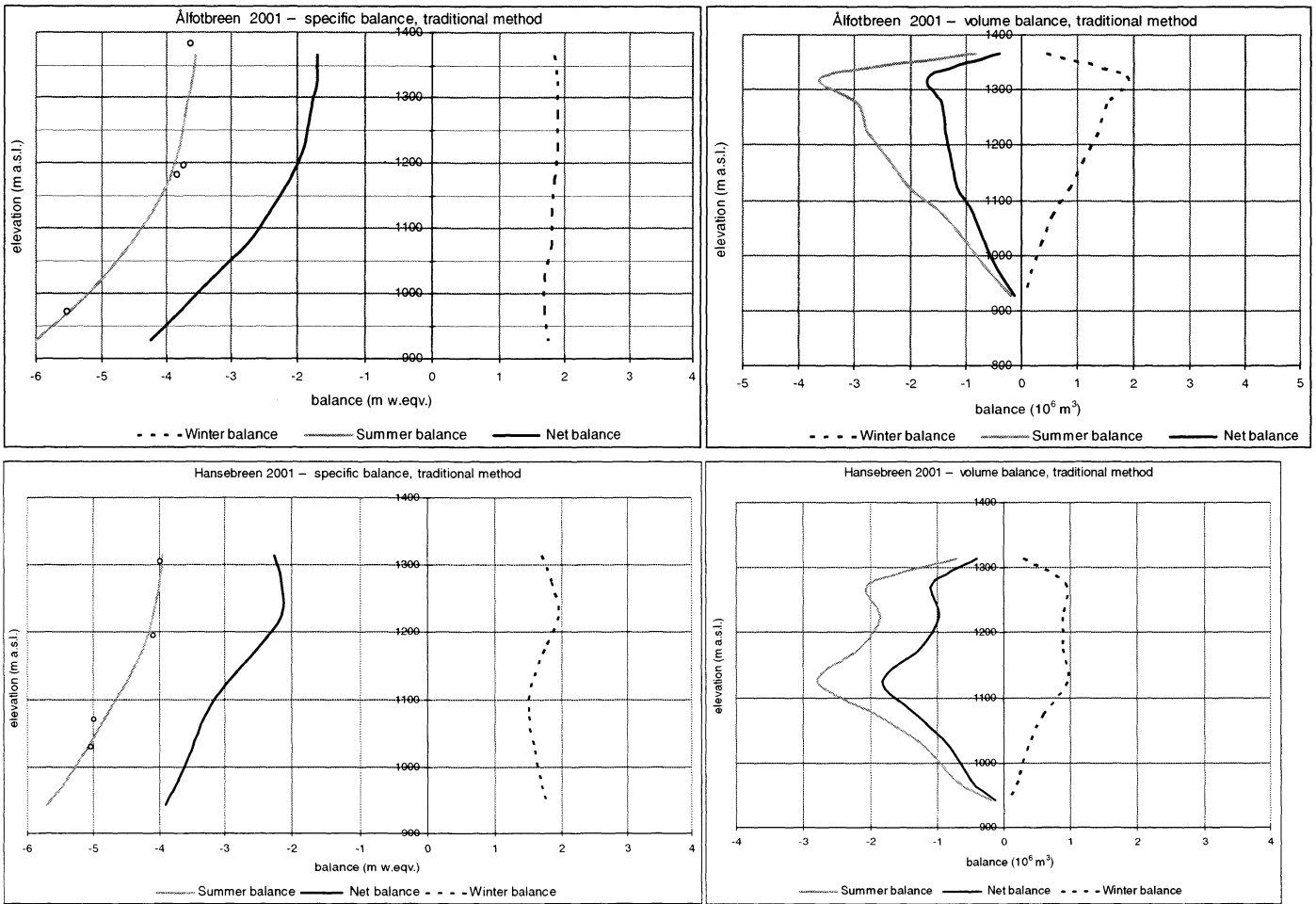


Figure 2-4
Mass balance diagram for Ålfotbreen (upper) and Hansebreen (lower) in 2001 showing altitudinal distribution of specific (left) and volumetric (right) winter, summer and net balance. Specific summer balance at each stake is shown (○).

Mass balance Ålfotbreen 2000/01 – traditional method							
Altitude (m a.s.l.)	Area (km ²)	Winter balance		Summer balance		Net balance	
		Measured 28th Apr 2001		Measured 18th Oct 2001		Summer surfaces 2000 - 2001	
		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	1,85	0,4	-3,55	-0,8	-1,70	-0,4
1300 - 1350	0,98	1,90	1,9	-3,60	-3,5	-1,70	-1,7
1250 - 1300	0,80	1,90	1,5	-3,70	-2,9	-1,80	-1,4
1200 - 1250	0,73	1,90	1,4	-3,80	-2,8	-1,90	-1,4
1150 - 1200	0,61	1,85	1,1	-3,95	-2,4	-2,10	-1,3
1100 - 1150	0,49	1,80	0,9	-4,20	-2,0	-2,40	-1,2
1050 - 1100	0,32	1,80	0,6	-4,55	-1,4	-2,75	-0,9
1000 - 1050	0,20	1,70	0,3	-4,95	-1,0	-3,25	-0,7
950 - 1000	0,11	1,70	0,2	-5,45	-0,6	-3,75	-0,4
903 - 950	0,03	1,75	0,1	-6,00	-0,2	-4,25	-0,1
903 - 1382	4,50	1,86	8,4	-3,95	-17,8	-2,09	-9,4

Mass balance Hansebreen 2000/01 – traditional method							
Altitude (m a.s.l.)	Area (km ²)	Winter balance		Summer balance		Net balance	
		Measured 28th Apr 2001		Measured 18th Oct 2001		Summer surface 2000 - 2001	
		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	1,70	0,30	-3,95	-0,70	-2,25	-0,40
1250 - 1300	0,50	1,85	0,93	-4,00	-2,00	-2,15	-1,08
1200 - 1250	0,45	1,95	0,88	-4,10	-1,85	-2,15	-0,97
1150 - 1200	0,51	1,75	0,89	-4,25	-2,15	-2,50	-1,27
1100 - 1150	0,62	1,55	0,96	-4,50	-2,79	-2,95	-1,83
1050 - 1100	0,40	1,50	0,60	-4,80	-1,93	-3,30	-1,33
1000 - 1050	0,23	1,60	0,37	-5,10	-1,19	-3,50	-0,82
950 - 1000	0,13	1,70	0,23	-5,45	-0,73	-3,75	-0,50
930 - 950	0,03	1,80	0,06	-5,70	-0,18	-3,90	-0,13
930 - 1327	3,06	1,71	5,2	-4,43	-13,5	-2,72	-8,3

Table 2-1

Winter, summer and net balance for Ålfotbreen (upper) and Hansebreen (lower) in 2001. The mean values for Ålfotbreen during the period 1963-2000 are 3.79 m (b_w), -3.39 m (b_s) and +0.40 m w.eqv. (b_n). The corresponding values for Hansebreen during the period 1986-2000 are 3.64 m, -3.62 m and +0.02 m w.eqv.

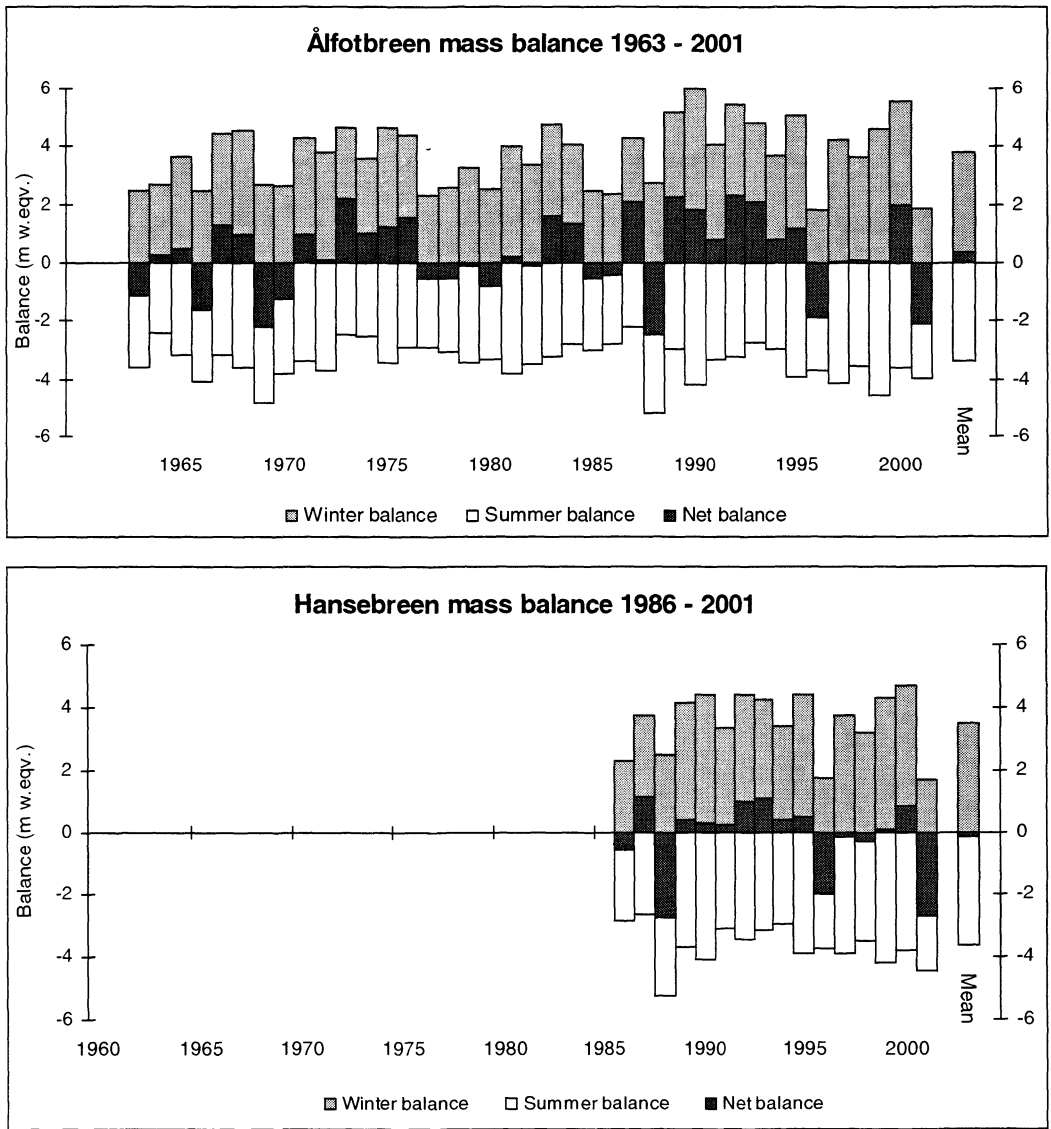


Figure 2-5
 Mass balance at Åfotbreen (upper) during the period 1963-2001 and Hansebreen (lower) during the period 1986-2001.

3. Nigardsbreen (Bjarne Kjølmoen)

Nigardsbreen (61°42'N, 7°08'E) is one of the largest and most famous outlet glaciers (47.8 km²) from Jostedalbreen, flowing south-east from the centre of the ice cap. Nigardsbreen accounts for approximately 10 % of the total area of Jostedalbreen, and extends from 1960 m a.s.l. down to approximately 320 m a.s.l.

Glaciological investigations in 2001 include mass balance and front position change. Some observations of the ice-dammed lake Brimkjelen at Tunsbergdalsbreen have also been performed (Fig. 3-6). Nigardsbreen has been the subject of mass balance investigations since 1962.

3.1 Mass balance 2001

Fieldwork

Snow accumulation measurements were undertaken 4th and 5th May and the calculation of winter balance is based on (Fig. 3-1):

- Direct measurements of the towers T95 and T56. Direct measurements of stakes in 5 different positions (600, 1000, 53, 54 and 94). It was also possible to make connections between measurements of 2 stakes in position 57.
- Core samples at position 53, 96 and 57.
- 180 snow depth soundings along approximately 33 km of profiles between 1325 and 1960 m a.s.l., and some soundings at 630 and 1000 m a.s.l. Due to little snow and a distinct summer surface (SS) the probing conditions were good all over the glacier surface. Down at the outlet the snow depth was about 0.5 m at 630 m altitude and about 2.5 m at 1000 m altitude. Up on the plateau snow depth varied between 3.5 and 5.5 m.
- Snow density was measured down to SS (3.8 m) at stake position 53 (1320 m a.s.l.) and down to 4.2 m depth (SS at 4.6 m) at position 57 (1960 m a.s.l.).

Location of stakes, towers, density pit, core samples and sounding profiles are shown in Figure 3-1.

Ablation measurements were carried out on 19th September. The net balance was measured directly at stakes in ten different positions between 630 and 1960 m a.s.l. There was between 0.5 and 1.5 m of snow remaining on the plateau. Between 5 and 15 cm of fresh snow had fallen in the upper parts of the glacier. On the glacier tongue the net melting between autumn 2000 and autumn 2001 was about 8.5 m of ice at 630 m altitude.

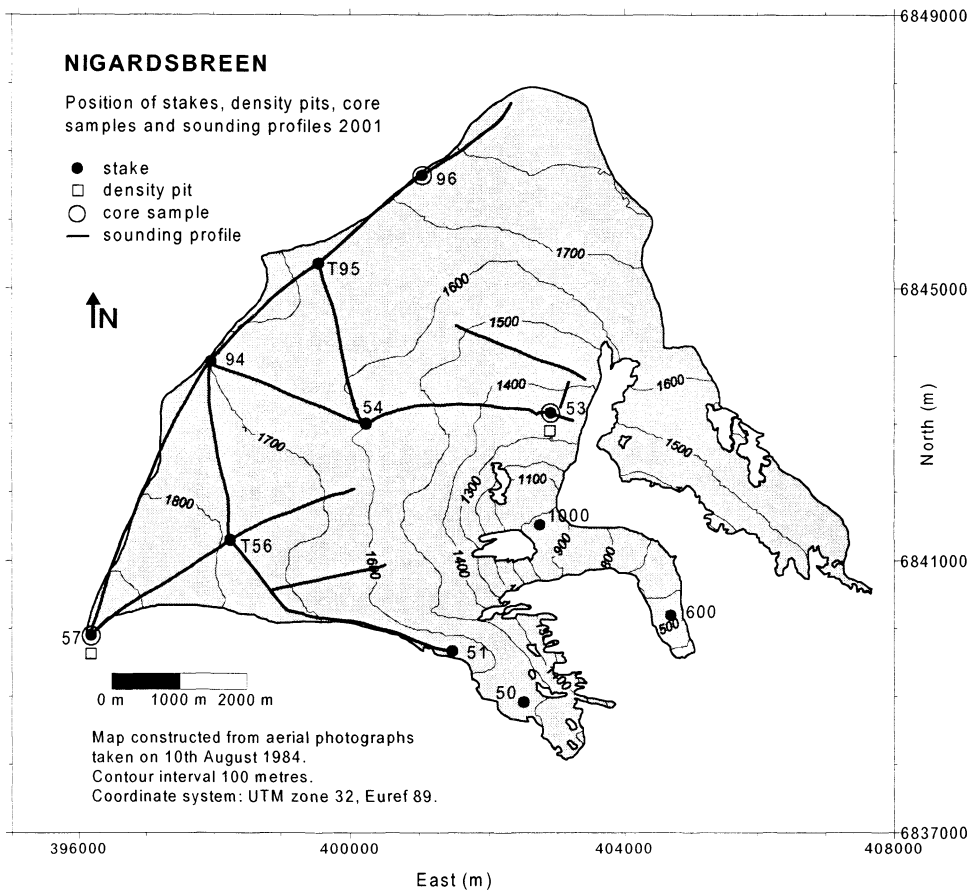


Figure 3-1
Location of towers and stakes, density pits, core samples and sounding profiles at Nigardsbreen in 2001.

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 two locations.

Some ablation occurred *after* the final measurements in September 2000. This ablation was counted as a negative contribution to the winter balance 2000/2001 as described in chapter 1. This negative winter balance was measured and calculated as 1.3 m w.eqv. at 600 m altitude, 0.8 m w.eqv. at 1000 m altitude and 0.2 m w.eqv. at 1320 m altitude, in total 0.1 m water equivalents.

Density profiles were modelled from the snow density measured at 1320 m a.s.l. (3.8 m snow) and 1960 m a.s.l. (4.6 m). Using these models gave a snow density of 0.43 g/cm³ (1320 m a.s.l.) and 0.46 g/cm³ (1960 m a.s.l.). The model from 1320 m altitude was used for all snow depth measurements carried out below 1640 m a.s.l., whereas the model from 1960 m altitude was used for elevations above 1640 m a.s.l.

The winter balance calculation was performed by plotting measurements (water equivalents) in a diagram. A curve was drawn based on visual evaluation (Fig. 3-3), and a mean value for each 100 m height interval estimated (Tab. 3-1). The elevations above 1320 m a.s.l. were well represented with point measurements. Below this altitude the curve pattern was based on some probings at 1000 and 630 m altitude.

The *winter balance*, hence, was 1.8 ± 0.2 m w.eqv., corresponding to a water volume of 84 ± 10 mill. m³. The result is 72 % of the mean value for the period 1962-2000. Only four years, 1970, 1977, 1986 and 1996, have shown a lower winter balance on Nigardsbreen. Excluding the additional ablation in late autumn 2000 the *winter accumulation* was 1.9 m water equivalents.

The winter balance was also calculated using a gridding method based on the aerial distribution of the snow depth measurements (Fig. 3-2). In areas with insufficient measurements some (13) 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 summarized. The result based on this method, which is a control of the traditional method, also showed a *winter balance* of 1.8 m w.eqv.

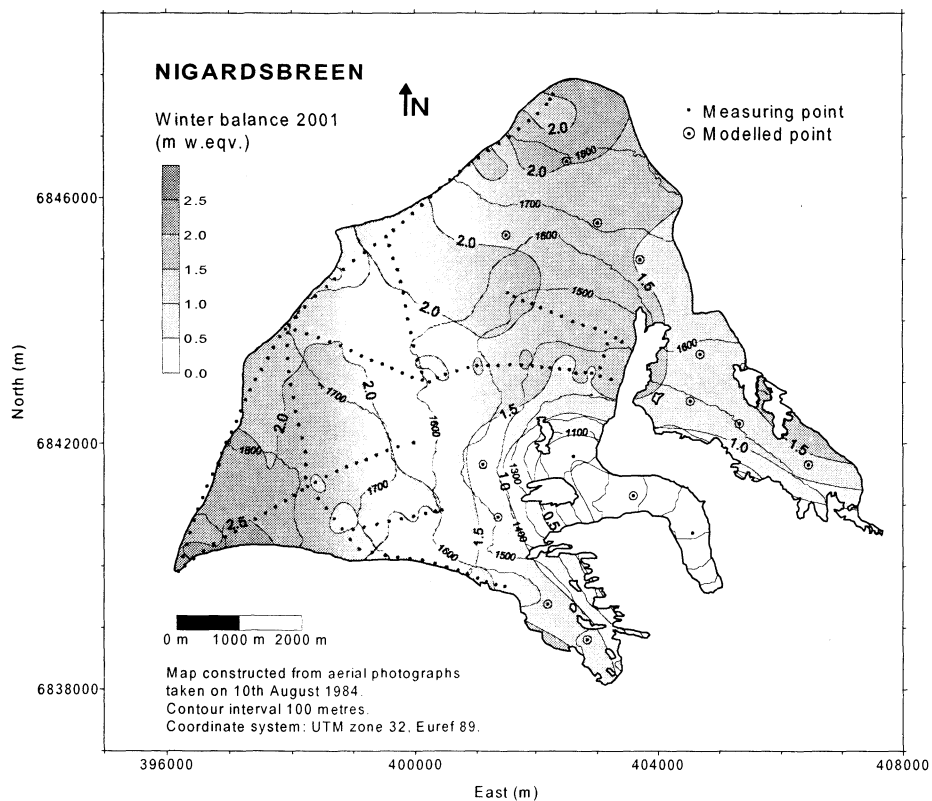


Figure 3-2
Winter balance at Nigardsbreen in 2001 interpolated from 180 measurements (•) of snow depth. In areas with few or no measurements thirteen extrapolated points (⊙) are added.

Summer balance

When calculating the summer balance the density of the remaining snow was estimated as 0.60 g/cm^3 . The density of melted firn was estimated between 0.65 and 0.75 g/cm^3 , and density of melted ice was estimated as 0.90 g/cm^3 .

The summer balance was measured and calculated directly at nine stakes, and increased from -1 m w.eqv. in the upper parts of the glacier to about -8 m down on the tongue. Based on estimated density and stake measurements the summer balance was calculated to be $-2.0 \pm 0.3 \text{ m w.eqv.}$, which is $-94 \pm 15 \text{ mill. m}^3$ of water. The result is 103% of the average for 1962-2000.

Some melting was registered *after* the final measurements in September 2001. This ablation amounted to 0.2 m w.eqv. at 1000 m altitude and 0.8 m w.eqv. at 615 m altitude. Distributed over the entire glacier surface the ablation amounted to 0.03 m w.eqv. This ablation will be included in the winter balance 2002.

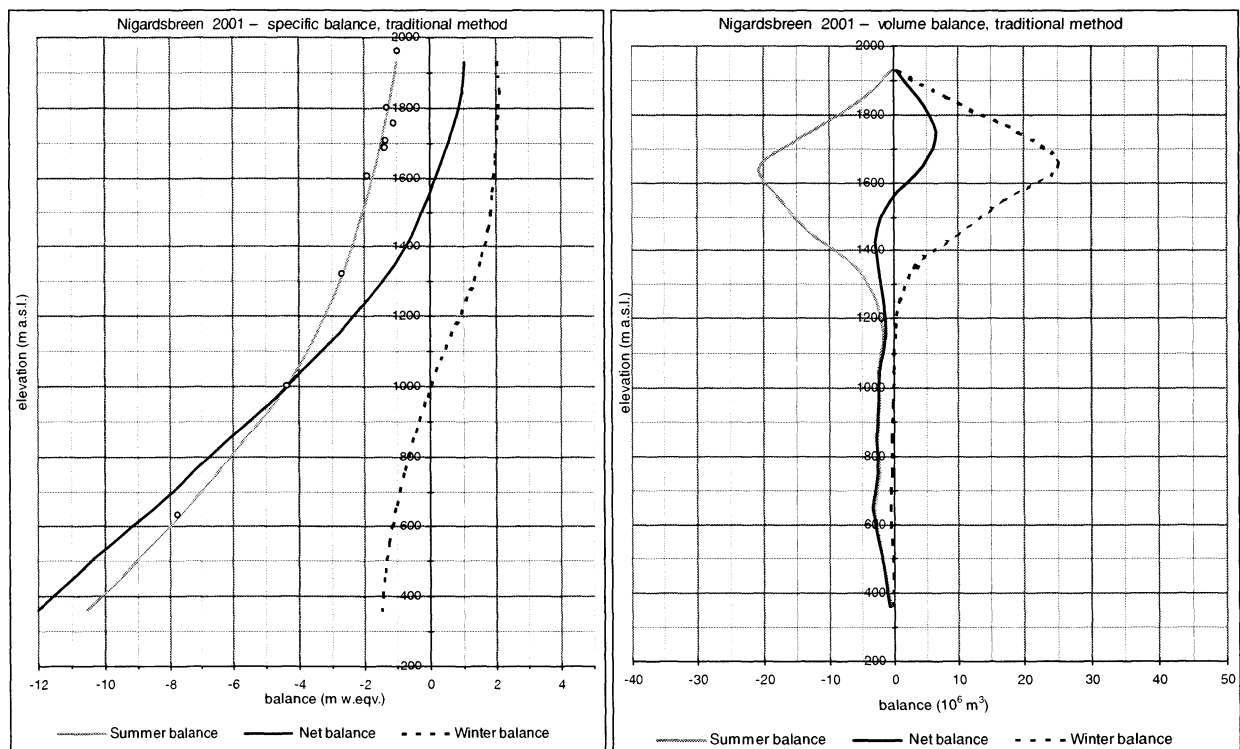


Figure 3-3
Mass balance diagram showing specific balance (left) and volume balance (right) for Nigardsbreen in 2001. Summer balance at nine stakes is shown as dots (•). The net balance curve intersects the y-axis and defines the ELA as 1560 m a.s.l. Thus the AAR was 64% .

Net balance

The net balance was calculated at stakes and towers in eleven positions. At stake 1000 the measurements were supplemented with correlated data from stake 600 .

The net balance for 2001, hence, was calculated as $-0.2 \text{ m} \pm 0.3 \text{ m w.eqv.}$, which is equal to a deficit of $10 \pm 15 \text{ mill. m}^3$ water. The mean value for the period 1962-2000 is $+0.50 \text{ m w.eqv.}$ (Fig. 3-4).

The diagram in Figure 3-3 indicates that the equilibrium line altitude (ELA) was 1560 m a.s.l. Accordingly, the Accumulation Area Ratio (AAR) was 64 %.

Mass balance Nigardsbreen 2000/01 – traditional method							
Altitude (m a.s.l.)	Area (km ²)	Winter balance		Summer balance		Net balance	
		Measured 4th May 2001		Measured 19th Sep 2001		Summer surface 2000 - 2001	
		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)
1900 - 1960	0,38	2,05	0,8	-1,00	-0,4	1,05	0,4
1800 - 1900	3,92	2,10	8,2	-1,15	-4,5	0,95	3,7
1700 - 1800	9,39	2,05	19,2	-1,35	-12,7	0,70	6,6
1600 - 1700	12,88	1,95	25,1	-1,60	-20,6	0,35	4,5
1500 - 1600	9,18	1,85	17,0	-1,90	-17,4	-0,05	-0,5
1400 - 1500	5,82	1,75	10,2	-2,20	-12,8	-0,45	-2,6
1300 - 1400	2,28	1,50	3,4	-2,55	-5,8	-1,05	-2,4
1200 - 1300	0,90	1,10	1,0	-2,95	-2,7	-1,85	-1,7
1100 - 1200	0,45	0,65	0,3	-3,45	-1,6	-2,80	-1,3
1000 - 1100	0,58	0,20	0,1	-4,05	-2,3	-3,85	-2,2
900 - 1000	0,47	-0,15	-0,1	-4,75	-2,2	-4,90	-2,3
800 - 900	0,44	-0,50	-0,2	-5,65	-2,5	-6,15	-2,7
700 - 800	0,33	-0,80	-0,3	-6,55	-2,2	-7,35	-2,4
600 - 700	0,39	-1,05	-0,4	-7,50	-2,9	-8,55	-3,3
500 - 600	0,24	-1,25	-0,3	-8,55	-2,1	-9,80	-2,4
400 - 500	0,12	-1,40	-0,2	-9,55	-1,1	-10,95	-1,3
320 - 400	0,05	-1,45	-0,1	-10,55	-0,5	-12,00	-0,6
320 - 1960	47,82	1,75	83,9	-1,97	-94,3	-0,22	-10,5

Table 3-1
Winter, summer and net balance for Nigardsbreen in 2001. Mean values for the period 1962-2000 are 2.42 (b_s), -1.92 m (b_s) and +0.50 m water equivalents (b_n).

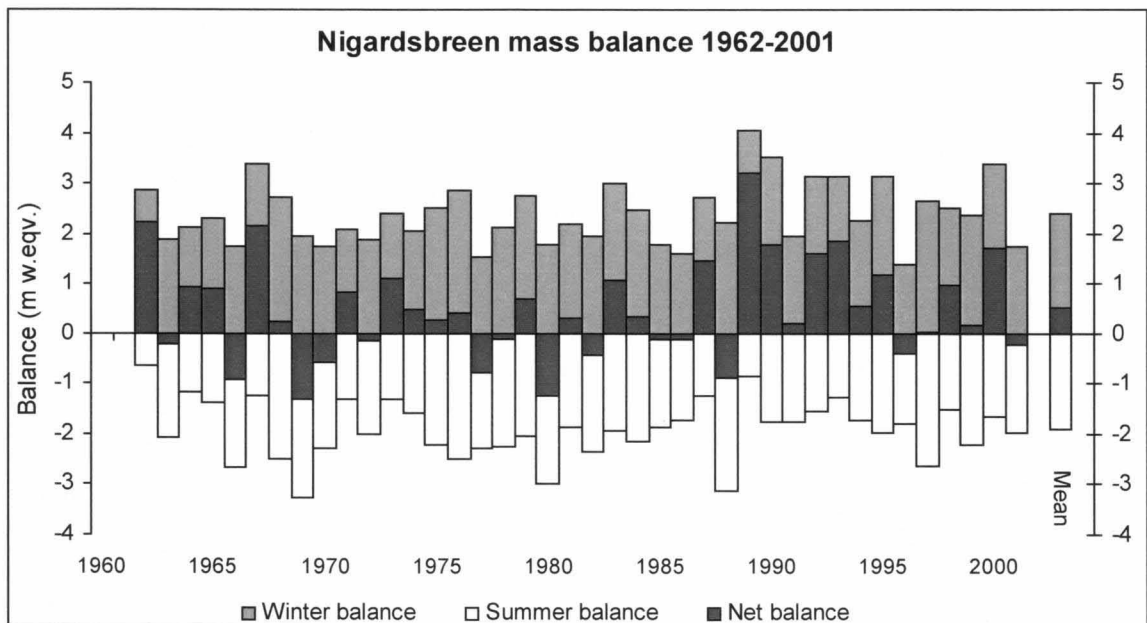


Figure 3-4
Annual mass balance at Nigardsbreen during the period 1962-2001. After 1988 there are only 2 years with negative net balance (1996 and 2001). The accumulated surplus for the period 1962-2001 amounts to 19.4 m water equivalent.

3.2 Front position change

Due to the advance of the glacier front position over the last few years, the glacier stream has changed pattern from one main river to several smaller fluctuating channels. This situation has persisted in 2001 (Fig. 3-5).



Figure 3-5

The last years front advance has induced changes in channel pattern of the glacier stream. The photographs are taken on 19th September 2001. They show that most of the melt water from the glacier comes out in a stream at the northeast side of the glacier terminus (to the left in the left photo and to the right in the right photo). Photo: Nils Haakensen.

Changes in front position are measured annually from fixed points along a straight line drawn from the original stream outlet. The measurement in October 2001 shows that the front position has receded slightly (4 m) since October 2000. This is the first year with recession since 1988. However, at the southwest side of the snout, at the former river course, the front has advanced some metres during the same period.

3.3 Tunsbergdalsbreen

Mass balance

From 1966 to 1972 mass balance measurements were made simultaneously at both Tunsbergdalsbreen (47.7 km²) 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 2001 the net balance at Tunsbergdalsbreen was estimated as -0.50 ± 0.45 m w.eqv., corresponding to a deficit of about 24 mill. m³ of water. Since 1962 the estimated accumulated net balance is about 7½ m w.eqv. The surplus has occurred since 1988.

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 2001 was about 1430 m a.s.l.

Brimkjelen

About 3 km above the western side of the glacier snout lies an ice-dammed lake named Brimkjelen. Due to the 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 m³ in 1982.

From 1984 to 1997 no systematic observations were made of the lake. Observations was resumed in the autumn of 1997 and continued in 2001 by photographing on 22nd August and 19th September (Fig. 3-6). The lake was empty on both occasions.



Figure 3-6
Brimkjelen photographed on 19th September 2001. As the photo shows, the lake was empty at this time. Photo: Nils Haakensen.

4. Austdalsbreen (Hallgeir Elvehøy and Laila P. Høivik)

Austdalsbreen (61°45'N, 7°20'E) is an eastern outlet of the northern part of Jostedalbreen, 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 2001 included mass balance, front position change and glacier velocity. Mass balance has been measured on Austdalsbreen since 1988.

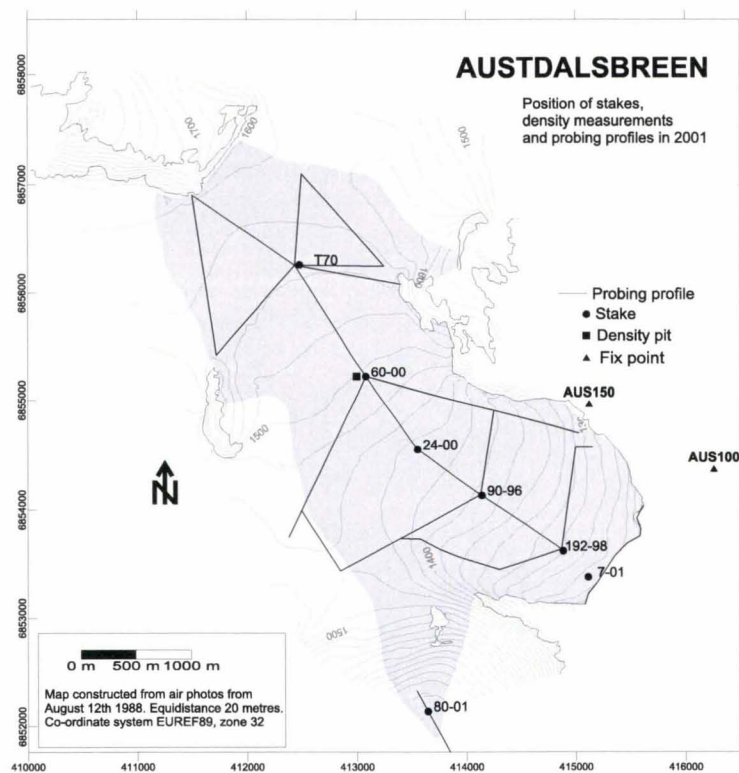


Figure 4-1
Location of stakes, density pits and sounding profiles at Austdalsbreen in 2001.

4.1 Mass balance 2001

The second half of September and most of October 2000 was unusually warm in West Norway, therefore melting continued after the ablation measurements. The ablation after 14th September 2000 was not included in the calculations of the mass balance for 2000, and was therefore counted as a negative contribution to the winter balance for 2001.

Fieldwork

Snow depth soundings at stake locations on 18th February 2001 showed that melting had taken place since the ablation measurements at stakes below 1550 m a.s.l. At stake 60-00 (1495 m a.s.l.) 0.15 m of snow had melted away, while 0.80 m of ice had melted at stake 7 (1235 m a.s.l.).

Winter accumulation was measured 6th May. The calculation of winter balance was based on the following data (Fig. 4-1):

- Snow depth measurements at stake 6-98 (1235 m a.s.l.), 7-99 (1235 m a.s.l.), 192-98 (1300 m a.s.l.), 43-96 (1340 m a.s.l.), 90-96 (1400 m a.s.l.), 24-00 (1440 m a.s.l.), 60-00 (1495 m a.s.l.) and T70 (1545 m a.s.l.). The stakes showed snow depths of 0.35, 0.80, 1.75, 2.25, 2.55, 2.90, 3.10 and 3.30 m respectively.
- Snow depth measurements by coring at 1730 m a.s.l. (stake 80-01) showing a snow depth of 2.5 m.
- Snow depth measured by sounding at 100 locations along 18 km of profiles. At Austdalsnuten above 1700 m a.s.l. the snow depth was 2½ - 3½ m. Between 1450 and 1600 m a.s.l. the snow depth was 2½ - 3½ m. Between 1300 and 1450 m a.s.l. the snow was 2 to 3 m deep, and below 1300 m a.s.l. the snow depth varied between 0 and 2 m. The summer surface from 2000 (SS) was easy to detect in all areas.
- Snow density measured down to SS at 3.1 m depth at stake 60-00 (1495 m a.s.l.). Mean snow density was 0.42 g/cm³.

Summer ablation and net balance was measured 20th September. The net balance was measured at six locations between 1300 and 1730 m a.s.l. All the winter snow had melted away at Austdalsbreen. At stake 80 (1730 m a.s.l.) an additional 1 m of firn from 1999/2000 had melted away. At stakes between 1440 and 1600 m a.s.l. (24-00, 60-00 and T70) 1.4 to 0.7 m of firn from 1999/2000 had melted away. At stake 90-96 (1400 m a.s.l.) 0.9 m firn from 1999/2000 and an additional 1.5 m of ice had melted away. At stake 192-98 (1300 m a.s.l.) 3.35 m of ice had melted away, and the lowermost stakes had melted out completely during the summer. The ice melting at stake 7 was estimated to 4.9 m. The transient snow line altitude (TSL) was higher than the top of the glacier (1760 m a.s.l.).

Results

The mass balance was calculated according to the stratigraphic method (see chap.1). The calculations are based on a map from 1988, and adjusted for glacier retreat between 1988 and 2001.

Winter balance

The winter balance was calculated as the sum of late autumn ablation calculated from stakes 20th September and 18th February, and snow accumulation calculated from measurements 9th May 2001.

Late autumn melting was registered at stakes up to 1545 m a.s.l. The density of melting snow and ice was set to 0.6 and 0.9 g/cm³, respectively. The altitudinal distribution of the autumn ablation was then estimated over the entire glacier. In total the late autumn melting was calculated to 0.2 m w.eqv., or 2.0 mill m³ water.

A profile correlating snow depth with water equivalent was calculated based on snow density measurements at 1495 m a.s.l. The mean density of 3.1 m of snow in this profile was 0.42 g/cm³. The profile was then used to convert all snow depth measurements to water equivalents.

Snow depth water equivalent values were plotted against altitude in a diagram. Based on averaging of values within 50 m altitude intervals and a visual evaluation, an altitudinal winter accumulation 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 a lot due to irregular topography and many crevasses which trap a large portion of the drifting snow. In this area the higher snow depth values are thought to be more representative.

From the winter accumulation curve a mean value for each 50 m altitude interval was determined. The winter accumulation was 1.2±0.2 m w.eqv. or 14±2 mill. m³ water.

The total winter balance, including autumn ablation, was calculated to 1.0±0.2 m w.eqv. which corresponds to a surplus volume of 12±2 mill. m³ water. This is 43 % of the 1988 – 2000 average (2.41 m w.eqv.), and the smallest winter balance ever measured at Austdalsbreen.

Summer balance

The summer balance was calculated 20th September for six stake positions between 1240 and 1730 m. Stake 7-01 (1235 m a.s.l.) had melted out during the summer, but the summer balance here was calculated from registered melting until 22nd August and estimated melting between 22nd August and 20th September. From these values a summer balance curve was drawn (Fig. 4-2).

Calving from the glacier terminus was calculated as the annual volume of ice (in water equivalents) 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/cm³,

u_{ice} is annual glacier velocity, 60±10 m/a (chapter 4.3),

u_f is front position change averaged across the terminus, -13±5 m/a (chapter 4.2),

W is terminus width, 1050±50 m, and

H is mean ice thickness along the terminus, 43±5 m based on surface altitude surveyed 14th September 2000 and a bottom topography map compiled from radar ice

thickness measurements (1986), hot water drilling (1987) and lake depth surveying (1988 and 1989).

This gave a calving volume of 2.9 ± 0.5 mill. m^3 water or 0.24 ± 0.04 m w.eqv. averaged across the glacier area (11.8 km^2).

The summer balance, including calving, was calculated to -2.7 ± 0.2 m w.eqv., which corresponds to -31 ± 2 mill. m^3 of water. The result is 122 % of the 1988-2000 average of -2.18 m w.eqv.

Net balance

The net balance at Austdalsbreen was calculated to -1.6 ± 0.3 m w.eqv., corresponding to -19 ± 3 mill. m^3 water. The 1988-2000 average is $+0.23$ m w.eqv. The entire glacier lay below the ELA for 2001, so the accumulation area ratio (AAR) was 0 %. The altitudinal distribution of winter-, summer- and net balances are shown in Figure 4-2 and Table 4-1. Results from 1988-2001 are shown in Figure 4-3.

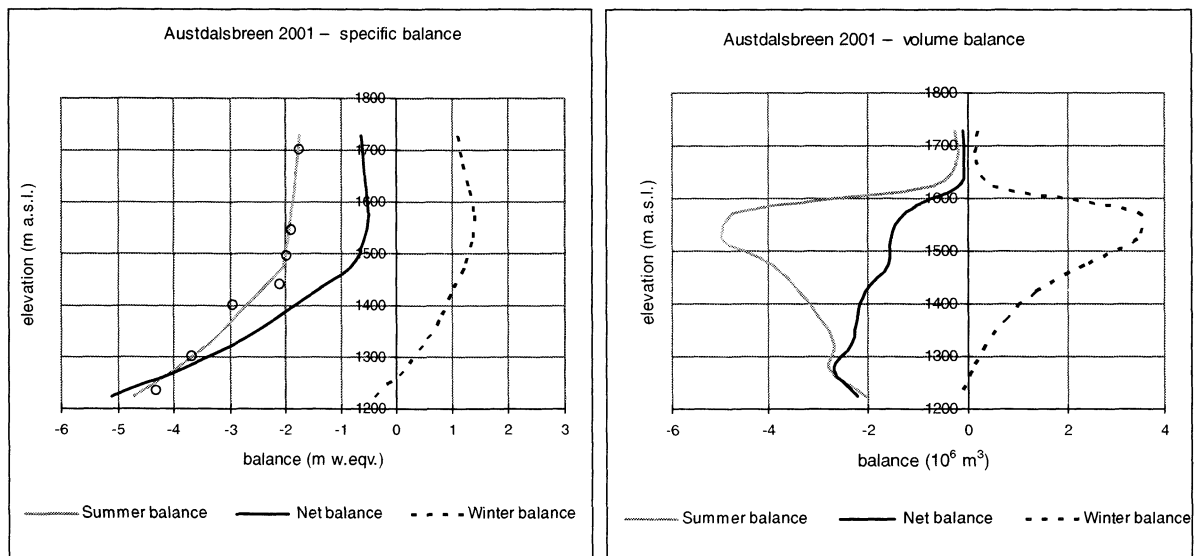


Figure 4-2
Altitudinal distribution of winter-, summer- and net balance shown as specific balance (left) and volume balance (right) at Austdalsbreen in 2001. Specific summer balance at seven locations is shown (o).

Mass balance Austdalsbreen 2000/01							
Altitude (m a.s.l.)	Area (km ²)	Winter balance		Summer balance		Net balance	
		Measured 6th May 2001		Measured 20th Sep 2001		Summer surface 2000 - 2001	
		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	1,10	0,17	-1,75	-0,27	-0,65	-0,10
1650 - 1700	0,13	1,20	0,15	-1,80	-0,23	-0,60	-0,08
1600 - 1650	0,38	1,30	0,49	-1,85	-0,70	-0,55	-0,21
1550 - 1600	2,45	1,40	3,43	-1,90	-4,65	-0,50	-1,22
1500 - 1550	2,54	1,35	3,43	-1,95	-4,95	-0,60	-1,52
1450 - 1500	1,92	1,22	2,34	-2,05	-3,94	-0,83	-1,60
1400 - 1450	1,36	0,98	1,33	-2,50	-3,39	-1,52	-2,06
1350 - 1400	1,01	0,76	0,77	-2,95	-2,98	-2,19	-2,21
1300 - 1350	0,79	0,46	0,36	-3,40	-2,68	-2,94	-2,31
1250 - 1300	0,69	0,10	0,07	-4,00	-2,75	-3,90	-2,68
1200 - 1250	0,44	-0,40	-0,17	-4,70	-2,04	-5,10	-2,22
Calving					-2,9		-2,9
1200 - 1757	11,84	1,04	12,4	-2,66	-31,5	-1,61	-19,1

Table 4-1
Altitudinal distribution of winter-, summer- and net balances at Austdalsbreen in 2001.

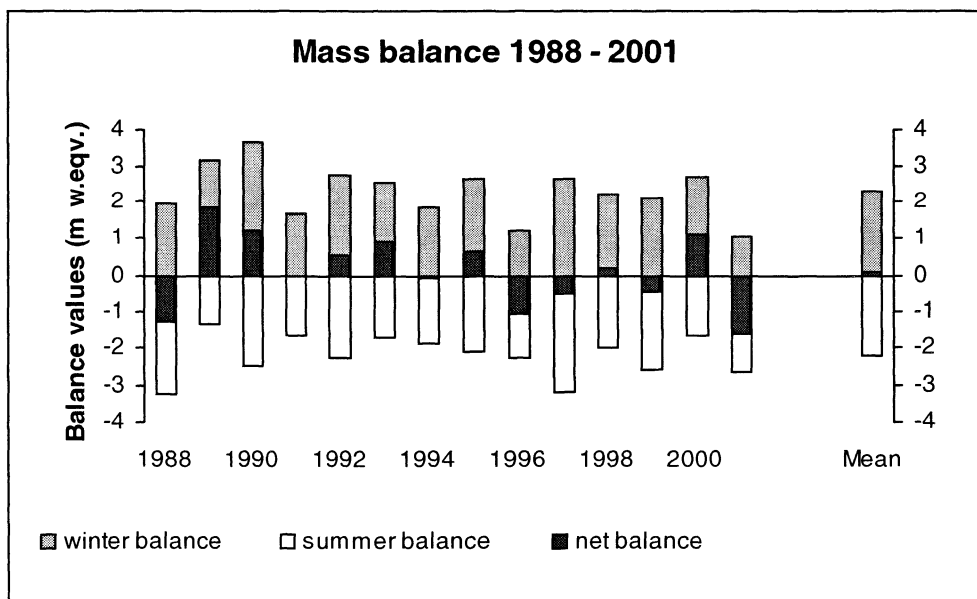


Figure 4-3
Winter-, summer and net balances at Austdalsbreen during the period 1988-2001.

4.2 Front position change

Six points along the terminus were surveyed on 20th September 2001. Between 14th September 2000 and 20th September 2001 the mean front position change was -13 ± 5 m (Fig. 4-4). Since 1988 the front position has retreated approximately 300 m.

Due to large variations in calving, the variations in front position throughout the year are large compared to the net change from year to year. Figure 4-5 illustrates how the front position at a central flow line has varied during the last 14 years. As a consequence of the lake regulation it was expected that the glacier terminus would retreat. A modelling effort resulted in a prediction for future front position change shown as a broken line in Figure 4-5.

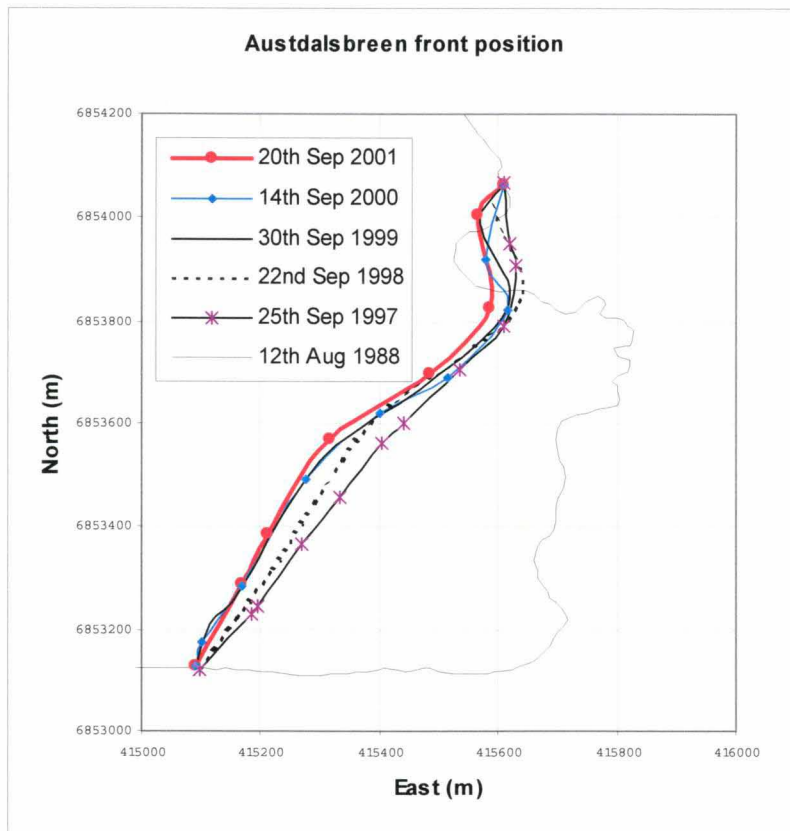


Figure 4-4
 Surveyed front position at Austdalsbreen in 1988, 1997, 1998, 1999, 2000 and 2001. Mean front position retreat between 14th September 2000 and 20th September 2001 was -13 m.

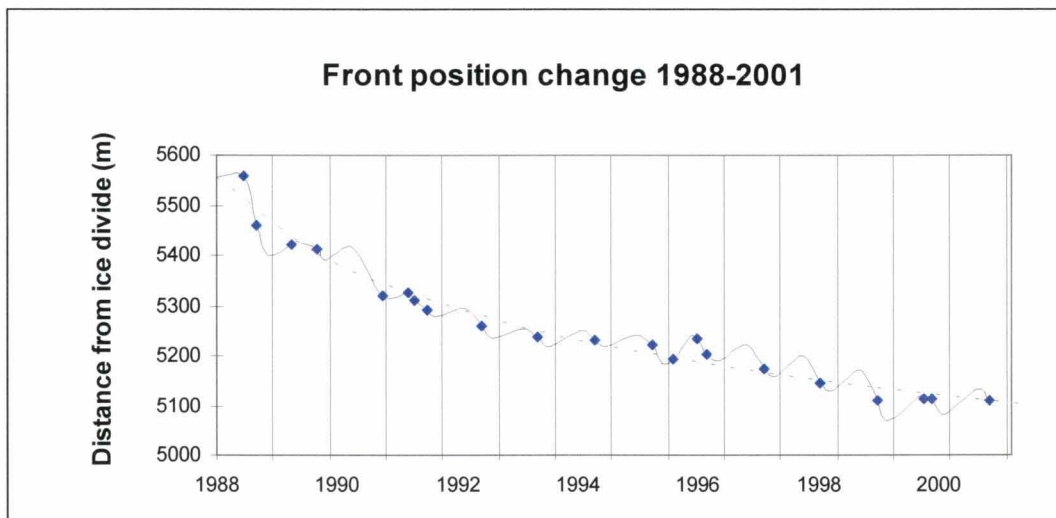


Figure 4-5
 Surveyed front position change along a central flow line shown as change in glacier length along this flow line (dots). The solid line indicates annual variations in front position. The glacier advances from December to July when the lake is frozen, and retreats during July-December due to 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 regulations and an annual net balance of -0.47 m w.eqv. (Laumann & Wold, 1992).

4.3 Glacier velocity

Glacier velocities are calculated from repeated surveys of stakes on the lower part of the glacier. The results are compared with results from 1988-2000 in Figure 4-6. The calculated stake velocities are similar to measured velocities the last three years.

To calculate the calving volume (chapter 4.1) we estimate the glacier velocity averaged across the front width and depth. Surface, centre line velocity is calculated from measurements at stake 6-98 and 7-99 (90 m/a and 80 m/a). 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 an terminus cross-sectional averaged glacier velocity of 60 ± 10 m/a, which is similar to the estimated velocity in 2000.

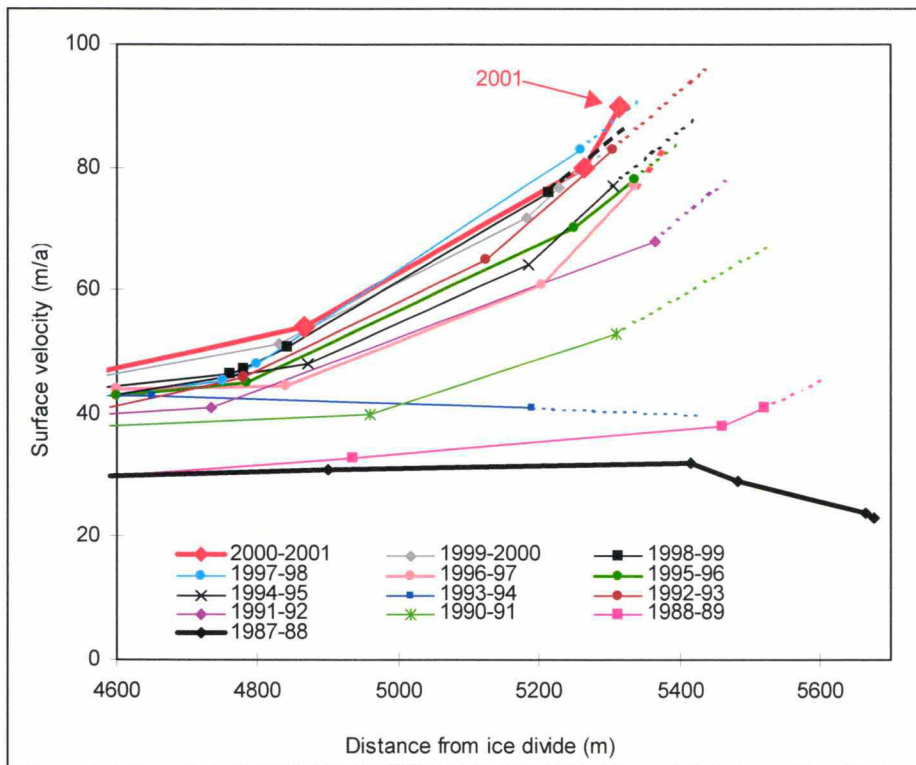


Figure 4-6
Glacier velocity (m/a, September-September) along a central flow line interpolated between averaged stake positions at the lower part of the glacier. Between the lowest stake and the terminus the velocity is extrapolated (broken line). The distance 4600 m from ice divide corresponds approximately to stake 192 (Fig. 4-1). Between 1988 and 2001 the terminus retreated 450 metres along the flow line.

5. Hardangerjøkulen (Hallgeir Elvehøy)

Hardangerjøkulen (61°30'N, 7°30'E) is the sixth largest (73 km²) glacier in Norway. The glacier is situated on the main water divide between Hardangerfjorden and Hallingdalen valley. In 1963, the Norwegian Polar Institute started mass balance measurements on the south-western outlet glacier Rembesdalskåka (17 km²), which drains to the valley Simadalen and Hardangerfjorden. This valley has been ravaged by jökulhlaups from the glacier-dammed Lake Demmevatnet, the latest 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.

In 2000, the University of Oslo started mass balance measurements on the northern outlet glacier Middalsbreen (7 km²), which drains towards Hallingdalen. Middalsbreen ranges in altitude from 1380 to 1865 m a.s.l.

Front position measurements were started at Middalsbreen by the University of Bergen in 1982. Statkraft initiated front position measurements at Rembesdalskåka in 1995. These measurements are described in chapter 15.1.

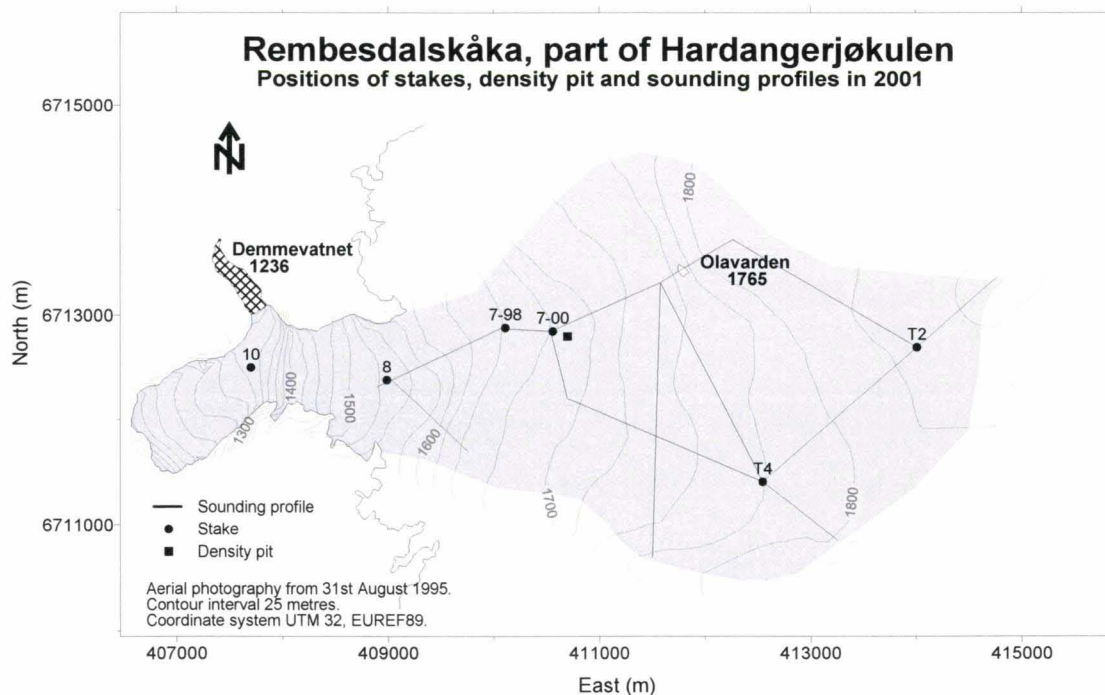


Figure 5-1
Location of stakes, density pit and sounding profiles at Rembesdalskåka, the south-western outlet of Hardangerjøkulen, in 2001.

5.1 Mass balance at Rembesdalskåka in 2001

The second half of September and most of October 2000 was unusually warm in West-Norway, and subsequently the melting continued after the ablation measurements. The ablation after 13th September 2000 was not included in the

calculations of the mass balance for 2000, and will be included in the winter balance for 2001.

Fieldwork

Snow depth soundings at stake locations on 18th December 2000 showed that melting had taken place at stakes below 1700 m a.s.l. At stakes 7-00 and 7-98, 0.4 m of snow had melted away, while 1.2 m of ice had melted at stake 10. Stake 8 was not found.

Winter accumulation was measured 9th May. Calculation of winter balance is based on the following data (Fig. 5-1):

- Snow depth measurements at stake 10 (1285 m a.s.l.), 7-98 (1645 m a.s.l.), 7-00 (1675 m a.s.l.), T4 (1770 m a.s.l.) and T2 (1830 m a.s.l.) showing snow depths of 1.0, 2.9, 2.0, 3.3, and 3.6 m respectively.
- Snow depth measurements by coring at 1530 m a.s.l. (stake 8) showing a snow depth of 1.3 m over ice.
- Snow density measured down to 2.0 m depth at stake 7 (1675 m a.s.l.). Mean snow density was 0.45 g/cm³. Below the SS at 2.0 m depth there was firn.
- Snow depth measured by sounding at 81 locations along 18 km of profiles on the glacier plateau above 1500 m a.s.l. Between 1500 and 1700 m a.s.l. the snow depth was 4½ to 6 m. Above 1700 m a.s.l. the snow depth was 5 to 6½ m. The SS was fairly easy to detect.

Summer ablation and net balance was measured 18th October. There was fresh snow on the glacier above 1650 m a.s.l. At the stakes the new snow was up to 0.3 m deep. The transient snow line (TSL) could not be detected, but the TSL altitude was probably approximately 1750 m a.s.l. The net balance was measured at four locations between 1645 and 1830 m a.s.l. At stakes T4 and T2, 0.3 and 0.7 m of snow, respectively, remained. At stakes 7-00 and 7-98, 1.60 and 1.05 m of firn from the winter 1997-98 had melted away. The greater loss of firn at 7-00 was due to less winter snow in this area. At stake 8, all the winter snow and 2.85 m of firn and ice had melted away. At location 10 on the glacier tongue (1285 m a.s.l.), the stake had melted out by 13th September, indicating at least 4 m of ice melt. Between 13th September and 18th October another 1.0 m of ice melted away at this stake.

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 late autumn melting is normally restricted to the lowermost parts of the glacier, insignificant compared to winter accumulation and summer ablation, and normally hard to determine accurately. This was not the case in 2000. The calculations are based on a map from 1995.

Winter balance

The winter balance was calculated as the sum of late autumn ablation calculated from stake measurements and soundings 13th September and 18th December 2000, and snow accumulation calculated from measurements 9th May 2001.

The altitudinal distribution of late autumn ablation was calculated from measurements at stakes at 1280, 1645 and 1675 m a.s.l. The density of melting snow and ice was set to 0.6 and 0.9 g/cm³, respectively. The upper limit of the late melting was set to 1750 m a.s.l. The late autumn melting was calculated to 0.2 m w.eqv., or 3.0 mill m³ water.

A snow depth - water equivalent profile for 9th May 2001 was calculated based on snow density measurements at 1675 m a.s.l. The mean density of 3 m of snow in this profile was 0.45 g/cm³. All snow depth measurements were transformed to water equivalents using this profile.

The snow depth, in water equivalent values, was plotted against altitude in a diagram. Based on averaging of values within 50 m altitude intervals and a visual evaluation, an altitudinal winter accumulation curve was drawn (Fig. 5-2). Below 1500 m a.s.l. the only snow depth measurement was at stake 10. In this area the accumulation curve had to be extrapolated from measurements at stake 10 and 8.

From the winter accumulation curve a mean value for each 50 m altitude interval was determined. The winter accumulation was 1.2 m w.eqv. or 21 ±3 mill. m³ water

The total winter balance, including autumn ablation, was calculated to 1.0 ±0.2 m w.eqv. or 18 ±3 mill. m³ water. This is 48 % of the 1963 – 2000 average of 2.15 m w.eqv., and 45 % of the 1996 - 2000 average of 2.27 m w.eqv. This year showed one of the 5 smallest winter balances ever measured at Hardangerjøkulen. The winter balance was similarly small in 1963 (1.15 m w.eqv.), 1969 (1.07 m), 1977 (1.20 m) and 1988 (0.99 m).

Summer balance

The summer balance was calculated for five stake positions between 1530 and 1830 m a.s.l. Stake 10 (1280 m a.s.l.) melted out during the summer, and measurements therefore give a minimum estimate only. But a linear regression model between summer balance in the altitude intervals 1650-1700 and 1250-1300 implies that the minimum estimate is a reasonable estimate. From these values a summer balance curve was drawn (Fig. 5-2).

The summer balance was calculated to -1.9 ±0.2 m w.eqv., corresponding to -32 ±3 mill. m³ of water. This is 97 % of the 1963-2000 average, which is -1.93 m w.eqv., and 82 % of the 1996-2000 average of -2.16 m w.eqv.

Net balance

The net balance at Rembesdalskåka was calculated to -0.8 ±0.3 m w.eqv. or -15 ±5 mill. m³ water. The 1963-2000 average is +0.21 m w.eqv., and the 1996-2000 average is +0.12 m. The ELA for 2001 determined from the net balance curve in Figure 5-2 is 1760 m a.s.l. The accumulation area ratio (AAR) was 44 %. The altitudinal

distribution of winter-, summer- and net balances are shown in Figure 5-2 and Table 5-1. Results from 1963-2001 are shown in Figure 5-3.

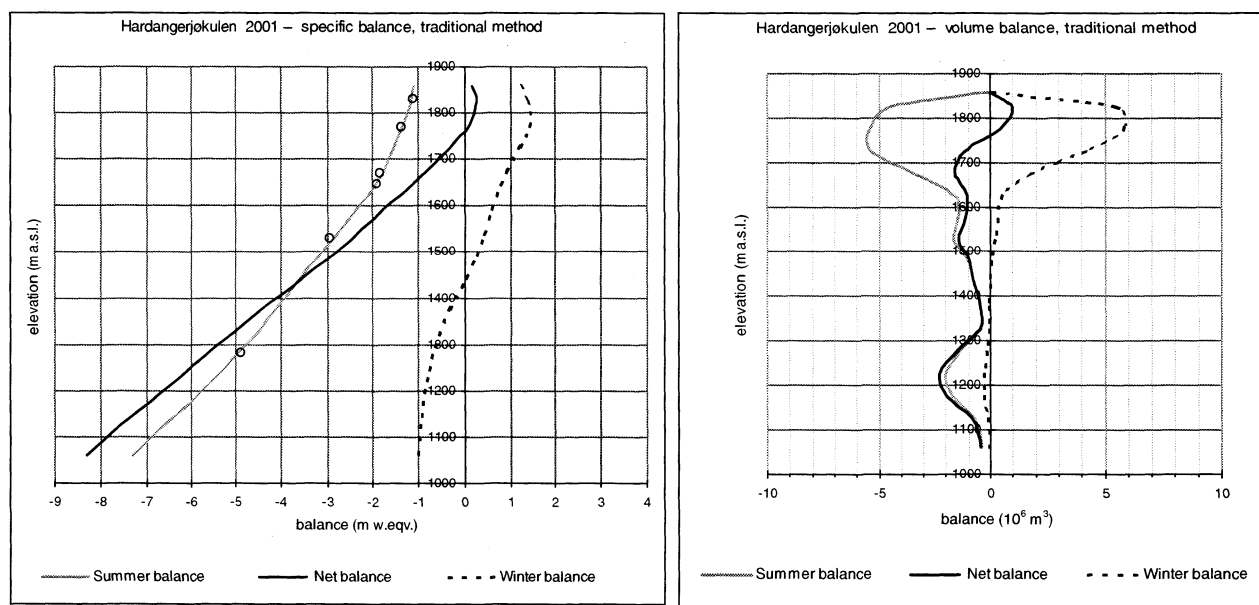


Figure 5-2
Altitudinal distribution of winter-, summer- and net balance shown as specific balance (left) and volume balance (right) at Rembesdalskåka, Hardangerjøkulen in 2001. Specific summer balance at six locations is shown (o).

Mass balance Hardangerjøkulen 2000/01 – traditional method							
Altitude (m a.s.l.)	Area (km ²)	Winter balance		Summer balance		Net balance	
		Measured 9th May 2001		Measured 18 Oct 2001		Summer surface 2000 - 2001	
		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)
1850 - 1865	0,09	1,25	0,1	-1,10	-0,1	0,15	0,0
1800 - 1850	3,93	1,40	5,5	-1,15	-4,5	0,25	1,0
1750 - 1800	4,03	1,45	5,8	-1,35	-5,4	0,11	0,4
1700 - 1750	3,46	1,22	4,2	-1,55	-5,3	-0,33	-1,1
1650 - 1700	1,94	0,92	1,8	-1,75	-3,4	-0,83	-1,6
1600 - 1650	0,75	0,73	0,5	-2,10	-1,6	-1,37	-1,0
1550 - 1600	0,59	0,55	0,3	-2,50	-1,5	-1,95	-1,2
1500 - 1550	0,57	0,40	0,2	-2,90	-1,6	-2,50	-1,4
1450 - 1500	0,29	0,20	0,1	-3,30	-1,0	-3,10	-0,9
1400 - 1450	0,19	-0,03	0,0	-3,70	-0,7	-3,73	-0,7
1350 - 1400	0,10	-0,30	0,0	-4,10	-0,4	-4,40	-0,4
1300 - 1350	0,10	-0,55	-0,1	-4,50	-0,4	-5,05	-0,5
1250 - 1300	0,27	-0,70	-0,2	-5,00	-1,4	-5,70	-1,5
1200 - 1250	0,36	-0,80	-0,3	-5,50	-2,0	-6,30	-2,3
1150 - 1200	0,28	-0,90	-0,3	-6,00	-1,7	-6,90	-1,9
1100 - 1150	0,11	-0,95	-0,1	-6,60	-0,7	-7,55	-0,8
1020 - 1100	0,05	-1,00	-0,1	-7,30	-0,4	-8,30	-0,4
1020 - 1865	17,1	1,03	17,7	-1,88	-32,1	-0,84	-14,5

Table 5-1
Altitudinal distribution of winter-, summer- and net balances at Rembesdalskåka, Hardangerjøkulen in 2001.

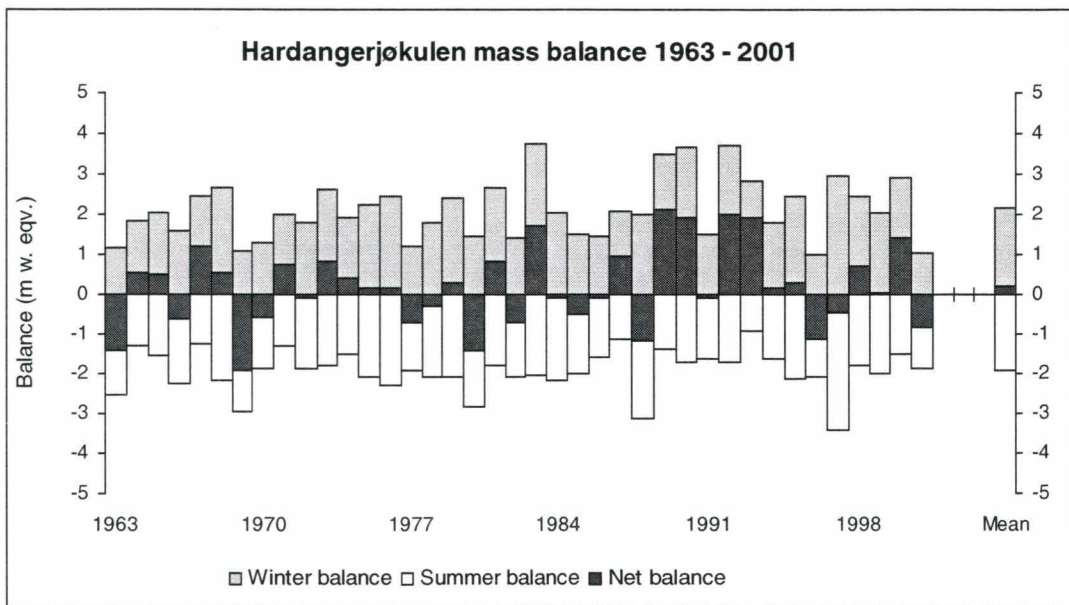


Figure 5-3
 Winter-, summer- and net balances at Hardangerjøkulen during the period 1963-2001. Mean values for the period are $b_w=2.12$ m, $b_s=-1.93$ m and $b_n=+0.19$ m water equivalents.

5.2 Mass balance at Midtdalsbreen in 2001

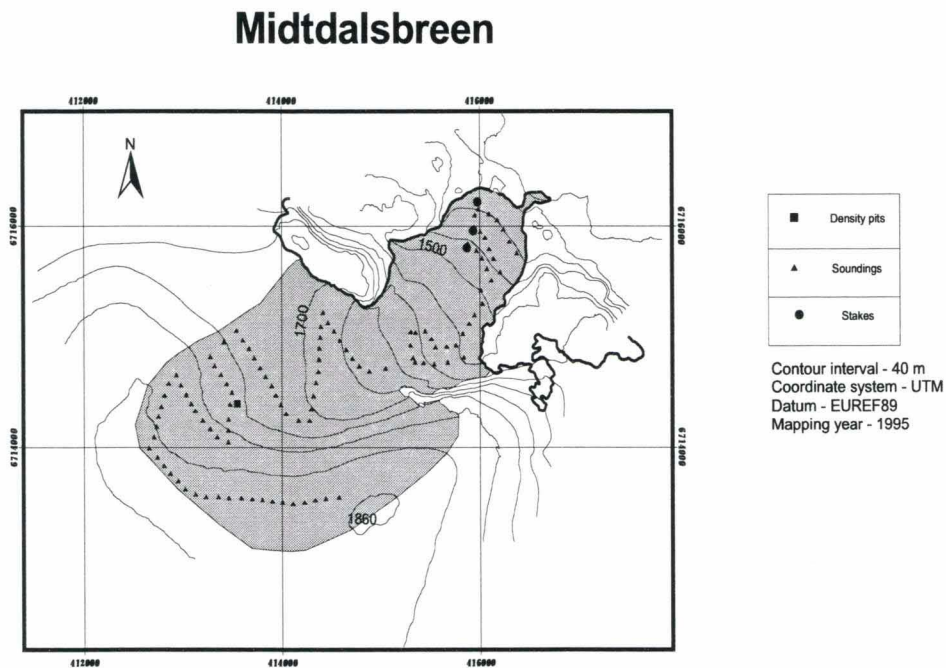


Figure 5-4
 Soundings, stakes and density measurements in 2001.

Fieldwork

The mass balance measurements at Midtdalsbreen were carried out by measuring the winter accumulation in late winter, and the amount of melting during the summer. The winter balance measurements took place 5th May. The snow depth was measured with a sounding stick and the snow properties were good. 111 point measurements were made, evenly distributed over the glacier (Fig. 5-4). The snow depth varied between 1.49 and 4.11 m.

Snow density was measured at one site on the upper part of the glacier, at 1750 m a.s.l. The mean density in the snow pack was 0.46 g/cm³, and was used to recalculate the snow depth measurements to water equivalents. The winter balance was interpolated with an inverse distance weighing interpolation, using the ESRI-software ARC/INFO.

Summer ablation measurements were carried out 20th September. Only three stakes on the lower part of the glacier (1456-1521 m a.s.l.) were measured at this time (Fig. 5-4). It was not possible to get to the upper part of the glacier because of highly crevassed areas that had become snow free. To estimate the total summer balance at Midtdalsbreen, measurements from the upper part of Rembesdalskåka were also used, from the two sites T4 (1770 m a.s.l.) and T2 (1830 m a.s.l.). Ablation measurements were carried out somewhat later on Rembesdalskåka than on Midtdalsbreen, and it is possible that further melting had occurred at the lower part of Midtdalsbreen in the meantime.

Based on the assumption that melt decreases linearly with altitude the summer balance was estimated using a linear regression. The result is presented in 50-m altitude intervals (Tab. 5-2). The elevation data is based on a map created from aerial photographs taken in 1995.

Results

Mass balance in 2001 (Fig. 5-5, Tab. 5-2) was negative, with a specific net balance of -0.64 m w.eqv. The winter- and summer balances were 1.26 and -1.90 m w.eqv. respectively. The net volume loss for the whole year was 4.3 mill. m³ water, from a winter surplus of 8.4 mill. m³ water and a summer loss of 12.7 mill. m³ water. Since the net balance was negative the ELA is high up on the glacier. From Figure 5-5 the ELA is estimated to be at 1785 m a.s.l. The AAR is calculated to be 35 %.

Mass balance Middalsbreen 2000/01							
Altitude (m a.s.l.)	Area (km ²)	Winter balance		Summer balance		Net balance	
		Measured 20 sep 2000		Measured 05 jan 2001		Summer surface 2000 - 2001	
		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)
1775 - 1862	2,28	1,30	3,0	-1,14	-2,6	0,16	0,4
1725 - 1775	0,81	1,26	1,0	-1,46	-1,2	-0,20	-0,2
1675 - 1725	1,22	1,23	1,5	-1,79	-2,2	-0,56	-0,7
1625 - 1675	0,53	1,52	0,8	-2,11	-1,1	-0,59	-0,3
1575 - 1625	0,40	1,32	0,5	-2,44	-1,0	-1,12	-0,4
1525 - 1575	0,39	1,03	0,4	-2,76	-1,1	-1,73	-0,7
1475 - 1525	0,48	1,10	0,5	-3,09	-1,5	-1,99	-1,0
1425 - 1475	0,31	1,11	0,3	-3,41	-1,1	-2,30	-0,7
1380 - 1425	0,28	1,30	0,4	-3,74	-1,0	-2,44	-0,7
1380 - 1862	6,69	1,26	8,4	-1,90	-12,7	-0,64	-4,3

Table 5-2
Specific and volume mass balance at Middalsbreen 2001.

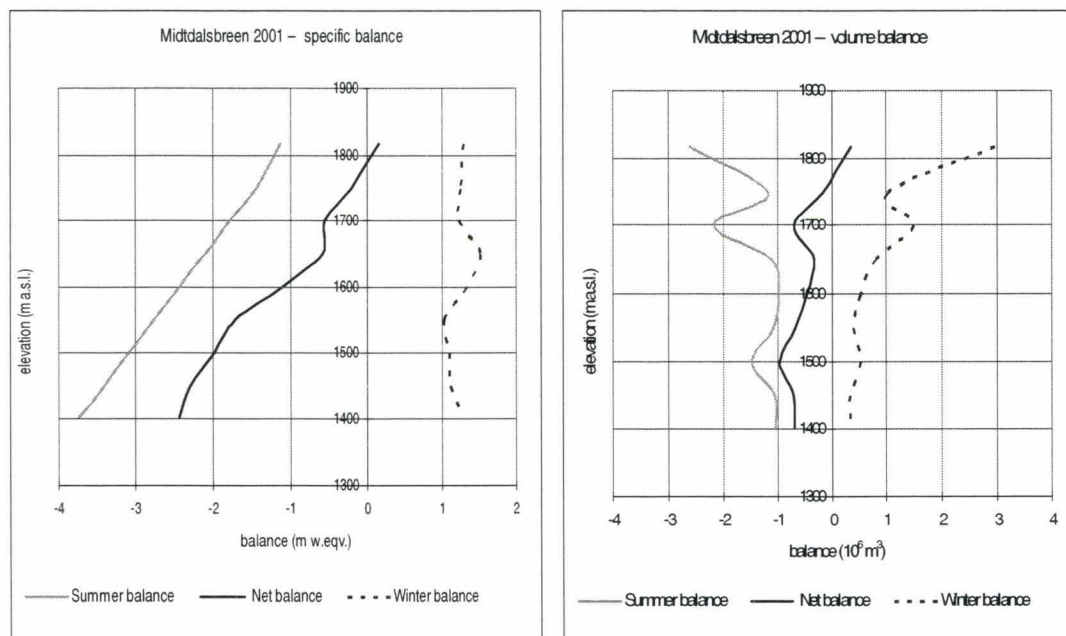


Figure 5-5
The winter-, summer- and net balance at Middalsbreen 2001, shown as specific balance (left) and volume balance (right).

The mass balance in 2001 was considerably more negative than the previous year. In 2000 the mass balance was positive, with a specific net balance of 1.32 m w.eqv. In summary mass balance for the years 2000 and 2001 was slightly positive, with a cumulative specific net balance of 0.54 m w.eqv.

6. Harbardsbreen (Bjarne Kjøllmoen)

Harbardsbreen (61°40'N, 7°35'E) is a plateau glacier situated approximately 25 km east of Jostedalbreen in the Breheimen area. The area is about 25 km², and of this about 13 km² drains eastward to Steindalselvi and Fivlemyrane reservoir (Fig. 6-1). The range in elevation is between 1250 and 1960 m a.s.l.

The glaciological investigations performed in 2001 include mass balance, air temperature measurements and observations of an ice-dammed lake. The investigations at Harbardsbreen started with aerial photography and mapping in 1996. Mass balance measurements were initiated in 1997 and were terminated in the autumn of 2001.

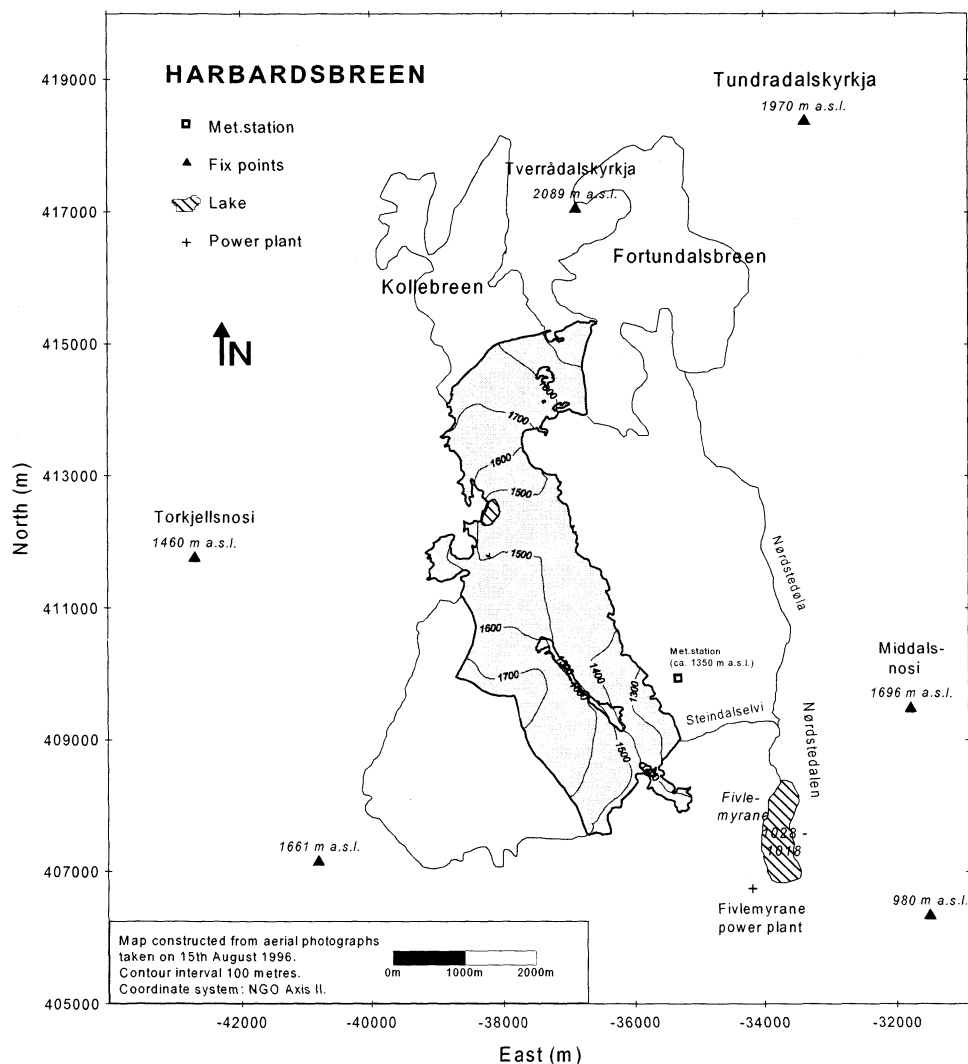


Figure 6-1
The total area of Harbardsbreen is about 25 km² of which approximately 13 km² drains eastward to Steindalselvi and Fivlemyrane reservoir. The investigations are performed on this east-facing part of the glacier.

6.1 Mass balance 2001

Fieldwork

Snow accumulation was measured on 7th May and the winter balance calculation is based on (Fig. 6-2):

- Direct measurements of stakes in 6 different positions (10, 20, 30, 40, 50 and 60) with corresponding snow depths of 2.3, 2.6, 2.7, 3.3, 2.7 and 2.5 m. In position 70 snow depth (3.0 m) was calculated by correlating measurements of a substitute stake with the original, which later emerged.
- Core samples at positions 45 and 70 showing snow depths of 2.7 and 2.6 m respectively.
- 151 snow depth soundings along about 22 km of profiles between 1280 and 1945 m a.s.l. The summer surface (SS) could be easily identified all over the glacier surface. The snow depth varied between 2.5 and 3 m.
- Snow density measurements down to 2.5 m depth (SS at 2.8 m) at stake position 30 (1495 m a.s.l.).

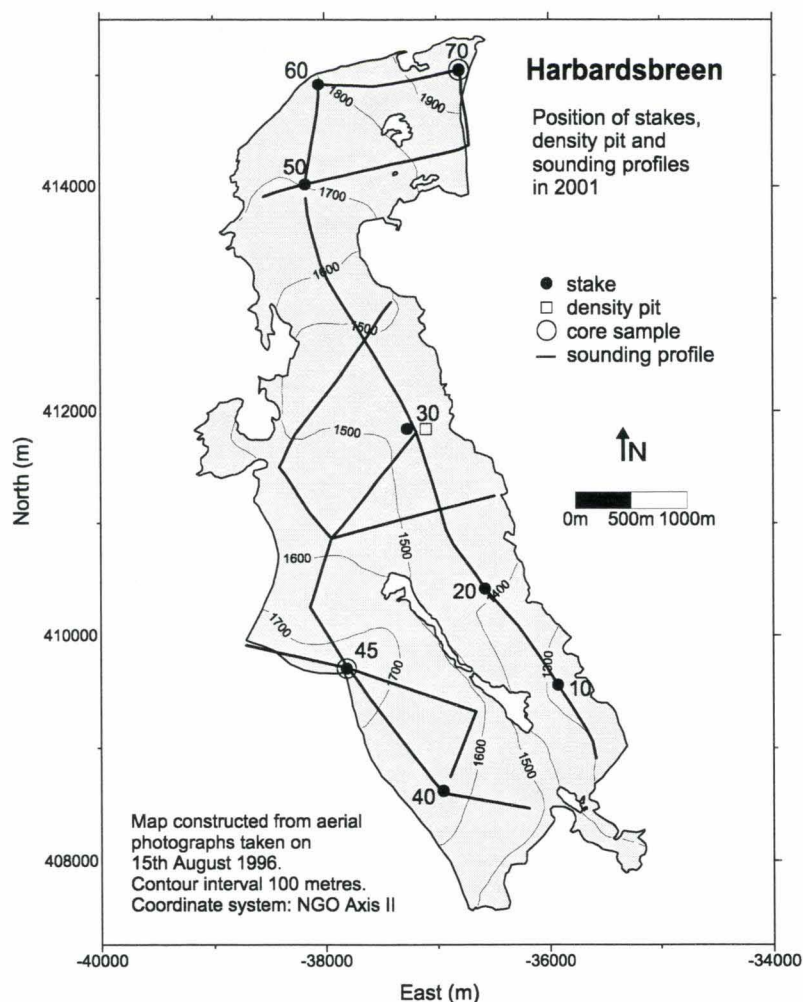


Figure 6-2
Location of stakes, density pit and sounding profiles at Harbardsbreen in 2001.

Ablation was measured on 19th September. The net balance was measured directly at stakes in 8 different positions between 1285 and 1945 m a.s.l. There was no snow remaining on the glacier surface from the winter 2000/2001. At the time of ablation measurements 2-3 cm of fresh snow had fallen.

Results

The calculations are based on a glacier map from 1996.

Winter balance

The winter balance calculations are based on point measurements of snow depth (stakes, probings and core drillings) and on measurements of snow density at one location.

Some ablation occurred *after* the final measurements in September 2000. This ablation was counted as a negative contribution to the winter balance 2000/2001 as described in chapter 1. This negative winter balance was measured and calculated as 0.7 m w.eqv. at 1285 m altitude, 0.5 m at 1415 m altitude and 0.1 m at 1490 m altitude, which amounts to a total of 0.1 m water equivalents.

A density profile was modelled from the snow density measured at 1495 m a.s.l. The mean snow density of 2.5 m snow was 0.37 g/cm^3 . The density model was used to convert all measured snow depths to water equivalents.

The winter balance calculation was performed by plotting measurements (water equivalents) in a diagram. A curve was drawn based on a visual evaluation (Fig. 6-4), and a mean value for each 50 m height interval was estimated (Tab. 6-1). The entire glacier surface was well represented with point measurements (Fig. 6-3).

The winter *balance*, hence, was calculated as $0.9 \pm 0.2 \text{ m w.eqv.}$, corresponding to a water volume of $12 \pm 3 \text{ mill. m}^3$. Excluding the additional ablation *after* the final measurements in September 2000, the winter *accumulation* was 1.0 m w.eqv. The result is 44 % of the mean value for the period 1997-2000. Previous results are 2.2 m (1997), 1.7 m (1998), 1.8 m w.eqv. (1999) and 2.3 m w.eqv. (2000).

The winter balance was also calculated using a gridding method based on the aerial distribution of the snow depth measurements (Fig. 6-3). 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, was also 0.9 m w.eqv.

Summer balance

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

The summer balance was directly measured and calculated at 7 stakes, and increased from -1.2 m w.eqv. at stake 70 (1945 m a.s.l.) to -3.2 m w.eqv. at stake 10 (1285 m a.s.l.). Based on estimated density and stake measurements the summer balance was calculated as $-2.0 \pm 0.3 \text{ m w.eqv.}$, which is $-26 \pm 4 \text{ mill. m}^3$ of water. The result is

equal to the average for 1997-2000. Previous results are -2.7 m (1997), -1.6 m (1998), -2.2 m (1999) and -1.5 m w.eqv. (2000).

Net balance

The net balance for 2001 was -1.1 ± 0.4 m w.eqv., corresponding a loss in volume of 15 ± 4 mill.m³ of water. This is the greatest deficit since the measurements started in 1997. According to Figure 6-4 the equilibrium line altitude was above the elevation range of the glacier, and thus the AAR is 0 %.

The mass balance results are shown in Table 6-1 and Figure 6-4. Historic mass balance results since 1997 are presented in Figure 6-5.

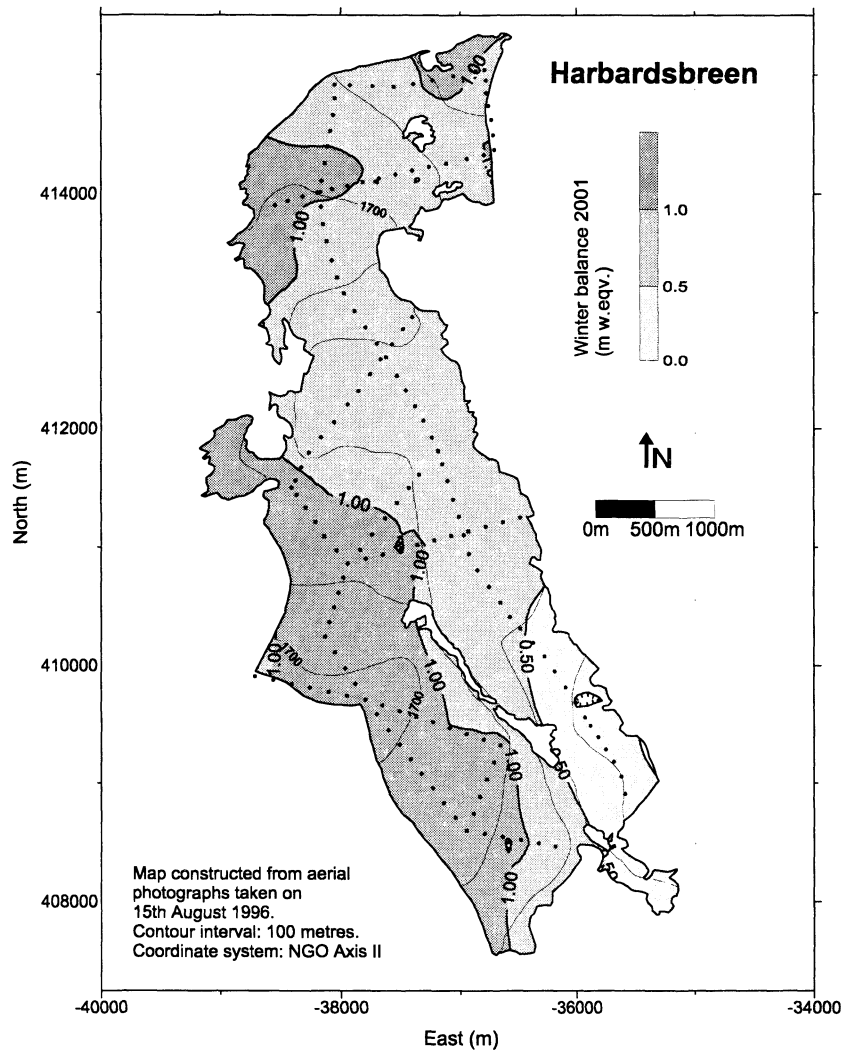


Figure 6-3
Winter balance at Harbardsbreen in 2001 interpolated from 153 snow depth measurements (*).

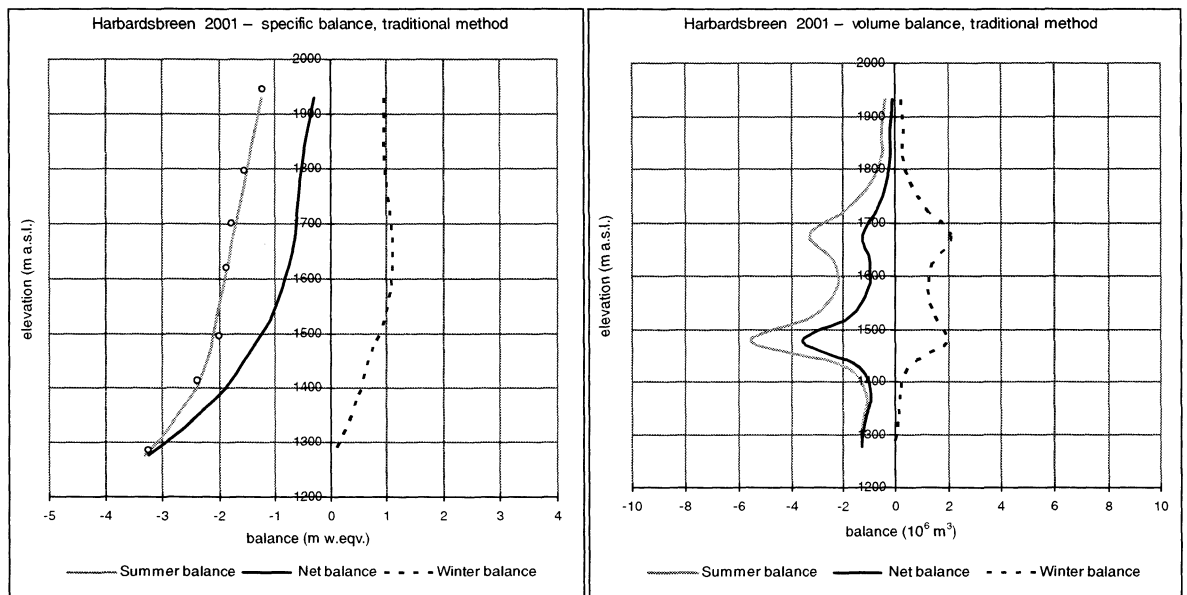


Figure 6-4
Mass balance diagram showing specific balance (left) and volume balance (right) for Harbardsbreen in 2001. Summer balance at seven stakes is shown (o).

Mass balance Harbardsbreen 2000/01 – traditional method							
Altitude (m a.s.l.)	Area (km ²)	Winter balance		Summer balance		Net balance	
		Measured 7th May 2001		Measured 20th Sep 2001		Summer surface 2000 - 2001	
		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)
1900 - 1960	0,28	0,95	0,3	-1,25	-0,4	-0,30	-0,1
1850 - 1900	0,35	0,95	0,3	-1,35	-0,5	-0,40	-0,1
1800 - 1850	0,32	0,95	0,3	-1,45	-0,5	-0,50	-0,2
1750 - 1800	0,58	1,00	0,6	-1,55	-0,9	-0,55	-0,3
1700 - 1750	1,12	1,05	1,2	-1,65	-1,8	-0,60	-0,7
1650 - 1700	1,89	1,10	2,1	-1,75	-3,3	-0,65	-1,2
1600 - 1650	1,27	1,10	1,4	-1,85	-2,3	-0,75	-1,0
1550 - 1600	1,16	1,05	1,2	-1,95	-2,3	-0,90	-1,0
1500 - 1550	1,57	0,95	1,5	-2,05	-3,2	-1,10	-1,7
1450 - 1500	2,56	0,75	1,9	-2,15	-5,5	-1,40	-3,6
1400 - 1450	0,82	0,60	0,5	-2,30	-1,9	-1,70	-1,4
1350 - 1400	0,43	0,45	0,2	-2,55	-1,1	-2,10	-0,9
1300 - 1350	0,42	0,25	0,1	-2,90	-1,2	-2,65	-1,1
1250 - 1300	0,39	0,06	0,0	-3,30	-1,3	-3,24	-1,3
1250 - 1960	13,16	0,88	11,6	-1,99	-26,2	-1,11	-14,6

Table 6-1
Winter, summer and net balance for Harbardsbreen in 2001. Mean values for the period 1997-2000 are $b_w=1.99$ m, $b_s=-2.00$ m and $b_n=-0.01$ m water equivalents.

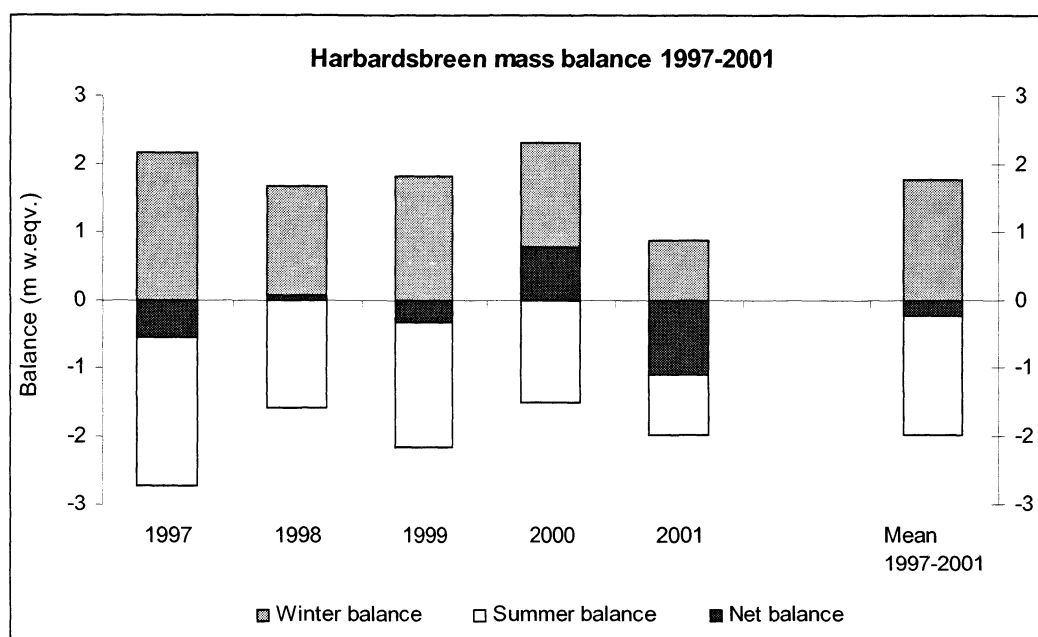


Figure 6-5
Mass balance at Harbardsbreen in the period 1997-2001.

6.2 Air temperature

A station for automatically recording air temperature was set up on the eastern side of Harbardsbreen (Fig. 6-1) in May 1997. Data is stored at the site and was transferred during field visits in 2001.

Air temperature results from Harbardsbreen (1320 m a.s.l.) for the period 1997-2001 are presented in Table 6-2, and compared with corresponding measurements from Sognefjell station (1413 m a.s.l.), run by the Norwegian Meteorological Institute. The values in the table indicate the daily mean air temperature for the "summer season" (defined as 1st June to 30th September).

Daily mean values 1 st June - 30 th September ("Summer season")			
Year	Harbardsbreen (°C)	Sognefjell (°C)	Lapse rate Ha./So. (°C/100 m)
1997	6,1	6,3	-0,26
1998	4,2	4,1	0,09
1999	¹⁾ 3,4	5,5	-2,24
2000	4,7	4,4	0,35
2001	5,6	4,7	0,95
Mean 1997-2001	4,8	5,1	-0,22
Mean 1980-1988	-	4,2	-

¹⁾ The value is probably erroneous.

Table 6-2
Mean air temperature at Harbardsbreen (1320 m a.s.l.) and Sognefjell (1413 m a.s.l.) in the "Summer season" (1st June - 30th September) for the period 1997-2001.

The mean summer temperature in 2001 was 5.6 °C at Harbardsbreen and 4.7 °C at Sognefjell. The results from 1997, 1998 and 2000 are approximately equal for the two stations. The results for 1999, however, differ by 2.0 °C. The difference probably indicates erroneous sampling at Harbardsbreen in 1999.

6.3 Ice-dammed lake

Observations (Tab. 6-3) of the ice-dammed lake at the western side of the glacier (altitude 1480 m a.s.l.) have been performed since 1992. The observations suggest frequent jökulhlaups (Kjøllmoen (ed.) 2000).

During 2001 the lake was photographed on 16th February, 7th May, 23rd August and 19th September (Fig. 6-6). The observations showed water in the lake in August, whereas it was empty in February, May and September. Field visits in July and September 2000 showed water in the lake. Hence, a jökulhlaup occurred during the autumn 2000 or early winter 2001. The channel was then closing late spring or early summer 2001.

Date	Observation
19 09 1992	Water in the lake
23 09 1993	Water in the lake (uncertain observation)
28 07 1994	Water in the lake
20 07 1996	Water in the lake
14 09 1996	Water in the lake
01 02 1997	Empty
19 05 1997	Much snow, but no visible water- or ice surface in the lake
25 07 1997	Water in the lake
24 09 1997	Water in the lake
15 05 1998	Much snow, probably some water in the lake
12 08 1998	Water in the lake
23 09 1998	Water in the lake
08 05 1999	Empty
30 07 1999	Empty
30 09 1999	Empty
29 04 2000	Empty
27 07 2000	Water in the lake
13 09 2000	Water in the lake
16.02.2001	Empty
07.05.2001	Empty
23.08.2001	Water in the lake
19.09.2001	Empty

Table 6-3
Observations of the glacier-dammed lake at Harbardsbreen in the period 1992-2001.

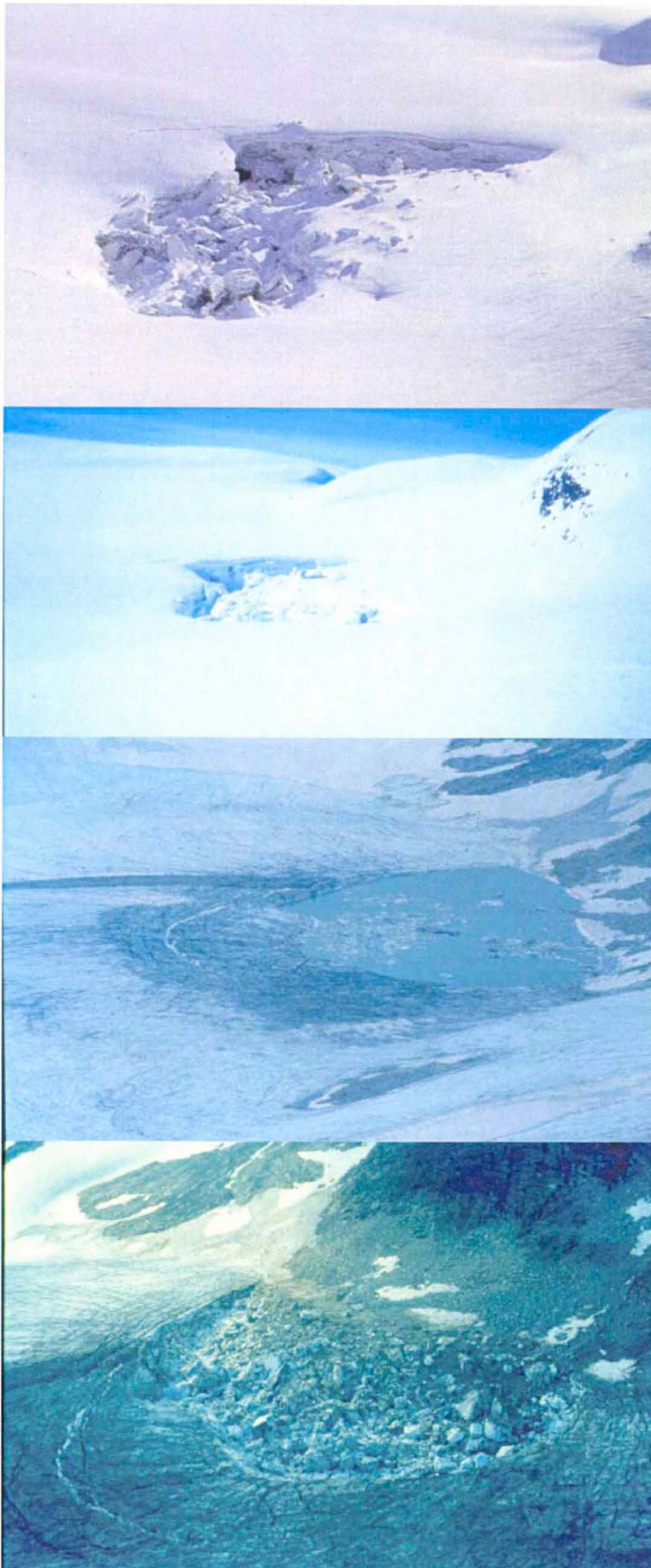


Figure 6-6
The glacier-dammed lake photographed on 16th February, 7th May, 23rd August and 19th September 2001. The lake was empty in February, May and September, whereas water was observed in August. Photo: Olav Osvoll (February), Hallgeir Elvehøy (May) and Nils Haakensen (August and September).

7. Storbreen (Liss M. Andreassen and Laila P. Høivik)

Storbreen (61°34' N, 8°8' E) is situated in the Leirdalen valley in the central part of Jotunheimen, a mountain area in central southern Norway (Fig. 7-1). The glacier has a total area of 5.4 km² 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.

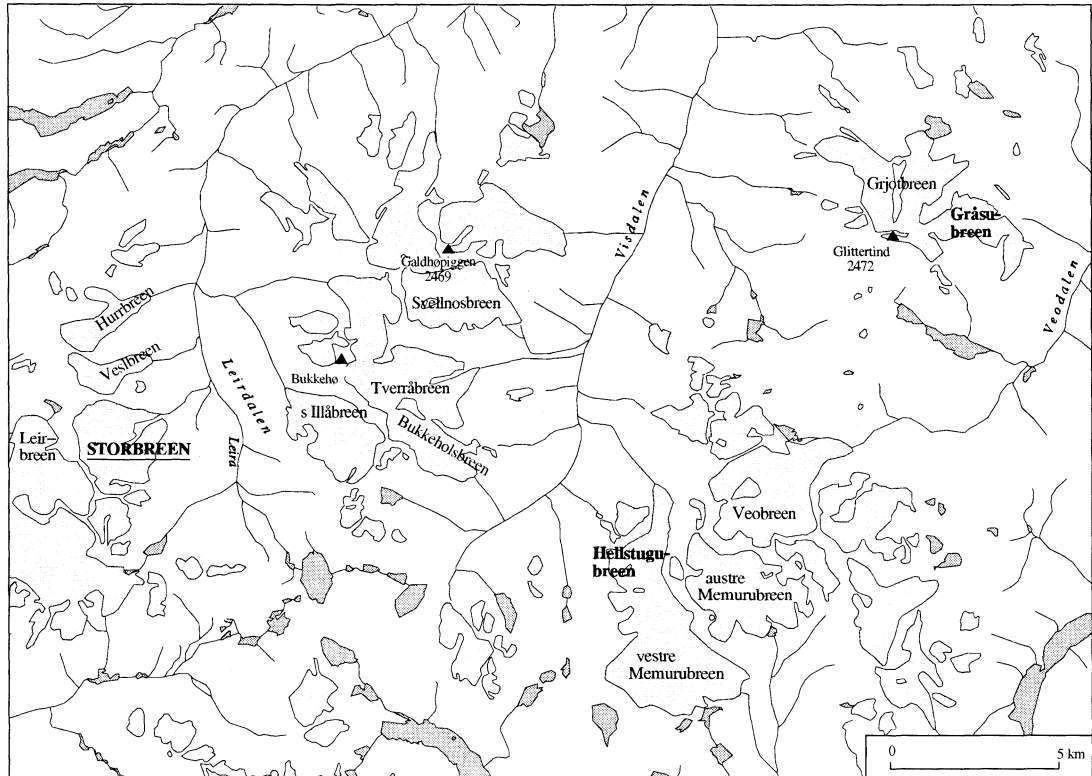


Figure 7-1
Location map showing Storbreen and other glaciers in the mountain area Jotunheimen. Mass balance measurements are carried out on Storbreen and Hellstugubreen in the central part and on Gråsubreen in the eastern part.

7.1 Mass balance 2001

Fieldwork

Accumulation measurements were carried out on 6th May. Stakes were visible at six different locations. Snow depth was measured at 162 points along 15 km of profiles, covering almost all height intervals 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 1.6 and 4.1 m, with a mean of 2.8 m.

Snow density was measured at stake 4 (1730 m a.s.l., Fig. 7.2) by sampling in a pit dug through the snow pack (2.8 m snow). Ablation measurements were carried out on 26th September. Summer and net balance was calculated from stakes at six locations.

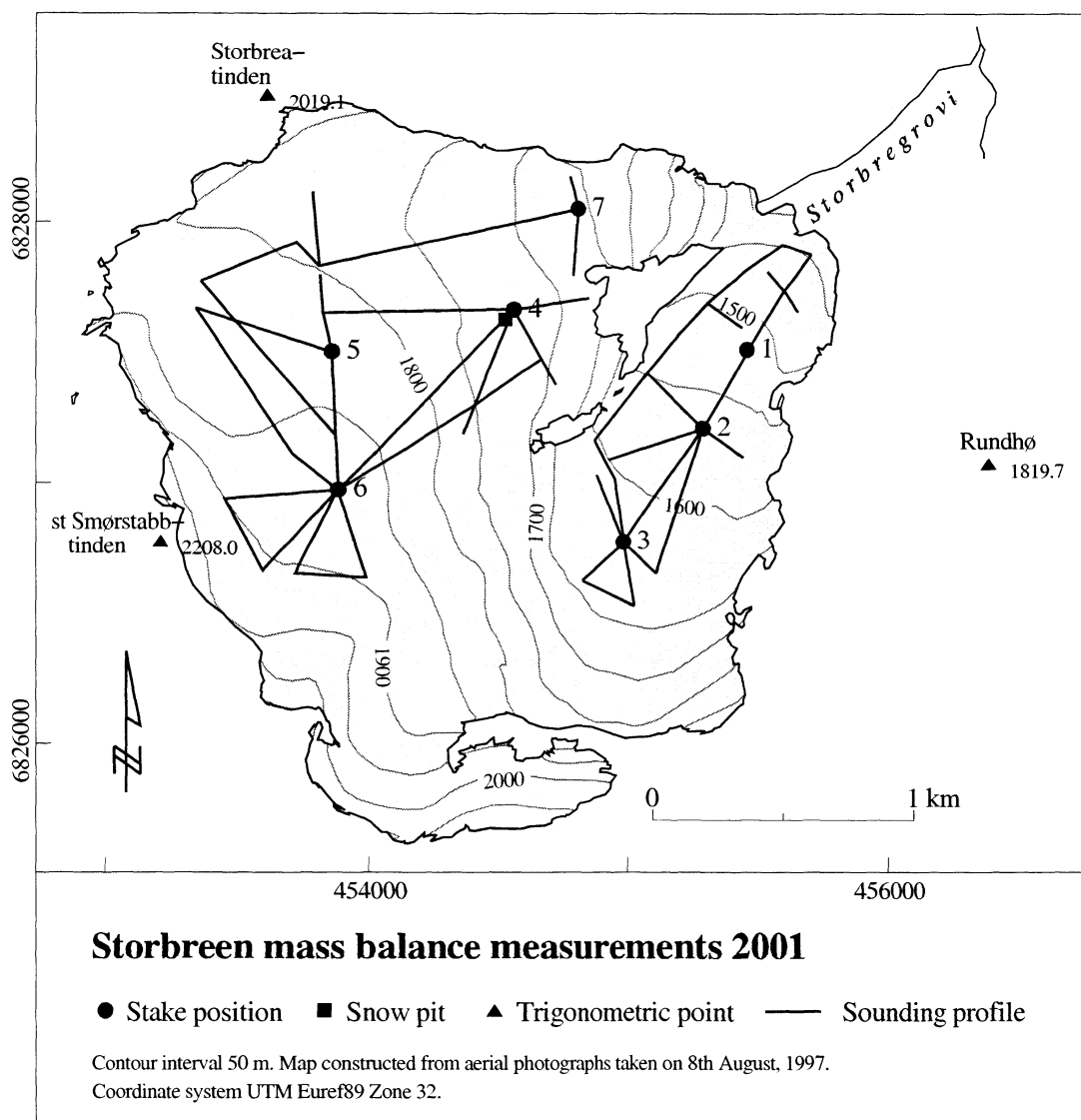


Figure 7-2
Map of Storbreen showing the mass balance programme in 2001.

Results

The collected 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 measurement. In addition, additional melting occurred after the ablation measurements in 2000 and had to be accounted for in the 2001 mass balance calculations.

The mean measured snow density was 0.39 g/cm^3 . The density profile was considered representative for the rest of the glacier. The winter accumulation was calculated by plotting the mean of the soundings within each 50-metre height interval against altitude, and drawing a representative curve. This gave a winter accumulation of 1.2

m w.eqv., which is 80 % of the mean for the period 1949-2000. The additional melting after the ablation measurements the previous year was calculated from stake recordings at six positions, giving an average melt of 0-0.5 m w.eqv. at each position. Above 1900 m a.s.l. there was no additional melt.

The winter balance was calculated by subtracting the extra melt from the winter accumulation. The specific winter balance, including additional melt, was thus calculated to be 1.1 ± 0.2 m w.eqv. This is 72 % of the mean for the period 1949-2000.

Summer balance

Summer balance was calculated directly from stakes in six locations and indirectly by net balance at one other location. The density of the remaining snow was assumed to be 0.6 g/cm^3 , based on measurements from previous years. The density of the melted ice was estimated to be 0.9 g/cm^3 . The summer balance was calculated to be -1.3 ± 0.2 m w.eqv, which is 79 % of the mean for the period 1949-2000.

Net balance

The net balance of Storbreen in 2001 was -0.27 ± 0.3 m w.eqv., which is equivalent to a lost volume of 1.5 ± 0.16 mill. m^3 water. The equilibrium line altitude (ELA) was 1855 m a.s.l., which corresponds to an accumulation area ratio (AAR) of 24 % (Fig. 7-3).

Since 1949 the glacier has had a deficit amounting to 11.0 m w.eqv. , with a mean annual net balance of -0.2 m w.eqv. (Fig. 7-4).

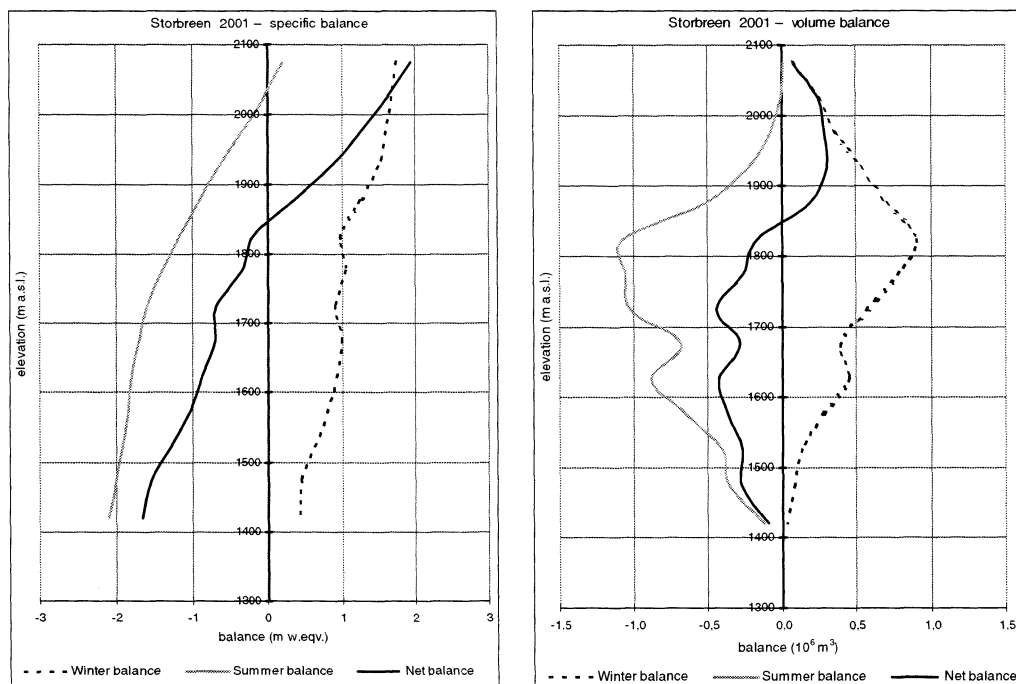


Figure 7-3
Mass balance diagram for Storbreen 2001, showing specific balance to the left and volume balance to the right.

Mass balance Storbreen 2000/01							
Altitude (m a.s.l.)	Area (km ²)	Winter balance		Summer balance		Net balance	
		Measured 06 mai 2001		Measured 00 jan 1900		Summer surfaces 2000 - 2001	
		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	0,20	0,01	1,95	0,08
2000 - 2050	0,15	1,67	0,25	-0,05	-0,01	1,62	0,24
1950 - 2000	0,23	1,60	0,37	-0,35	-0,08	1,25	0,29
1900 - 1950	0,36	1,50	0,54	-0,65	-0,23	0,85	0,31
1850 - 1900	0,57	1,25	0,71	-0,92	-0,52	0,33	0,19
1800 - 1850	0,92	0,98	0,90	-1,17	-1,08	-0,19	-0,17
1750 - 1800	0,75	1,05	0,79	-1,40	-1,05	-0,35	-0,26
1700 - 1750	0,64	0,91	0,58	-1,60	-1,02	-0,69	-0,44
1650 - 1700	0,40	0,99	0,40	-1,70	-0,68	-0,71	-0,28
1600 - 1650	0,49	0,93	0,46	-1,80	-0,88	-0,87	-0,43
1550 - 1600	0,35	0,81	0,28	-1,85	-0,65	-1,04	-0,36
1500 - 1550	0,21	0,65	0,14	-1,92	-0,40	-1,27	-0,27
1450 - 1500	0,18	0,45	0,08	-2,00	-0,36	-1,55	-0,28
1390 - 1450	0,06	0,44	0,03	-2,10	-0,13	-1,66	-0,10
1390 - 2100	5,35	1,05	5,59	-1,32	-7,09	-0,28	-1,50

Table 7-1
The distribution of winter, summer and net balance in 50 m altitude intervals for Storbreen in 2001.

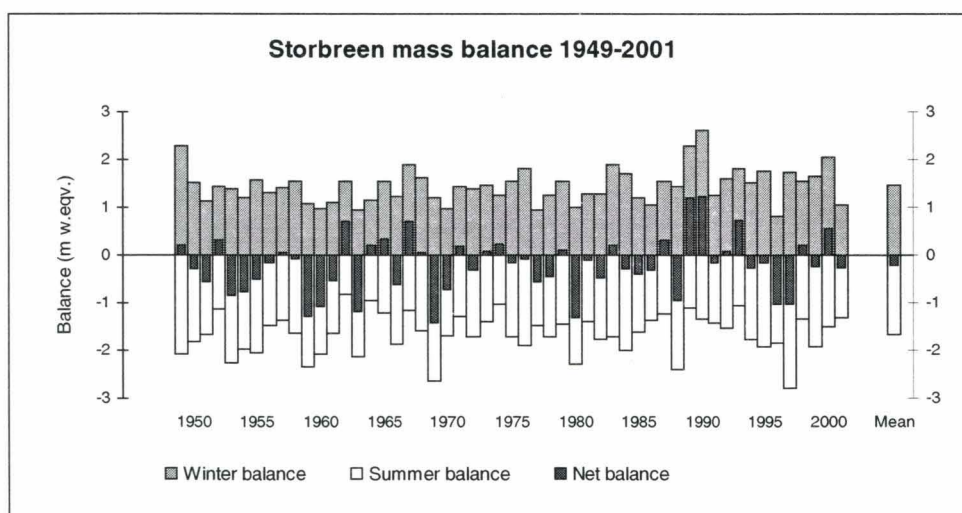


Figure 7-4
Winter, summer and net balance at Storbreen for the period 1949-2001.

7.2 Front position change

The front position at Storbreen had a net retreat of 12 m from September 1999 to September 2001. Notice that this is a two-year period, since the front position was not measured in September 2000 as the front was snow-covered. In 1999 the front was in about the same position as in 1988. In total the front position has retreated about 1040 m since measurements began in 1902.

8. Hellstugubreen (Liss M. Andreassen, Laila P. Høivik)

Hellstugubreen (61°34'N, 8° 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 km² (Fig. 8-1). Mass balance investigations have been carried out annually since 1962.

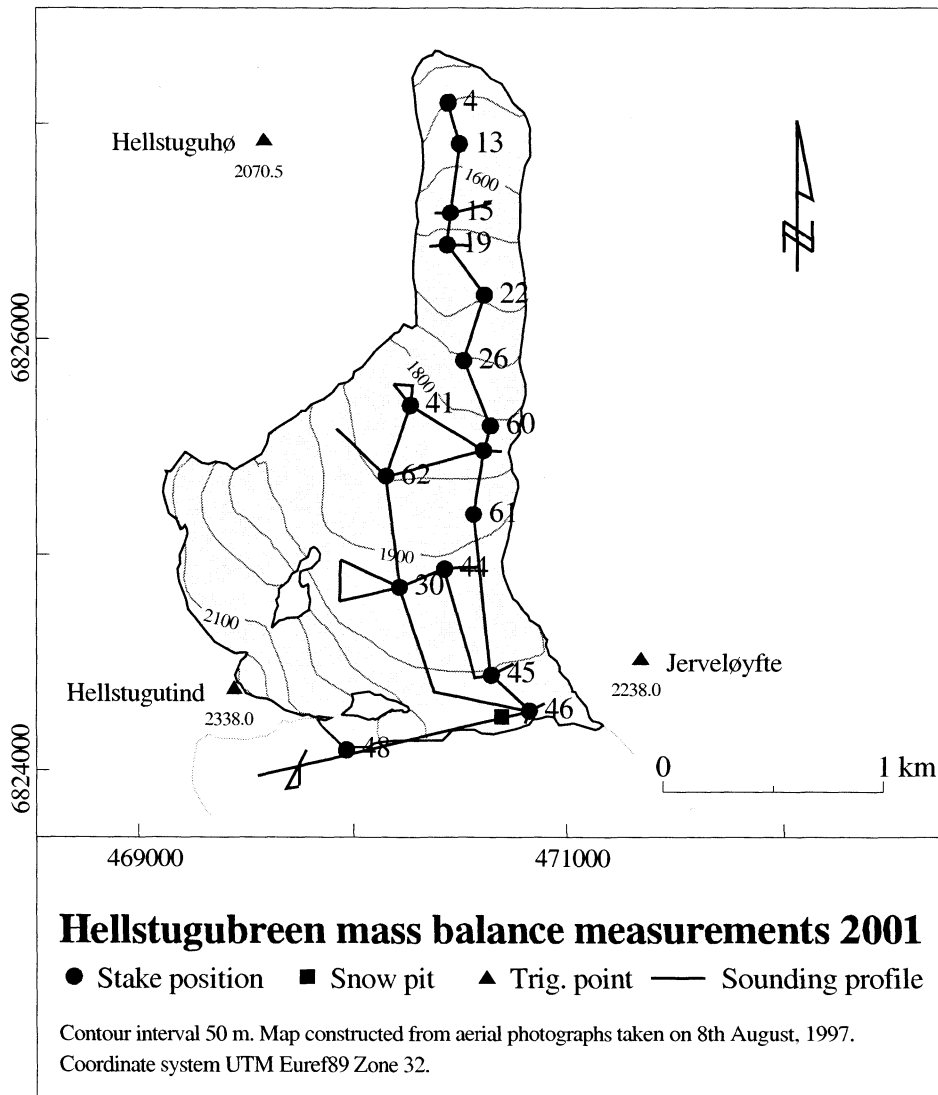


Figure 8-3
Map of Hellstugubreen showing the mass balance programme in 2001. Figure 7-1 shows a location map of the study glaciers in Jotunheimen.

8.1 Mass balance 2001

Fieldwork

Accumulation measurements were carried out on 7th May. Stakes at 13 locations had survived the winter. Snow depth was measured at 88 points along 9.6 km of profiles covering most of the glacier. The probing conditions were good, and the summer

surface the previous year was easy to identify over the whole glacier. The snow depth varied between 1.4 and 3.8 metres, with a mean depth of 2.6 m. 76 % of the measurements were between 2 and 3 metres.

The snow density was measured by sampling in a pit at 1950 m a.s.l. The total snow depth was 3.2 m. Below the uppermost 1.5 metres the snow was very granular/sugary, which made it impossible to measure the density beneath this level.

Ablation measurements were carried out on 27th September, on stakes at 15 locations. The location of stakes, density pit and sounding profiles are shown in Figure 8-1.

Results

The collected mass balance results are presented in Table 8-1 and Figure 8-2.

Winter balance

The winter balance was calculated from soundings and the snow density measurement, which was considered to be representative for the rest of the glacier. The winter accumulation was calculated by plotting the mean of the soundings within each 50-metre height interval against altitude, and drawing a representative curve. This gave a winter accumulation of 0.9 ± 0.2 m w.eqv., which is 79 % of the mean for the period 1962-99.

The additional melt after the previous year's ablation measurements was calculated from stake recordings, giving an extra melt of up to 0.5 w.eqv. Above 1900 m a.s.l. there was no additional melt. The winter balance was calculated by subtracting the extra melt from the winter accumulation. The specific winter balance was thus calculated to be 0.85 ± 0.2 m w.eqv. This is 76 % of the mean for the period 1962-2000.

Summer balance

The summer balance was calculated from 13 stakes. The density of the remaining snow was assumed to be 0.6 g/cm^3 and the density of the remaining firm to be 0.7 g/cm^3 . The density of the melting ice was estimated to be 0.9 g/cm^3 . The summer balance was calculated to be -1.2 ± 0.2 m w.eqv., which is 89 % of the mean value for the entire observation period.

Net balance

The net balance of Hellstugubreen in 2001 was -0.36 ± 0.3 m w.eqv., which amasses to a lost volume of 1.1 ± 0.09 mill. m^3 water. The equilibrium line altitude (ELA) was 1910 m a.s.l. and the AAR was 48 % (Fig. 8-2). Since 1962 there has been a cumulative mass loss of 10.6 m w.eqv. from Hellstugubreen, the equivalent of -0.27 m w.eqv. per year.

Mass balance Hellstugubreen 2000/01							
Altitude (m a.s.l.)	Area (km ²)	Winter balance		Summer balance		Net balance	
		Measured 07 mai 2001		Measured 27 sep 2001		Summer surfaces 2000 - 2001	
		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)
2150 - 2210	0,02	1,23	0,03	-0,33	-0,01	0,90	0,02
2100 - 2150	0,09	1,20	0,11	-0,42	-0,04	0,78	0,07
2050 - 2150	0,28	1,10	0,31	-0,48	-0,13	0,62	0,17
2000 - 2050	0,18	0,95	0,17	-0,59	-0,11	0,36	0,07
1950 - 2000	0,38	1,02	0,39	-0,76	-0,29	0,26	0,10
1900 - 1950	0,61	1,03	0,63	-0,97	-0,59	0,06	0,04
1850 - 1900	0,35	0,94	0,33	-1,15	-0,40	-0,21	-0,07
1800 - 1850	0,33	0,81	0,27	-1,30	-0,43	-0,49	-0,16
1750 - 1800	0,13	0,70	0,09	-1,50	-0,20	-0,80	-0,11
1700 - 1750	0,10	0,62	0,06	-1,70	-0,18	-1,08	-0,11
1650 - 1700	0,17	0,52	0,09	-1,93	-0,33	-1,41	-0,24
1600 - 1650	0,13	0,42	0,05	-2,20	-0,28	-1,78	-0,23
1550 - 1600	0,16	0,25	0,04	-2,55	-0,41	-2,30	-0,37
1500 - 1550	0,08	0,04	0,00	-2,96	-0,23	-2,92	-0,23
1480 - 1500	0,02	-0,12	0,00	-3,17	-0,06	-3,29	-0,06
1480 - 2210	3,03	0,85	2,56	-1,21	-3,67	-0,36	-1,10

Table 8-2
The distribution of winter, summer and net balance in 50 m altitude intervals for Hellstugubreen in 2001.

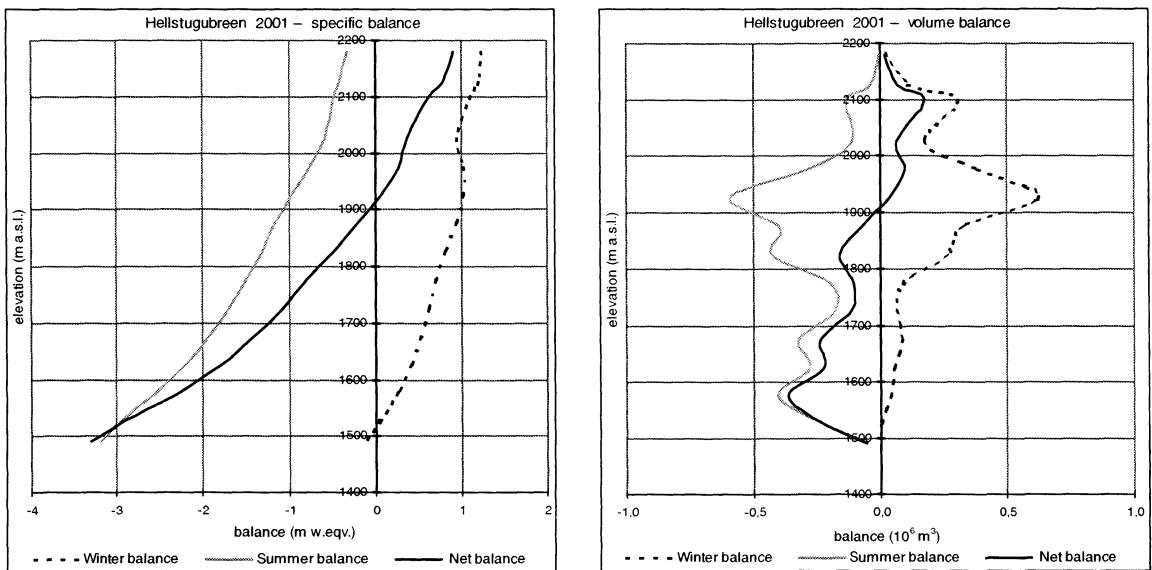


Figure 8-2
Mass balance diagram for Hellstugubreen 2001, showing specific balance to the left and volume balance to the right.

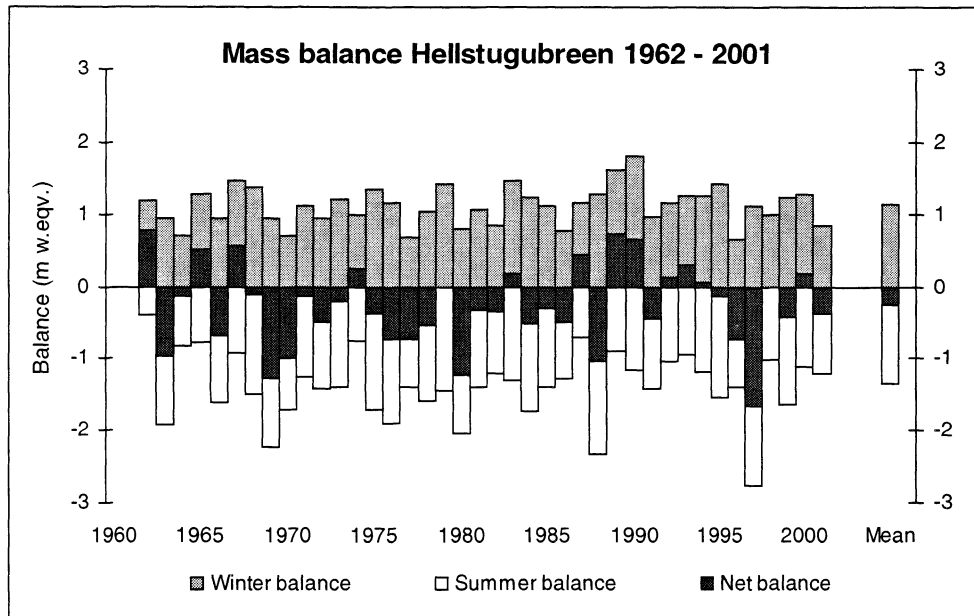


Figure 8-3
Winter, summer and net balance at Hellstugubreen for the period 1962-2001.

8.2 Front position change

Hellstugubreen had a small net retreat of 4 metres in front position from September 2000 to September 2001. The total retreat in front position is thus 1004 m since measurements began in 1901.

9. Gråsubreen (Liss M. Andreassen and Laila P. Høivik)

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 km² 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.

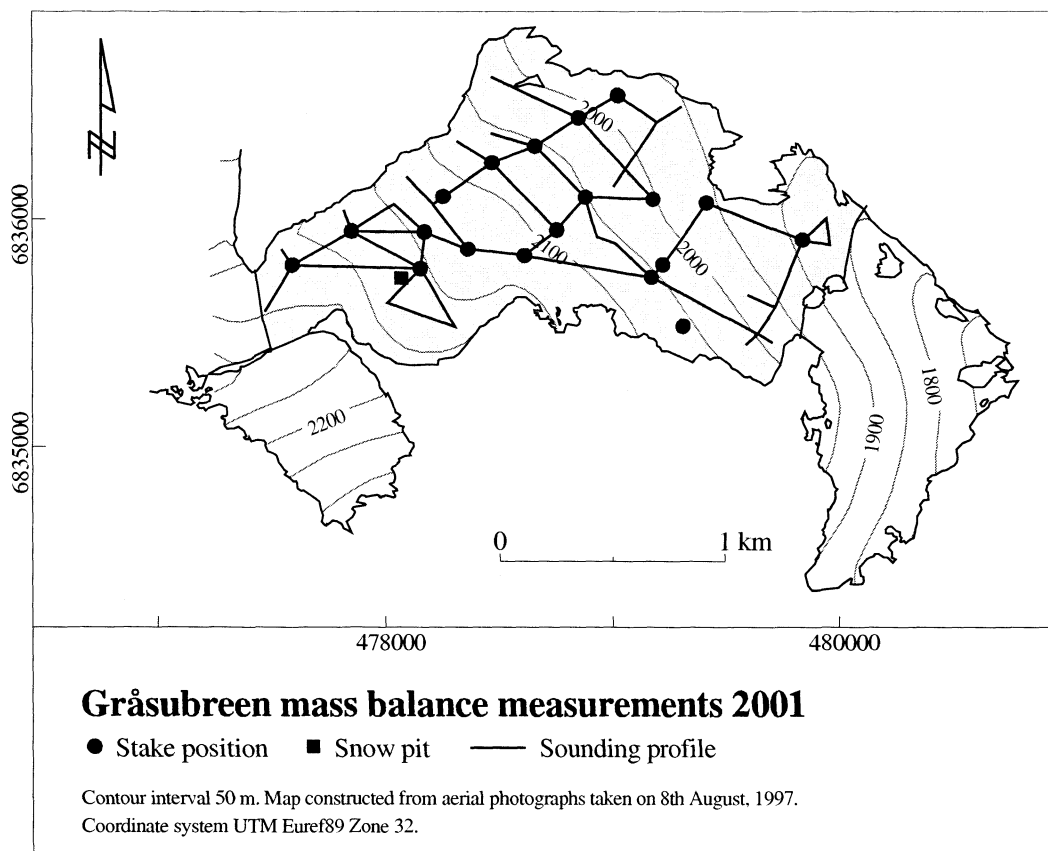


Figure 9-4
Map of Gråsubreen (shaded in grey) showing the mass balance programme in 2001. A location map of Gråsubreen and other glaciers in Jotunheimen is shown in Figure 7-1.

9.1 Mass balance 2001

Fieldwork

Accumulation measurements were carried out on 9th May. Stakes in 17 locations were measured. 123 snow depth measurements were made along 12 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 1.2 and 3.7 m, with a mean of 2.3 m.

The snow density was measured at 2180 m a.s.l. in a pit dug through the winter snow pack (2.0 m snow). Ablation measurements were carried out on 28th September, when stakes in 18 locations were measured.

Results

The collected mass balance results are presented in Table 9-1 and Figure 9-2.

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 0.40 g/cm^3 . The winter accumulation was calculated by plotting the mean of the soundings within each 50-meter height interval against altitude, and drawing a representative curve. This gave a winter accumulation of 0.9 m w.eqv., which is 113 % of the mean for the period 1962-2000.

The additional melting after the previous year's ablation measurements was calculated from stake recordings at 16 locations, giving an extra melt of 0.01-0.18 m w.eqv. at thirteen of the locations. Any superimposed ice that formed this year was impossible to measure due to the additional melt. The winter balance was calculated by subtracting the extra melt from the winter accumulation. The specific winter balance was thus calculated to be 0.8 ± 0.2 m w.eqv. This is 102 % of the mean for the period 1962-2000.

Summer balance

Summer balance was calculated from direct measurements of stakes in 15 locations. The density of the remaining snow was assumed to be 0.6 g/cm^3 . The density of the melted ice and firn was estimated to be 0.90 and 0.70 g/cm^3 respectively. The resulting summer balance was -0.8 ± 0.3 m w.eqv., which is 75 % of the mean for the period 1962-2000.

Net balance

Gråsubreen was almost in balance in 2001, with a small positive net balance of 0.02 ± 0.3 m w.eqv. The equilibrium line altitude (ELA) was 2070 m a.s.l., which corresponds to an accumulation area ratio (AAR) of 45 % (Fig. 9-2).

Since 1962 there has been a cumulative mass loss of 9.9 m w.eqv. from Gråsubreen. Most of this mass loss occurred in the 1970s and 1980s. Since 1988 the glacier has been more or less in balance (Fig 9-3).

Mass balance Gråsübreen 2000/01							
Altitude (m a.s.l.)	Area (km ²)	Winter balance		Summer balance		Net balance	
		Measured 09 mai 2001		Measured 28 sep 2001		Summer surfaces 2000 - 2001	
		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	0,88	0,04	-0,15	-0,01	0,73	0,03
2200 - 2250	0,17	0,85	0,14	-0,26	-0,04	0,59	0,10
2150 - 2200	0,26	0,87	0,23	-0,40	-0,11	0,47	0,12
2100 - 2150	0,34	0,74	0,25	-0,56	-0,19	0,18	0,06
2050 - 2100	0,37	0,75	0,28	-0,72	-0,27	0,03	0,01
2000 - 2050	0,42	0,75	0,31	-0,88	-0,37	-0,13	-0,05
1950 - 2000	0,36	0,85	0,30	-1,05	-0,38	-0,20	-0,07
1900 - 1950	0,14	0,89	0,13	-1,27	-0,18	-0,38	-0,05
1830 - 1900	0,15	0,85	0,13	-1,45	-0,22	-0,60	-0,09
1830 - 2290	2,25	0,80	1,81	-0,78	-1,76	0,02	0,05

Table 9-3
The distribution of winter, summer and net balance in 50 m altitude intervals for Gråsübreen in 2001.

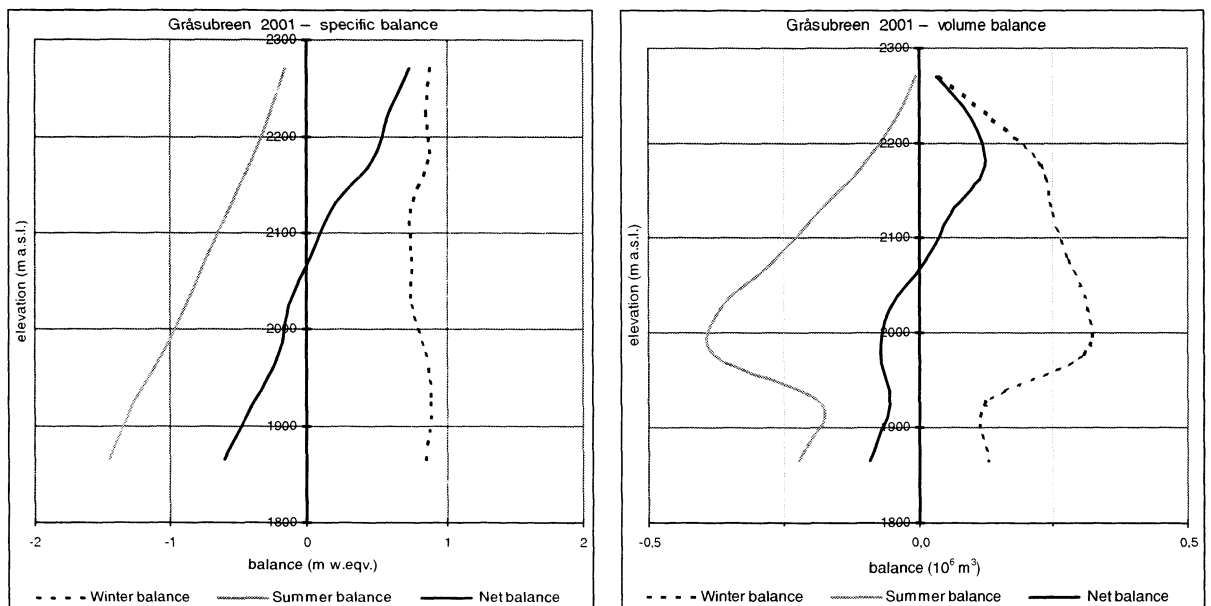


Figure 9-5
Mass balance diagram for Gråsübreen 2001, showing specific balance to the left and volume balance to the right.

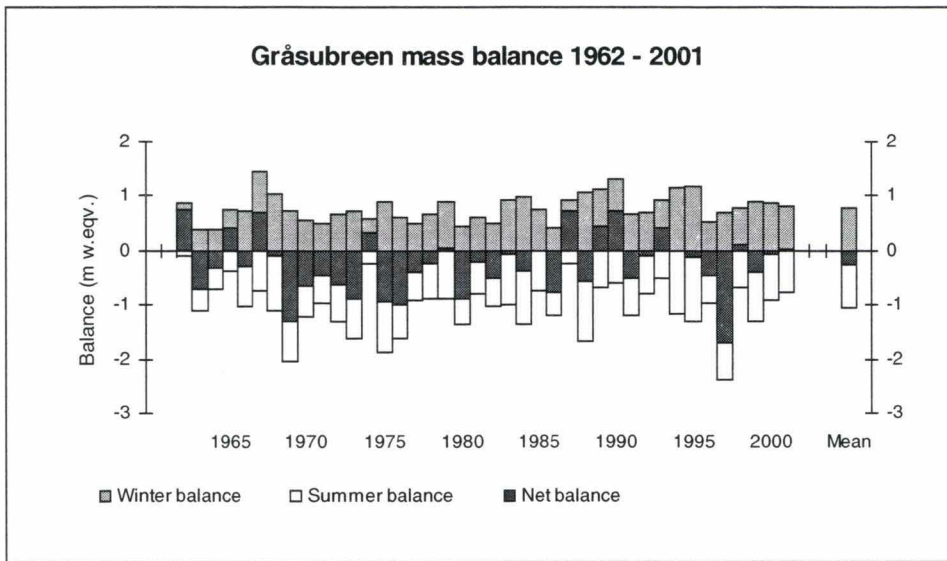


Figure 9-3
Winter, summer and net balance at Gråsubreen during the period 1962-2001. Gråsubreen has had an average annual mass loss of 0.25 m w.e.v. in this period.

10. Svartisheibreen (Hallgeir Elvehøy)

Located south-west of western Svartisen icecap, Svartisheibreen (66°35'N, 13°45'E) covers 5.5 km² and drains to the river Glomåga and lake Langvatnet. The glacier ranges from 1530 m a.s.l. down to the proglacial lake Heiavatnet at 774 m a.s.l., into which the glacier calves. The glacier has been monitored in connection with a planned hydropower development. Since 1995 the monitoring programme has been reduced to observations of lake level in Heiavatnet to see if jøkulhlaups occur, and observations of the snow line altitude to calculate annual net balance. In 2001 Svartisheibreen was used as a test site in the EU-funded project OMEGA (development of an Operational Monitoring system for European Glacial Areas) in the 5th Frame Programme.

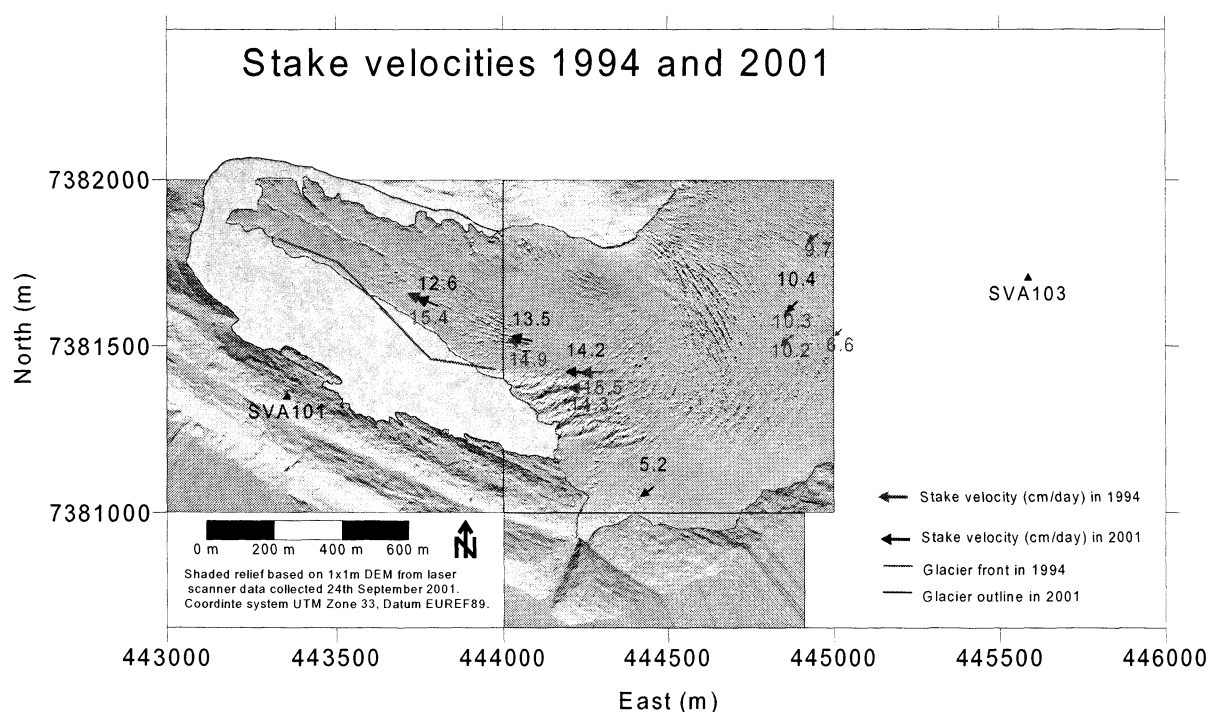


Figure 10-1
Horizontal stake velocity (cm pr day) in 1994 (11th August – 15th September) and 2001 (24th August – 9th October) on the lower part of Svartisheibreen. The glacier front in Heiavatnet in 1994 is defined by 4 points. The glacier outline in 2001 is defined from shaded relief and contour lines based on a 1m x 1m DEM. The elevation of Heiavatnet in 2001 was 768 m a.s.l., 6 metres below the lake level in 1994.

10.1 Observations 2001

Heiavatnet

The lake Heiavatnet was observed on 24th August and 9th October 2001. The river from the lake was dry. The lake level was measured with GDM from fix point SVA101 on 24th August to 767.45 m a.s.l., 6 m below the normal bedrock outlet. The lake level after the jøkulhlaup in 1991 was 766.7 m a.s.l., after which the water was

kept low during most of the proceeding winter (Kjøllmoen & Kennett 1995). The glacier outline in the lake is defined from shaded relief and contour lines based on a 1m x 1m digital elevation model. The DEM was generated from point elevations measured by an airborne laser scanner 24th September 2001.

Velocity measurements

Four stakes close to Heiavatnet and one stake at 900 m a.s.l. were positioned using GDM from SVA101 24th August and 9th October 2001. The stake positions were chosen to match stake positions used in 1994. Mean velocity and direction of movement for the period were calculated based on these positions (Fig. 10-1).

Equilibrium line altitude

Vertical aerial photographs were taken over Svartisheibreen 25th August 2001 (Fotonor AS, contract Nr. 01139, scale 1:15 000). From these images the transient snow line (TSL) was estimated to 1150 m a.s.l. Between 24th August and 9th October approximately 1½ m ice melted on the glacier tongue. At Engabreen the first snowfall came 25th September, and this was considered to be the end of the melting season both at Engabreen and at Svartisheibreen. The estimated ELA 25th September 2001 was 1200 m a.s.l.

10.2 Results

Changes in front position

The front position in 2001 determined from laser scanner data was compared to the front position in 1994 interpolated from four point measurements using GDM. The changes in front position are minor (Fig. 10-1). This is in good agreement with front position observations during the last few years showing minor changes only.

Changes in glacier velocity

Stake velocities calculated from repeated positioning in late summer 1994 and 2001 have been compared (Fig. 10-1). The comparison indicated that the glacier tongue close to the lake has experienced a significant decrease in velocity, shown by a decrease of 2.8 and 1.4 cm/d respectively on the two westernmost stakes. At the uppermost stake measured in 2001 (around 900 m a.s.l.) the change in velocity was insignificant, indicating that the ice flow in this area has not changed in this period. At the fourth stake close to the eastern end of the lake the difference in velocity could be caused partly by a difference in location due to crevasses.

The lowering of the lake level between 1994 and 2001 has probably contributed to the decrease in velocity close to the lake. The western part of the glacier tongue is most likely afloat, and slowly disintegrating.

Net balance 2001

The net balance of Svartisheibreen was estimated using two different methods; one using the observed net balance on Engabreen ($b_n = -1.0$ m w.eqv.), and the other using the observed ELA at Svartisheibreen. The net balance at Engabreen was calculated as the sum of snow accumulation and summer balance (see Chapter 11). Both methods are based on the mass balance measurements carried out on Svartisheibreen in the period 1988-1994 (see Figs. 10-2 and 10-3).

The net balance was -0.9 m w.eqv. based on Engabreen net balance, and -1.9 m w.eqv. based on the ELA at Svartisheibreen. Combining these results gives an estimate of the net balance of -1.4 ± 0.4 m w.eqv. The results for the period 1995-2001 are listed in Table 10-1. Cumulative specific balance for the period 1969-2001 is estimated to $+10$ m w.eqv. (Fig. 10-4).

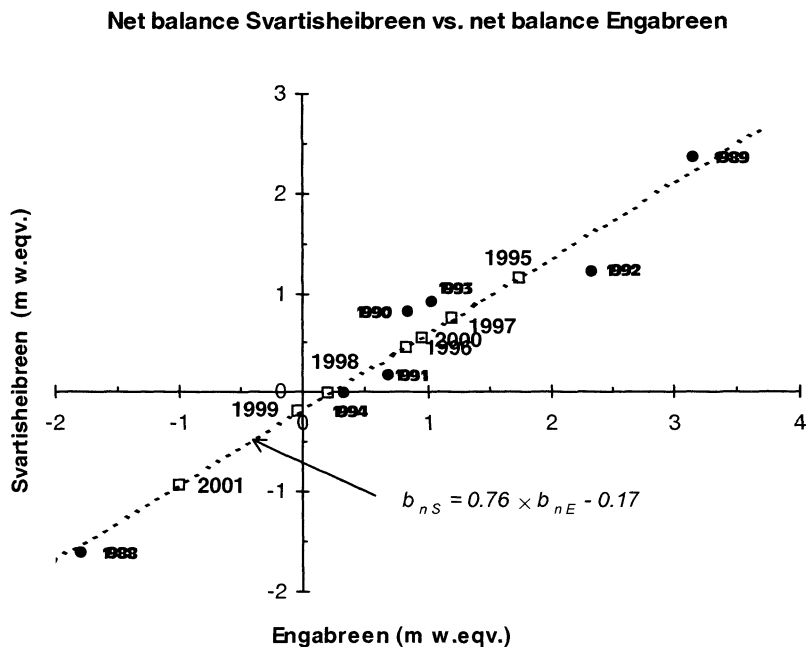


Figure 10-2
 Linear regression between net balance of Engabreen and Svartisheibreen (•) based on simultaneous observations during the period 1988-94. Net balance of Svartisheibreen for the period 1995-2001 (◻) is modelled using regression equations.

Svartisheibreen
Net balance vs. equilibrium line altitude

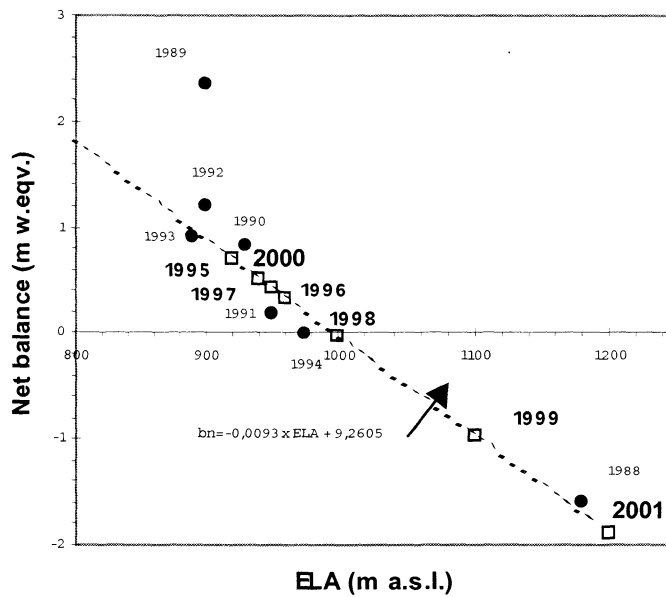


Figure 10-3
Linear regression between the elevation line altitude (ELA) and net balance (b_n) on Svartisheibreen based on measurements for the period 1988-94 (•). The results from 1989 were discarded in the regression analysis. Net balance for the period 1995-2001 (◻) is modelled using a regression equation.

Year	Date of visit	ELA (m a.s.l.)	Heiavatnet filled ?	Net balance		
				method 1 ¹	method 2 ²	mean
1995	20 th Sep	920	Yes	1.2	0.7	0.9
1996	19 th Sep	960	Yes	0.5	0.3	0.4
1997	4 th Oct	940 ³	Yes	0.7	0.6	0.7
1998	1 st Oct	1000	Yes	0.0	0.0	0.0
1999	22 nd .Sep	1100	No	-0.2	-1.0	-0.6
2000	21 st Sep	950	No	1.0	0.4	0.7
2001	24 th Sep	1200 ⁴	No	-0.9	-1.9	-1.4

¹Based on relation between net balance of Engabreen and Svartisheibreen.

²Based on relation between ELA and net balance at Svartisheibreen

³Estimated from summer observations

⁴Estimated from aerial photographs from 25th August and further melting until 25th September.

Table 10-1
Observations of the equilibrium line altitude (ELA) at Svartisheibreen, the water level in Heiavatnet, and modelled net balance of Svartisheibreen for the period 1995 - 2001.

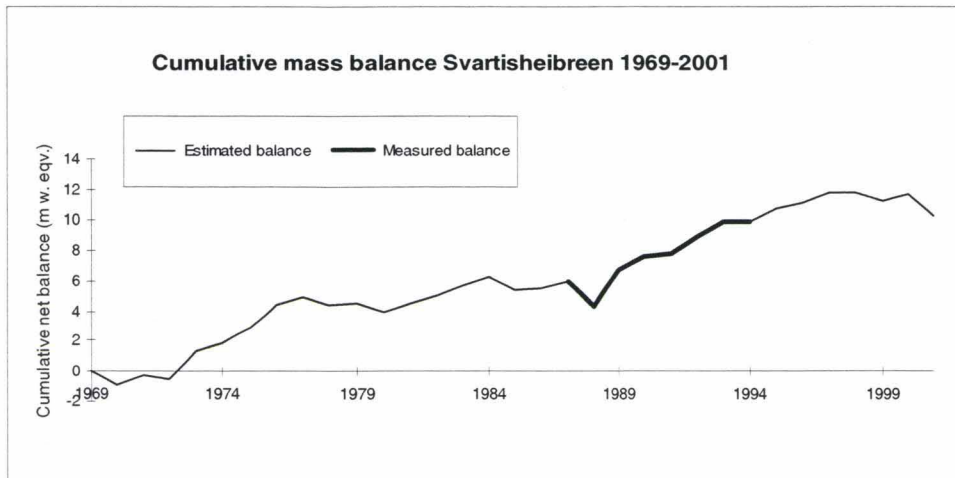


Figure 10-4
Cumulative specific net balance of Svartisheibreen for the period 1969-2001. Estimated net balance (thin solid line) is modelled from net balance on Engabreen (1969-87), and from the ELA on Svartisheibreen and net balance of Engabreen (1995-2001).

11. Engabreen (Hallgeir Elvehøy and Miriam Jackson)

Engabreen (66°40'N, 13°45'E) is a 38 km² north-western outlet from the western Svartisen icecap. It covers an altitude range from 1594 m a.s.l. (at Snøtind) down to 7 m a.s.l. (at Engabrevatnet), as shown in Figure 11-1. Mass balance measurements have been performed annually since 1970.

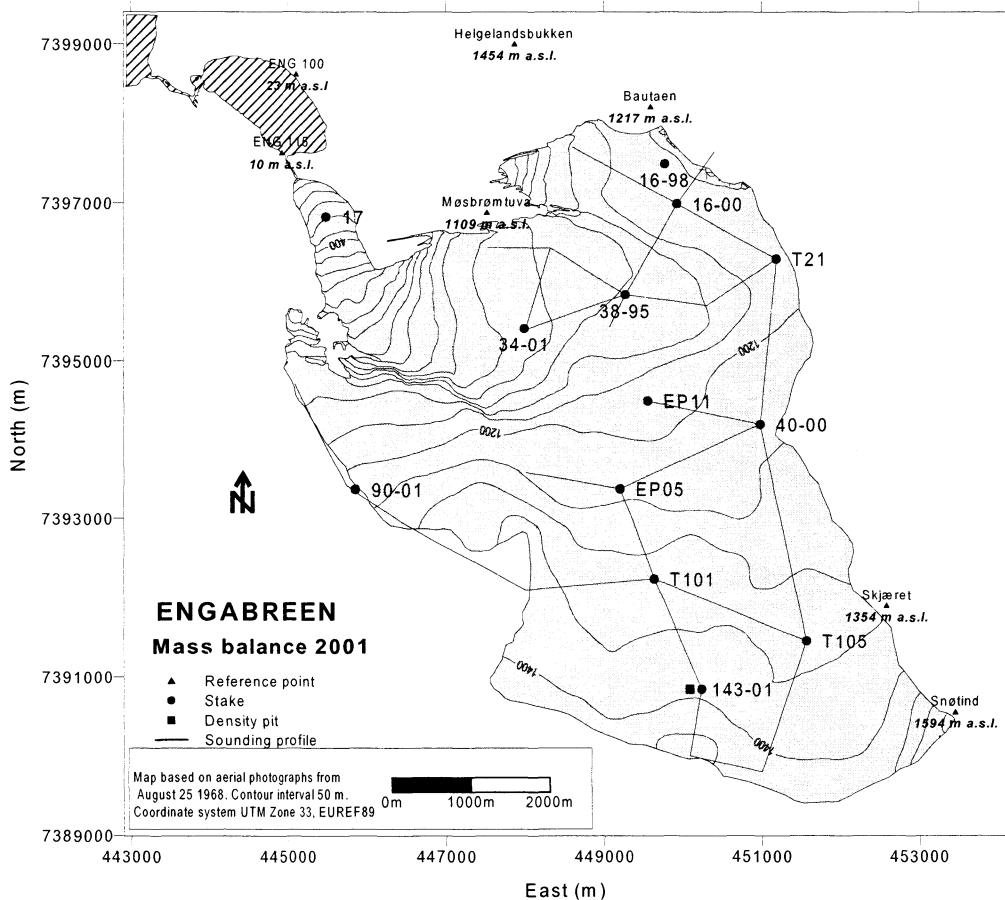


Figure 11-1
Location of stakes, density pit and sounding profiles at Engabreen in 2001.

11.1 Mass balance 2001

Fieldwork

The melting that occurred after the summer ablation measurements 21st September 2000 was estimated by comparing snow depth soundings and stake readings 8th March and in May 2001. On the plateau, between 0.6 and 0.8 m of snow from the winter 2000 had melted away between 21st September and the start of winter accumulation in mid-October. At one location on the glacier tongue, about 2½ m of ice had melted away by 8th March. About 1½ m of this ice had probably melted away by the end of October.

Winter accumulation measurements were carried out between 24th and 29th May. The locations of stakes and towers, density pit, core samples and sounding profiles are shown in Figure 11-1. The calculation of winter accumulation is based on:

- Direct measurements of snow depth at stake 17, stake 38-95, stake 37-00, tower T21, stake 16-98, stake 16-00, stake 40-00, tower T101 and tower T105, giving 0.0, 3.5, 3.6, 3.4, 4.1, 4.2, 4.1, 4.2 and 4.3 m of snow respectively. At stake 17, 3.1 m of ice had melted since 21st September 2000.
- Core samples collected between 24th and 29th May at 960 m a.s.l. (stake 34), 1180 m a.s.l. (stake EP11), 1215 m a.s.l. (stake 90), 1240 m a.s.l. (stake EP5) and 1400 m a.s.l. (stake 143). The samples gave 2.3, 3.8, 3.4, 4.6 and 4.7 m of snow respectively.
- Snow density measured to a depth of 4.5 m at 1400 m a.s.l. (stake 143). Mean snow density was 0.44 g/cm³.
- 175 snow depth soundings along approximately 36 km of profiles. The snow depth was between 3½ and 5 m above 1200 m a.s.l., and 2½ to 4½ m between 950 and 1200 m a.s.l.
- The transient snow line (TSL) in the icefall, located about 500 m a.s.l.

The net balance measurements were carried out 26th September and 10th October. The first new snow fell on the 27th September, but it had melted away as high as 1055 m a.s.l. (stake 38) by 10th October. The TSL was observed at about 1350 m a.s.l., but some net melting had taken place on the north west slope of Snøtind (above approximately 1550 m a.s.l.).

The net balance was observed at 11 positions ranging from 300 to 1400 m a.s.l. At the glacier tongue (300 m a.s.l.) 8 m of ice had melted during the summer. At 960 m a.s.l. all the winter snow and 3¼ m of ice had melted. Between 1000 and 1200 m a.s.l. 3 - 4 m of snow and 1 - 2 m of firn had melted away. During the course of the summer 4 - 4½ m of snow and some firn had melted at the stakes on the upper plateau. About ½ m of snow was left at stake 143.

Results

The mass balance is normally 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, insignificant compared to winter accumulation and summer ablation, and normally hard to determine accurately. This was not the case in 2000.

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 winter balance for 2001 was calculated as the sum of late autumn ablation calculated from comparison of stake measurements and soundings on the 8th March, and snow accumulation calculated from soundings in May 2001.

The altitudinal distribution of the autumn melting was estimated based on observations and estimates of ablation after 21st September 2000 at 9 locations on Engabreen. The density of the melted snow was set to 0.6 g/cm³. From this distribution the total volume of autumn ablation was calculated as -20 mill. m³ water or -0.5 m w.eqv.

The calculations of snow accumulation are based on point measurements of snow depth (towers, probing and core drillings) and on snow density measurements (Fig. 11-1). A water equivalent profile was modelled from the snow density measured at stake 143. Using this model, the mean snow density for 5 m of snow was calculated as 0.46 g/cm³. The model was then used to calculate the water equivalent value of all the snow depth measurements.

Point values of the snow water equivalent (SWE) were plotted against altitude in a diagram, and a curve was drawn based on visual evaluation. No snow depth observations were carried out below 950 m a.s.l. For these elevations the snow accumulation curve was interpolated based on the observed TSL at 500 m a.s.l., and observed negative winter balance at stake 17 (300 m a.s.l.) reduced for estimated melting between 21st September and mid-October. Based on this altitudinal distribution curve, the snow accumulation was calculated as 1.6 ± 0.2 m w.eqv., which corresponds to a volume of 60 ± 8 mill. m³ of water.

Within each altitude interval the winter balance was calculated as the sum of autumn ablation and snow accumulation at that elevation. In total the winter balance was calculated as 1.1 ± 0.2 m w.eqv., which corresponds to a volume of 40 ± 8 mill. m³ of water. This is 35 % of the mean value for the period from 1970-2000 (2.95 m w.eqv.), and 34 % of the mean value for the 5-year period 1996-2000. This is the smallest winter balance recorded at Engabreen.

Summer balance

The summer balance was measured and calculated directly at thirteen stakes and towers between 300 and 1400 m a.s.l. Based on the measurements an altitudinal distribution curve was drawn (Fig. 11-2). The summer balance was calculated to -2.6 ± 0.2 m w.eqv., which equals a volume of -98 ± 8 mill m³ water (Tab. 11-1). This is 116 % of the average for the period 1970-2000, and 112% of the average for the 5-year period 1996-2000.

Net balance

The net balance of Engabreen for 2001 was calculated as -1.5 ± 0.3 m w.eqv., which corresponds to a volume loss of 60 ± 10 mill. m³ water. The mean value for the period 1970-2000 is $+0.78$ m w.eqv., and $+0.74$ m w.eqv for the period 1996-2000. Because of the autumn melting the net balance at the uppermost stake (143) was slightly

negative, indicating that the entire glacier was below the equilibrium line altitude (ELA), (Fig. 11-2). This gives an accumulation area ratio (AAR) of 0 %.

The mass balance results are shown in Figure 11-2 and Table 11-1. The results from 2001 are compared to mass balance results for the period 1970 - 2000 in Figure 11-3.

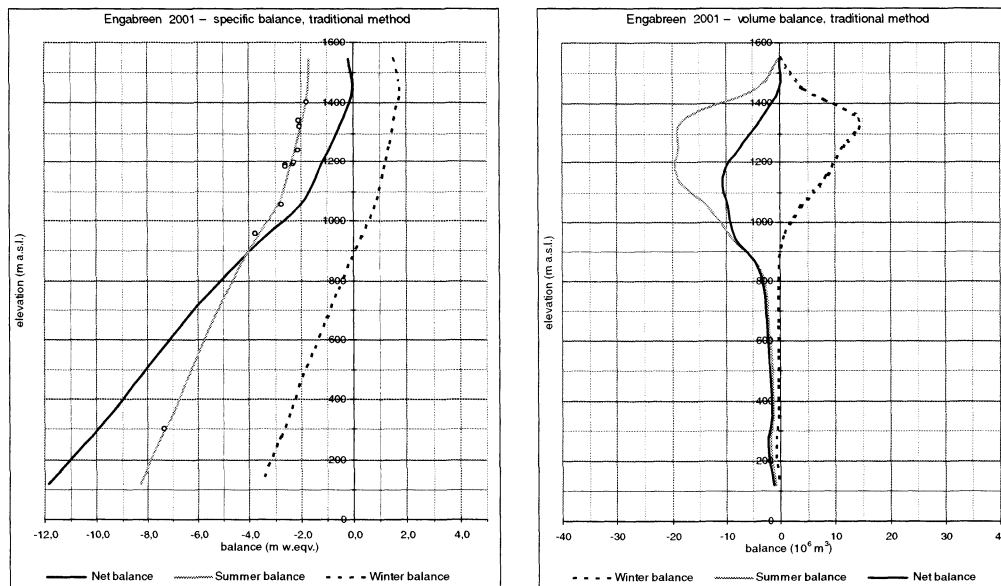


Figure 11-2
Mass balance diagram showing specific balance (left) and volume balance (right) for Engabreen in 2001. Summer balance at stakes and towers is shown as circles (*). The net balance curve does not intersect the y-axis and the ELA is undefined. Thus the AAR was 0%.

Mass balance Engabreen 2000/01 – traditional method							
Altitude (m a.s.l.)	Area (km ²)	Winter balance		Summer balance		Net balance	
		Measured 26th May 2001		Measured 26th Sep 2001		Summer surface 2000 - 2001	
		Specific (m w.equiv.)	Volume (10 ⁶ m ³)	Specific (m w.equiv.)	Volume (10 ⁶ m ³)	Specific (m w.equiv.)	Volume (10 ⁶ m ³)
1500 - 1594	0,12	1,52	0,2	-1,70	-0,2	-0,18	0,0
1400 - 1500	2,51	1,71	4,3	-1,75	-4,4	-0,04	-0,1
1300 - 1400	9,35	1,53	14,3	-1,90	-17,8	-0,37	-3,5
1200 - 1300	8,55	1,33	11,4	-2,20	-18,8	-0,87	-7,4
1100 - 1200	7,60	1,10	8,4	-2,50	-19,0	-1,40	-10,6
1000 - 1100	4,66	0,82	3,8	-2,90	-13,5	-2,08	-9,7
900 - 1000	2,46	0,30	0,7	-3,70	-9,1	-3,40	-8,4
800 - 900	0,94	-0,18	-0,2	-4,35	-4,1	-4,53	-4,3
700 - 800	0,50	-0,67	-0,3	-4,95	-2,5	-5,62	-2,8
600 - 700	0,37	-1,12	-0,4	-5,50	-2,0	-6,62	-2,4
500 - 600	0,27	-1,59	-0,4	-6,00	-1,6	-7,59	-2,0
400 - 500	0,21	-2,05	-0,4	-6,50	-1,4	-8,55	-1,8
300 - 400	0,17	-2,45	-0,4	-7,00	-1,2	-9,45	-1,6
200 - 300	0,22	-2,90	-0,6	-7,60	-1,7	-10,50	-2,3
40 - 200	0,10	-3,55	-0,4	-8,30	-0,8	-11,85	-1,2
40 - 1594	38,0	1,05	39,9	-2,58	-98,1	-1,53	-58,2

Table 11-1
Specific and volume winter, summer, and net balance calculated for 100 m elevation intervals at Engabreen in 2001.

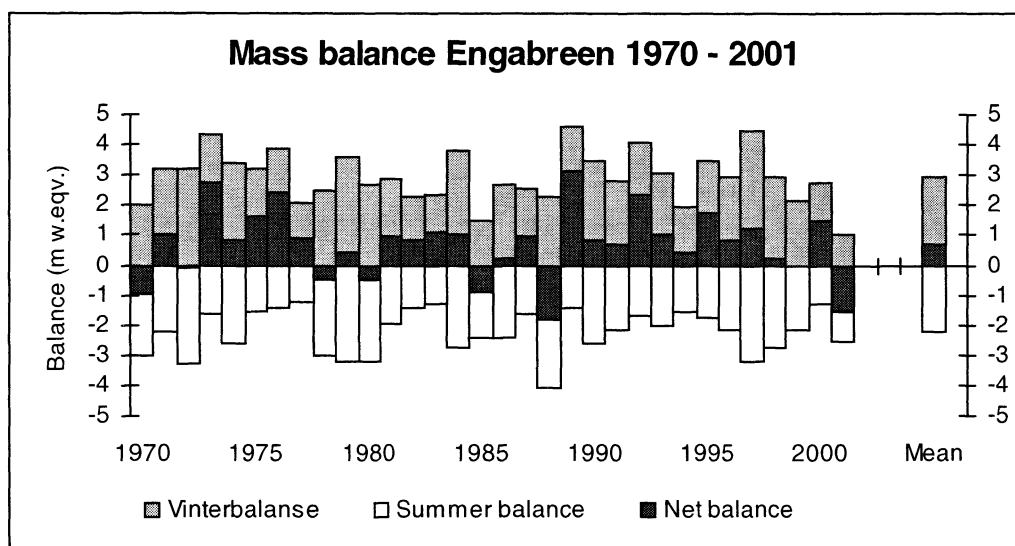


Figure 11-3
Mass balance at Engabreen during the period 1970-2001. The accumulated surplus amounts to 23 m water equivalents.

11.2 Front position change

Changes in front position are observed from fixed points aligned along the central flow direction of the glacier. On 26th September 2001 the glacier had melted back 10 m compared to 21st September 2000. The terminus is now close to the position it had in 1984 before the 1985-91 retreat (Fig 11-4).

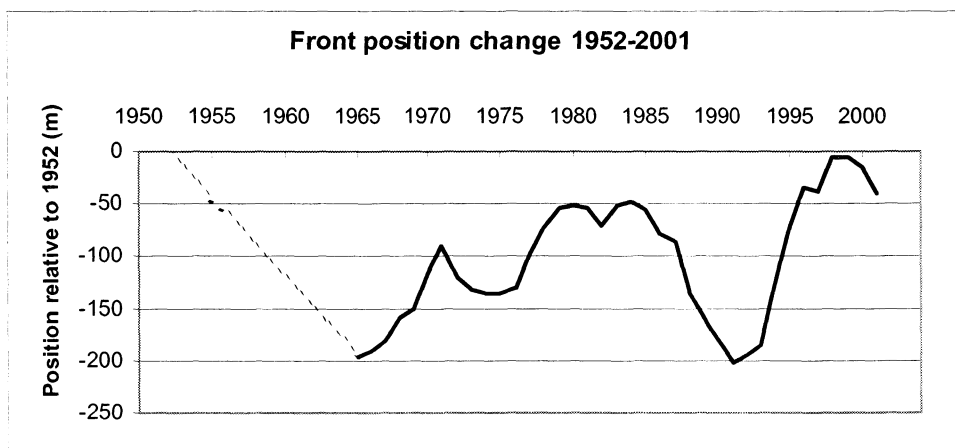


Figure 11-4
Front position change between 1952 and 2001 measured as change in position along a line parallel to a central flow line. The location of the line (the fix points) was shifted in 1996 due to an assessment of avalanche risk at the original line. The two lines had been measured simultaneously for some time.

11.3 Glacier velocity

The mass balance stake network has been positioned repeatedly since May 2000 using precision dGPS to calculate horizontal and vertical velocities. The fix point at Bautaen has been used as a reference point for differential calculations. Stakes were

positioned on 27th May and 21st September 2000, and on 27th May, 22nd August and 24th September 2001.

The velocities vary during the year, but due to varying periods between measurements these variations are not quantified yet. These variations will be further analysed later when more data is available. In Figure 11-5 horizontal mean velocities are presented.

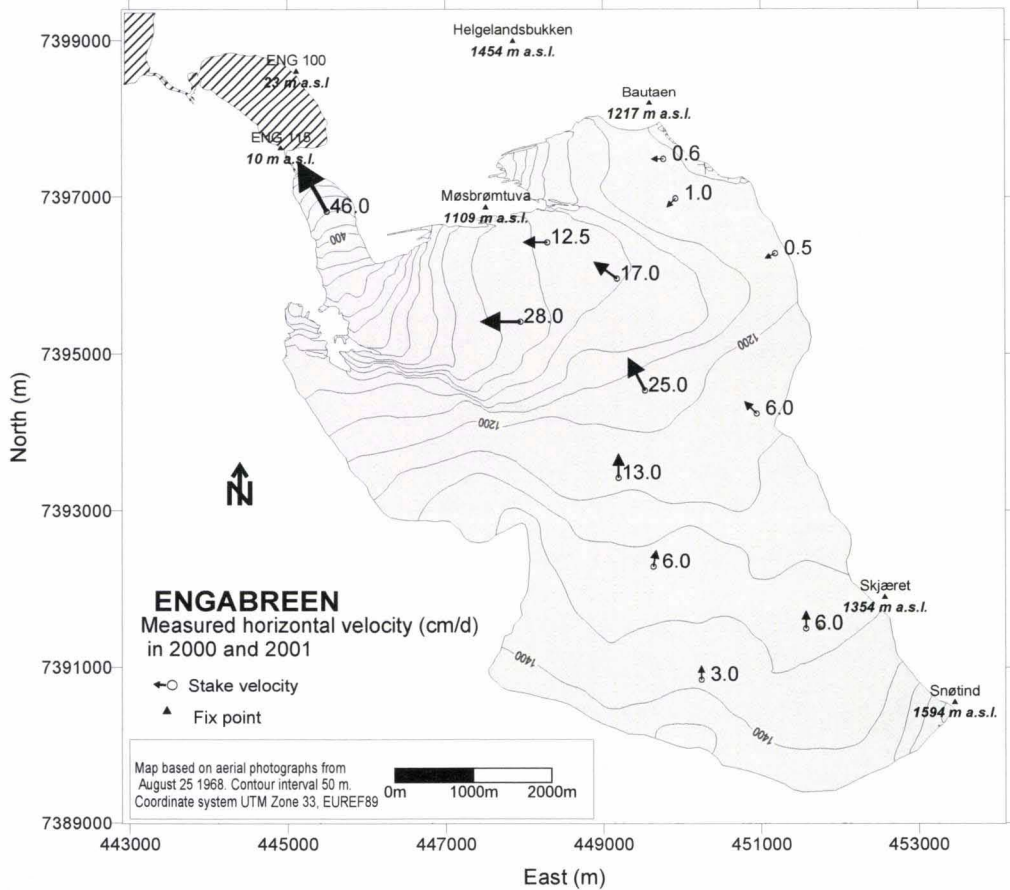


Figure 11-5
Glacier velocity measured at stakes in 2000 and 2001. The velocities shown do not represent exactly the same period for each stake.

11.4 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 11-5). The station has been recording data since 1995 with some data gaps. The nearest meteorological station is in Glomfjord (39 m a.s.l.) 19 km north of Skjæret. The Norwegian Meteorological Institute (DNMI) has run this station since 1912.

The temperature record from Glomfjord shows that close to sea level like at the glacier tongue, there can be repeated periods of melting throughout the winter (Fig 11-6). The temperature record from Skjæret shows that in the autumn of 2000 extensive melting took place at the glacier plateau between mid-September and mid-October. On the upper part of the glacier the melting season started in mid-June and

ended around 24th September. The mean temperature gradient in 2001 between Glomfjord and Skjæret was $-0.75\text{ }^{\circ}\text{C}/100\text{m}$. During the melting season (15th June – 24th September) the temperature gradient was slightly lower ($-0.67\text{ }^{\circ}\text{C}/100\text{m}$).

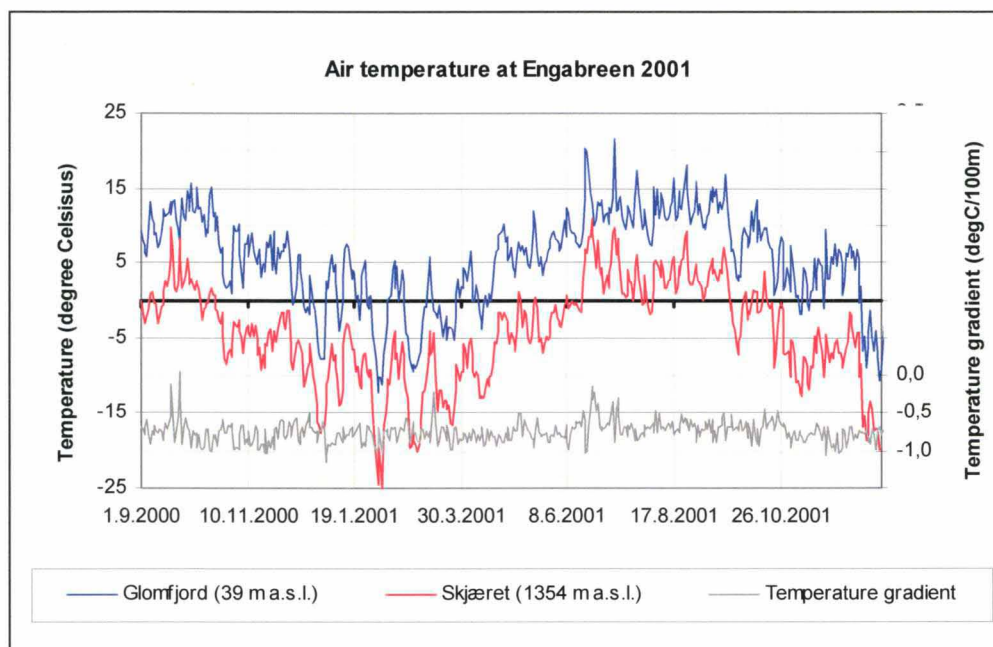


Figure 11-6
Daily mean air temperature at Skjæret (159.20.20) and Glomfjord (80700) between 1st September 2000 and 31st December 2001, and daily temperature gradient between Glomfjord and Skjæret.

11.5 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 NVEs document series for 2000, entitled ‘Svartisen Subglacial Laboratory’.

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 2001. A further two load cells were installed in November 1997 and were also still operating in 2001. The load cells in question are Geonor P-105 Earth Pressure Cells. These load cells record data at 15 or 20 minute intervals (more frequently when experiments are being performed). A new load cell was installed on 20th March, 2001. This new load cell installed during March, worked only intermittently and ceased functioning altogether on 19th July, so data from it is not represented in these graphs. During 2001, the load cells were operational between 2nd March and 30th March, and from 28th May until the end of the year.

Pressure sensor records for the first period with data in 2001, starting on 2nd March, are shown in Figure 11-7. The first 11 days of the record are very stable, reflecting

typical wintertime conditions when there is very little meltwater under the glacier. Experimental work started on 13th March, so the large variations in pressure on and after this date are artificial, not due to natural causes. Data for the period from 20th to 30th March are not shown, as there was much experimental work in progress then leading to very noisy data, and the experimental results will be reported elsewhere.

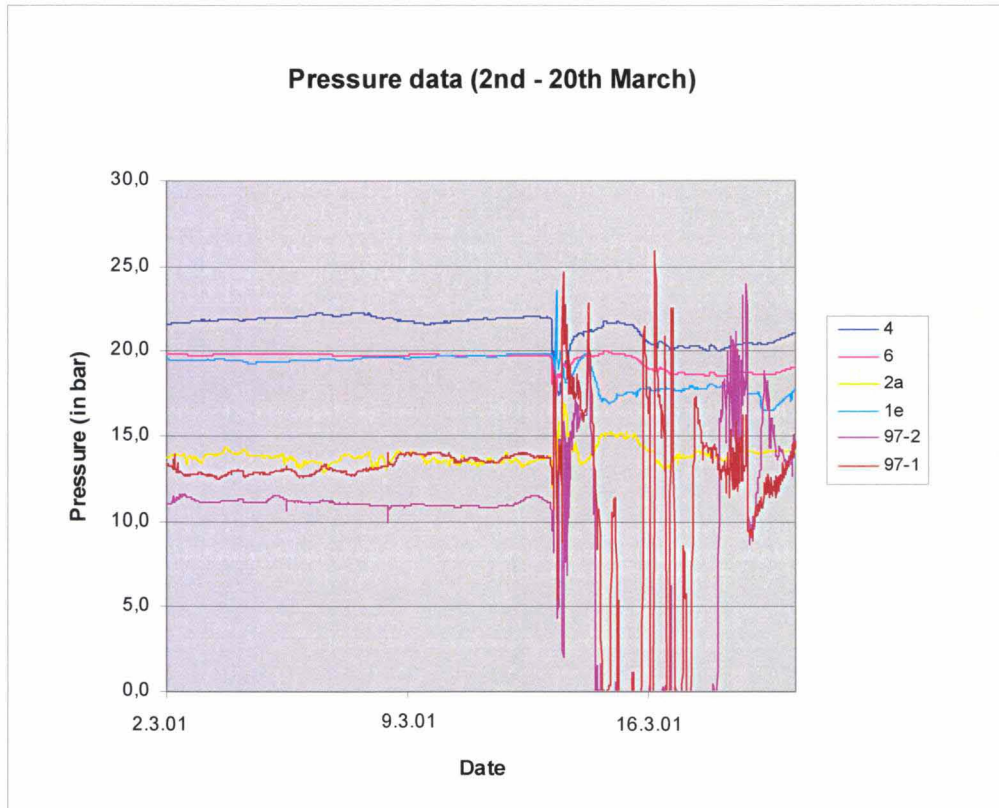


Figure 11-7
Data logger records for the period 2nd – 20th March.

Pressure sensor records for the summer period, from 28th May until 21st August, are shown in Figure 11-8. Due to an equipment problem, no data were recorded between 30th March and 28th May. Many of the peaks and troughs in the pressure data correspond to periods with changes in water input (rapid increases due to precipitation, for example) and are often reflected in changes in water discharge as measured subglacially or at the glacier tongue.

The pressure spikes on about 5th and 9th June are probably both related to peaks in the water discharge as measured in the water tunnel below Engabreen, which is an accurate measure of subglacial water flow on the whole. The discharge spikes themselves are rather low, three and five cubic metres per second respectively, but they represent several times greater than that in the preceding weeks, and signify the start of a well-developed subglacial drainage system for the year. High precipitation (about 35 mm in a day) and a quick response in the discharge measured (from below 20 cubic metres per second to 35 cubic metres per second), after several dry days with corresponding low discharge are probably the cause for the pressure spikes on about 20th August. Even heavier rain (almost 50 mm) and discharge levels on 31st July

seemed to have little effect on pressure. However, this was preceded by several days of rain and quite high discharge, so the day of heaviest rain will have caused little change in subglacial conditions.

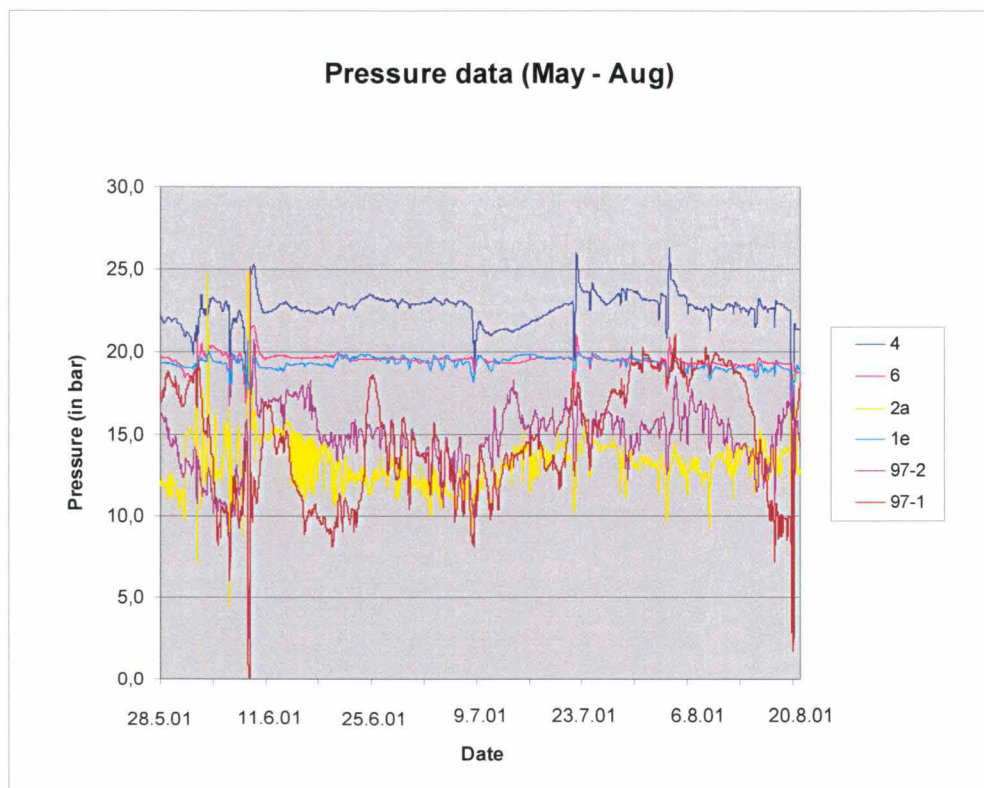


Figure 11-8
Data logger records for the period 28th May – 21st August.

Pressure sensor records for the late summer period, from 21st August until 24th September, are shown in Figure 11-9. The data for this period is relatively noisy, especially for the newer sensors, 97-1 and 97-2. The pressure spikes on about 27th August and 1st September, most obvious in the data from 97-1, correlate well with peaks in discharge. The first peak in subglacial discharge was very sharp and reached values of more than 50 cubic metres per second. The second was more gradual and reached only half the discharge, but seems to have had almost as dramatic an effect on the subglacial pressure.

Into September the data becomes 'quieter'. There are spikes in the pressure on about 20th September, related to a fairly sharp peak in subglacial discharge, but after this the discharge decreases to less than 10 cubic metres per second for the first time since June.

Data logger records for the period 24th September to 31st December are shown in Figure 11-10. The first 10 days of this record is rather puzzling. Most sensors show a gradual decrease in pressure, followed by a sharp trough about 1st October, followed by a sharp spike. The discharge records seem to show no correlation – a gradual decrease in discharge to three cubic metres per second by 1st October, followed by a fairly sharp peak of almost seven cubic metres per second on 3rd October. The sensors

97-1 and 97-2 lie fairly close together, so the sharp variations in pressure at these sensors may be explained by one or more clasts passing over the area, but the initial activity on 1st October is somewhat harder to explain.

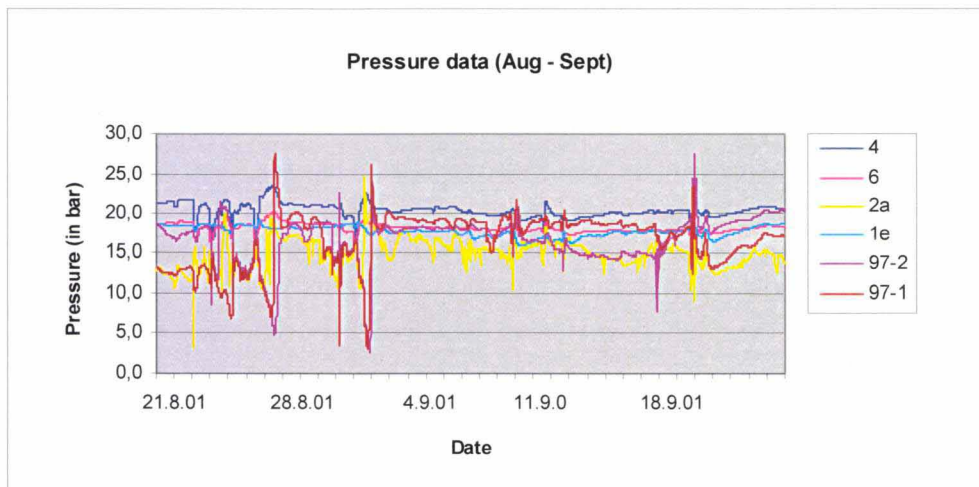


Figure 11-9
Data logger records for the period 21st August – 24th September.

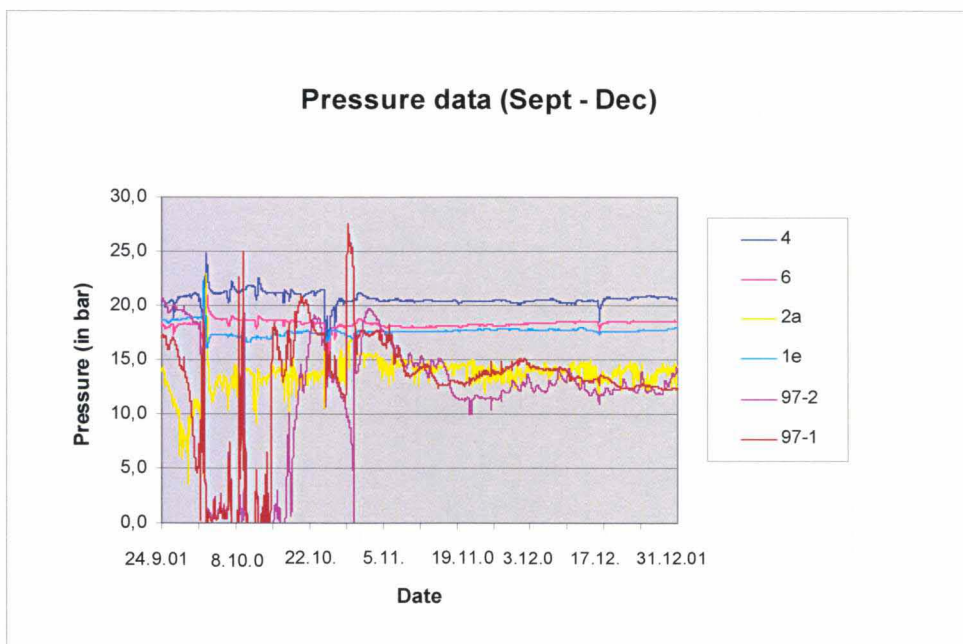


Figure 11-10
Data logger records for the period 24th September – 31st December.

The event on 29th October is interesting. The pressure sensors 97-1 and 97-2 showed very similar readings immediately preceding this, followed by a fairly sharp drop, then very sharp rise in pressure at 97-2, synchronised with a very sharp rise followed by a fairly sharp drop in pressure at 97-1. 97-1 is on the lee side of a bump, just downstream from 97-2. As this event is not seen at all in the other load cells, it may be that this was due to a large clast that passed over 97-1, sharply increasing the

pressure here, but relieving the pressure at 97-2. The pressure recorded throughout November and December shows relatively little variation. The event on 16th December recorded by all the load cells corresponds with a doubling in subglacial water flow to 0.6 cubic metres per second, as recorded in the subglacial tunnel.

Two major research projects took place in the subglacial laboratory in 2001. The first one involved a group of American researchers led by Neal Iverson of Iowa State University and Denis Cohen of Yale University, in collaboration with Urs Fischer of ETH in Zurich. Two experiments were performed. The first consisted of installing a smooth granite tablet flush with the bedrock surface so that the debris-charged basal ice slid across it. The shear traction on the tablet, total normal stress, water pressure at the tablet surface, and upward heat flux were measured. There were problems with some of the sensors, so the tablet was taken down again after only a few days.

In the other experiment, a trough was blasted in the rock bed and filled with ~ 2.5 tons of simulated till. Instruments recorded shear deformation (tilt meters), dilation and contraction, total normal stress, and pore-water pressure. Pore pressure was manipulated by feeding water to the base of the till with a high-pressure pump, operated from the rock tunnel below. The second project was led by Gaute Lappégard of the University of Oslo, who performed several high pressure pump experiments, and measured the resulting variation in pressure recorded at the load cells.

12. 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 km² and drains the western Svartisen ice cap to Lake Storglomvatnet (Fig. 12-1). Most of its area is located between 900 and 1300 m a.s.l. Three outlet glaciers calve into the lake. Mass balance measurements were carried out during the four years from 1985 to 1988, and started again in 2000.

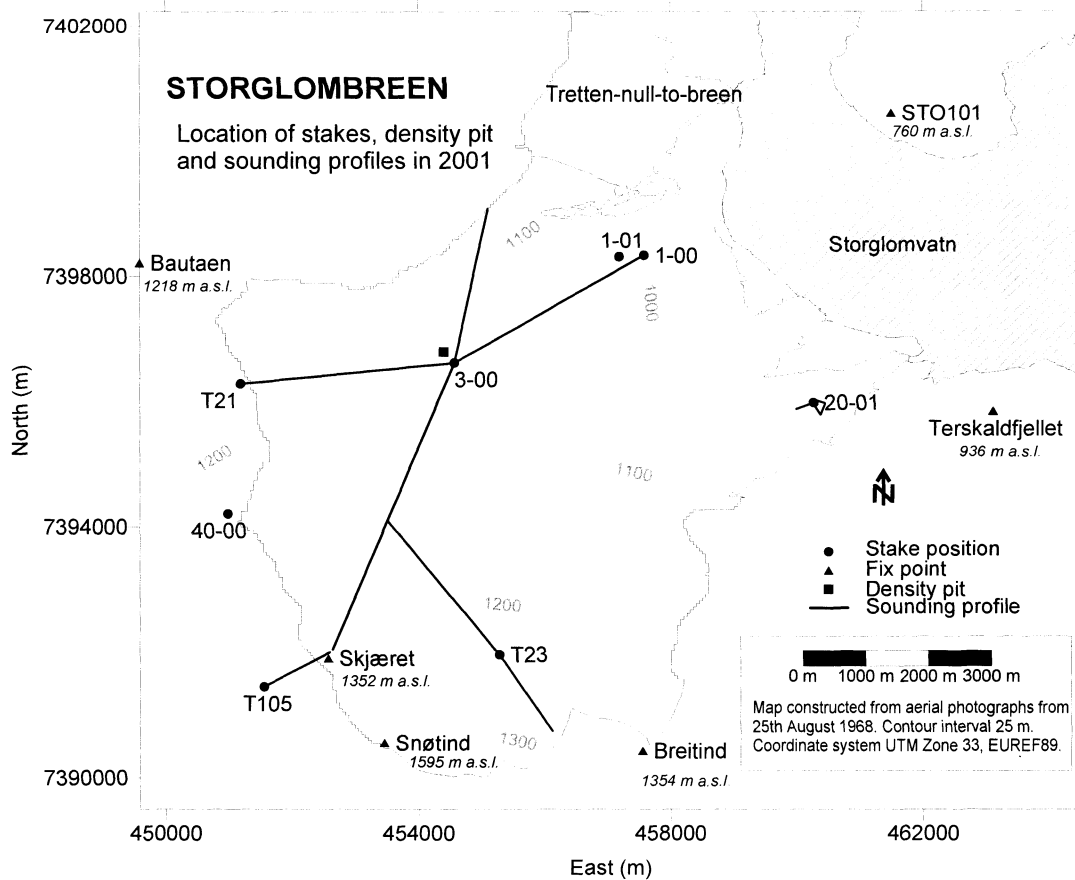


Figure 12-1
Location of stakes, density pit and sounding profiles at Storglombreen in 2001. To calculate the summer balance, three stakes on Engabreen positioned close to Storglombreen were also used.

Simplified observation network

Based on the extensive monitoring program from 1985-88, a simplified observation network for mass balance measurements has been established. Figure 12-2 shows a linear regression between mean water equivalent for all snow depths along the 1985-88 profiles (corresponding to the 2001 profiles in Fig.12-1), and specific winter balance for the entire glacier. A linear regression was performed between summer balance at stake 3 and specific summer balance for the entire glacier. The calculations were performed using a map from 1968 and drainage divides calculated from bottom topography and ice thickness (Kennett & Elvehøy, 1995).

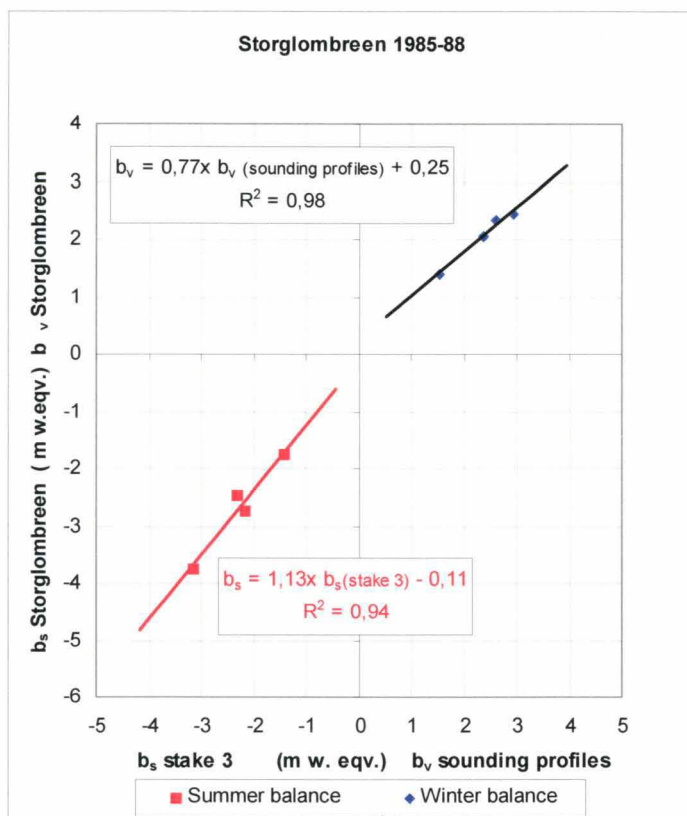


Figure 12-2
 In black: regression between winter balance calculated from balance maps (Y-axis) and selected snow depth profiles (X-axis).
 In red: regression between summer balance calculated from balance maps (Y-axis) and summer balance at stake 3 (X-axis). The summer balance values are without calving.

12.1 Mass balance 2001

The second half of September and most of October 2000 was unusually warm, and melting therefore continued after the ablation measurements. The ablation after 21st September 2000 was not included in the calculations of the mass balance for 2000, and was therefore included in the winter balance of 2001.

Fieldwork

By comparing snow depth soundings and stake readings in May 2001, the melting after the summer ablation measurements on 21st September 2000 could be estimated. At stakes 3-00 and T23, 0.7 m of snow had melted between 21st September and the start of snow accumulation in mid-October.

Winter accumulation measurements were carried out between 24th and 26th May. The location of stakes, density pit, core samples and sounding profiles are shown in Figure 12-1. The calculation of the winter balance was based on:

- Snow depth at stake 20-01, stake 1-00, stake 3-00 and stake T23, which was 0.75, 2.35, 3.30 and 3.10 m respectively. At stake T21, stake 40-00 and stake T105 on Engabreen, the snow depth was 3.40, 4.10 and 4.30 m respectively.
- Snow density measured to a depth of 3.3 m at stake 3-00. Mean snow density was 0.48 g/cm³.

- 88 snow depth soundings along approximately 18 km of profiles in the area located between 900 and 1300 m a.s.l. Most observations showed between 3 and 4 m of snow, and the summer surface was generally well defined.

Summer ablation measurements were carried out 24th September. At that time no fresh snow had fallen on the glacier. All the winter snow had melted away on the glacier with a possible exception of minor areas on the north slopes of Snøtind. The firn line was observed between 1000 and 1000 m a.s.l.

The net balance was observed at four positions, at 910, 1005, 1125 and 1235 m a.s.l. At stake 20-01 (910 m a.s.l.), 0.75 m of snow and 4.3 m of ice had melted away. At the three stakes on the plateau 3-3½ m of snow and 1-1½ m of firn had melted away. At the three stakes at Engabreen 3½-4 m of snow and 0.3-1.6 m of firn had melted away.

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 lowermost parts of the glacier, insignificant compared to winter accumulation and summer ablation, and normally hard to determine accurately. This was not the case in 2000.

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

The mass balance was also calculated using the regression equations established from the observation period 1985-1988 (Fig. 12-2).

Winter balance

The winter balance for 2001 was calculated as the sum of late autumn ablation calculated from comparison of stake measurements and soundings in May 2001, and snow accumulation calculated from soundings in May 2001.

The altitudinal distribution of the autumn melting was estimated based on the observations of ablation after 21st September 2000 at Storglombreen and the three stakes at Engabreen. The density of the winter snow was set to 0.6 g/cm³. From this distribution the total volume of ablation was calculated as 26 mill. m³ water or 0.4 m w.eqv.

The winter accumulation was calculated from point measurements of snow depth (stakes and soundings) and measurements of snow density at stake 3-00 (Fig. 12-1). 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 0.51 g/cm³. This model was used to convert all snow depth observations to water equivalent values.

The total winter accumulation was calculated from the altitudinal distribution of the snow accumulation. 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 to guide the curve below 900 m a.s.l. and above 1300 m a.s.l. Using this method the winter accumulation was calculated as 1.6 ± 0.2 m w.eqv., which corresponds to a volume of 100 ± 10 mill. m^3 of water. This is 75% of the 1985-88 mean (2.08 m w.eqv.).

The winter accumulation was also calculated using the regression equation defined in Figure 12-2. The mean water equivalent for 83 snow depth measurements along the profiles shown in Figure 12-1 was 1.66 m. This corresponds to a specific winter balance of 1.5 m, which is close to the result above.

The winter balance in each altitude interval was calculated as the sum of autumn ablation and snow accumulation. The specific winter balance was 1.2 ± 0.2 m w.eqv. or 72 ± 8 mill. m^3 water. The winter balance is shown in Figure 12-3 and Table 12-1.

Summer balance

The summer balance was measured and calculated directly at three positions on Storglombreen (20-01, 3-00 and T23) and three positions on Engabreen (T21, 40-00, and T105) located very close to the ice divide (Fig. 12-1). In addition, the summer balance at stake 1-01 was estimated from snow depth in May, melting between 22nd August and 24th September, and melting at stakes 20-01 and 3-00. The summer balance curve was drawn based on these seven point values with support of the mean balance curve for the period 1985-1988.

The contribution from calving and ice avalanches was estimated, as it was for the period 1985-1988. This contribution is estimated to -7 mill. m^3 water, based on an estimated 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, totaled -180 ± 20 mill. m^3 water, which is equal to a specific balance of -2.9 ± 0.3 m w.eqv. The mean summer balance for the period 1985-1988 was -2.8 m w.eqv.

The summer balance was also calculated with the regression equation shown in Figure 12-2. The summer balance at stake 3-00 was -2.36 m w.eqv., which corresponds to a specific summer balance excluding calving for Storglombreen of -2.8 m w.eqv., and -2.9 m w.eqv. with calving included, close to the result above.

Net balance

The net balance of Storglombreen for 2001 was -1.8 ± 0.4 m w.eqv., which corresponds to a mass loss of 110 ± 30 mill. m^3 water. The mean value for 1985-1989 was -0.75 m w.eqv. Since practically all of the winter snow melted away during the summer, the equilibrium line altitude (ELA) was undefined, and the accumulation area ratio (AAR) is 0%.

The mass balance results are shown in Table 12-1 and Figure 12-3. The results from 2001 are compared to mass balance results for the period 1985-1988 and 2000 in Figure 12-4.

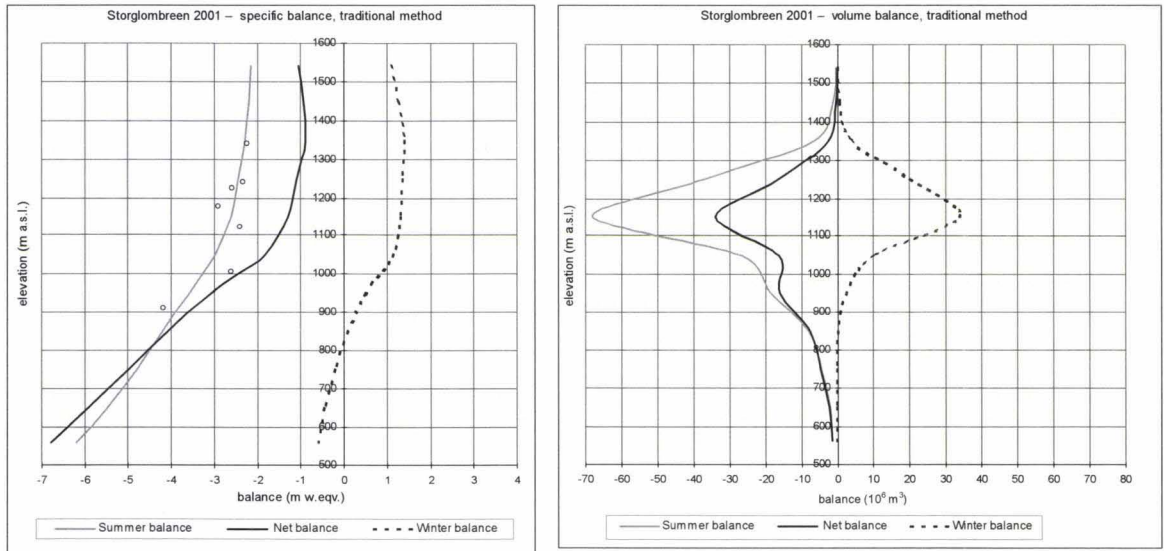


Figure 12-3
Winter-, summer and net balance for Storglombreen in 2001, showing specific balance (left) and volume balance (right). Summer balance at stakes is shown as circles (°).

Winter balance Storglombreen 2000/01 – traditional method							
Altitude (m a.s.l.)	Area (km ²)	Winter balance		Summer balance		Net balance	
		Measured 26 mai 2001		Measured 24 sep 2001		Summer surface 2000 - 2001	
		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	1,10	0,20	-2,15	-0,39	-1,05	-0,19
1400 - 1500	0,58	1,25	0,72	-2,20	-1,27	-0,95	-0,55
1300 - 1400	2,89	1,40	4,04	-2,30	-6,64	-0,90	-2,60
1200 - 1300	15,02	1,35	20,28	-2,45	-36,80	-1,10	-16,52
1100 - 1200	26,23	1,30	34,10	-2,60	-68,21	-1,30	-34,10
1000 - 1100	8,91	1,15	10,25	-3,00	-26,73	-1,85	-16,48
900 - 1000	5,16	0,50	2,58	-3,60	-18,59	-3,10	-16,01
800 - 900	1,91	0,10	0,19	-4,20	-8,01	-4,10	-7,82
700 - 800	0,95	-0,20	-0,19	-4,80	-4,55	-5,00	-4,74
600 - 700	0,38	-0,45	-0,17	-5,50	-2,08	-5,95	-2,25
520 - 600	0,22	-0,60	-0,13	-6,20	-1,39	-6,80	-1,52
Calving					-7,2		-7,2
520 - 1580	62,43	1,15	71,9	-2,91	-181,8	-1,76	-110,0

Table 12-1
Specific (left) and volume (right) winter, summer, and net balance calculated for 100 m elevation intervals at Storglombreen 2001.

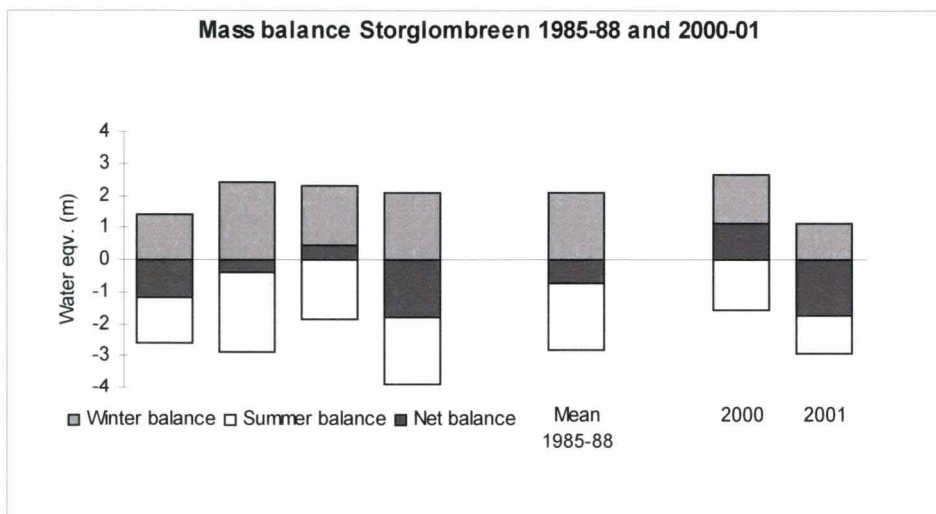


Figure 12-4
Mass balance at Storglombreen during the period 1985-1988 and 2000-01.

12.2 Front position change

Storglombreen has three distinct front segments that calve into the lake Storglomvatnet (Fig. 12-1). Observation of the front position changes began in autumn 2000, and will be continued in order to document changes associated with changes in the water level of the reservoir. The front of the calving outlet from glacier Tretten-null-to-breen is observed also (Fig. 12-1). One part of the glacier terminus is shown in figure 12-5, which illustrates that avalanching is a primary ablation process along the glacier terminus.



Figure 12-5
The southern part of the northern outlet of Storglombreen on 9th October 2001. The lake level in Storglomvatnet was 579 m a.s.l., 6 metres below highest regulated lake level (HRV). There is bedrock visible between the glacier and the lake. The vertical ice cliff is 10 to 20 metres high. Photo: Hallgeir Elvehøy

12.3 Glacier velocity

The mass balance stake network has been positioned repeatedly since May 2000 using precision dGPS to calculate horizontal and vertical velocities. The fix point at Bautaen has been used as a fix point. Stakes were positioned on 27th May and 21st September 2000, and on 27th May, 22nd August and 24th September 2001.

The velocities show a little variation during the year. These variations will be further analysed later when more data is available. In Figure 12-6 horizontal annual mean velocities are presented.

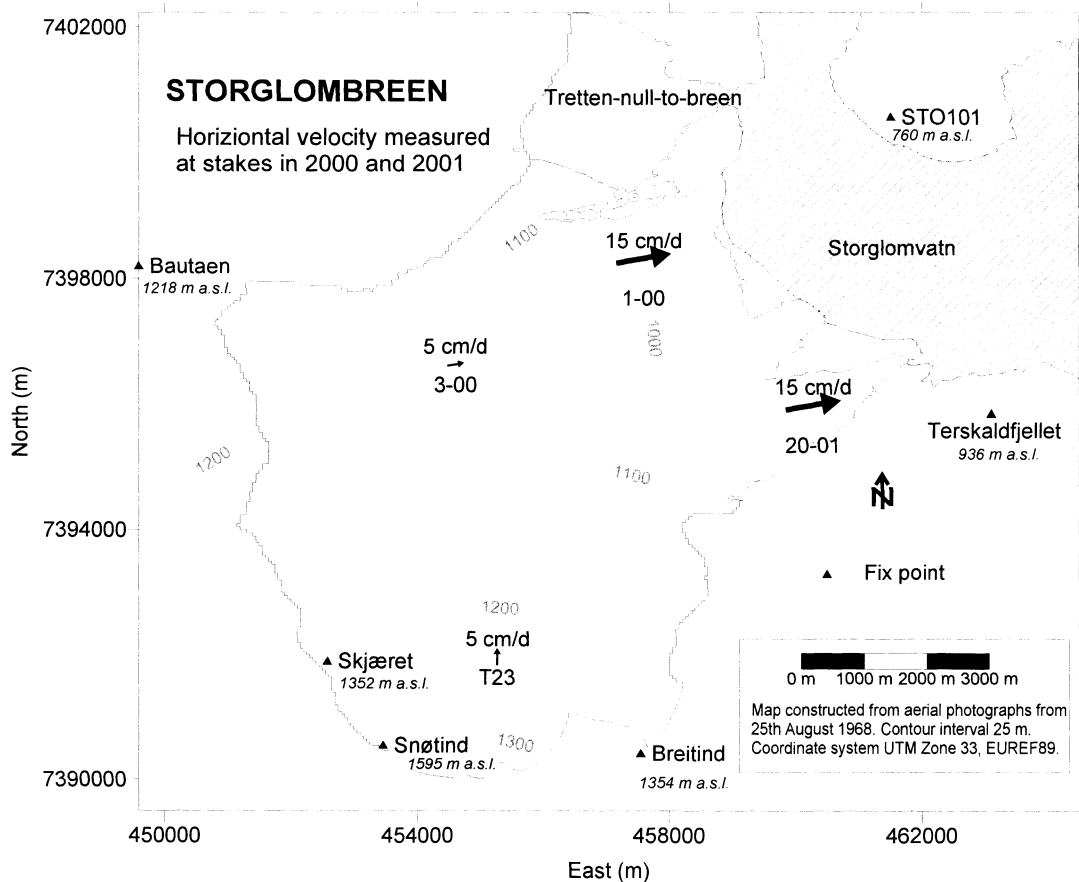


Figure 12-6
Glacier velocity measured at stakes in 2000 and 2001.

13. Blámannsisen (Rune V. Engeset)

In September 2001 a large amount of water that was previously dammed by a glacier arm of Blámannsisen (67°20'N, 16°05'E) flowed under the glacier into the Sisovatn reservoir (Figure 13-1). Altogether about 40 million cubic metres that previously drained to Sweden now drains to a hydropower plant at Siso. This is the first jökulhlaup (outburst from a glacier-dammed lake) recorded here. The jökulhlaup is a direct consequence of climate change that has caused the glacier to thin until it no longer functions effectively as a dam.

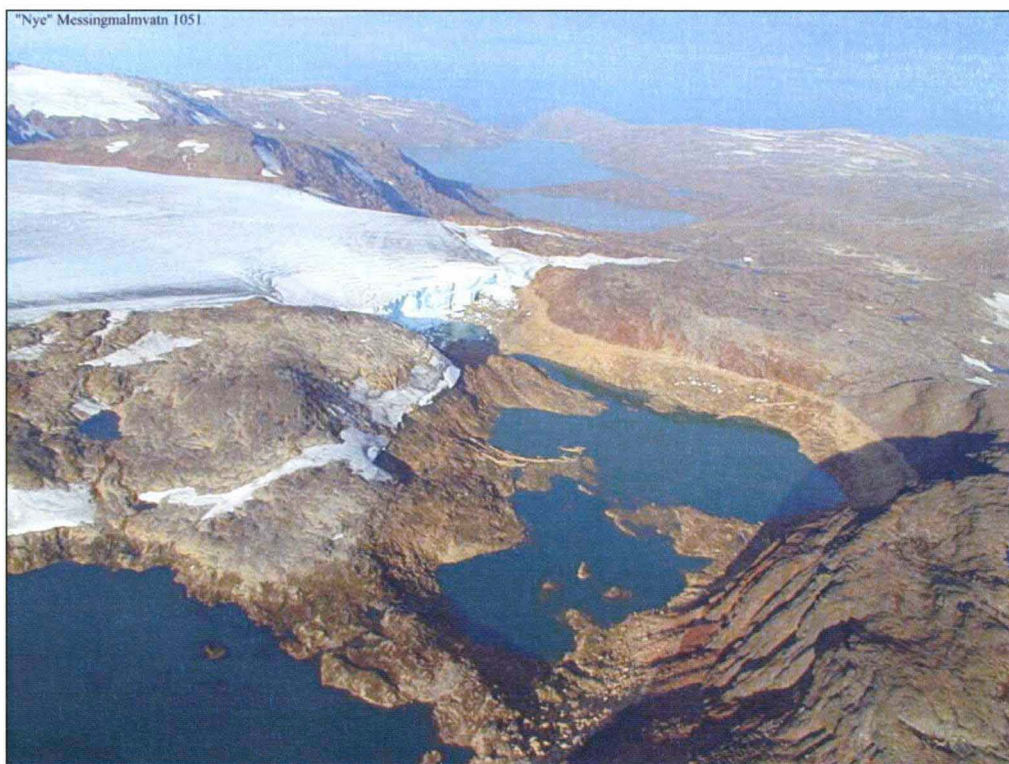


Figure 13-1
Photo of the drained lake at Blámannsisen. The water drained under the glacier (figure centre) and down to Sisovatn (uppermost part of figure). The shoreline clearly shows the previous water level, from when the glacier drained over a rock threshold at 1051 m a.s.l. towards Sweden. Photo Hans Martin Hjemaas, Elkem ASA.

13.1 Jökulhlaup in 2001

Personnel at Elkems Siso hydropower station (see map in Figure 13-2) noted on September 5th 2001 that the water level in the Sisovatn reservoir had increased rapidly for unknown reasons. Over the next two days the water level increased 2.5 m, giving an unexpected addition of about 40 million m³ in a reservoir with a capacity of about 500 million m³. Inflow increased from a normal level of about 3-4 million m³ per day to 9.3, 17.5 and 19.7 million m³ on September 5th, 6th and 7th respectively.

In 1990 NVE had warned of the danger of a jökulhlaup in the area if the glacier decreased, based on ice thickness measurements with radar (Kennett, 1990).

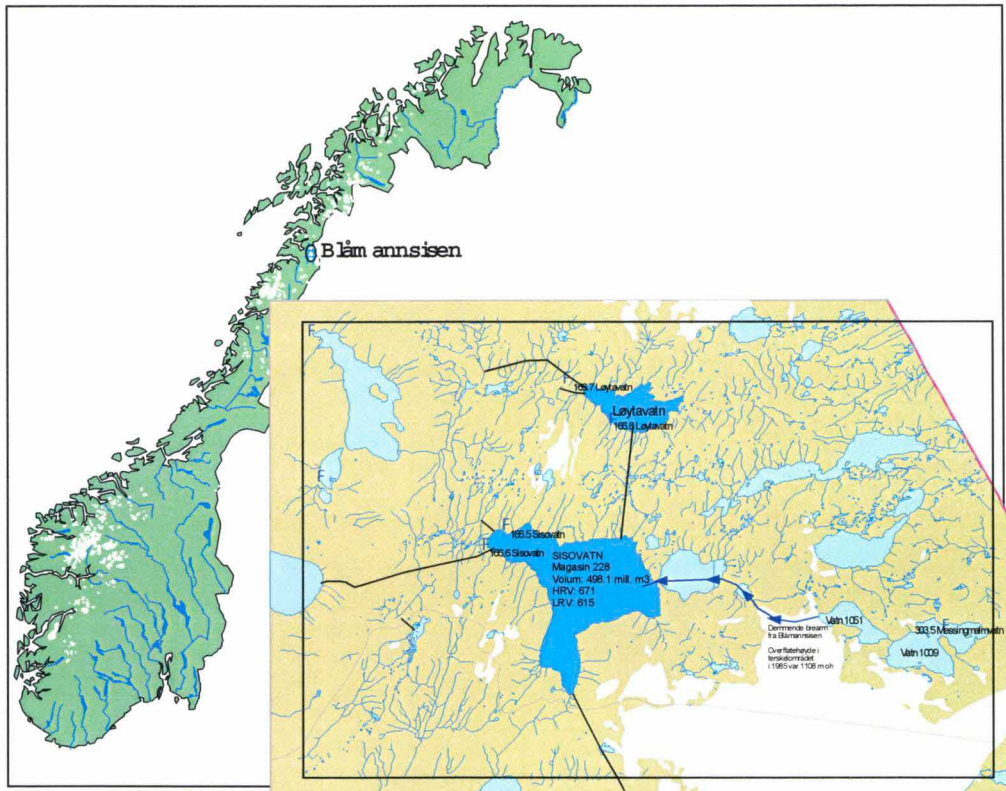


Figure 13-2
Map of area.

Elkem ASA inspected the area by helicopter on September 18th and confirmed our theory that the jökulhlaup was due to draining of upper Messingmalmvatn (called Vatn 1051 in this text). The drainage route is shown in Figure 13-3. The approximately 1.5 km² Vatn 1051 was previously dammed by a northwest-draining outlet glacier from Blåmannsisen, which at 87 km² is Norway's fifth largest glacier.

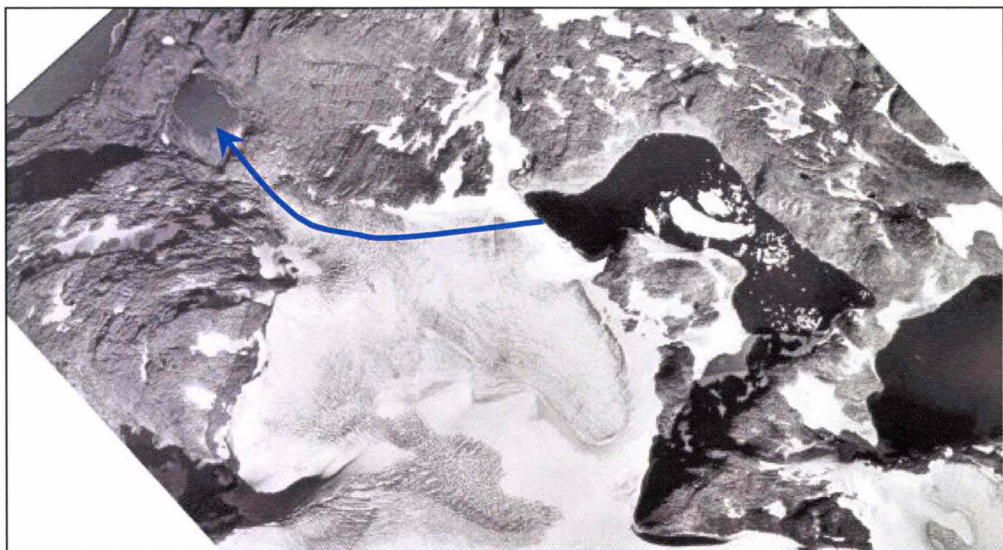


Figure 13-3
Aerial photograph of drainage area taken on 1 September 1998. The arrow shows the drainage path under the glacier. Photo Fjellanger Widerøe AS.

Before the jökulhlaup the glacier blocked drainage westward, and the lake drained through an outlet eastward towards Sweden. After the lake emptied, three basins with a little water in each remained. The shoreline showing the water level before the jökulhlaup is clearly visible. Based on GPS measurements it is estimated that the water level sank about 60 m.

The outburst formed a 4.5 km long tunnel under the glacier ice, which is up to 200 m thick. Both the tunnel entrance and exit are shown in Figure 13-4. We assume that the water pressure lifted up the ice draining down towards Vatn 1051. When the water eventually managed to seep under the ice, a tunnel was quickly formed due to frictional heating. Investigations under the 150-200 m thick ice of Engabreen (Svartisen) and Bondhusbreen (Folgefonna) have shown that such tunnels close at a rate of 10-15 cm per day. The tunnel walls close because the ice deforms under the weight of the overlying ice.



Figure 13-4
The water outburst formed a tunnel under the ice. The tunnel entrance is shown to the left, the exit to the right. Photo Hans Martin Hjemaas, Elkem ASA.

The jökulhlaup phenomenon

A large amount of water was released from Vatn 1051 over a short period of time, as is typical for Norwegian jökulhlaups (Fig. 13-5). Other known jökulhlaups in Norway include several drainings of Demmevatn by Hardangerjøkulen, Brimkjelen on Jostedalbreen, Øvre Mjølkedalsvatn in Jotunheimen, the ice-dammed lake by Harbardsbreen, Skadevatn by Vetledalsbreen, the lake by Østerdalsisen (Svartisen), and the ice-dammed lake by Strupbreen in Lyngen. For more details of these events, see Liestøl (1956), Elvehøy et al. (1997), and Kjöllmoen (2000).

The volume of water registered from Blåmannsisen for this event is of the same order as from the catastrophic jökulhlaup from Demmevatn that flowed down Simadalen in 1893 and caused large material losses. This shows that watercourse regulation, such as is the case with the Sisovatn reservoir, often protects the local population and community from the damages that such floods can cause.

Jökulhlaups occur often and cause a lot of damage in Iceland. A volcanic eruption under Vatnajökull in October 1996 (Gudmundsson et al., 1997) caused rapid melting and produced a large quantity of water (estimated to be 3.2 km³) in Grimsvötn. This

resulted in an extreme jökulhlaup with a water discharge of up to 50.000 m³/s in November of the same year.



Figure 13-5
Vatn 1051 almost totally drained. The picture on the left shows the approximately 80 m high ice dam which burst, while that on the right shows the bottom of the lake. Photo Hans-Martin Hjemaas.

A result of climate change

Previous ice thickness measurements from 1990 and a map of the glacier surface from 1985 indicated that if the ice surface (which had an elevation of 1108 m a.s.l. in 1985) decreased about 30 m in elevation, the glacier ice would no longer be able to dam the lake (Kennett, 1990). Despite the fact that we have no recent measurements of the height of the glacier surface or the glacier's mass balance, it is reasonable to assume that the jökulhlaup was caused by a decrease in ice thickness near the rock threshold. Such a change is due to a negative mass balance over a period of time, that is, that winter precipitation has not compensated for the melting of snow and ice during summer. This phenomenon is a consequence of climate change in this area.

In order to be better prepared for natural catastrophes related to glaciers, NVE is presently participating in a large EU-financed research project called GLACIORISK. Through this project we attempt to develop tools that can be used to detect, monitor and prevent future disasters caused by glaciers. The project is in co-operation with the Geophysical Institute at the University of Oslo, as well as research institutions in France, Italy, Austria, Switzerland and Iceland.

There are several exciting questions connected to this jökulhlaup. This is a clear signal of the climate changes to which we are now exposed. But, will such a water outburst be repeated, and in which case, how often can it be expected to occur? How large an outburst will new changes in the glacier entail? How quickly will Vatn 1051 refill with water? How quickly will the tunnel under the glacier close again? How large are the changes in input and input area to the Sisovatn reservoir? Our aim is to study several of these questions in order to better understand the mechanisms behind and the consequences of such unusual natural phenomena.

Elkem ASA commissioned NVE to study the event, and to assess possible new jökulhlaups from the lake. This study was started in autumn 2001 and will continue throughout 2002.

14. Langfjordjøkelen (Bjarne Kjøllmoen)

Langfjordjøkelen (70°10'N, 21°45'E) is a plateau glacier situated on the border of Troms and Finnmark counties, approx. 60 km northwest of Alta. It has an area of about 8.4 km² (1994), and of this 3.7 km² drains eastward to the lake Andrevann (Fig. 14-1). The investigations are performed on this east facing part, ranging from 280 to 1050 m a.s.l.

The glaciological investigations in 2001 include mass balance, change in front position and air temperature measurements. Langfjordjøkelen has been the subject of mass balance measurements since 1989 with the exception of 1994 and 1995. The winter and summer balances for these two years are estimated based on meteorological observations (Kjøllmoen 2002). The net balance during the period 1966-1994 is modelled and compared with earlier map studies (Kjøllmoen 1999).



Figure 14-1

The mass balance measurements are performed at the east-facing outlet (3.7 km²), which drains to Andrevann lake (255 m a.s.l.). A station for air temperature measuring is located between the glacier terminus and the inlet of Andrevann. Photo by Fotonor AS 1994 (Contract No. 94168).

14.1 Mass balance 2001

Fieldwork

Snow accumulation was measured on 6th June and the calculation of winter balance is based on (Fig. 14-2):

- Direct measurements of stakes in position 10 (480 m a.s.l.), 20 (670 m a.s.l.), 25 (745 m a.s.l.) and 30 (900 m a.s.l.) showing snow depths of 1.5, 2.4, 2.8, and 2.6 m. Soundings beside the stakes indicated some ablation *after* the final measurements in October 2000, amounting to 0.3 m ice at 480 m altitude, 0.2 m ice at 670 m altitude and 0.1 m ice at 745 m altitude.
- 74 snow depth soundings along about 11 km of profiles between 320 and 1050 m a.s.l. The summer surface was distinct up to 900 m altitude and more ambiguous in the areas between 900 and 1050 m a.s.l. The snow depth increased from about 1 m at the tongue to about 3½ m in the upper parts of the glacier.
- Snow density was measured down to 2.5 m depth (SS at 2.6 m) at 900 m altitude.

Location of stakes, density pit and sounding profiles are shown in Figure 14-2.

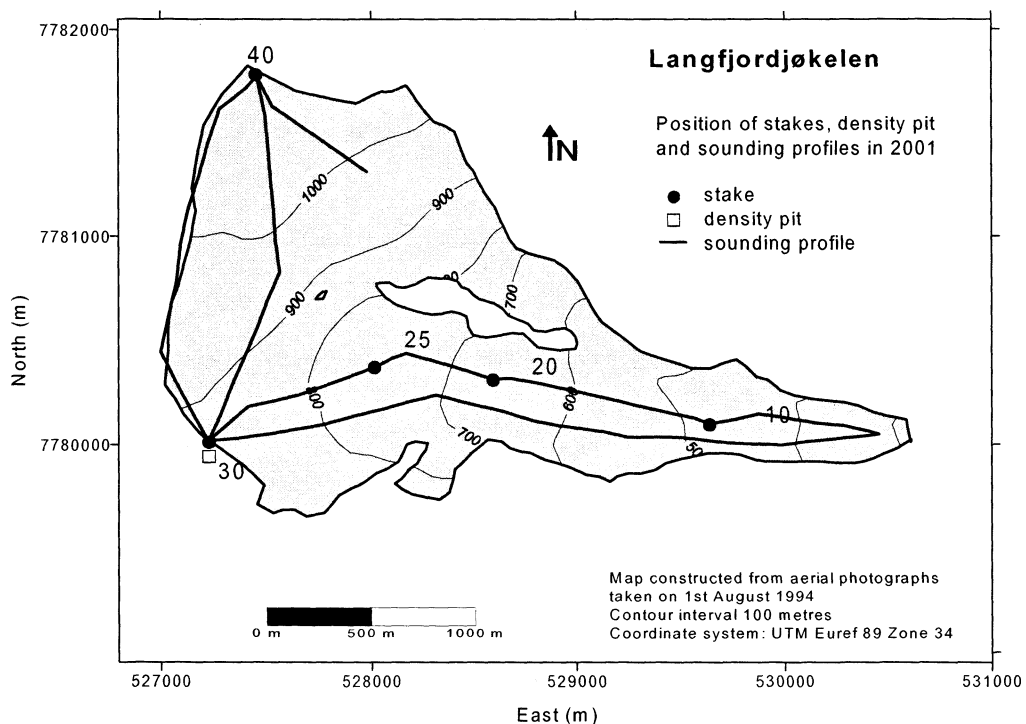


Figure 14-2
Locations of stakes, sounding profiles and density pit at Langfjordjøkelen in 2001.

Ablation was measured on 7th October. The net balance was measured directly at stakes in all five locations between 480 and 1050 m a.s.l. There was no snow remaining on the glacier from the winter 2000/2001. Between 45 and 70 cm 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 and probings) and on one snow density measurement.

The ablation registered *after* the final measurements in October 2000 was counted as a negative contribution to the winter balance 2000/2001 as described in chapter 1. This negative winter balance was measured and calculated as 0.1 m w.eqv.

A density profile was modelled from the snow density measurement at 900 m altitude. The mean density of 2.6 m snow was 0.49 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 a visual evaluation (Fig. 14-4) and a mean value for each 100 m height interval estimated (Tab. 14-1).

The winter *balance*, hence, was calculated as $1.4 \pm 0.2 \text{ m w.eqv.}$, corresponding to a water volume of $5 \pm 1 \text{ mill. m}^3$. The result is 59 % of the mean value for the periods 1989-1993 and 1996-2000. This is the second lowest winter balance measured since the measurements started in 1989 (1.3 m in 1999). Excluding the additional ablation *after* the final measurements in October 2000, the winter *accumulation* was 1.5 m w.eqv.

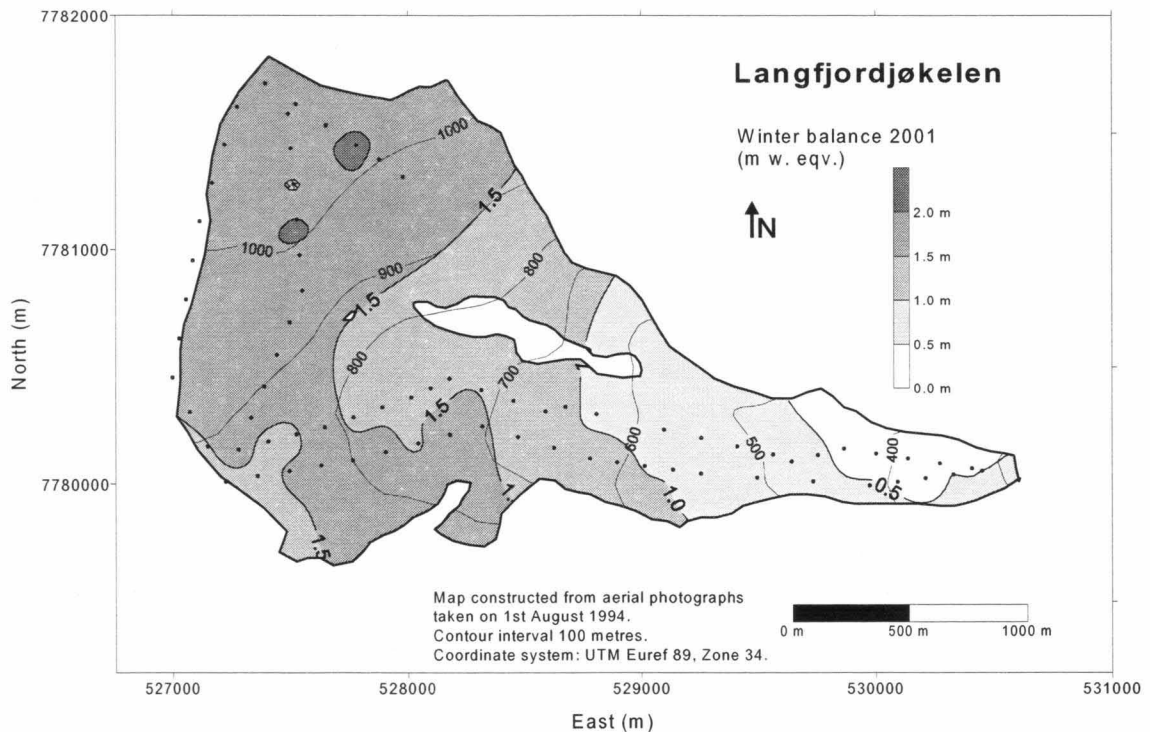


Figure 14-3
Winter balance at Langfjordjøkelen in 2001 interpolated from 74 snow depth measurements (-).

The winter balance was also calculated using a gridding method based on the aerial distribution of the snow depth measurements (Fig. 14-3). 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 1.4 m w.eqv.

Summer balance

The density of melted firn was estimated between 0.70 and 0.80 g/cm³, while the density of melted ice was estimated as 0.90 g/cm³.

The summer balance was measured and calculated at 4 stakes, and increased from -3.3 m w.eqv. at 900 m altitude to -4.6 m down on the tongue (480 m a.s.l.). Based on estimated density and stake measurements, the summer balance was calculated to be -3.6 ± 0.3 m w.eqv., which is -13 ± 1 mill. m³ of water. The result is 130 % of the average for the periods 1989-1993 and 1996-2000. This is the greatest summer loss since 1989.

Net balance

Hence, the net balance at Langfjordjøkelen for 2001 was -2.3 ± 0.4 m w.eqv., which equals a volume loss of 8 ± 1 mill. m³ of water (Tab. 14-1). The result is the greatest deficit measured at Langfjordjøkelen since 1989. Figure 14-4 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 %.

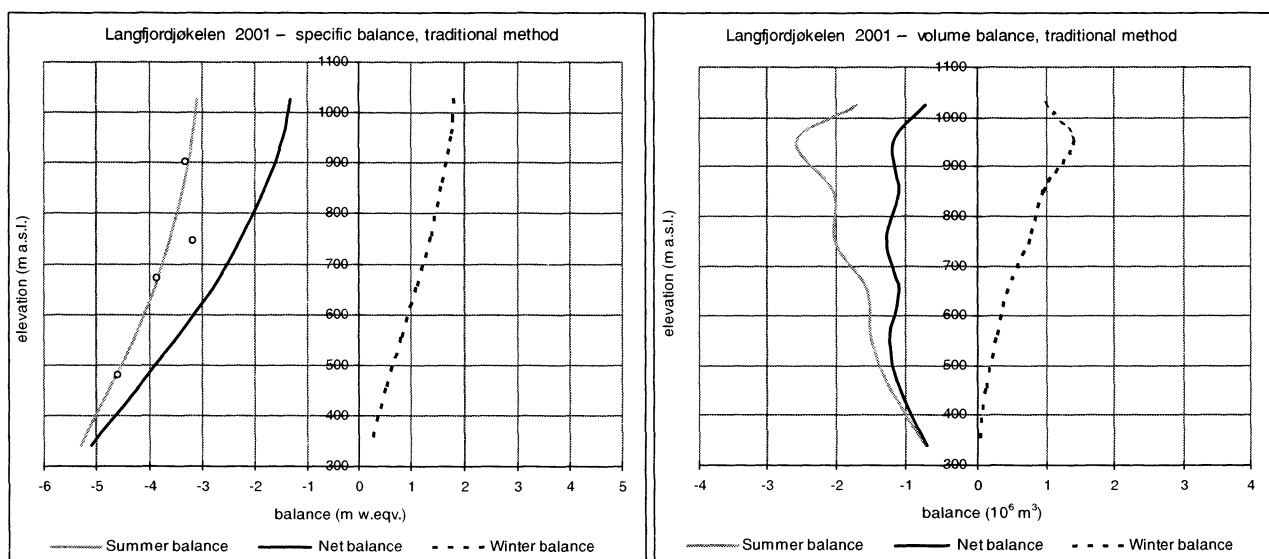


Figure 14-4
Mass balance diagram showing specific balance (left) and volume balance (right) for Langfjordjøkelen in 2001. Summer balance at 4 stakes is shown (•).

Mass balance Langfjordjøkelen 2000/01 – traditional method							
Altitude (m a.s.l.)	Area (km ²)	Winter balance		Summer balance		Net balance	
		Measured 6rd June 2001		Measured 7th Oct 2001		Summer surface 2000 - 2001	
		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	1,80	1,0	-3,10	-1,7	-1,30	-0,7
900 - 1000	0,81	1,75	1,4	-3,20	-2,6	-1,45	-1,2
800 - 900	0,61	1,55	0,9	-3,35	-2,0	-1,80	-1,1
700 - 800	0,56	1,35	0,8	-3,60	-2,0	-2,25	-1,3
600 - 700	0,39	1,10	0,4	-3,90	-1,5	-2,80	-1,1
500 - 600	0,35	0,80	0,3	-4,30	-1,5	-3,50	-1,2
400 - 500	0,25	0,50	0,1	-4,75	-1,2	-4,25	-1,1
280 - 400	0,14	0,20	0,0	-5,30	-0,7	-5,10	-0,7
280 - 1050	3,65	1,36	5,0	-3,64	-13,3	-2,28	-8,3

Table 14-1

Winter, summer and net balance for Langfjordjøkelen in 2001. Mean values for the period 1989-2000 (modelled values for 1994 and 1995 included) are $b_w=2,29$ m, $b_s=-2,73$ m and $b_n=-0,44$ m w.eqv.

14.2 Mass balance 1994 and 1995

In 1994 and 1995 mass balance measurements were not performed at Langfjordjøkelen. Winter and summer balance is estimated in Kjølmoen 1999. The data input and method of calculation used in this estimation is considered faulty. Thus, another estimation based on meteorological data has been carried out (Kjølmoen 2002).

The meteorological method is called the PT-model. Accumulated snow during the winter season and ablation of snow and ice during the summer season is modelled using air temperature and precipitation as data input.

Air temperature data from Weather station No. 9235 (The Norwegian Meteorological Institute, DNMI) and Langfjordjøkelen station No. 211.4 (NVE) is employed in the model. Precipitation data comes from Weather station No. 9270 (DNMI).

The PT-model is calibrated to the mass balance measured at Langfjordjøkelen during the periods 1989-1993 and 1996-1998.

The winter, summer and net balance results for 1994 and 1995 are shown in Table 14-2.

Year	b_w	b_s	b_n	Σb_n	B_w	B_s	B_n
	Specific balance (m w.eqv.)				Volume balance ($10^6 m^3$)		
1989	2.40	-2.96	-0.56	-0.56	8.8	-10.8	-2.0
1990	2.74	-3.06	-0.32	-0.88	10.0	-11.2	-1.2
1991	2.31	-2.31	0.00	-0.88	8.5	-8.5	0.0
1992	2.68	-2.49	0.19	-0.69	9.8	-9.1	0.7
1993	2.55	-2.35	0.20	-0.49	9.3	-8.6	0.7
1994	1.9	-2.6	-0.7	-1.22	6.9	-9.5	-2.6
1995	2.3	-2.1	0.2	-0.97	8.4	-7.7	0.7
1996	2.25	-2.23	0.02	-0.95	8.2	-8.1	0.1
1997	2.65	-3.34	-0.69	-1.64	9.7	-12.2	-2.5
1998	1.80	-3.24	-1.44	-3.08	6.6	-11.8	-5.3
1999	1.33	-2.91	-1.58	-4.66	4.9	-10.6	-5.7
2000	2.51	-3.12	-0.61	-5.27	9.2	-11.4	-2.2
2001	1.36	-3.64	-2.28	-7.55	5.0	-13.3	-8.3
Mean 1989-2001	2.22	-2.80	-0.58		8.1	-10.2	-2.1

Table 14-2
Winter, summer and net balance for Langfjordjøkelen during the period 1989-2001 including the new modelled values for 1994 and 1995.

Since the mass balance measurements started in 1989 there have been 2 years with a non-significant positive net balance (0.2 m w.eqv. in 1992 and 1993). The glacier was almost in balance during 2 separate years (1991 and 1996), whereas a negative balance occurred in 7 separate years. The modelled net balance results for the years 1994 and 1995 are -0.7 and +0.2 m w.eqv. The mean net balance for the period 1989-2001 (modelled values included) is -0.58 m w.eqv. The accumulated negative net balance since 1989 is 7.6 m w.eqv. (28 mill. m^3 of water). Most of the deficit has occurred after 1996 (Fig. 14-5).

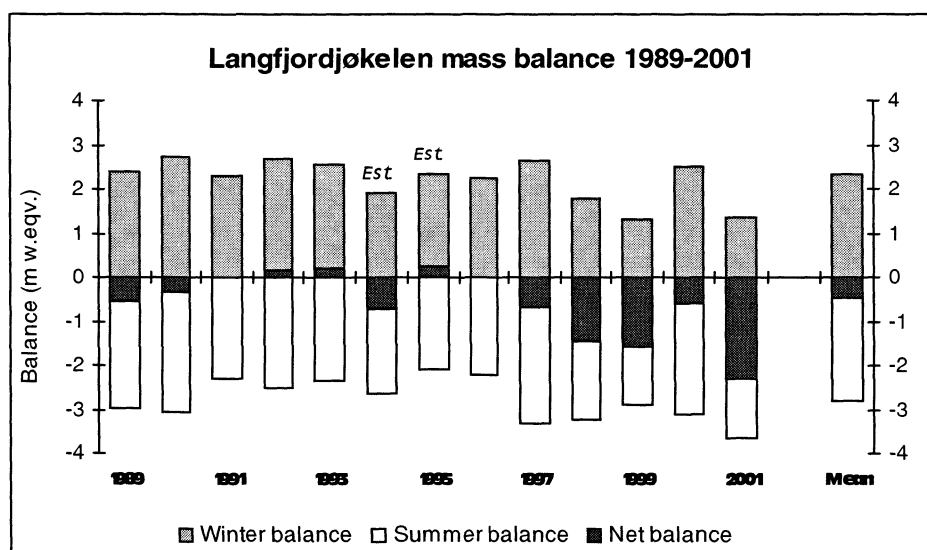


Figure 14-5
Mass balance at Langfjordjøkelen during the period 1989-2001. The accumulated deficit amounts to 7.6 m water equivalents. The values for 1994 and 1995 are modelled.

14.3 Mass balance 1966-1994

Map studies

Map studies of Langfjordjøkelen with a view to volume changes are presented in Kjølmoen 1999. By using Digital Terrain Models (DTM) the volume change during the period 1966-1994 was estimated to a deficit of 83 mill. m³ or about 20 m water equivalents.

PT-model

The mass balance results derived from the DTMs are verified by using the meteorological method (Kjølmoen 2002). The PT-model, data input (temperature and precipitation) and calibration data is the same as used in chapter 14-2.

The net balance during the period 1966-1994 was calculated as -19.7 m water equivalents.

Accordingly, the net balance for 1966-1994 achieved by the PT-model is equal to the result derived from the DTMs.

14.4 Front position change

Annual measurements of the change in front position were initiated in 1998. The measurements are performed using traditional methods. The distance from the glacier terminus to marked fix points is measured using measuring tape. To achieve comparable results the measurements are always performed in the autumn.

Due to fresh snow the front position could not be measured during the fieldwork in October 2001. However, measurements from October 2000 and August 2001 show a retreat in front position of 23 metres. The accumulated recession since July 1998 is 93 metres.

14.5 Air temperature

A station for automatically recording air temperature was initiated in August 1997. The recording station (No. 211.4, 270 m a.s.l.) is located by the glacier stream between the glacier terminus and Andrevann (Fig. 14-1).

Due to technical problems the measuring results for the period 1997 to the end of October 1999 are probably faulty. However, the results for 2000 and 2001 can be observed as correct.

Table 14-3 show daily mean temperatures for the “summer seasons” 2000 and 2001. The summer season is defined as the period between 1st June and 30th September. The values at Langfjordjøkelen are compared with measurings from Nordstraum Weather station (No. 9235) in Kvænangen (ca. 35 km south of Langfjordjøkelen), operated by the Norwegian Meteorological Institute (DNMI).

Daily mean values 1 st June - 30 th September ("Summer season")			
Year	Langfjordjøkelen (°C)	Nordstraum (°C)	Lapse rate La./No. (°C/100 m)
2000	^{*)} 7,4	10,3	1,09
2001	8,3	11,1	1,03
Mean 2000-2001	7,9	10,7	1,06
Mean 1966-2000	-	10,1	-

^{*)} Data is extrapolated from 1st June to 12th July 2000.

Table 14-3

Mean air temperature at Langfjordjøkelen (ca. 275 m a.s.l.) and the Weather station Nordstraum (6 m a.s.l.) in the "Summer season" (1st June – 30th September) for the years 2000 and 2001. Mean values for 2000 and 2001 are shown for both stations and the average for 1966-2000 is shown for Nordstraum.

15. Glacier monitoring (Liss Marie Andreassen and Miriam Jackson)

15.1 Front position change

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

In 2001 front position change was measured at 24 glaciers, 21 in southern Norway and 3 in northern Norway (Fig. 15-1).

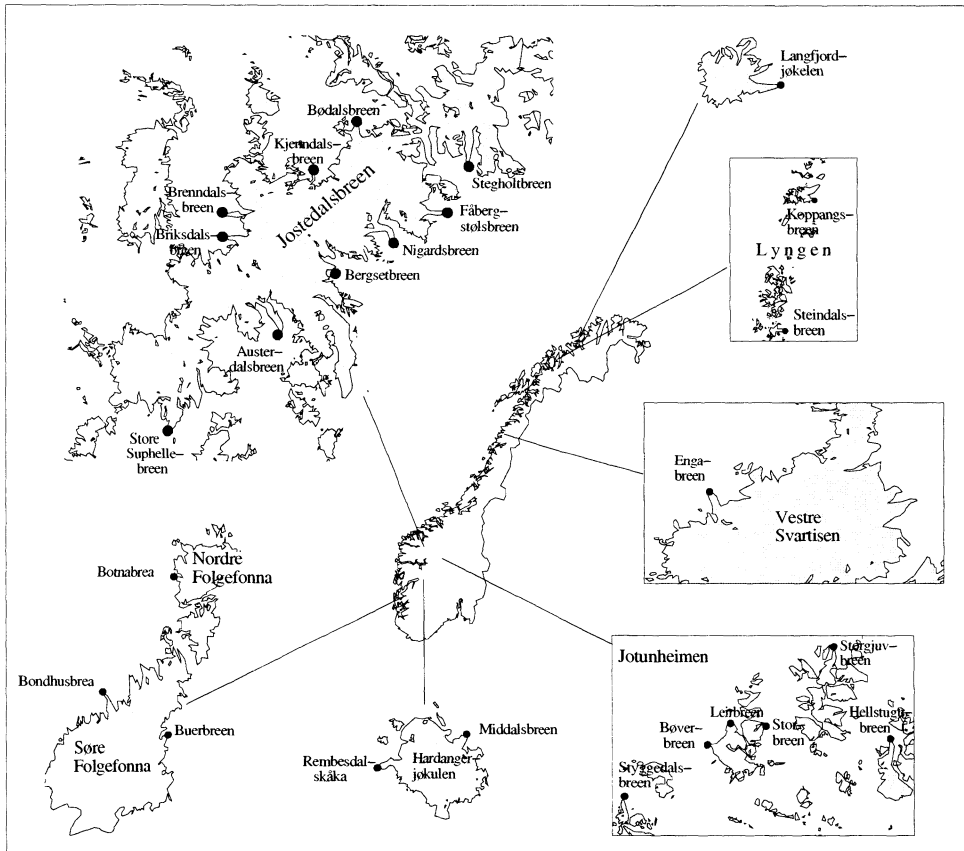


Figure 15-1
Location map showing glaciers where front position measurements were performed in 2001. Steindalsbreen in Lyngen was not observed in 2001. Notice that the different glacier areas are not to scale.

Methods

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

Results

The front position changes from autumn 2000 to autumn 2001 at the observed glaciers are shown in Table 15-1. Only at one glacier, Storgjuvbreen in Jotunheimen, was a noticeable net advance (defined as more than 2 m) registered in the observation period. Storgjuvbreen had a positive net change of 5 m. By contrast, in the previous period of 1999-2000, noticeable positive changes were observed at 11 of 24 glaciers (46 %).

Minor or no changes (between -2 and +2 m) were observed at 5 of the glaciers, while the remaining 18 glaciers (75 %) had a noticeable negative change in this period. 11 of the glaciers showed a net retreat in front position amounting to more than 10 m. The largest retreats were found at Kjenndalsbreen and Rembesdalskåka, -48 m and -46 m respectively.

All of the 3 observed glaciers in northern Norway showed a pronounced retreat in front position. In southern Norway, the main trend is glacier retreat. However, the continental area of Jotunheimen is an exception, with a noticeable positive change observed at one glacier and only minor changes otherwise.

Area	Glacier	Change (m)	Measured by
Jostedalsbreen	Austerdalsbreen	-20	NVE
	Bergsetbreen	-13	NVE
	Brenndalsbreen	-17	Universitet Trier, Germany
	Briksdalsbreen	1	NVE
	Bødalsbreen	-9	Universitet Trier, Germany
	Fåbergstølsbreen	-20	NVE
	Kjenndalsbreen	-48	Universitet Trier, Germany
	Nigardsbreen	-4	NVE
	Stegholtbreen	-15	NVE
	Store Supphellebre	-9	Norwegian Glacier Museum
Folgefonna	Buerbreen	-6	NVE
	Bondhusbrea	-9	Statkraft SF
	Botnabrea	0	Statkraft SF
Hardangerjøkulen	Midtdalsbreen	1	University of Bergen
	Rembesdalskåka	-46	Statkraft SF
Jotunheimen	Bøverbreen	2	Universitet Trier, Germany
	Hellstugubreen	-4	NVE
	Leirbreen	-7	NVE
	Storbreen	-12	NVE
	Storgjuvbreen	5	Universitet Trier, Germany
	Styggedalsbreen	2	NVE
Svartisen	Engabreen	-25	NVE
Lyngen	Koppangsbreen	-12	NVE
Finmark	Langfjordjøkelen	-25	NVE

Table 15-1
Net front position change between autumn 2000 and autumn 2001 at 24 glaciers in Norway. See Figure 15-1 for location.

15.2 Monitoring of Baklibreen

An ice fall occurred from the glacier Baklibreen ($61^{\circ}40'N$, $7^{\circ}05'E$), an outlet glacier from Jostedalsbreen, in the summer of 1986. The glacier area was calculated as 3.05 km^2 in 1984, and it covers an elevation range from 1950 m a.s.l. to about 1200 m a.s.l. The icefall occurred in Krundalen, a side valley of Jostedal. 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^2 , have fallen from a height of 600-700 m, and to have had a total volume of $200\,000 \text{ m}^3$. 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 Glaciorisk project.

The footpath on which the tourists were killed is now inaccessible due to the recent advance of neighbouring glacier Bergsetbreen (see Fig. 15-2). The glacier front of Bergsetbreen advanced 360 m between 1984 and 1997 (Sorteberg, 1998), so Baklibreen is not such an immediate threat as it was. However, the glacier front retreated slightly (6 m) between 1997 and 2001, so Baklibreen could become hazardous again before long. Over the same period, 1984 to 1997, Baklibreens glacier front advanced 350 m (Sorteberg, 1998).



Figure 15-2.
Bergsetbreen in October 2001 with Baklibreen in the upper valley to the right.
Photo: Miriam Jackson.

Aerial photography and stake measurements were used to study Baklibreen. A comparison of aerial photographs from 1964 and 1984 show that ice thickness decreased significantly over most of the glacier over this period. A terrain model made from the 1984 aerial photographs was compared with glacier surface measurements done in 1989. These showed little change in the glacier in this period.

made from the 1984 aerial photographs was compared with glacier surface measurements done in 1989. These showed little change in the glacier 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 Kjølmoen (ed.) (2000). Small falls of ice blocks from Baklibreen were observed every year between 1992 and 1999.

Survey points on the glacier in 1999 and 2001 are shown in Figure 15-3. For more recent measurements on Baklibreen (since 1993), a survey point was established on a nearby prominent rock outcrop, and sightings were made with a GDM to different points on the glaciers. These points were visited by helicopter, and prisms were used for sighting. For the three points which are coincidental for the two years, there is a difference in elevation of between 0 and 3 m, with the 2001 points having a slightly lower elevation than those measured in 1999. However, the 1999 survey was performed on 30th July, and the 2001 survey being performed on 19th September, giving an extra seven weeks of melting which may account for the difference.

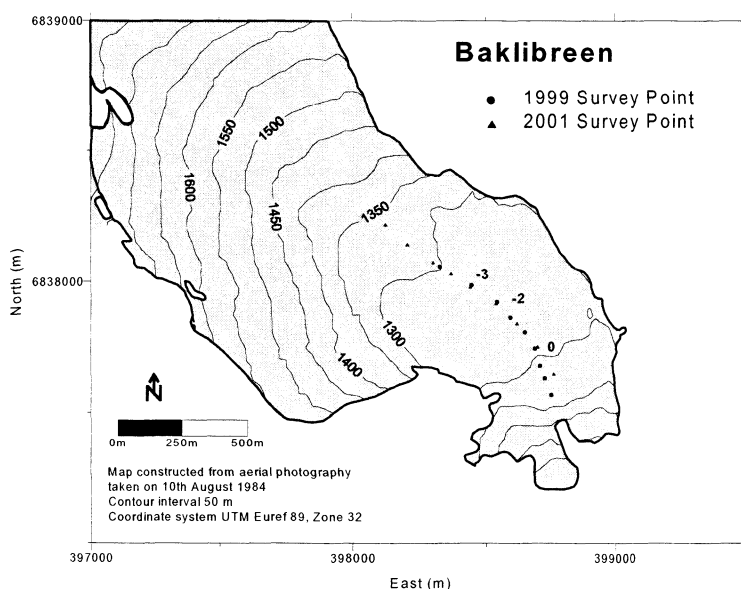


Figure 15-3.
Map of Baklibreen showing survey points on the glacier in 1999 and 2001, and the difference in elevations for the three coincident points.

16. References

- Elvehøy, H., J. Kohler, R. Engeset and L.M. Andreassen.
1997: Jøkulhlaup fra Demmevatn. *NVE Rapport 17 1997*, 36 pp.
- Engeset R.V. (ed.)
1999: Inflow to Storglomvatn Reservoir in Norway. *NVE Report 2 1999*, 135 pp.
- Gudmundsson, M.T., F. Sigmundsson and H. Björnsson.
1997: Ice-volcano interactions of the 1996 Gjalp subglacial eruption, Vatnajökull, Iceland. *Nature*, 389.
- Jackson M.
2000: Svartisen Subglacial Laboratory. *NVE Document 14 2000*, 27 pp.
- Kennett, M.
1990: Kartlegging av istykkelse og feltavgrensning på Blåmannsisen 1990. *NVE Rapport 8 1990*, 20 pp.
- Kennett, M. & H. Elvehøy.
1995: Bestemmelse av dreneringsgrensene for inntak til Svartisen Kraftverk. *NVE Rapport 22 1995*, 18 pp.
- Kjøllmoen, B.
1999: Breundersøkelser på Langfjordjøkelen 1998. *NVE Dokument 2 1999*, 24 pp.
- Kjøllmoen, B., (ed.).
2000: Glasiologiske undersøkelser i Norge 1999. *NVE Rapport 2 2000*, 140 pp.
- Kjøllmoen, B. and H.C. Olsen.
2002: Langfjordjøkelen i Vest-Finnmark. Glasihydrologiske undersøkelser. *NVE Dokument 4 2002*, 35 pp.
- Kjøllmoen, B. & M. Kennett.
1995: Breundersøkelser på Svartiseibreen 1988-94. *NVE Rapport 17 1995*, 35 p.
- Laumann T. & B. Wold.
1992: Reactions of a calving glacier to large changes in water level. *Annals of Glaciology 16*, p. 158-162.
- Liestøl, O.
1956: Glacier dammed lakes in Norway. *Norsk Polarinstitutt med. 81*.
- Sorteberg, H.K.
1998: Regional Breovervåking i Sør-Norge 1997. *NVE Rapport 8 1998*, 21 pp.
- 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 p.

Appendix A

Publications published in 2001

Andreassen, L.M. and H.C. Udnæs

2001: Snøfordeling gjennom en smeltesesong. *NVE Oppdragsrapport 1 2001*, 20 pp.

Elvehøy, H.

2001: Sluttrapport for glasiologiske undersøkelser på Jostefonn 1996-2001. *NVE Oppdragsrapport 11 2001*, 28 pp.

Engeset, R.V., H.K. Sorteberg and H.C. Udnæs.

2001: Snow pillows: Use and verification. *Reprint No. 109 from proceedings of the fourth international conference on Snow Engineering Recent Advances and Developments*, p. 45-51.

Engeset, R.V., H. Elvehøy, L.M. Andreassen, N. Haakensen, B. Kjøllmoen, L.A. Roald and E. Roland.

2001: Modelling of historic variations and future scenarios of the mass balance of Svartisen ice cap, northern Norway. *Reprint No. 108 from Annals of Glaciology 31 2000*, p. 97-103.

Kjøllmoen, B. (ed.).

2001: Glaciological investigations in Norway in 2000. *NVE Report 2 2001*, 122 pp.



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