REPORT

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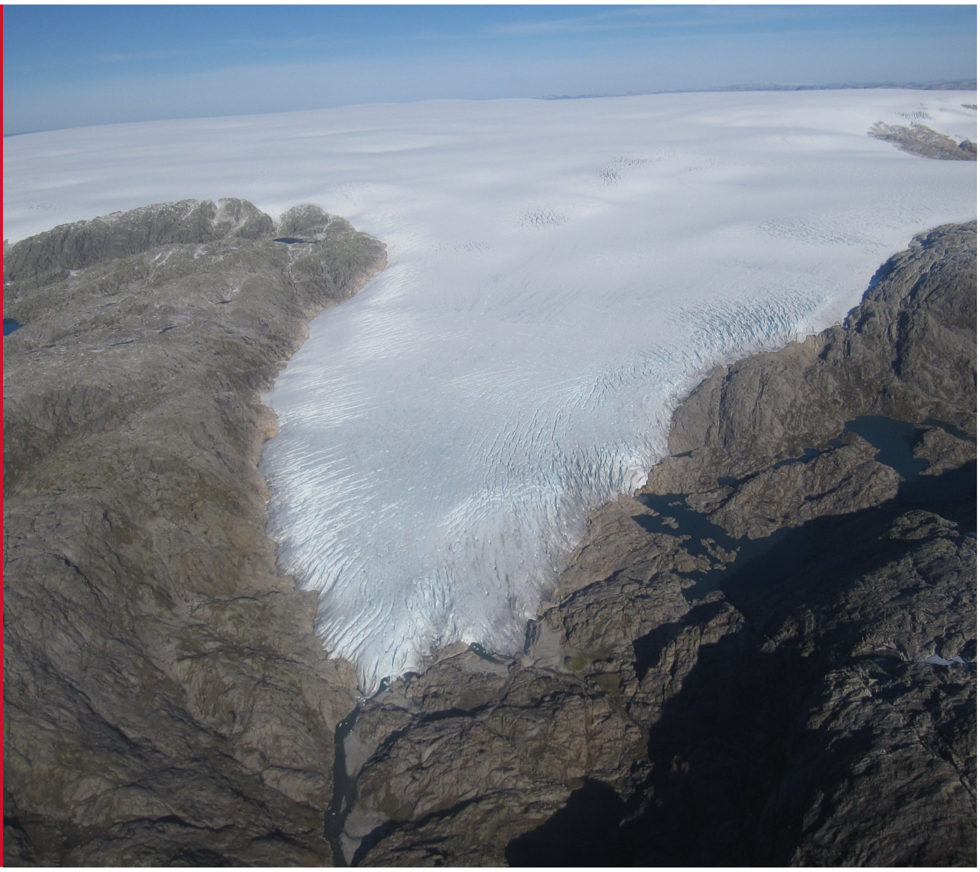
Glaciological investigations in Norway 2017

Bjarne Kjøllmoen (Ed.), Liss M. Andreassen, Hallgeir Elvehøy and Miriam Jackson



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Forsidefoto: Svelgjabreen, a southwest-facing glacier outlet from the southern part of Søndre Folgefonna. The photo was taken on 6th October 2016 by Bjarne Kjøllmoen.
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Summary: Results of glaciological investigations performed at Norwegian glaciers in 2017 are presented in this report. The main part concerns mass balance investigations. Results from investigations of glacier length changes are discussed in a separate chapter.

Keywords: Glaciology, Mass balance, Glacier length change, Glacier dynamics, Meteorology, Jøkulhlaup, Subglacial laboratory.

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Glaciological investigations in Norway 2017

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2018

Contents

Preface

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

The report is based on investigations of several Norwegian glaciers. Measurements of mass balance, glacier length change, glacier velocity, meteorology and other glaciological investigations are presented. Most of the investigations were ordered by private companies and have been published previously as reports to the respective companies. The annual results from mass balance and glacier length changes are also reported to the World Glacier Monitoring Service (WGMS) in Switzerland.

The report is published in English with a summary in Norwegian. The purpose of this report is to provide a joint presentation of the investigations and calculations made mainly by NVE's Section for Glaciers, Ice and Snow during 2017. The chapters are written by different authors with different objectives, but are presented in a uniform format. The individual authors hold the professional responsibility for the contents of each chapter. The fieldwork is mainly the result of co-operative work amongst the personnel at NVE.

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

Oslo, October 2018

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Director,
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Summary

Mass balance

Mass balance investigations were performed on fifteen glaciers in Norway in 2017.

The winter balance for five of the reference glaciers (those with a mass balance series back to at least 1981) was lower than the 1981-2010 average, and two were greater than average. Engabreen had the greatest relative winter balance with 142 % of the reference period and Gråsubreen had the lowest with 33 %.

The summer balance was lower than the 1981-2010 average for six of the reference glaciers. Only Ålfotbreen had a greater than average summer balance with 105 %. Nigardsbreen had the lowest relative summer balance with 72 % of the reference period.

Consequently, the annual balance was negative for four of the reference glaciers (Ålfotbreen, Storbreen, Hellstugubreen and Gråsubreen) and positive for three of the reference glaciers (Nigardsbreen, Rembesdalskåka and Engabreen).

Glacier length change

Glacier length changes were measured at 24 glaciers in southern Norway and 7 glaciers in northern Norway. Twenty-one of the glaciers had a decrease in length, nine were unchanged and one had a small advance. The greatest retreats were observed at Nigardsbreen (54 m), an outlet from Jostedalsbreen ice cap, Gråfjellsbrea (43 m), an outlet from southern Folgefonna ice cap and Koppangsbreen (32 m), a valley glacier in Troms, northern Norway.

Sammendrag

Massebalanse

I 2017 ble det utført massebalansemålinger på 15 breer i Norge – tre i Nord-Norge og tolv i Sør-Norge.

Av referansebreene (de breene som har massebalanseserie tilbake til 1981 eller lengre) ble vinterbalansen mindre enn gjennomsnittet for referanseperioden 1981-2010 for fem breer og større enn gjennomsnittet for to breer. Engabreen hadde relativt størst vinterbalanse med 142 % av referanseperioden og Gråsubreen hadde relativt minst med 33%.

Sommerbalansen ble mindre enn gjennomsnittet for seks av referansebreene. Bare Ålfotbreen hadde større sommerbalanse enn gjennomsnittet med 105 %. Nigardsbreen hadde relativt minst sommerbalanse med 72 % av referanseperioden.

For de sju referansebreene ble det negativ massebalanse på fire av dem (Ålfotbreen, Storbreen, Hellstugubreen og Gråsubreen) og positiv balanse på tre (Nigardsbreen, Rembesdalskåka og Engabreen).

Lengdeendringer

Lengdeendringer ble målt på 24 breer i Sør-Norge og 7 breer i Nord-Norge. Tjueen av breutløperne hadde tilbakegang, ni var uendret og én hadde litt framgang. Størst tilbakegang ble målt på Nigardsbreen (54 m), Gråfjellsbrea (43 m) og Koppangsbreen (32 m).

1. Glacier investigations in Norway 2017

1.1 Mass balance

Surface mass balance is the sum of surface accumulation and surface ablation and includes loss due to calving. The surface mass-balance series of the Norwegian Water Resources and Energy Directorate (NVE) contains annual (net), winter and summer balances. If the winter balance is greater than the summer balance, the annual 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 annual balance is negative and the glacier volume decreases.

Acronyms and terminology

Many acronyms and terminologies are used in this report. Mass balance terms are in accordance with Cogley et al. (2011) and Østrem and Brugman (1991).

AAR
Accumulation-area ratio. The ratio (expressed as a percentage) of the area of the accumulation zone to the area of the entire glacier.

Ablation
All processes that reduce the mass of the glacier, mainly caused by melting. Other processes of ablation can be calving, sublimation, windborne snow and avalanching.

Accumulation
All processes that add to the mass of the glacier, mainly caused by snowfall. Other processes of accumulation can be deposition of hoar, freezing rain, windborne snow and avalanching.

Airborne laser scanning (Lidar)
Airborne laser scanning or *Lidar* (Light Detection And Ranging) is an optical remote sensing technique used for measuring position and altitude of the earth surface. For the purpose of mapping glaciers airborne laser scanning is most useful.

Annual balance (b_a/B_a)
The sum of *accumulation* and *ablation* over the *mass-balance year* calculated for a single point ($b_w + b_s = b_a$) and for a *glacier* ($B_w + B_s = B_a$).

AO
The Arctic Oscillation is a climate index of the state of the atmosphere circulation over the Arctic.

Area-altitude distribution
The glacier is classified in height intervals (50 or 100 m) and the areas within all intervals give the *Area-altitude distribution*.

Density
In this report *density* means the ratio of the mass of snow, *firn* or ice to the volume that it occupies. The *snow density* is measured annually during snow measurements in

April/May. *Firn density* is measured occasionally during ablation measurements in September/October. *Ice density* is not measured but estimated as 900 kg m^{-3}.

DTM
Digital terrain model. A digital model of a terrain surface created from terrain elevation data.

ELA
Equilibrium-line altitude. The spatially averaged altitude (m a.s.l.) where *accumulation* and *ablation* are equal.

Firn
Snow which is older than one year and has gone through an ablation period.

GNSS/dGNSS
Global Navigation Satellite System/differential. A generic term for all satellite-based navigation systems, e.g. the American GPS, the Russian GLONASS, the Chinese BeiDou and the European Galileo. Differential GNSS (*dGNSS*) makes use of data from at least one reference station which is located in a precise, known location. The purpose of the dGNSS technique is to enhance the accuracy of the measurements.

Homogenisation of mass balance series
A procedure to correct for errors, non-conformity and biases that are not a result of real changes in the mass balance, but are due to variations in methodology or changes in observation pattern or method of calculation.

Jøkulhlaup
A *jøkulhlaup* or Glacier Lake Outburst Flood (GLOF) is a sudden release of water from a glacier. The water source can be a glacier-dammed lake, a pro-glacial moraine-dammed lake or water stored within, under or on the glacier.

Mass balance (also called Glaciological mass balance or Surface mass balance)
The ratio between the *accumulation* and the *ablation* for a glacier. In this report the term *mass balance* is equal to «Glaciological mass balance» or «Surface mass balance», which means that internal melting is not taken into account.

NAO
The North Atlantic Oscillation is the anomaly in sea level pressure difference between the Icelandic low pressure system and the Azores high pressure system in the Atlantic Ocean. When positive (that is, Azores pressure greater than Iceland pressure, winds from the west are strong, and snow accumulation in Scandinavia is high).

Orthophoto
An aerial photograph which is geometrically adjusted such that the scale is uniform. The orthophoto has the same characteristics and lack of distortion as a map.

Probing/sounding
Measuring method for snow depth measurements using thin metal rods.

Snow coring
Use of a coring auger to obtain cylindrical samples of snow and *firn*. The purpose is to measure the *density* of the snow or to identify the *summer surface*.

Stake
Aluminum poles inserted in the glacier for measuring snow accumulation (depth) and melting.

Stratigraphic system
A method for calculating the glacier *mass balance*. In principal the method describes the annual balance between two successive *summer surfaces*.

Summer balance (b_s/B_s)
The sum of *accumulation* and *ablation* over the summer season. Internal melting is not included. The summer balance can be calculated for a single point (b_s) and for a glacier (B_s).

Summer surface (S.S.)
The surface on which the first snow, that does not melt immediately, of the new balance year falls.

TLA
Transient Snow Line Altitude. The average snow line altitude at any instant, particularly during the *ablation* season.

Tower
Galvanised steel towers installed on the glacier for measuring snow depth and melting. A tower can survive greater snow *accumulation* than a *stake*.

UAV
Unmanned aerial vehicle. An aircraft (commonly a drone) without a human pilot.

Water equivalent/Snow water Equivalent (SWE)
The amount of snow, *firn* and ice (m) converted to the amount of water expressed as «metres water equivalent» (m w.e.).

Winter balance (b_w/B_w)
The sum of *accumulation* and *ablation* over the winter season. The winter balance can be calculated for a single point (b_w) and for a glacier (B_w).

www.senorge.no
An open web portal showing daily updated maps of snow, weather and water conditions, and climate for Norway.

Method

Methods used to measure mass balance in the field have in principle remained unchanged over the years, although the number of measurements has varied (Andreassen et al., 2005; 2016). With the experience gained from many years of measurements, the measurement network was simplified on individual glaciers at the beginning of the 1990s.

Winter balance

The winter balance is normally measured in April or May by probing to the previous year's summer surface along regular profiles or grids. Stake readings are used to verify the soundings 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 sounding alone, snow coring is also used to confirm the sounding results. Snow density is measured in pits at one or two locations at different elevations on each glacier.

Summer and annual balance

Summer and annual balances are obtained from measurements of stakes and towers (Fig. 1-1), usually performed in September or October. Below the glacier's equilibrium line the annual balance is 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 annual balance is positive. Based on past experience, snow density of the remaining snow in the accumulation area is typically assumed to be 600 kg m^{-3}. After especially cold summers, or if there is more snow than usual remaining at the end of the summer, snow density is either measured using snow-cores or is assumed to be 650 kg m^{-3}. The density of melted firn is, depending on the age, assumed to be between 650 and 800 kg m^{-3}. The density of melted ice is taken as 900 kg m^{-3}.

Figure 1-1
Tower used for summer and annual balance on Engabreen in August 2017. Photo: Jostein Aasen.

Stratigraphic method

The mass balance is usually calculated using the stratigraphic method, which means the balance between two successive "summer surfaces" (i.e. surface minima). Consequently, the measurements describe the state of the glacier *after* the end of melting and *before* fresh snow has fallen. On some occasions ablation *after* the final measurements in September/October can occur. Measuring this additional ablation can sometimes be done later in the autumn, and then will be included in that year's summer balance. However, often measuring and calculating the 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.

Uncertainty

The uncertainty of the mass balance measurements depends on the uncertainty in the point measurements themselves, the uncertainty in spatial integration of the point measurements to glacier averaged values (representativeness, number of points and uncovered parts) and the uncertainty of the glacier reference area (uncertainties in area-altitude changes and ice-divides) (Zemp et al., 2013). The uncertainty of the point measurements are related to uncertainties in identifying the previous summer surface, in measurements of stakes and towers, in the density measurements and estimates and conversion to snow water equivalents.

As most of the factors are not easily quantified from independent measurements, a best qualified estimate is used to quantify the uncertainties (Andreassen et al., 2016). The determined values of uncertainties are therefore based on subjective estimates.

Mass balance programme

In 2017 mass balance measurements were performed on fifteen glaciers in Norway - twelve in southern Norway and three in northern Norway (Fig. 1-2). Included in this number is one small ice mass, Juvfonne, which can be characterised as an ice patch rather than a glacier (chap. 8). In southern Norway, six of the glaciers (Ålfotbreen, Nigardsbreen, Rembesdalskåka, Storbreen, Hellstugubreen and Gråsubreen) have been measured for 55 consecutive years or more. They constitute a west-east profile extending from the maritime Ålfotbreen glacier with an average winter balance of 3.6 m w.e. to the continental Gråsubreen with an average winter balance of 0.8 m w.e. Storbreen in Jotunheimen has the longest series of all glaciers in Norway with 69 years of measurements, while Engabreen at Svartisen has the longest series (48 years) in northern Norway. The six long-term glaciers in southern Norway together with Engabreen in northern Norway, constitute the so-called reference glaciers. For the seven reference glaciers a reference period (1981-2010) is defined and the balance values for 2017 are compared with the average of the reference period. A comprehensive review of the glacier mass balance and length measurements in Norway is given in Andreassen et al. (2005).

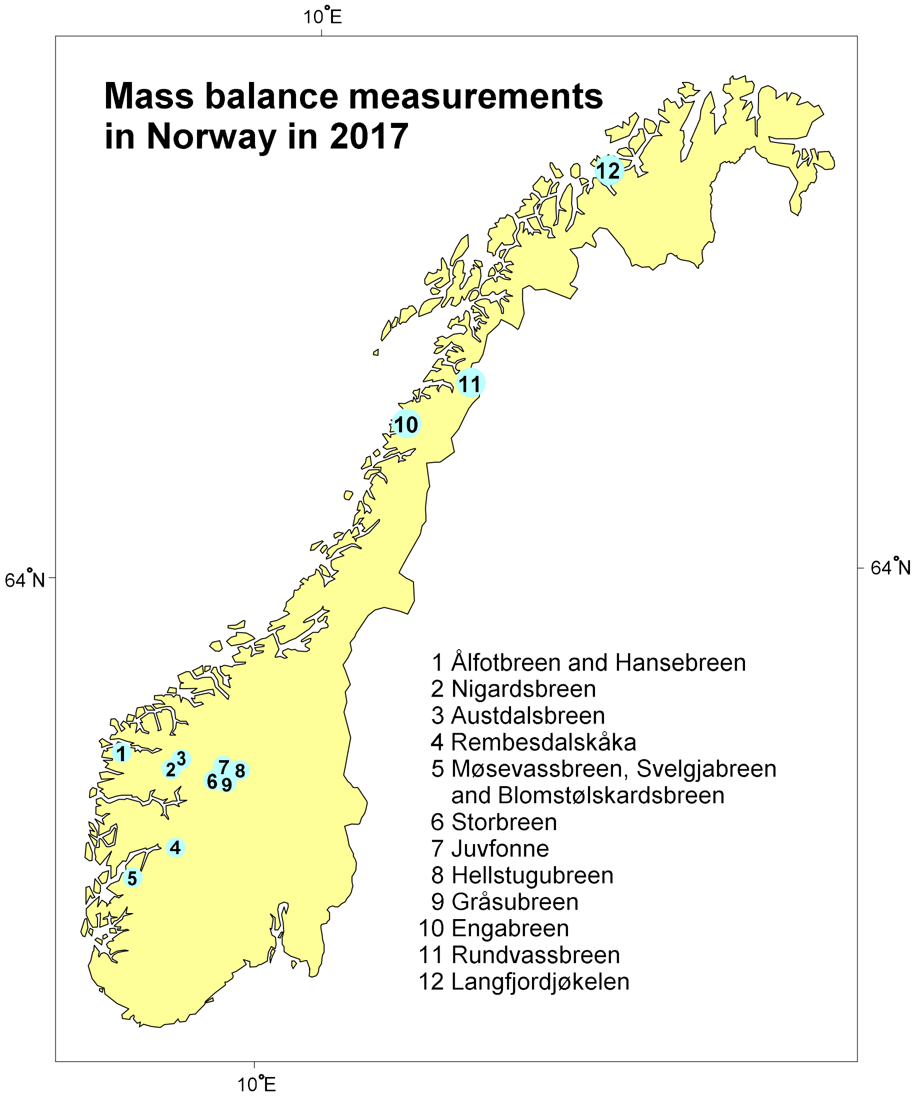


Figure 1-2
Location of the glaciers on which mass balance studies were performed in 2017.

Mass balance studies performed on Norwegian glaciers in 2017 are reported in the chapters following.

The mass balance (winter, summer and annual balance) is given both in volume (m^3 water) and specific water equivalent (m w.e.) for each 50 or 100 m height interval. The results are presented in 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.

Weather conditions and mass balance results for the reference glaciers

Winter weather

The winter season 2016/17 started with mild and dry weather in northern Norway and cool and dry weather in southern Norway. At the end of 2016 the weather changed and December and January were snow-rich in northern and western Norway. February was quite normal, while March and April were rather mild and snow-rich.

Snow accumulation and winter balance

The winter balance for five of the reference glaciers was lower than the average of the reference period 1981-2010, and two glaciers were greater than average. Engabreen had the greatest relative winter balance with 142 % of the reference period and Gråsubreen had the lowest with 33 %.

Summer weather

The summer season started with cool weather in south and normal temperatures in north. July and August continued with normal temperatures over the whole country. The summer season finished with a warm September in northern and western Norway.

Ablation and summer balance

The summer balance was lower than the average for six of the reference glaciers. Only Ålfotbreen had greater summer balance than average with 105 %. Nigardsbreen had the lowest relative summer balance with 72 % of the reference period.

Annual balance

The annual balance was negative for four of the seven reference glaciers (Ålfotbreen, Storbreen, Hellstugubreen and Gråsubreen) and positive for three of the glaciers (Nigardsbreen, Rembesdalskåka and Engabreen). Ålfotbreen had the greatest deficit with −0.8 m w.e. and Engabreen the greatest surplus with +1.3 m w.e.

The results from the mass balance measurements in Norway in 2017 are shown in Table 1-1. Winter (B_w), summer (B_s) and annual balance (B_a) are given in metres water equivalent (m w.e.) averaged over the entire glacier area. The figures in the "% of ref." column show the current results as a percentage of the average for the period 1981-2010. The annual balance results are compared with the mean annual balance in the same way. ELA is the equilibrium line altitude (m a.s.l.) and AAR is the accumulation area ratio (%).

Circulation patterns AO and NAO

Norway's climate is strongly influenced by large-scale circulation patterns and westerly winds are dominant. Much of the variation in weather from year to year, in particular the winter precipitation, may be attributed to variations in circulation and wind patterns in the North Atlantic Ocean. Indices such as the North Atlantic Oscillation (NAO) and the Arctic Oscillation (AO) are used to describe the variation in the pressure gradients in the northern latitudes, and the resulting effects on temperature and storm tracks. When the NAO or AO is positive, the coast of Norway experiences warm and wet winters resulting in high winter precipitation on the glaciers. When the NAO or AO is negative, the winters are colder and drier with less precipitation on the glaciers (Hanssen-Bauer and Førland, 1998; Nesje et al., 2000). Although NAO is more commonly used, Rasmussen (2007) found better correlations for winter balance with AO than NAO for nine of the 10 longest mass balance glaciers in Norway. In winter 2016/2017 (October-April) NAO and AO were positive overall (0.67 and 0.26 calculated from monthly means, source: http://www.cpc.ncep.noaa.gov/), resulting in above normal winter precipitation for most glaciers. All months had positive NAO indices except for November (NAO and AO) and April (AO). The large-scale circulation indices NAO and AO are in units of standard deviations from the mean, in which both statistics are calculated from multi-year records of the two indices.

Table 1-1
Summary of results from mass balance measurements performed in Norway in 2017. The glaciers in southern Norway are listed from west to east. The figures in the *% of ref.* column show the current results as a percentage of the average for the period 1981-2010.

Glacier	*Period*	*Area (km²)*	*Altitude (m a.s.l.)*	*B_w (m)*	*% of ref.*	*B_s (m)*	*% of ref.*	*B_a (m)*	*B_a ref.*	*ELA (m a.s.l.)*	*AAR (%)*
Ålfotbreen	1963-17	4.0	890-1368	3.26	87	−4.01	105	−0.75	−0.08	1305	21
Hansebreen	1986-17	2.8	927-1310	3.48	[1)]101	−4.66	[1)]116	−1.18	[1)]−0.59	>1310	0
Møsevassbreen	2017	15.5	873-1617	3,13		-3,00		0,13		1335	63
Svelgjabreen	2007-17	22.3	829-1634	2.97	[2)]96	−2.90	[2)]99	0.06	[2)]0.15	1325	61
Blomstølskardsbreen	2007-17	22.5	1011-1634	3.02	[2)]93	−2.80	[2)]106	0.22	[2)]0.60	1405	68
Nigardsbreen	1962-17	46.6	330-1952	2.17	96	−1.58	72	0.59	0.06	1440	84
Austdalsbreen	1988-17	10.6	1200-1747	2.42	[3)]111	[4)]−2.23	[3)]82	0.19	[3)]−0.54	1410	74
Rembesdalskåka	1963-17	17.3	1066-1854	2.26	106	−1.62	75	0.64	−0.02	1612	83
Storbreen	1949-17	5.1	1400-2102	1.17	79	−1.69	93	−0.52	-0.33	1800	41
Juvfonne[5)]	2010-17	0.2	1840-1998	1.69		−1.43		0.25			
Hellstugubreen	1962-17	2.9	1482-2229	0.73	65	−1.32	87	−0.59	−0.39	1960	27
Gråsubreen	1962-17	2.1	1833-2283	0.26	33	−0.97	83	−0.71	−0.37	undef.	
Engabreen	1970-17	36.2	111-1544	3.67	142	−2.42	93	1.25	−0.01	1025	84
Rundvassbreen	2002-04 2011-17	11.6 10.8	788-1537 853-1527	2.01	[6)]109	−1.57	[6)]60	0.44	−0.78 [6)]−0.78	1155	69
Langfjordjøkelen	1989-93 1996-17	3.7 3.2	280-1050 302-1050	2.08	[7)]101	−2.35	[7)]77	−0.27	[7)]−0.98	810	56

[1)]Calculated for the measured period 1986-2016
[2)]Calculated for the measured period 2007-2016
[3)]Calculated for the measured period 1988-2016
[4)]Contribution from calving amounts to −0.17 m for B_a
[5)]Calculated for a point only, b_w, b_s and b_a
[6)]Calculated for the measured periods 2002-04 and 2011-2016
[7)]Calculated for the measured periods 1989-93 and 1996-2016

Figure 1-3 gives a graphical presentation of the mass balance results in southern Norway for 2017. The west-east gradient is evident for both winter and summer balances. The results for 2017 show positive mass balance for eight of the fifteen measured glaciers in Norway.

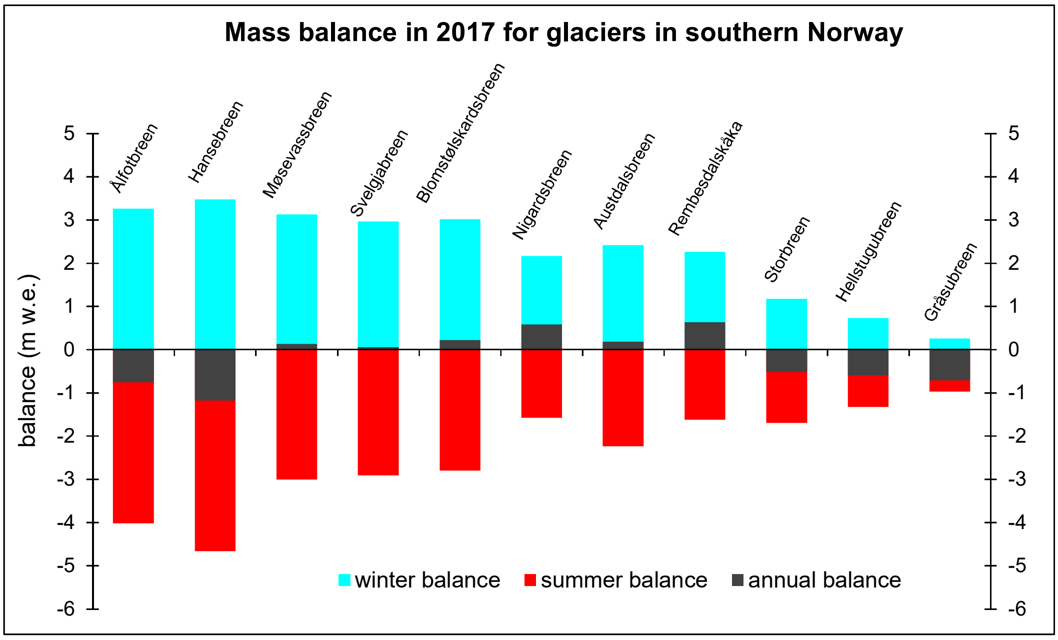


Figure 1-3
Mass balance in 2017 in southern Norway. The glaciers are listed from west to east.

The cumulative annual balance for the six reference glaciers in southern Norway for the period 1963-2017 is shown in Figure 1-4. The maritime glaciers, Ålfotbreen, Nigardsbreen and Rembesdalskåka, showed a marked increase in volume during the period 1989-95. The surplus was mainly the result of several winters with heavy snowfall. Nigardsbreen is the only glacier with a mass surplus over the period 1963-2017.

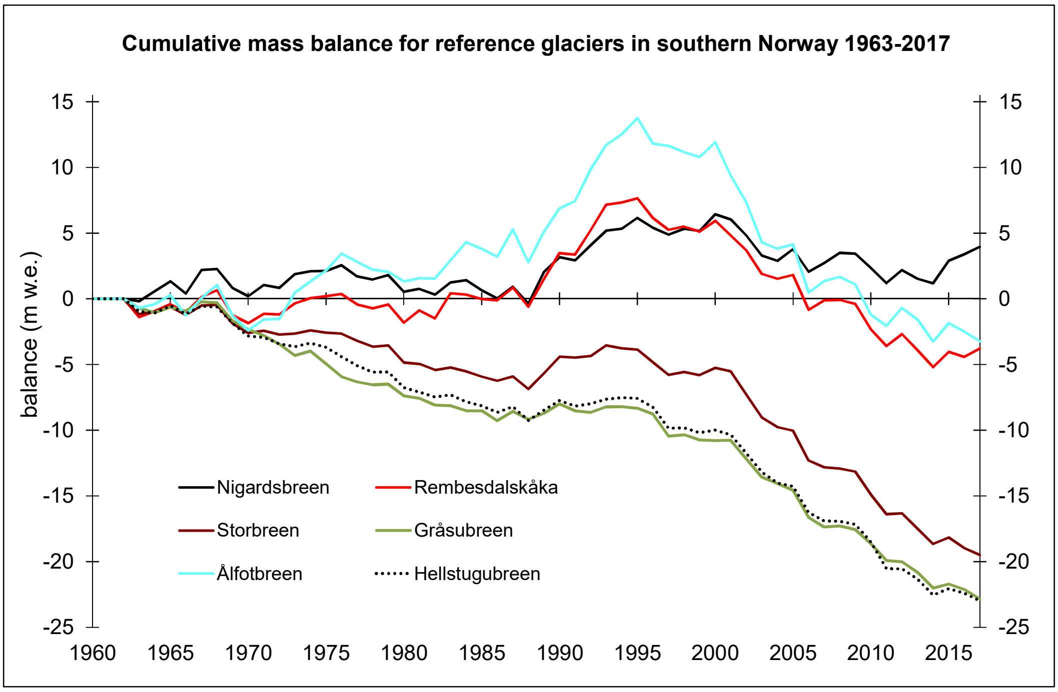


Figure 1-4
Cumulative mass balance for the six reference glaciers Ålfotbreen, Nigardsbreen, Rembesdalskåka, Storbreen, Hellstugubreen and Gråsubreen for the period 1963-2017.

1.3 Other investigations

Glacier length change measurements were performed at 31 glaciers in Norway in 2017. Some of the glaciers have a measurement series going back to about 1900. The length changes are described in chapter 14.

Glacier dynamics (velocity) have been studied at Austdalsbreen since 1987 (chap. 5). The measurements continued in 2017. Glacier velocity was also measured at Storbreen from 2016 to 2017 (chap. 7).

Meteorological observations have been performed at Engabreen (chap. 11).

Svartisen Subglacial Laboratory was initiated in 1992 and has since been used by researchers from several different countries (Jackson, 2000). An overview of pressure measurements in the laboratory is given in chapter 11.

A few jøkulhlaups occurred in 2017 and these are described in chapter 14.

2. Ålfotbreen (Bjarne Kjøllmoen)

Ålfotbreen ice cap (61°45′N, 5°40′E) has an area of 10.6 km^2 (2010) and is, together with Blåbreen (Fig. 2-1), one of the westernmost and most maritime glacier in Norway. Mass balance studies have been carried out on two adjacent north-facing outlet glaciers – Ålfotbreen (4.0 km^2,) and Hansebreen (2.8 km^2). The westernmost of these two has been the subject of mass balance investigations since 1963, and has always been reported as Ålfotbreen. The adjacent glacier east of Ålfotbreen has been given the name Hansebreen (Fig. 2-1), and has been measured since 1986. None of the outlet glaciers from the icecap are given names on the official maps.

Figure 2-1
Ålfotbreen ice cap to the right and Blåbreen to the left photographed on 29th September 2010 by Blom AS. Map source: Norgeibilder.no.

2.1 Mass balance 2017

Fieldwork

Snow accumulation measurements were performed on 10th and 11th May and the calculation of winter balance was based on measurement of stakes in seven different positions and 73 snow depth soundings on Ålfotbreen, and stakes in six different positions and 55 snow depth soundings on Hansebreen (Fig. 2-2). Comparison of stake readings and snow soundings indicated no significant melting after the ablation measurements in October 2016. Generally the sounding conditions were good over the whole glacier. A solid ice layer was detected at 4.5 m depth. The snow depth varied from 3.1 m to 8.2 m on Ålfotbreen, and from 4.5 m to 10.0 m on Hansebreen. Snow density was measured in one location (1229 m a.s.l.), applicable for both glaciers. The mean snow density of 6.4 m snow was 533 kg m^{-3}.

The locations of stakes, snow pit and soundings are shown in Figure 2-2.

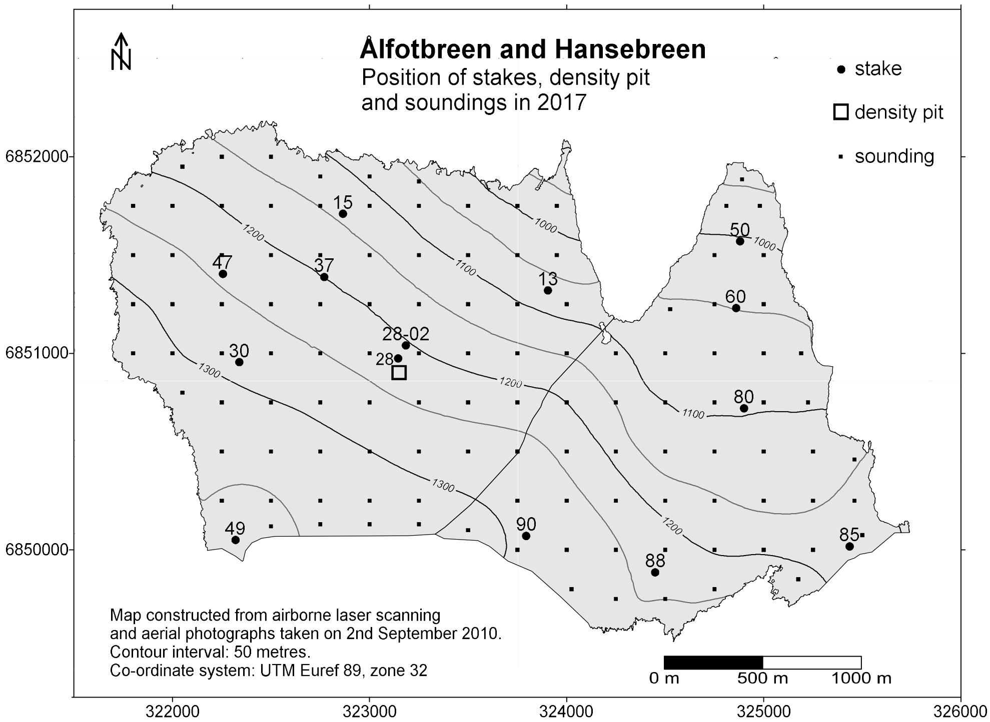


Figure 2-2
Location of stakes, soundings and snow pit at Ålfotbreen (left) and Hansebreen (right) in 2017.

Adjustment of snow depths

In 2017 there were some differences between snow depths measured by stake readings and by soundings in the same position on Ålfotbreen. The most significant differences were measured at stake 28 (2.20 m diff.), stake 49 (1.23 m) and stake 30 (0.75 m), where the sounded snow depths were greatest. The measured snow depths in all stake positions are shown in Figure 2-3.

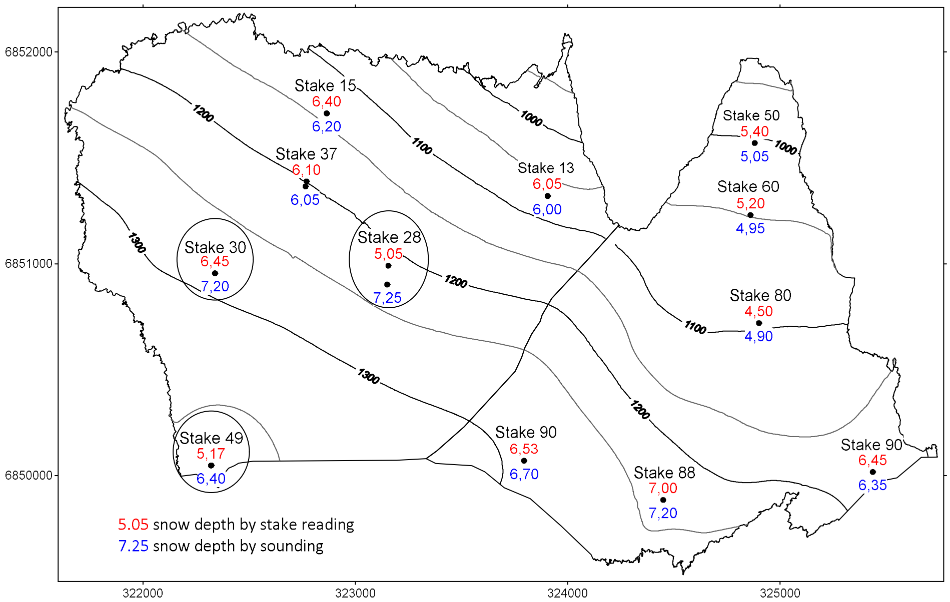


Figure 2-3
Snow depths measured by stake readings (red font) and by soundings (blue font) on Ålfotbreen and Hansebreen in 2017. The greatest differences were at stakes 28, 49 and 30.

Generally snow depth measured by stake readings are considered as most reliable provided that the stakes were not curved or had not sunk. The snow depth differences for the three stakes 28, 49 and 30 are significant and all indicate that the sounded snow depths were overestimated. It is reasonable to assume that other sounded snow depths close to these three stakes were overestimated as well. Consequently the sounded snow depths in the upper areas of Ålfotbeen were adjusted. The adjustment was done by using the snow depth differences at stakes 37, 13, 30, 28, 49 and 90 (Fig. 2-3) as input data for an area-weighted adjustment of 43 snow depth soundings south of stake 37 (Fig. 2-4). Adjustments were performed for Ålfotbreen only because there were no significant differences between stake readings and soundings on Hansebreen.

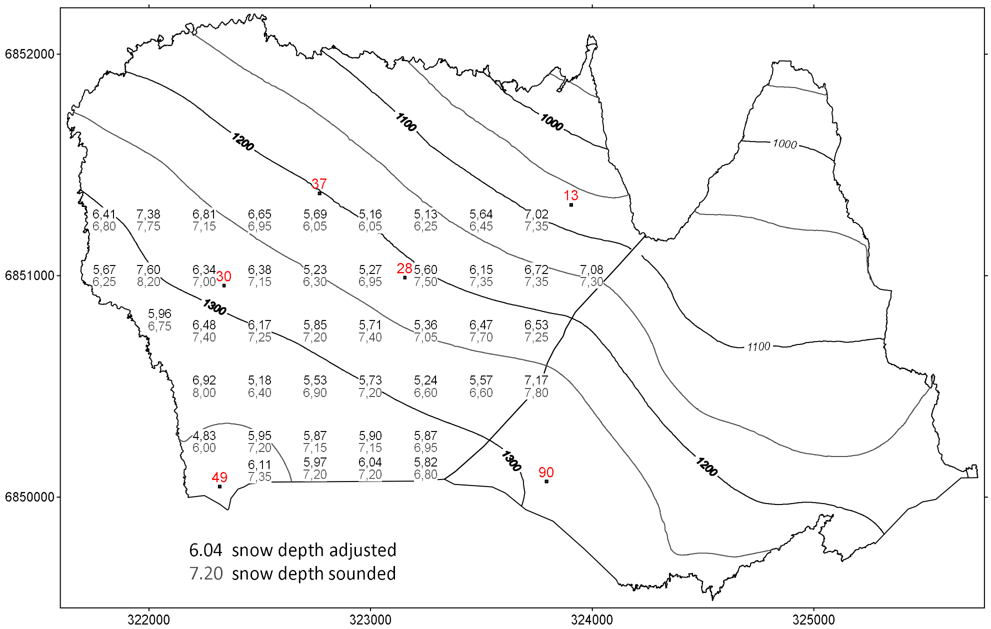


Figure 2-4
Original snow depth soundings (grey) and adjusted snow depths (black) at Ålfotbreen.

Ablation was measured on 19th October (Fig. 2-5). The annual balance was measured at stakes in eight positions on Ålfotbreen and six positions on Hansebreen (Fig. 2-2). At the time of the ablation measurements up to 30 cm of fresh snow had fallen.

Figure 2-5
Stake reading and GNSS positioning of stake 90 during the ablation measurements on 19th October.
Photo: Bjarne Kjøllmoen.

Results

The calculations are based on the DTM from 2010.

All height intervals are well-represented with point measurements (b_w) for both glaciers except the very lowest interval (890-950 m a.s.l.) at Ålfotbreen. As a consequence of the adjusted snow depths the accuracy of winter balance at Ålfotbreen is somewhat higher this year.

The winter balance was calculated as a mean value for each 50 m height interval and was 3.3 ±0.3 m w.e. at Ålfotbreen, which is 87 % of the mean winter balance for the reference period 1981-2010. The winter balance on Hansebreen was calculated as 3.5 ±0.2 m w.e., which is 101 % of the mean winter balance for the measurement period 1986-2016. Spatial distribution of the winter balance at Ålfotbreen and Hansebreen is shown in Figure 2-6.

Based on estimated density and stake measurements the summer balance was also calculated as a mean value for each 50 m height interval and was −4.0 ±0.3 m w.e. on Ålfotbreen, which is 105 % of the reference period. The summer balance on Hansebreen was −4.7 ±0.3 m w.e., which is 116 % of the mean winter balance for 1986-2016.

Hence, the annual balance was negative for both glaciers. Ålfotbreen had a deficit of −0.8 ±0.4 m w.e. The mean annual balance for the reference period 1981-2010 is −0.08 m w.e. However, over the last ten years (2008-2017), the mean annual balance was −0.46 m w.e. and seven of these years had a negative annual balance. The annual balance at Hansebreen was −1.2 ±0.4 m w.e. The mean value for the measurement period 1986-2016 is −0.59 m w.e. Over the last ten years the mean annual balance was −0.92 m w.e.

The mass balance results are shown in Table 2-1 and the corresponding curves for specific and volume balance are shown in Figure 2-7.

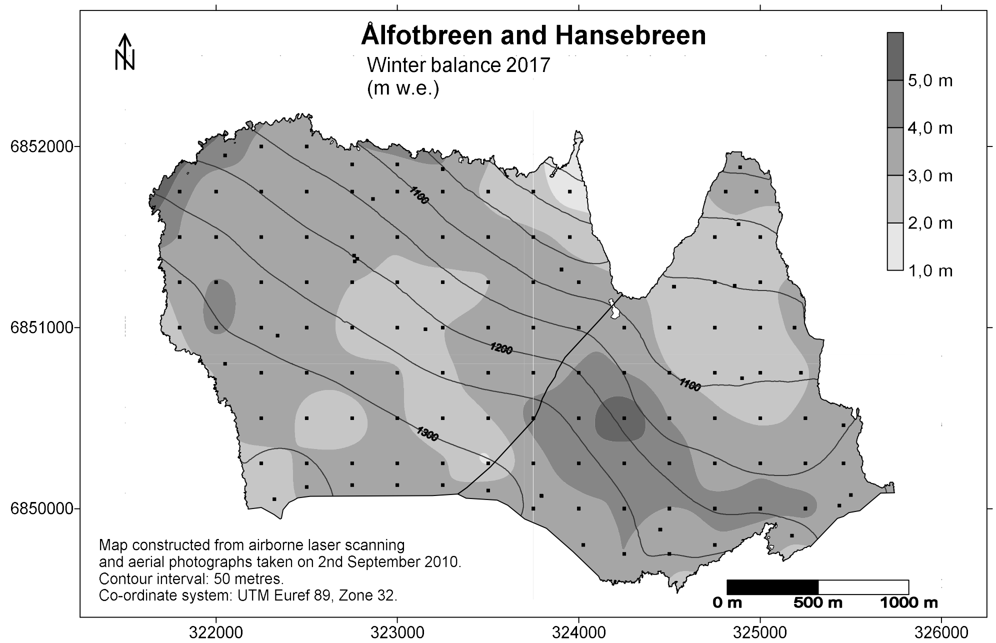


Figure 2-6
Spatial distribution of winter balance at Ålfotbreen and Hansebreen in 2017.

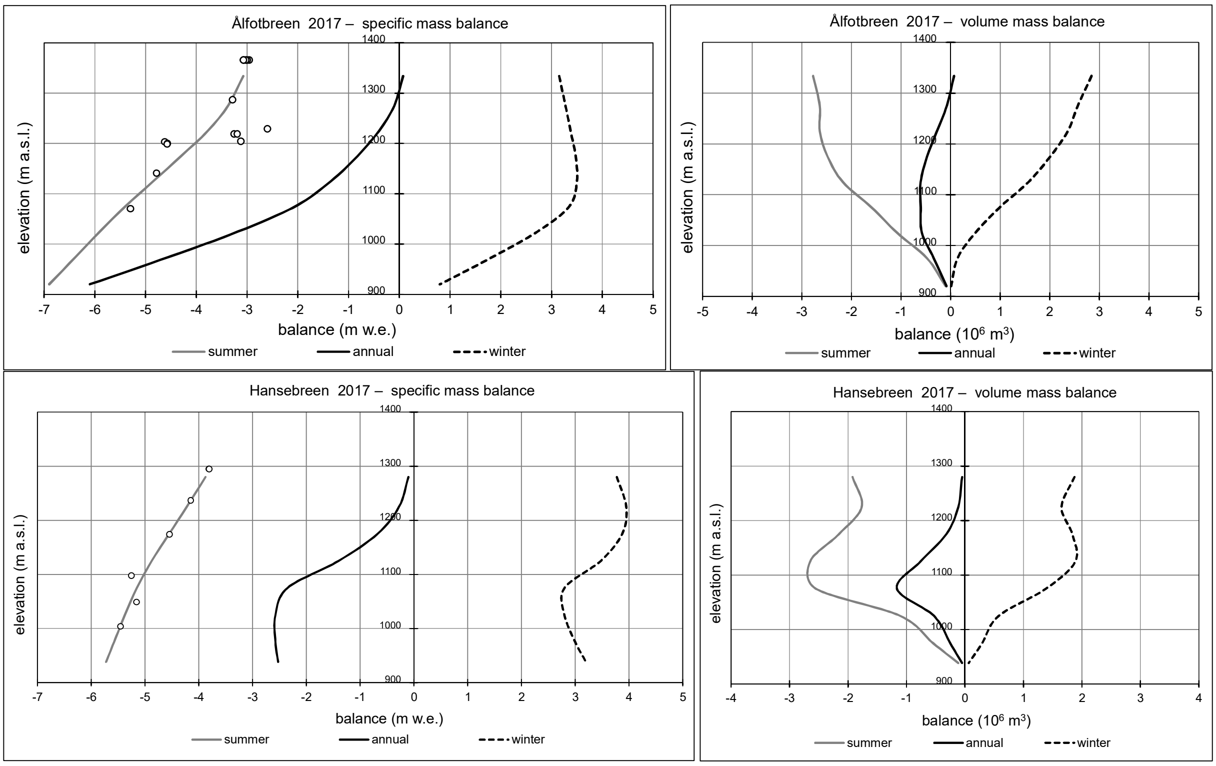


Figure 2-7
Mass balance diagram for Ålfotbreen (upper) and Hansebreen (lower) in 2017 showing altitudinal distribution of specific (left) and volumetric (right) winter, summer and annual balance. Specific summer balance at each stake is shown (○).

Table 2-1
Winter, summer and annual balance for Ålfotbreen (upper) and Hansebreen (lower) in 2017.

Mass balance Ålfotbreen 2016/17 – stratigraphic system

		Winter mass balance Measured 10th May 2017		Summer mass balance Measured 19th Oct 2017		Annual mass balance Summer surface 2016 - 2017	
Altitude (m a.s.l.)	Area (km^2)	Specific (m w.e.)	Volume (10^6 m^3)	Specific (m w.e.)	Volume (10^6 m^3)	Specific (m w.e.)	Volume (10^6 m^3)
1300 - 1368	0.90	3.15	2.8	-3.08	-2.8	0.07	0.1
1250 - 1300	0.78	3.28	2.6	-3.38	-2.6	-0.10	-0.1
1200 - 1250	0.70	3.38	2.4	-3.78	-2.6	-0.40	-0.3
1150 - 1200	0.58	3.48	2.0	-4.30	-2.5	-0.83	-0.5
1100 - 1150	0.45	3.50	1.6	-4.85	-2.2	-1.35	-0.6
1050 - 1100	0.30	3.35	1.0	-5.40	-1.6	-2.05	-0.6
1000 - 1050	0.18	2.73	0.5	-5.90	-1.1	-3.18	-0.6
950 - 1000	0.08	1.85	0.1	-6.38	-0.5	-4.53	-0.3
890 - 950	0.01	0.80	0.0	-6.90	-0.1	-6.10	-0.1
890 - 1368	**3.98**	**3.26**	**13.0**	**-4.01**	**-16.0**	**-0.75**	**-3.0**

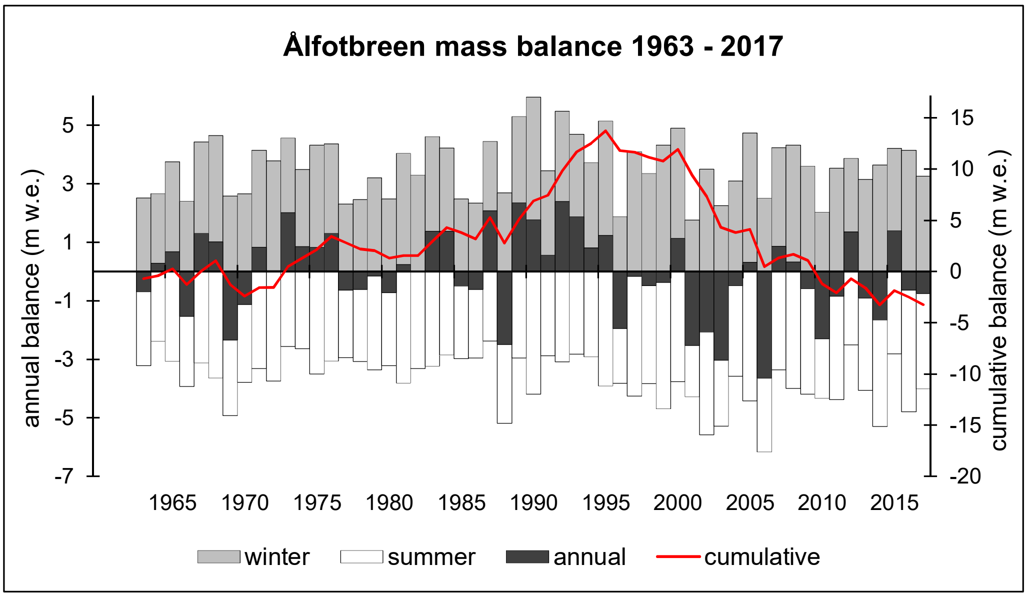
Mass balance Hansebreen 2016/17 – stratigraphic system

		Winter mass balance Measured 10th May 2017		Summer mass balance Measured 19th Oct 2017		Annual mass balance Summer surface 2016 - 2017	
Altitude (m a.s.l.)	Area (km^2)	Specific (m w.e.)	Volume (10^6 m^3)	Specific (m w.e.)	Volume (10^6 m^3)	Specific (m w.e.)	Volume (10^6 m^3)
1250 - 1310	0.50	3.78	1.87	-3.88	-1.92	-0.10	-0.05
1200 - 1250	0.42	3.95	1.65	-4.23	-1.77	-0.27	-0.11
1150 - 1200	0.47	3.88	1.84	-4.55	-2.16	-0.68	-0.32
1100 - 1150	0.54	3.48	1.89	-4.88	-2.65	-1.40	-0.76
1050 - 1100	0.50	2.80	1.39	-5.15	-2.55	-2.35	-1.16
1000 - 1050	0.21	2.80	0.58	-5.38	-1.11	-2.58	-0.53
950 - 1000	0.10	3.00	0.29	-5.58	-0.55	-2.58	-0.25
927 - 950	0.02	3.20	0.06	-5.73	-0.11	-2.53	-0.05
927 - 1310	**2.75**	**3.48**	**9.6**	**-4.66**	**-12.8**	**-1.18**	**-3.2**

According to Figure 2-7 the ELA lies at 1305 m a.s.l. on Ålfotbreen and above the highest point (>1310 m a.s.l.) on Hansebreen. Consequently the AAR is 21 % for Ålfotbreen and 0 % for Hansebreen.

2.2 Mass balance 1963(86)-2017

The historical mass balance results for Ålfotbreen and Hansebreen are presented in Figure 2-8. The cumulative annual balance for Ålfotbreen over 1963-2017 is −3.2 m w.e., which gives a mean annual balance of −0.06 m w.e. a^{-1}. The cumulative annual balance for Hansebreen for 1986-2017 is −19.4 m w.e., which gives a mean annual balance of −0.61 m w.e. a^{-1}.



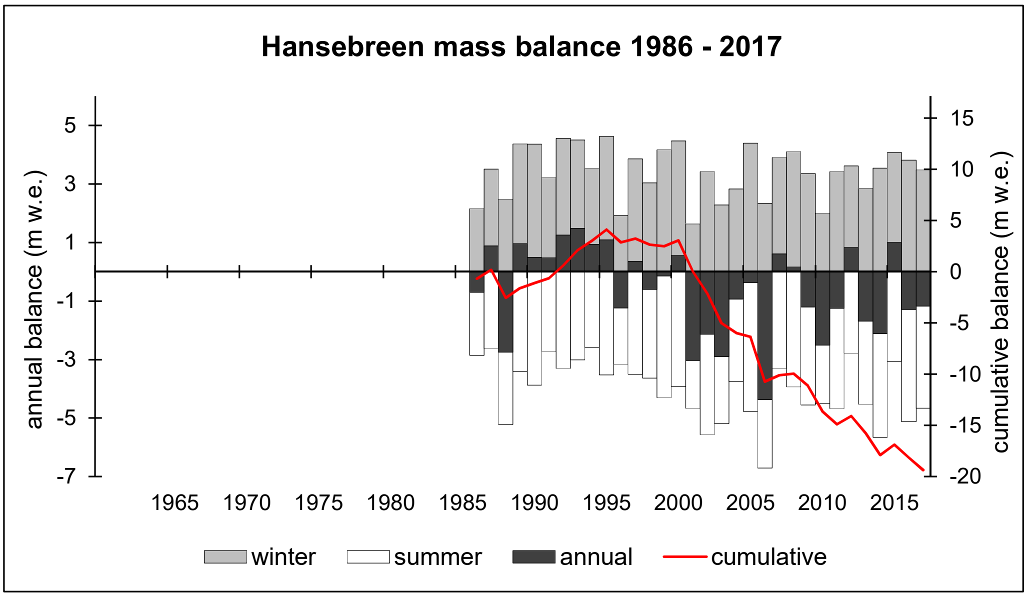


Figure 2-8
Mass balance at Ålfotbreen (upper) 1963-2017 and Hansebreen (lower) 1986-2017. Cumulative mass balance is given on the axis to the right.

3. Folgefonna (Bjarne Kjøllmoen)

Folgefonna is situated in the south-western part of Norway between Hardangerfjorden to the west and the mountain plateau Hardangervidda to the east. It is divided into three separate ice caps - Northern, Middle and Southern Folgefonna. Southern Folgefonna (60°1′N, 6°20′E) is the third largest (158 km^2 in 2013) ice cap in Norway. In 2007 mass balance measurements began on two adjacent south-facing outlet glaciers of Southern Folgefonna – Svelgjabreen (22.3 km^2) (Fig. 3-1) and Blomstølskardsbreen (22.5 km^2). In 2017, mass balance was measured also at the neighbouring glacier to the west, Møsevassbreen (Fig. 3-1).

Mass balance measurements were previously carried out at Svelgjabreen/Blomstølskardsbreen (then called Blomsterskardsbreen) in 1971 (Tvede, 1973), and annual balance only was measured in 1970 and in the period 1972-77 (Tvede and Liestøl, 1977).

3.1 Mapping

A new survey of Møsevassbreen, Svelgjabreen and Blomstølskardsbreen was performed in 2017. The glacier surface was mapped by aerial photographs and airborne laser scanning on 27th and 31st August (Fig. 3-1) (Terratec, 2017).

A Digital Terrain Model (DTM) was calculated based on the laser scanning data. The glacier boundary was determined from an orthophoto composed of the aerial photos. The ice divides between the different glaciers were calculated using GIS and compared with the ice divides from 2007 and 2013. The ice divides from 2017 were similar to the 2007 and 2013 divides. Hence the 2007 ice divides are used here.

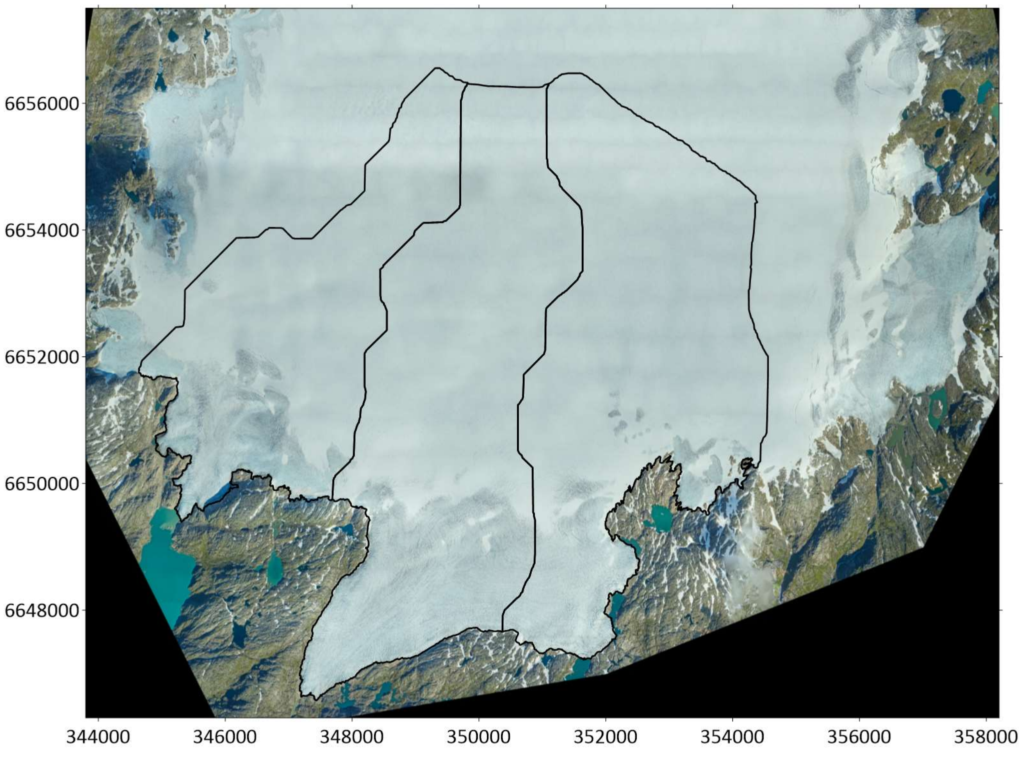


Figure 3-1
Orthophoto of Møsevassbreen (left), Svelgjabreen (middle) and Blomstølskardsbreen (right) from aerial photographs on 31st August 2017. Photo: Terratec AS.

3.2 Mass balance 2017

Fieldwork

Snow accumulation measurements were performed on 2nd May and the calculation of winter balance was based on measurement of five stakes and 37 snow depth probings on Møsevassbreen, five stakes and 39 snow depth probings on Svelgjabreen, and three stakes and 34 snow depth probings on Blomstølskardsbreen (Fig. 3-2). Comparison of stake readings and probings indicated no significant melting after the ablation measurements in October 2016. Overall the sounding conditions were good, however the summer surface was somewhat difficult to identify in the accumulation area. The snow depth varied from 3.5 m to 7.9 m at Møsevassbreen, from 3.4 m to 8.0 m at Svelgjabreen, and from 2.8 m to 7.9 m at Blomstølskardsbreen. Snow density was measured in one location (1517 m a.s.l.) applicable for all three glaciers. The mean density of 6.1 m snow was 467 kg m^{-3}. Ablation was measured on 9th October. The annual balance was measured directly at stakes in six positions on Møsevassbreen, seven positions on Svelgjabreen and seven positions on Blomstølskardsbreen (Fig. 3-2). There was 2-3 m of snow remaining in the uppermost areas from the winter season 2016/2017. At the time of the ablation measurements up to 1.25 m of fresh snow had fallen.

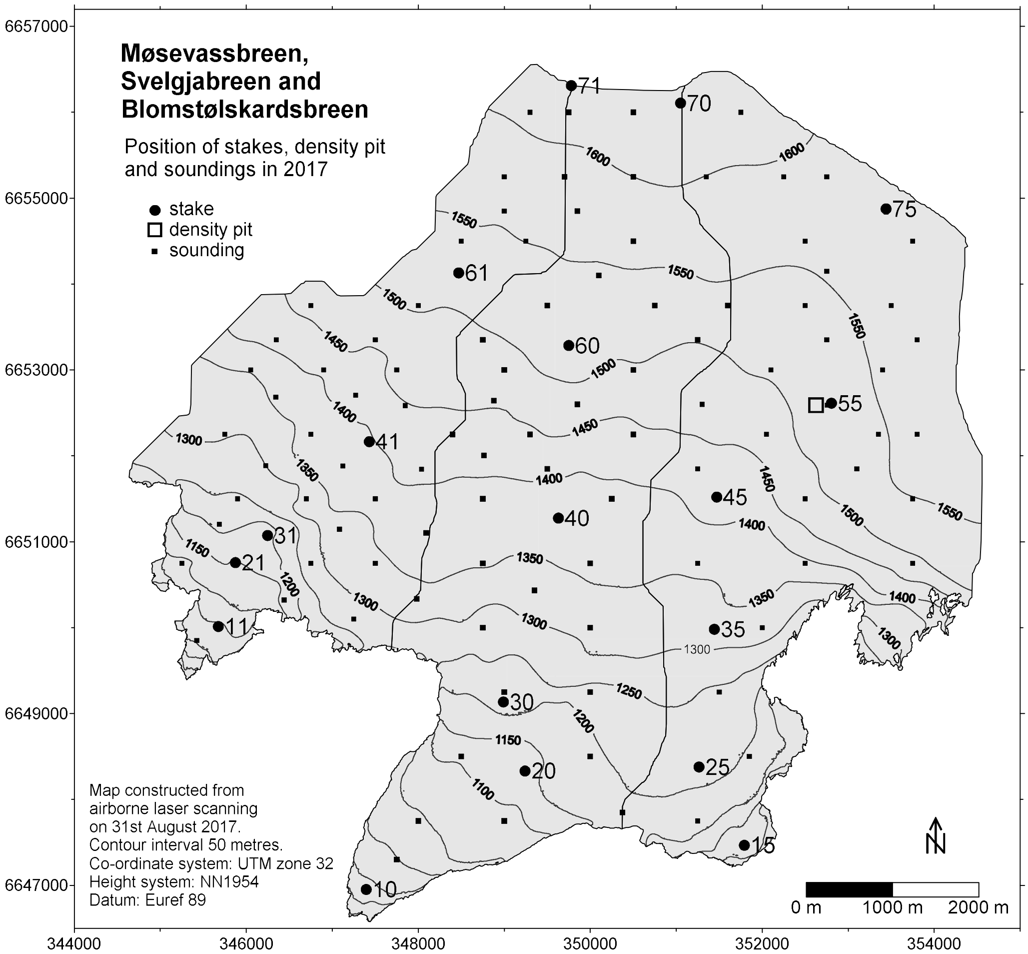


Figure 3-2
Location of stakes, soundings and density pit on Møsevassbreen, Svelgjabreen and Blomstølskardsbreen in 2017.

Results

The calculations are based on the DTM from 2017.

Stake measurements in position 71 are included in the mass balance calculations for both Møsevassbreen and Svelgjabreen, and measurements in position 70 are included for both Svelgjabreen and Blomstølskardsbreen. All height intervals are well-represented with point measurements (b_w) for both glaciers except the lowest intervals at Møsevassbreen (873-1000 m a.s.l.) and Svelgjabreen (829-900 m a.s.l.).

The winter balance was calculated as a mean value for each 50 m height interval and was 3.1 ±0.2 m w.e. at Møsevassbreen, and 3.0 ±0.2 m w.e. at both Svelgjabreen and Blomstølskardsbreen. Spatial distribution of the winter balance is shown in Figure 3-3.

Based on estimated density and stake measurements the summer balance was calculated as −3.0 ±0.3 m w.e. at Møsevassbreen, −2.9 ±0.3 m w.e. at Svelgjabreen and −2.8 ±0.3 m w.e. at Blomstølskardsbreen.

Hence, the annual balance was calculated as +0.1 ±0.4 m w.e. at Møsevassbreen and Svelgjabreen, and +0.2 ±0.4 m w.e. at Blomstølskardsbreen.

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

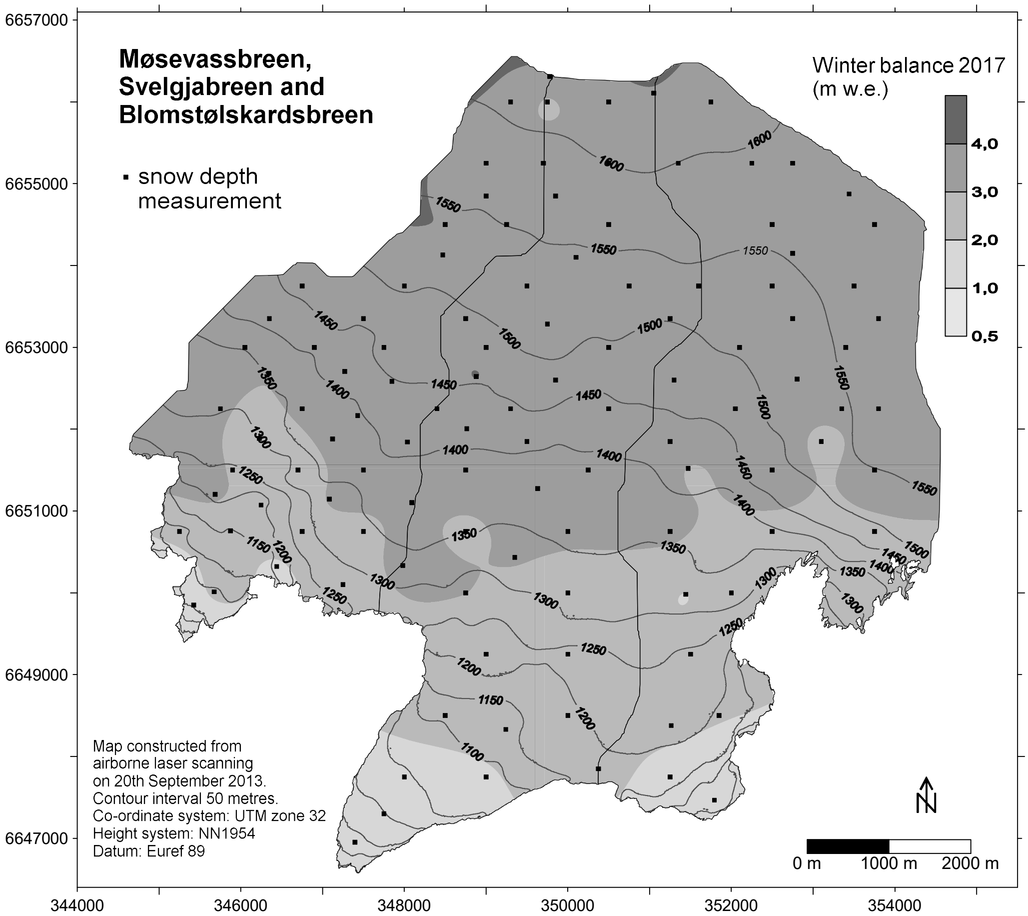


Figure 3-3
Spatial distribution of winter balance at Møsevassbreen, Svelgjabreen and Blomstølskardsbreen in 2017.

According to Figure 3-4, the ELA lies at 1325 m a.s.l. on Svelgjabreen and at 1320 m a.s.l. on Blomstølskardsbreen. Accordingly the AAR is 60 % for Svelgjabreen and 81 % for Blomstølskardsbreen.

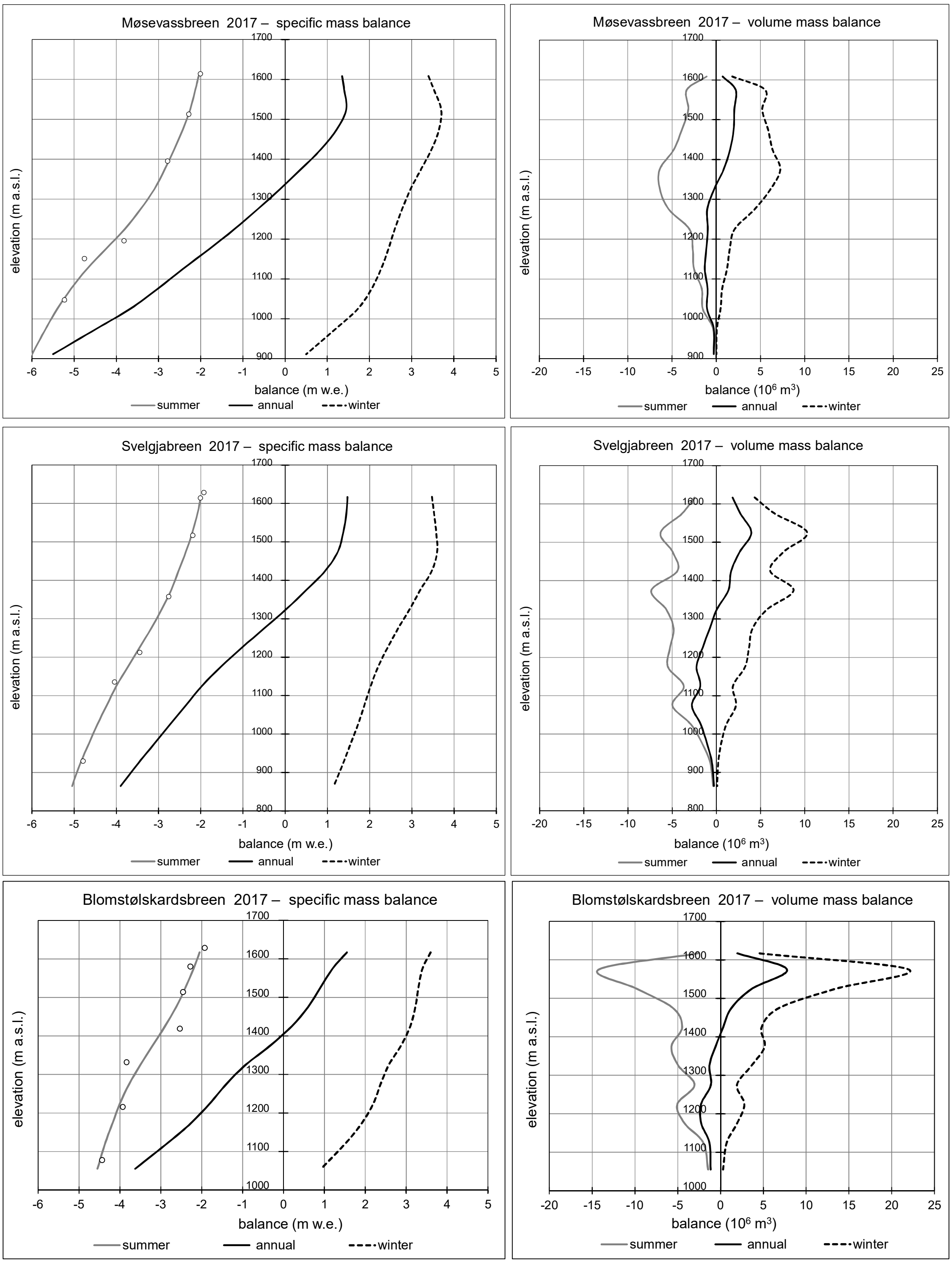


Figure 3-4
Mass balance diagrams for Møsevassbreen (upper), Svelgjabreen (middle) and Blomstølskardsbreen (lower) in 2017. Specific summer balance at the stake positions is shown as circles (○).

Table 3-1
Winter, summer and annual balances for Møsevassbreen (upper), Svelgjabreen (middle) and Blomstølskardsbreen (lower) in 2017.

Mass balance Møsevassbreen 2016/17 – stratigraphic system

		Winter mass balance Measured 2nd May 2017		Summer mass balance Measured 9th Oct 2017		Annual mass balance Summer surface 2016 - 2017	
Altitude (m a.s.l.)	Area (km^2)	Specific (m w.e.)	Volume (10^6 m^3)	Specific (m w.e.)	Volume (10^6 m^3)	Specific (m w.e.)	Volume (10^6 m^3)
1600 - 1617	0.53	3.40	1.8	-2.05	-1.1	1.35	0.7
1550 - 1600	1.57	3.53	5.5	-2.13	-3.3	1.40	2.2
1500 - 1550	1.41	3.70	5.2	-2.25	-3.2	1.45	2.0
1450 - 1500	1.61	3.65	5.9	-2.43	-3.9	1.23	2.0
1400 - 1450	1.83	3.48	6.4	-2.63	-4.8	0.85	1.6
1350 - 1400	2.25	3.23	7.2	-2.85	-6.4	0.38	0.8
1300 - 1350	2.06	2.98	6.1	-3.10	-6.4	-0.13	-0.3
1250 - 1300	1.57	2.78	4.3	-3.43	-5.4	-0.65	-1.0
1200 - 1250	0.80	2.60	2.1	-3.80	-3.0	-1.20	-1.0
1150 - 1200	0.63	2.45	1.5	-4.25	-2.7	-1.80	-1.1
1100 - 1150	0.54	2.28	1.2	-4.70	-2.5	-2.43	-1.3
1050 - 1100	0.32	2.05	0.7	-5.08	-1.6	-3.03	-1.0
1000 - 1050	0.28	1.73	0.5	-5.40	-1.5	-3.68	-1.0
950 - 1000	0.06	1.20	0.1	-5.68	-0.4	-4.48	-0.3
873 - 950	0.05	0.50	0.0	-6.00	-0.3	-5.50	-0.3
873 - 1617	**15.49**	**3.13**	**48.5**	**-3.00**	**-46.5**	**0.14**	**2.1**

Mass balance Svelgjabreen 2016/17 – stratigraphic system

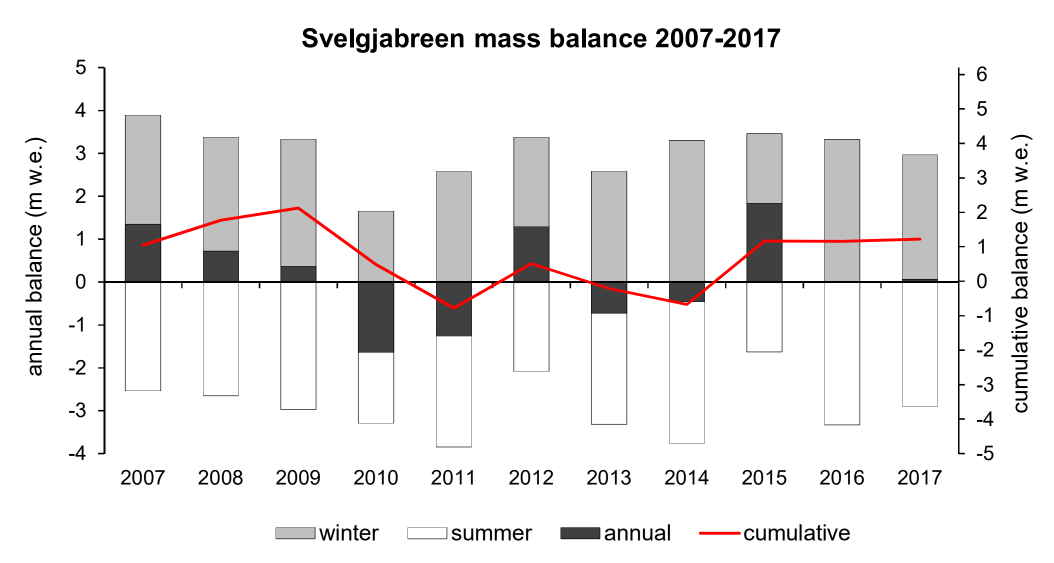
		Winter mass balance Measured 2nd May 2017		Summer mass balance Measured 9th Oct 2017		Annual mass balance Summer surface 2016 - 2017	
Altitude (m a.s.l.)	Area (km^2)	Specific (m w.e.)	Volume (10^6 m^3)	Specific (m w.e.)	Volume (10^6 m^3)	Specific (m w.e.)	Volume (10^6 m^3)
1600 - 1634	1.24	3.48	4.3	-2.00	-2.5	1.48	1.8
1550 - 1600	1.87	3.53	6.6	-2.08	-3.9	1.45	2.7
1500 - 1550	2.87	3.58	10.3	-2.20	-6.3	1.38	3.9
1450 - 1500	2.11	3.60	7.6	-2.35	-5.0	1.25	2.6
1400 - 1450	1.75	3.48	6.1	-2.53	-4.4	0.95	1.7
1350 - 1400	2.73	3.20	8.7	-2.70	-7.4	0.50	1.4
1300 - 1350	1.94	2.95	5.7	-2.93	-5.7	0.03	0.0
1250 - 1300	1.52	2.68	4.1	-3.18	-4.8	-0.50	-0.8
1200 - 1250	1.52	2.43	3.7	-3.45	-5.2	-1.03	-1.6
1150 - 1200	1.47	2.20	3.2	-3.73	-5.5	-1.53	-2.2
1100 - 1150	0.92	2.03	1.9	-4.00	-3.7	-1.98	-1.8
1050 - 1100	1.18	1.88	2.2	-4.23	-5.0	-2.35	-2.8
1000 - 1050	0.65	1.73	1.1	-4.45	-2.9	-2.73	-1.8
950 - 1000	0.34	1.55	0.5	-4.65	-1.6	-3.10	-1.1
900 - 950	0.14	1.38	0.2	-4.85	-0.7	-3.48	-0.5
829 - 900	0.07	1.15	0.1	-5.05	-0.4	-3.90	-0.3
829 - 1634	**22.34**	**2.97**	**66.3**	**-2.90**	**-64.9**	**0.06**	**1.4**

Mass balance Blomstølskardsbreen 2016/17 – stratigraphic system

		Winter mass balance Measured 2nd May 2017		Summer mass balance Measured 9th Oct 2017		Annual mass balance Summer surfaces 2016 - 2017	
Altitude (m a.s.l.)	Area (km^2)	Specific (m w.e.)	Volume (10^6 m^3)	Specific (m w.e.)	Volume (10^6 m^3)	Specific (m w.e.)	Volume (10^6 m^3)
1600 - 1634	1.27	3.60	4.6	-2.05	-2.6	1.55	2.0
1550 - 1600	6.47	3.40	22.0	-2.20	-14.2	1.20	7.8
1500 - 1550	4.08	3.30	13.5	-2.40	-9.8	0.90	3.7
1450 - 1500	2.12	3.23	6.8	-2.63	-5.6	0.60	1.3
1400 - 1450	1.55	3.10	4.8	-2.90	-4.5	0.20	0.3
1350 - 1400	1.79	2.88	5.2	-3.20	-5.7	-0.33	-0.6
1300 - 1350	1.41	2.58	3.6	-3.50	-4.9	-0.93	-1.3
1250 - 1300	0.81	2.38	1.9	-3.78	-3.0	-1.40	-1.1
1200 - 1250	1.26	2.20	2.8	-4.00	-5.1	-1.80	-2.3
1150 - 1200	1.00	1.93	1.9	-4.18	-4.2	-2.25	-2.3
1100 - 1150	0.46	1.55	0.7	-4.35	-2.0	-2.80	-1.3
1011 - 1100	0.32	0.93	0.3	-4.55	-1.4	-3.63	-1.2
1011 - 1634	**22.54**	**3.02**	**68.1**	**-2.80**	**-63.1**	**0.22**	**5.0**

3.2 Mass balance 2007-2017

The historical mass balance results for Svelgjabreen and Blomstølskardsbreen are presented in Figure 3-5. The cumulative annual balance for Svelgjabreen for 2007-17 is +1.5 m w.e., which gives a mean annual balance of +0.14 m w.e. a^{-1}. The cumulative annual balance for Blomstølskardsbreen for 2007-17 is +6.2 m w.e., which gives a mean annual balance of +0.56 m w.e. a^{-1}.



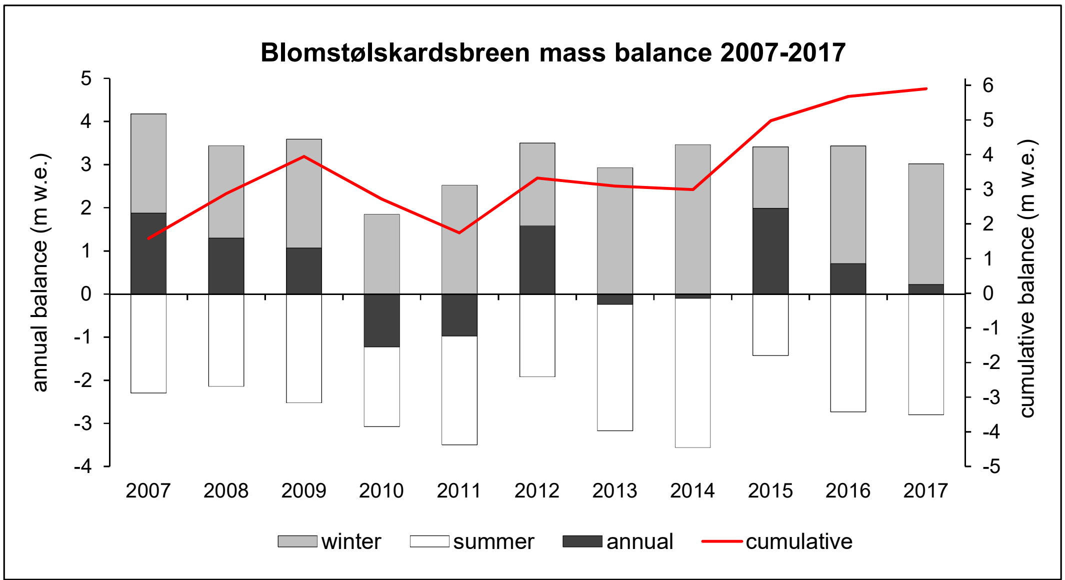


Figure 3-5
Winter, summer and annual balance at Svelgjabreen (upper) and Blomstølskardsbreen (lower) for 2007-2017. Cumulative mass balance is given on the right axis.

4. Nigardsbreen (Bjarne Kjøllmoen)

Nigardsbreen (61°42′N, 7°08′E) is one of the largest and best known outlet glaciers from Jostedalsbreen. It has an area of 46.6 km^2 (2013) and flows south-east from the centre of the ice cap. Nigardsbreen accounts for approximately 10 % of the total area of Jostedalsbreen, and extends from 1952 m a.s.l. down to 330 m a.s.l. (Fig. 4-1).

Glaciological investigations in 2017 include mass balance and glacier length change. Nigardsbreen has been the subject of mass balance investigations since 1962. A re-analysed mass balance series for Nigardsbreen 1962-2013 is presented in Kjøllmoen (2016).

Figure 4-1
The upper part of the outlet of Nigardsbreen photographed in August 2017. Photo: Hallgeir Elvehøy.

4.1 Mass balance 2017

Fieldwork

Snow accumulation measurements were performed on 21st June and the calculation of winter balance is based on measurement of seven stakes and 74 snow depth soundings (Fig. 4-2). Comparison of sounded snow depth and stake readings indicated no melting after the ablation measurements in October 2016. The sounding conditions were good and the summer surface was easy to identify over the whole glacier area. The snow depth varied between 2.4 and 6.1 m on the plateau. On the tongue, there was no snow in position 600 (588 m a.s.l.). The snow depth was not measured in position 1000 (965 m a.s.l.). Snow density was measured in position 94 (1683 m a.s.l.), and the mean density of 4.1 m snow was 541 kg m^{-3}.

Ablation was measured on 18th October. Measurements were made at stakes and towers in nine locations (Fig. 4-2). In the accumulation area there was between 1.0 and 3.5 m of snow remaining from winter 2016/17. At the time of measurement, there was between 0.7 and 1.7 m of fresh snow at stakes on the glacier plateau.

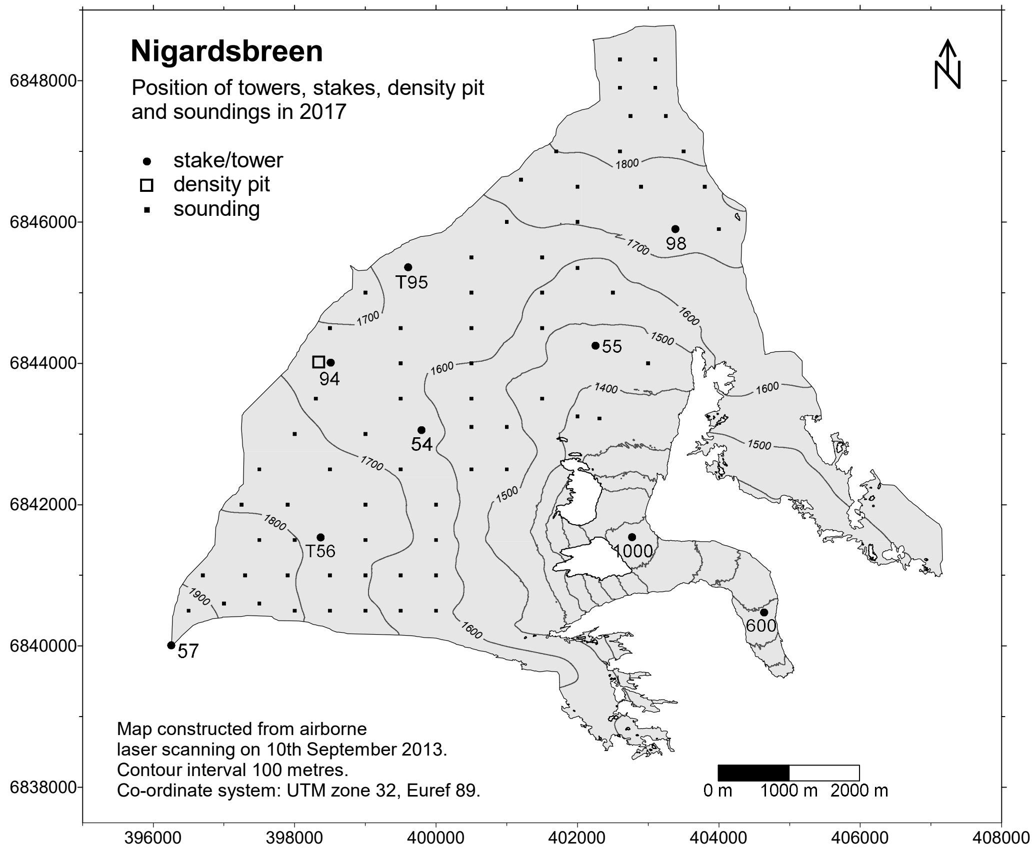


Figure 4-2
Location of towers, stakes, snow pit and soundings on Nigardsbreen in 2017.

Results

The calculations are based on the DTM from 2013.

The elevations above 1350 m a.s.l., which cover about 90 % of the catchment area, were well-represented with point measurements. Below this altitude the curve pattern was based on point measurements at 965 and 588 m altitude.

The winter balance was calculated as a mean value for each 100 m height interval and was 2.2 ±0.2 m w.e., which is 96 % of the mean winter balance for the reference period 1981-2010. Spatial distribution of the winter balance is shown in Figure 4-3.

Based on estimated density and stake measurements the summer balance was also calculated as a mean value for each 100 m height interval and was −1.6 ±0.3 m w.e., which is 72 % of the reference period.

Hence the annual balance was positive, at 0.6 m ±0.4 m w.e. The mean annual balance for the reference period 1981-2010 is +0.06 m w.e. Over the past ten years (2008-2017), the mean annual balance was +0.13 m w.e.

The mass balance results are shown in Table 4-1 and the corresponding curves for specific and volume balance are shown in Figure 4-4.

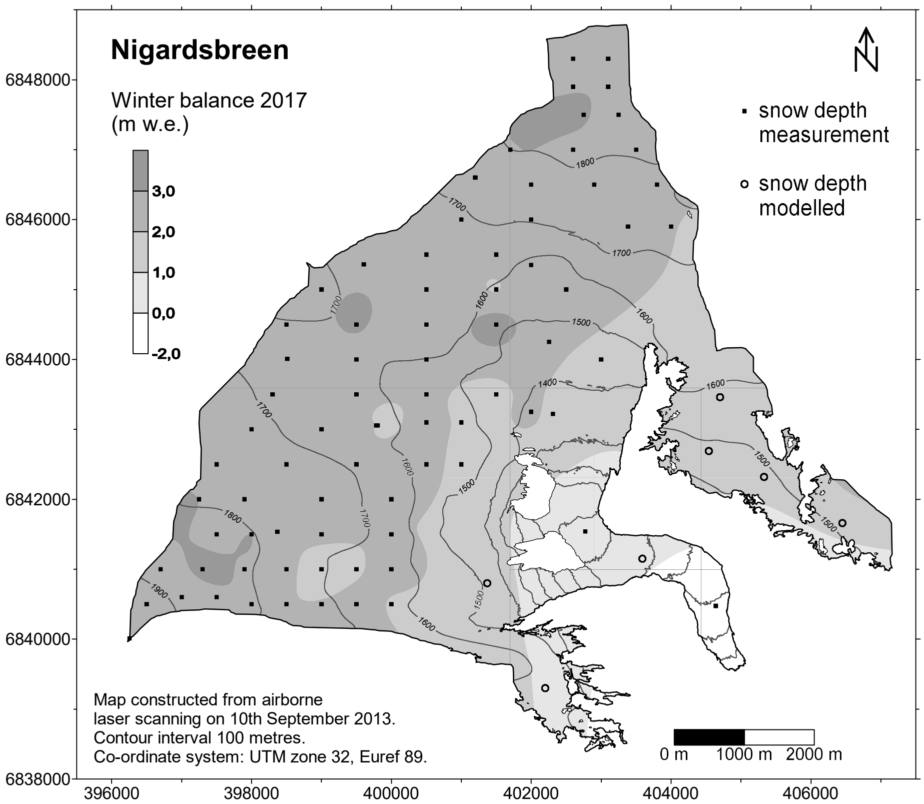


Figure 4-3
Spatial distribution of winter balance at Nigardsbreen in 2017. In areas with insufficient measurements seven simulated points were inserted based on previous measurements.

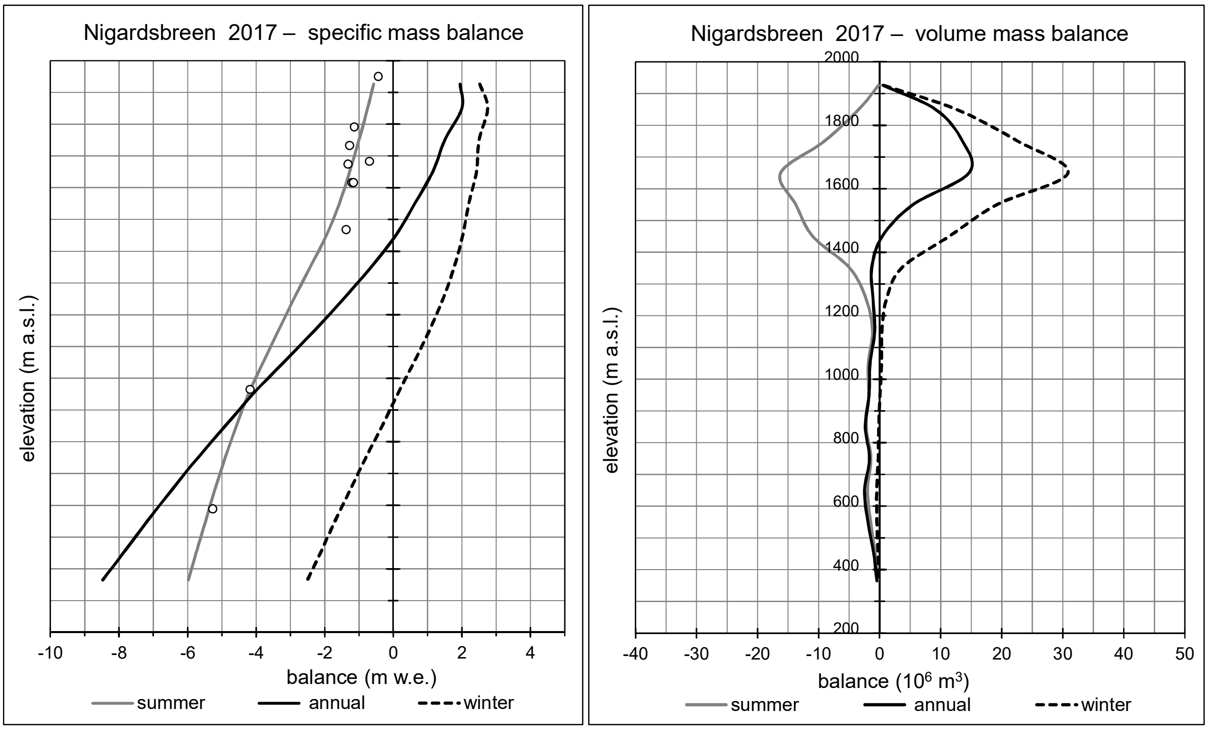


Figure 4-4
Mass balance diagram showing specific balance (left) and volume balance (right) for Nigardsbreen in 2017. Specific summer balance at ten stake positions is shown as circles (○).

According to Figure 4-4, the Equilibrium Line Altitude was 1440 m a.s.l. Consequently the Accumulation Area Ratio was 84 %.

Table 4-1
Winter, summer and annual balance for Nigardsbreen in 2017.

Mass balance Nigardsbreen 2016/17 – stratigraphic system

Altitude (m a.s.l.)	Area (km²)	Winter mass balance Measured 21st June 2017 Specific (m w.e.)	Volume (10^6 m³)	Summer mass balance Measured 18th Oct 2017 Specific (m w.e.)	Volume (10^6 m³)	Annual mass balance Summer surface 2016 - 2017 Specific (m w.e.)	Volume (10^6 m³)
1900 - 1952	0.28	2.53	0.7	-0.58	-0.2	1.95	0.5
1800 - 1900	4.58	2.75	12.6	-0.75	-3.4	2.00	9.2
1700 - 1800	9.05	2.50	22.6	-1.00	-9.1	1.50	13.6
1600 - 1700	12.72	2.43	30.9	-1.28	-16.2	1.15	14.6
1500 - 1600	8.72	2.20	19.2	-1.58	-13.7	0.63	5.5
1400 - 1500	5.61	2.03	11.4	-1.95	-10.9	0.08	0.4
1300 - 1400	2.02	1.78	3.6	-2.43	-4.9	-0.65	-1.3
1200 - 1300	0.75	1.45	1.1	-2.90	-2.2	-1.45	-1.1
1100 - 1200	0.35	1.05	0.4	-3.35	-1.2	-2.30	-0.8
1000 - 1100	0.50	0.60	0.3	-3.80	-1.9	-3.20	-1.6
900 - 1000	0.42	0.13	0.1	-4.23	-1.8	-4.10	-1.7
800 - 900	0.48	-0.33	-0.2	-4.58	-2.2	-4.90	-2.4
700 - 800	0.29	-0.80	-0.2	-4.90	-1.4	-5.70	-1.7
600 - 700	0.39	-1.25	-0.5	-5.20	-2.0	-6.45	-2.5
500 - 600	0.27	-1.70	-0.5	-5.48	-1.5	-7.18	-1.9
400 - 500	0.12	-2.13	-0.3	-5.75	-0.7	-7.88	-1.0
330 - 400	0.06	-2.50	-0.1	-5.98	-0.3	-8.48	-0.5
330 - 1952	**46.61**	**2.17**	**101.0**	**-1.58**	**-73.6**	**0.59**	**27.4**

4.2 Mass balance 1962-2017

The historical mass balance results for Nigardsbreen are presented in Figure 4-5. The cumulative annual balance for 1962-2017 is +6.2 m w.e., which gives a mean annual balance of +0.11 m w.e. a^{-1}.

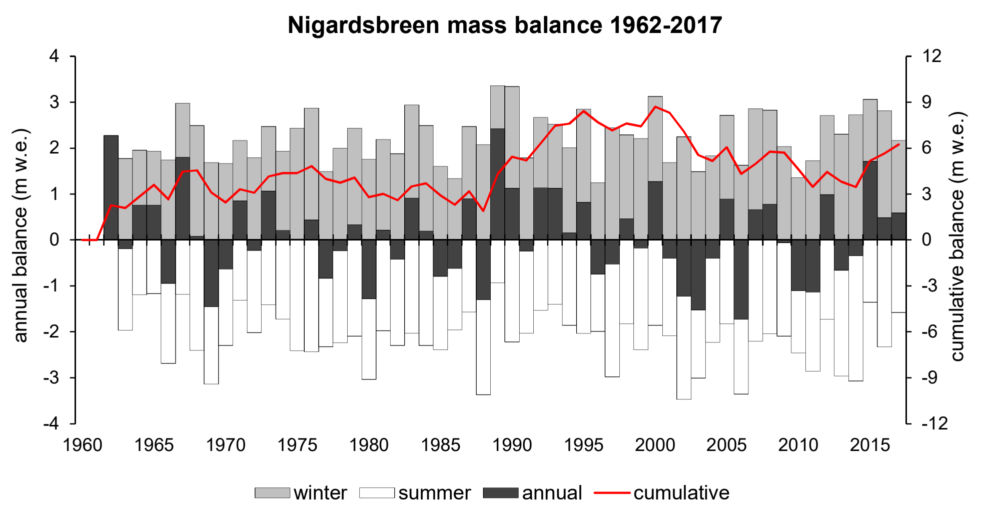


Figure 4-5
Winter, summer and annual balance at Nigardsbreen for 1962-2017. Cumulative mass balance is given on the right axis.

5. Austdalsbreen (Hallgeir Elvehøy)

Austdalsbreen (61°45′N, 7°20′E) is an eastern outlet of the northern part of Jostedalsbreen, ranging in altitude from 1200 to 1747 m a.s.l. The glacier terminates in Austdalsvatnet, which has been part of the hydropower reservoir Styggevatnet since 1988. Glaciological investigations at Austdalsbreen started in 1986 in connection with the construction of the hydropower reservoir.

The glaciological investigations in 2017 included mass balance, front position change and glacier velocity. The mass balance has been measured at Austdalsbreen since 1988.

5.1 Mass balance 2017

Fieldwork

Stakes were maintained through the winter in four of eight stake locations. Comparison of stake readings and snow depth soundings on 27th January 2017 indicated 15 cm and 5 cm of ice melt at stakes A92 and A90, respectively, after the measurement on 5th October 2016. This melting was included in the mass balance for 2015/16.

Snow accumulation measurements were performed on 10th May. The calculation of winter balance was based on measurement of four stakes, two corings and 40 snow depth soundings (Fig. 5-2). Detecting the summer surface was relatively easy. The snow depth varied from 3.65 to 6.40 m. Snow density was measured in one location (1490 m a.s.l.). The mean snow density of 5.0 m snow was 461 kg m^{-3}.

The stakes below 1400 m a.s.l. were measured on 23rd August, and two stakes were redrilled (Fig. 5-1). Stake heights were 4 to 4.5 m longer than measured on 10th May.

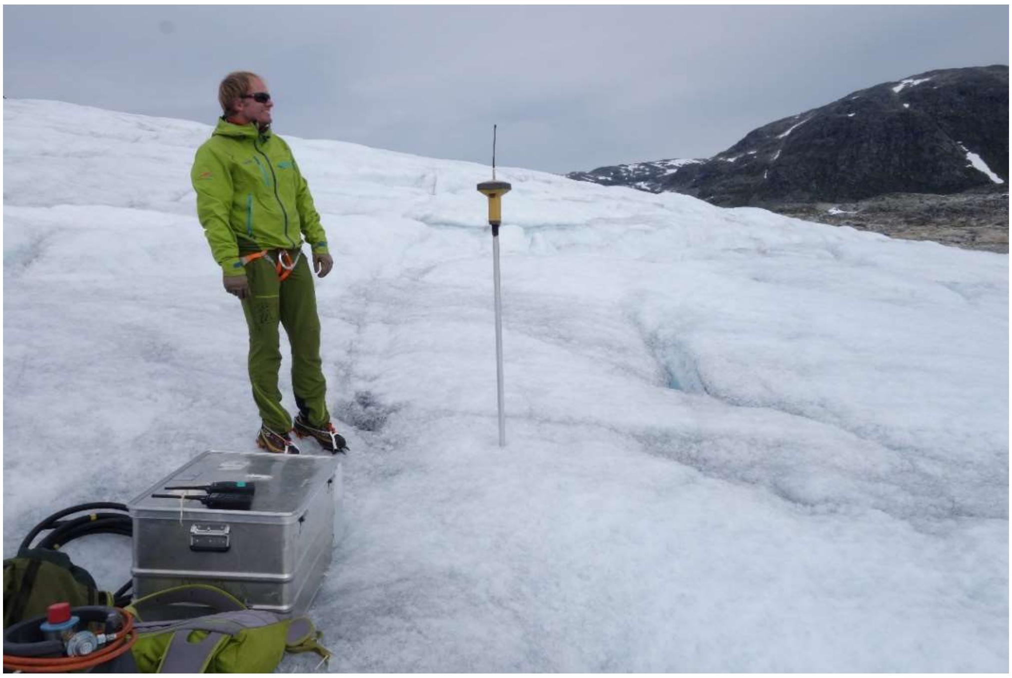


Figure 5-1
Stake A06 (see Fig. 5-2 for location) is positioned using dGNSS on 23rd August 2017. Photo: Hallgeir Elvehøy.

Summer and annual balance measurements were carried out on 18th October. There was up to 0.75 m of new snow on the glacier. Thirteen stakes in eight locations were found. The stakes were 1 to 1.5 m longer than in August. Based on stake observations, the temporary snow line altitude was approximately 1400 m a.s.l.

Results

The calculations are based on a DTM from 17th October 2009. The winter balance was calculated from snow depth and snow density measurements on 10th May. A function correlating snow depth with water equivalent was calculated based on snow density measurements at stake A60 (1490 m a.s.l.). The winter balance was 26 ±2 mill. m^3 water or 2.4 ±0.2 m w.e., which is 111 % of the 1988-2016 average (2.18 m w.e.). The winter balance was calculated from the spatial distribution of the 46 point measurements as 2.55 m w.e. (Fig. 5-2).

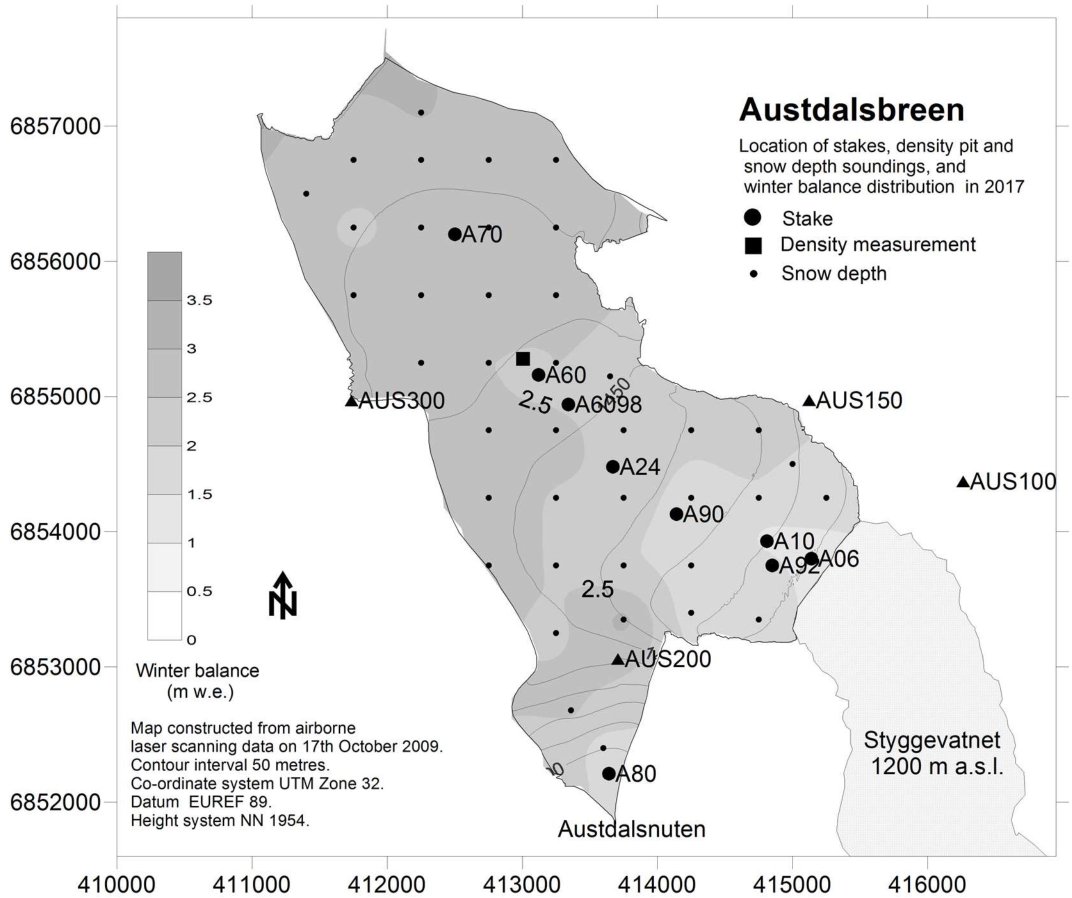


Figure 5-2
Location of stakes, density pit and snow depth soundings, and winter balance at Austdalsbreen in 2017 from 46 water equivalent values calculated from snow depth measurements.

The summer balance was calculated for ten stakes in eight stake locations between 1250 and 1720 m a.s.l. The summer balance curve was drawn from these ten point values (Fig. 5-3).

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

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

where ρ_{ice} is 900 kg m^{-3}, u_{ice} is annual glacier velocity (34 ±10 m a^{-1}, chap. 5.3), u_f is front position change averaged across the terminus (−11 ±5 m a^{-1}, chap. 5.2), W is terminus width (930 ±20 m) and H is mean ice thickness at the terminus (47 ±5 m). The mean ice thickness was calculated from mean surface elevations along the calving terminus surveyed on 5th October 2016 (1222 m a.s.l.) and 18th October 2017 (1227 m a.s.l.), and mean bottom elevation along the terminus (1178 m a.s.l.) calculated from a bottom topography map compiled from radar ice thickness measurements (1986), hot water drilling (1987) and lake depth surveying (1988 and 1989). The resulting calving volume was 1.8 ±0.8 mill. m^3 water equivalent.

The summer balance including calving was calculated as −24 ±3 mill. m^3 of water, which corresponds to −2.2 ±0.3 m w.e. The result is 82 % of the 1988-2016 average (−2.71 m w.e.). The calving volume was 8 % of the summer balance.

The annual balance at Austdalsbreen was calculated as +2 ±3 mill. m^3 water, corresponding to 0.2 ±0.3 m w.e. The average annual balance for the measurement period 1988-2017 is −0.54 m w.e. The ELA in 2017 was at 1408 m a.s.l., which corresponds to an AAR of 74 %. The altitudinal distribution of winter, summer and annual balance is shown in Figure 5-3 and Table 5-1. Results from 1988-2017 are shown in Figure 5-4.

Table 5-1
Altitudinal distribution of winter, summer and annual balances for Austdalsbreen in 2017.

Mass balance Austdalsbreen 2016/17 – stratigraphic system

		Winter mass balance Measured 10th May 2017		Summer mass balance Measured 18th Oct 2017		Annual mas balance Summer surfaces 2016 - 2017	
Altitude (m a.s.l.)	Area (km^2)	Specific (m w.e.)	Volume (10^6 m^3)	Specific (m w.e.)	Volume (10^6 m^3)	Specific (m w.e.)	Volume (10^6 m^3)
1700 - 1747	0.126	1.70	0.2	-1.25	-0.2	0.45	0.1
1650 - 1700	0.139	1.90	0.3	-1.35	-0.2	0.55	0.1
1600 - 1650	0.182	2.20	0.4	-1.50	-0.3	0.70	0.1
1550 - 1600	1.892	2.65	5.0	-1.60	-3.0	1.05	2.0
1500 - 1550	2.792	2.70	7.5	-1.70	-4.7	1.00	2.8
1450 - 1500	1.604	2.60	4.2	-1.80	-2.9	0.80	1.3
1400 - 1450	1.378	2.50	3.4	-2.20	-3.0	0.30	0.4
1350 - 1400	0.931	2.00	1.9	-2.60	-2.4	-0.60	-0.6
1300 - 1350	0.821	1.85	1.5	-3.00	-2.5	-1.15	-0.9
1250 - 1300	0.536	1.70	0.9	-3.40	-1.8	-1.70	-0.9
1200 - 1250	0.228	1.55	0.4	-3.80	-0.9	-2.25	-0.5
Calving					-1.8		-1.8
1200 - 1747	10.629	**2.42**	**25.7**	**-2.23**	**-23.7**	**0.19**	**2.0**

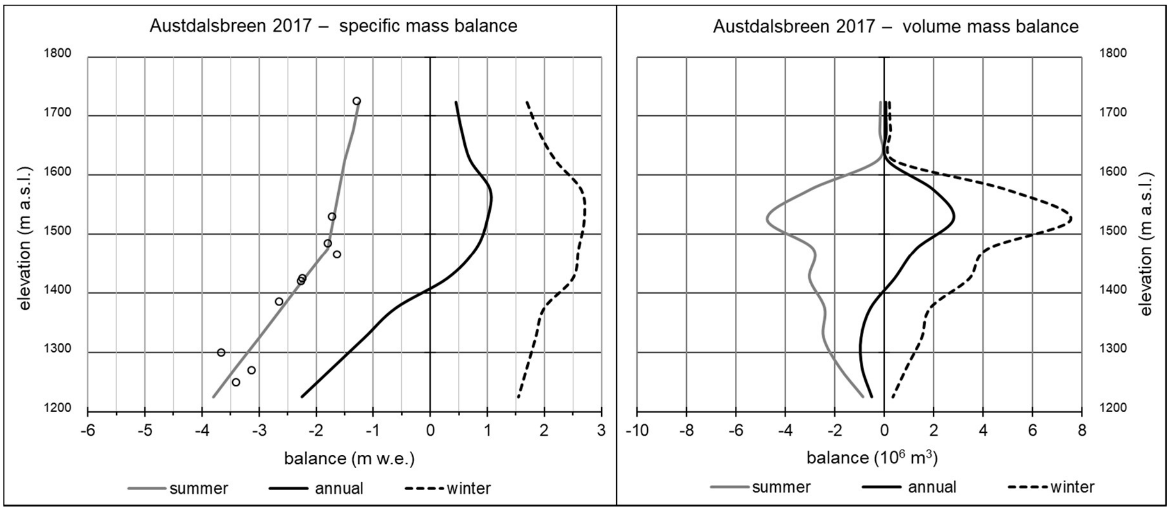


Figure 5-3
Altitudinal distribution of winter, summer and annual balance is shown as specific balance (left) and volume balance (right) at Austdalsbreen in 2017. Specific summer balance at ten stakes in eight stake locations is shown (○).

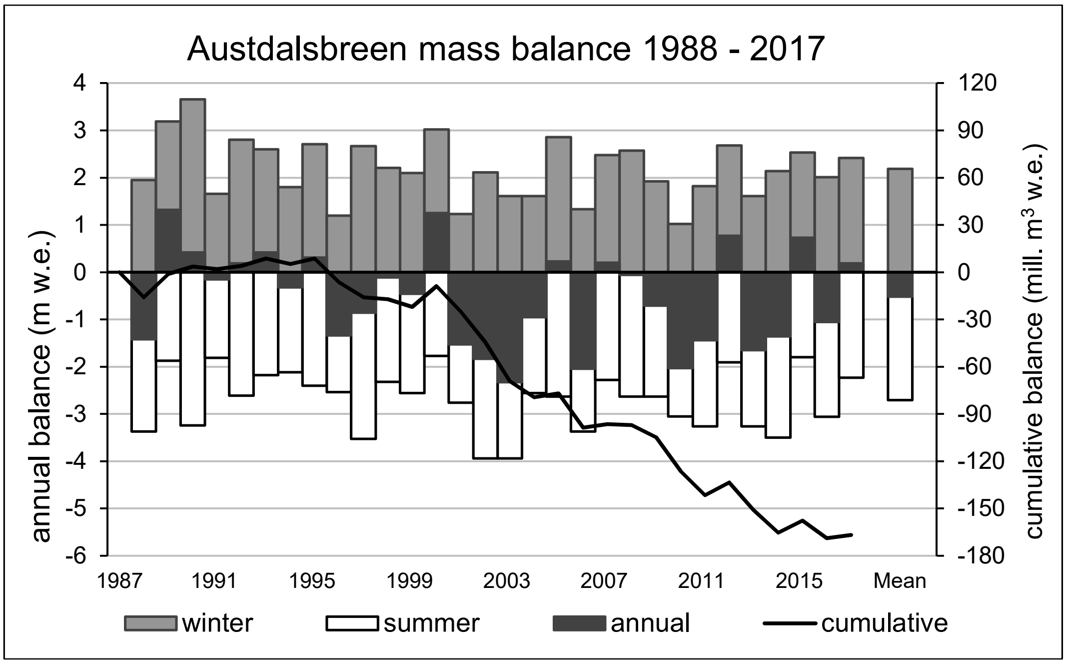


Figure 5-4
Winter, summer, annual and cumulative balance at Austdalsbreen during the period 1988-2017. Mean winter and summer balance is 2.18 and −2.72 m w.e., respectively. The cumulative mass balance is −167 mill m³ w.e. which corresponds to −15.6 m w.e.

5.2 Front position change

Eight points along the calving terminus were surveyed on 18th October 2017. The mean front position change was −11 ±5 m (Fig. 5-5) between 5th October 2016 and 18th October 2017. The width of the calving terminus was 930 ±20 m. Since 1988 the glacier terminus has retreated about 660 m, whilst the glacier area has decreased by approximately 0.622 km^2.

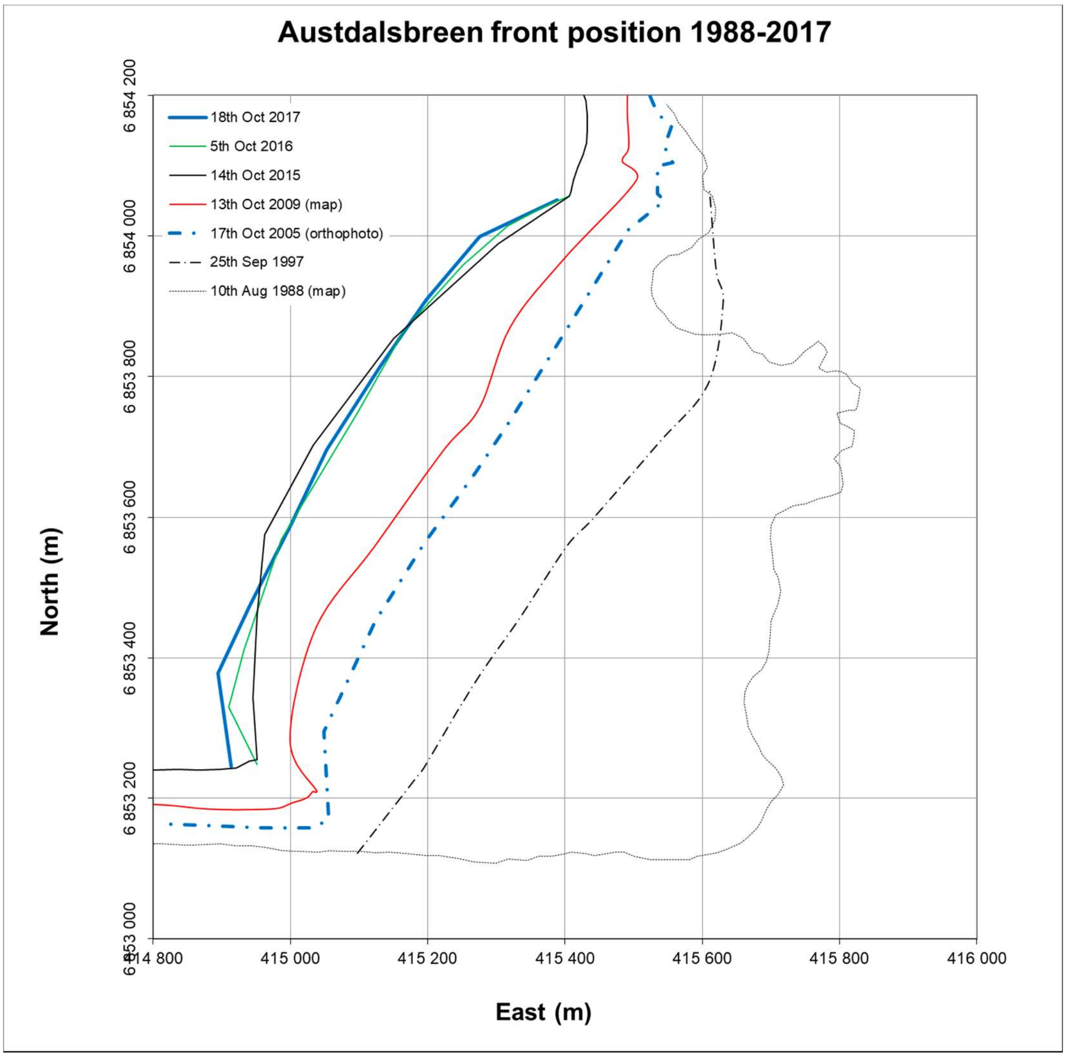


Figure 5-5
Surveyed front position of Austdalsbreen in 1988 when the lake was regulated, and in 1997, 2005, 2009 and 2015-17. The mean front position change between 5h October 2016 and 18th October 2017 was −11 m.

5.3 Glacier dynamics

Glacier velocities are calculated from repeated surveys of stakes. The stake network was surveyed on 16th August and 5th October 2016, and 10th May, 23rd August and 18th October 2017. Annual velocities were calculated for nine stake locations for the period 5th October 2016 – 18th October 2017 (378 days). The annual velocities at stake locations close to the terminus were 49 m a^{-1} at A6 (40 m a^{-1} in 2016), 55 m a^{-1} at A92 (50 m a^{-1} in 2016), and 43 m a^{-1} at A10 (41 m a^{-1} in 2016).

The glacier velocity averaged across the front width and thickness must be estimated in order to calculate the calving volume (chap. 5.1). Due to lower velocities at stake A6 than at A92, the expected velocity increase towards the calving front is neglected, and A6 is assumed to be representative for the centre line surface velocity. The glacier velocity averaged over the cross-section 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. The resulting glacier velocity averaged across the terminus for 2016/2017 is 34 ±10 m a^{-1}.

6. Rembesdalskåka (Hallgeir Elvehøy)

Rembesdalskåka (17 km^2, 60°32′N, 7°22′E) is a southwestern outlet glacier from Hardangerjøkulen, the sixth largest (73 km^2) glacier in Norway. The glacier is situated on the main water divide between Hardangerfjorden and Hallingdalen valley, and drains towards Simadalen valley and Hardangerfjorden. In the past Simadalen has been flooded by jøkulhlaups from the glacier-dammed lake Demmevatnet (Fig. 6-1) (see section 14.2), the most recent occurring in 2014, twice in 2016 and again in 2017.

In 1963, the Norwegian Polar Institute began mass balance measurements on Rembesdalskåka. The Norwegian Water Resources and Energy Directorate (NVE) has been responsible for the mass balance investigations since 1985. The investigated basin covers the altitudinal range between 1066 and 1854 m a.s.l. (2010).

Figure 6-1
Lake Demmevatnet on 18th October 2017. The lake drained in a jøkulhlaup on 27th-28th October. Demmevasshytta can be seen to the left in the mountainside above the glacier. Photo: Hallgeir Elvehøy.

6.1 Mass balance 2017

Fieldwork

The stake network was measured on 8th January and 27th January. Snow depth sounding and stake measurements at stake H10 on 5th January 2017 showed no ice melt after the autumn measurements on 25th October 2016.

The snow accumulation was measured as late in the season as 27th June. Three stakes on the glacier plateau showed up to 4.4 m of snow. Snow depth was measured at 61 sounding locations in a 500 by 500 m grid on the glacier plateau above 1500 m a.s.l. (Fig. 6-2). The snow depth was between 3 and 5 m above 1650 m a.s.l., and between 1 and 4 m between 1500 and 1650 m a.s.l. The summer surface (SS) was well defined. On the lower part of the glacier, snow depth was measured at 1200 and 1400 m a.s.l. The mean snow density down to 4.00 m depth at stake H7 was 599 kg m^{-3}. The snow depth to the SS was 5.0 m.

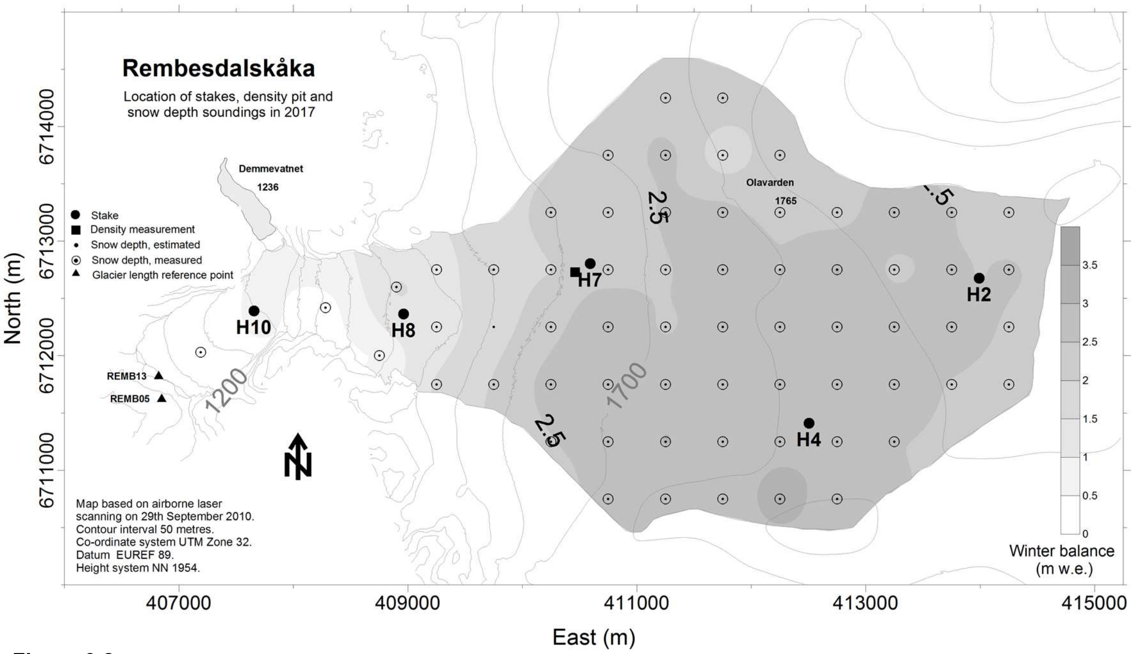


Figure 6-2
Winter balance at Rembesdalskåka interpolated from 61 snow depth soundings and five stake measurements of snow depth (•) and one estimated point.

On 22nd August the TLA was about 1500 m a.s.l. close to stake H8. At the glacier tongue all the winter snow and 1.8 m of ice had melted. At the upper stakes about 1.7 m of snow had melted, and up to 3 m of snow remained.

Summer and annual balance were measured on 18th October. There was up to 80 cm of new snow at stakes above 1500 m a.s.l. From stake measurements, the TLA was about 1500 m a.s.l. Up to 2.35 m of snow remained above the TLA. All the snow and 1.00 and 3.75 m of ice melted during the summer at stakes H8 and H10, respectively. The density of 2.35 m of remaining snow at H4 was 606 kg m^{-3}.

A snow depth sounding and stake measurement at stake H8 on 29th November 2017 indicated no ice melt after the autumn measurements on 18th October 2017.

Results

The calculation of the mass balance is based on a DTM from 2010. The winter balance was calculated from the snow depth and snow density measurements on 27th June. A snow depth-water equivalent profile was calculated based on snow density measurements at location H7 (1655 m a.s.l.). The snow depth measurements were transformed to water equivalent values using this profile. From the calculated water equivalent values, averages for 50 m elevation bands were calculated and plotted against altitude. An altitudinal winter balance curve was drawn from these averages (Fig. 6-3). Below 1500 m a.s.l. the winter balance curve was extrapolated from the measurements at stakes H8 (1510 m a.s.l.) and H10 (1250 m a.s.l.) and soundings at 1200 and 1400 m a.s.l. A value for each 50 m elevation was then determined from this curve. The resulting winter balance was 2.3 ±0.2 m w.e. or 39 ±3 mill. m^3 water. This is 106 % of the 1981-2010 average of 2.14 m w.e. a^{-1}, and 97 % of the 2012-16 average of 2.33 m w.e. a^{-1}.

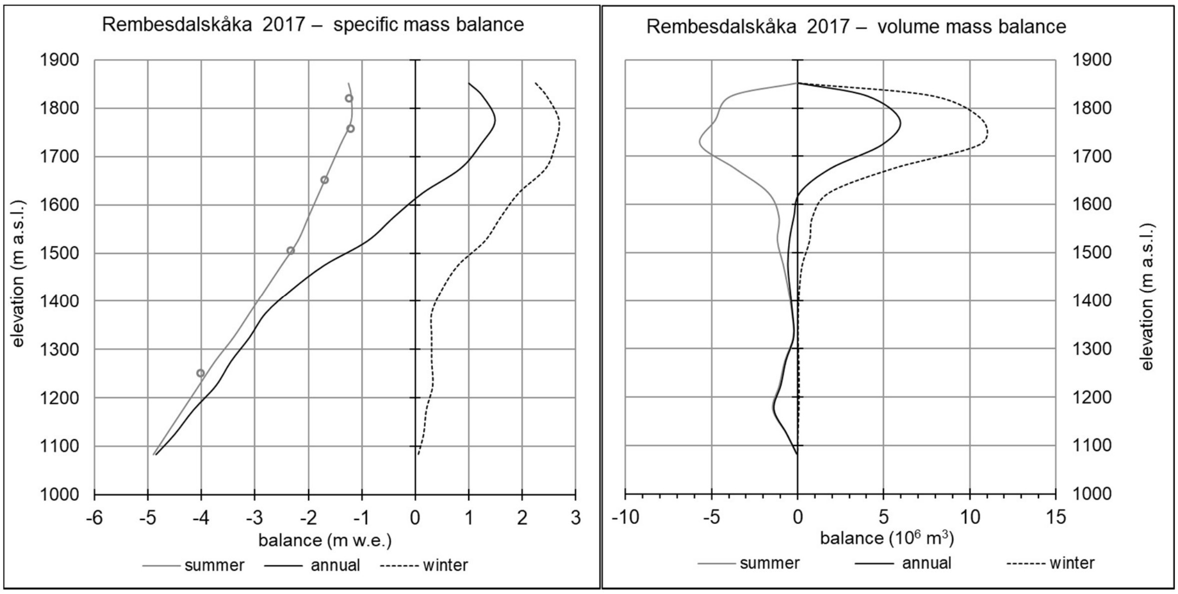


Figure 6-3
Altitudinal distribution of winter, summer and annual mass balance is shown as specific balance (left) and volume balance (right). Specific summer balance at five stakes is shown (○).

The true date of the 2017 mass balance maximum is probably around 19th May, and 0.1 to 0.3 m w.e. had melted by 27th June on the glacier plateau (www.senorge.no), (Saloranta, 2014). During the early part of the melt season, surface melt and refreezing in the winter snow pack increased the snow density to about 600 kg m^{-3}. On the glacier tongue below 1200 m a.s.l. all the winter snow had melted by 27th June. The winter maximum probably occurred around 5th May (www.senorge.no).

Based on the snow depth measurements the spatial distribution of the winter balance was interpolated using the kriging method. One point in the upper icefall was estimated. The distributed winter balance is shown in Figure 6-2, and the mean winter balance was 2.34 m w.e.

The date of the 2017 mass balance minimum for Rembesdalskåka was assessed by visual inspection of the daily changes in gridded data of the snow amount from www.senorge.no. Snow accumulation at the highest part of the glacier plateau probably started on 20th September and on the glacier tongue on 24th October.

The summer balance was calculated directly at all five stake locations. The density of the remaining snow at stakes H2, H4 and H7 was set as 600 kg m^{-3}, and the density of melted ice at H10 and H8 was set as 900 kg m^{-3}. The summer balance curve in Figure 6-3 was drawn from the five point values. The summer balance was calculated as −1.6 ±0.2 m w.e., corresponding to −28 ±3 mill. m^3 of water. This is 75 % of the 1981-2010 normal average, which is −2.16 m w.e. a^{-1}, and 65 % of the 2012-16 average of −2.50 m w.e. a^{-1}.

Table 6-1
Altitudinal distribution of winter, summer and annual mass balance at Rembesdalskåka in 2017.

Mass balance Rembesdalskåka 2016/17 – stratigraphic system

Altitude (m a.s.l.)	Area (km^2)	Winter mass balance Measured 27th June 2017 Specific (m w.e.)	Volume (10^6 m^3)	Summer mass balance Measured 18th Oct 2017 Specific (m w.e.)	Volume (10^6 m^3)	Annual mass balance Summer surface 2016 - 2017 Specific (m w.e.)	Volume (10^6 m^3)
1850 - 1854	0.029	2.25	0.1	-1.25	0.0	1.00	0.0
1800 - 1850	3.213	2.46	7.9	-1.20	-3.9	1.26	4.0
1750 - 1800	3.992	2.69	10.7	-1.20	-4.8	1.49	5.9
1700 - 1750	4.048	2.62	10.6	-1.40	-5.7	1.22	4.9
1650 - 1700	2.281	2.44	5.6	-1.60	-3.6	0.84	1.9
1600 - 1650	0.957	1.94	1.9	-1.80	-1.7	0.14	0.1
1550 - 1600	0.545	1.60	0.9	-2.00	-1.1	-0.40	-0.2
1500 - 1550	0.535	1.30	0.7	-2.20	-1.2	-0.90	-0.5
1450 - 1500	0.336	0.80	0.3	-2.50	-0.8	-1.70	-0.6
1400 - 1450	0.197	0.50	0.1	-2.80	-0.6	-2.30	-0.5
1350 - 1400	0.108	0.30	0.0	-3.10	-0.3	-2.80	-0.3
1300 - 1350	0.074	0.30	0.0	-3.40	-0.3	-3.10	-0.2
1250 - 1300	0.199	0.30	0.1	-3.75	-0.7	-3.45	-0.7
1200 - 1250	0.262	0.32	0.1	-4.05	-1.1	-3.73	-1.0
1150 - 1200	0.333	0.20	0.1	-4.35	-1.4	-4.15	-1.4
1100 - 1150	0.143	0.15	0.0	-4.65	-0.7	-4.50	-0.6
1066 - 1100	0.012	0.05	0.0	-4.90	-0.1	-4.85	-0.1
1066 - 1854	**17.264**	**2.26**	**39.0**	**-1.62**	**-27.9**	**0.64**	**11.1**

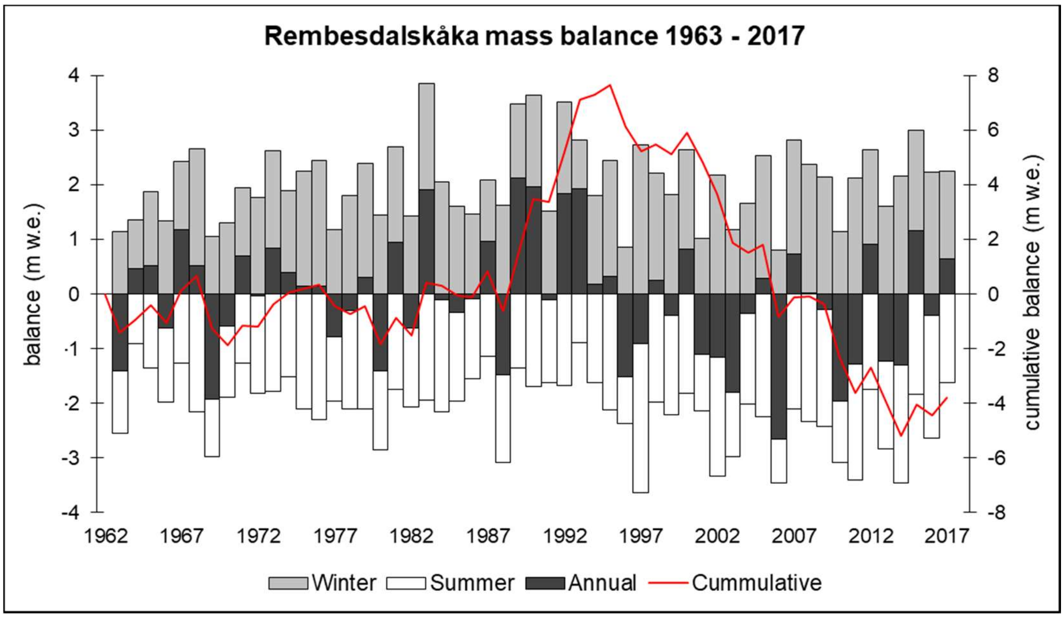


Figure 6-4
Winter, summer, annual and cumulative mass balance at Rembesdalskåka during the period 1963-2017. Mean values (1963-2017) are B_w=2.06 m w.e a^{-1} and B_s=−2.13 m w.e a^{-1}.

The annual balance at Rembesdalskåka was calculated as 0.6 ±0.3 m w.e. or 11 ±5 mill. m^3 water. The 1981-2010 normal value is -0.02 m w.e. a^{-1}, and the 2012-2016 average is −0.17 m w.e. a^{-1}. The altitudinal distribution of winter, summer and annual balances is shown in Figure 6-3 and Table 6-1. The ELA was 1612 m a.s.l. and the corresponding AAR was 83 %. Results from 1963-2017 are shown in Figure 6-4. The cumulative annual balance is −58 mill. m^3 w.e. Since 1995 the glacier has had a mass deficit of −189 mill. m^3 w.e.

7. Storbreen (Liss M. Andreassen)

Storbreen (61°34′N, 8°8′E) (now written with –an ending on official maps: Storbrean) is situated in the Jotunheimen mountain massif in central southern Norway. The glacier has relatively well-defined borders and is surrounded by high peaks (Fig. 7-1). Mass balance has been measured since 1949 there and front position (change in length) since 1902 (chap. 14.1).

Storbreen has a total area of 5.1 km^2 and ranges in altitude from 1400 to 2102 m a.s.l. (map of 2009, Fig. 7-2). The mass balance for 2017 was calculated based on the DTM and glacier outline from 2009.

Figure 7-1
Storbreen on 26th September 2017 showing the southern terminus and upper part.
Photo: Liss M. Andreassen.

7.1 Mass balance 2017

Field work

Snow accumulation measurements were performed on 2nd May. Stakes in 7 positions were visible and a total of 120 snow depth soundings were made (Fig. 7-2). The stake readings showed additional surface melting after the ablation measurements on 12th September in the previous mass balance year. The snow depth varied between 1.95 and 6.22 m, the mean being 3.47 m. Snow density was measured at stake 4 at 1715 m a.s.l. (3.12 m snow). The average measured snow density was 456 kg m^{-3}. Ablation measurements were performed on 26-27th September at stakes in all positions. There was snow and firn remaining at stakes 5, 6 and 8.

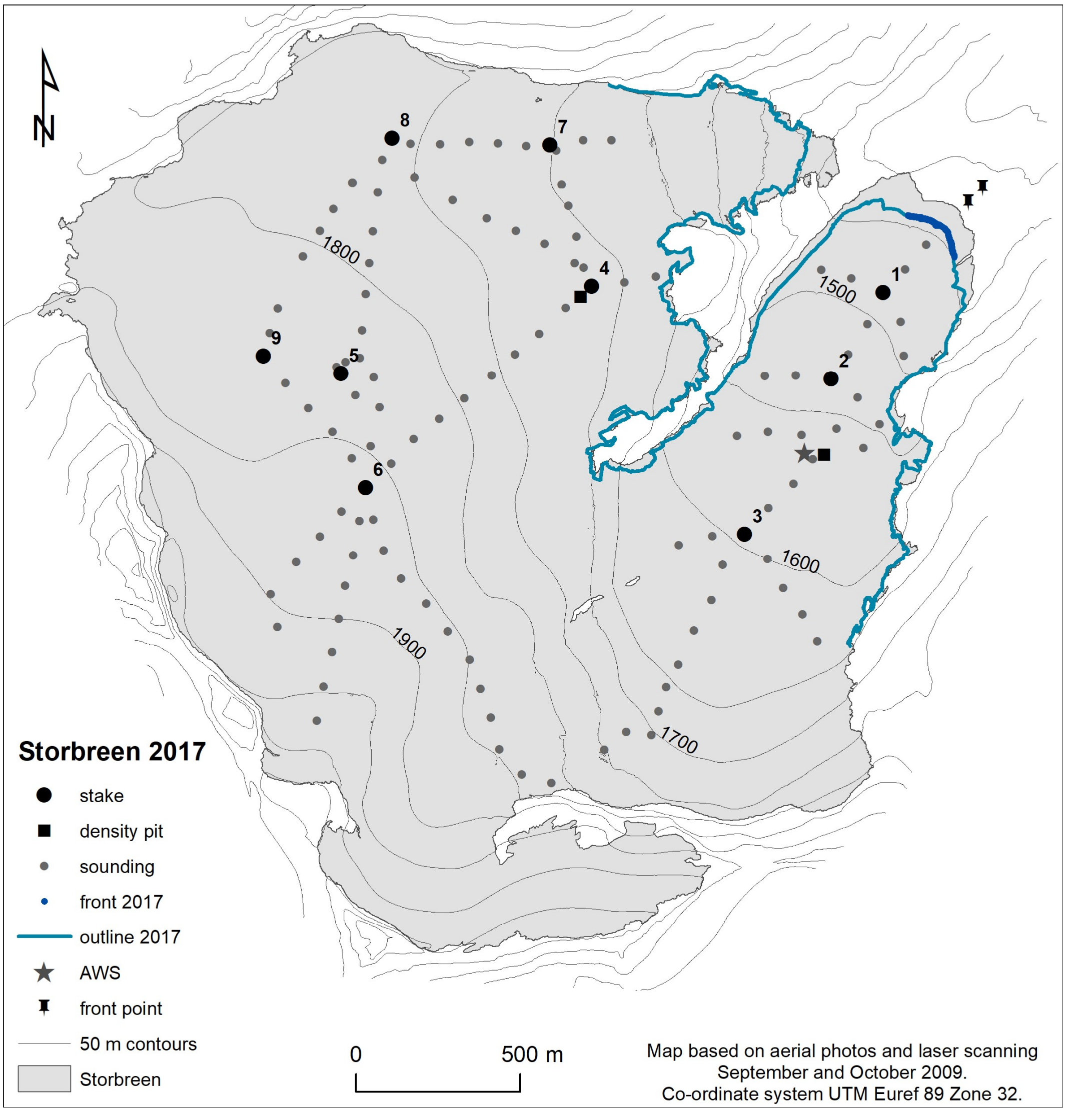


Figure 7-2
Location of stakes, soundings and density pits at Storbreen in 2017. The 50 m contours and the glacier outline is from aerial photos and laser scanning acquired in September and October 2009. The position of the automatic weather station (AWS), reference points used for length change (front point) measurements (see chap. 14.1) and part of the glacier outline mapped from an orthophoto taken by a drone on 26th September (outline 2017) and GNSS measurements (front 2017) on 27th September are also shown.

Results

The winter accumulation was calculated from the mean of the soundings within each 50-metre height interval and was 1.37 ± 0.2 m w.e. Subtracting melting that occurred after the measurements on 9th September 2015 resulted in a winter balance of 1.17 m w.e. ± 0.2 m w.e., which is 76 % of the mean winter balance for the reference period 1971-2000. Summer (and annual) balance was calculated directly from stakes at eight locations. The summer balance was interpolated to 50 m height intervals based on the stake readings and was −1.69 ±0.2 m w.e., which is 118 % of the mean summer balance for the reference period 1971-2000. The annual balance of Storbreen was −0.52 ±0.3 m w.e. in 2017. The equilibrium-line altitude (ELA) calculated from the annual balance diagram (Fig. 7-3) was ~1800 m a.s.l. resulting in an accumulation area ratio (AAR) of 41 %.

The mass balance results are shown in Table 7-1 and the corresponding curves for specific and volume balance are shown in Figure 7-3.

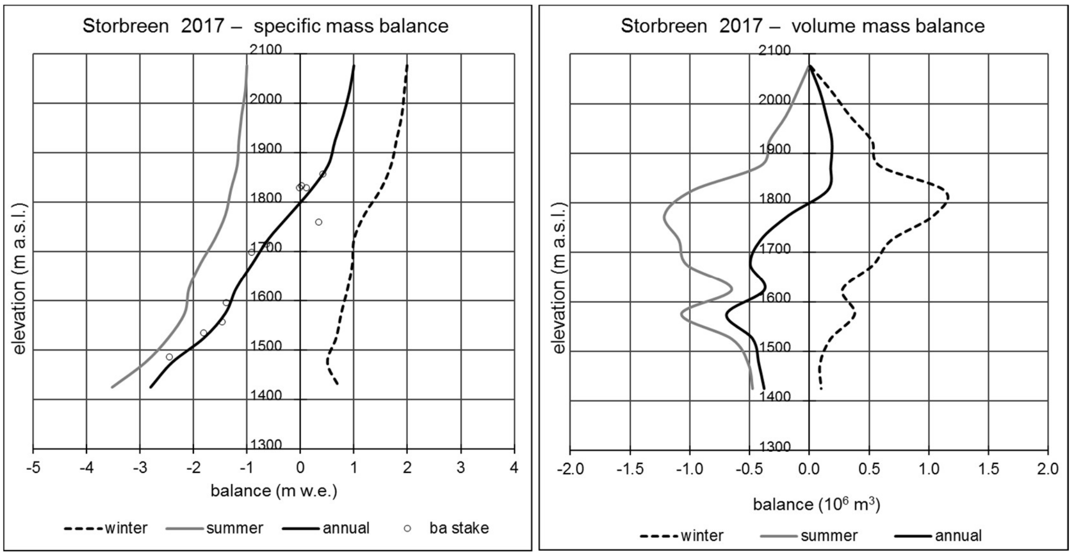


Figure 7-3
Mass balance versus altitude for Storbreen 2017, showing specific balance on the left and volume balance on the right. Winter accumulation soundings and summer and annual balance at eleven stakes are also shown. Winter balance is adjusted for additional melt (not shown) after ablation measurement on 12th September 2017.

Table 7-1
The distribution of winter, summer and annual balance in 50 m altitudinal intervals for Storbreen in 2017.

Mass balance Storbreen 2016/17 – stratigraphic system

Altitude (m a.s.l.)	Area (km^2)	Winter mass balance, Measured 2 May 2017: Specific (m w.e.)	Winter: Volume (10^6 m^3)	Summer mass balance, Measured 27 Sep 2017: Specific (m w.e.)	Summer: Volume (10^6 m^3)	Annual mass balance, Summer surfaces 2016-17: Specific (m w.e.)	Annual: Volume (10^6 m^3)
2050 - 2102	0.00	2.00	0.01	-1.00	0.00	1.00	0.00
2000 - 2050	0.10	1.95	0.19	-1.03	-0.10	0.92	0.09
1950 - 2000	0.18	1.90	0.34	-1.10	-0.20	0.80	0.14
1900 - 1950	0.29	1.80	0.52	-1.15	-0.33	0.65	0.19
1850 - 1900	0.35	1.70	0.59	-1.18	-0.41	0.52	0.18
1800 - 1850	0.75	1.50	1.13	-1.30	-0.98	0.20	0.15
1750 - 1800	0.87	1.20	1.04	-1.40	-1.21	-0.20	-0.17
1700 - 1750	0.68	1.00	0.68	-1.60	-1.09	-0.60	-0.41
1650 - 1700	0.55	0.97	0.53	-1.87	-1.03	-0.90	-0.49
1600 - 1650	0.31	0.88	0.28	-2.08	-0.65	-1.20	-0.37
1550 - 1600	0.50	0.76	0.38	-2.16	-1.07	-1.40	-0.69
1500 - 1550	0.26	0.67	0.18	-2.47	-0.65	-1.80	-0.47
1450 - 1500	0.18	0.50	0.09	-2.90	-0.51	-2.40	-0.42
1400 - 1450	0.14	0.72	0.10	-3.52	-0.48	-2.80	-0.38
1400 - 2102	**5.14**	**1.17**	**6.04**	**-1.69**	**-8.70**	**-0.52**	**-2.66**

7.2 Mass balance 1949-2017

The cumulative balance over 1949-2017 is –24.4 m w.e, and the mean annual balance for this period of 69 years is −0.35 m w.e. (Fig. 7-4). For the period 2001-2017 the mean annual balance is −0.84 m w.e.

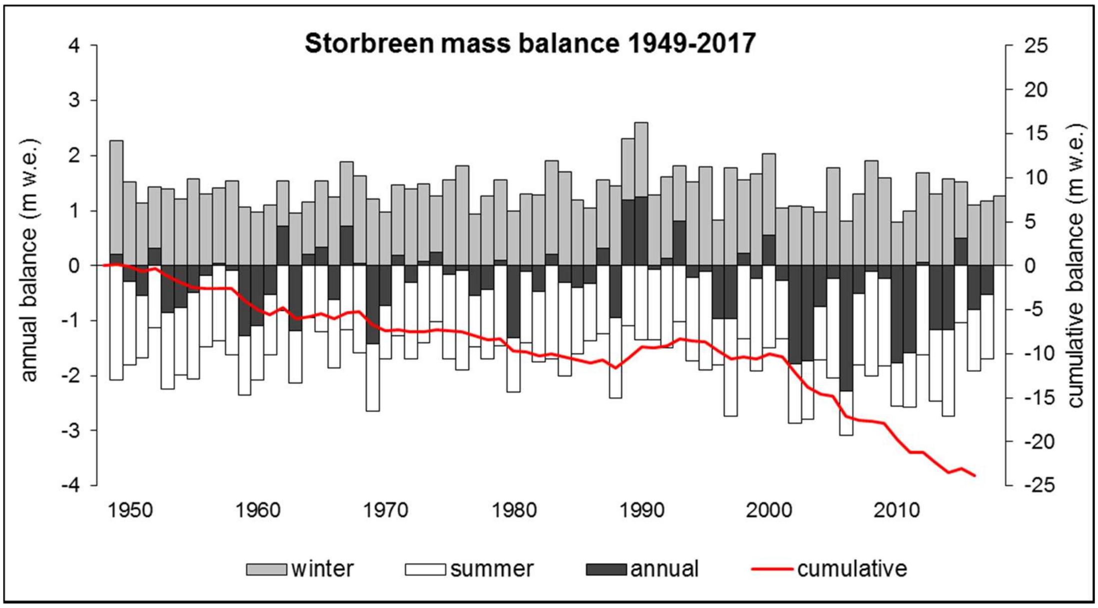


Figure 7-4
Winter, summer, annual and cumulative mass balance at Storbreen for the period 1949-2017.

7.3 Survey

The lower part of Storbreen was surveyed with a fixed wing drone on 26th September 2017 (Andreassen and De Marco, 2018). The imagery was used to produce an orthophoto (Fig. 7-5). Surveys by GNSS and drone show retreat of the glacier since the 2009 mapping. The northern tongue has retreated 90-120 m and the southern tongue where the front measurements are carried out has retreated 60-110 m from 2009 to 2017.

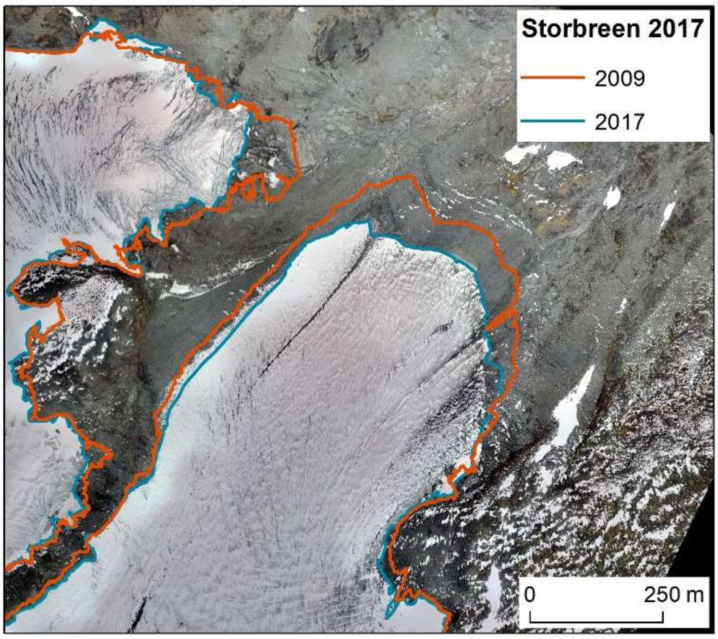


Figure 7-5
Orthophoto of the lower part of Storbreen on 26th September. The photo was acquired using a fixed wing drone.

7.4 Ice velocity 2016-2017

The surface ice velocity was calculated from GNSS measurements of the stakes. The position of the stakes were measured on 12th September 2016 and on 26th – 27th September 2017. For two of the stakes, however, measurements represents the period 9th September 2015 to 12th September 2016 as measurements were not usable from 2017. The calculated surface ice velocities reveal annual velocities between 2.6 and 10.3 m/year (Fig. 7-6). The uncertainty of the measurements are between 0.1 and 0.5 m.

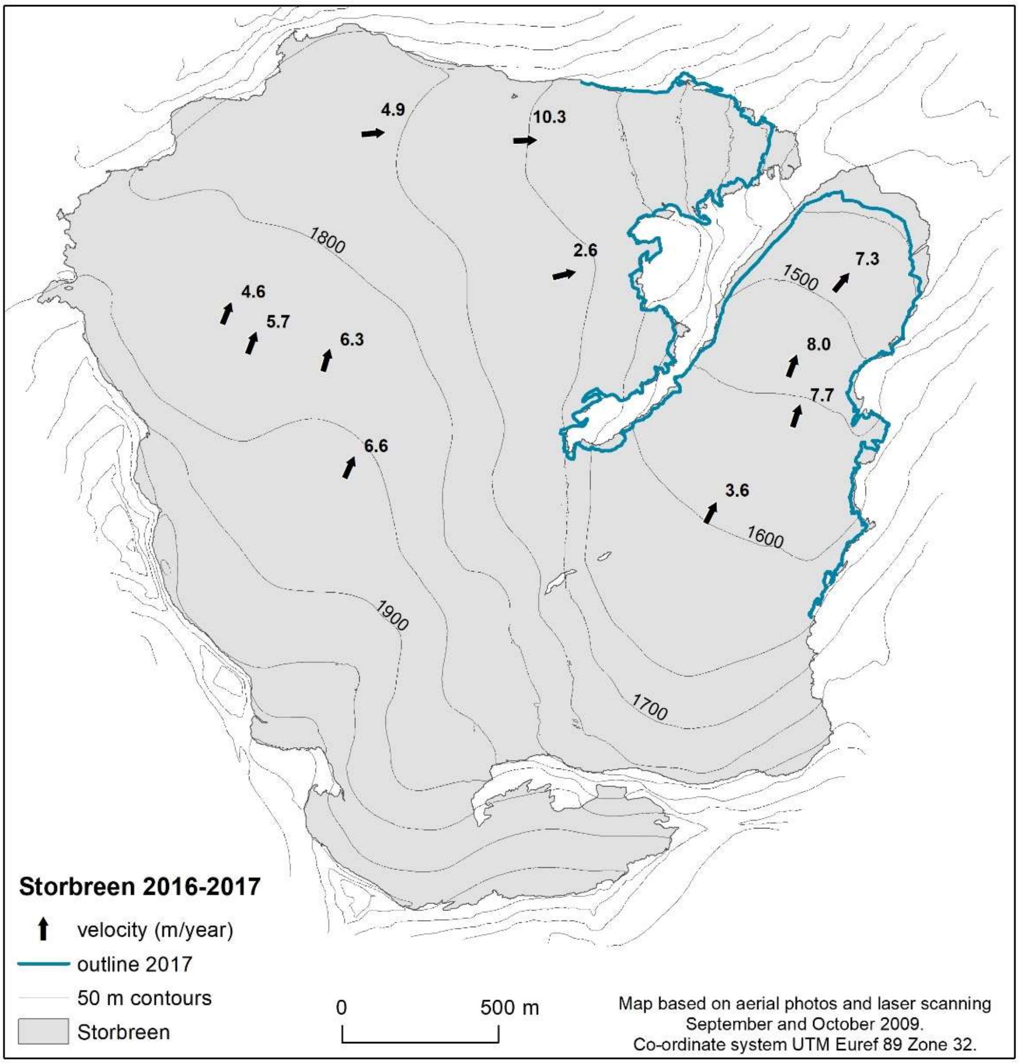


Figure 7-6
Map of Storbreen showing annual surface velocities calculated from stake position measurements on 12th September 2016 and 26th -27th September 2017. For two of the stakes (stake 7 (10.3 m/year) and stake at the AWS (7.7 m/year)) measurements represents the period 9th September 2015 to 12th September 2016. See also Figure 7-2.

8. Juvfonne (Liss M. Andreassen)

Juvfonne (61°40′N, 8°21′E) is a small, ice patch situated in the Jotunheimen mountain massif in central southern Norway (Fig. 8-1). Mass balance measurements began in May 2010. The measurements on Juvfonne were started as a contribution to 'Mimisbrunnr\ Klimapark 2469' – a nature park and forum for research and dissemination activities in the alpine region around Galdhøpiggen, the highest mountain peak in Norway (2469 m a.s.l.). Measurements of the ice reveal old ice, the age of the ice is ca. 7600 cal years BP at the bottom (Ødegård et al., 2017).

The observation programme of Juvfonne in 2017 consisted of accumulation measurements in spring, seasonal and annual balances measured at one stake, and survey of the ice patch extent and front position. A survey of the ice patch was also done with an unmanned aerial vehicle (UAV) in August and September 2017. Mass balance calculations are based on a digital terrain model and digital outline derived from airborne laser scanning and orthophoto taken on 17th September 2011. According to this survey Juvfonne has an area of 0.127 km^2 and altitudinal range from 1841 to 1986 m a.s.l. The extent of Juvfonne has been surveyed annually on foot with a Global Navigation Satellite System (GNSS) instrument mounted on a backpack since 2010. The measurements of areal extent show that the ice patch shrinks and grows along the whole of the margin.

Figure 8-1
Juvfonne on 1st August 2017. Only a small part of the ice patch had bare ice exposed at that time. Photo: Solveig H. Winsvold.

8.1 Survey 2017

The ice patch extent was measured with handheld GNSS on 18th September along the whole perimeter except parts of the southern rim. Parts of the ice patch were snow-covered at the time of the survey (Fig. 8-2). Juvfonne was also photographed with an UAV on 1st August and 18th and 25th September. Due to weather and light conditions that were not favourable in the September surveys, the results from 1st August are presented here. These results were used to produce an orthophoto (Fig. 8-2) and digital terrain model of the surface. The total area including seasonal and perennial snow was 0.183 km^2.

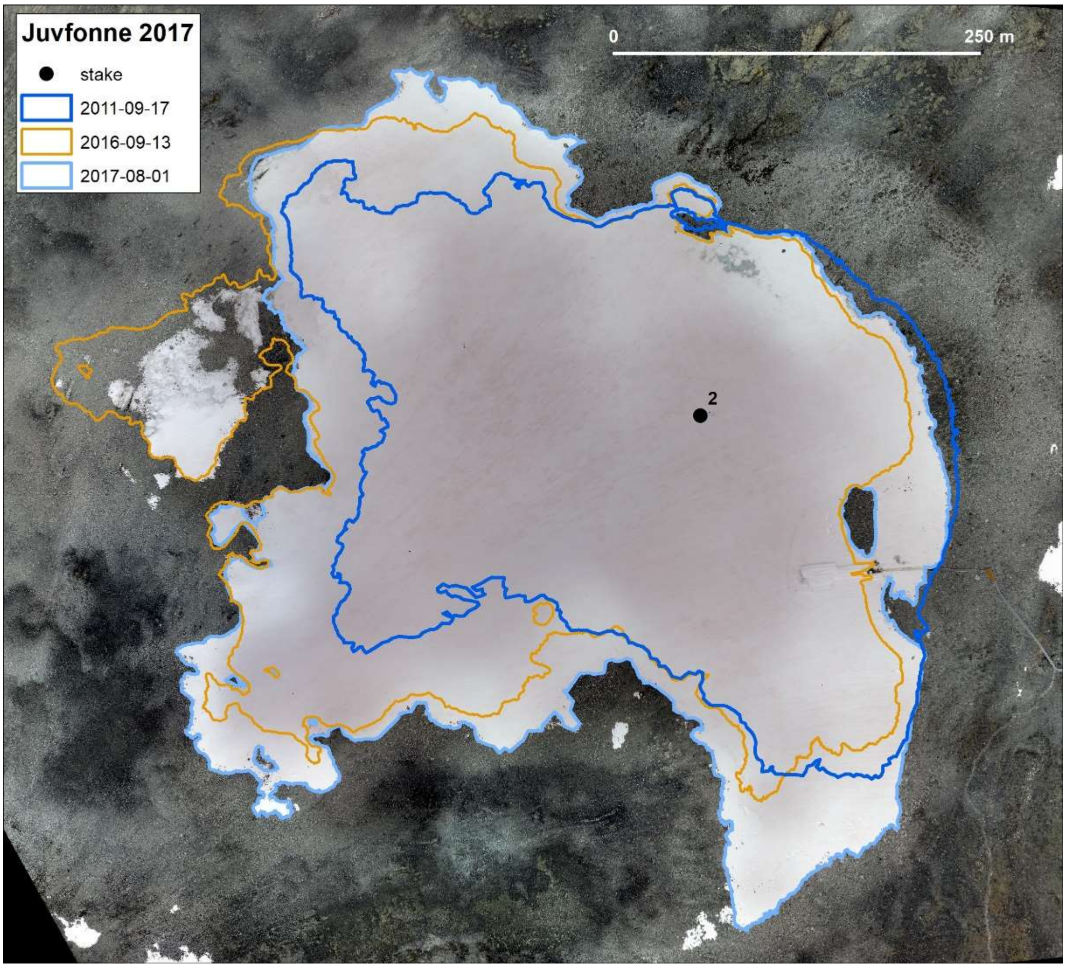


Figure 8-2
Orthophoto of Juvfonne on 1st August September 2017 derived from a UAV survey. The extent of the icepatch in 2017 derived from GNSS on the same day and partly digitised from the orthophoto. The position of stake 2 and the ice patch extent in 2011 and 2016 are also shown.

8.2 Mass balance 2017

Field work

The accumulation measurements on Juvfonne were carried out on 11th May. A total of 28 snow depth soundings were made (Fig. 8-3). Snow depths varied between 1.95 and 4.25 m with a mean of 3.32 m. The snow density was measured in a pit down to the previous summer surface near stake 2, where the depth down to the 2016 summer surface was 3.85 m. The density of only the uppermost 2.5 m was measured, which had a density of 438 kg m^{-3}.

Ablation measurements were carried out on 25th September at stake 2. There was fresh snow covering the remaining snow from the winter. The density of the remaining snow was assumed to be 600 kg m^{-3}.

Results

Seasonal surface mass balances have been measured since 2010 at stake 2. In 2017 the remaining snow gave a surplus at this location. The winter balance (1.69 m w.e.) exceeded the summer balance (−1.43 m w.e.), giving a net surplus of 0.25 ±0.1 m w.e. at this location. The cumulative mass balance for stake 2 over the eight years of measurements is –9.7 m w.e., or –1.22 m w.e. a^{-1} (Fig. 8-4). Glacier-wide mass balance was not calculated; this was calculated for only the first year of measurements 2009/2010 when more stakes were measured.

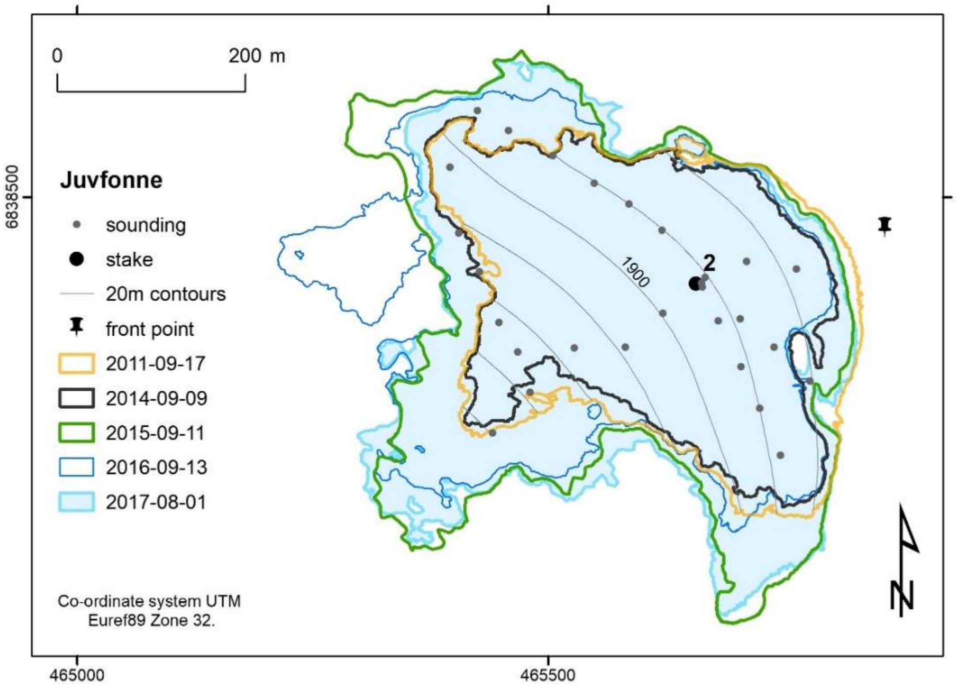


Figure 8-3
Location of snow depth soundings in 2017 and the position of stake 2 where density is measured. The ice patch extents in 2017 (combined GNSS and UAV orthophoto), 2016 (GNSS-measurements), 2015 (GNSS-measurements), 2014 (GNSS-measurements) and 2011 (orthophoto) are shown. Front point marks the reference point for front position and length change measurements (see chap. 14.1).

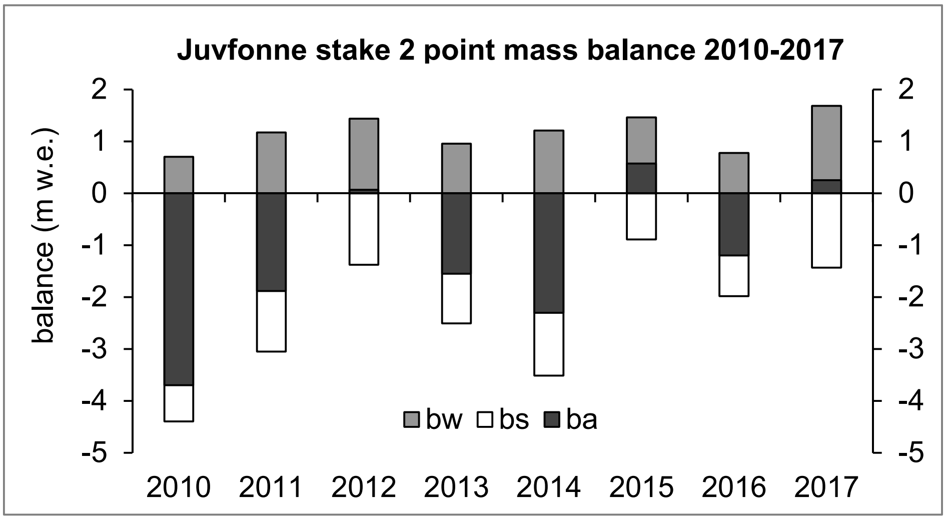


Figure 8-4
Point mass balance at stake 2 at Juvfonne 2010-2017, given as winter balance (b_w), summer balance (b_s) and annual balance (b_a).

9. Hellstugubreen (Liss M. Andreassen)

Hellstugubreen (61°34′N, 8° 26′E) (now written with –an ending on official maps: Hellstugubrean) is a north-facing valley glacier situated in central Jotunheimen (Fig. 9-1). The glacier shares a border with Vestre Memurubre glacier. Annual mass balance measurements began in 1962. The calculations presented here are based on the latest survey of the glacier from 2009. According to this map, Hellstugubreen ranges in elevation from 1482 to 2229 m a.s.l. and has an area of 2.9 km^2, but measurements along the terminus show retreat since 2009 (Fig. 9-2).

Figure 9-1
Hellstugubreen during the ablation measurements on 19th September 2017. Photo: Liss M. Andreassen.

9.1 Mass balance 2017

Field work

Accumulation measurements were performed on 3rd May. Stake readings indicated additional melting after the ablation measurements on 12th September 2016. Snow depths were measured in 70 positions between 1537 and 2161 m a.s.l., overing most of the altitudinal range of the glacier. The snow depth varied between 0.47 and 3.73 m, with a mean of 2.18 m. Snow density was measured in a density pit at 1954 m a.s.l. The total snow depth was 2.55 m and the resulting density was 397 kg m^{-3}. Ablation measurements were carried out on 19th September, fresh snow covered the middle and upper parts of the glacier (Fig. 9-3). The snowline from the previous winter was thus not possible to observe on site.

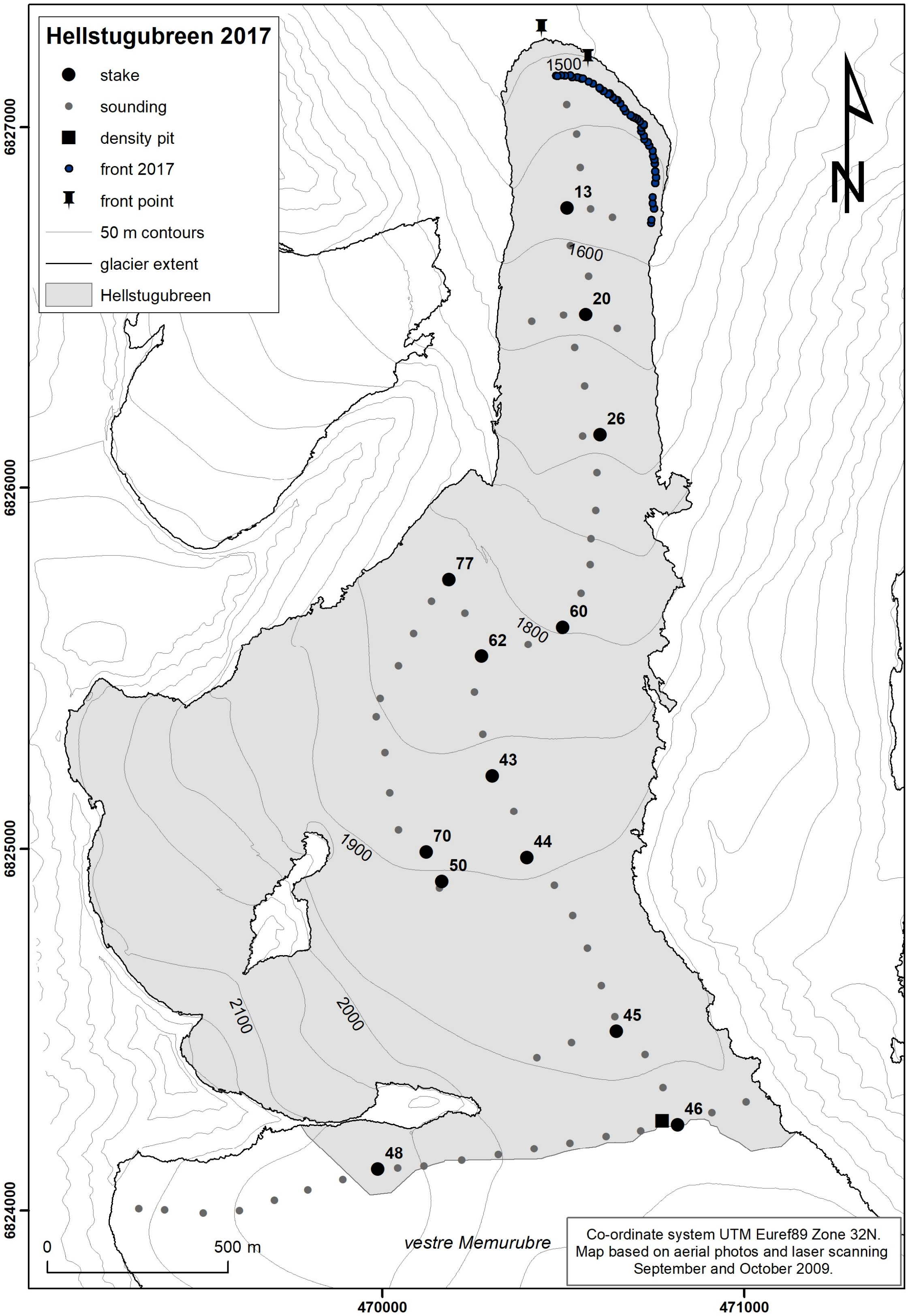


Figure 9-2
Map of Hellstugubreen showing the location of stakes, snow depth soundings and snow pit in 2017. Since 2009 the glacier terminus has retreated. Part of the terminus (front 2017) mapped by GNSS-survey in shown on the map together as well as front reference points used for front position and length change measurements (chap. 14-1).

Figure 9-3
Fresh snow covered the glacier during the ablation measurements on 19th September 2017. Photo: Solveig H. Winsvold.

Results

The calculations are based on the DTM from 2009. The winter accumulation was calculated as the mean of the soundings within each 50-metre height interval and was 0.87 ±0.2 m w.e. Subtracting for additional melt, the winter balance was 0.69 ±0.2 m w.e. which is 63 % of the mean winter balance for the reference period 1971-2000. The summer balance was interpolated to 50 m height intervals based on the stake readings and was –1.26 ±0.2 m w.e., which is 95 % of the mean summer balance for the reference period 1971-2000. The annual balance of Hellstugubreen was −0.57 ±0.3 m w.e. The equilibrium line altitude (ELA) was estimated as 1960 m a.s.l., resulting in an accumulation area ratio (AAR) of 27 %. The mass balance results are shown in Table 9-1 and the corresponding curves for specific and volume balance are shown in Figure 9-4.

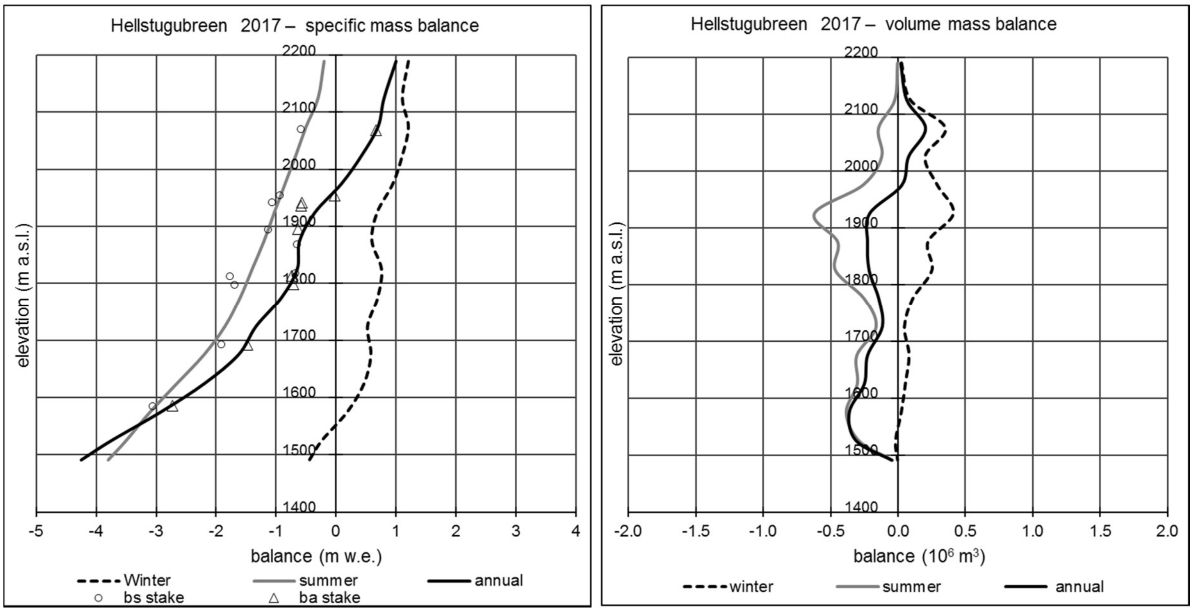


Figure 9-4
Mass balance diagram for Hellstugubreen in 2017, showing specific balance on the left and volume balance on the right. Summer and annual balance at stakes are also shown.

Table 9-1
The distribution of winter, summer and annual balance in 50 m altitudinal intervals for Hellstugubreen in 2017.

Mass balance Hellstugubreen 2016/17 – stratigraphic system

Altitude (m a.s.l.)	Area (km^2)	Winter mass balance Measured 3rd May 2017 Specific (m w.e.)	Volume (10^6 m^3)	Summer mass balance Measured 19th Sep 2017 Specific (m w.e.)	Volume (10^6 m^3)	Annual mass balance Summer surfaces 2016 - 2017 Specific (m w.e.)	Volume (10^6 m^3)
2150 - 2229	0.02	1.20	0.02	-0.20	0.00	1.00	0.02
2100 - 2150	0.08	1.10	0.09	-0.30	-0.02	0.80	0.06
2050 - 2100	0.29	1.20	0.35	-0.50	-0.15	0.70	0.20
2000 - 2050	0.18	1.10	0.20	-0.67	-0.12	0.43	0.08
1950 - 2000	0.31	0.94	0.29	-0.85	-0.26	0.09	0.03
1900 - 1950	0.60	0.68	0.41	-1.03	-0.62	-0.35	-0.21
1850 - 1900	0.37	0.59	0.22	-1.20	-0.45	-0.61	-0.23
1800 - 1850	0.33	0.75	0.25	-1.40	-0.46	-0.65	-0.22
1750 - 1800	0.16	0.69	0.11	-1.60	-0.25	-0.91	-0.14
1700 - 1750	0.09	0.52	0.05	-1.85	-0.16	-1.33	-0.12
1650 - 1700	0.14	0.57	0.08	-2.20	-0.31	-1.63	-0.23
1600 - 1650	0.11	0.46	0.05	-2.65	-0.30	-2.19	-0.25
1550 - 1600	0.12	0.18	0.02	-3.10	-0.38	-2.92	-0.36
1500 - 1550	0.08	-0.24	-0.02	-3.50	-0.29	-3.74	-0.31
1482 - 1500	0.01	-0.45	0.00	-3.80	-0.04	-4.25	-0.05
1482 - 2229	**2.90**	**0.73**	**2.11**	**-1.32**	**-3.83**	**-0.59**	**-1.71**

9.2 Mass balance 1962-2017

The cumulative annual balance of Hellstugubreen since 1962 amounts to –22.2 m w.e. (Fig. 9-5), giving a mean annual deficit of 0.39 m w.e. per year. Since 2001, the cumulative mass balance is –13.0 m w.e., giving a mean annual deficit of 0.78 m w.e. for this period.

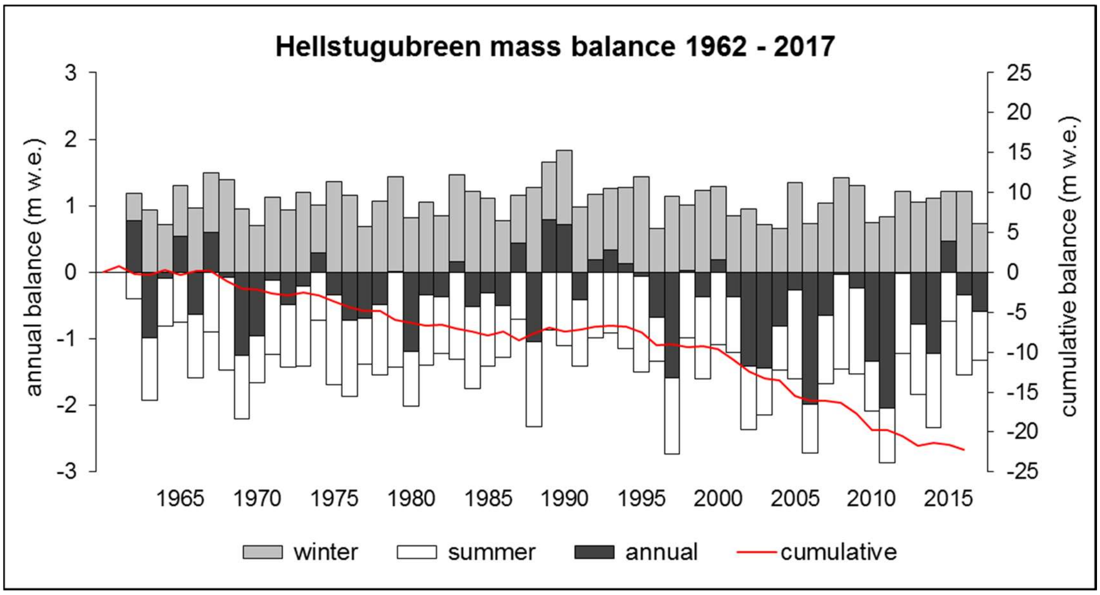


Figure 9-5
Winter, summer and annual balance at Hellstugubreen for 1962-2017, and cumulative mass balance for the whole period.

10. Gråsubreen (Liss M. Andreassen)

Gråsubreen (61°39′N, 8°37′E) (now written with an -an ending on official maps: Gråsubrean) is a small, polythermal glacier in the eastern part of the Jotunheimen mountain area in southern Norway (Fig. 10-1). Gråsubreen has an area of 2.12 km^2 and ranges in elevation from 1833 to 2283 m a.s.l. (map of 2009). Mass balance investigations have been carried out annually since 1962. Gråsubreen is the easternmost glacier, has the smallest mass turnover and the densest stake network of the monitored glaciers in Norway.

Ice temperature and ice thickness measurements carried out in 2012 show that Gråsubreen consists of relatively thin, cold ice which is underlain by a zone of temperate ice in the central, thicker part of the glacier where the ice is more than 130 m thick (Sørdahl, 2013; Andreassen et al., 2015). The distribution of accumulation and ablation at Gråsubreen is strongly dependent on the glacier geometry. In the central part of the glacier snowdrift causes a relatively thin snow pack, whereas snow accumulates in sheltered areas at lower elevations. Thus at Gråsubreen the equilibrium line altitude (ELA) and accumulation area ratio (AAR) are often difficult to define from the mass balance curve or in the field, and the estimated values of ELA and AAR have little physical significance.

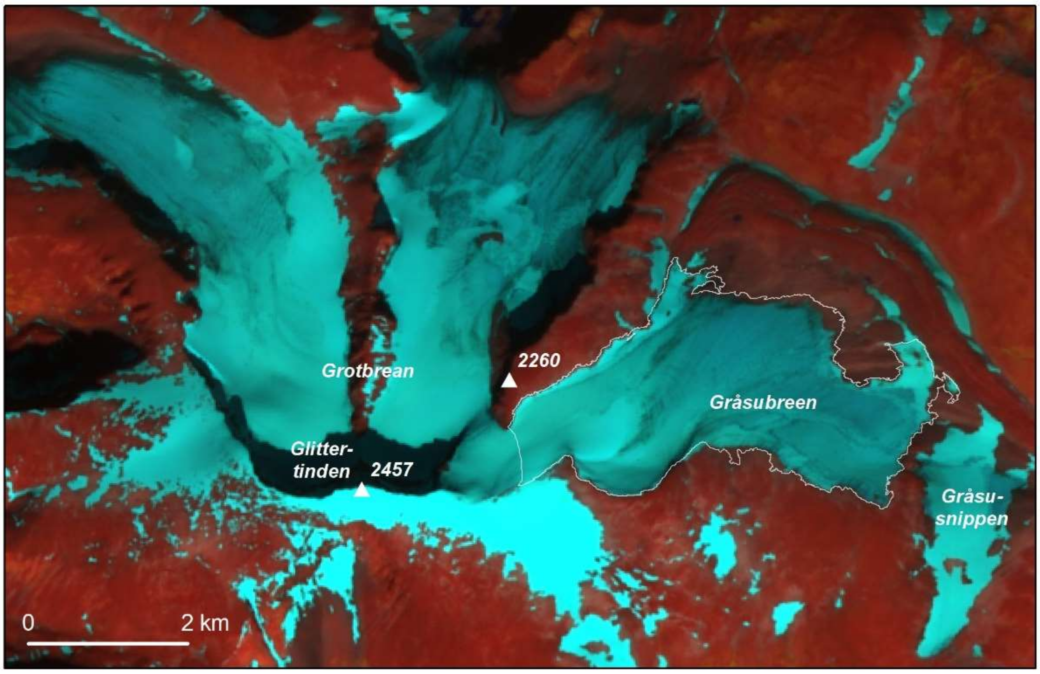


Figure 10-1
False colour composite Sentinel-2 L1C satellite image of Gråsubreen and surrounding area on 27th August 2017. The white outline shows the 2009 extent of Gråsubreen. Glaciers and snowfields are shown in blue, bedrock in red. The second highest peak in Norway, Glittertinden, 2457 m a.s.l., is marked. Source for satellite image: Copernicus Sentinel data 2017.

10.1 Mass balance 2017

Fieldwork

Accumulation measurements were performed on 14-15th June 2017. The calculation of winter balance is based on stake measurements in 11 different positions and snow depth soundings in 98 positions between 1871 and 2268 m a.s.l (Fig. 10-2). The snow depth varied between 0.01 and 2.55 with a mean of 0.76 m. Much of the glacier had very little snow. The snow density was measured in a density pit near stake 8 (elevation 2142 m a.s.l.) where the total snow depth was 1.0 m and the mean density was 488 kg m^{-3}. Ablation measurements were carried out on 28th September 2017, when all visible stakes were measured. A fresh layer of snow covered most of the glacier, and thus the end of summer snowline. The calculation of summer and annual balance was based on stakes in 13 and 14 different positions respectively.

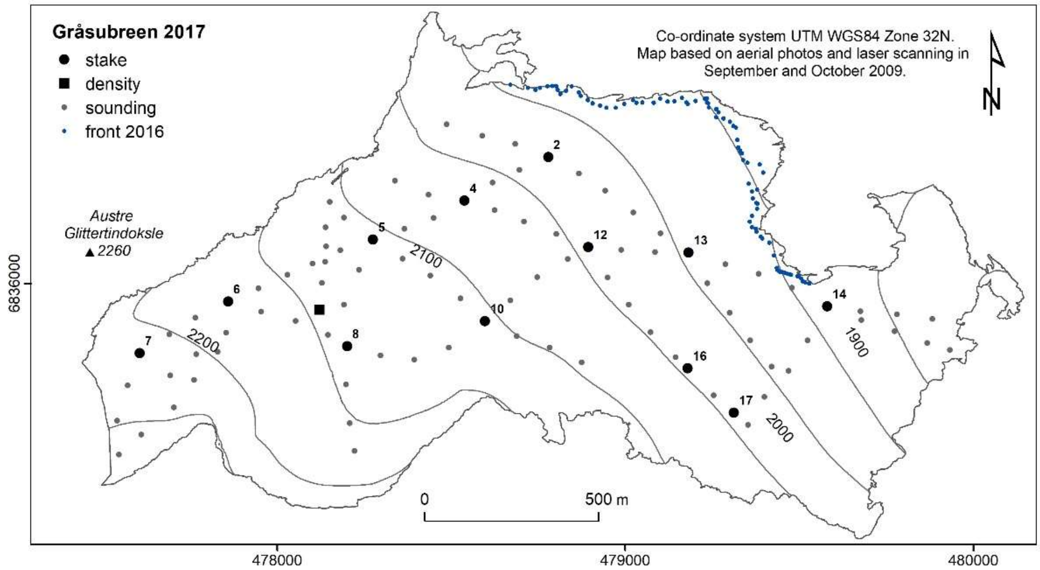


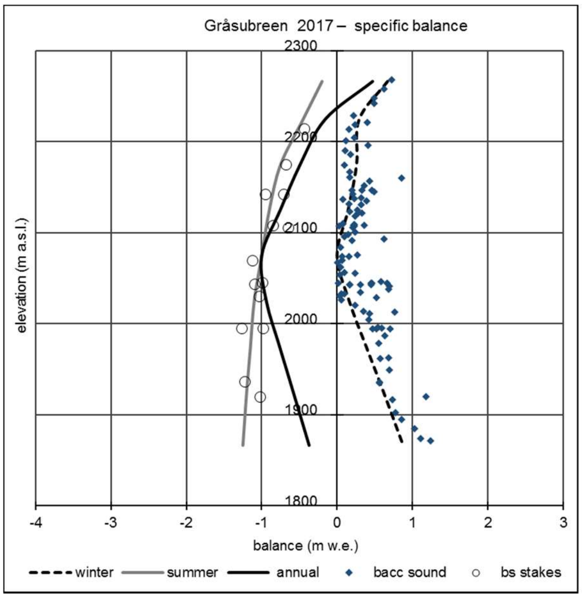
Figure 10-2
Map of Gråsubreen showing the location of stakes, density pit and soundings in 2017.

Results

The winter balance was calculated as the mean of the soundings within each 50-metre height interval. This gave a winter accumulation of 0.39 ±0.1 m w.e., which is 49 % of the mean winter balance for the reference period 1971-2000. The winter accumulation was adjusted for additional melt. This resulted in a winter balance of 0.26 m w.e., which is only 33 % of the mean of the reference period and the lowest recorded since measurements began. However, the adjustment of additional melt and the late accumulation measurements when some snow had probably already melted, may partly explain the low B_w. Summer and annual balance were calculated from direct measurements of stakes. The resulting summer balance was −0.97 ±0.25 m w.e., which is 91 % of the mean summer balance for the reference period 1971-2000.

The annual balance of Gråsubreen was negative in 2017, −0.71 ±0.3 m w.e. The ELA and AAR were not defined from the mass balance curve or in the field.

The mass balance results are shown in Table 10-1 and the corresponding curves for specific and volume balance are shown in Figure 10-3.



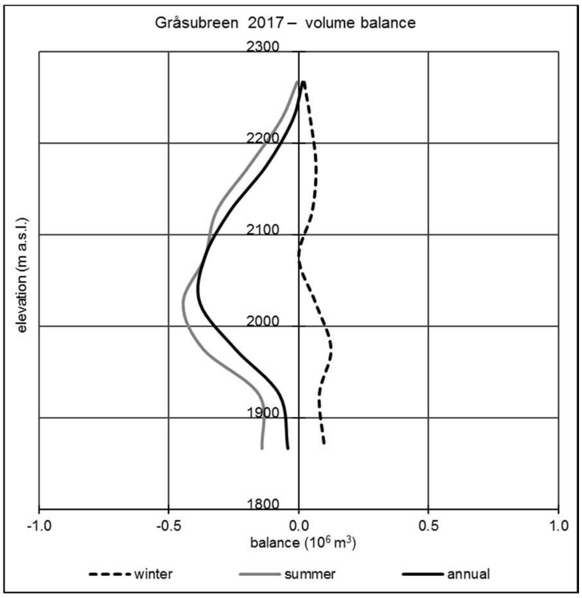


Figure 10-3
Mass balance diagram for Gråsubreen for 2017, showing specific balance on the left and volume balance on the right. Winter and summer balance at the stakes are also shown together with the individual snow depth soundings.

Table 10-1
The distribution of winter, summer and annual balance in 50 m altitudinal intervals for Gråsubreen in 2017.

Mass balance Gråsubreen 2016/17 – stratigraphic system

Altitude (m a.s.l.)	Area (km^2)	Winter mass balance Measured 14-15 June 2017 Specific (m w.e.)	Volume (10^6 m^3)	Summer mass balance Measured 28 Sep 2017 Specific (m w.e.)	Volume (10^6 m^3)	Annual mass balance Summer surfaces 2016 - 2017 Specific (m w.e.)	Volume (10^6 m^3)
2250 - 2283	0.03	0.67	0.02	-0.20	-0.01	0.47	0.01
2200 - 2250	0.15	0.29	0.04	-0.45	-0.07	-0.16	-0.02
2150 - 2200	0.26	0.26	0.07	-0.75	-0.19	-0.49	-0.13
2100 - 2150	0.35	0.15	0.05	-0.90	-0.32	-0.75	-0.27
2050 - 2100	0.36	0.00	0.00	-1.00	-0.36	-1.00	-0.36
2000 - 2050	0.41	0.16	0.07	-1.10	-0.45	-0.94	-0.38
1950 - 2000	0.32	0.39	0.12	-1.15	-0.37	-0.76	-0.24
1900 - 1950	0.13	0.62	0.08	-1.20	-0.15	-0.58	-0.07
1833 - 1900	0.11	0.88	0.10	-1.25	-0.14	-0.37	-0.04
1833 - 2283	**2.12**	**0.26**	**0.55**	**-0.97**	**-2.05**	**-0.71**	**-1.50**

10.2 Mass balance 1962-2017

The cumulative annual balance of Gråsubreen is –22 m w.e. since measurements began in 1962 (Fig. 10-4). The average annual balance is thus –0.39 m w.e. a^{-1}. The mass loss of Gråsubreen has accelerated since 2000, the mean annual balance for the period 1962-2000 (39 years) is –0.26 m w.e, compared with the period 2001-2017 (17 years), which has a mean of –0.73 m w.e.

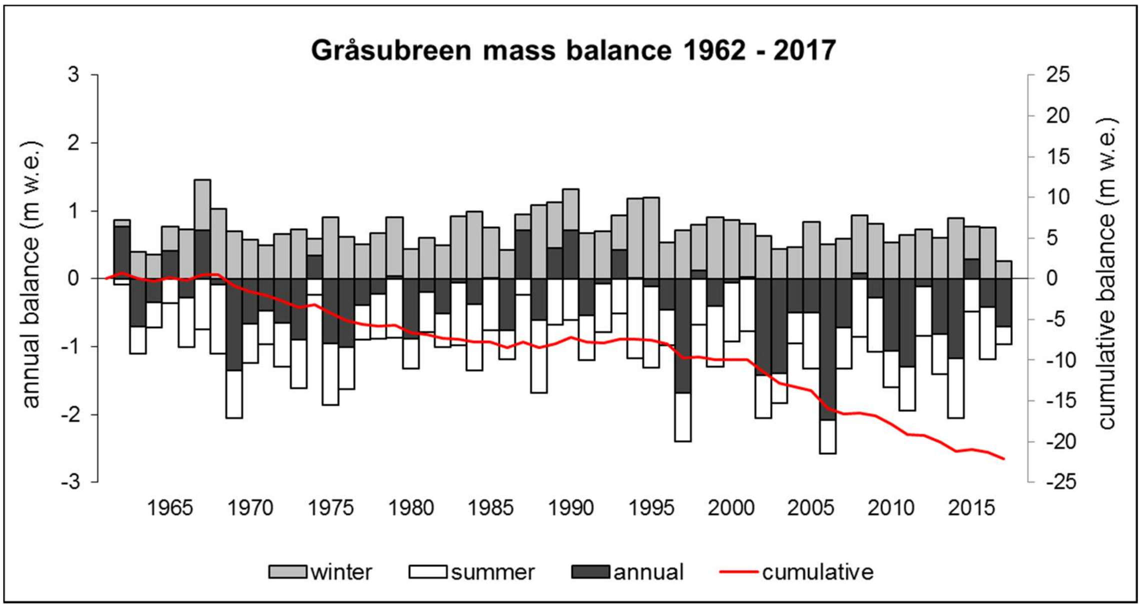


Figure 10-4
Winter, summer and annual balance for Gråsubreen for 1962-2017, and cumulative mass balance for the whole period.

10.3 Ice velocity 2015-2017

The stake positions were measured with GNSS on 28th September 2015 and again on 21st - 22nd September 2017 (Fig. 10-5). The surface ice velocity was calculated for this two-year period and showed annual velocities between 0.3 and 4.2 m/year (Fig. 10-6), giving daily velocities of less than 2 cm. The uncertainty of the measurements is within 0.1 to 0.5 m. Thus the measurements show detectable, although low surface velocities. The interior parts with the thickest ice (Sørdal, 2013; Andreassen et al., 2015) have the highest velocities.

Figure 10-5
Stake position measurements at stake location 7 (two stakes) in September 2015. The surface was covered with fresh snow. See also Figure 10-2. Photo: Liss M. Andreassen.

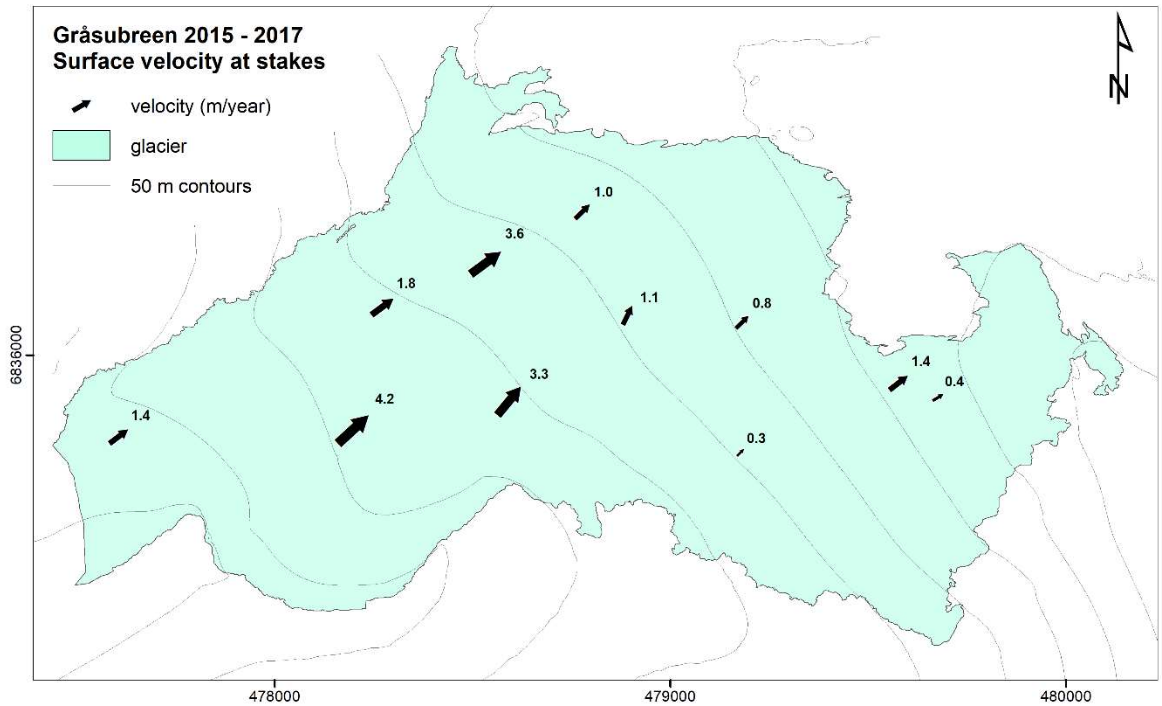


Figure 10-6
Map of Gråsubreen showing annual surface velocities calculated from stake position measurements on 21st and 22nd September 2015 and 28th September 2017. See also Figure 10-2.

11. Engabreen (Hallgeir Elvehøy and Miriam Jackson)

Engabreen (66°40′N, 13°45′E) is a 36 km^2 northwestern outlet from the western Svartisen ice cap (Fig. 11-1). It covers an altitude range from 1544 m a.s.l. (at Snøtind) down to 111 m a.s.l. (2016). Length change observations started in 1903 (chap. 14) and mass balance measurements have been performed annually since 1970. The pressure sensor records from the Svartisen Subglacial Laboratory under Engabreen date back to 1992. Results from 2017 are presented in Section 11-3.

Figure 11-1
Engabreen on 3rd August 2017. Photo: Hallgeir Elvehøy.

11.1 Mass balance 2017

Fieldwork

Stakes in five positions were measured on 8th February and showed up to 6 m of snow. Stake E105 was not found. Comparison of stake length and sounding at E17 on the glacier tongue showed that 0.3 m of ice had melted after 11th October 2016. Comparison of stake readings and probing at E34 indicates no significant melting after the ablation measurements on 11th October 2016.

The snow accumulation measurements were performed on 30th May. Four stakes on the glacier plateau showed up to 8.5 m of snow. Snow depth was measured at 20 sounding locations along the profile from the summit at 1464 m a.s.l. to E34 (Fig. 11-2). The snow depth was between 5 and 8 metres. The summer surface (S.S.) was difficult to define above 1200 m a.s.l. The mean snow density down to the S.S. at 8.0 m depth at stake E5 was 517 kg m^{-3}. Stake E17 on the glacier tongue was measured on 24th May, and showed no change since 8th February.

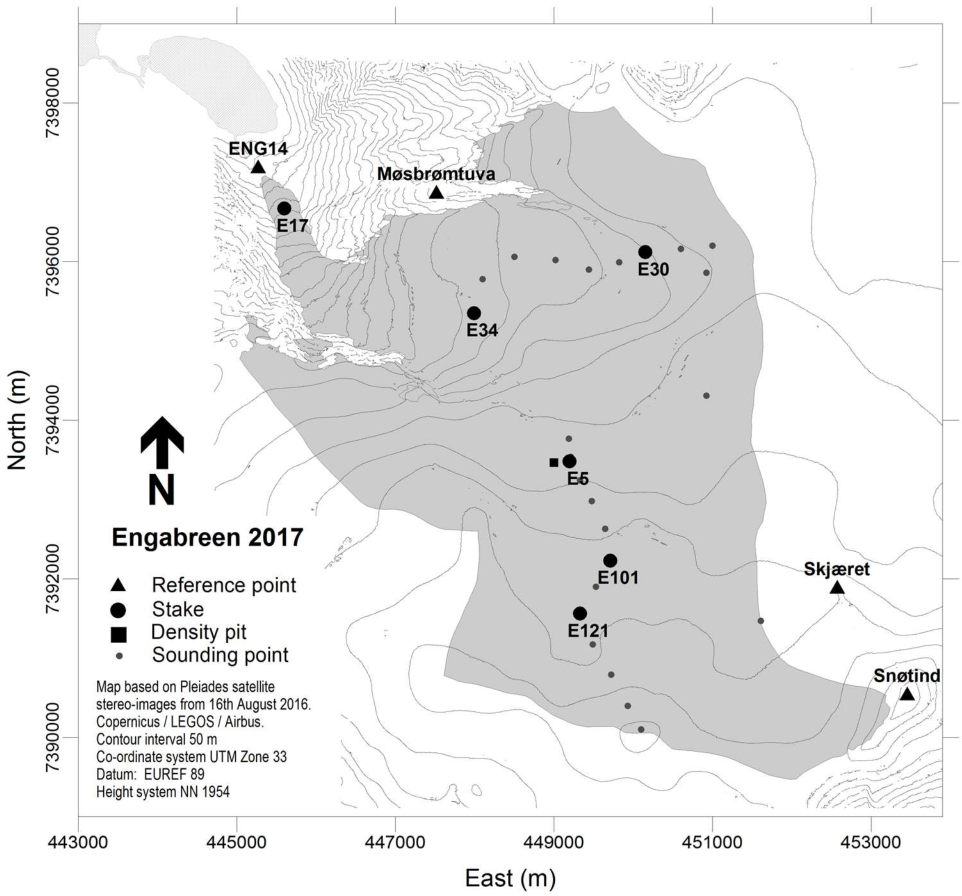


Figure 11-2
Location of stakes, density pit and sounding profiles on Engabreen in 2017.

Between 1 and 6 m of snow remained at stakes on the glacier plateau on 3rd August. The stake on the glacier tongue had melted out a couple of days earlier, and it was redrilled. More than 5 m of ice had melted since 24th May.

The summer ablation measurements were carried out late in the season, on 21st November. There was up to 2.75 m of new snow at the stakes. Stakes were found in six locations on the plateau. From stake measurements the TLA at the end of the melt season was about 1000 m a.s.l. Up to 4.4 m of snow remained at stakes above the TLA. All the snow and 1.05 m of ice melted during the summer at stake E34. Stake measurements on the glacier tongue showed that more than 9.25 m of ice melted between 24th May and 21st November.

Results

The calculations are based on a DTM from 16th August 2016. The date of the 2017 mass balance minimum at Engabreen was assessed by visual inspection of the daily changes in gridded data of snow amount from www.senorge.no (Saloranta, 2014). The snow accumulation probably started on the higher part of the glacier plateau on 13th October and on the lower part of the glacier plateau on 18th October.

The winter balance for 2017 was calculated from the snow depth and snow density measurements. A function correlating snow depth with Snow Water Equivalent (SWE) was calculated based on snow density measurements at stake E5. This function was then used to calculate the point winter balance of the snow depth measurements. Mean values of altitude and SWE in 100 m elevation bins were calculated and plotted. An altitudinal winter balance curve was drawn from a visual evaluation of the mean values. Below 900 m a.s.l., the winter balance curve was interpolated from the calculated winter balance at stakes E34 and E17. The winter balance in each 100 m altitude interval was determined from this curve. The specific winter balance was calculated as 3.7 ±0.2 m w.e. This is 142 % of the average winter balance for the period 1981-2010 (2.58 m w.e. a^{-1}), and 132 % of the average for the period 2012-2016 (2.79 m w.e. a^{-1}).

The point summer balance was calculated directly at six stake locations between 300 and 1340 m a.s.l. The specific summer balance was calculated from the summer balance curve drawn from these six point values (Fig. 11-3) as −2.4 ±0.2 m w.e. This is 93 % of the average summer balance for the period 1981-2010 (−2.60 m w.e. a^{-1}) but 80 % of the average for the period 2012-2016 (−3.04 m w.e. a^{-1}). The resulting annual balance was +1.25 ±0.3 m w.e. (Tab. 11-3). The ELA was assessed as 1025 m a.s.l. from the annual balance curve in Figure 11-4. This corresponds to an AAR of 84 %. All the calculations are based on a DTM from 2016.

The annual surface mass balance at Engabreen for 1970-2017 is shown in Figure 11-4. The cumulative surface mass balance since the start of mass balance investigations at Engabreen is +0.9 m w.e., showing that the change in glacier volume has been small. However, the glacier volume increased between 1970 and 1977, and again between 1988 and 1997, and decreased between 1977 and 1988. During the last 20 years (1997-2017), the glacier volume has decreased by 6.5 m w.e., or −0.32 m w.e. a^{-1} (Fig. 11-5).

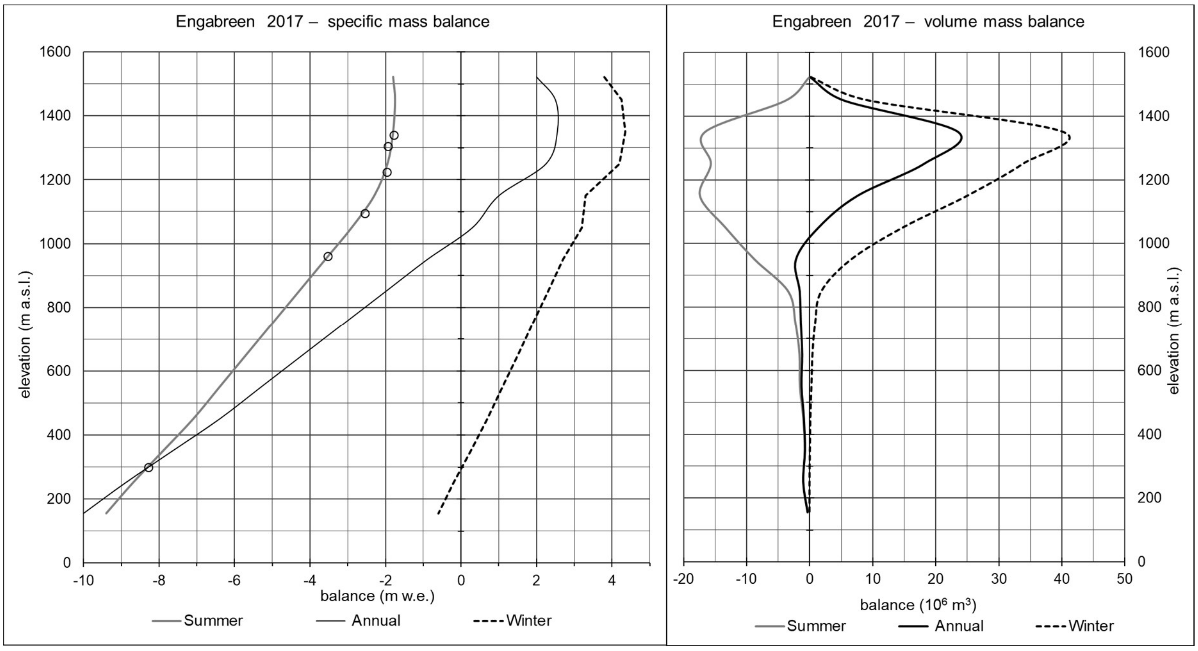


Figure 11-3
Mass balance diagram showing specific balance (left) and volume balance (right) for Engabreen in 2017. Summer balance at six stake locations (○) is shown.

Table 11-1
Specific and volume winter, summer and annual balance calculated for 100 m elevation intervals at Engabreen in 2017.

Mass balance Engabreen 2016/17 – stratigrafic system

		Winter mass balance		Summer mass balance		Annual mass balance	
		Measured 30 mai 2017		Measured 21nov 2017		Summer surfaces 2016 - 2017	
Altitude (m a.s.l.)	Area (km^2)	Specific (m w.e.)	Volume (10^6 m^3)	Specific (m w.e.)	Volume (10^6 m^3)	Specific (m w.e.)	Volume (10^6 m^3)
1500 - 1544	0.05	3.80	0.2	-1.80	-0.1	2.00	0.1
1400 - 1500	2.13	4.25	9.0	-1.75	-3.7	2.50	5.3
1300 - 1400	9.24	4.35	40.2	-1.80	-16.6	2.55	23.6
1200 - 1300	8.04	4.20	33.8	-1.95	-15.7	2.25	18.1
1100 - 1200	7.57	3.30	25.0	-2.30	-17.4	1.00	7.6
1000 - 1100	4.61	3.20	14.7	-2.90	-13.4	0.30	1.4
900 - 1000	2.43	2.70	6.6	-3.60	-8.8	-0.90	-2.2
800 - 900	0.80	2.30	1.8	-4.30	-3.4	-2.00	-1.6
700 - 800	0.46	1.90	0.9	-5.00	-2.3	-3.10	-1.4
600 - 700	0.29	1.50	0.4	-5.70	-1.6	-4.20	-1.2
500 - 600	0.25	1.10	0.3	-6.40	-1.6	-5.30	-1.3
400 - 500	0.14	0.70	0.1	-7.10	-1.0	-6.40	-0.9
300 - 400	0.10	0.25	0.0	-7.90	-0.8	-7.65	-0.8
200 - 300	0.12	-0.20	0.0	-8.70	-1.0	-8.90	-1.0
111 - 200	0.04	-0.60	0.0	-9.40	-0.3	-10.00	-0.4
111 - 1544	**36.25**	**3.67**	**133.0**	**-2.42**	**-87.7**	**1.25**	**45.3**

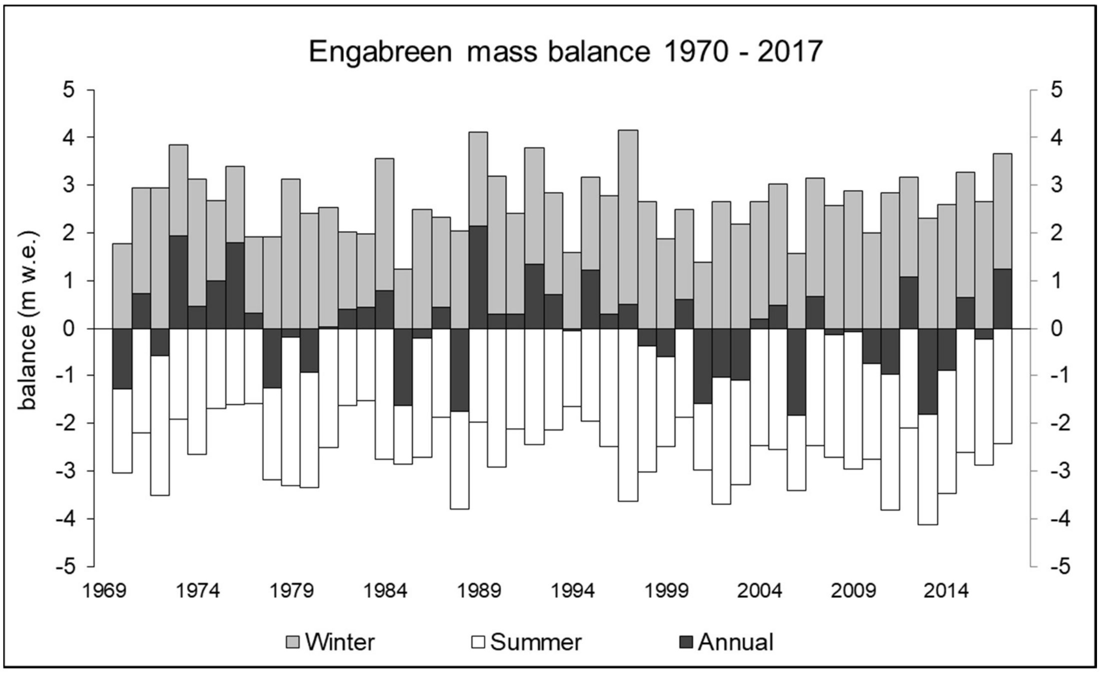


Figure 11-4
Mass balance at Engabreen during the period 1970-2017. The average winter and summer balances are B_w =2.67 m w.e. and B_s =−2.65 m w.e. Results from 1970-2008 were calibrated (Andreassen et al., 2016), and 2009-10 and 2013-15 were recalculated (Elvehøy, 2016 and Kjøllmoen et al., 2017).

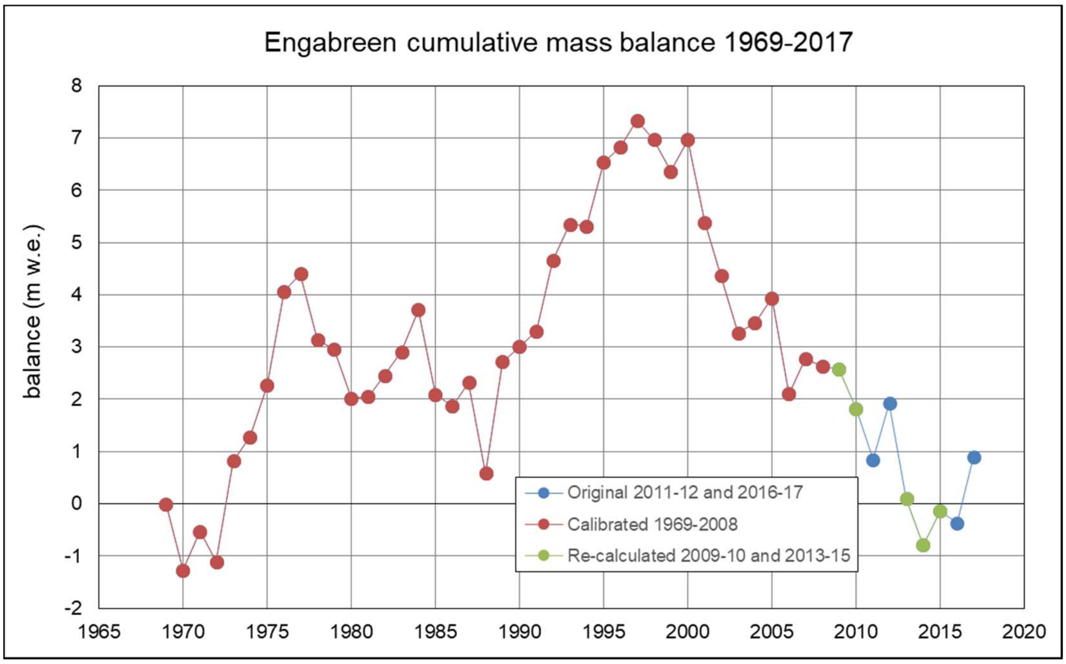


Figure 11-5
Cumulative mass balance at Engabreen from 1969 to 2017.

Figure 11-6
Stake E121 on Engabreen on 21st November 2017. Photo: Hallgeir Elvehøy.

11.2 Meteorological observations

A meteorological station recording air temperature and global radiation at 3 m level is located on the nunatak Skjæret (1364 m a.s.l., Fig. 11-2) close to the drainage divide between Engabreen and Storglombreen. The station has been operating since 1995. In 2017 there were data gaps between 9th and 29th April, and between 9th October and 21st November.

The summer mean temperature (1st June – 30th September) at Skjæret in 2017 was 3.0 °C, the same as the mean summer temperature for 18 years between 1995 and 2017, which is also 3.0 °C. The melt season on the upper part of the glacier plateau started on 3rd June and probably lasted until the end of September. The summer temperature in 2017 was similar to the 2015 summer temperature (Fig. 11-7), resulting in comparable summer balance results (−2.61 m w.e. in 2015 compared with −2.42 m w.e. in 2017).

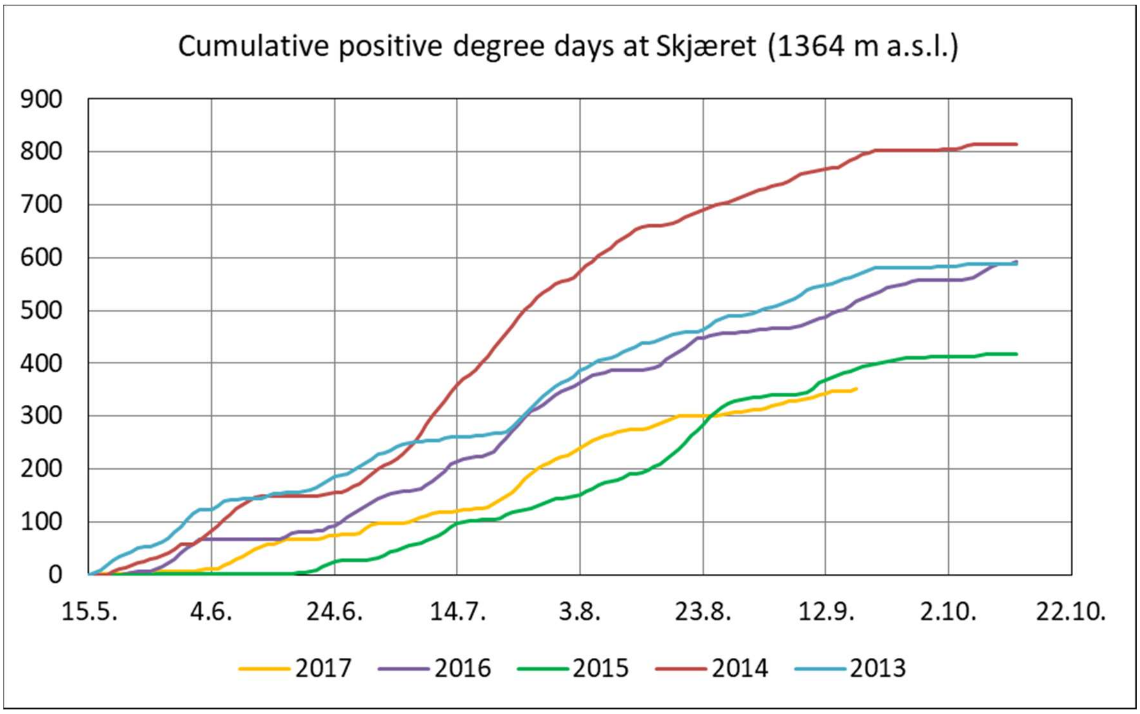


Figure 11-7
The daily mean temperature for days with positive mean temperature is accumulated from 15th May until 13th October (18th September in 2017). Days with negative mean temperature are shown as no increase in positive degree-days.

11.3 Svartisen Subglacial Laboratory

Svartisen Subglacial Laboratory is a unique facility situated under Engabreen. Laboratory buildings and research shaft are located about 1.5 km along a tunnel that is part of a large hydropower development (Fig. 11-8). The research shaft allows direct access to the bed of the glacier, and is used for measuring subglacial parameters, extracting samples and performing experiments (Jackson, 2000).

Six load cells were installed at the bed of the glacier next to the research shaft in December 1992 in order to measure variations in subglacial pressure (Fig. 11-9). The load cells are Geonor Earth Pressure Cells (P-100 and P-105). Readings are made from the load cells at 15-minute intervals. Two new load cells were installed in November 1997, and the sensors were replaced in the same boreholes in 2012. There are five load cells that still record data. The data from the load cells are briefly summarised here but are publicly available for more comprehensive analysis. The inter-annual variability of the load cells is examined in detail in Lefeuvre et al. (2015). Note that the graphs of load cell pressure have different axes.

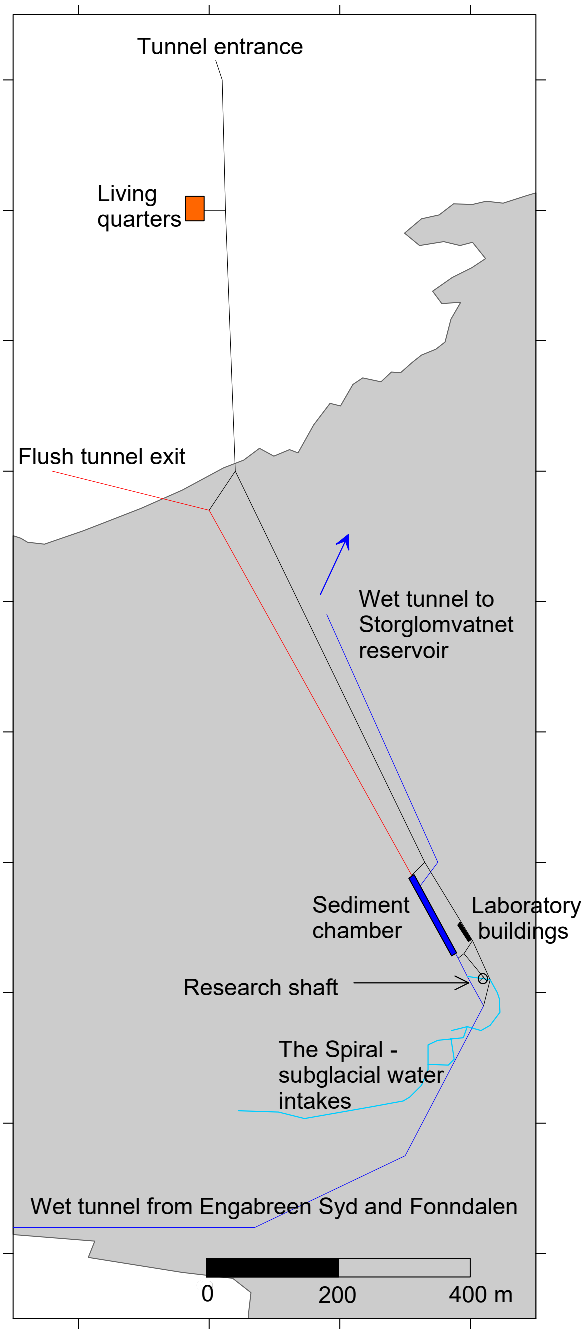


Figure 11-8
Map of tunnel system under Engabreen, showing research shaft and other facilities.

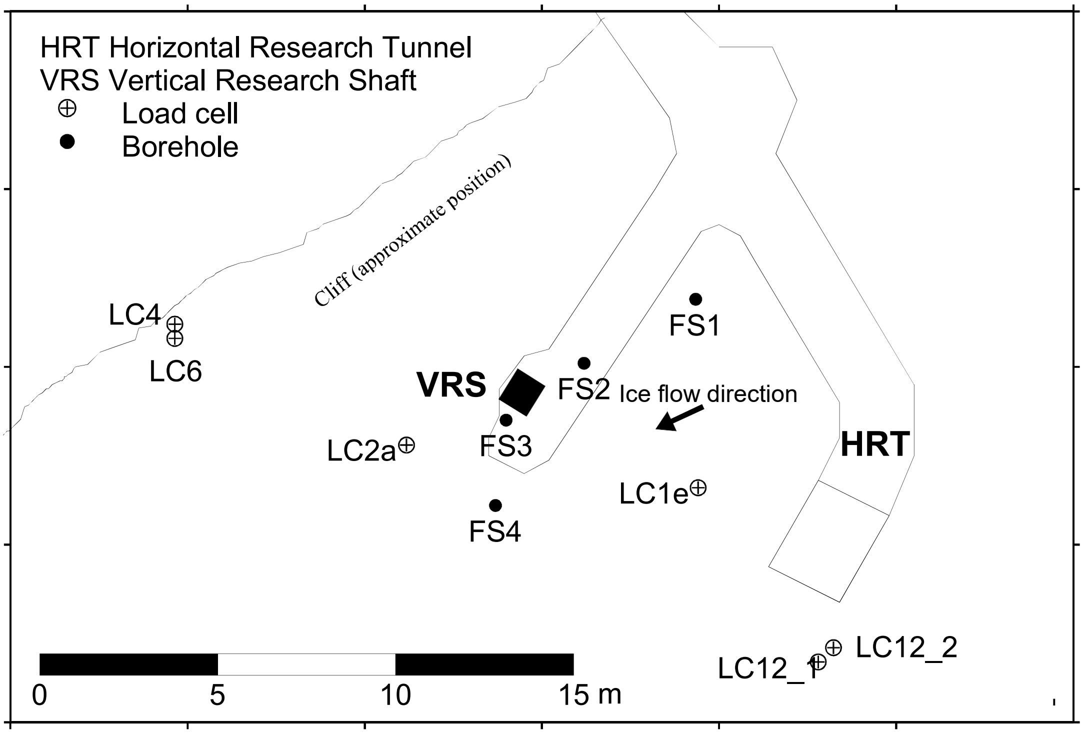


Figure 11-9
Tunnel system showing locations of horizontal research tunnel (HRT), vertical research shaft (VRS) and load cells (LC). Boreholes from the tunnel to the glacier bed, FS, are also shown.

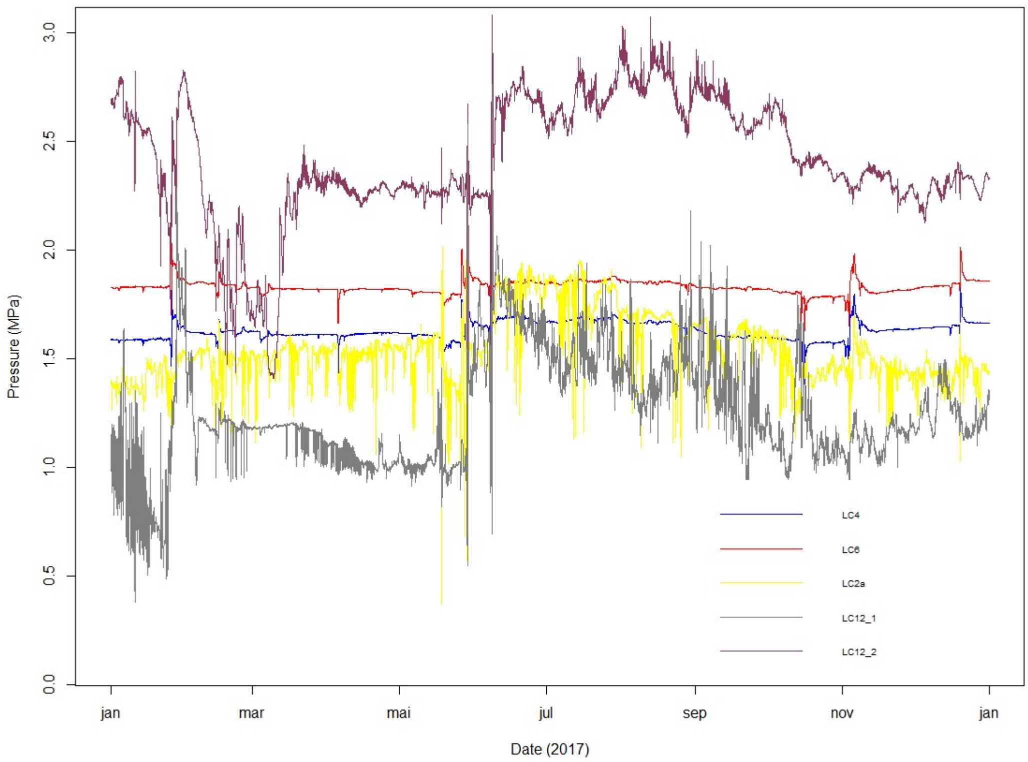


Figure 11-10
The twelve-month record for five of the load cells (LC1e recorded only intermittently).

Figure 11-10 shows the pressure record for 2017 for five load cells: – load cell pair LC4 and LC6, which are installed in a relatively quiet environment; load cell pair LC12_1 and LC12_2, which are in a more exposed, noisier environment and LC2a. All load cells are installed at the glacier-bedrock interface within 20 m of each other. The pressure signal for 2017 is atypical compared with most other years. Generally, the winter months are quiet, as there is little melt and thus only minor changes at the glacier bed. However, due to intense precipitation in late January there was a lot of discharge into the tunnel system and presumably also under the glacier as recorded at a discharge station in the wet tunnel from Fonndalen that measures inflow that consists of a combination of snow melt, glacier melt and precipitation (Fig. 11-11). There is a similar, but smaller event in February, in this case due to unseasonably warm temperatures. After this, there is low discharge measured in the subglacial tunnel system until the spring melt begins in mid-May. Discharge in the summer months shows progressively bigger peaks until mid-August, but then there is a short period of very low discharge in late August. The high discharge resumes after this, and then decreases from early September onwards. There is a sudden increase in discharge in mid-October with smaller peaks in discharge in early November and late December.

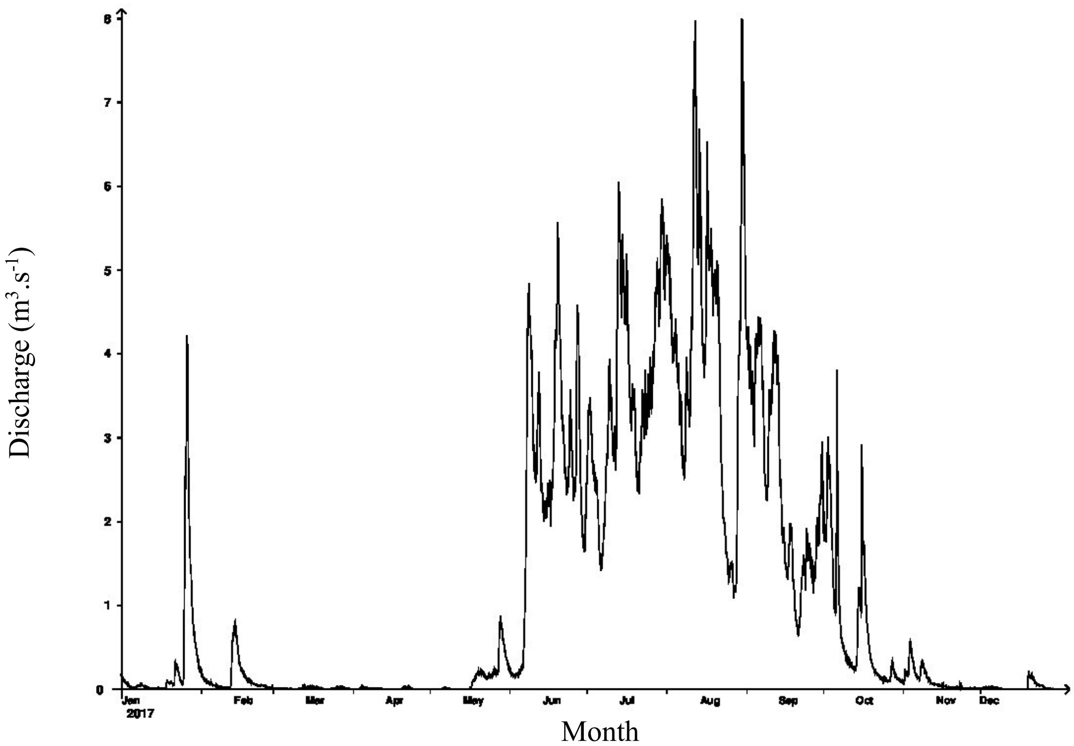


Figure 11-11
Discharge measured in the wet tunnel from Engabreen Syd and Fonndalen, underneath the glacier (see Fig. 11-8). The discharge comes from snow melt, glacier melt and precipitation.

The inflow of water to the glacier system in late January triggers an immediate response at the glacier bed (Fig 11-10). Only March to mid-May is a typical, quiescent winter period. Discharge is high during the summer, then lower and more stable in late autumn.

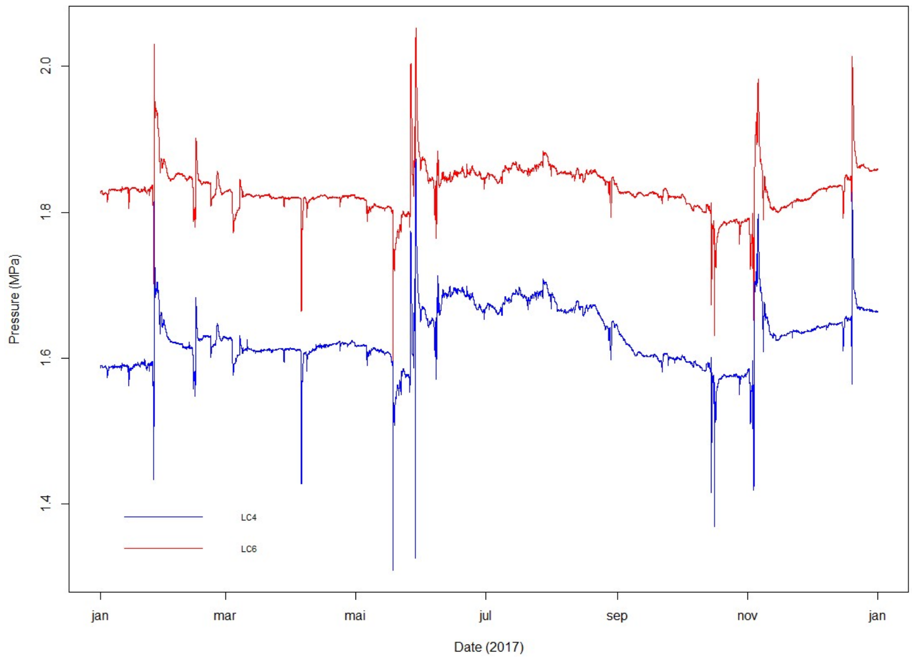


Figure 11-12
Pressure measured at load cells LC4 and LC6 for 2017.

Load cells LC4 and LC6 are located in an overhang in a quiet environment and thus respond to only significant changes at the glacier bed (Fig. 11-12). There is an immediate response at the load cells to the discharge event in late January, marked by a sharp drop then rise in pressure at the glacier bed. There is a similar, smaller response to the increased discharge in mid-February.

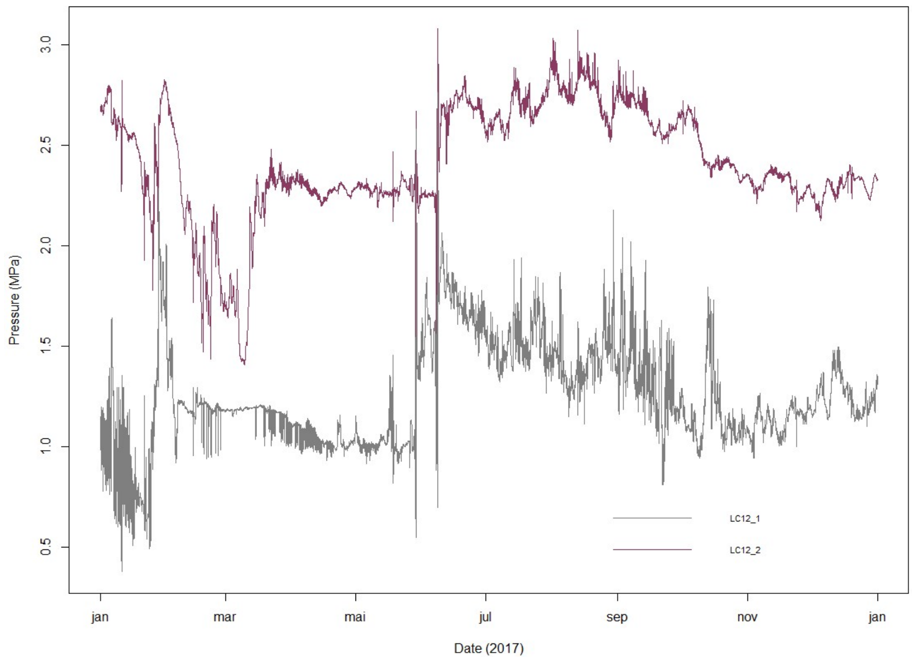


Figure 11-13
Pressure measured at load cells LC12_1 and LC12_2 in 2017.

Load cells LC12_1 and LC12_2 are in a more exposed environment, so the resulting pressure signal is noisier (Fig. 11-13). However, the response to changes in discharge is usually similar at the two load cells. Note also the close relationship between the amount of discharge in the tunnel system (Fig. 11-11) and the response at these two load cells.

12. Rundvassbreen (Bjarne Kjøllmoen)

Rundvassbreen (Fig. 1-2) is a northern outlet glacier of the ice cap Blåmannsisen (67°20′N, 16°05′E). At 80 km^2 (2010), it is the fifth largest ice cap in Norway. Rundvassbreen has an area of 10.8 km^2 (2017) and extends from 1527 m elevation down to 853 m a.s.l. (Fig. 12-1). Rundvassbreen is adjacent to lake Vatn 1051, from which a jøkulhlaup drained beneath the glacier in September 2001. Since then several more jøkulhlaups have occurred, the latest in September 2016. A comprehensive observation programme related to the jøkulhlaups was started in autumn 2001 (Engeset, 2002) and mass balance measurements were included in spring 2002 and continued until 2004. A homogenised mass balance series for Rundvassbreen 2002-04 is presented in Kjøllmoen (2017). An extensive observation programme was resumed in 2011.

12.1 Mapping

A new survey of Rundvassbreen was performed in 2017. The glacier surface was mapped by aerial photographs and airborne laser scanning on 5th September (Fig. 12-1) (Terratec, 2017).

A Digital Terrain Model (DTM) was calculated based on the laser scanning data. The glacier boundary was determined from an orthophoto composed of the aerial photos. The ice divides to the adjacent glaciers were calculated using GIS and compared with the ice divides from 2011. The ice divides from 2017 were similar to the 2011 divides. Hence the 2011 ice divides are used here.

Figure 12-1
Orthophoto of the northern part of Rundvassbreen from aerial photographs on 5th September 2017.

12.1 Mass balance 2017

Fieldwork

Snow accumulation measurements were performed on 9th May and the calculation of winter balance was based on measurement of five stakes and 98 snow depth soundings (Fig. 12-2). Comparison of sounded snow depth and stake readings indicated no melting after the ablation measurements in September 2016. The summer surface (S.S.) was easy to identify up to stake position 50 (1323 m a.s.l.). Above this altitude the S.S. was somewhat harder to detect. The snow depth varied between 2.0 and 7.0 metres. Snow density was measured in position 60 (1389 m a.s.l.), and the mean snow density of 5.9 m snow was 437 kg m^{-3}.

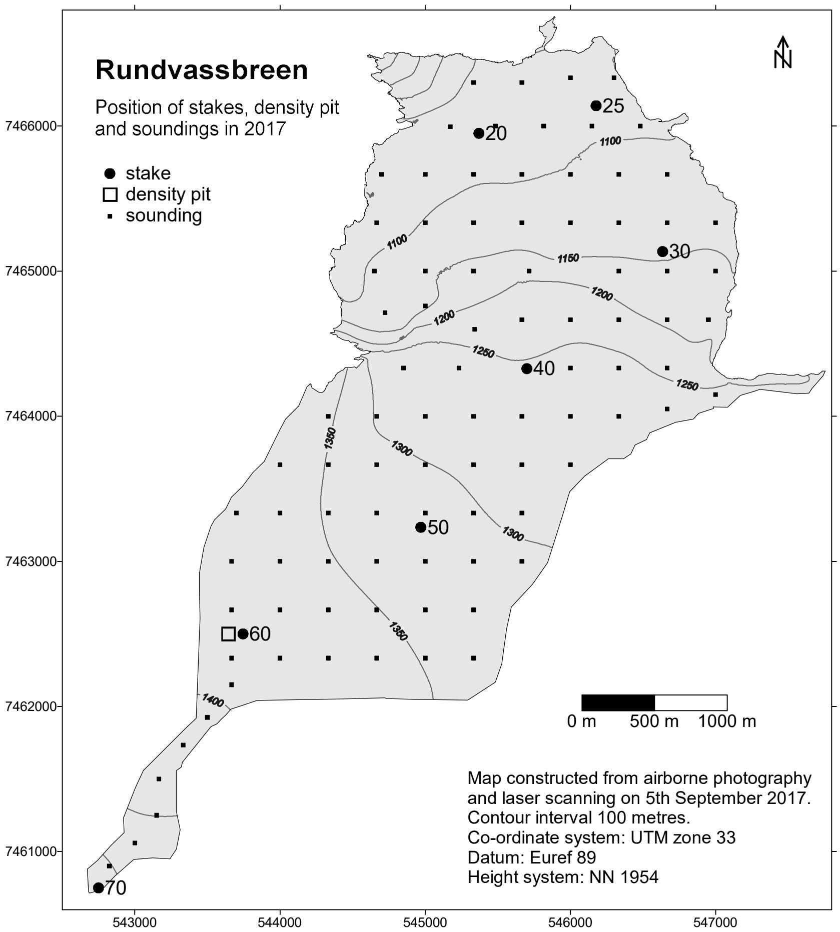


Figure 12-2 Location of stakes, soundings and snow pit, and spatial distribution of winter balance at Rundvassbreen in 2017.

Ablation was measured on 27th September (Fig. 12-3). The annual balance was measured at stakes in six locations (Fig. 12-2). In the accumulation areas there was up to 2.8 m of snow remaining from winter 2016/17. At the time of measurement, no fresh snow had fallen.

Results

The calculations are based on the DTM from 2017.

The elevations above 1065 m a.s.l., which cover 97 % of the glacier catchment area, are well-represented with snow depth measurements. Below 1065 m elevation the winter balance curve is extrapolated based on experience from previous years with point measurements down to 940 m a.s.l.

Figure 12-3
Ablation measurements in September 2017 included stake readings and stake positioning by GNSS. Photo: Miriam Jackson.

The winter balance was calculated as a mean value for each 50 m height interval and was 2.0 ±0.2 m w.e., which is 109 % of the mean winter balance for the years 2002-04 and 2011-16. Spatial distribution of the winter balance is shown in Figure 12-4.

The elevations above 1082 m a.s.l., which cover 93 % of the glacier catchment area, are well-represented with point measurements of ablation. Below 1082 m elevation the summer balance curve is extrapolated based on experience from previous years with point measurements down to 945 m a.s.l.

Based on estimated density and stake measurements the summer balance was also calculated as a mean value for each 50 m height interval and was −1.6 ±0.3 m w.e., which is 60 % of the mean summer balance 2002-04 and 2011-16.

Hence the annual balance was positive at +0.4 m ±0.4 m w.e. The mean annual balance for 2002-03 and 2011-16 is −0.78 m w.e.

The mass balance results are shown in Table 12-1 and the corresponding curves for specific and volume balance are shown in Figure 12-5.

According to Figure 12-5, the Equilibrium Line Altitude was 1155 m a.s.l. Consequently the Accumulation Area Ratio was 69 %.

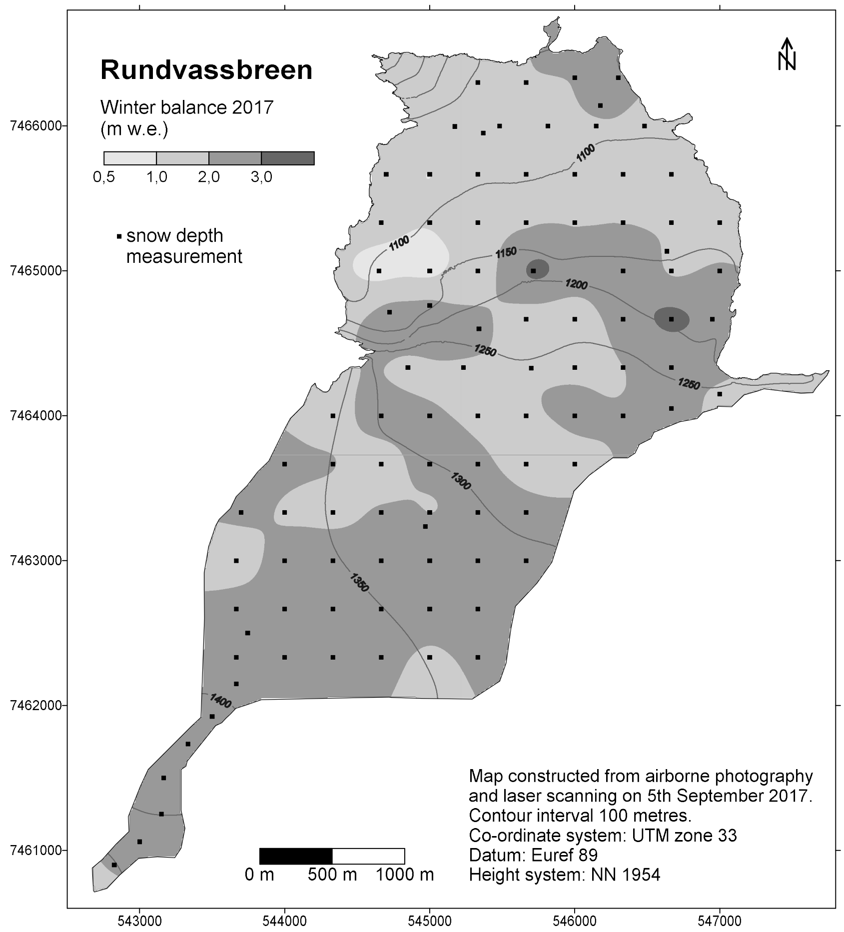
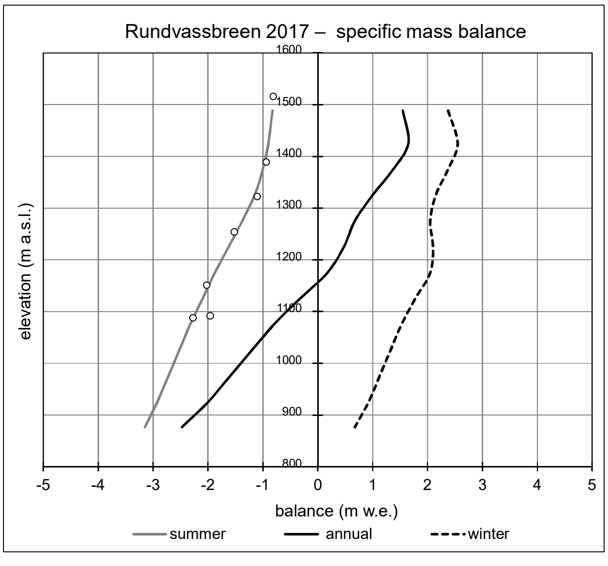


Figure 12-4
Spatial distribution of winter balance on Rundvassbreen in 2017.



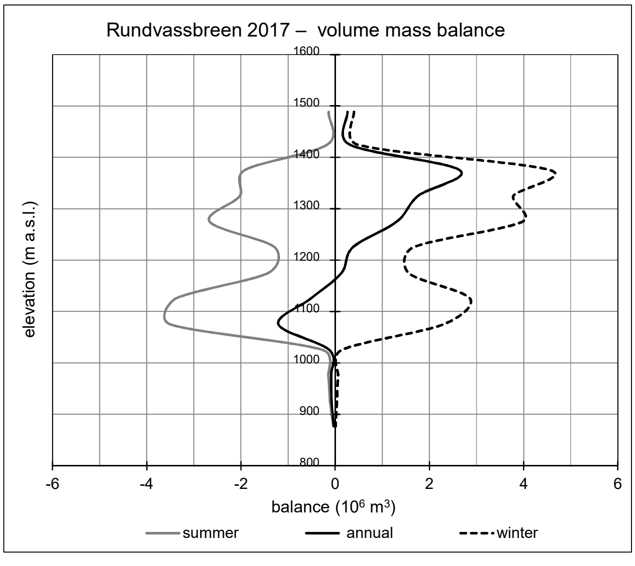


Figure 12-5
Mass balance diagram showing specific balance (left) and volume balance (right) for Rundvassbreen in 2017. Specific summer balance at seven stake positions is shown as circles (○). The summer balance at the uppermost stake (70) is estimated.

Table 12-1
Winter, summer and annual balance for Rundvassbreen in 2017.

Mass balance Rundvassbreen 2016/17 – stratigraphic system							
		Winter mass balance Measured 9th May 2017		Summer mass balance Measured 27th Sep 2017		Annual mass balance Summer surface 2016 - 2017	
Altitude (m a.s.l.)	Area (km²)	Specific (m w.e.)	Volume (10^6 m³)	Specific (m w.e.)	Volume (10^6 m³)	Specific (m w.e.)	Volume (10^6 m³)
1450 - 1527	0.17	2.38	0.4	-0.83	-0.1	1.55	0.3
1400 - 1450	0.19	2.55	0.5	-0.90	-0.2	1.65	0.3
1350 - 1400	1.92	2.38	4.6	-1.00	-1.9	1.38	2.6
1300 - 1350	1.76	2.15	3.8	-1.15	-2.0	1.00	1.8
1250 - 1300	1.94	2.05	4.0	-1.38	-2.7	0.68	1.3
1200 - 1250	0.79	2.10	1.7	-1.63	-1.3	0.48	0.4
1150 - 1200	0.76	2.05	1.6	-1.88	-1.4	0.18	0.1
1100 - 1150	1.61	1.78	2.9	-2.10	-3.4	-0.33	-0.5
1050 - 1100	1.51	1.53	2.3	-2.33	-3.5	-0.80	-1.2
1000 - 1050	0.10	1.33	0.1	-2.53	-0.3	-1.20	-0.1
950 - 1000	0.05	1.13	0.1	-2.73	-0.1	-1.60	-0.1
900 - 950	0.04	0.93	0.0	-2.93	-0.1	-2.00	-0.1
853 - 900	0.01	0.68	0.0	-3.15	0.0	-2.48	0.0
853-1527	**10.8**	**2.01**	**21.8**	**-1.57**	**-17.1**	**0.44**	**4.7**

12.2 Mass balance 2002-04 and 2011-17

The historical mass balance results for Rundvassbreen are presented in Figure 12-6. The cumulative annual balance for 2011-17 is −4.2 m w.e., which gives a mean annual balance of −0.66 m w.e. a^{-1}.

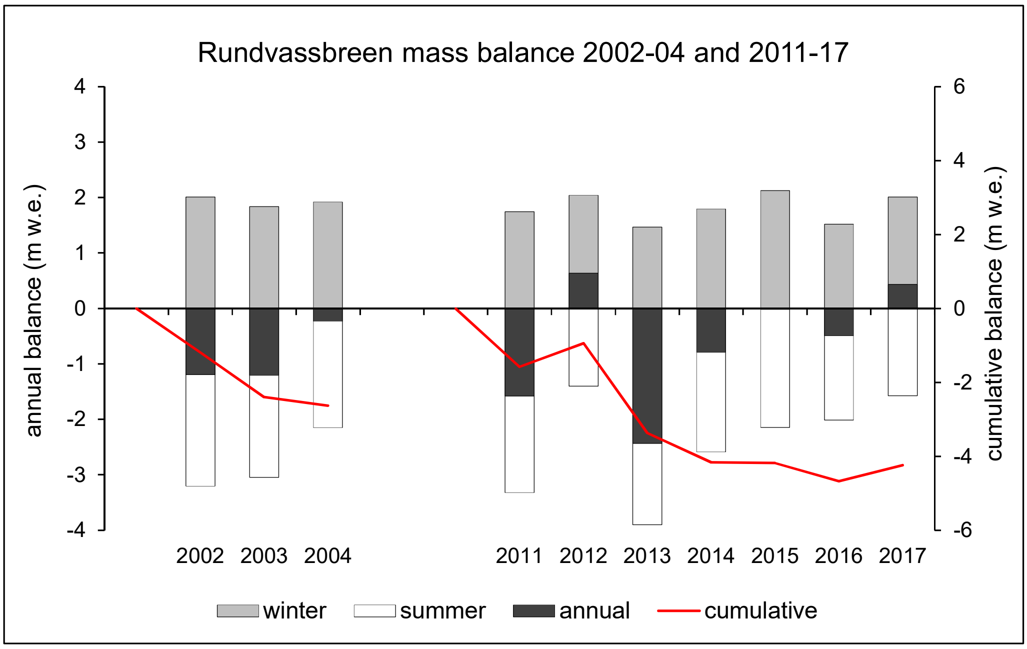


Figure 12-6
Winter, summer and annual balance at Rundvassbreen for 2002-04 and 2011-17.

13. Langfjordjøkelen (Bjarne Kjøllmoen)

Langfjordjøkelen (70º10′N, 21º45′E) is a plateau glacier situated on the border of Troms and Finnmark counties, approximately 60 km northwest of the city of Alta. It has an area of about 7.7 km^2 (2008), and of this 3.2 km^2 drains eastward. The investigations are performed on this east-facing part (Fig. 13-1) ranging in elevation from 302 to 1050 m a.s.l.

The glaciological investigations in 2017 include mass balance and change in glacier length (chap. 14). Langfjordjøkelen has been the subject of mass balance measurements since 1989 with the exception of 1994 and 1995.

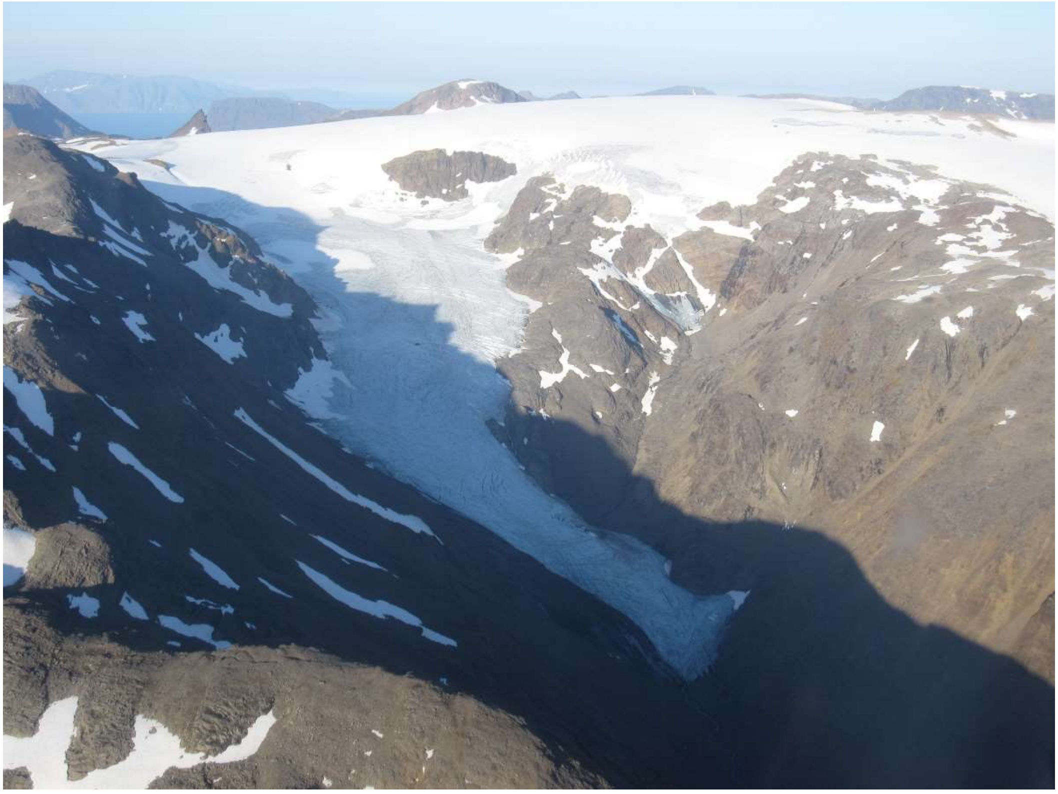


Figure 13-1
The east-facing outlet of Langfjordjøkelen photographed on 29th September 2017. Photo: Bjarne Kjøllmoen.

13.1 Mass balance 2017

Fieldwork

Snow accumulation was measured on 25th and 26th April and the calculation of winter balance was based on measurements of 62 snow depth soundings (Fig. 13-2). The snow depth varied between 2.1 and 7.1 m with an average of 4.6 m. Snow density was measured in position 25 (718 m a.s.l.) and the mean density of 4.2 m snow was 418 kg m^{-3}.

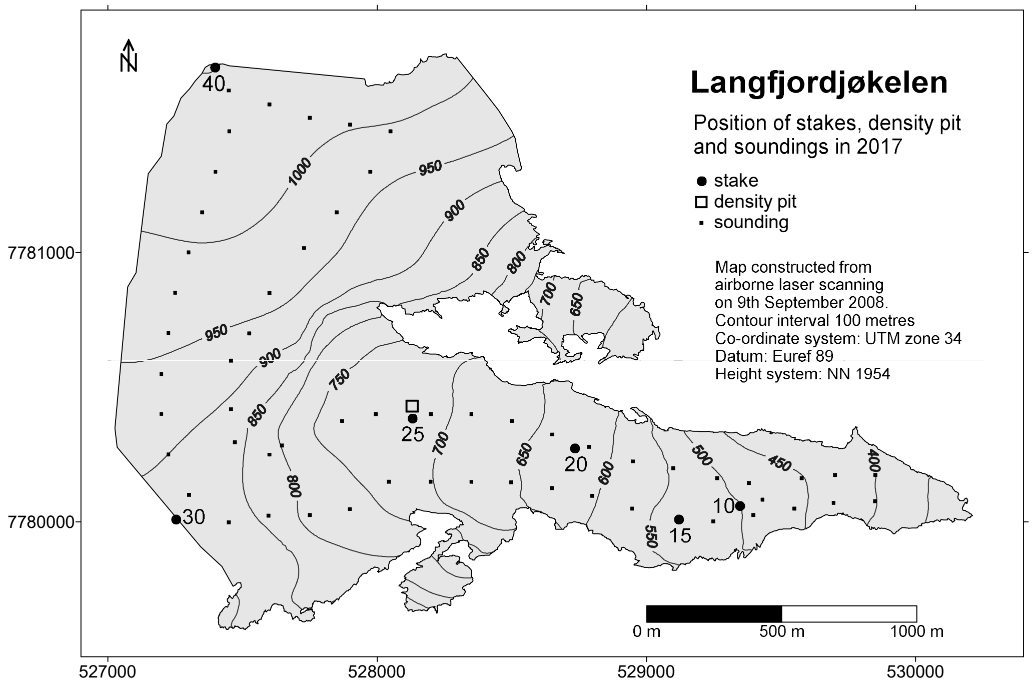


Figure 13-2
Location of stakes, soundings and snow pit at Langfjordjøkelen in 2017.

Ablation was measured on 29th September. The annual balance was measured at stakes in six locations (Fig. 13-2). There was about 1 m of snow remaining at the uppermost stake from the winter season 2016/17. No fresh snow had fallen on the glacier at the time of measurement.

Results

The calculations are based on the DTM from 2008.

The elevations above 401 m a.s.l., which cover 98 % of the glacier catchment area, are well-represented with snow depth measurements. Below 401 m elevation the winter balance curve is extrapolated.

The winter balance was calculated as a mean value for each 50 m height interval and was 2.1 ±0.2 m w.e., which is 101 % of the mean winter balance for the years 1989-93 and 1996-2016. Spatial distribution of the winter balance is shown in Figure 13-3.

The elevations above 500 m a.s.l., which cover 92 % of the glacier catchment area, are well-represented with point measurements of ablation. Below 500 m elevation the summer balance curve is extrapolated.

Based on estimated density and stake measurements the summer balance was also calculated as a mean value for each 50 m height interval and was −2.4 ±0.3 m w.e., which is 77 % of the mean summer balance 1989-93 and 1996-2016.

Hence the annual balance was negative, at −0.3 ±0.4 m w.e. The mean annual balance for 1989-93 and 1996-2016 is −0.98 m w.e. Over the past ten years (2008-17), the mean annual balance is −1.06 m w.e.

The mass balance results are shown in Table 13-1 and the corresponding curves for specific and volume balance are shown in Figure 13-4.

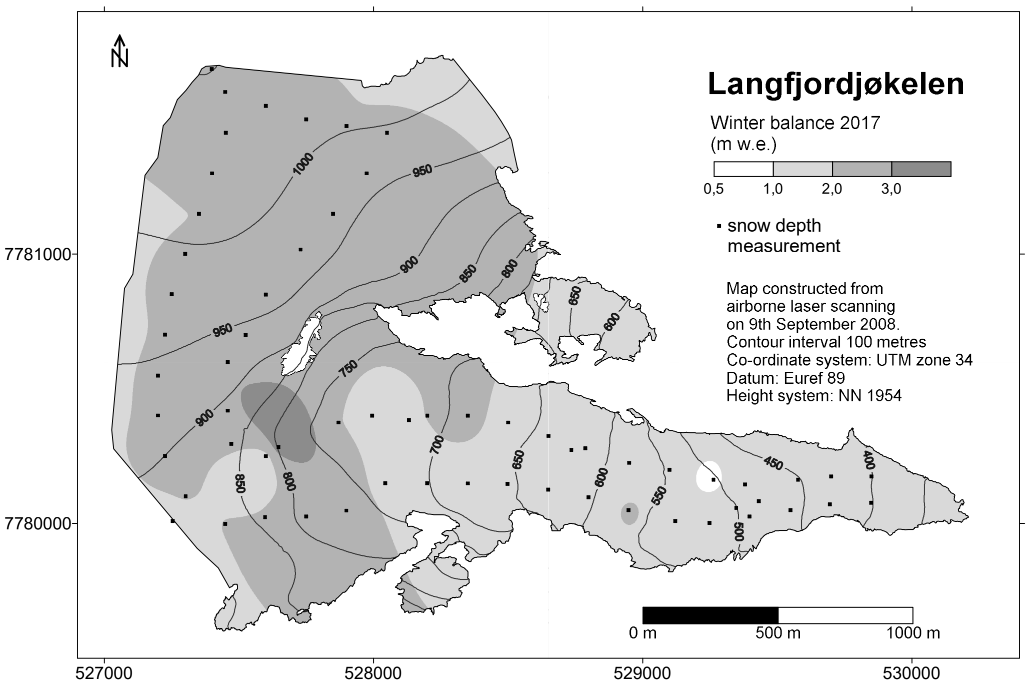


Figure 13-3
Spatial distribution of winter balance at Langfjordjøkelen in 2017.

According to Figure 13-4, the Equilibrium Line Altitude lies at 810 m a.s.l. Consequently the Accumulation Area Ratio was 56 %.

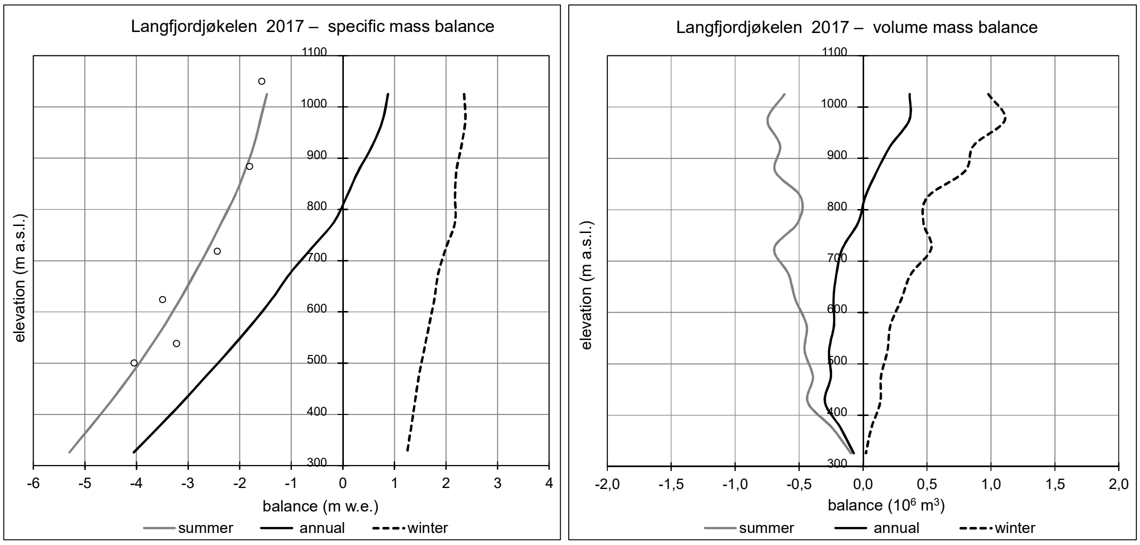


Figure 13-4
Mass balance diagram showing specific balance (left) and volume balance (right) for Langfjordjøkelen in 2017. Specific summer balance for six stakes is shown as circles (○).

Table 13-1
Winter, summer and annual balance for Langfjordjøkelen in 2017.

Mass balance Langfjordjøkelen 2016/17 – stratigraphic system							
		Winter mass balance Measured 25th Apr 2017		Summer mass balance Measured 29th Sep 2017		Annual mass balance Summer surface 2016 - 2017	
Altitude (m a.s.l.)	Area (km²)	Specific (m w.e.)	Volume (10^6 m³)	Specific (m w.e.)	Volume (10^6 m³)	Specific (m w.e.)	Volume (10^6 m³)
1000 - 1050	0.42	2.35	1.0	-1.48	-0.6	0.88	0.4
950 - 1000	0.47	2.38	1.1	-1.60	-0.7	0.78	0.4
900 - 950	0.38	2.30	0.9	-1.73	-0.6	0.58	0.2
850 - 900	0.36	2.20	0.8	-1.90	-0.7	0.30	0.1
800 - 850	0.23	2.18	0.5	-2.10	-0.5	0.07	0.0
750 - 800	0.22	2.18	0.5	-2.35	-0.5	-0.18	0.0
700 - 750	0.27	2.00	0.5	-2.60	-0.7	-0.60	-0.2
650 - 700	0.20	1.85	0.4	-2.88	-0.6	-1.03	-0.2
600 - 650	0.17	1.78	0.3	-3.15	-0.5	-1.38	-0.2
550 - 600	0.13	1.68	0.2	-3.45	-0.4	-1.78	-0.2
500 - 550	0.12	1.58	0.2	-3.78	-0.5	-2.20	-0.3
450 - 500	0.10	1.48	0.1	-4.13	-0.4	-2.65	-0.3
400 - 450	0.10	1.40	0.1	-4.50	-0.4	-3.10	-0.3
350 - 400	0.05	1.33	0.1	-4.90	-0.2	-3.58	-0.2
302 - 350	0.02	1.25	0.0	-5.30	-0.1	-4.05	-0.1
302 - 1050	**3.22**	**2.08**	**6.7**	**-2.35**	**-7.6**	**-0.27**	**-0.9**

13.2 Mass balance 1989-2017

The historical mass balance results for Langfjordjøkelen are presented in Figure 13-5. The balance year 2016/17 was the twenty-first successive year with significant negative annual balance at Langfjordjøkelen. The cumulative annual balance for 1989-2017 (estimated values for 1994 and 1995 included) is –26.1 m w.e., which gives a mean annual balance of –0.90 m w.e. a^{-1}.

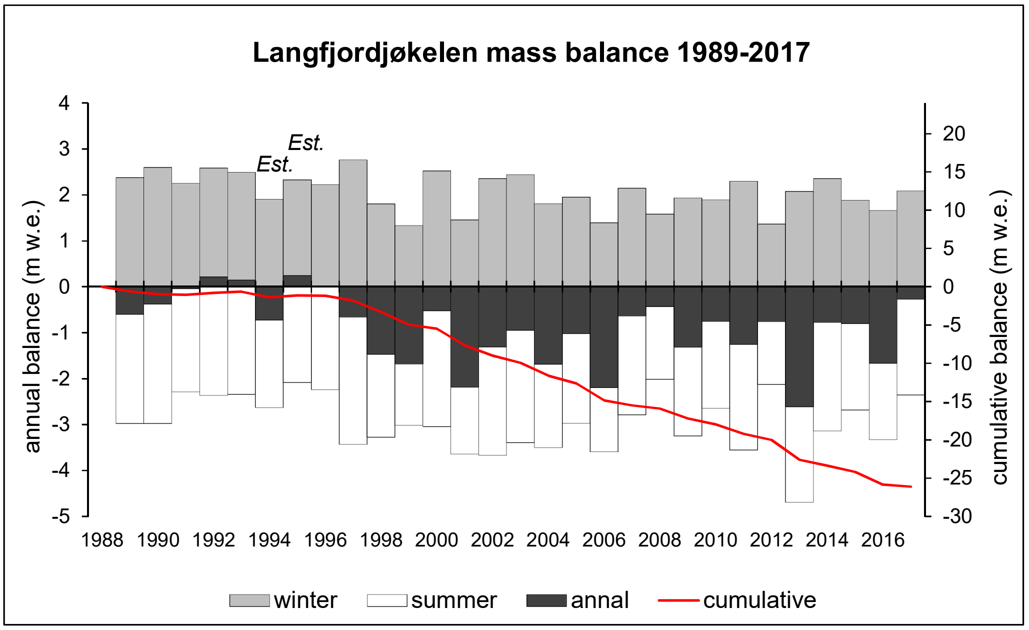


Figure 13-5
Mass balance at Langfjordjøkelen for the period 1989-2017. The total accumulated mass loss for 1989-2017 is 26 m w.e. (includes estimated values for 1994 and 1995).

14. Glacier monitoring

(Hallgeir Elvehøy and Miriam Jackson)

14.1 Glacier length change

Observations of glacier length change at Norwegian glaciers started in 1899. Between 1899 and 2017, glacier length change has been measured for several years at 73 glaciers. The total number of observations is 2689 up to and including 2017. The median and mean number of observations at one glacier is 25 and 37, indicating many glaciers with few observations. The median and mean number of observations in one year is 21 and 23 glaciers per year, respectively. In 1911, 45 glaciers were measured, and in 1992 only 8 glaciers were measured. At Briksdalsbreen, the length change was measured every year between 1900 and 2015, resulting in 115 observations. Stigaholtbreen, Fåbergstølsbreen (Fig. 14-2) and Nigardsbreen have more than 100 observations, too. Twenty-one glaciers have more than 50 observations, and an additional eleven glaciers have more than 30 observations. The longest record in northern Norway is from Engabreen with 85 measurements since 1903. The monitoring programme for 2017 is shown in Figure 14-1.

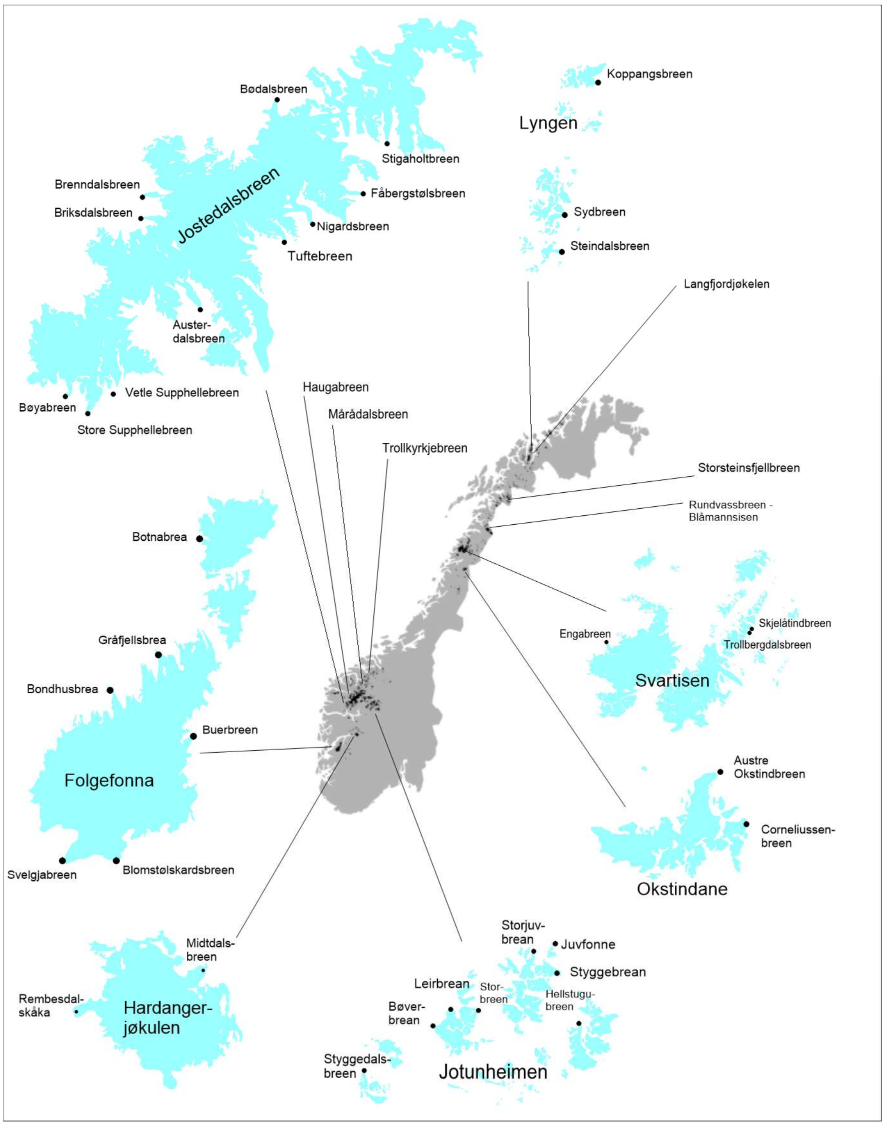


Figure 14-1 Location map showing glaciers where length change observations were performed in 2017. Note that the different glacier areas are not to the same scale.

Figure 14-2
Fåbergstølsbreen on 23rd August 2017. The length change reference point FAAB02 is located on a rock surface encircled in the photo. When the glacier reached its maximum in 2000 the terminus was approximately at this point. Between 2000 and 2017 the glacier retreated 382 metres. Photo: Hallgeir Elvehøy.

Monitoring programme

The monitoring programme for glacier length change includes 37 glaciers, 26 glaciers in southern Norway and 11 glaciers in northern Norway (Fig. 14-1 for location). The area of the monitored glaciers is 420 km², and they constitutes about 16 % of the glacier area in Norway (Andreassen et al., 2012). Measurements have been abandoned in recent years at five outlet glaciers from Jostedalsbreen due to glacier recession making conventional length measurements difficult, dangerous or meaningless. Among them was Briksdalsbreen where the measurements were halted in 2015 after 115 years of continuous measurements.

Methods

The distance to the glacier terminus from one or several fixed points is measured in defined directions, usually in September or October each year. The change in distance gives a rough estimate of the length change of the glacier. The representativeness for the glacier tongue of the annual length change calculated from measurements from one reference point can be questionable. However, when longer time periods are considered the measurements give valuable information about glacier fluctuations, as well as regional tendencies and variations (Andreassen et al., 2005).

Results 2017

Thirty-one glaciers were measured - seven glaciers in northern Norway and 24 glaciers in southern Norway. The results for 2017, period of measurements and number of observations (calculated length changes) are listed in Table 14-1. Data are also available at www.nve.no/glacier. The annual length change varied from +3 m (Svelgjabreen and Blomstølskardsbreen) to −54 m (Nigardsbreen). Two glaciers advanced slightly, eight glaciers had minor length changes (±2 m) and the remaining 21 glaciers showed retreat. Six glaciers in the monitoring programme were not measured.

Table 14-1
Glacier length change measured in 2017. See Figure 14-1 for glacier locations.

	Glacier	Glacier-ID	2017	Observer	Period(s)	Number obs.
Finnmark & Troms	Langfjordjøkelen	54	-14	NVE	1998-	19
	Koppangsbreen	205	-32	NVE	1998-	15
	Sydbreen	257	-2	NVE	2007-	10
	Steindalsbreen	288	-6	NVE	1998-	15
Nordland	Storsteinsfjellbreen	675	-5	NVE	2006-	10
	Rundvassbreen	941	-9	SISO	2011-	5
	Engabreen	1094	-8	S	1903-	85
	Skjelåtindbreen	1272	NM	NVE	2014-	1
	Trollbergdalsbreen	1280	NM	NVE	2010-	5
	Austre Okstindbreen	1438	NM	NVE	1908-44, 2006-	26
	Corneliussenbreen	1439	NM	NVE	2006-	8
Sunnmøre & Breheimen	Trollkyrkjebreen	1804	NM	NVE	1944-74, 2008-	20
	Heimsta Mårådalsbreen	2430	-31	NVE	2002-	5
Jostedalsbreen	Fåbergstølsbreen	2289	-27	NVE	1899-	112
	Nigardsbreen	2297	-54	NVE	1899-	107
	Haugabreen	2298	-18	NBM	1933-41, 2013-	12
	Brenndalsbreen	2301	NM	NVE	1900-62, 1964-65, 1996-	80
	Tuftebreen	2308	-23	NVE	2007-	10
	Austerdalsbreen	2327	0	NVE	1905-19, 1933-	97
	Vetle Supphellebreen	2355	+2	NBM	1899-44, 2011-	42
	Stigaholtbreen	2480	-17	NVE	1903-	111
Jotunheimen	Juvfonne	2597	-4	NVE	2010-	5
	Styggebrean	2608	+1	NFS	1951-63, 2011-	15
	Storjuvbrean	2614	-12	NVE	1901-07, 08-12, 33-61, 97-	57
	Storbreen	2636	-6	NVE	1900-01, 1902-	80
	Leirbrean	2638	-20	NVE	1907-77, 1979-	58
	Bøverbrean	2643	-22	NVE	1903-76, 1997-	44
	Styggedalsbreen	2680	+2	NVE	1901-	96
	Hellstugubreen	2768	-10	NVE	1901-	78
Hordaland	Midtdalsbreen	2964	-13	AN	1982-	35
	Rembesdalskåka	2968	-2	S	1917-	42
	Botnabrea	3117	-2	GK	1996-	15
	Gråfjellsbrea	3127	-43	S	2002-	13
	Buerbreen	3131	0	NVE	1900-	70
	Bondhusbrea	3133	-27	S	1902-	86
	Svelgjabreen	3137	+3	SKL	2007-	9
	Blomstølskardsbreen	3141	+3	SKL	1994-	18

NM – not measured in 2017

Observers other than NVE:
SISO Siso Energi
S Statkraft
NBM Norsk Bremuseum & Ulltveit-Moe senter for klimaviten, Fjærland
NFS Norsk fjellsenter, Lom
AN Prof. Atle Nesje, University of Bergen
GK Geir Knudsen, Tyssedal
SKL Sunnhordland Kraftlag

14.2 Jøkulhlaups

Jøkulhlaups or Glacier Lake Outburst Floods (GLOFs) were registered at two glaciers in Norway in 2017. One of the glaciers is an unnamed cirque glacier in Jostedalen and the other is Rembesdalskåka (chap. 6), which has had several previous events. An NVE report (Jackson and Ragulina, 2014) gives a summary of all known events from glaciers in Norway up to 2014.

Jostedalen – glacier 2487

An event was recorded in Jostedalen in August 2017. At first, it was thought to have come from Stigaholtbreen, but later investigation showed that it came from a small cirque glacier (unnamed glacier with id number 2487). A hydrologist in Statkraft Energi AS in Gaupne, Even Loe, saw that the river from Stigaholtbreen in Jostedalen was very brown in the last week of August 2017. He described it as "brown, in flood conditions and as thick as porridge" while all the other rivers feeding into Jostedøla river were blue-green with little water flow. River discharge from Stigaholten was not estimated, but there was much more water in Stegaholtbreelvi, the river from Stigaholtbreen than from Lodalsbreelvi, the river in Stordalen southwest of Stigaholtbreen. Reconnaissance of the glacier showed clear signs of water and gravel/sand on Stigaholtbreen from the cirque glacier (glacier id 2487) west of the glacier tongue, and that the snow on Stigaholtbreen had been washed away. There were no signs that there had been a glacier-dammed lake at the cirque glacier, so the water must have been stored under the glacier. Aerial photos from 2010 show evidence that there have been previous events from this glacier.

Figure 14-3
Left - Stigaholtbreen looking downstream, showing sediment lying across the glacier. Middle – Close-up of the sediment on the glacier, showing that the snow lying there had been washed away. Right – view of the cirque glacier where the event originated. Photos: Even Loe, Statkraft Energi AS.

An aerial photo of Stigaholtbreen and the adjacent cirque glacier from 2010 shows dark marks across the glacier that appear to be relic marks from previous events. These marks gradually move downstream due to glacier flow. As there are several marks this suggests that these events have occurred repeatedly from the cirque glacier.

Figure 14-4
Aerial photo from 2010 showing the unnamed cirque glacier 2487 to the left and part of Stigaholtbreen to the right. Blue arrows point to the traces of previous flood events from glacier 2487 on the tongue of Stigaholtbreen. Photo: www.norgeibilder.no.

Rembesdalskåka

One event was registered from Demmevatn, a glacier-dammed lake at the margin of Rembesdalskåka, in 2017. Demmevatnet has a long history of jøkulhlaups, dating from before 1800, and including several catastrophic floods in 1893, 1937 and 1938. Several drainage tunnels were constructed to lower the water level, and no events were registered after 1938 for over 70 years. However, extensive thinning of the glacier led to a new event in August 2014 (Jackson and Ragulina, 2014) and two further events in 2016 (Kjøllmoen et al, 2017).

Statkraft Energi AS, a hydropower company in the area, reported that Demmevatn was empty when they performed measurements on the glacier in late November. Further investigation by Statkraft Energi AS of the hydropower reservoir data showed that there was a sudden increase of 1.87 m in the level of the reservoir, Rembesdalsvatn, from about 2:30 pm on 27th October to 12 pm on 28th October. This corresponds to about 1.85 million m^3 water. At this time there was no hydropower production or transfer of water from the reservoir Sysenvatn to Rembesdalsvatn. Water flow increased from 5 to 40 m^3/s in a short time. Hence, 27th October is identified as the probable time of the jøkulhlaup, although the emptied lake wasn't observed until 29th November.

Middagstuvebreen – mitigation work

A lake adjacent to the glacier Middagstuvebreen has been identified as a possible source of a jøkulhlaup (Jackson and Ragulina, 2014). Nordvatnet is a lake at 824 m a.s.l. with an area of 0.75 km^2 that may be dammed by the glacier from the peak Middagstuva, unofficially called Middagstuvebreen. The lake depth has not been measured but the lake volume is probably at least 10 million m^3. Field measurements were performed in 2015 and 2016 but were inconclusive regarding whether the level of the glacier bed was above or below the lake level. In 2015, dGNSS was used to measure the surface elevation of the glacier at the edge closest to the lake. Radar measurements were performed on the glacier, concentrating on the glacier above a possible drainage path if a jøkulhlaup occurred (Fig. 14-5). However, due to steep valley sides and somewhat complicated bedrock topography, it was not possible to state unambiguously whether a jøkulhlaup could occur.

Figure 14-5
DGPS measurements of the glacier surface in August 2015 (left) and radar measurements of the glacier thickness in June 2016 (right). Photos: Hallgeir Elvehøy and Miriam Jackson.

There are several important structures downstream of the lake that could be affected including an electricity transformer station, several houses as well as the coastal highway, so it was thought pragmatic to lower the surface of the lake anyway. The work was completed in October 2017 (Fig. 14-6), and the lake level was lowered by 2.3 – 2.5 m, corresponding to a decrease in lake volume of about 2 million m^3.

Figure 14-6
The finished drainage channel looking towards Nordvatnet in October 2017 (left). Nordvatnet in March 2018 looking towards the glacier (right). Photos: Leif Martin Hansen and Miriam Jackson.

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Appendix A

Publications published in 2017

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Appendix B

Mass balance measurements in Norway – an overview

Mass balance measurements were carried out at 45 Norwegian glaciers during the period 1949-2017. The table lists characteristic data for the investigated glaciers. The Glacier ID refers to ID in the glacier inventory of Norway (Andreassen et al., 2012).

Area/ No. Glacier	Glacier ID	Lat., Long.	Area (km^2)	Altitude (m a.s.l.)	Mapping year	Period	No. of years
Ålfotbreen							
1 Ålfotbreen	2078	61°45', 5°38'	4.0	890-1368	2010	1963-	55
2 Hansebreen	2085	61°44', 5°40'	2,8	927-1310	2010	1986-	32
Folgefonna							
3-4 Blomsterskardsbreen	1)	59°58', 6°19'	45.7	850-1640	1959	1970-77	8
3 Svelgjabreen	3137	59°58', 6°18'	22.3	829-1634	2017	2007-17	11
4 Blomstølskardsbreen	3141	59°59', 6°21'	22.5	1011-1634	2017	2007-17	11
5 Bondhusbrea	3133	60°02', 6°20'	10.7	477-1636	1979	1977-81	5
6 Breidablikkbrea	3128	60°03', 6°22'	3.9 3.2	1217-1660 1232-1648	1959 2013	1963-68 2003-13	17
7 Gråfjellsbrea	3127	60°04', 6°24'	9.7 8.1	1034-1656 1049-1647	1959 2013	64-68, 74-75 2003-13	18
8 Blåbreen	3126	60°05', 6°26'	2.3	1060-1602	1959	1963-68	6
9 Ruklebreen	3129	60°04', 6°26'	1.8	1603-1235	1959	1964-68	5
10 Midtre Folgefonna	2)	60°08', 6°28'	8.6	1100-1570	1959	1970-71	2
Jostedalsbreen							
11 Jostefonn	3)	61°25', 6°33'	3.8	960-1622	1993	1996-2000	5
12 Vesledalsbreen	2474	61°50', 7°16'	4.1	1126-1745	1966	1967-72	6
13 Tunsbergdalsbreen	2320	61°36', 7°02'	52.2	536-1942	1964	1966-72	7
14 Nigardsbreen	2297	61°42', 7°08'	46.6	330-1952	2013	1962-	56
15 Store Supphellebreen	2352	61°31', 6°48'	12.0	80-300/ 720-1740	1966	1964-67, 73- 75, 79-82	11
16 Austdalsbreen	2478	61°45', 7°20'	10.6	1197-1747	2009	1988-	30
17 Spørteggbreen	4)	61°36', 7°28'	27.9	1260-1770	1988	1988-91	4
18 Harbardsbreen	2514	61°41', 7°40'	13.2	1242-1978	1996	1997-2001	5
Hardangerjøkulen							
19 Rembesdalskåka	2968	60°32', 7°22'	17.3	1066-1854	2010	1963-	55
20 Midtdalsbreen	2964	60°33', 7°26'	6.7	1380-1862	1995	2000-2001	2
21 Omnsbreen	2919	60°39', 7°28'	1.5	1460-1570	1969	1966-70	5
Jotunheimen							
22 Tverråbreen	2632	61°35', 8°17'	5.9	1415-2200		1962-63	2
23 Blåbreen	2770	61°33', 8°34'	3.6	1550-2150	1961	1962-63	2
24 Storbreen	2636	61°34', 8°08'	5.1	1400-2102	2009	1949-	69
25 Vestre Memurubre	2772	61°31', 8°27'	9.2	1565-2270	1966	1968-72	5
26 Austre Memurubre	2769	61°33', 8°29'	8.7	1627-2277	1966	1968-72	5
27 Juvfonne	2597	61°40', 8°21'	0.2	1840-1998	2004	2010-	8
28 Hellstugubreen	2768	61°34', 8°26'	2.9	1482-2229	2009	1962-	56
29 Gråsubreen	2743	61°39', 8°37'	2.1	1833-2284	2009	1962-	56
Okstindbreene							
30 Charles Rabot Bre	1434	66°00', 14°21'	1.1	1090-1760	1965	1970-73	4
31 Austre Okstindbre	1438	66°00', 14°17'	14.0	730-1750	1962	1987-96	10
Svartisen							
32 Høgtuvbreen	1144	66°27', 13°38'	2.6	588-1162	1972	1971-77	7
33 Svartisheibreen	1135	66°33', 13°46'	5.7	765-1424	1995	1988-94	7
34 Engabreen	1094	66°40', 13°45'	36.2	111-1544	2016	1970-	48
35 Storglombreen	5)	66°40', 13°59'	59.2 62.4	520-1580 520-1580	1968	1985-88 2000-05	10
36 Tretten-null-tobreen	1084	66°43', 14°01'	4.3	580-1260	1968	1985-86	2
37 Glombreen	1052	66°51', 13°57'	2.2	870-1110	1953	1954-56	3
38 Kjølbreen	1093	66°40', 14°05'	3.9	850-1250	1953	1954-56	3
39 Trollbergdalsbreen	1280	66°42', 14°26'	2.0 1.8	907-1366 907-1369	1968 1998	1970-75 1990-94	11
Blåmannsisen							
40 Rundvassbreen	941	67°17', 16°03'	11.7 10.8	788-1533 853-1527	1998 2017	2002-04 2011-17	10
Skjomen							
41 Blåisen	596	68°20', 17°51'	2.2	860-1204	1959	1963-68	6
42 Storsteinsfjellbreen	675	68°13', 17°54'	6.2 5.9	926-1846 969-1852	1960 1993	1964-68 1991-95	10
43 Cainhavarre	703	68°06', 17°59'	0.7	1214-1538	1960	1965-68	4
Vest-Finnmark							
44 Svartfjelljøkelen	26	70°14', 21°57'	2.7	500-1080	1966	1978-79	2
45 Langfjordjøkelen	54	70°10', 21°45'	3.6 3.2	277-1053 302-1050	1994 2008	1989-93 1996-	27

1) 3137 and 3141, 2) 3119, 3120 and 3121, 3) 2146 and 2148

4) 2519, 2520, 2522, 2524, 2525, 2527, 2528, 2530, 2531 and 2532, 5) 1092 and 1096

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