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Glaciological investigations in Norway 2018

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



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Forsidefoto: Hansebreen (left) and Ålfotbreen (right), two north-facing glaciers in western Norway. The photo was taken on 13th August 2018 by Hallgeir Elvehøy.

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Summary: Results of glaciological investigations performed at Norwegian glaciers in 2018 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, Ice velocity, Meteorology, Jökulhlaup, Subglacial laboratory.

Norwegian water resources
and energy directorate (NVE)
Middelthunsgate 29
P.O. box 5091 Majorstua
0301 OSLO, Norway

Telephone: +47 22 95 95 95

Email: nve@nve.no

Internet: www.nve.no

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Glaciological investigations in Norway 2018

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Preface

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

The report is based on 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 2018. 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, November 2019



Svein Taksdal
Director,
Hydrology Department



Rune V. Engeset
Head of section,
Section for Glaciers, Ice and Snow

Summary

Mass balance

Mass balance investigations were performed on eleven glaciers in Norway in 2018.

The winter balance for six of the reference glaciers (mass balance series back to at least 1981) was lower than the 1981-2010 average. Only Nigardsbreen had a greater winter balance than average. Gråsubreen had the lowest relative winter balance with 49 % of the reference period average.

The summer balance was higher than the 1981-2010 average for all seven reference glaciers. Gråsubreen had the highest relative summer balance with 190 % of the reference period average and Storbreen had its highest summer balance (-3.24 m w.e.) since measurements started in 1949.

Consequently, the annual balance was negative for all seven reference glaciers, and of these seven, Ålfotbreen had the greatest deficit with -2.0 m w.e. Hansebreen had the greatest deficit of all measured glaciers in Norway with -2.7 m w.e. Storbreen and Gråsubreen had their second greatest deficits since measurements started in 1949 and 1963, respectively.

Glacier length change

Glacier length changes were measured at 26 glaciers in southern Norway and 6 glaciers in northern Norway. Twenty-nine of the glaciers had a decrease in length and three glaciers had a small advance. The greatest retreats were observed at Engabreen (140 m) and Gråfjellsbrea (125 m).

Sammendrag

Massebalanse

I 2018 ble det utført massebalansemålinger på 11 breer i Norge – to i Nord-Norge og ni 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 seks breer. Bare Nigardsbreen hadde større vinterbalanse enn gjennomsnittet. Gråsubreen hadde relativt minst vinterbalanse med 49 % av referanseperioden.

Sommerbalansen ble større enn gjennomsnittet for alle sju referansebreene. Gråsubreen hadde relativt størst sommerbalanse med 190 % av referanseperioden og Storbreen hadde den største sommerbalansen (-3,24 m v.ekv.) som er målt siden målingene startet i 1949.

Som følge av lite snø og mye smelting ble det negativ massebalanse for alle sju referansebreene og Ålfotbreen hadde størst underskudd med -2,0 m v.ekv. Hansebreen hadde det største underskuddet av alle de målte breene med -2,7 m v.ekv. Storbreen og Gråsubreen hadde det nest største underskuddet som er målt siden målingene startet i hhv. 1949 og 1963.

Lengdeendringer

Lengdeendringer ble målt på 26 breer i Sør-Norge og 6 breer i Nord-Norge. Tjueni av breutløperne hadde tilbakegang og tre hadde litt framgang. Størst tilbakegang ble målt på Engabreen (140 m) og Gråfjellsbrea (125 m).

1. Glacier investigations in Norway 2018

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) include 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 ice 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.

GLOF

Glacier Lake Outburst Flood. See Jökulhlaup.

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.

Jökulhlaup

A *jökulhlaup* 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.

Orthometric elevation

The elevation above the geoid, which is an irregular surface shape that is adjusted to the ellipsoid by a proper geoid model. *Orthometric elevation* is for practical purposes “elevation above sea level” (m a.s.l.).

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 method

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 snow line at any instant, particularly during the *ablation* season.

Tower

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

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 (Fig. 1-1). 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.

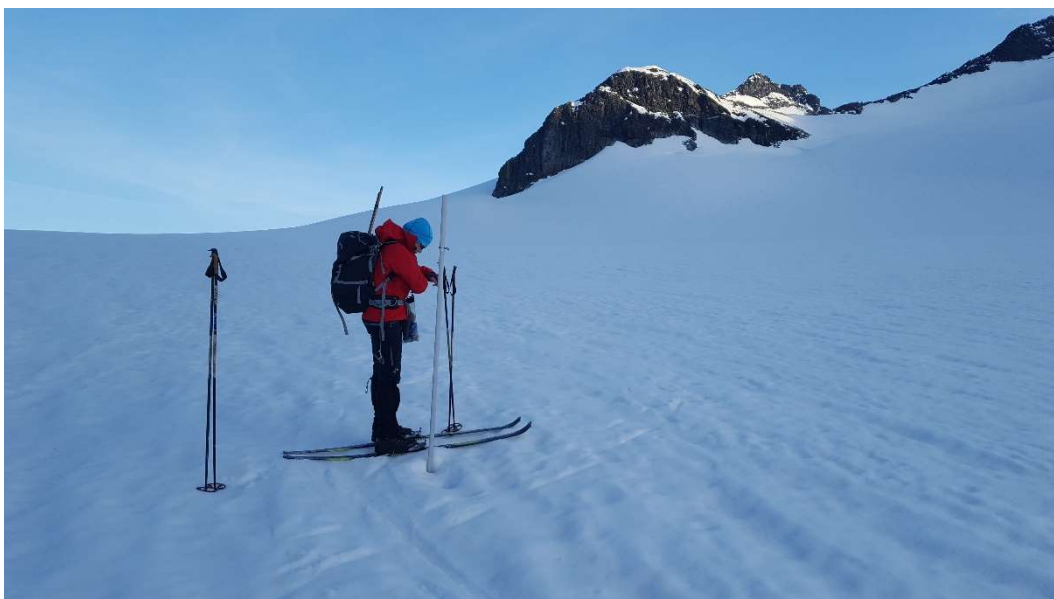


Figure 1-1
Stake reading on Hellstugubreen in May 2018. Photo: Anund Kvambekk.

Summer and annual balance

Summer and annual balances are obtained from measurements of stakes and towers, 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} .

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, measuring and calculating the additional ablation often 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 mainly 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 unmeasured areas of the glacier) 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 thus based on subjective estimates.

Mass balance programme

In 2018 mass balance measurements were performed on eleven glaciers in Norway - nine in southern Norway and two in northern Norway (Fig. 1-2). Included in this total is one small ice mass, Juvfonne, which can be characterised as an ice patch rather than a glacier (chap. 7). In southern Norway, six of the glaciers (Ålfotbreen, Nigardsbreen, Rembesdalskåka, Storbreen, Hellstugubreen and Gråsubreen) have been measured for 56 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 water equivalent 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 70 years of measurements, while Engabreen at Svartisen has the longest series (49 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 2018 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).

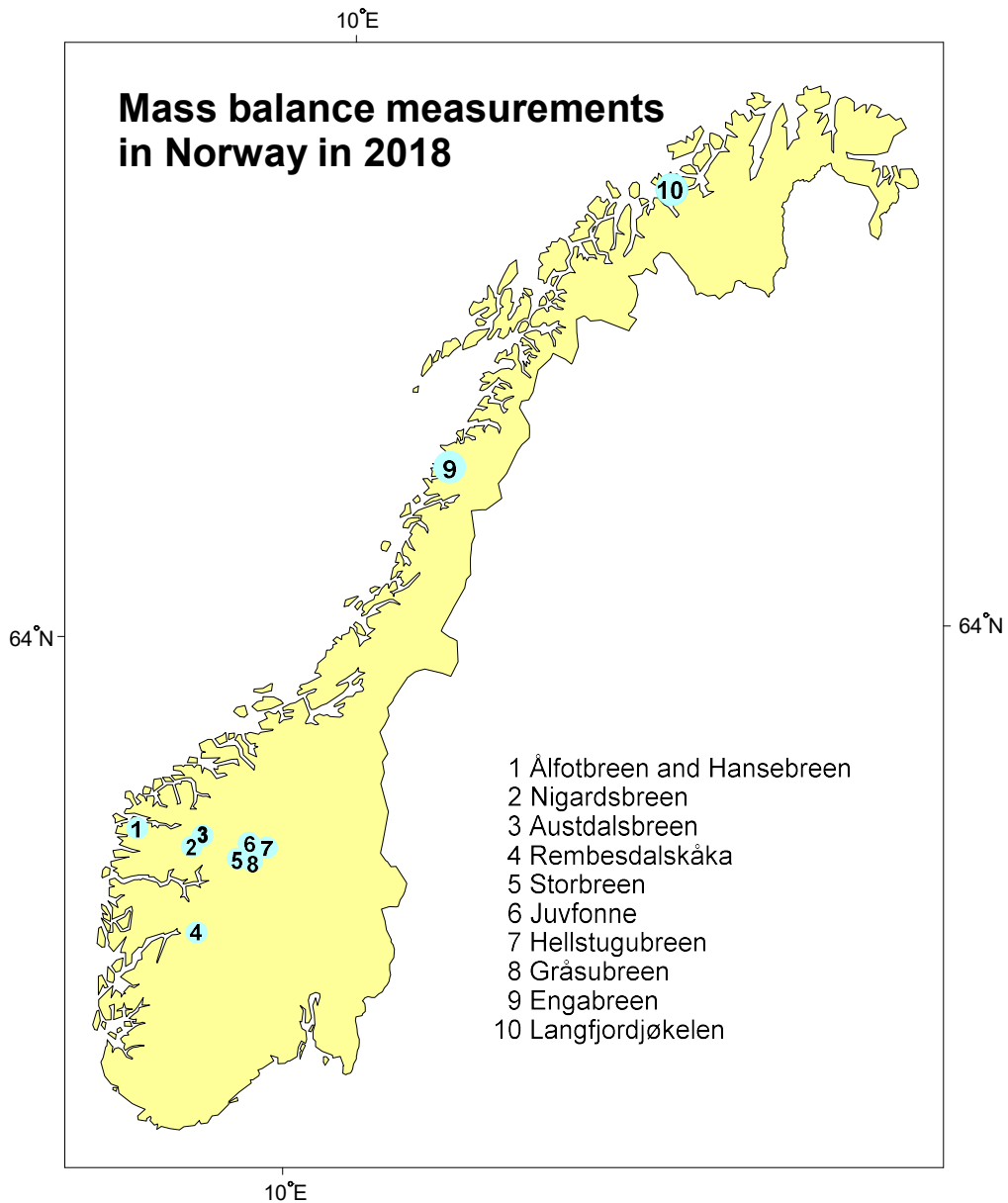


Figure 1-2
Location of the glaciers at which mass balance studies were performed in 2018.

Mass balance studies performed on Norwegian glaciers in 2018 are reported in the following chapters.

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

Winter weather

The first three months (October, November and December) of the winter season 2017/18 were snow-rich in southern Norway, but rather dry in northern Norway. The second part of the winter season was snow-poor and cold over most of the country.

Snow accumulation and winter balance

The winter balance for six of the reference glaciers was lower than the average of the reference period 1981-2010. Only Nigardsbreen had a greater winter balance than average with 105 %. Gråsubreen had the lowest relative winter balance with 49 % of the reference period value.

Summer weather

The summer season started suddenly in May with high temperatures over the whole country. In southern Norway the warm weather continued throughout June and July, while August was about normal. In northern Norway the summer continued with rather cool weather in June, and then high temperatures again in July and August.

Ablation and summer balance

The summer balance was higher than the average for all seven reference glaciers. Gråsubreen had the highest relative summer balance with 190 % of the reference period and Storbreen had its highest summer balance (-3.24 m w.e.) since measurements started in 1949.

Annual balance

The annual balance was negative for all seven reference glaciers, and Ålfotbreen had the greatest deficit with -2.0 m w.e. Hansebreen had the greatest deficit of all measured glaciers with -2.7 m w.e. Storbreen and Gråsubreen had the second greatest deficit since measurements started in 1949 and 1962, respectively.

The results from the mass balance measurements in Norway in 2018 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 2017/2018 (October-April) NAO and AO were positive overall (0.628 and -0.002 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 March where both NAO and AO were highly negative. The AO was also slightly negative in November, December and January. 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 2018. 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 (km ²)	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	1963-18	4.0	890-1368	2.84	76	-4.88	127	-2.04	-0.08	>1368	0
Hansebreen	1986-18	2.8	927-1310	2.65	¹⁾ 77	-5.30	¹⁾ 131	-2.65	¹⁾ -0.61	>1310	0
Nigardsbreen	1962-18	46.6	330-1952	2.37	105	-3.22	147	-0.85	0.06	1675	36
Austdalsbreen	1988-18	10.6	1200-1747	1.91	²⁾ 88	³⁾ -3.45	²⁾ 128	-1.54	²⁾ -0.52	>1747	0
Rembesdalskåka	1963-18	17.3	1066-1854	1.94	91	-3.21	149	-1.27	-0.02	>1854	0
Storbreen	1949-18	5.1	1400-2102	1.27	85	-3.24	178	-1.97	-0.33	2005	3
Juvfonne ⁴⁾	2010-18	0.2	1840-1998	1.78		-3.50		-1.72			
Hellstugubreen	1962-18	2.9	1482-2229	0.90	80	-2.53	167	-1.63	-0.39	2100	4
Gråsubreen	1962-18	2.1	1833-2283	0.39	49	-2.21	190	-1.82	-0.37	undef.	
Engabreen	1970-18	36.2	111-1544	1.75	68	-3.38	131	-1.63	-0.01	>1544	0
Langfjordjøkelen	1989-93 1996-18	3.7 2.6	280-1050 338-1043	1.54	⁵⁾ 74	-3.67	⁵⁾ 123	-2.13	⁵⁾ -0.92	>1043	0

¹⁾ Calculated for the measured period 1986-2017

²⁾ Calculated for the measured period 1988-2017

³⁾ Contribution from calving amounts to -0.38 m for B_a

⁴⁾ Calculated for a point only, b_w, b_s and b_a

⁵⁾ Calculated for the measured periods 1989-93 and 1996-2017

Figure 1-3 presents the mass balance results in southern Norway for 2018. The west-east gradient is evident for both winter and summer balances. The results for 2018 show a negative mass balance for all eleven measured glaciers in Norway.

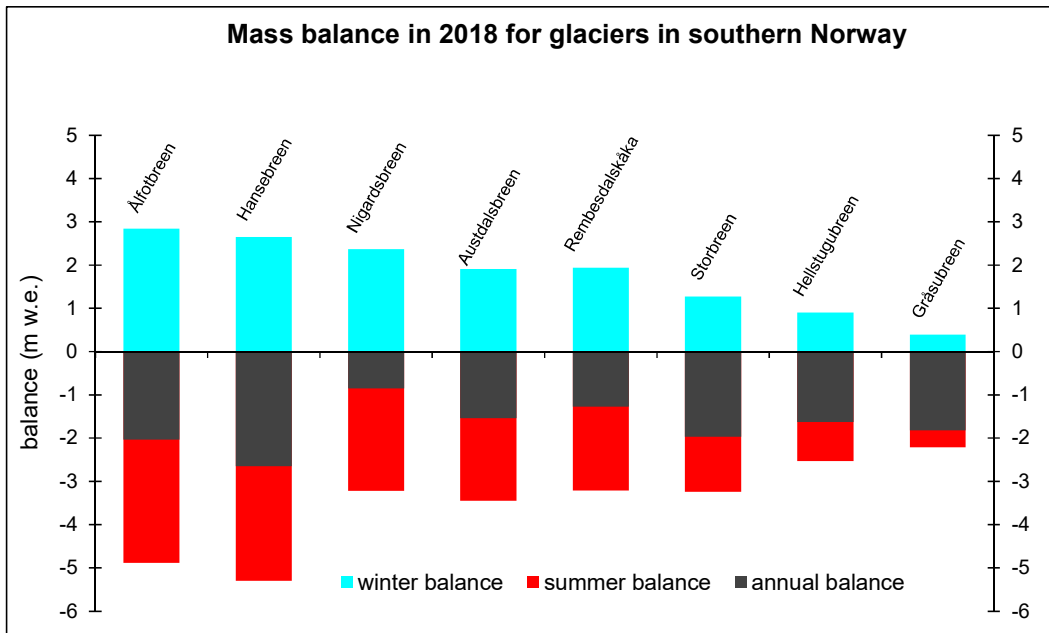


Figure 1-3
Mass balance in 2018 in southern Norway. The glaciers are listed from west to east.

The cumulative annual balance for the six reference glaciers in southern Norway for the period 1963-2018 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 1963-2018.

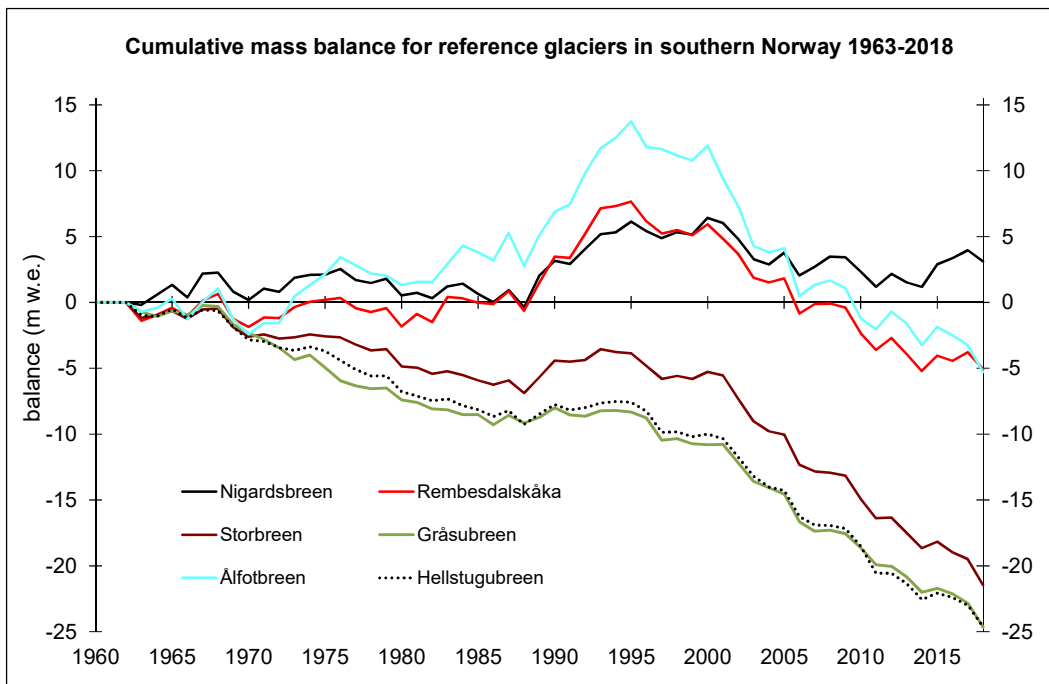


Figure 1-4
Cumulative mass balance for the six reference glaciers in southern Norway, Ålfotbreen, Nigardsbreen, Rembesdalskåka, Storbreen, Hellstugubreen and Gråsusbreen, for the period 1963-2018.

1.3 Other investigations

Glacier length change measurements were performed at 32 glaciers in Norway in 2018. Some of the glaciers have a measurement series going back to about 1900. The length changes are summarised in chapter 12.

Glacier dynamics (surface velocity) have been studied at Austdalsbreen since 1987 (chap. 4). The measurements continued in 2018. Glacier velocity was also measured at Ålfotbreen and Hansebreen (chap. 2) and Nigardsbreen (chap. 3) for the period 2017-2018.

Meteorological observations were performed at Engabreen (chap. 10) and Langfjordjøkelen (chap. 11).

The 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 10.

Several jøkulhlaups (glacier floods) have occurred in 2018 and these are also described in chapter 12.

2. Ålfotbreen (Bjarne Kjøllmoen)

Ålfotbreen ice cap (61°45'N, 5°40'E) has an area of 10.6 km² (2010) and is, together with Blåbreen (Fig. 2-1), one of the westernmost and most maritime glaciers in Norway. Mass balance studies have been carried out on two adjacent north-facing outlet glaciers – Ålfotbreen (4.0 km²,) and Hansebreen (2.8 km²). 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 photographed on 29th September 2010 by Blom AS. Map source: Norgebilder.no.

2.1 Mass balance 2018

Fieldwork

Snow accumulation measurements were performed on 15th and 16th May and the calculation of winter balance was based on measurement of stakes in six different positions and 77 snow depth soundings on Ålfotbreen, and stakes in four 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 2017. Generally the sounding conditions were good over the whole glacier. In the upper areas a solid ice layer was detected 10-20 cm above the S.S. The snow depth varied from 2.5 m to 6.4 m on Ålfotbreen, and from 3.2 m to 5.9 m on Hansebreen. Snow density was measured in one location (1228 m a.s.l.), applicable for both glaciers. The mean snow density of 5.4 m snow was 572 kg m⁻³. The measured mean snow density for the twenty-year period 1998-2017 was 520 kg m⁻³.

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

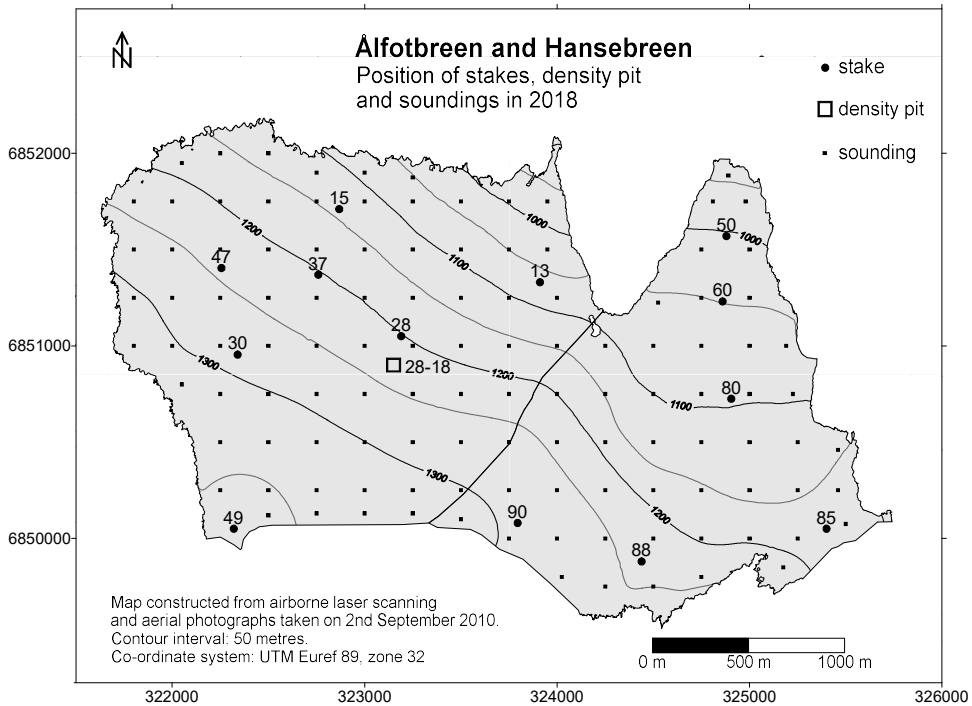


Figure 2-2
Location of stakes, soundings and snow pit at Alfotbreen (left) and Hansebreen (right) in 2018.

Ablation was measured on 11th October (Fig. 2-3). The annual balance was measured at stakes in seven positions on Alfotbreen and six positions on Hansebreen (Fig. 2-2). At the time of the ablation measurements up to 1.3 m of fresh snow had fallen.



Figure 2-3
Stake reading, probing fresh snow and GNSS positioning of stake 49 during the ablation measurements on 11th October. Photo: Bjarne Kjølmoen.

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.) on Ålfotbreen.

The winter balance was calculated as a mean value for each 50 m height interval and was 2.8 ± 0.2 m w.e. at Ålfotbreen, which is 76 % of the mean winter balance for the reference period 1981-2010. The winter balance on Hansebreen was calculated as 2.6 ± 0.2 m w.e., which is 77 % of the mean winter balance for the measurement period 1986-2017. Spatial distribution of the winter balance at Ålfotbreen and Hansebreen is shown in Figure 2-4.

The density of melted firn was assumed to be between 700 and 850 kg m^{-3} , and the density of melted ice was set as 900 kg m^{-3} . 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 -4.9 ± 0.3 m w.e. on Ålfotbreen, which is 127 % of the reference period. The summer balance on Hansebreen was -5.3 ± 0.3 m w.e., which is 131 % of the mean winter balance for 1986-2017.

Hence, the annual balance was negative for both glaciers. Ålfotbreen had a deficit of 2.0 ± 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 (2009-2018), the mean annual balance was -0.69 m w.e. and eight of those years had a negative annual balance. The annual balance at Hansebreen was -2.7 ± 0.4 m w.e. The mean value for the measurement period 1986-2017 is -0.61 m w.e. Over the last ten years the mean annual balance was -1.21 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 2-5.

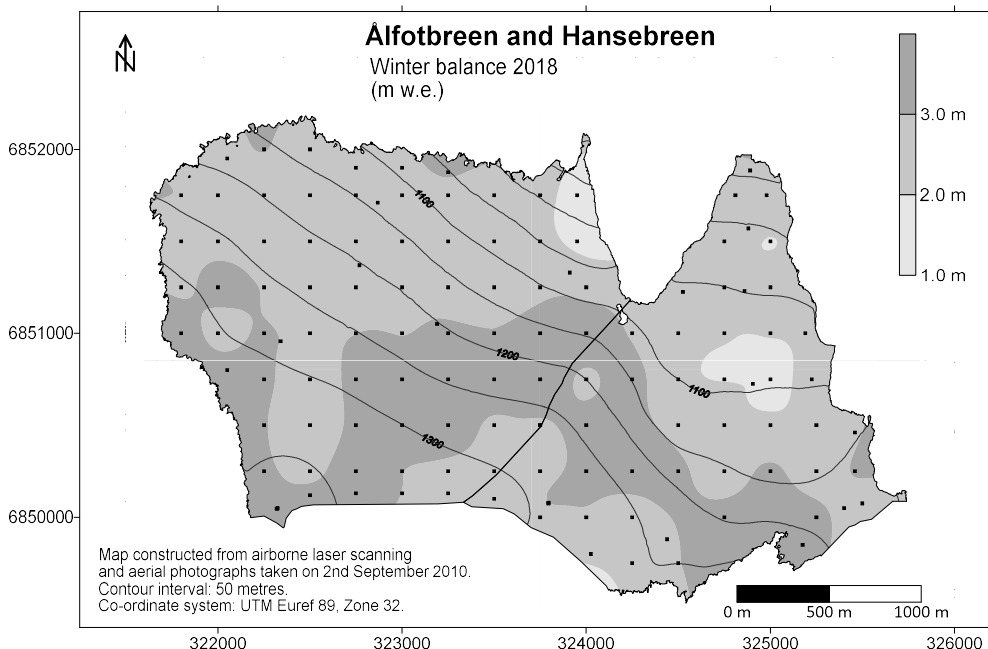


Figure 2-4
Spatial distribution of winter balance on Ålfotbreen and Hansebreen in 2018.

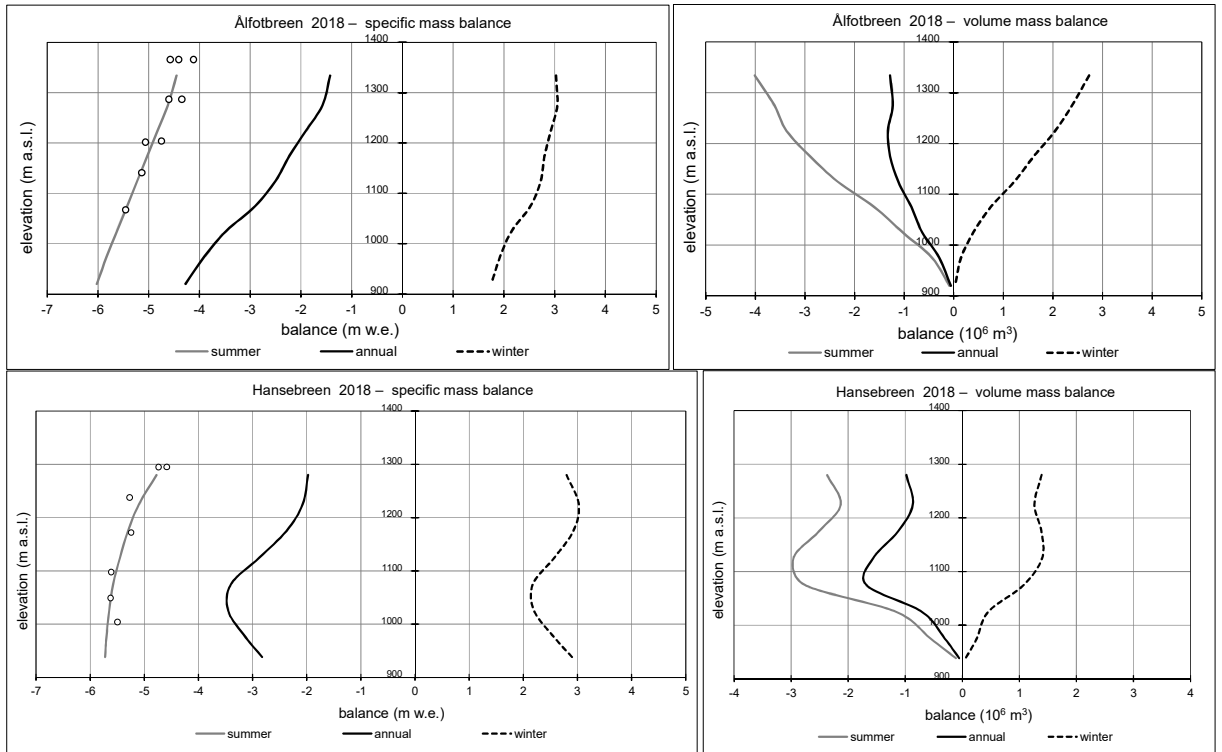


Figure 2-5
Mass balance diagram for Alftobreen (upper) and Hansebreen (lower) in 2018 showing altitudinal distribution of specific (left) and volumetric (right) winter, summer and annual balance. Specific summer balance at each stake is shown (○).

Table 2-1
Winter, summer and annual balance for Alftobreen (upper) and Hansebreen (lower) in 2018.

Mass balance Alftobreen 2017/18 – stratigraphic system							
Altitude (m a.s.l.)	Area (km ²)	Winter mass balance Measured 15th May 2018		Summer mass balance Measured 11th Oct 2018		Annual mass balance Summer surface 2017 - 2018	
		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	3.03	2.7	-4.45	-4.0	-1.43	-1.3
1250 - 1300	0.78	3.05	2.4	-4.63	-3.6	-1.58	-1.2
1200 - 1250	0.70	2.93	2.0	-4.83	-3.4	-1.90	-1.3
1150 - 1200	0.58	2.80	1.6	-5.03	-2.9	-2.23	-1.3
1100 - 1150	0.45	2.73	1.2	-5.23	-2.3	-2.50	-1.1
1050 - 1100	0.30	2.53	0.7	-5.43	-1.6	-2.90	-0.9
1000 - 1050	0.18	2.15	0.4	-5.63	-1.0	-3.48	-0.6
950 - 1000	0.08	1.93	0.1	-5.83	-0.4	-3.90	-0.3
890 - 950	0.01	1.75	0.0	-6.03	-0.1	-4.28	-0.1
890 - 1368	3.98	2.84	11.3	-4.88	-19.4	-2.04	-8.1

Mass balance Hansebreen 2017/18 – stratigraphic system							
Altitude (m a.s.l.)	Area (km ²)	Winter mass balance Measured 15th May 2018		Summer mass balance Measured 11th Oct 2018		Annual mass balance Summer surface 2017 - 2018	
		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	2.80	1.39	-4.78	-2.37	-1.98	-0.98
1200 - 1250	0.42	3.03	1.26	-5.10	-2.13	-2.08	-0.87
1150 - 1200	0.47	2.93	1.39	-5.30	-2.51	-2.38	-1.13
1100 - 1150	0.54	2.58	1.40	-5.45	-2.96	-2.88	-1.56
1050 - 1100	0.50	2.18	1.08	-5.58	-2.76	-3.40	-1.68
1000 - 1050	0.21	2.20	0.45	-5.65	-1.16	-3.45	-0.71
950 - 1000	0.10	2.58	0.25	-5.70	-0.56	-3.13	-0.31
927 - 950	0.02	2.90	0.06	-5.73	-0.11	-2.83	-0.06
927 - 1310	2.75	2.65	7.3	-5.30	-14.6	-2.65	-7.3

According to Figure 2-5 the ELA lies above the highest point on both glaciers. Consequently the AAR is 0 %.

2.2 Mass balance 1963(86)-2018

The historical mass balance results for Ålfotbreen and Hansebreen are presented in Figure 2-6. The cumulative annual balance for Ålfotbreen for 1963-2018 is -5.3 m w.e., which gives a mean annual balance of -0.09 m w.e. a^{-1} . The cumulative annual balance for Hansebreen for 1986-2018 is -22.0 m w.e., which gives a mean annual balance of -0.67 m w.e. a^{-1} .

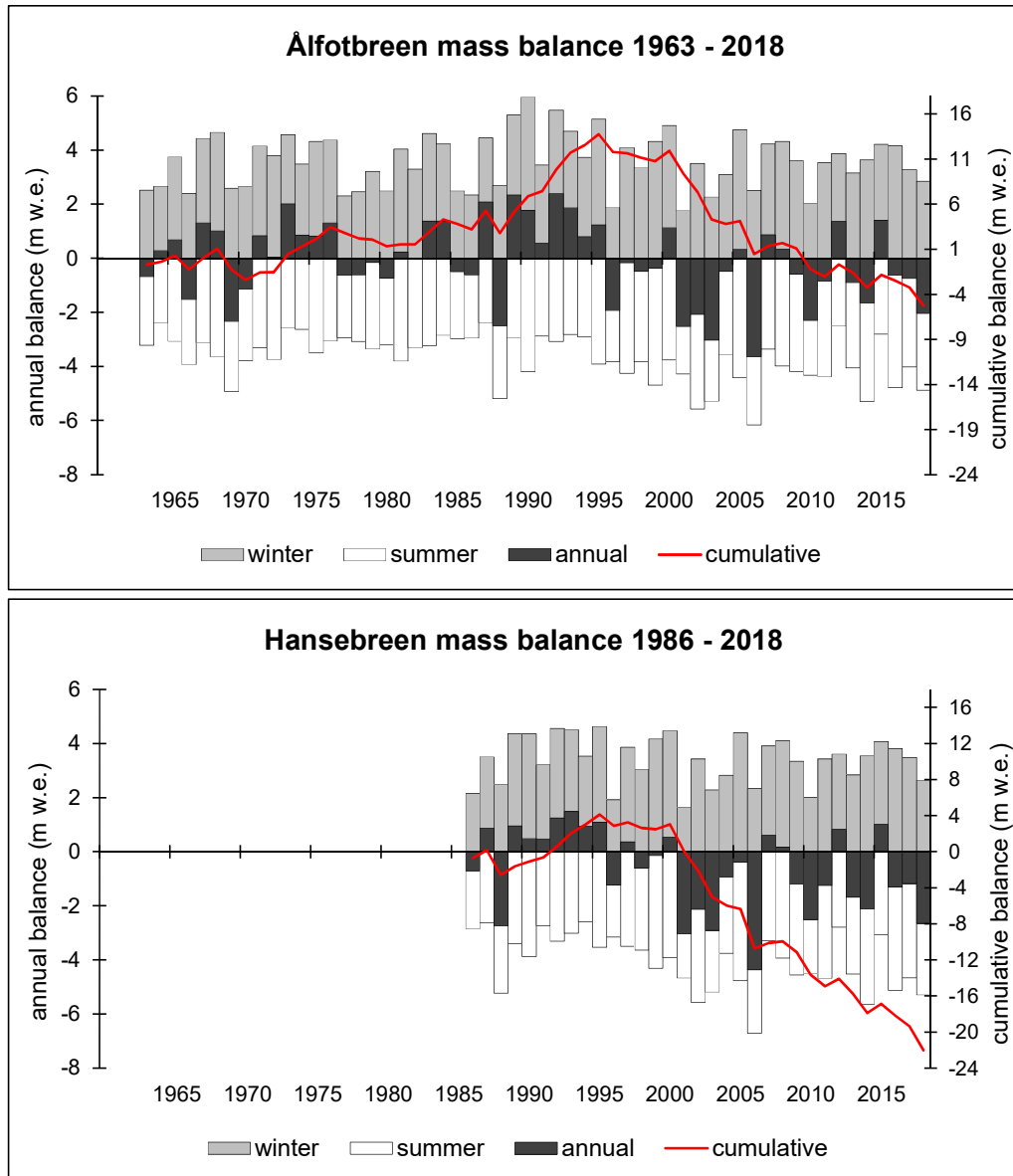


Figure 2-6
Mass balance at Ålfotbreen (upper) 1963-2018 and Hansebreen (lower) 1986-2018. Cumulative mass balance is given on the axis to the right.

2.3 Ice velocity

The surface ice velocity was calculated from repeated GNSS measurements of ten stakes. The positions of the stakes were measured on 9th August and 19th October 2017, and 13th August and 11th October 2018. For one of the stakes, however, measurements represent the period from 27th August 2014 to 13th August 2018 as measurements from 2017 were not usable.

The positions were measured by using Topcon GR3 dual frequency GNSS receivers placed close to the stakes (Fig. 2-3). The GNSS data were post-processed using the software program “Topcon Tools”. Data from the SATREF reference station Gloppen was used for post-processing the GNSS data.

The calculated surface ice velocities show mean annual velocities between 0.2 and 11.8 m a⁻¹ (Fig. 2-7). The uncertainty of the GNSS positioning is assumed to be ± 0.5 m.

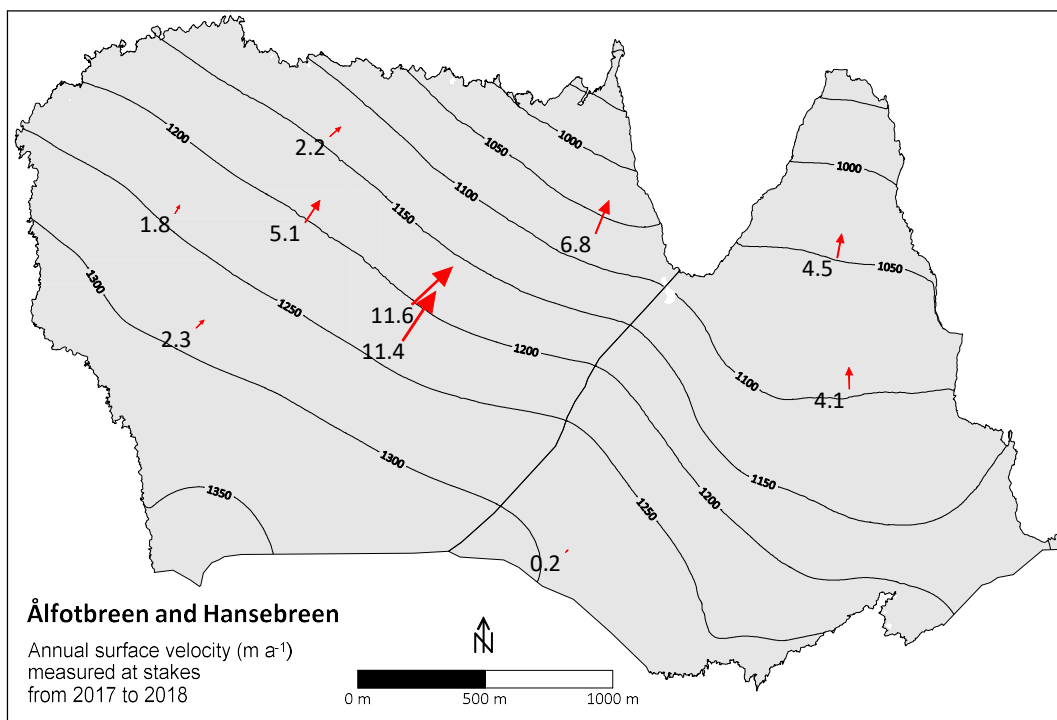


Figure 2-7
Map of Ålfotbreen and Hansebreen showing mean annual surface velocities calculated from stake position measurements in August and October 2017 and 2018. For one of the stakes (stake 80, see Fig. 2-2) the velocity is for a period from August 2014 to August 2018.

3. Nigardsbreen (Bjarne Kjøllmoen)

Nigardsbreen (61°42'N, 7°08'E) is one of the largest and best known outlet glaciers from Jostedalsgreen. It has an area of 46.6 km² (2013) and flows south-east from the centre of the ice cap. Nigardsbreen accounts for approximately 10 % of the total area of Jostedalsgreen, and extends from 1952 m a.s.l. down to 330 m a.s.l. (Fig. 3-1).

Glaciological investigations in 2018 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).

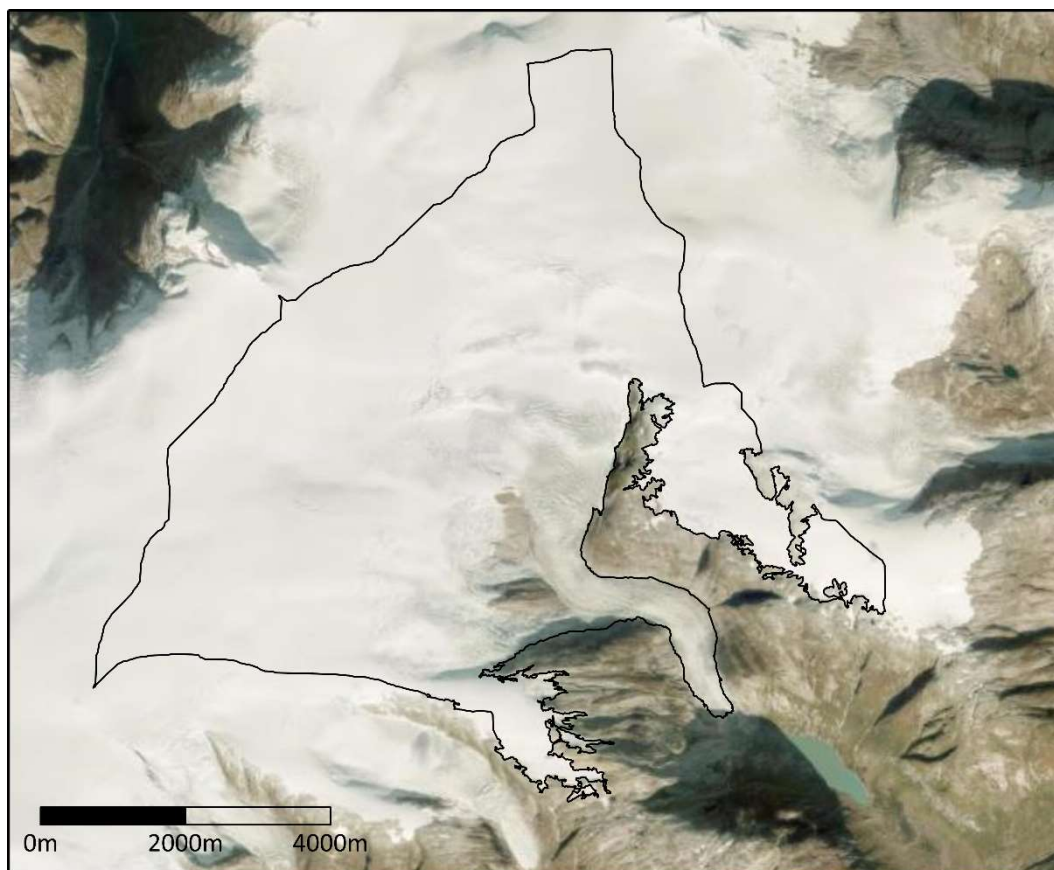


Figure 3-1
Nigardsbreen photographed in September 2010 by Blom AS. The glacier outline is from 2013.
Map source: Norgebilder.no.

3.1 Mass balance 2018

Fieldwork

Snow accumulation measurements were performed on 15th May and the calculation of winter balance is based on measurement of eight stakes and 113 snow depth soundings (Fig. 3-2). Comparison of sounded snow depth and stake readings indicated no melting after the ablation measurements in October 2017. In spite of modest snow depths the sounding conditions were rather bad and the summer surface was difficult to identify, particularly in the uppermost areas. The snow depth varied between 2.4 and 5.7 m on the plateau. On the glacier tongue, the snow depth was 1.6 m at stake position 1000 (980 m

a.s.l.) and 0.9 m at stake position 600 (593 m a.s.l.). Snow density was measured at stake position 94 (1682 m a.s.l.), and the mean density of 4.6 m snow was 547 kg m^{-3} .

Ablation was measured on 26th October. Measurements were made at stakes and towers in nine locations (Fig. 3-2). In the accumulation area there was between 0.4 and 1.5 m of snow remaining from winter 2017/18. At the time of measurement, there was between 1.8 and 2.4 m of fresh snow at stakes on the glacier plateau.

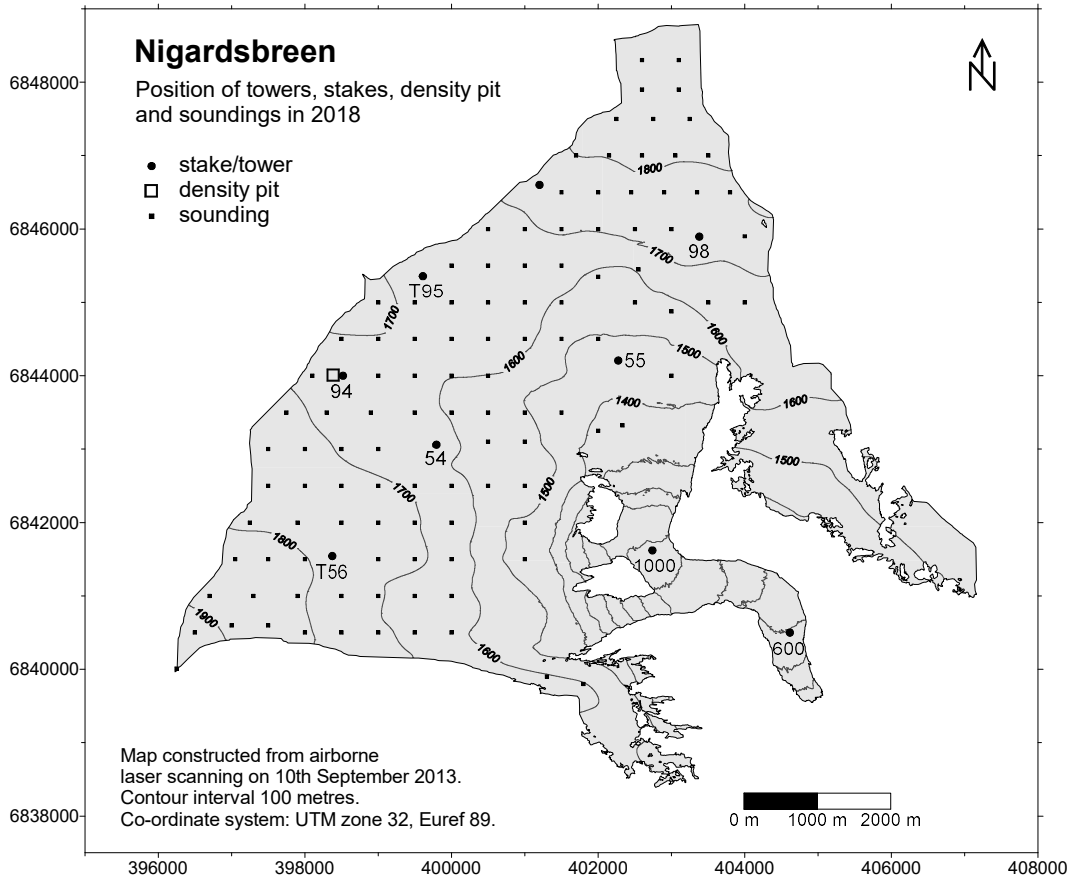


Figure 3-2
Location of towers, stakes, snow pit and soundings on Nigardsbreen in 2018.

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 980 and 593 m elevation.

The winter balance was calculated as a mean value for each 100 m height interval and was $2.4 \pm 0.2 \text{ m w.e.}$, which is 105 % of the mean winter balance for the reference period 1981-2010. Spatial distribution of the winter balance is shown in Figure 3-3.

The density of remaining snow was assumed to be 600 kg m^{-3} . The density of melted firn was estimated as 650 kg m^{-3} and the density of melted ice was set as 900 kg m^{-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 -3.2 ± 0.3 m w.e., which is 147 % of the reference period.

Hence the annual balance was negative, at $-0.9 \text{ m} \pm 0.4 \text{ m w.e.}$ The mean annual balance for the reference period 1981-2010 is $+0.06 \text{ m w.e.}$ Over the past ten years (2009-2018), the mean annual balance was -0.04 m w.e.

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

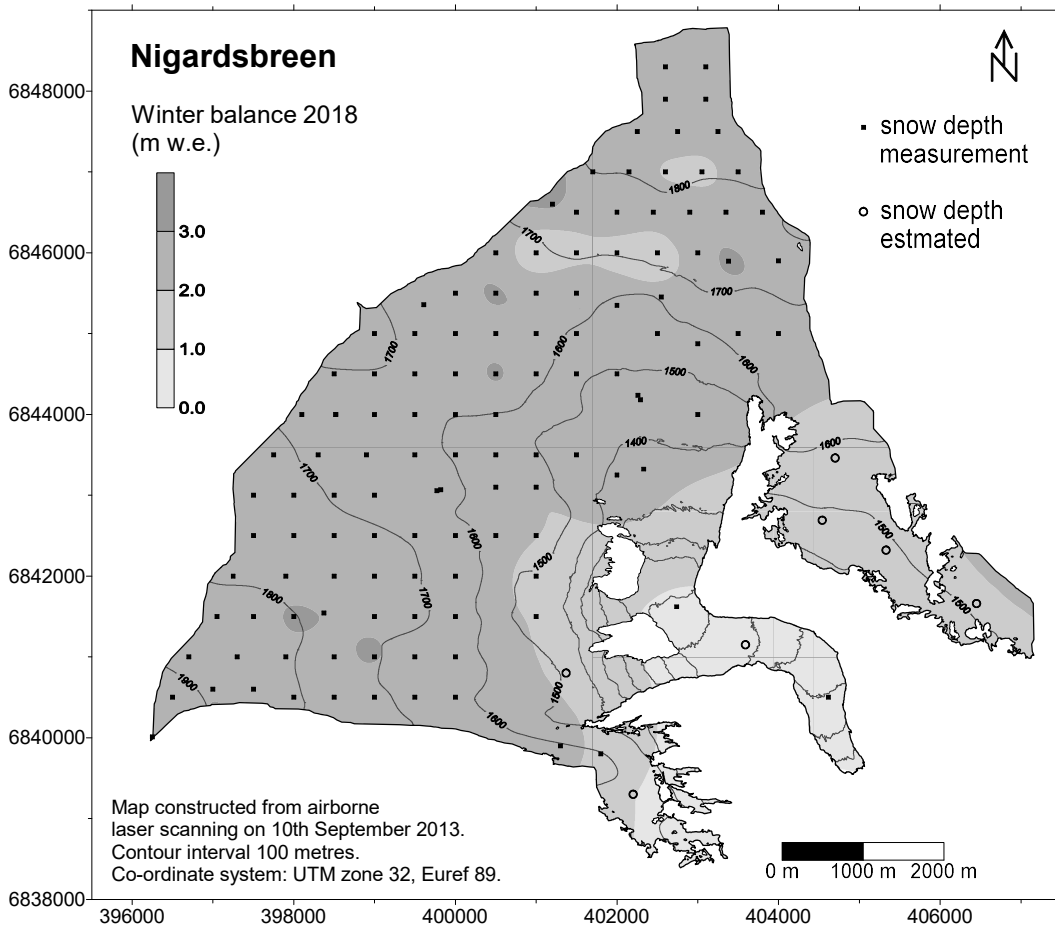


Figure 3-3
Spatial distribution of winter balance on Nigardsbreen in 2018. In areas with insufficient measurements seven simulated values were used based on previous measurements.

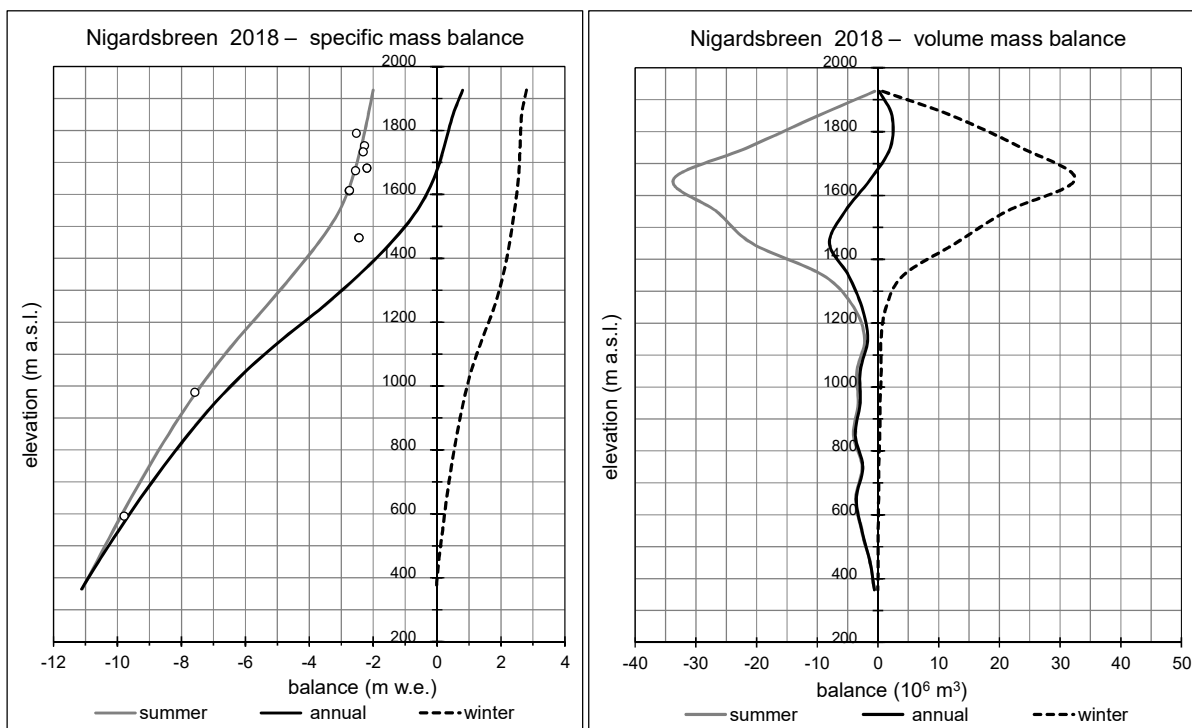


Figure 3-4
Mass balance diagram showing specific balance (left) and volume balance (right) for Nigardsbreen in 2018. Specific summer balance at nine stake positions is shown as circles (○).

According to Figure 3-4, the Equilibrium Line Altitude was 1675 m a.s.l. Consequently the Accumulation Area Ratio was 36 %.

Table 3-1
The altitudinal distribution of winter, summer and annual balance in 100 m intervals for Nigardsbreen in 2018.

Mass balance Nigardsbreen 2017/18 – stratigraphic system							
Altitude (m a.s.l.)	Area (km ²)	Winter mass balance Measured 15th May 2018		Summer mass balance Measured 26th Oct 2018		Annual mass balance Summer surface 2017 - 2018	
		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)
1900 - 1952	0.28	2.80	0.8	-2.00	-0.6	0.80	0.2
1800 - 1900	4.58	2.65	12.1	-2.15	-9.8	0.50	2.3
1700 - 1800	9.05	2.60	23.5	-2.38	-21.5	0.23	2.0
1600 - 1700	12.72	2.55	32.4	-2.65	-33.7	-0.10	-1.3
1500 - 1600	8.72	2.43	21.2	-3.05	-26.6	-0.63	-5.5
1400 - 1500	5.61	2.28	12.8	-3.70	-20.8	-1.43	-8.0
1300 - 1400	2.02	2.08	4.2	-4.50	-9.1	-2.43	-4.9
1200 - 1300	0.75	1.80	1.4	-5.35	-4.0	-3.55	-2.7
1100 - 1200	0.35	1.43	0.5	-6.23	-2.2	-4.80	-1.7
1000 - 1100	0.50	1.08	0.5	-7.03	-3.5	-5.95	-2.9
900 - 1000	0.42	0.83	0.3	-7.75	-3.3	-6.93	-2.9
800 - 900	0.48	0.63	0.3	-8.40	-4.0	-7.78	-3.7
700 - 800	0.29	0.45	0.1	-9.00	-2.6	-8.55	-2.5
600 - 700	0.39	0.30	0.1	-9.58	-3.7	-9.28	-3.6
500 - 600	0.27	0.18	0.0	-10.13	-2.7	-9.95	-2.7
400 - 500	0.12	0.05	0.0	-10.65	-1.3	-10.60	-1.3
330 - 400	0.06	-0.03	0.0	-11.10	-0.6	-11.13	-0.6
330 - 1952	46.61	2.37	110.3	-3.22	-150.0	-0.85	-39.7

3.2 Mass balance 1962-2018

The historical mass balance results for Nigardsbreen are presented in Figure 3-5. The cumulative annual balance for 1962-2018 is +5.4 m w.e., which gives a mean annual balance of +0.09 m w.e. a⁻¹.

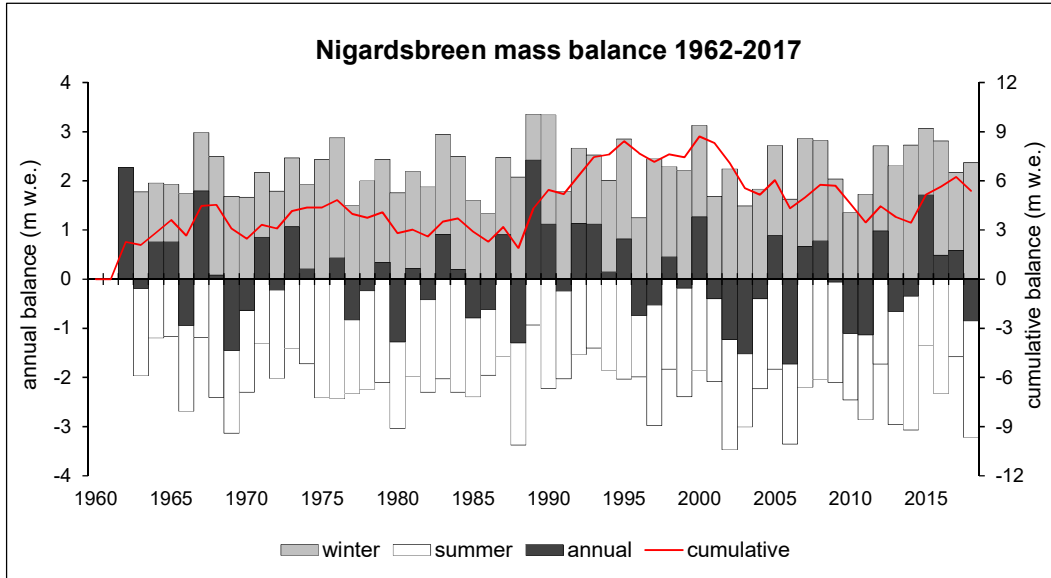


Figure 3-5
Winter, summer and annual balance at Nigardsbreen for 1962-2018. Cumulative mass balance is given on the right axis.

3.3 Ice velocity

The surface ice velocity was calculated from repeated GNSS measurements of six stakes. The positions of the stakes were measured on 18th October 2017 and 26th October 2018. For two of the stakes, however, measurements represent the period from 21st August 2015 to 18th October 2017 and 21st August 2015 to 26th October 2018, respectively.

The positions were measured by using Topcon GR3 dual frequency GNSS receivers placed on top of (Fig. 3-6), or close to the stakes. The GNSS data were post-processed using the software program “Topcon Tools”. Data from the SATREF reference station Jostedalén was used for post-processing the GNSS data.

The calculated surface ice velocities show mean annual velocities between 3 and 215 m a⁻¹ (Fig. 3-7). The uncertainty of the GNSS positioning is assumed to be ±0.5 m.



Figure 3-6
GNSS positioning of stake 55 (see Fig. 3-2) on 18th October 2017. Photo: Jostein Aasen.

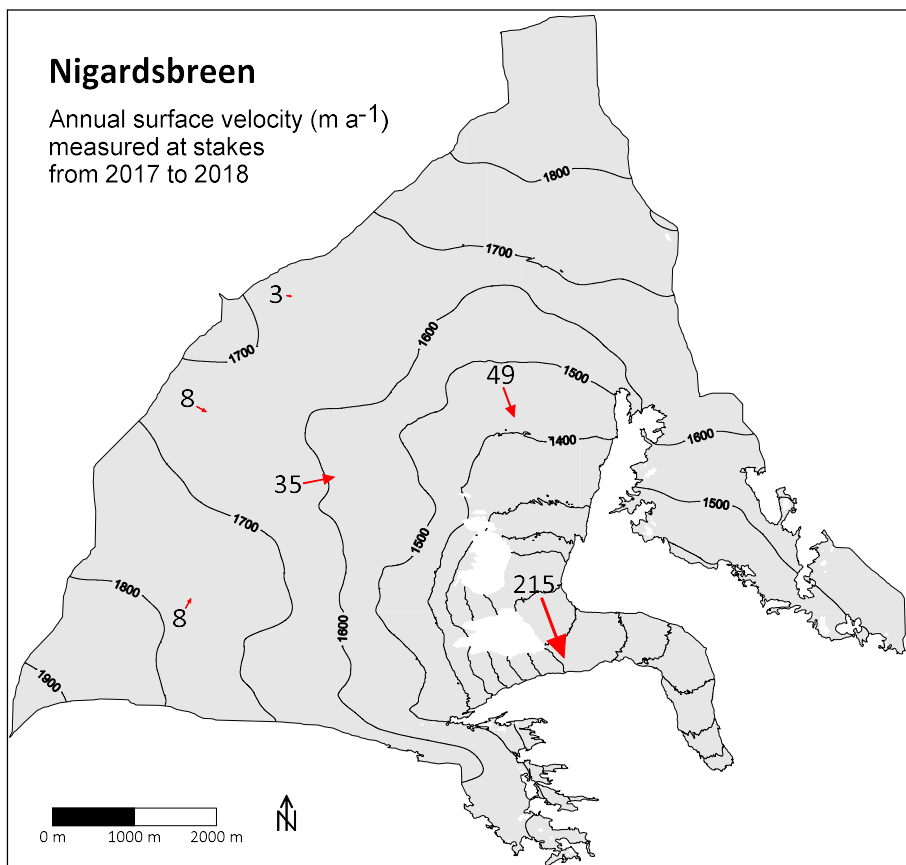


Figure 3-7
Map of Nigardsbreen showing mean annual surface velocities calculated from stake position measurements in October 2017 and 2018. For two of the stakes, stakes 94 and T95, (see Fig. 3-2) the velocity represent periods from 21st August 2015 to 18th October 2017 and from 21st August 2015 to 26th October 2018, respectively.

4. Austdalsbreen (Hallgeir Elvehøy)

Austdalsbreen (61°45'N, 7°20'E) is an eastern outlet of the northern part of Jostedalbreen, 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 2018 included mass balance, front position change and glacier velocity. The mass balance has been measured at Austdalsbreen since 1988.

4.1 Mass balance 2018

Fieldwork

Stakes were maintained through the winter in all stake locations except A80. Snow accumulation measurements were performed on 7th May. The calculation of winter balance was based on measurements in six stake locations and 26 out of 40 snow depth sounding locations (Fig. 4-2). Detecting the summer surface was relatively easy. The snow depth varied from 2.3 to 4.4 metres, and the average snow depth was 3.5 metres. Snow density was measured in one location (1490 m a.s.l.). The mean snow density of 4.1 m snow was 502 kg m⁻³.



Figure 4-1
Stake A80 (see Fig. 4-2 for location) on 1st August 2018. A second stake, bent down to the ice surface in the autumn 2016, is seen in the background (inset). Photo: Hallgeir Elvehøy.

The stake network was measured on 1st August. Stakes A92 and A10 had melted out. Stake location A6 was abandoned due to its close vicinity to the terminus. Between 4 and 5 metres of snow and ice had melted since 7th May. Only at A70, had a small amount of winter snow remained.

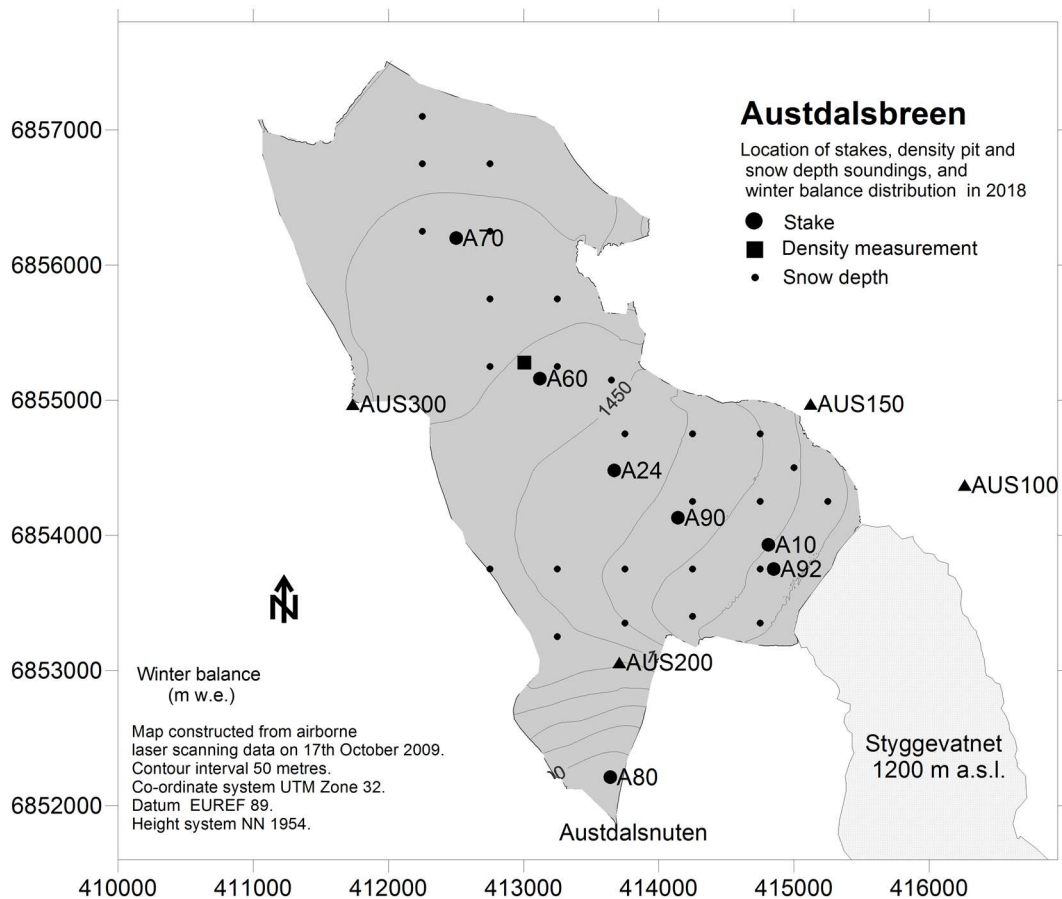


Figure 4-2
Location of stakes, density pit and snow depth soundings, and winter balance at Austdalsbreen in 2018 from 26 water equivalent values calculated from snow depth measurements.

Summer and annual balance measurements were carried out on 26th October. There was up to 2.2 m of new snow on the glacier. Stakes were found in all of the seven locations. The stakes were 1 to 1.5 m longer than in August. Based on stake observations, all the winter snow had melted, and consequently the ELA was above the top of the glacier (1747 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 7th May. A function correlating snow depth with water equivalent values was calculated based on snow density measurements at stake A60 (1490 m a.s.l.). The winter balance was 20 ± 2 mill. m³ water or 1.9 ± 0.2 m w.e., which is 88 % of the 1988-2017 average (2.17 m w.e.).

The summer balance was calculated directly for four stake locations between 1380 and 1520 m a.s.l. At A10 and A92 the snow and ice melt between May and August was estimated from A90. The snow and firn melt at A80 between May and August was estimated from snow melt at A70 and net change between October 2017 and August 2018 at A80. The summer balance curve was drawn from these seven point values (Fig. 4-3).

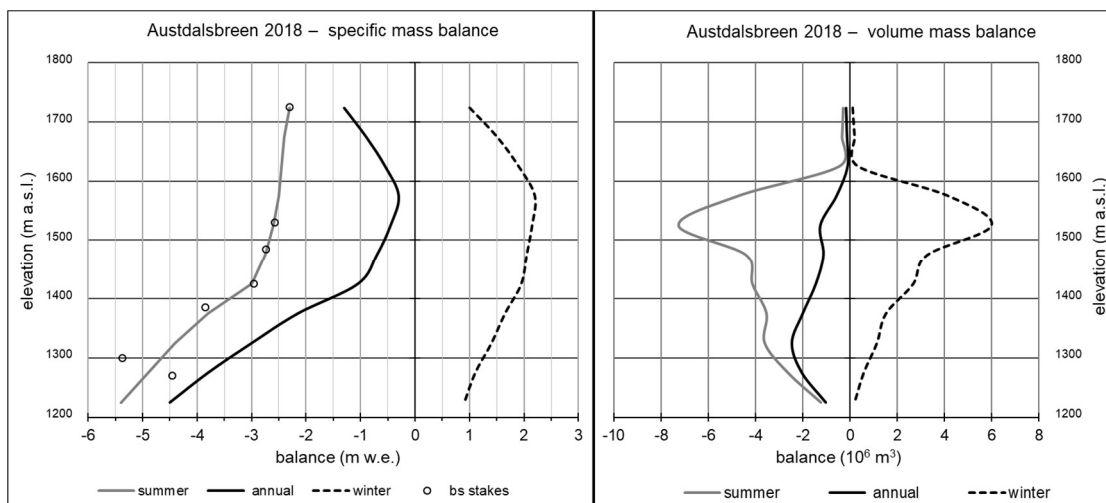


Figure 4-3
Altitudinal distribution of winter, summer and annual balance is shown as specific balance (left) and volume balance (right) at Austdalsbreen in 2018. Specific summer balance, bs, at seven stake locations is shown (○).

Table 4-1
Altitudinal distribution of winter, summer and annual balances for Austdalsbreen in 2018.

Mass balance Austdalsbreen 2017/18 – stratigraphic system							
Altitude (m a.s.l.)	Area (km ²)	Winter mass balance Measured 7th May 2018		Summer mass balance Measured 26th Oct 2018		Annual mass balance Summer surfaces 2017 - 2018	
		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	0.13	1.00	0.1	-2.30	-0.3
1650 - 1700	0.14	1.50	0.2	-2.40	-0.3	-0.90	-0.1
1600 - 1650	0.18	1.90	0.3	-2.45	-0.4	-0.55	-0.1
1550 - 1600	1.89	2.20	4.2	-2.50	-4.7	-0.30	-0.6
1500 - 1550	2.79	2.15	6.0	-2.60	-7.3	-0.45	-1.3
1450 - 1500	1.60	2.05	3.3	-2.75	-4.4	-0.70	-1.1
1400 - 1450	1.38	1.95	2.7	-3.00	-4.1	-1.05	-1.4
1350 - 1400	0.93	1.65	1.5	-3.80	-3.5	-2.15	-2.0
1300 - 1350	0.82	1.40	1.1	-4.40	-3.6	-3.00	-2.5
1250 - 1300	0.54	1.10	0.6	-4.90	-2.6	-3.80	-2.0
1200 - 1250	0.23	0.90	0.2	-5.40	-1.2	-4.50	-1.0
Calving					-4.0		-4.0
1200 - 1747	10.63	1.91	20.3	-3.44	-36.6	-1.53	-16.3

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 (36 ± 10 m a⁻¹, chap. 4.3), u_f is front position change averaged across the terminus (-61 ± 5 m a⁻¹, chap. 4.2), W is terminus width (930 ± 20 m) and H is mean ice thickness at the terminus (49 ± 5 m). The mean ice thickness was calculated from mean surface elevations along the calving terminus surveyed on 18th October 2017 and 26th October 2018, and mean bottom elevation along the terminus

calculated from a bottom topography map compiled from radar ice thickness measurements (1986), hot water drilling (1987), lake depth surveying (1988 and 1989), and orthophotos from 2010 and 2015 (www.norgebilder.no). The resulting calving volume was 4.0 ± 0.8 mill. m^3 water equivalent.

The summer balance including calving was calculated as -37 ± 3 mill. m^3 of water, which corresponds to -3.4 ± 0.3 m w.e. The result is 127 % of the 1988-2017 average (-2.70 m w.e.). The calving volume was 11 % of the summer balance.

The annual balance at Austdalsbreen was calculated as -16 ± 3 mill. m^3 water, corresponding to -1.5 ± 0.3 m w.e. The average annual balance for the period 1988-2017 is -0.52 m w.e. The ELA in 2018 was above the summit at 1747 m a.s.l., and consequently the AAR was 0 %. The altitudinal distribution of winter, summer and annual balance is shown in Table 4-1 and Figure 4-3. Results from 1988-2018 are shown in Figure 4-4.

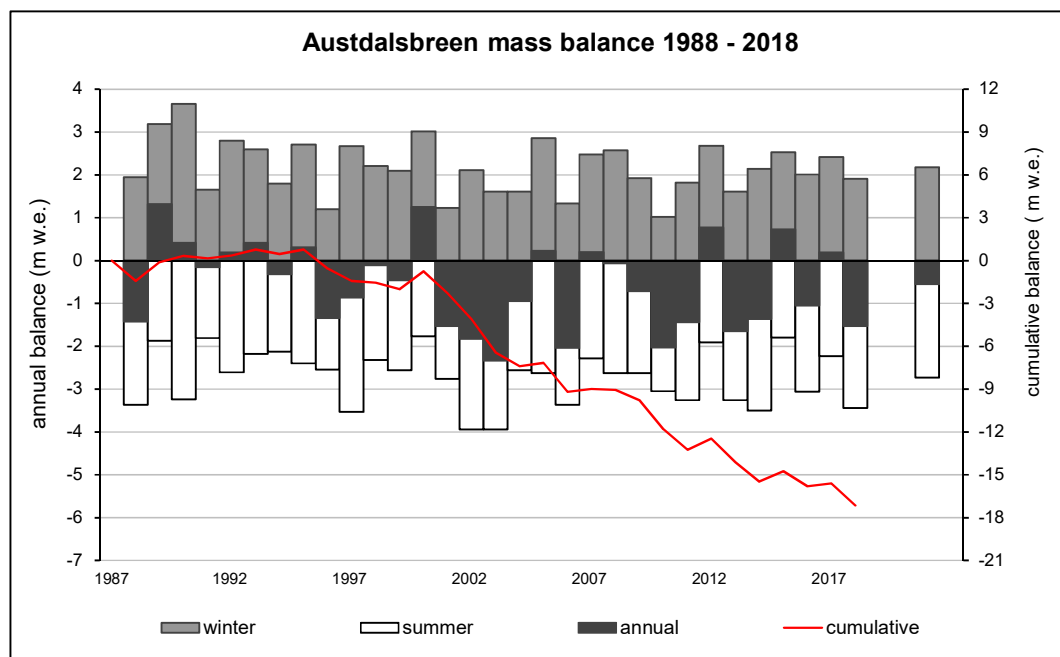


Figure 4-4
Winter, summer, annual and cumulative balance at Austdalsbreen during the period 1988-2018. Mean winter and summer balance is 2.18 and -2.73 m w.e., respectively. The cumulative mass balance is -17.1 m w.e.

4.2 Front position change

Twelve points along the calving terminus were surveyed on 26th October 2018. The mean front position change was -61 ± 5 m between 18th October 2017 and 26th October 2018 (Fig. 4-5). The width of the calving terminus was 930 ± 20 m. Since 1988 the glacier terminus has retreated about 720 m, corresponding to 0.678 km².

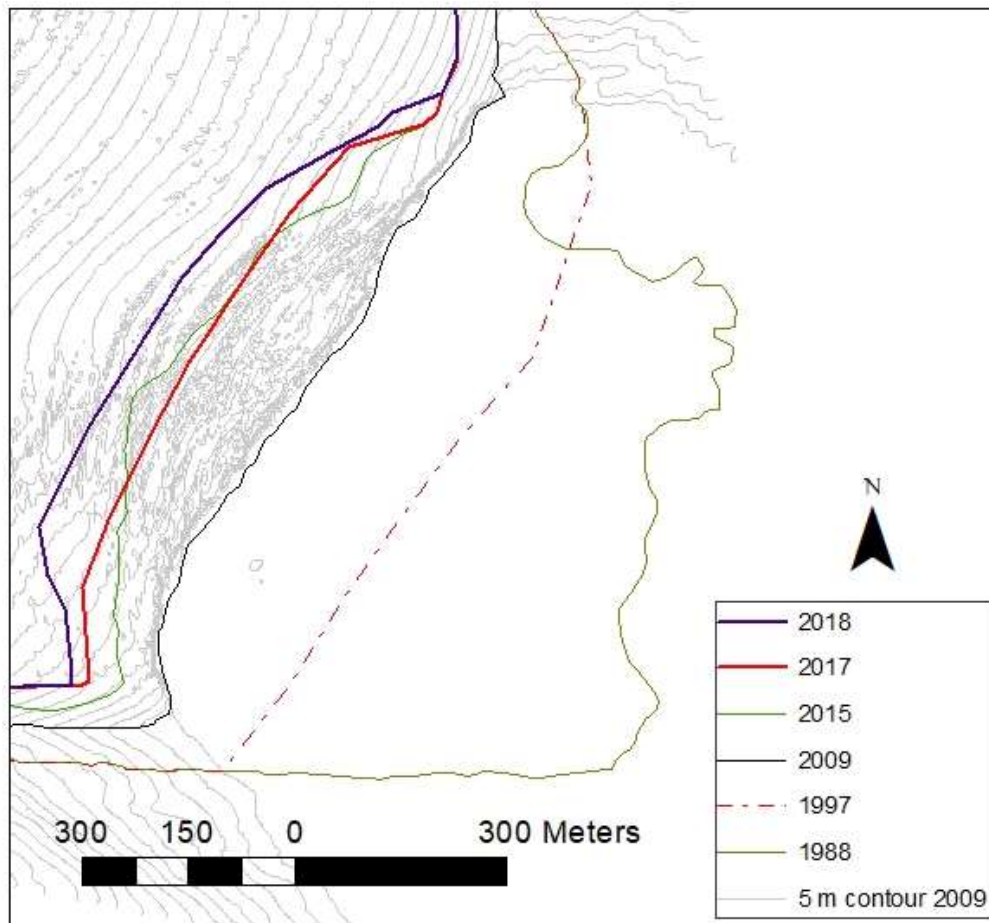


Figure 4-5
 Surveyed front position of Austdalsbreen in 1988 when the lake was regulated, and in 1997, 2009 and 2015-18. The mean front position change between 18th October 2017 and 26th October 2018 was -61 m.

4.3 Glacier dynamics

Glacier velocities are calculated from repeated surveys of stakes. The stake network was surveyed on 18th October 2017, and 7th May, 1st August and 26th October 2018. Annual velocities were calculated for seven stake locations for the period 18th October 2017 – 26th October 2018 (373 days). The average velocity at A10 and A92 between 7th May and 1st August (85 days) was estimated to be equal to the winter velocity (18th Oct – 7th May). The resulting annual velocities at stake locations close to the terminus were 61 m a⁻¹ at A92 (55 m a⁻¹ in 2017), and 43 m a⁻¹ at A10 (43 m a⁻¹ in 2017).

The glacier velocity averaged across the front width and thickness must be estimated in order to calculate the calving volume (chap. 4.1). Due to lower velocities at stake A10 than at A92, we assume no significant velocity increase towards the calving front. Further we assume the average of A10 and A92 is 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 2017/2018 is 36 ± 10 m a⁻¹.

5. Rembesdalskåka (Hallgeir Elvehøy)

Rembesdalskåka (17 km², 60°32'N, 7°22'E) is a southwestern outlet glacier from Hardangerjøkulen, the sixth largest (73 km²) glacier in Norway. The glacier is situated on the main water divide between Hardangerfjorden and Hallingdalen valley, and drains towards Simadalen valley and Hardangerfjorden (Fig. 5-1). In the past Simadalen was flooded by jökulhlaups from the glacier-dammed lake Demmevatnet (Fig. 5-2 and section 12.2). Since 2014 several jökulhlaups have occurred, but they have been captured by the reservoir Rembesdalsvatnet, thus causing no damage.

Mass balance measurements were initiated on Rembesdalskåka in 1963 by the Norwegian Polar Institute. 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 5-1
The lower part of Rembesdalskåka on 24th May 2018. The glacier drains to Rembesdalsvatnet and Simadalen (upper left). The lake is now a reservoir for Sima Hydroelectric Power Station.
Photo: Hallgeir Elvehøy.

5.1 Mass balance 2018

Fieldwork

The mass balance stake network was measured on 29th November, 9th January and 14th March. Comparison of 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.

The snow accumulation was measured on 24th May. Stakes were maintained in all five stake locations. Snow depth was measured at 64 sounding locations in a 500 by 500 m grid on the glacier plateau above 1500 m a.s.l. (Fig. 5-2). The snow depth was between 2.9 and

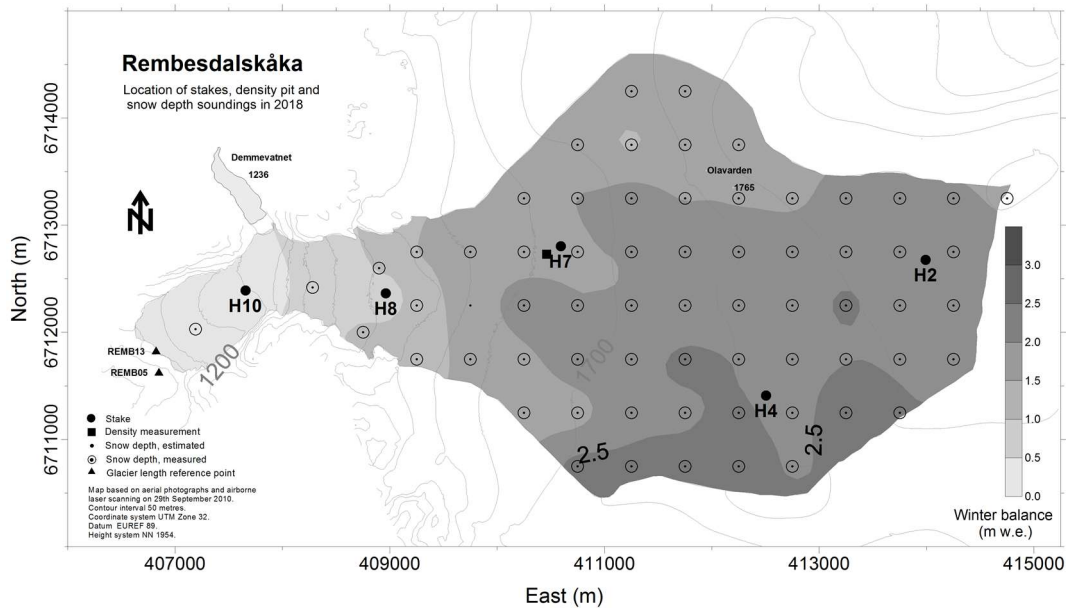


Figure 5-2
Winter balance at Rembedalskåka interpolated from 65 snow depth soundings and five stake measurements of snow depth and one estimated point in the upper ice fall (1600 m a.s.l.).

5.0 m above 1650 m a.s.l., and between 1.85 and 2.75 m between 1500 and 1650 m a.s.l. The summer surface (S.S.) was well defined. The mean snow density down to the summer surface at 3.1 m depth at stake H7 was 576 kg m^{-3} . On the lowest part of the glacier all the winter snow had already melted (Fig. 5-1).

On 14th August only a small amount of winter snow remained at the two uppermost stakes. Stakes H10 and H8 had melted out.

Summer and annual balance were measured on 22nd November. There was up to 1.7 m of new snow at H2 and H4, which were the only stakes that could be measured. Between 0.7 and 0.8 metres of snow and firn had melted before the winter accumulation started.

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 24th May. A snow depth-water equivalent profile was calculated based on snow density measurements at location H7 (1655 m a.s.l.). The measured snow depths 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. 5-3). 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 $1.9 \pm 0.2 \text{ m w.e.}$ or $33 \pm 3 \text{ mill. m}^3 \text{ water}$. This is 91 % of the 1981-2010 average of $2.14 \text{ m w.e. a}^{-1}$.

Based on the snow depth measurements the spatial distribution of the winter balance was interpolated using the kriging method. One snow depth point in the upper icefall was estimated. The distributed winter balance is shown in Figure 5-2, and the mean winter balance was 1.87 m w.e.

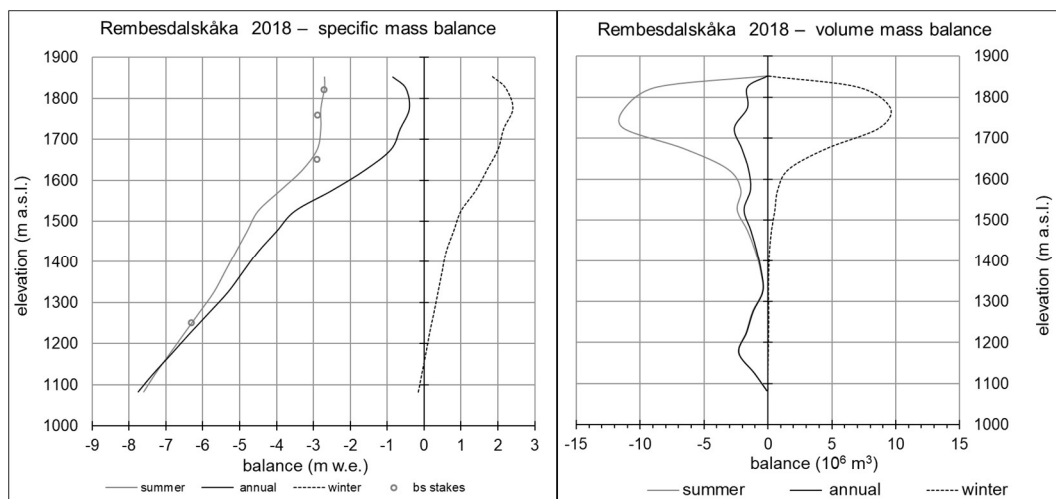


Figure 5-3
Altitudinal distribution of winter, summer and annual mass balance is shown as specific balance (left) and volume balance (right). Specific summer balance, b_s , at four stakes is shown (○).

Table 5-1
Altitudinal distribution of winter, summer and annual mass balance at Rembesdalskåka in 2018.

Mass balance Rembesdalskåka 2017/18 – stratigraphic system							
Altitude (m a.s.l.)	Area (km ²)	Winter mass balance Measured 24th May 2018		Summer mass balance Measured 22nd Nov 2018		Annual mass balance Summer surface 2017 - 2018	
		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)
1850 - 1854	0.029	1.85	0.1	-2.70	-0.1	-0.85	0.0
1800 - 1850	3.213	2.20	7.1	-2.70	-8.7	-0.50	-1.6
1750 - 1800	3.992	2.40	9.6	-2.80	-11.2	-0.40	-1.6
1700 - 1750	4.048	2.15	8.7	-2.80	-11.3	-0.65	-2.6
1650 - 1700	2.281	2.00	4.6	-2.90	-6.6	-0.90	-2.1
1600 - 1650	0.957	1.70	1.6	-3.30	-3.2	-1.60	-1.5
1550 - 1600	0.545	1.40	0.8	-3.90	-2.1	-2.50	-1.4
1500 - 1550	0.535	1.00	0.5	-4.50	-2.4	-3.50	-1.9
1450 - 1500	0.336	0.80	0.3	-4.80	-1.6	-4.00	-1.3
1400 - 1450	0.197	0.60	0.1	-5.10	-1.0	-4.50	-0.9
1350 - 1400	0.108	0.49	0.1	-5.40	-0.6	-4.91	-0.5
1300 - 1350	0.074	0.38	0.0	-5.70	-0.4	-5.32	-0.4
1250 - 1300	0.199	0.27	0.1	-6.10	-1.2	-5.83	-1.2
1200 - 1250	0.262	0.15	0.0	-6.50	-1.7	-6.35	-1.7
1150 - 1200	0.333	0.05	0.0	-6.90	-2.3	-6.85	-2.3
1100 - 1150	0.143	-0.06	0.0	-7.30	-1.0	-7.36	-1.1
1066 - 1100	0.012	-0.15	0.0	-7.60	-0.1	-7.75	-0.1
1066 - 1854	17.264	1.94	33.5	-3.21	-55.5	-1.27	-22.0

The date of the 2018 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 12th September and on the glacier tongue on 15th September.

The summer balance was calculated directly at the two uppermost stake locations. Melting at H7 after 14th August was estimated as slightly higher than at H4. There are no observations of melt on the glacier below 1600 m a.s.l. The amount of ice melt at location H10 was estimated for the periods 1st June – 14th August and 14th August – 15th September

from air temperature at the meteorological stations Finsevang, Midtstova and Fet in Eidfjord. The calculations were based on the empirical relation between melt at H10 and mean air temperature at the three stations in periods between 2012 and 2017. The results for the first period varied between 5.6 and 6.3 metres. This implies that the stake had melted out recently on 14th August. The estimates for the second period varied between 1.3 and 1.4 metres of ice.

The density of 0.7 m of melted firn from 2017 at H2 and H4 was set as 650 kg m^{-3} . At H7, the density of 1.05 m of firn from 2017 and 0.5 m of firn from 2015 was set as 650 and 700 kg m^{-3} , respectively. The density of melted ice at H10 was set as 900 kg m^{-3} .

The summer balance curve in Figure 5-3 was drawn from four point values. The summer balance was calculated as $-3.2 \pm 0.2 \text{ m w.e.}$, corresponding to $-55 \pm 3 \text{ mill. m}^3$ of water. This is 149 % of the 1981-2010 normal average, which is $-2.16 \text{ m w.e. a}^{-1}$.

The annual balance at Rembesdalskåka was calculated as $-1.3 \pm 0.3 \text{ m w.e.}$ or $-22 \pm 5 \text{ mill. m}^3$ water. The 1981-2010 normal average is $-0.02 \text{ m w.e. a}^{-1}$. The ELA was higher than the top of the glacier ($>1854 \text{ m a.s.l.}$), and the corresponding AAR was 0 %. This is the 9th year since 2000 with the ELA higher than the top of the glacier. The altitudinal distribution of winter, summer and annual balances is shown in Figure 5-3 and Table 5-1. Results from 1963-2018 are shown in Figure 5-4. The cumulative annual balance is $-86 \text{ mill. m}^3 \text{ w.e.}$ Since 1995, the glacier has had a mass deficit of 221 mill. $\text{m}^3 \text{ w.e.}$

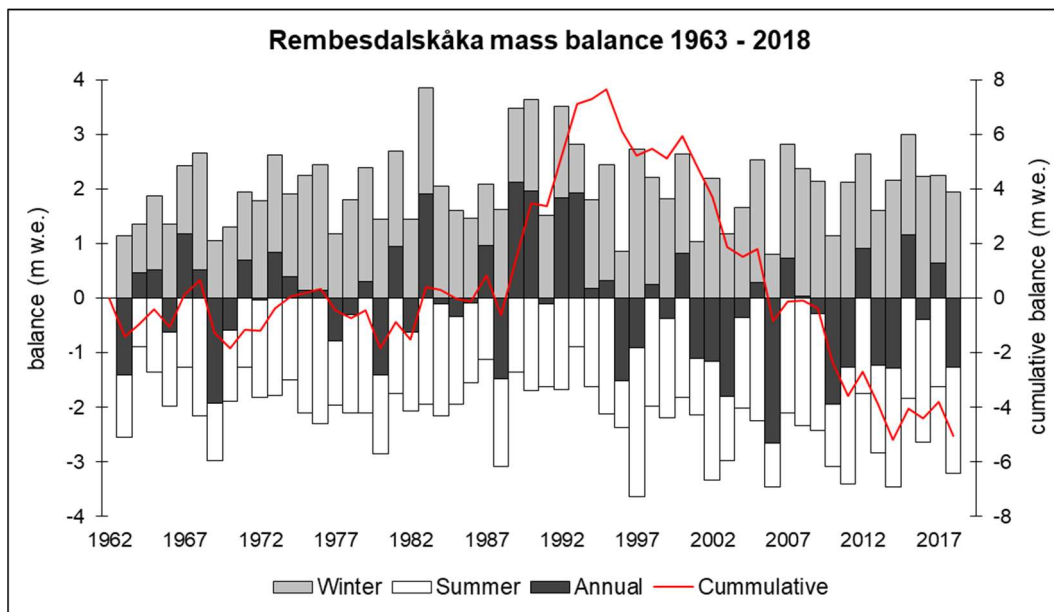


Figure 5-4
Winter, summer, annual and cumulative mass balance at Rembesdalskåka during the period 1963-2018.
Mean values (1963-2018) are $B_w=2.06 \text{ m w.e. a}^{-1}$ and $B_s=-2.15 \text{ m w.e. a}^{-1}$.

6. Storbreen (Liss M. Andreassen)

Storbreen (61°34'N, 8°8'E) (now written with –an ending on official maps: Storbreen) is situated in the Jotunheimen mountain massif in central southern Norway. The glacier has a relatively well-defined border and is surrounded by high peaks (Fig. 6-1). Mass balance has been measured there since 1949 and front position (change in length) has been measured since 1902 (chap. 12.1).

Storbreen has a total area of 5.1 km² and ranges in altitude from 1400 to 2102 m a.s.l. (map of 2009, Fig. 6-2). The mass balance for 2018 was calculated based on the DTM and glacier outline from 2009.



Figure 6-1
Storbreen on 16th October 2018 taken from helicopter, looking west. Winter snow covered the upper parts of the glacier. Photo: Liss M. Andreassen.

6.1 Mass balance 2018

Field work

Snow accumulation measurements were performed on 7th and 8th May. Stakes in 7 positions were visible and a total of 146 snow depth soundings between 1447 and 1968 m a.s.l. were made (Fig. 6-2). The snow depth varied between 1.1 and 3.8 m, the mean being 2.7 m. Snow density was measured at stake 4 at 1715 m a.s.l. where the total snow depth was 2.5 m snow, the snow density was measured for the first 1.9 m. The average snow density measured was 429 kg m⁻³. Ablation measurements were performed on 16th October at stakes in all positions. The upper parts of the glacier were covered in snow (Fig. 6-1).

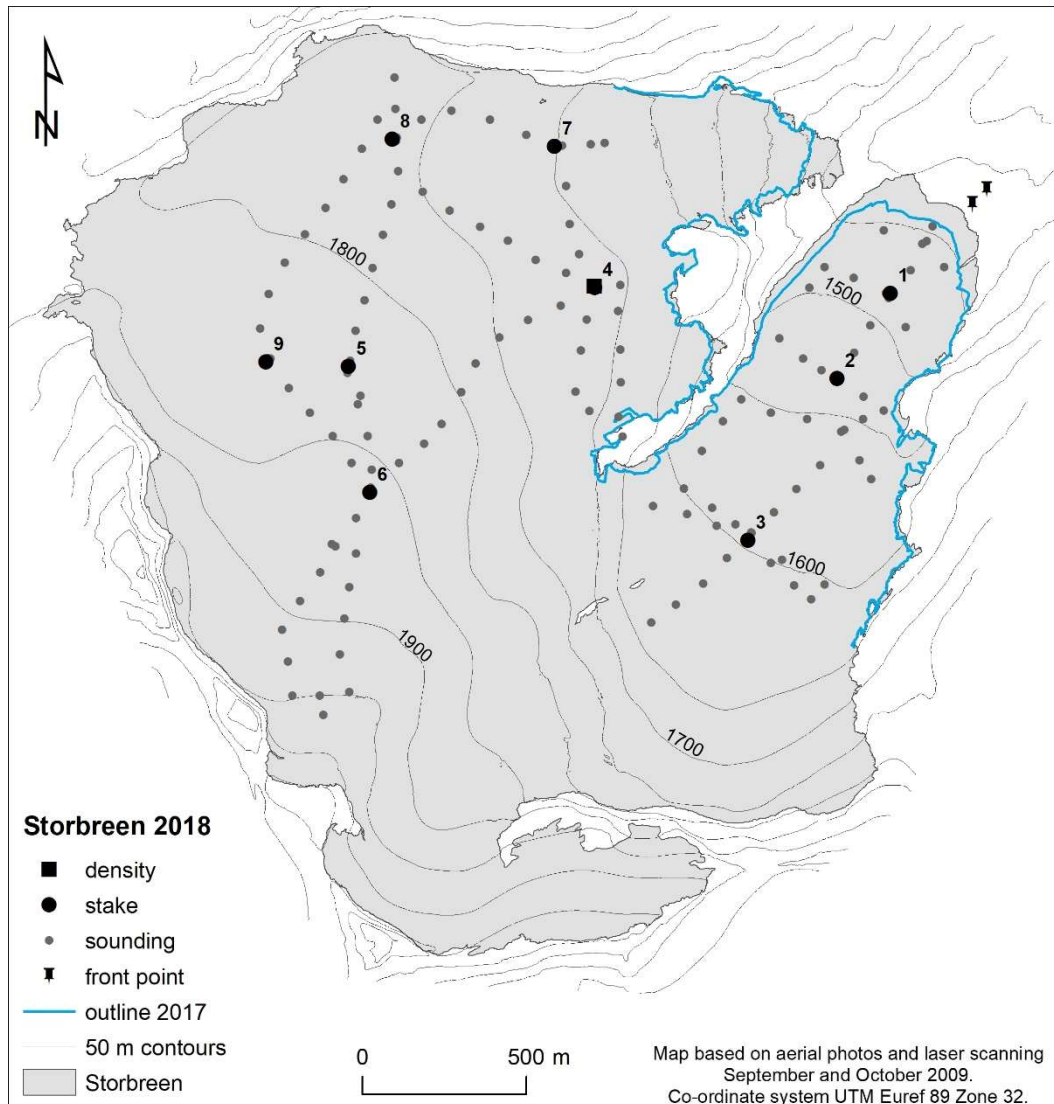


Figure 6-2
Location of stakes, soundings and density pits at Storbreen in 2018. The 50 m contours and the glacier outline is from aerial photos and laser scanning acquired in September and October 2009. Outline 2017 was mapped from an orthophoto taken by a drone on 26th September 2017. Front point: reference points used for length change (front point) measurements (see chap. 12.1).

Results

The winter balance was calculated from the mean of the soundings within each 50-metre height interval and was 1.27 ± 0.2 m w.e., which is 85 % of the mean winter balance for the reference period 1981-2010. Summer and annual balance was calculated directly from stakes at nine locations. The summer balance was interpolated to 50 m height intervals based on the stake readings and was -3.24 ± 0.2 m w.e., which is 178 % of the mean summer balance for the reference period 1981-2010. The annual balance of Storbreen was -1.97 ± 0.3 m w.e. in 2018. The end of season snowline was not observed due to fresh snow. The equilibrium-line altitude (ELA) calculated from the annual balance diagram (Fig. 6-3) was ~ 2005 m a.s.l. resulting in an estimated accumulation area ratio (AAR) of 3 %.

The mass balance results are shown in Table 6-1 and the corresponding curves for specific and volume balance are shown in Figure 6-3.

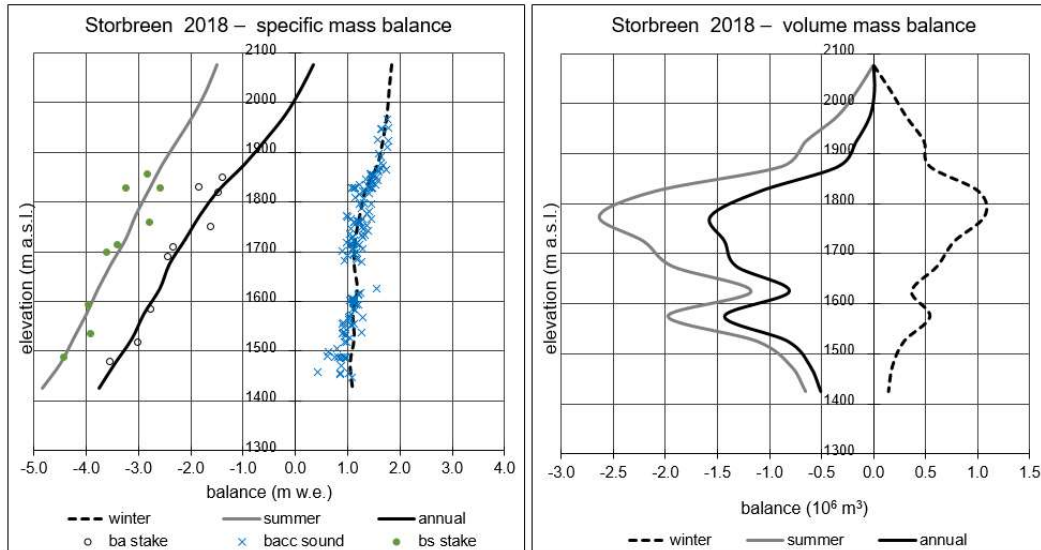


Figure 6-3
Mass balance versus altitude for Storbreen 2018, showing specific balance on the left and volume balance on the right. Winter accumulation soundings (bacc sound), summer and annual balance at nine stakes are also shown.

Table 6-1
The distribution of winter, summer and annual balance in 50 m altitudinal intervals for Storbreen in 2018.

Mass balance Storbreen 2017/18 – stratigraphic system							
Altitude (m a.s.l.)	Area (km ²)	Winter mass balance Measured 7 May 2018		Summer mass balance Measured 16 Oct 2018		Annual mass balance 2017 - 2018	
		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)
2050 - 2102	0.00	1.85	0.01	-1.50	-0.01	0.35	0.00
2000 - 2050	0.10	1.80	0.17	-1.70	-0.16	0.10	0.01
1950 - 2000	0.18	1.76	0.32	-1.95	-0.35	-0.19	-0.03
1900 - 1950	0.29	1.68	0.49	-2.25	-0.65	-0.57	-0.16
1850 - 1900	0.35	1.58	0.54	-2.55	-0.88	-0.97	-0.34
1800 - 1850	0.75	1.35	1.01	-2.80	-2.11	-1.45	-1.10
1750 - 1800	0.87	1.24	1.07	-3.05	-2.64	-1.81	-1.57
1700 - 1750	0.68	1.14	0.78	-3.25	-2.21	-2.11	-1.43
1650 - 1700	0.55	1.12	0.61	-3.53	-1.93	-2.41	-1.32
1600 - 1650	0.31	1.18	0.37	-3.78	-1.18	-2.60	-0.81
1550 - 1600	0.50	1.10	0.55	-4.00	-1.98	-2.90	-1.43
1500 - 1550	0.26	1.12	0.30	-4.25	-1.12	-3.13	-0.82
1450 - 1500	0.18	1.05	0.18	-4.50	-0.79	-3.45	-0.61
1400 - 1450	0.14	1.09	0.15	-4.85	-0.65	-3.76	-0.51
1400 - 2102	5.14	1.27	6.54	-3.24	-16.67	-1.97	-10.13

6.2 Mass balance 1949-2018

The cumulative balance for 1949-2018 is -26 m w.e., and the mean annual balance for this period of 70 years is -0.38 m w.e. (Fig. 6-4). For the period 2001-2018 the mean annual balance is -0.9 m w.e.

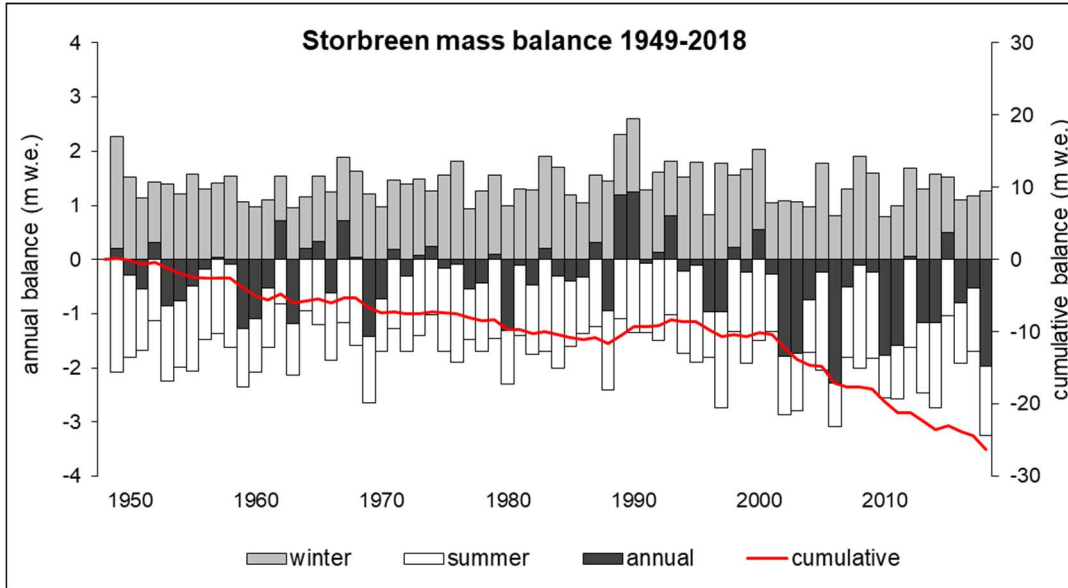


Figure 6-4
Winter, summer, annual and cumulative mass balance at Storbreen for the period 1949-2018.

7. 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. 7-1). Mass balance measurements began in May 2010. The measurements on Juvfonne were started as a contribution to 'Mimisbrunnr/Klimapark 2469' – a nature park and outdoor discovery centre in the alpine region around Galdhøpiggen, the highest mountain peak in Norway (2469 m a.s.l.). Measurements of the ice show the age is ca. 7600 cal years before present at the base (Ødegård et al., 2017).

The observation programme of Juvfonne in 2018 consisted of accumulation measurements in spring, seasonal and annual balances measured at one stake, and survey of the ice patch extent and front position. Mass balance calculations are based on a digital terrain model and outline derived from airborne laser scanning and orthophoto taken on 17th September 2011. According to this survey Juvfonne has an area of 0.127 km² and altitudinal range from 1841 to 1986 m a.s.l.



Figure 7-1
Juvfonne on 17th October 2018. Juvfonne had experienced repeated snow falls in late summer and a layer of fresh snow covered most of the ice patch. Photo: Liss M. Andreassen.

7.1 Survey 2018

The ice patch extent was covered in snow at the time of the ablation measurements and the full areal extent was thus not measured in 2018. Some points along the terminus were measured with handheld GPS on 30th July. The ice patch retreated further after this date (Fig. 7-2). The front position was measured on 17th October 2018 showing a retreat of 61 m since 18th September 2017 (chap. 12-1).

7.2 Mass balance 2018

Field work

The accumulation measurements on Juvfonne were carried out on 8th May. A total of 36 snow depth soundings were made (Fig. 7-2). Snow depths varied between 1.11 and 4.22 m with a mean of 2.96 m. The snow density was measured in a pit down to the previous summer surface near stake 2, where the depth to the 2017 summer surface was 3.8 m. The density of only the uppermost 2 m was measured, which had a density of 451

kg m^{-3} . Ablation measurements were carried out on 17th October at stake 2. A layer of fresh snow covered most of the ice patch at that time (Fig. 7-1).

Results

Seasonal surface mass balances have been measured since 2010 at stake 2 (Fig. 7-3). In 2018 the point winter balance was 1.78 ± 0.15 m w.e., the point summer balance was -3.50 ± 0.1 m w.e and the annual balance was -1.72 ± 0.1 m w.e. at this location. The cumulative mass balance for stake 2 over the nine years of measurements is -11.5 m w.e., or -1.27 m w.e. a^{-1} (Fig. 7-4). Glacier-wide mass balance was not calculated; this was calculated for only the first year of measurements 2009/2010 when more stakes were measured.

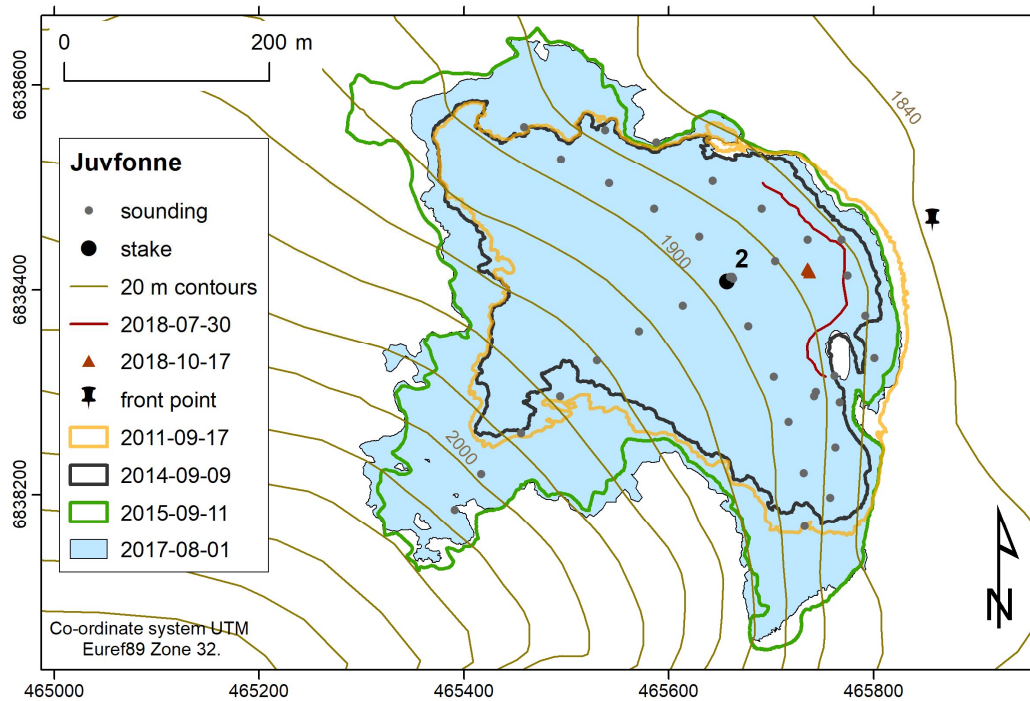


Figure 7-2

Location of snow depth soundings in 2018 and the position of stake 2 where density is measured. The ice patch extent in 2017 (combined GNSS and UAV orthophoto), 2016 (GNSS-measurements), 2015 (GNSS-measurements), 2014 (GNSS-measurements) and 2011 (orthophoto) are shown. The terminus positions on 30th July and 17th October 2018 are also marked. “Front point” marks the reference point for front position and length change measurements (see chap. 12.1). The 20 m contours are taken from the Norwegian Mapping Authority (Kartverket).

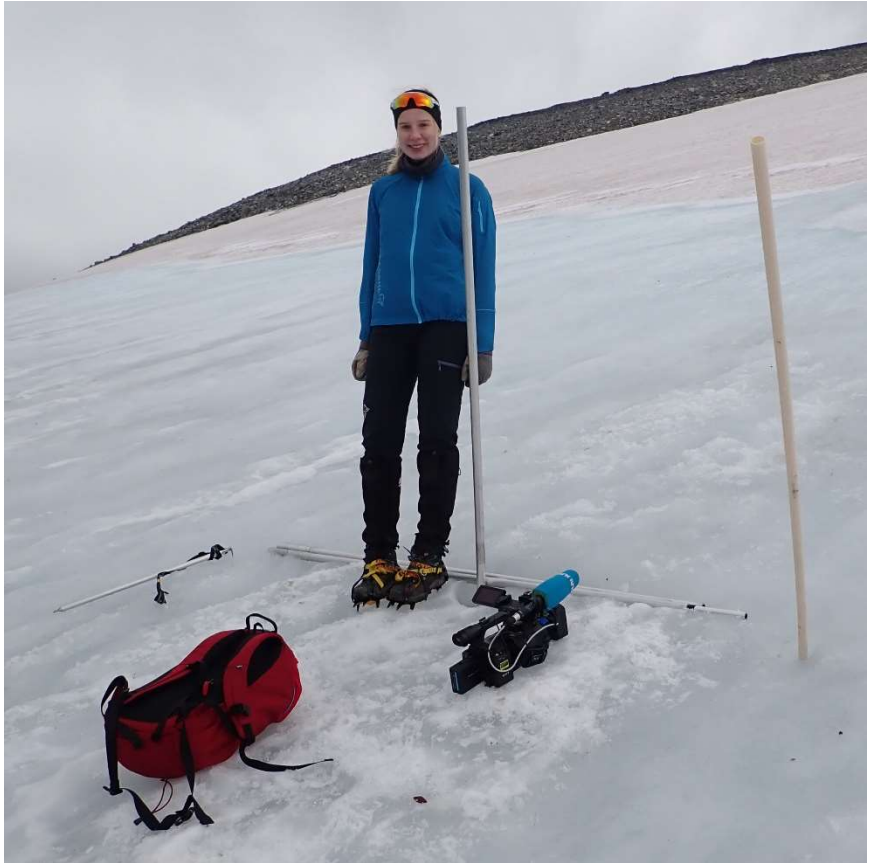


Figure 7-3
 Point mass balance is measured at stake 2, often using several stakes in the same position.
 The surface was snow free on 30th July 2018. Photo: Liss M. Andreassen.

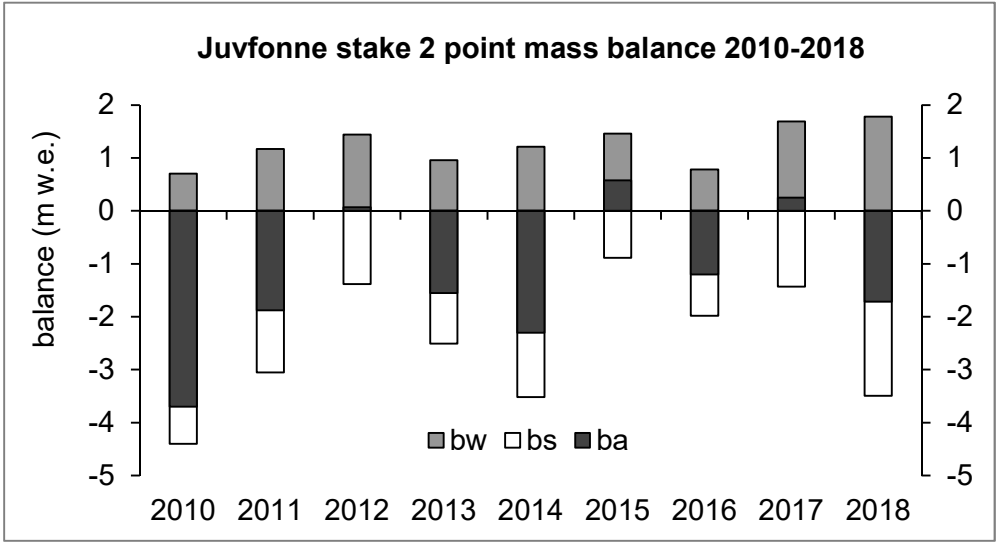


Figure 7-4
 Point mass balance at stake 2 at Juvfonne 2010-2018, given as winter balance (b_w), summer balance (b_s) and annual balance (b_a).

8. 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. 8-1). 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 km², but measurements along the terminus show a marked retreat since 2009 (Fig. 8-2).

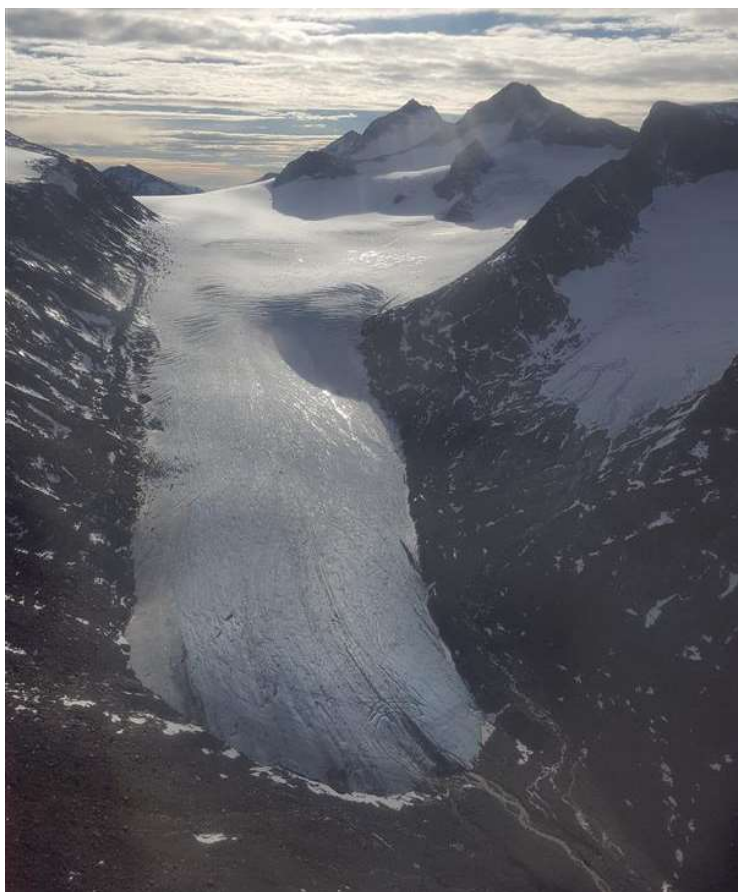


Figure 8-1
Hellstugubreen at the time of
ablation measurements on
16th October 2018.
Photo: Liss M. Andreassen.

8.1 Mass balance 2018

Field work

Accumulation measurements were performed on 23rd and 24th May. Stake readings indicated additional melting after the ablation measurements on 19th September 2017. Snow depths were measured in 95 positions between 1529 and 2091 m a.s.l., covering most of the altitudinal range of the glacier (Fig. 9-2). The snow depth varied between 0.35 and 3.00 m, with a mean of 1.76 m. Snow density was measured in a density pit at 1954 m a.s.l. The total snow thickness measured was 2.3 m and the resulting density was 483 kg m⁻³. Ablation measurements were carried out on 16th October when fresh snow covered the middle and upper parts of the glacier (Fig. 8-1).

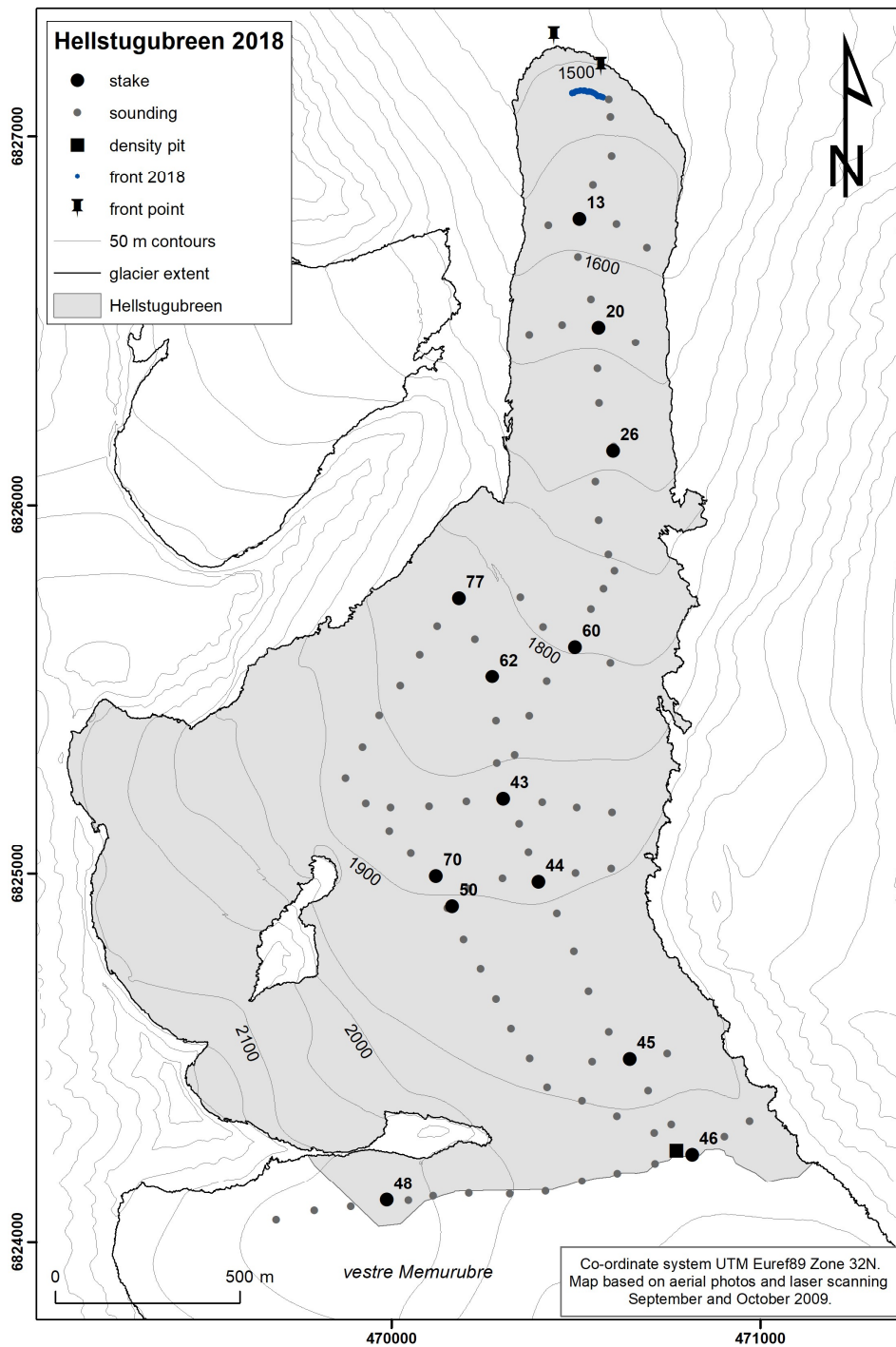


Figure 8-2
Map of Hellstugubreen showing the location of stakes, snow depth soundings and snow pit in 2018. The glacier terminus has retreated since 2009. Part of the terminus (front 2018) mapped by GNSS-survey is shown on the map. Front point: reference points used for front position and length change measurements (chap. 12-1). The glacier retreated 90-130 m in this area between 2009 and 2018.

Results

The calculations are based on the DTM from 2009. The winter balance was calculated as the mean of the soundings within each 50-metre height interval and was 0.90 ± 0.2 m w.e., which is 80% of the mean winter balance for the reference period 1981-2010. The summer balance was interpolated to 50 m height intervals based on the stake readings and was

-2.53 ±0.2 m w.e., which is 167 % of the mean summer balance for the reference period 1981-2010. The annual balance of Hellstugubreen was -1.63 ±0.3 m w.e. The equilibrium line altitude (ELA) was above the highest stake and estimated as 2070 m a.s.l., but was not possible to observe in situ due to fresh snow. The ELA was estimated to be 2100 m a.s.l., resulting in an accumulation area ratio (AAR) of 4 %. The mass balance results are shown in Table 8-1 and the corresponding curves for specific and volume balance are shown in Figure 8-4.

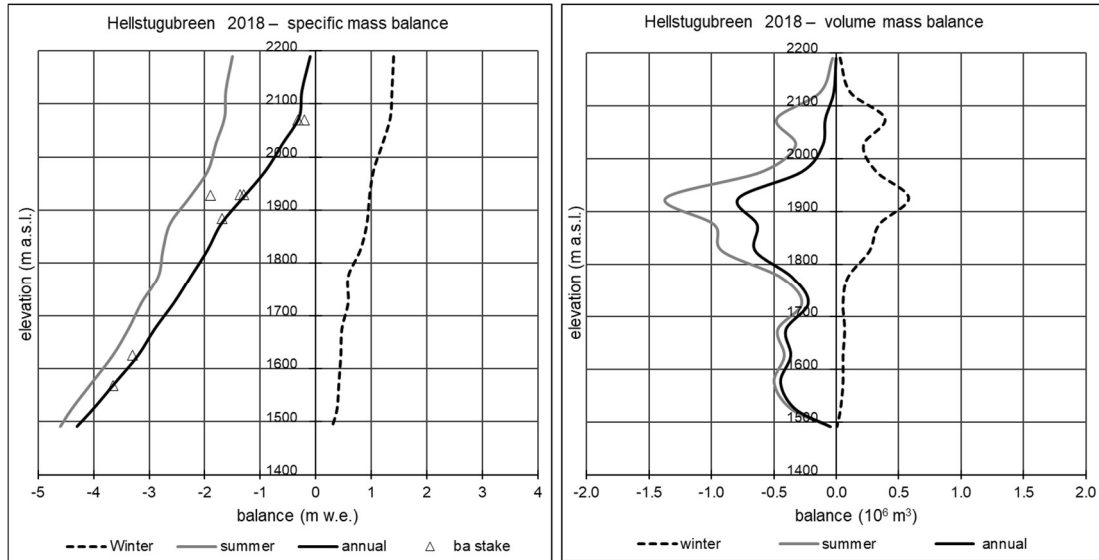


Figure 8-3
Mass balance diagram for Hellstugubreen in 2018, showing specific balance on the left and volume balance on the right. Summer and annual balance at stakes are also shown.

Table 8-1
The distribution of winter, summer and annual balance in 50 m altitudinal intervals for Hellstugubreen in 2018.

Mass balance Hellstugubreen 2017/18 – stratigraphic system							
Altitude (m a.s.l.)	Area (km ²)	Winter mass balance		Summer mass balance		Annual mass balance	
		Measured 23rd May 2018		Measured 16th Oct 2018		Summer surfaces 2017 - 2018	
		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)
2150 - 2229	0.02	1.40	0.03	-1.50	-0.03	-0.10	0.00
2100 - 2150	0.08	1.37	0.11	-1.62	-0.13	-0.25	-0.02
2050 - 2100	0.29	1.34	0.39	-1.64	-0.48	-0.30	-0.09
2000 - 2050	0.18	1.20	0.22	-1.80	-0.33	-0.60	-0.11
1950 - 2000	0.31	1.04	0.32	-1.94	-0.60	-0.90	-0.28
1900 - 1950	0.60	0.97	0.58	-2.27	-1.37	-1.30	-0.78
1850 - 1900	0.37	0.92	0.34	-2.62	-0.98	-1.70	-0.63
1800 - 1850	0.33	0.80	0.27	-2.75	-0.91	-1.95	-0.65
1750 - 1800	0.16	0.59	0.09	-2.84	-0.45	-2.25	-0.35
1700 - 1750	0.09	0.59	0.05	-3.14	-0.28	-2.55	-0.22
1650 - 1700	0.14	0.47	0.07	-3.37	-0.47	-2.90	-0.40
1600 - 1650	0.11	0.46	0.05	-3.66	-0.42	-3.20	-0.36
1550 - 1600	0.12	0.42	0.05	-4.02	-0.50	-3.60	-0.45
1500 - 1550	0.08	0.39	0.03	-4.39	-0.36	-4.00	-0.33
1482 - 1500	0.01	0.30	0.00	-4.60	-0.05	-4.30	-0.05
1482 - 2229	2.90	0.90	2.61	-2.53	-7.34	-1.63	-4.73

8.2 Mass balance 1962-2018

The cumulative annual balance of Hellstugubreen since 1962 is -24 m w.e. (Fig. 8-4), giving a mean annual deficit of 0.39 m w.e. per year. The cumulative mass balance is -14.7 m w.e. since 2001.

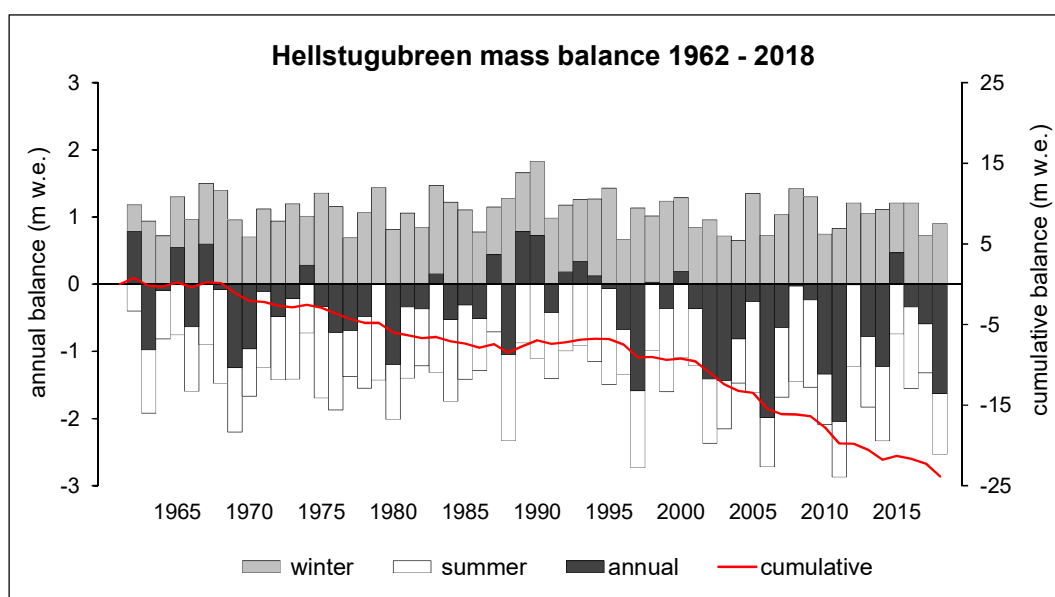


Figure 8-4
Winter, summer and annual balance at Hellstugubreen for 1962-2018, and cumulative mass balance for the whole period.

9. 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. 9-1). Gråsubreen has an area of 2.12 km² 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 snow drifting removes snow causing 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 9-1
Gråsubreen on 16th October 2018. View towards east showing northern parts of the glacier.
Photo: Liss M. Andreassen.

9.1 Mass balance 2018

Fieldwork

Accumulation measurements were performed on 4-5th June 2018. The calculation of winter balance is based on stake measurements and snow depth soundings in 102 positions between 1866 and 2269 m a.s.l. (Fig. 9-2). The snow depth varied between 0.00 and 3.99 with a mean and median of 0.76 and 0.74 m respectively. Much of the glacier had very little snow and the glacier melt season had already started at the time of measurements. The snow density was measured in a density pit near stake 5 (elevation 2102 m a.s.l.) where the total snow depth was 0.84 m and the mean density was 456 kg m^{-3} . Ablation measurements were carried out on 16th October 2018, when all visible stakes were measured. All stakes were snow free at the time of measurements. The calculation of annual balance was based on stakes in seven different positions.

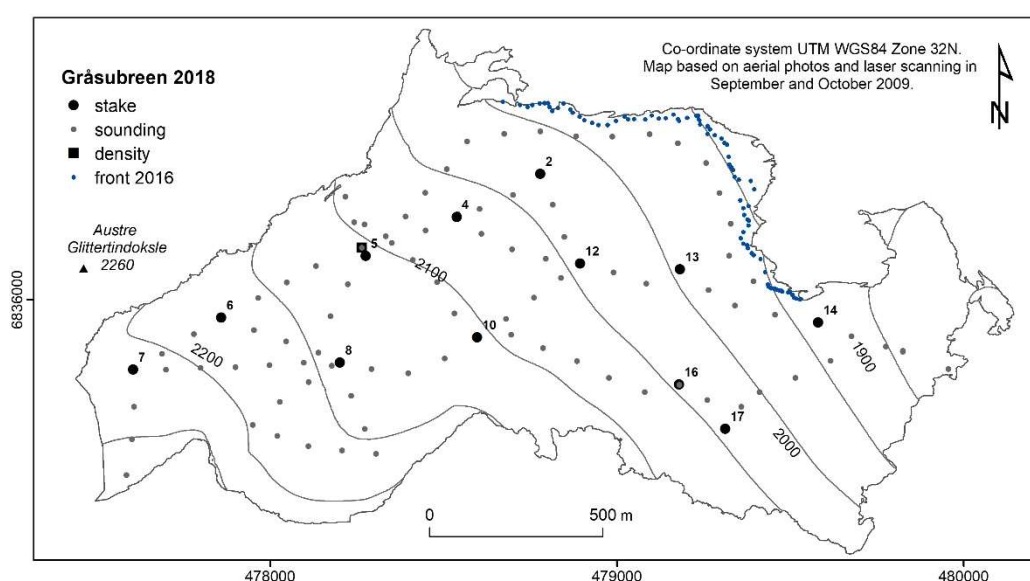


Figure 9-2
Map of Gråsubreen showing the location of stakes, density pit and soundings in 2018, as well as front measurements in 2016.

Results

The winter balance was calculated as the mean of the soundings within each 50-metre height interval. This gave a winter balance of $0.39 \pm 0.1 \text{ m w.e.}$, which is 49% of the mean winter balance for the reference period 1981-2010. Summer and annual balance were calculated from direct measurements of stakes. The resulting summer balance was $-2.21 \pm 0.3 \text{ m w.e.}$, which is 190 % of the mean summer balance for the reference period 1981-2010.

The annual balance of Gråsubreen was negative in 2018, $-1.82 \pm 0.3 \text{ m w.e.}$ The ELA and AAR were not defined from the mass balance curve or in the field.

The mass balance results are shown in Table 9-1 and the corresponding curves for specific and volume balance are shown in Figure 9-3.

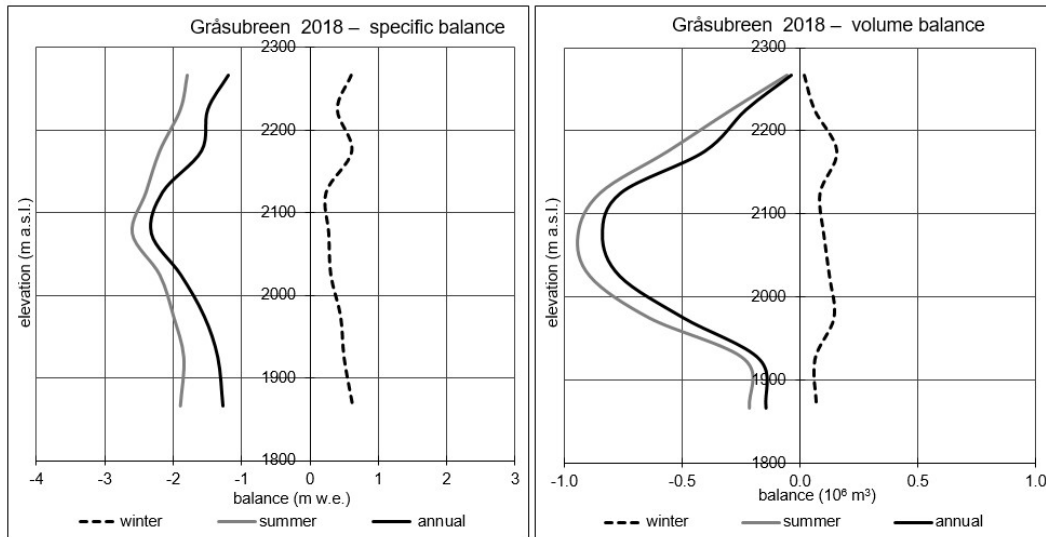


Figure 9-3
Mass balance diagram for Gråsüreen for 2018, showing specific balance on the left and volume balance on the right. Winter and summer balance at the stakes and individual snow depth soundings are also shown.

Table 9-1
The distribution of winter, summer and annual balance in 50 m altitudinal intervals for Gråsüreen in 2018.

Mass balance Gråsüreen 2017/18 – stratigraphic system							
Altitude (m a.s.l.)	Area (km ²)	Winter mass balance Measured 4-5 June 2018		Summer mass balance Measured 16 Oct 2018		Annual mass balance Summersurfaces 2017 - 2018	
		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)
2250 - 2283	0.03	0.60	0.02	-1.80	-0.06	-1.20	-0.04
2200 - 2250	0.15	0.40	0.06	-1.90	-0.29	-1.50	-0.23
2150 - 2200	0.26	0.61	0.16	-2.20	-0.56	-1.59	-0.41
2100 - 2150	0.35	0.24	0.08	-2.40	-0.85	-2.16	-0.76
2050 - 2100	0.36	0.28	0.10	-2.60	-0.94	-2.32	-0.84
2000 - 2050	0.41	0.31	0.12	-2.20	-0.89	-1.89	-0.77
1950 - 2000	0.32	0.45	0.14	-2.00	-0.64	-1.55	-0.50
1900 - 1950	0.13	0.50	0.06	-1.85	-0.23	-1.35	-0.17
1833 - 1900	0.11	0.62	0.07	-1.90	-0.21	-1.28	-0.14
1833 - 2283	2.12	0.39	0.82	-2.21	-4.68	-1.82	-3.86

10.2 Mass balance 1962-2018

The cumulative annual balance of Gråsubreen is -24 m w.e. since measurements began in 1962 (Fig. 9-4). The average annual balance is thus -0.39 m w.e. a^{-1} .

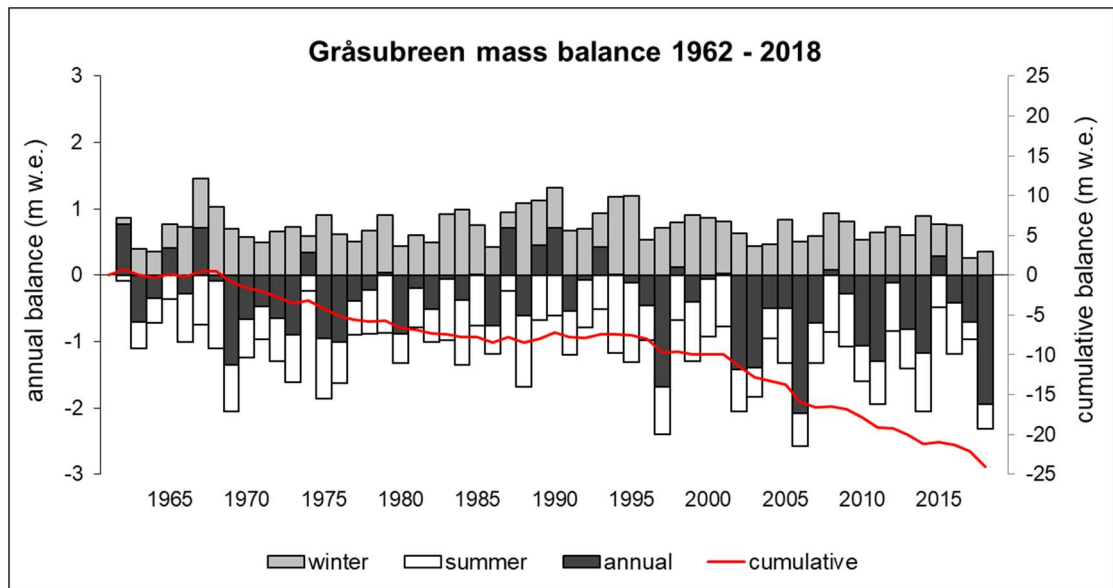


Figure 9-4
Winter, summer and annual balance for Gråsubreen for 1962-2018, and cumulative mass balance for the whole period.

10. Engabreen (Hallgeir Elvehøy and Miriam Jackson)

Engabreen (66°40'N, 13°45'E) is a 36 km² north-western outlet from the western Svartisen ice cap (Fig. 10-1). 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. 12) 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 2018 are presented in Section 10-3.



Figure 10-1
Rock outcrops emerge from the ice due to glacier thinning at about 1100 m a.s.l. east of Møsbrømtuva. Photo taken on 7th August 2018 by Hallgeir Elvehøy.

10.1 Mass balance 2018

Fieldwork

Stakes in five locations on the plateau were observed on 27th February and showed between 2 and 4 metres of snow.

The snow accumulation measurements were performed on 15th May. Five stakes on the glacier plateau were located and used to validate the snow depth soundings. Snow depth was measured at 24 sounding locations along the profile from the summit at 1464 m a.s.l. to E34 (Fig. 10-2). The snow depth was between 2 and 5 metres. The summer surface was easy to define. The mean snow density down to the summer surface at 3.3 m depth at stake E5 was 522 kg m⁻³.

On 7th August, stakes E34 and E17 had melted out, and they were redrilled. Up to 1.3 m of snow remained at stakes above 1225 m a.s.l.

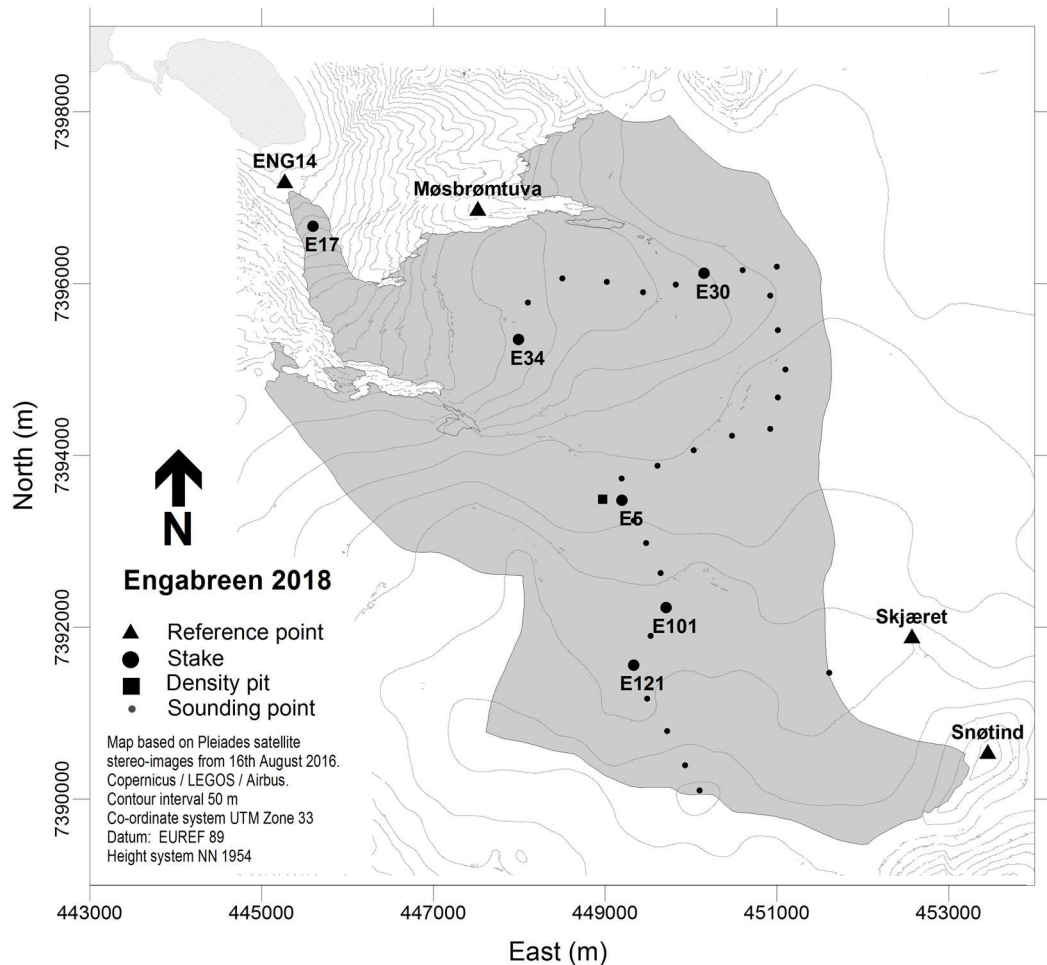


Figure 10-2
Location of stakes, density pit and sounding profiles on Engabreen in 2018.

The summer ablation measurements were carried out on 25th October. There was up to 2.75 m of new snow at the stakes. Stakes were found in five locations on the plateau. At the uppermost stake location E121 at 1350 m a.s.l. almost all the winter snow had melted during the summer. Consequently, the temporary snow line altitude at the end of the melt season was around 1350 m a.s.l. At stake E34, 960 m a.s.l., all the winter snow and at least 4.9 m of ice melted during the summer. At stake E17 on the glacier tongue at least 9.35 m of ice melted between 15th May and 25th October.

Results

The calculations are based on a DTM from 16th August 2016. The date of the 2018 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 16th September and on the lower part of the glacier plateau on 24th September.

The winter balance for 2018 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 1.7 ± 0.2 m w.e. This is 68 % of the average winter balance for the period 1981-2010 (2.58 m w.e. a^{-1}).

The point summer balance was calculated directly for four stake locations between 1100 and 1340 m a.s.l. Stake E17 melted out a couple of days before 7th August, but was observed on 24th July. Due to warm weather in this 14-day period, a high melt rate (12 cm/day) was assumed. At stake E34 all of the snow and at least 2.65 m of ice had melted. Based on comparison with stake E30, the melt rate at E34 between 15th May and 7th August was assessed as 5.5 cm/day.

The specific summer balance was calculated from the summer balance curve drawn from these six point values (Fig. 10-4) as -3.4 ± 0.2 m w.e. This is 131 % of the average summer balance for the period 1981-2010 (-2.60 m w.e. a^{-1}). The resulting annual balance was -1.6 ± 0.3 m w.e. (Tab. 10-1). The ELA was higher than the top of the glacier (>1544 m a.s.l.), and consequently the AAR was 0 %.



Figure 10-3
Engabreen on 7th August 2018. This glacier has retreated 536 metres since 1999 when it reached the delta in Lake Engabrevatnet, and 2018. Photo: Hallgeir Elvehøy.

Table 10-1
Specific and volume winter, summer and annual balance calculated for 100 m elevation intervals at Engabreen in 2018.

Mass balance Engabreen 2017/18 – stratigraphic system							
Altitude (m a.s.l.)	Area (km ²)	Winter mass balance Measured 15th May 2018		Summer mass balance Measured 26th Oct 2018		Annual mass balance Summer surfaces 2017 - 2018	
		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	1.90	0.1	-2.20	-0.1	-0.30	0.0
1400 - 1500	2.13	2.15	4.6	-2.20	-4.7	-0.05	-0.1
1300 - 1400	9.24	2.10	19.4	-2.30	-21.3	-0.20	-1.8
1200 - 1300	8.04	1.95	15.7	-2.65	-21.3	-0.70	-5.6
1100 - 1200	7.57	1.75	13.3	-3.50	-26.5	-1.75	-13.3
1000 - 1100	4.61	1.50	6.9	-4.50	-20.7	-3.00	-13.8
900 - 1000	2.43	1.10	2.7	-5.40	-13.1	-4.30	-10.5
800 - 900	0.80	0.80	0.6	-6.00	-4.8	-5.20	-4.1
700 - 800	0.46	0.55	0.3	-6.40	-2.9	-5.85	-2.7
600 - 700	0.29	0.30	0.1	-6.80	-1.9	-6.50	-1.9
500 - 600	0.25	0.00	0.0	-7.20	-1.8	-7.20	-1.8
400 - 500	0.14	-0.30	0.0	-7.70	-1.1	-8.00	-1.2
300 - 400	0.10	-0.60	-0.1	-8.20	-0.8	-8.80	-0.9
200 - 300	0.12	-0.90	-0.1	-8.70	-1.0	-9.60	-1.1
111 - 200	0.04	-1.20	0.0	-9.20	-0.3	-10.40	-0.4
111 - 1544	36.25	1.75	63.3	-3.38	-122.4	-1.63	-59.1

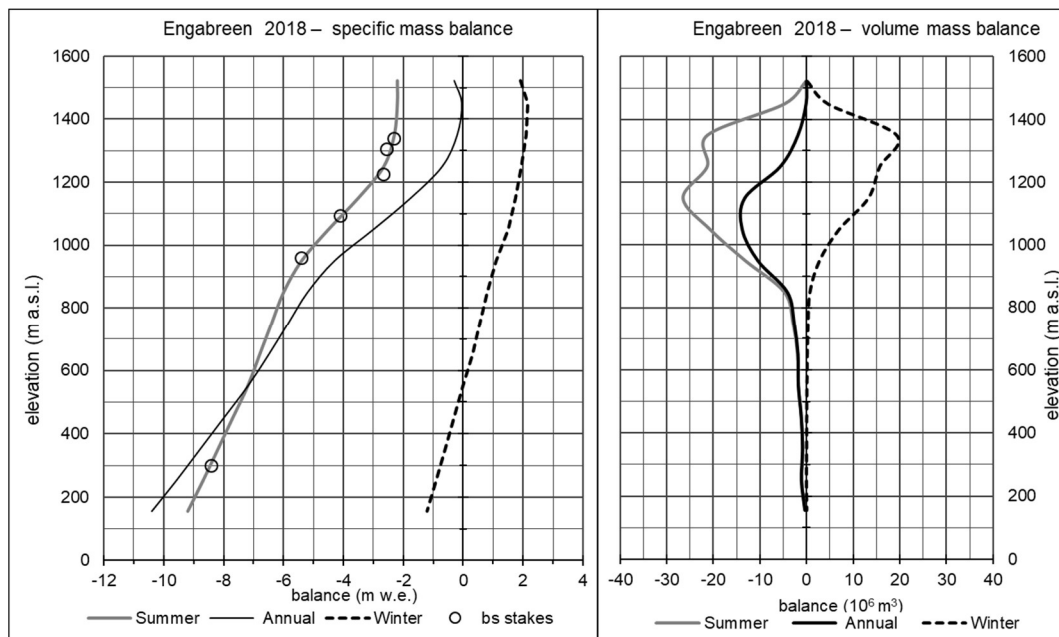


Figure 10-4
Mass balance diagram showing specific balance (left) and volume balance (right) for Engabreen in 2018. Summer balance at six stake locations (○) is shown.

10.2 Mass balance 1970-2018

The annual surface mass balance at Engabreen for 1970-2018 is shown in Figure 10-4. The cumulative surface mass balance since the start of mass balance investigations at Engabreen is -0.7 m w.e., showing that the long-term 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. The mass increase from 1970 to 1997 (28 years) was 7.3 m w.e., or $+0.26$ m w.e. a^{-1} . During the last 21 years (1997-2018), the glacier volume has decreased by 8.1 m w.e., or -0.39 m w.e. a^{-1} (Fig. 10-5).

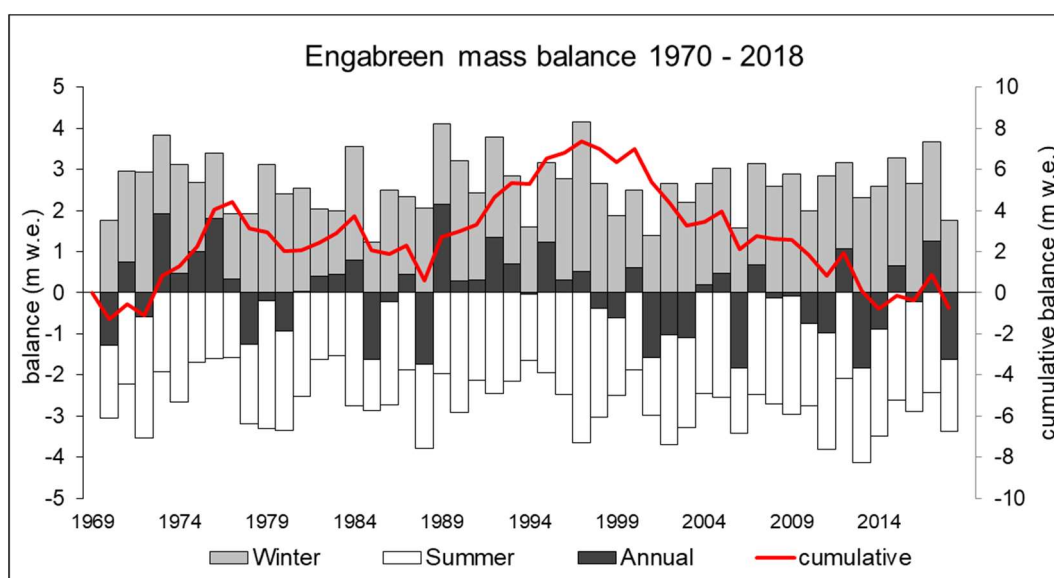


Figure 10-5
Mass balance at Engabreen during the period 1970-2018. The average winter and summer balances are $B_w = 2.65$ m w.e. and $B_s = -2.66$ m w.e.

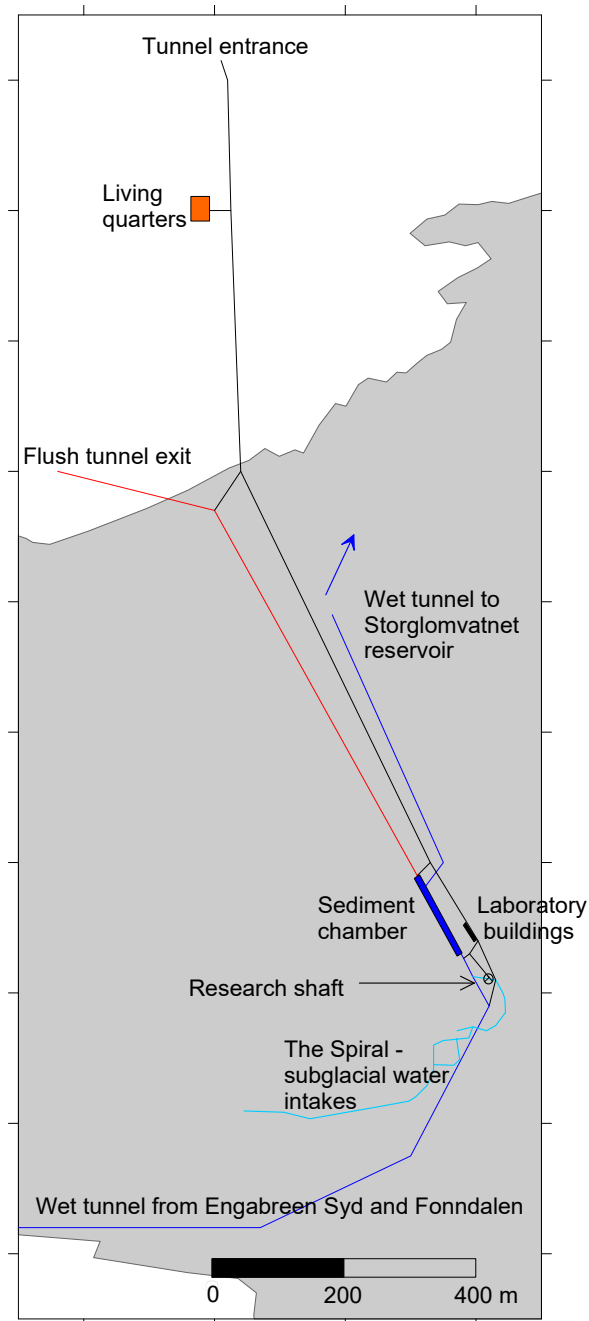
10.3 Meteorological observations

A meteorological station recording air temperature and global radiation at 3 m above ground level is located on the nunatak Skjæret (1364 m a.s.l., Fig. 10-2) close to the drainage divide between Engabreen and Storglombreen. The station has been operating since 1995. Data were collected continuously without gaps in 2018.

The summer mean temperature (1st June – 30th September) at Skjæret in 2018 was 2.9 °C, close to the mean summer temperature for 18 years between 1995 and 2017, which is 3.01 °C. The melt season on the upper part of the glacier plateau started on 1st July and probably lasted until 16th September. The period between 9th July and 3rd August was particularly warm with a mean daily temperature in this period of 9.5 °C.

10.4 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. 10-6). The research shaft allows direct access to the bed of the glacier 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. 10-7). 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. Five load cells are still in operation and record data. All load cells are installed at the glacier-bedrock interface within 20 m of each other. The inter-annual variability of the load cells is examined in detail in Lefeuvre et al. (2015).

The 2018 data from the load cells are briefly summarised here but also are available for more comprehensive analysis. Due to equipment problems in 2018, load cell data exist for the period 1st January to 15th May only.

Seismic data are also recorded in the subglacial tunnel.

Figure 10-6
Map of tunnel system under Engabreen, showing research shaft and other facilities.

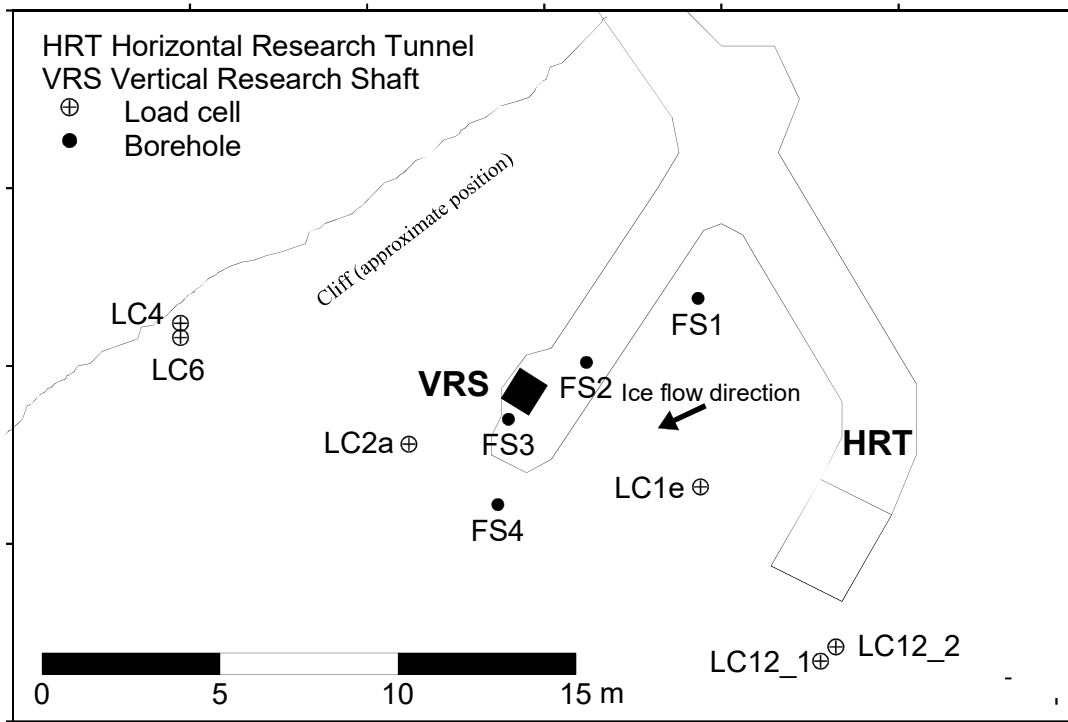


Figure 10-7
 Research shaft showing locations of horizontal research tunnel (HRT), vertical research shaft (VRS) and load cells (LC). Boreholes from the tunnel to the glacier bed (FS) are also shown.

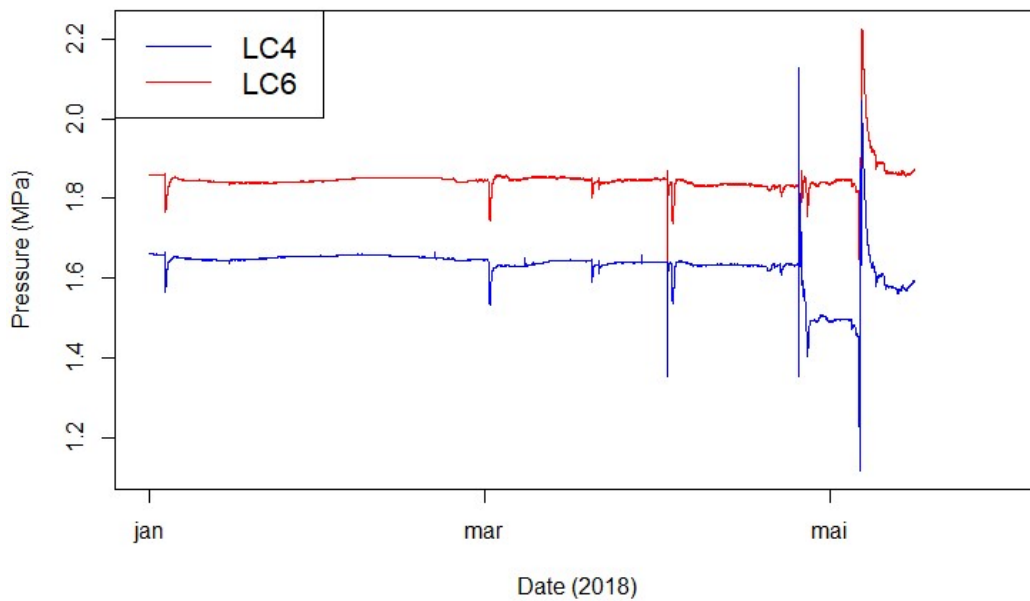


Figure 10-8
 Pressure at load cells LC4 and LC6 for January to May 2018.

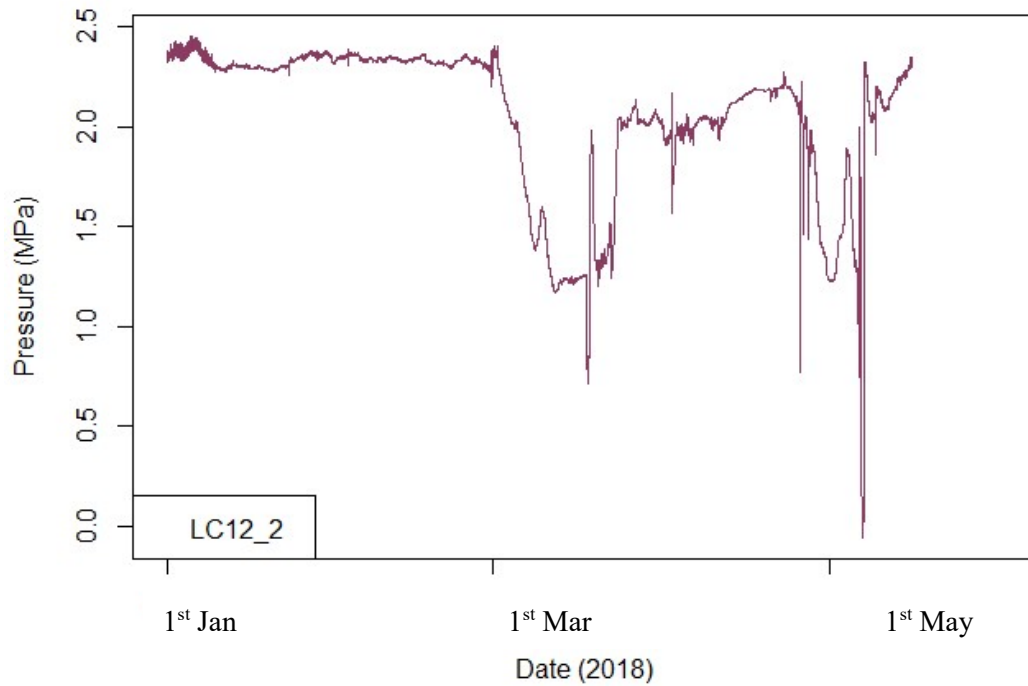


Figure 10-9
Pressure at load cell LC12_2 for January to May 2018.

Figure 10-8 shows the pressure record for January to May 2018 for load cell pair LC4 and LC6, which are installed in a relatively quiet environment. Figure 10-9 shows the record for the same period for load cell LC12_2, which although it is only a few metres from the other two load cells, is in an environment that is much more exposed to changes at the bed of the glacier.

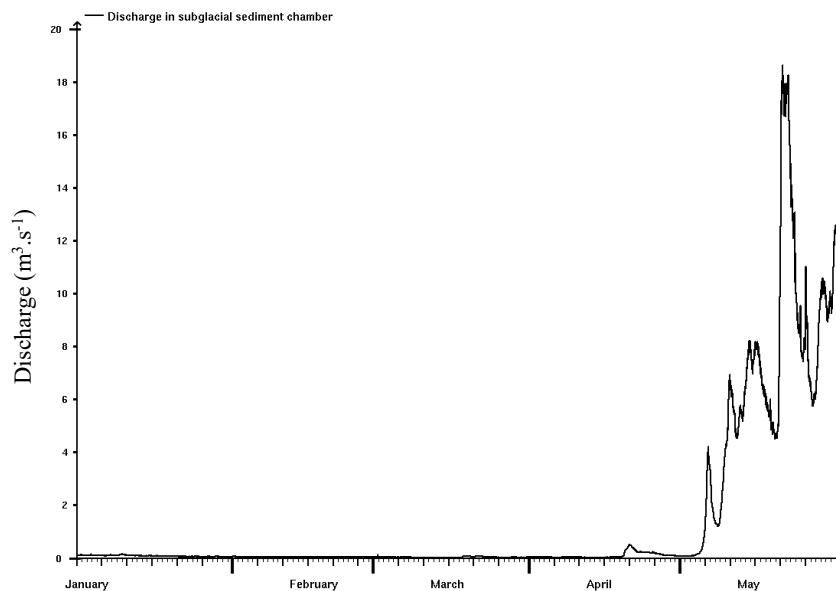


Figure 10-10
Discharge measured from January to May 2018 in the sediment chamber under Engabreen (see Fig. 10-6). The discharge is the sum of snow melt, glacier melt and precipitation.

The load cells all appear to respond to an event in early March. The signal is distinct but short-lived at the two “quiet” load cells, LC4 and LC6, but much longer lasting at LC12_2. The response is similar to that seen when there is a sudden input of water to the glacier bed, but in this case, the subglacial drainage (Fig. 10-10) shows very little flow. There are two more events in April which are seen at the three load cells shown here, but do not seem to have an obvious cause from the discharge record. However, even small changes in discharge can have a large effect when these occur early in the season, when the subglacial drainage system is undeveloped.

The first distinctive event in the subglacial discharge occurs about 5th May, when the discharge suddenly increases from little more than zero to $4 \text{ m}^3.\text{s}^{-1}$ in just a few hours. At load cells LC4 and LC6 there is a sudden drop in pressure, possibly in response to glacier uplift, then an increase in pressure right afterward, before the pressure values return to their pre-event values. At LC12_2, the pressure drops almost to zero, then returns to the pre-event value.

11. Langfjordjøkelen (Bjarne Kjøllmoen)

Langfjordjøkelen (70°10'N, 21°45'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 6.2 km² (2018), and of this 2.6 km² drains eastward. The investigations are performed on this east-facing part (Fig. 11-1), ranging in elevation from 338 to 1043 m a.s.l.

The glaciological investigations in 2018 include mass balance and change in glacier length (chap. 12). Langfjordjøkelen has been the subject of mass balance measurements since 1989 with the exception of 1994 and 1995.



Figure 11-1
The east-facing outlet of Langfjordjøkelen photographed on 15th August 2018. Photo: Miriam Jackson.

11.1 Mapping

A new survey of Langfjordjøkelen was performed in 2018. The glacier surface was mapped by airborne laser scanning on 1st September (Terratec, 2018). Due to technical problems aerial photos were not taken.

A Digital Terrain Model (DTM) was generated based on the laser scanning data (x, y and z). The glacier boundary was determined from the laser data (intensity values) by Terratec. Further processing and improvement was carried out by using shaded relief from the DTM supported with an orthophoto from August 2015. The ice divides for the east-facing glacier part were calculated using GIS and compared with the ice divides from 2008. The ice divides from 2018 were similar to the 2008 divides. Hence the 2008 ice divides were used in the following work.

The mapping from 2018 showed extensive glacier changes compared with the previous mapping in 2008. The area for the whole contiguous ice cap had shrunk from 7.7 to 6.2 km² (Fig. 11-2). Some of this area decrease (0.16 km²) was related to separation of glacier cover in the north-western part of the ice cap (Fig. 11-2). The corresponding shrinkage for the east-facing part of the glacier was from 3.2 to 2.6 km². The recession of the east-facing glacier snout from 2008 to 2018 was about 275 metres (Fig. 11-2).

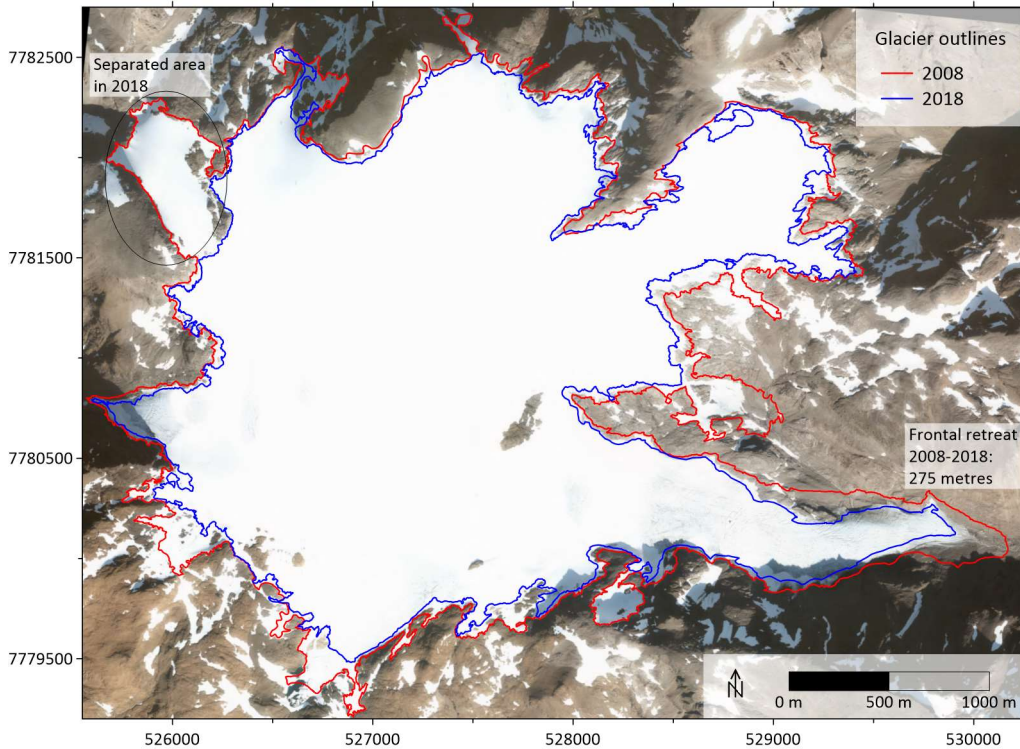


Figure 11-2
 Glacier outlines from mappings in 2008 (red) and 2018 (blue). The base image is orthophoto from August 2015. Source: <https://norgebilder.no>.

Based on the new DTM from 2018 the area-altitude distribution was changed from the 2008 DTM (Fig. 11-3). As shown in Figure 11-3 the area was reduced in all height intervals.

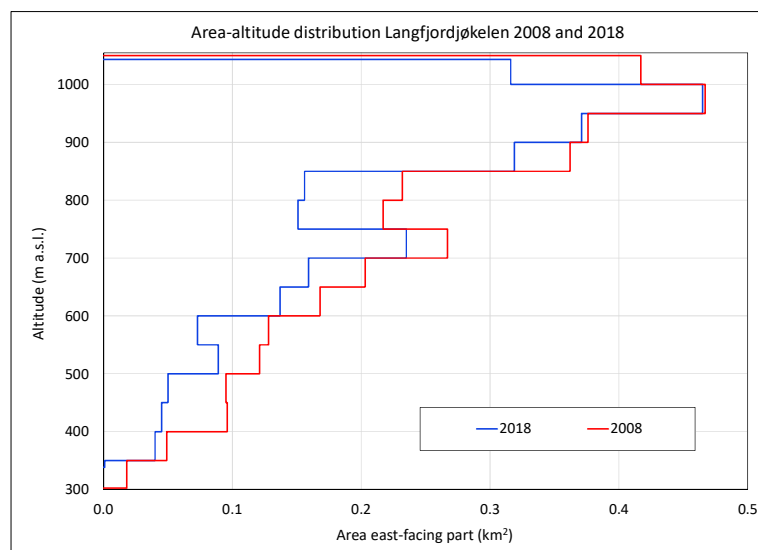


Figure 11-3
 Area-altitude distribution for the east-facing part of Langfjordjøkelen in 2008 (red) and 2018 (blue).

11.2 Mass balance 2018

Fieldwork

Snow accumulation was measured on 10th May and the calculation of winter balance was based on measurements of two stakes and 60 snow depth soundings (Fig. 11-4). The snow depth varied between 1.0 and 3.9 m with an average of 3.0 m. Snow density was measured in position 25 (702 m a.s.l.) and the mean density of 3.2 m snow was 489 kg m^{-3} .

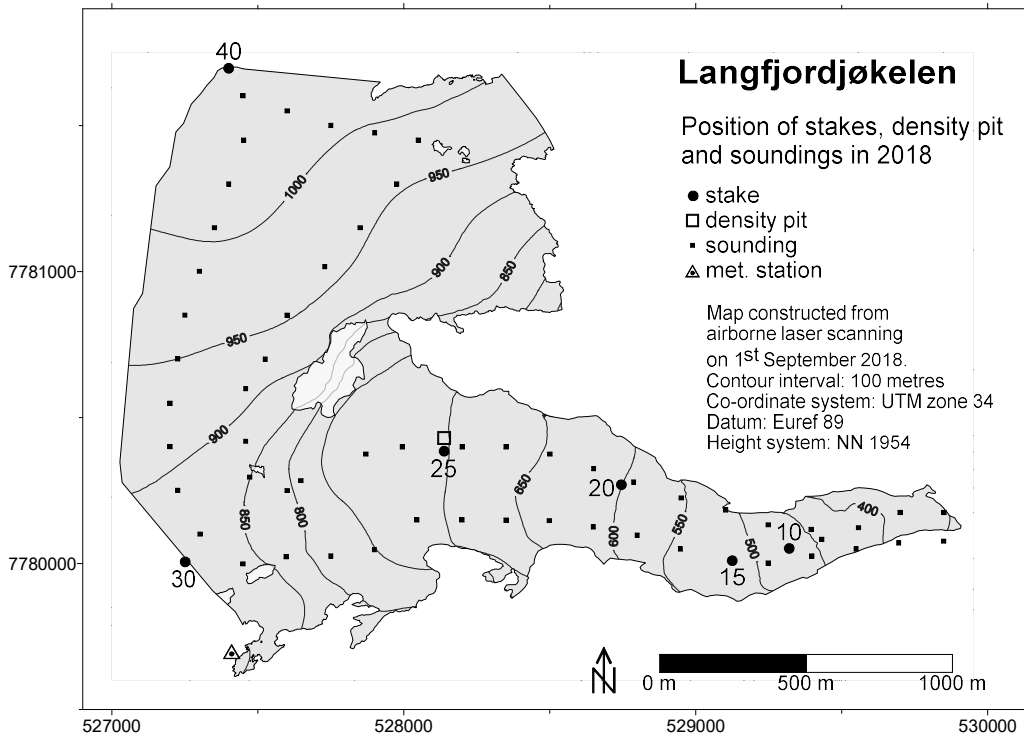


Figure 11-4
Location of stakes, soundings and snow pit at Langfjordjøkelen in 2018.

Ablation was measured on 12th October. The annual balance was measured at stakes in six locations (Fig. 11-4). There was no snow remaining on the glacier from the winter season 2017/18. At the time of measurement between 60 and 90 cm of fresh snow had fallen on the glacier.

Results

The calculations are based on the new DTM from 2018.

All elevations are well-represented with snow depth measurements. The winter balance was calculated as a mean value for each 50 m height interval and was $1.5 \pm 0.2 \text{ m w.e.}$, which is 74 % of the mean winter balance for the years 1989-93 and 1996-2017. Spatial distribution of the winter balance is shown in Figure 11-5.

The ablation stakes cover elevations from the glacier summit to 475 m a.s.l. The summer balance curve is extrapolated below 475 m elevation. 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 $-3.7 \pm 0.3 \text{ m w.e.}$, which is 123 % of the mean summer balance 1989-93 and 1996-2017.

Hence the annual balance was negative, at -2.1 ± 0.4 m w.e. The mean annual balance for 1989-93 and 1996-2017 is -0.92 m w.e. The mean annual balance for the past ten years (2009-18) is -1.16 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.

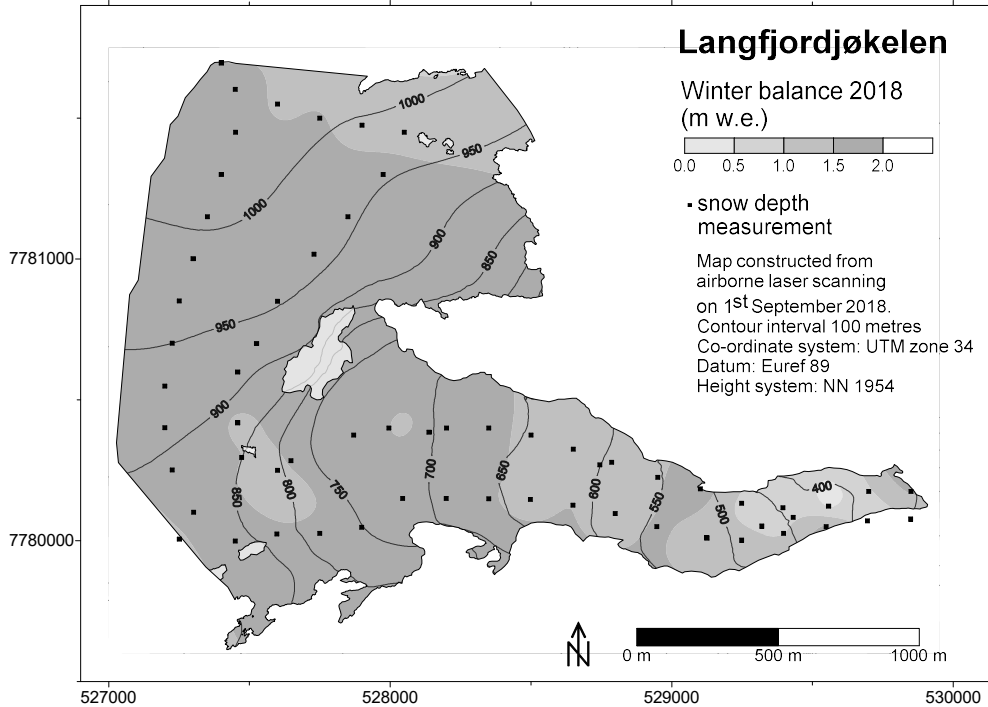


Figure 11-5
Spatial distribution of winter balance at Langfjordjøkelen in 2018.

According to Figure 11-6, the Equilibrium Line Altitude lay above the highest point of the glacier. Consequently the Accumulation Area Ratio was 0 %.

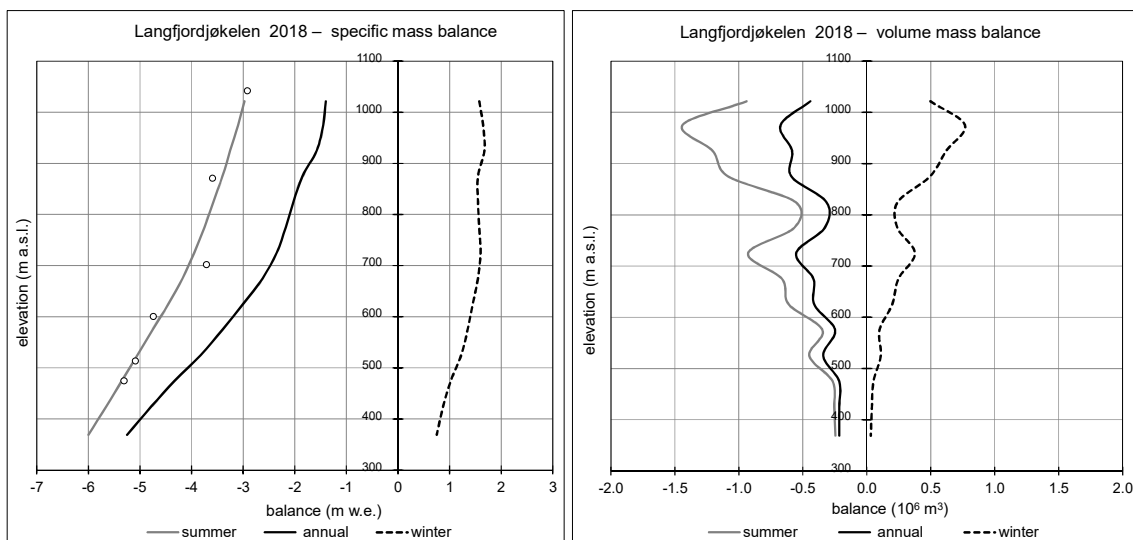


Figure 11-6
Mass balance diagram showing specific balance (left) and volume balance (right) for Langfjordjøkelen in 2018. Specific summer balance for six stakes is shown as circles (o).

Table 11-1
Winter, summer and annual balance for Langfjordjøkelen in 2018.

Mass balance Langfjordjøkelen 2016/17 – stratigraphic system							
Altitude (m.a.s.l.)	Area (km ²)	Winter mass balance Measured 25th Apr 2017		Summer mass balance Measured 29th Sep 2017		Annual mass balance Summer surface 2016 - 2017	
		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)
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

11.2 Mass balance 1989-2018

The historical mass balance results for Langfjordjøkelen are presented in Figure 11-7. The cumulative annual balance for 1989-2018 (estimated values for 1994 and 1995 included) is -27.5 m w.e., which gives a mean annual balance of -0.92 m w.e. a^{-1} .

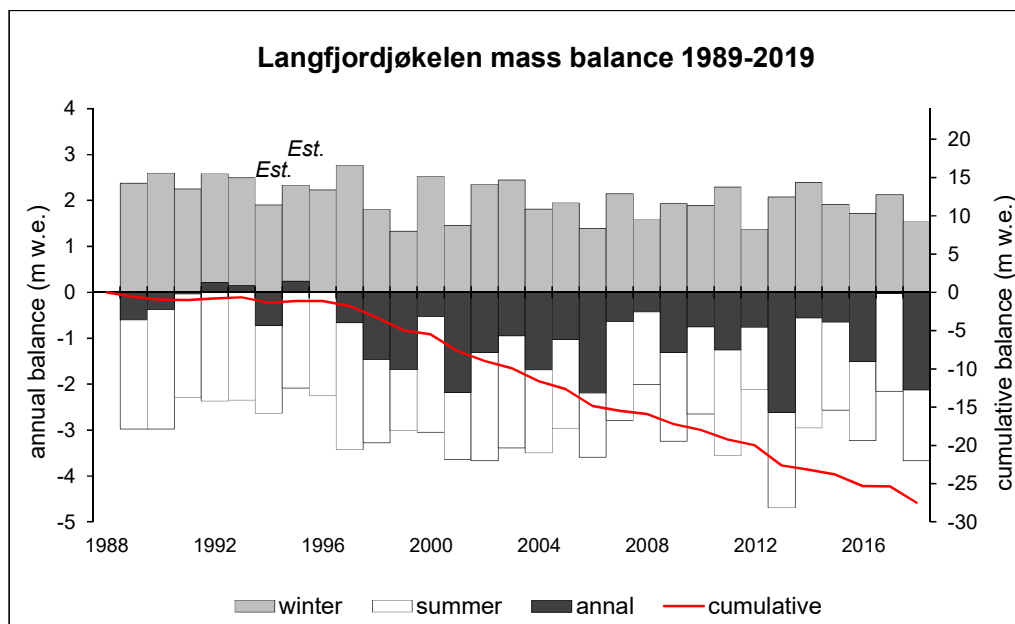


Figure 11-7
Mass balance at Langfjordjøkelen for the period 1989-2018. The total accumulated mass loss for 1989-2018 is 27.5 m w.e. (includes estimated values for 1994 and 1995).

11.3 Meteorological observations

A meteorological station (Langfjord Met, Fig. 11-8) recording air temperature, global radiation, wind speed and wind direction at 3 m above ground level is located on the rock ground south of the glacier (915 m a.s.l., Fig. 11-4) close to the glacier margin. The station has been in operation since August 2006. However, the data record for 2006-2008 and 2011 is incomplete. Thus, reliable data exist for the periods 2009-2010 and 2012-2018 only.

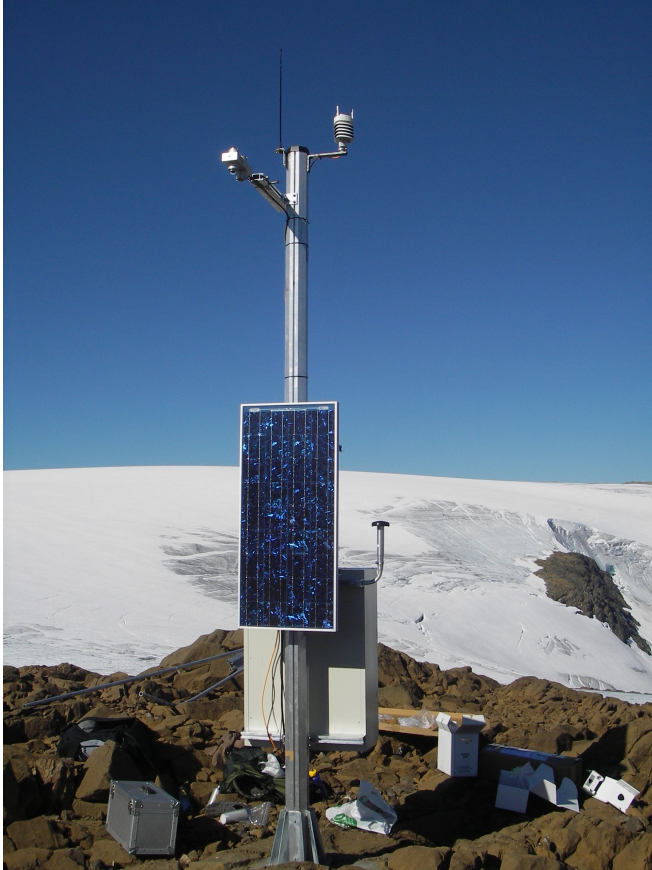


Figure 11-8
The meteorological station
“Langfjord Met” was installed in
August 2006.
Photo: Frode Kvernhaugen.

The mean summer temperature (1st June – 30th September) at Langfjord Met in 2018 was 5.3 °C. The mean summer temperature for 2009-10 and 2012-17 was 4.4 °C. The melt season on the upper part of the glacier (above 900 m a.s.l.) started about 14th June and lasted until about 24th September. The second half of July (16th-31st) was particularly warm with a mean daily temperature of 14.8 °C. The monthly summer temperatures were 0.5 °C (June), 11.6 °C (July), 5.7 °C (August) and 2.9 °C (September).

12. Glacier monitoring

(Hallgeir Elvehøy and Miriam Jackson)

12.1 Glacier length change

Observations of glacier length change at Norwegian glaciers started in 1899. Between 1899 and 2018, glacier length change has been measured over several years at 73 glaciers. The total number of observations is 2732 up to and including 2018. The median and mean from number of observations for a single glacier is 26 and 37, respectively, 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

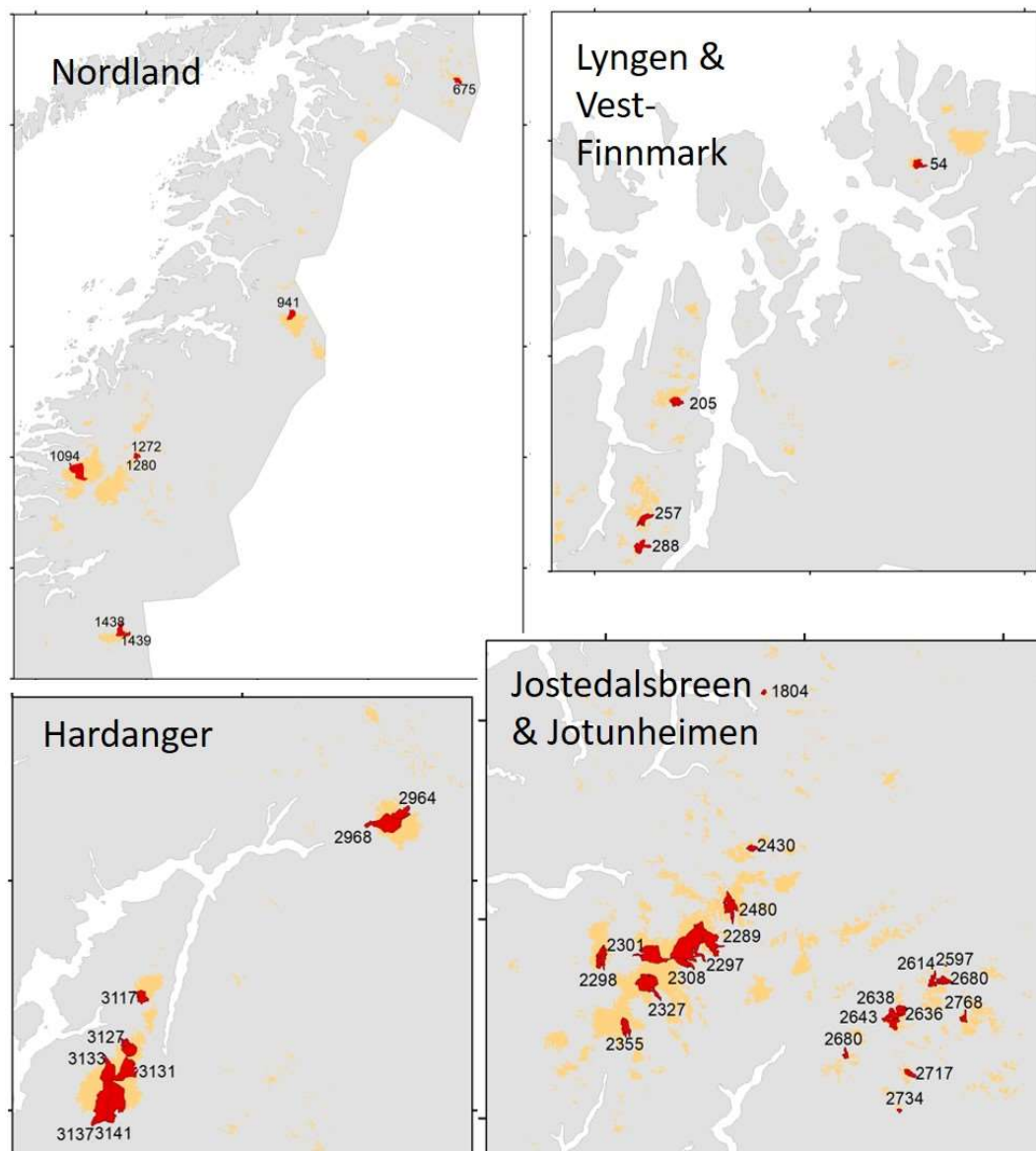


Figure 12-1
Map showing glaciers included in the length change monitoring programme (in red) with glacier IDs (Tab. 12-1). Note that the different glacier areas are not to the same scale.

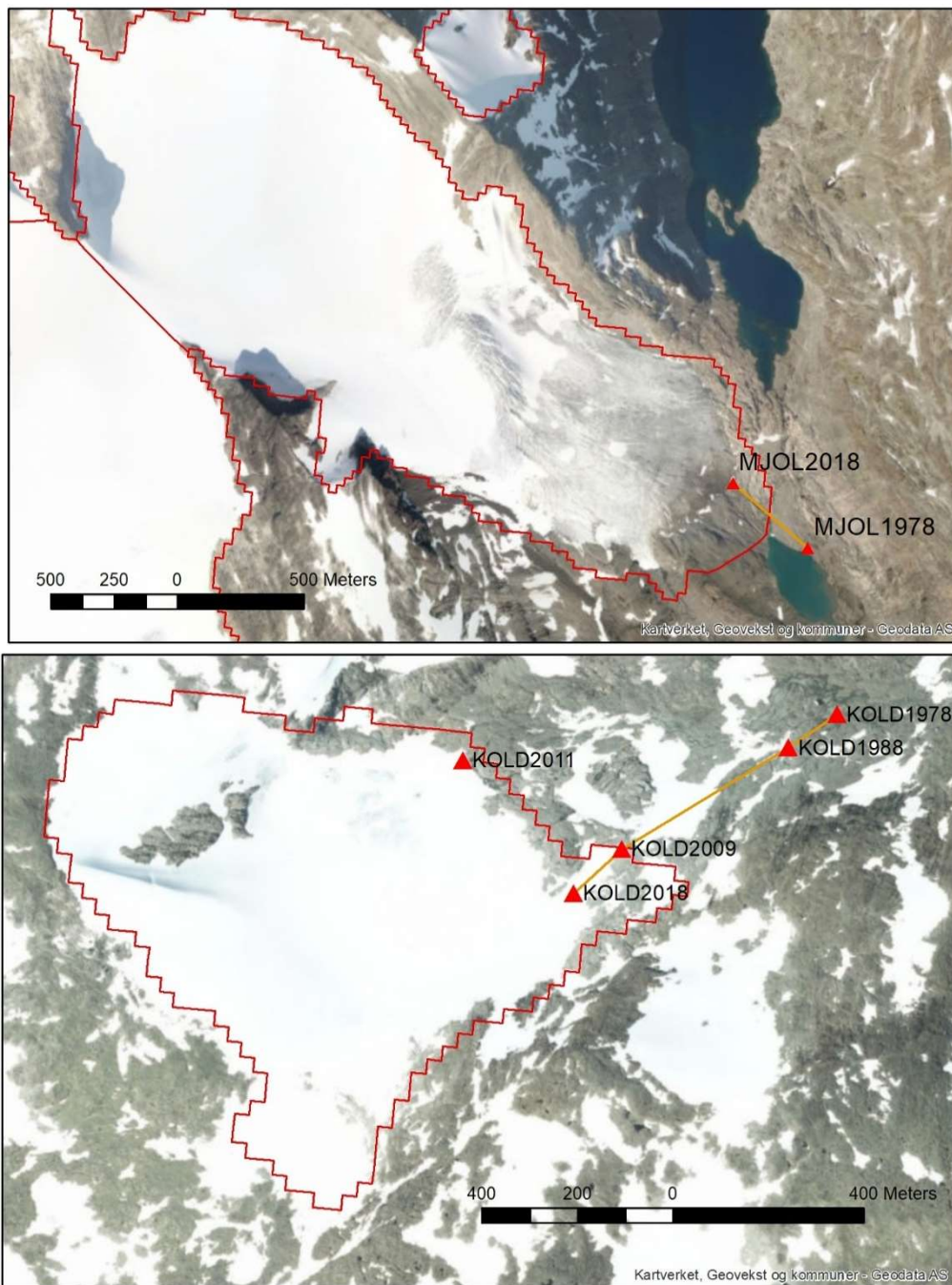


Figure 12-2
Mjølkedalsbreen in 2017 (top) and Koldedalsbreen in 2018 (bottom) with reference points and measuring line. The glacier outline in 2003 from the national glacier inventory (Andreassen and others, 2012) is shown. Orthophoto: www.norgebilder.no.

every year between 1900 and 2015, resulting in 115 observations. Measurements were abandoned in 2015 when glacier recession made conventional length measurements meaningless. Stigaholtbreen, Fåbergstølsbreen and Nigardsbreen also have more than 100 observations each. 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 Engabreen with 86 measurements since 1903. The monitoring programme for 2018 is shown in Figure 12-1.

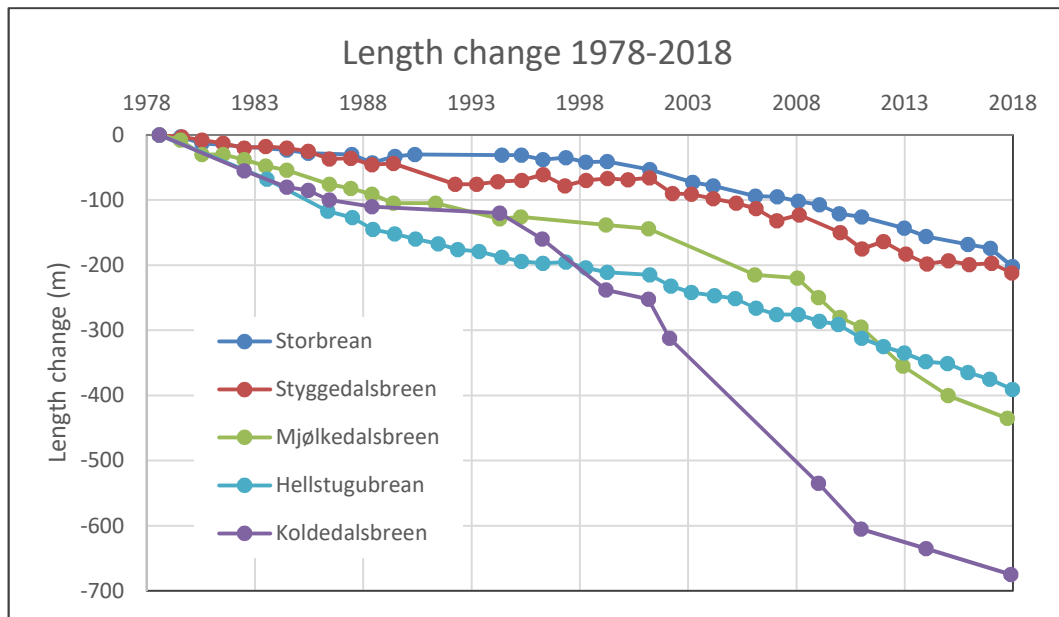


Figure 12-3
Cumulative length change at Mjølkedalsbreen and Koldedalsbreen compared to three glaciers in Jotunheimen with continuous length change measurements. See Figure 12-1 for locations.

Monitoring programme

The present monitoring programme for glacier length change includes 39 glaciers, 28 glaciers in southern Norway and 11 glaciers in northern Norway (Fig. 12-1 for location). The area of the monitored glaciers is 380 km², and they constitutes about 14 % of the glacier area in Norway (Andreassen et al., 2012).

Mjølkedalsbreen (area 3.21 km², altitudinal range 1384-1937 m a.s.l.) and Koldedalsbreen (area 0.75 km², altitudinal range 1484-1806 m a.s.l.) in Jotunheimen have been monitored since 1978 by Birger Løvland (Fig. 12-4), a cabin-owner at Eidsbugarden, and the glaciers are included in NVE's monitoring programme from 2018. Figure 12-2 shows reference points and measuring line at both glaciers. Figure 12-3 shows their record since 1978 as well as the records of Styggedalsbreen, Storbrean and Hellstugubreen. Koldedalsbreen retreated 675 metres between 1978 and 2018. Between 1978 and 1994 the recession was -8 m/year, but increased to -28 m/year between 1994 and 2009. Since 2009 the retreat has slowed down to 16 m/year. The length of this glacier has been more than halved since 1978, and the glacier is now wider than its length. Consequently, it can be re-classified from a valley glacier to a cirque-type glacier.

Mjølkedalsbreen retreated 435 metres between 1978 and 2018. Between 1978 and 1994 the recession was -8 m/year. It slowed to -2 m/year between 1994 and 2001. Since 2001 the retreat sped up to -17 m/year. Until 1937 Mjølkedalsbreen dammed Øvre Mjølkedalsvatnet on its north-eastern side, diverting the run-off westwards to Skogadalen and Sognefjorden. Due to glacier recession, 15 jøkulhlaups from Øvre Mjølkedalsvatnet occurred between 1855 and 1937 (Liestøl, 1956; Jackson and Ragulina, 2014).

Steindalsbreen in Lyngen (BreID 288) has been measured by NVE since 1998. Geoffrey Corner at the Arctic University of Norway put up reference marks in front of the glacier in 1976. His observations between 1976 and 1998 has been included in the record. Hence, the

length change record for Steindalsbreen has been extended from 20 to 42 years. The total retreat in this period is 558 metres.

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 2018

Thirty-two glaciers were measured - six glaciers in northern Norway and 26 glaciers in southern Norway. The results for 2018, period(s) of measurements and number of observations (calculated length changes) are listed in Table 12-1. Data are available at www.nve.no/glacier. One glacier advanced slightly, two glaciers had minor length changes (± 2 m) and the remaining 29 glaciers showed retreat. The annual length change varied from +5 m (Bondhusbrea) to -140 m (Engabreen). Seven glaciers in the monitoring programme were not measured in 2018.

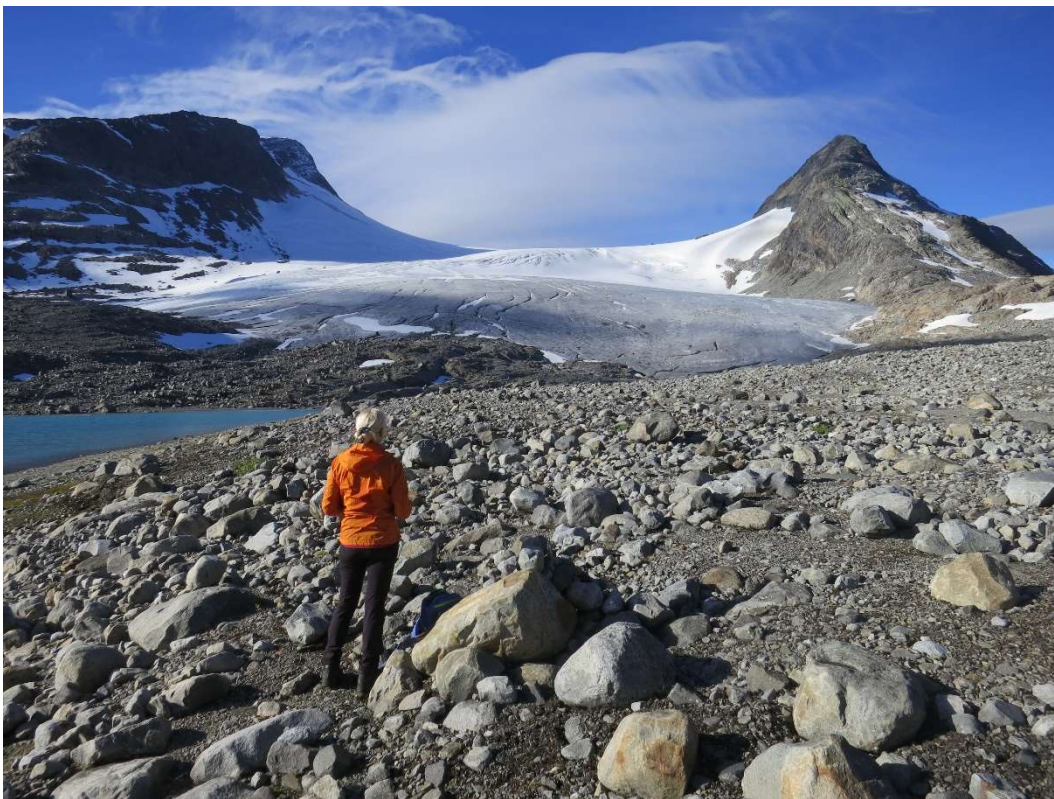


Figure 12-4
Mjølkedalsbreen seen from the original reference point MJOL1978 in 2015. The distance to the glacier was 400 metres. Photo: Birger Løvland.

Table 12-1
Glacier length change measured in 2018. See Figure 12-1 for glacier locations.

	Glacier	Glacier-ID	2018	Observer	Period(s)	Number obs.
Finnmark & Troms	Langfjordjøkelen	54	-36	NVE	1998-	20
	Koppangsbreen	205	-38	NVE	1998-	16
	Sydbreen	257	-24	NVE	2007-	11
	Steindalsbreen	288	-45	NVE	1998-	16
Nordland	Storsteinsfjellbreen	675	NM	NVE	2006-	10
	Rundvassbreen	941	-20	SISO	2011-	6
	Engabreen	1094	-140	S	1903-	86
	Skjelåtindbreen	1272	NM	NVE	2014-	1
	Trollbergdalsbreen	1280	NM	NVE	2010-	4
	Austre Okstindbreen	1438	NM	NVE	1908-44, 2006-	26
	Corneliusenbreen	1439	NM	NVE	2006-	8
Sunnmøre & Breheimen	Trollkyrkjebreen	1804	-22*	NVE	1944-74, 2008-	21
	Heimsta Mårådalsbreen	2430	NM	NVE	2002-	5
Jostedalbreen	Fåbergstolsbreen	2289	+1	NVE	1899-	113
	Nigardsbreen	2297	-81	NVE	1899-	108
	Haugabreen	2298	-16	NBM	1933-41, 2013-	13
	Brenndalsbreen	2301	-55*	NVE	1900-62, 1964-65, 1996-	81
	Tuftebreen	2308	-33	NVE	2007-	11
	Austerdalsbreen	2327	-35	NVE	1905-19, 1933-	98
	Vetle Supphellebreen	2355	-6	NBM	1899-44, 2011-	43
	Stigaholtbreen	2480	+2	NVE	1903-	112
Jotunheimen	Juvfonne	2597	-61	NVE	2010-	6
	Styggebreen	2608	-22	NFS	1951-63, 2011-	16
	Storjuvbreen	2614	-22	NVE	1901-07, 08-12, 33-61, 97-	58
	Storbreen	2636	-28	NVE	1902-	80
	Leirbreen	2638	-46	NVE	1907-77, 1979-	59
	Bøverbreen	2643	-92	NVE	1903-76, 1997-	43
	Styggedalsbreen	2680	-15	NVE	1901-	97
	Mjølkedalsbreen	2717	-35**	BL	1978-	23
	Koldedalsbreen	2734	-40***	BL	1978-	14
	Hellstugubreen	2768	-16	NVE	1901-	79
Hardanger	Midtdalsbreen	2964	-21	AN	1982-	36
	Rembesdalskåka	2968	-19	S	1917-	43
	Botnabrea	3117	NM	GK	1996-	15
	Gråfjellsbrea	3127	-125	S	2002-	14
	Buerbreen	3131	-20	NVE	1900-	71
	Bondhusbrea	3133	+5	S	1902-	87
	Svelgjabreen	3137	-25	SKL	2007-	10
	Blomstølskardsbreen	3141	-29	SKL	1994-	19

* – two years, ** – three years, *** – four years,

NM – not measured in 2018

Observers other than NVE:

SISO Siso Energi

S Statkraft

NBM Norsk Bremuseum & Ulltveit-Moe senter for klimaviten, Fjærland

NFS Norsk fjellsenter, Lom

BL Birger Løvland, Eidsbugarden

AN Prof. Atle Nesje, University of Bergen

GK Geir Knudsen, Tyssedal

SKL Sunnhordland Kraftlag

Revision of the length change record for Stigaholtbreen

Background

Stigaholtbreen is a southern outlet from northern Jostedalbreen. The glacier area is 12.5 km², it spans the elevation interval between 819 and 1773 m a.s.l., and it is about 8.5 km long (Andreassen et al, 2012). Glacier length change measurements at Stigaholtbreen started in 1903 (Rekstad, 1904). This record is one of the longest continuous records in Norway spanning 112 years in 2018. When Winsvold et al. (2014) compared glacier changes identified in Landsat satellite images to this length change record, the discrepancy was considerable. As the original reference marks from 1903 were located in 2018, a revision of the length change record was possible.

Ideally, cumulative glacier length change should agree with distance between mapped glacier termini, and the cumulative glacier length should be the same in years when the glacier terminus is located in the same position. Some differences must be expected and are due to how representative the measuring line is and the changing shape of the glacier tongue, as well as different dates of maps and photos (mainly obtained in summer) and glacier length observations (mainly performed in autumn). However, the difference between cumulative length change measurements and surveyed or photographed changes at Stigaholtbreen was considerable. To resolve this, the supplementary information has been analysed, and the glacier length change record of Stigaholtbreen has been revised.

Length change observations

The annual measurements have been carried out using traditional methods. Cairns or other marks were used as fixed points, and distances have been measured using a tape measure or electronic distance meter in defined directions to the glacier boundary.

1903-1932: Two reference points (STEG_M1 and STEG_M2) were established in 1903, and the distance from one of them (STEG_M2, close to the river, Fig. 12-5) was reported as 28.8 metres (Rekstad, 1904; Fig 12-6 for locations). From 1907, the annual length change was reported for two lines, a central line (probably from STEG_M2) and a western line (probably not from STEG_M1) (Rekstad, 1911). According to the annual reports from Bergen Museum, the glacier front advanced 37 metres between 1903 and 1910, retreated 93 metres from 1910 until 1922, and advanced again 45 metres from 1922 to 1932. The net change between 1903 and 1932 was a retreat of 11 metres. As the reported advance between 1903 and 1910 exceeded the distance from M2 to the glacier in 1903, the original cairn next to the marks probably was destroyed. However, the mark carved into the rock face was preserved.

1932-1996: Since 1932 the original observer's reports have been available. The central line close to the river was abandoned in 1932. As the glacier retreated up-valley, new reference marks (probably cairns) were established along the western line. The measured distance from reference marks to the glacier could be as long as 400 metres in steep terrain. The cumulative length change from 1932 to 1996 is reported as -1021 metres. The retreat rate was fairly slow between 1932 and 1938 (-6 m/year), but much higher between 1938 and 1972 (-43 m/year). Between 1972 and 1996 the retreat rate slowed again (-6 m/year).

1996-2018: Stigaholtbreen advanced 31 metres between 1996 and 2000. Since 2000, the glacier has retreated about 220 metres. Two reference points (STEG89 and STEG07) established in 1989 and 2007 have been used, and their locations are known (Fig. 12-6).



Figure 12-5
Stigaholtbreen on 1st August 2018. The reference point STEG_M2 is located within the red circle.
Photo: Hallgeir Elvehøy.

Summary of available maps and aerial vertical photographs

1945: Aerial photographs taken on 9th September 1945 (RAF).

1966: National topographic maps (1:50000) constructed from aerial photographs taken on 19th July 1966.

1993: National topographic maps (1:50 000) constructed from aerial photographs taken on 23rd August 1993.

2005: Ortho-rectified aerial photographs taken 10th September 2005.
(www.norgebilder.no).

2010: Ortho-rectified aerial photographs taken 29th September 2010
(www.norgebilder.no).

Ground-based photography

In July 1971 the terminus of Stigaholtbreen was at a bedrock threshold (Fig. 12-6). In 1966 the terminus was downstream of this cliff.



Figure 12-6
Stigaholtbreen in July 1971. Photo: Arve M. Tvede.

Method

Reports from the observers (1932 to present) are checked against the length change record. The mapped front positions (1945, 1966, 1993, Fig 12-7) were plotted on a line defined by STEG_M2 and STEG89 representing a central flow line on the western bank of the river. The different periods were evaluated. Where calibration was needed, the annual length changes were adjusted linearly using the ratio of the distance between mapped termini to the corresponding cumulative length change.

Results

There are some discrepancies between the reported length change series and the observations. In 1960 the reported distance 208 m indicated an advance of 15 m but the reported length change was -60 m. In 1961 the reported distance was 300 m, and the reported length change was -17 m, indicating that the correct distance in 1960 was 283 metres. This discrepancy was probably sorted out without being recorded in the files. In 1970 the reported length change was -116 m, but the reported distances indicate -97 metres. This discrepancy is corrected here.

In the observer's reports from 1932 to 1935 the central reference mark was referred to as the cross, probably referring to the cross carved into a rock face at STEG_M2 in 1903. This implies that the original mark from 1903 was used. As the reported net length change between 1903 and 1932 is only -11 metres, the record from 1903 to 1932 is probably correct.

The measurements between 1932 and 1946 were referenced to the same reference mark (neither STEG_M2 nor STEG_M1), and the retreat rate was moderate (-17 m/year). The horizontal distance between STEG_M2 and the terminus position in 1945 (250 m) corresponds fairly well to the length changes between 1903 and 1945 (-204 m). Hence, the record between 1932 and 1946 is assumed to be correct. The difference in distance from

STEG_M2 between 1945 and 1966 is 540 metres in contrast to the cumulative length change from 1945 to 1966 of 807 metres. Consequently, the period 1946-66 was calibrated (Tab. 12-2). The difference in distance from STEG_M2 between 1966 and 1993 is 300 metres in contrast to the cumulative length change from 1966 to 1993 of 620 metres. The position of the reference marks used since 1989 is known. The distance from STEG89 to the mapped terminus position from 1993 corresponds to distances measured on the ground

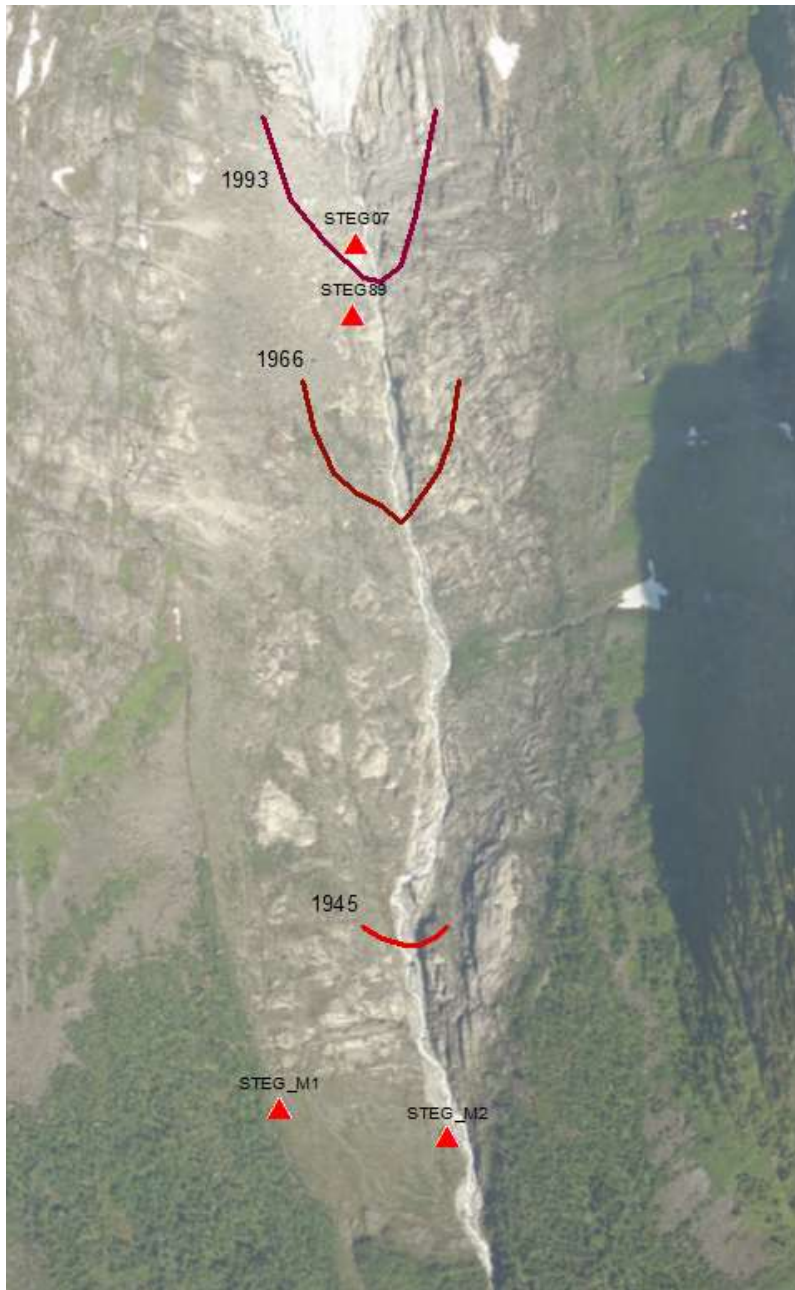


Figure 12-7
Orthophoto from September 2017 showing glacier front positions from 1945, 1966 and 1993, and known reference points. The distance from STEG_M2 to the glacier terminus in 2017 was 1290 metres.
Orthophoto: www.norgeibilder.no.

within acceptable limits when differences in dates of observation are considered. Hence, the record between 1989 and 1993 is probably correct. A reference point established in 1972 (STEG72) was used until 1989. The exact location of this reference point is unknown,

but the cumulative length change between 1972 and 1989 is fairly small (−107 metres), and the period 1972 – 1989 is assumed correct. Consequently, the period from 1966 to 1972 was calibrated (Tab. 12-2). After 1993 the distances from reference marks to geo-located terminus positions correspond to ground measured distances within acceptable limits when differences in dates of observation are considered. Hence, the record since 1993 is assumed to be correct.

Table 12-2
Differences between the original length change record and mapped front positions.

	Original length change (m)	Map change (m)	Correction (m)	Corrected period
1945 – 1966	−807	−540	267	1946 – 1966
1966 – 1993	−620	−300	320	1966 – 1972

The original and revised cumulative glacier length change is shown in Figure 12-8. The advancing and retreating periods are unchanged, but the amount of change has been adjusted to match the distance between mapped or otherwise known front positions. The revised length change record is available at www.nve.no/glacier.

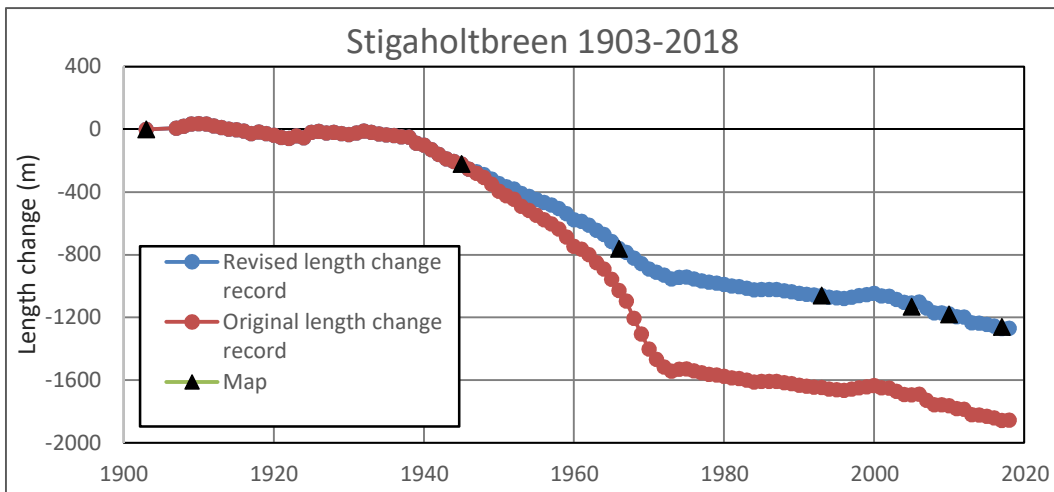


Figure 12-8
Original and revised glacier length change record for Stigaholtbreen between 1903 and 2018.

12.2 Jøkulhlaups

Jøkulhlaups or Glacier Lake Outburst Floods (GLOFs) were registered at eight glaciers in Norway in 2018. However, four of the events were observed on satellite images only, and would not have been observed by conventional means. Hence, the high number of events this year should not necessarily be taken as an increase in frequency.

Events were observed at Rundvassbreen, Rembesdalskåka, Frostisen and Tystigbreen. Satellite images show that jøkulhlaups probably also occurred at Marabreen, Sandåbreen, Fortundalsbreen and Vestre Memurubreen, but there are no ground-based observations of these events.

Blåmannsisen (Rundvassbreen)

A jøkulhlaup occurred at Rundvassbreen, a northern outlet glacier of the Blåmannsisen icecap east of Fauske in northern Norway. About 22 million cubic metres of water drained under the glacier in late August.

Several previous events of a similar magnitude have been recorded from this glacier (Jackson and Ragulina, 2014). The first known jøkulhlaup was in September 2001, when 35 million cubic metres of water from Messingmalmvatnet, a glacier-dammed lake suddenly emptied under the glacier and subsequently to the hydropower reservoir Sisovatnet. Previously the water had drained over a rock sill and flowed into a river in Sweden (Engeset et al., 2005). The next event occurred four years later, in 2005, and was approximately the same volume of water but did not occur until one year after Messingmalmvatnet had refilled to the pre-jøkulhlaup level. Subsequent events occurred when the lake was less than full, and at shorter intervals between events. The next jøkulhlaup from a full lake occurred in 2014, and was the first time in nine years that there was a jøkulhlaup of a similar volume to the 2001 and 2005 events (Jackson and Ragulina, 2014). It was then two years until the next event in September 2016. The most recent event was also two years after the previous event. Four of the eight repeat-events have occurred after a two-year interval. All recorded events from Blåmannsisen have been in late summer, i.e. August or September (Tab. 12-3).

Table 12-3
Dates and approximate volumes of jøkulhlaups from Blåmannsisen. The volume in 2001 was estimated from the change in volume of water in the reservoir Sisovatnet.

Year	Date	Water volume	Water level before event
2001	5 th – 7 th September	35 mill. m ³	full (1053 m a.s.l.)
2005	27 th – 29 th August	35 mill. m ³	full (1053 m a.s.l.)
2007	29 th August	20 mill. m ³	~ half-full
2009	6 th – 7 th September	20 mill. m ³	~ half-full
2010	8 th – 17 th September	11 mill. m ³	less than half-full
2011	22 nd September	12 mill. m ³	less than half-full (ca. 1029 m a.s.l.)
2014	10 th – 12 th August	35 mill. m ³	full (probably 1053 m a.s.l.)
2016	28 th – 29 th September	26 mill. m ³	> half-full (ca. 1040.7 m a.s.l.)
2018	25 th – 26 th August	22 mill. m ³	> half-full (ca. 1039.8 m a.s.l.)

The most recent event occurred on 25th August 2018. The water level before the event was about 1039.8 m a.s.l. About 11 a.m. on 25th August, there were observations of “some” water in the glacier river. Six to seven hours later, there was significant discharge in the glacier river. The hydropower company have a video recording of the situation at this time. By morning of 26th, the discharge in the glacier river appeared to be back to normal. The water level measured after the event was 1007.3 m a.s.l., hence the water level sank by 32.5 m, and the volume of this event was approximately 22 million m³. Figure 12-9 shows change in water level in the hydropower reservoir Sisovatn, as well as change in the input to the reservoir.

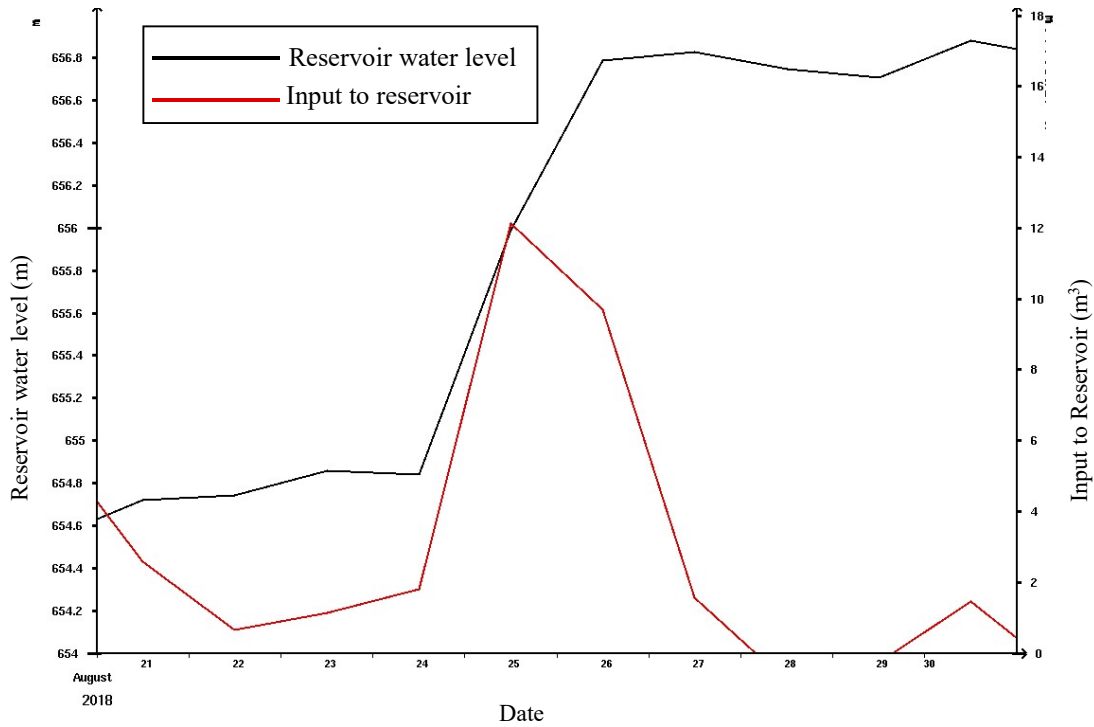


Figure 12-9
Changes in water level in the Sisovatn reservoir (left axis) and calculated input to the reservoir during the event (right axis). Source: Siso Energi AS.

Rembesdalskåka (Hardangerjøkulen)

It was observed that the glacier-dammed lake, Demmevatnet, was empty on the morning of 11th August 2018 (Fig. 12-10). The hydropower company noted that the water level in the hydropower reservoir downstream from the glacier, Rembesdalsvatnet, had increased considerably during the night of 10th August. There have been many previous events from this glacier-dammed lake, some of them causing extensive damage, and tunnels were constructed to alleviate the danger. Between 1938 and 2014 there were no events, but due to glacier thinning the water is now able to escape under the glacier again and there have been five recorded events between 2014 and 2018. The volume that drained in this latest event is not known, but probably similar to previous events since 2014 of 1.4 to 1.9 million cubic metres, and thus significantly smaller than events that occurred in the 1890s that had calculated volumes of 35 million m³ (Liestøl, 1956).



Figure 12-10
The drained lake after the jökulhlaup in August 2018. Photo: Hans Otto Kaltenborn, DNT.

Frostisen (BreID: 752)

Reports of high discharge on 5th – 6th August in a steep ravine called “Storrapet” that drains into the fjord Sør-Skjomen near Narvik in northern Norway, suggest a jökulhlaup occurred from Frostisen, the glacier that lies above the ravine. “Rap” is an alternative Norwegian word for landslide or avalanche. When Frostisen was larger, there were frequent icefalls down this ravine, occurring daily during the summer. The ice from these icefalls formed a regenerated glacier at the bottom of the ravine (Hoel and Werenskiold, 1962).

On the evening of 5th August, the water in the river in Storrapet was cloudy, and looked like it contained a lot of fine sediment. About 19:30 or 20:00, the water discharge suddenly increased, and there were also a lot of rocks and other sediment. The discharge decreased during the night of 6th August and throughout 7th, although discharge was still higher than normal on 8th August. Satellite images are inconclusive regarding the location of the glacier-dammed lake that drained and a possible source is a small lake at the margin of the glacier south of the peak Gangnesaksla. However, based on local topography and examination of satellite images available, a source north of Gangnesaksla is more plausible.

Tystigbreen (BreID: 2435)

Indication of a possible jökulhlaup was observed on Tystigbreen, a glacier complex in Stryn northeast of Jostedalbreen, by a skier on 26th June 2018. It is unknown when the event took place, but presumably in late spring or early summer. The location of the event was about 800-900 m south of an unnamed peak with height 1805 m a.s.l. (see Fig. 12-11). Aerial photographs from 2015 also show ice blocks in the same location and no water, suggesting that there has been at least one previous event.

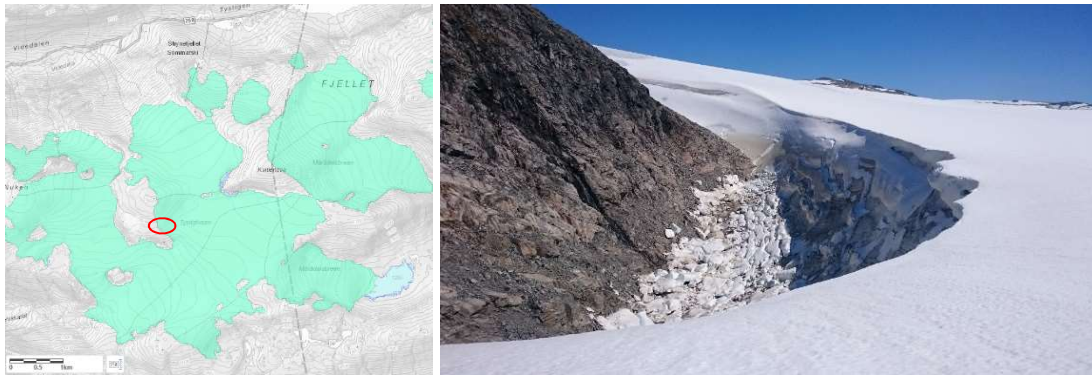


Figure 12-11
Location of 2018 event (left, marked by red oval) and the drained lake as seen in June 2018.
 Photo to right: Arve Tvede.

Events observed on satellite images only

Marabreen (BreID 2364)

An event is thought to have occurred from a glacier-dammed lake at the glacier Marabreen, a small outlet glacier at the southwestern edge of Jostedalsgreen, in summer 2018. The event was identified based on changes in Sentinel images from 26th July and 1st September (Fig. 12-12). Higher resolution images from Planet.com refine the period to 21st to 26th August. The water from this event would have drained to the hydropower reservoir Trollavatnet. Changes in the water level of the reservoir were analysed to see if the event could be observed, but the volume of the glacier-dammed lake is minimal compared with the volume of the reservoir and no clear evidence of the event was detected. However, significant rainfall was recorded on 23rd August, and this may have triggered an event.

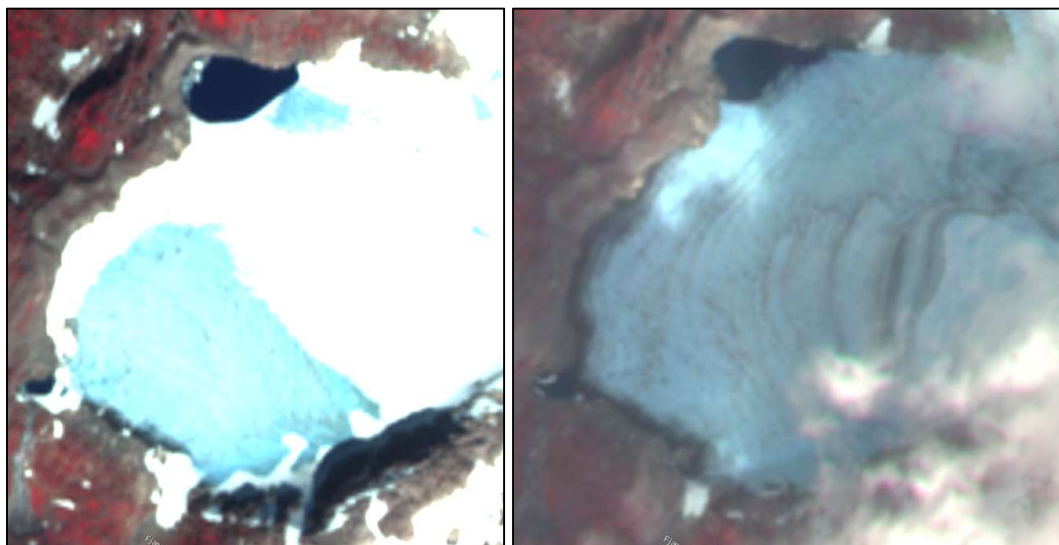


Figure 12-12
Sentinel satellite images showing a glacier-dammed lake north of Marabreen on 26th July (LHS) and 1st September (RHS).

Vestre Memurubreen (BreID: 2772)

Comparison of satellite images from 13th July and 28th July 2017 show that a small glacier-dammed lake south of the Vestre Memurubreen, a small glacier in Jotunheimen north of Gjende, may have drained in this period (Fig. 12-13). Examination of satellite images from 2017 suggest a previous event may have occurred between 20th July and 22nd August. There

is no hydrological station downstream of the glacier that could have detected increased discharge in this period, nor eyewitness records of an event.



Figure 12-13
Sentinel satellite images showing a glacier-dammed lake south of Vestre Memurubreen on 13th July (LHS) and 28th July 2018 (RHS).

Fortundalsbreen (BreID: 2505)

Fortundalsbreen is a glacier complex consisting of two glacier units and lies northeast of Harbardsbreen in Breheimen national park. On the east side of the northernmost glacier unit is a marginal lake called Heksegryta (Fig. 12-14). Satellite images from 13th and 26th June 2018 show there was a substantial decrease in the area of this glacier-dammed lake, and it presumably emptied under the glacier during this period. The area of the glacier lake before and after the event was 0.04 km² and 0.01 km² respectively. There are no active hydrological stations downstream so there is no corroborating evidence for this event. Examination of satellite images from 2017 suggest there may have been an event between 20th July and 22nd August.

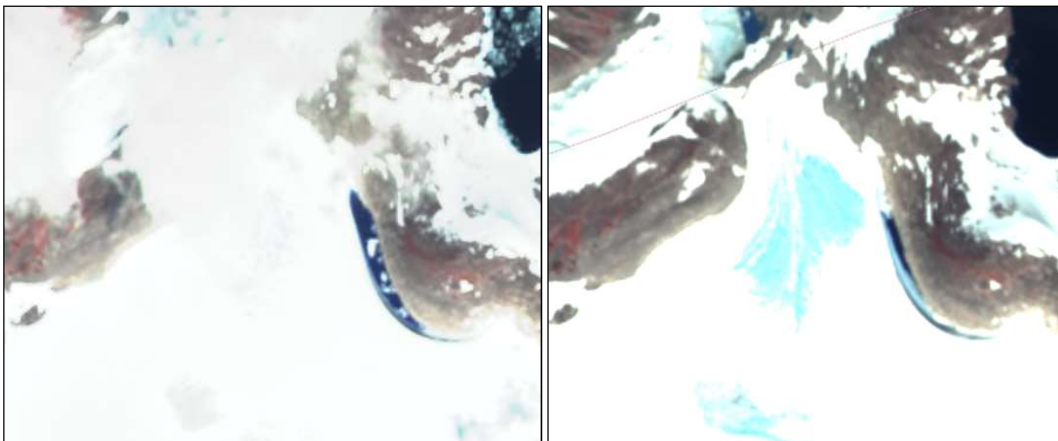


Figure 12-14
Sentinel images from 13th June (left) and 26th June (right) 2018.

Sandåbreen (BreID 2434)

Sandåbreen is a small glacier unit northeast of Jostedalsbreen. A glacier-dammed lake is visible to the north of the glacier, bounded by the mountain ridge Skridulaupen (Fig. 12-15). An aerial photo from 2010 shows no evidence of a lake, but it is clearly visible in 2015 (however, a very small water body was also visible in 2005). A comparison of satellite images from 20th July and 26th July 2018 show that the lake decreased in size from about 0.04 km² to 0.03 km². The water probably drained under the glacier, emerged on the southeast side and subsequently drained into the lake Rauddalsvatn. There are no active hydrological stations that could have recorded increased discharge from the event. A study of satellite images from previous years suggest that glacier lake drainage events may have occurred in 2016 and 2017 also (Nagy and Andreassen, 2019).

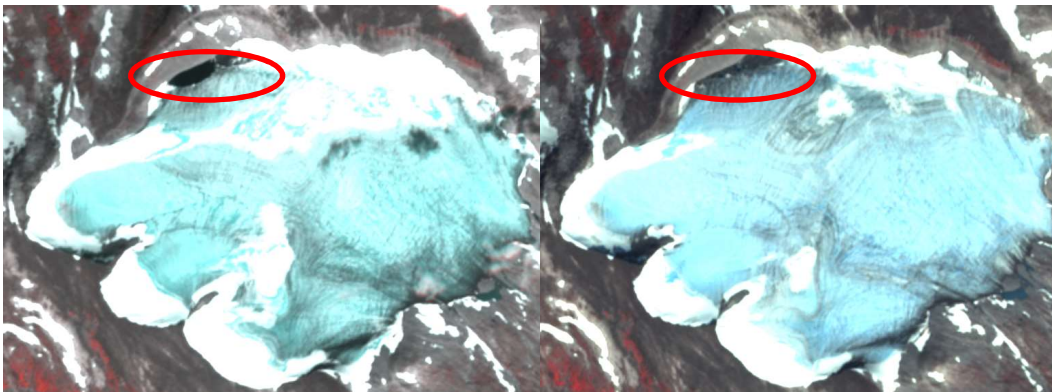


Figure 12-15
Sentinel images from 20th July (left) and 26th July (right) 2018. The red ellipse shows the glacier-dammed lake.

13. References

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Appendix A

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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 1949-2018. 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
Alfotbreen							
1 Alfotbreen	2078	61°45', 5°38'	4.0	890-1368	2010	1963-	56
2 Hansebreen	2085	61°44', 5°40'	2.8	927-1310	2010	1986-	33
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	1217-1660	1959	1963-68	6
			3.2	1232-1648	2013	2003-13	11
7 Gråfjellsbrea	3127	60°04', 6°24'	9.7	1034-1656	1959	64-68, 74-75	7
			8.1	1049-1647	2013	2003-13	11
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
Jostedalbreen							
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-	57
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-	31
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-	56
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-	70
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-	9
28 Hellstugubreen	2768	61°34', 8°26'	2.9	1482-2229	2009	1962-	57
29 Gråsubreen	2743	61°39', 8°37'	2.1	1833-2284	2009	1962-	57
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-	49
35 Storglombreen	⁵⁾	66°40', 13°59'	59.2	520-1580	1968	1985-88	4
			62.4	520-1580		2000-05	6
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	907-1366	1968	1970-75	6
			1.8	907-1369	1998	1990-94	5
Blåmannsisen							
40 Rundvassbreen	941	67°17', 16°03'	11.7	788-1533	1998	2002-04	3
			10.8	853-1527	2017	2011-17	7
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	926-1846	1960	1964-68	5
			5.9	969-1852	1993	1991-95	5
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	277-1053	1994	1989-93	5
			2.6	338-1043	2018	1996-	23

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



NVE

Norges vassdrags- og energidirektorat

MIDDELTHUNSGATE 29
POSTBOKS 5091 MAJORSTUEN
0301 OSLO
TELEFON: (+47) 22 95 95 95

www.nve.no