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Glaciological investigations in Norway 2019

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Cover photo: Juvfonne, a small ice patch in the Jotunheimen mountain massif.
The photo was taken on 27th August 2019 by Liss M. Andreassen.

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Abstract: Results of glaciological investigations performed at Norwegian glaciers in 2019 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.

Key words: Glaciology, Mass balance, Glacier length change, Glacier dynamics, Ice velocity, Meteorology, Jøkulhlaup, Subglacial laboratory.

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Glaciological investigations in Norway 2019

The Norwegian Water Resources and Energy Directorate (NVE)
2020

Contents

Preface

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

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

The report is published in English with a summary in Norwegian. The purpose of this report is to provide a joint presentation of the glacier investigations and calculations made mainly by NVE's Section for Glaciers, Ice and Snow during 2019. 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, September 2020

Hege Hisdal
Director,
Hydrology Department

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

In memory of Gunnar Østrem
(1922-2020)

Gunnar Østrem in Jotunheimen in summer 1959.

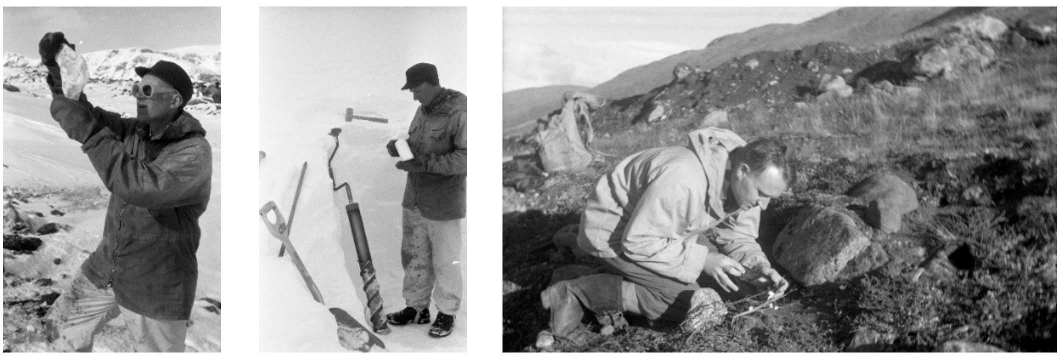
Gunnar Østrem (1922-2020)

Gunnar Østrem was born on 22nd March 1922 and died on 12th January 2020, almost 98 years old. Gunnar Østrem was an extraordinary, enthusiastic, inspiring and creative glaciologist and leader. In 1962 he established the Glacier section ("Brekontoret") at the Norwegian Water Resources and Energy Directorate (NVE), whose main task was to establish a network of mass balance measurements in Norway to aid in the planning of hydropower plants. Gunnar made a significant contribution to the development of methods for measuring mass balance. He co-authored "Glacier mass balance measurements: A manual for field and office work', which became the standard reference for mass balance measurements. Due to his experience he was invited to Canada to establish a Canadian network of glacier mass balance investigations. He took on several international assignments for UNESCO and others organisations in India, Chile, Turkey, Argentina, and elsewhere. Østrem was appointed professor in physical geography at the University of Stockholm, and was visiting professor at Carleton University in Ottawa.

Østrem's scientific production was considerable. He was author or co-author of about 80 scientific articles or publications – eight of them after his retirement – and the last one was published in 2006. After he retired, he continued to attend scientific meetings and inspired many students to work in glaciology. Gunnar Østrem received the Norwegian honour "The King's Medal of Merit" in gold for his achievements. He also received the Hans Egede medal of the Royal Danish Geographical Society and Sweden's Royal Academy of Science J. A. Wahlberg silver medal. He was made an honorary member of the International Glaciological Society in 2001.

Gunnar's 85th birthday in 2007 was celebrated at NVE with a half-day glacier symposium, which took place on 22nd March, World Water Day. Gunnar himself started the proceedings with a captivating presentation of his work in Canada in the 1960s establishing mass balance measurements. He enchanted the audience for 40 minutes with his speech and many fascinating anecdotes from his time there. In real Østrem fashion ice cream and sweets were served in the coffee break. In 2012 he was an active participant in the organising committee for the 50th anniversary of "Brekontoret", the glacier section, at NVE.

We in NVE are proud and grateful to have had Gunnar Østrem as colleague and friend over several decades. He had a lifelong interest in glaciology and was an inspiration to all of us. This issue of the "Glasiologiske undersøkelser i Norge/Glaciological Investigations in Norway" report series is dedicated to Gunnar.



Gunnar Østrem doing fieldwork in Jotunheimen in the early 1960s.

Summary

Mass balance

Mass balance investigations were performed on eleven glaciers in Norway in 2019.

The winter balance for all six reference glaciers (mass balance series back to at least 1981) in southern Norway was lower than the 1981-2010 average. In northern Norway, Engabreen had a greater winter balance than the 1981-2010 average. Gråsubreen in Jotunheimen had the lowest relative winter balance with 34 % of the reference period average and Hellstugubreen had its lowest winter balance (0.6 m w.e.) since measurements started in 1962.

The summer balance was greater than the 1981-2010 average for all seven reference glaciers. Gråsubreen had the greatest relative summer balance with 169 % of the reference period average.

Consequently, the annual balance was negative for all six reference glaciers in southern Norway, and of these six, Ålfotbreen had the greatest deficit with −2.4 m w.e. Hansebreen had the greatest deficit of all measured glaciers in Norway with −3.0 m w.e. and Hellstugubreen and Gråsubreen had their third greatest deficits since measurements started in 1962. Engabreen had a positive mass balance at 0.8 m w.e.

Glacier length change

Glacier length changes were measured at 26 glaciers in southern Norway and 10 glaciers in northern Norway. All 36 glaciers showed a decrease in length. The greatest retreats were observed at Gråfjellsbrea (82 m) and Nigardsbreen (81 m).

Sammendrag

Massebalanse

I 2019 ble det utført massebalansemålinger på 11 breer i Norge – to i Nord-Norge og ni i Sør-Norge.

For alle seks referansebreene (de breene som har massebalanseserie tilbake til 1981 eller lengre) i Sør-Norge ble vinterbalansen mindre enn gjennomsnittet for referanseperioden 1981-2010. I Nord-Norge hadde Engabreen større vinterbalanse enn gjennomsnittet. Gråsubreen i Jotunheimen hadde relativt minst vinterbalanse med 34 % av referanse-perioden og Hellstugubreen fikk den minste vinterbalansen (0.6 m v.ekv.) siden målingene startet i 1962.

Sommerbalansen ble større enn gjennomsnittet for alle sju referansebreene. Gråsubreen hadde relativt størst sommerbalanse med 169 % av referanseperioden.

Som en konsekvens av lite snø og mye smelting ble det negativ massebalanse for alle seks referansebreene i Sør-Norge, og av disse seks breene hadde Ålfotbreen størst underskudd med −2,4 m v.ekv. Hansebreen hadde det største underskuddet av alle de målte breene med −3,0 m v.ekv. Hellstugubreen og Gråsubreen hadde det tredje største underskuddet som er målt siden målingene startet i 1962. Engabreen fikk positiv massebalanse med 0,8 m v.ekv.

Lengdeendringer

Lengdeendringer ble målt på 26 breer i Sør-Norge og 10 breer i Nord-Norge. Alle 36 bre-utløperne hadde tilbakegang. Størst tilbakegang ble målt på Gråfjellsbrea (82 m) og Nigardsbreen (81 m).

1. Glacier investigations in Norway 2019

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.

ADP
Acoustic Doppler Profiler is a hydroacoustic current meter generally used to measure water current velocities over a depth range using the Doppler effect of sound waves scattered back from particles within the water column.

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

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

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

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

Density
In this report *density* means the ratio of the mass of snow, *firn* or ice to the volume that it occupies. The *snow density* is measured annually during snow measurements in April/May. *Firn density* is measured occasionally during ablation measurements in September/October. *Ice density* is not measured but estimated as 900 kg m^{-3}.

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

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

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

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

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

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

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

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

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 on Norwegian glaciers have generally remained unchanged over the years, although the number of measurements has varied (Andreassen et al., 2016). With the experience gained from many years of measurements, the measurement network was simplified on individual glaciers at the beginning of the 1990s.

Winter balance

The winter balance is normally measured in April or May by probing to the previous year's summer surface along regular profiles or grids. Stake readings are used to verify the soundings where possible. Since the stakes can disappear during particularly snow-rich winters, and since it is often difficult to distinguish the summer surface (S.S.) by sounding alone, snow coring is also used to confirm the sounding results. Snow density is measured in pits at one or two locations at different elevations on each glacier (Fig. 1-1).

Figure 1-1
Snow density measured on Storbreen in May 2019. Photo: Liss M: Andreassen.

Summer and annual balance

Summer and annual balances are obtained from measurements of stakes and towers, usually performed in September or October. Below the elevation of a 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, depending on the age, is 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 2019 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 57 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 0.7 m w.e. Storbreen in Jotunheimen has the longest series of all glaciers in Norway with 71 years of measurements, while Engabreen at Svartisen has the longest series (50 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 2019 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. (2020).

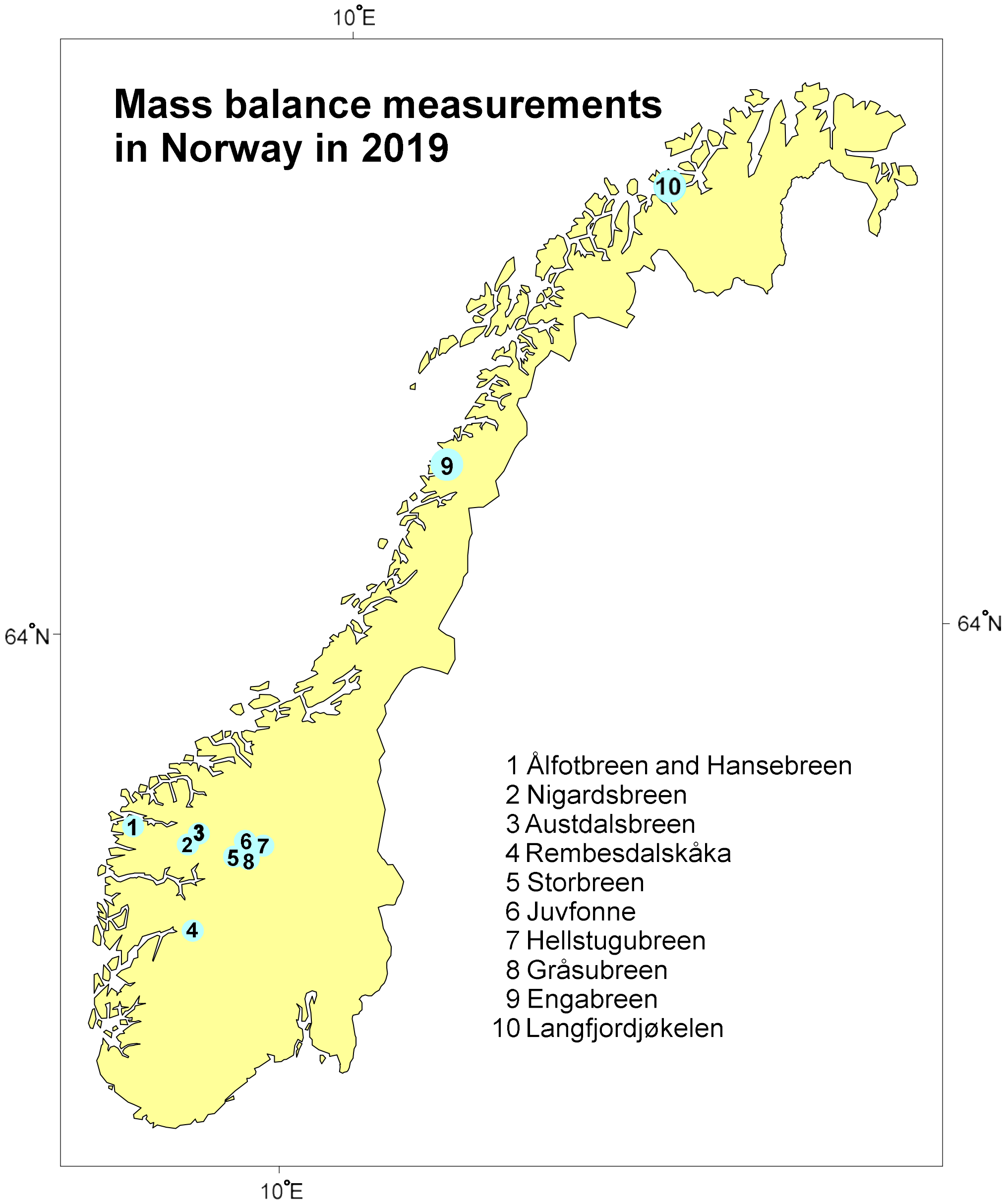


Figure 1-2
Location of the glaciers at which mass balance studies were performed in 2019.

Mass balance studies performed on Norwegian glaciers in 2019 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 winter season 2018/19 started with a snow-rich October in western Norway. The following months November and December were mild with little snow over most of the country. In southern Norway the rest of the winter was mild with little snow. However, in northern Norway the weather was cold and snow-rich from January to the end of March.

Snow accumulation and winter balance

The winter balance for all six reference glaciers in southern Norway was lower than the average of the reference period 1981-2010. Engabreen in northern Norway had a greater winter balance than average with 134 %. Gråsubreen had the lowest relative winter balance with 34 % of the reference period value. Hellstugubreen had its lowest winter balance (0.6 m w.e.) since measurements started in 1962.

Summer weather

The summer season was warm from June to September over most of the country. The exception was Finnmark in northern Norway where June was rather cool.

Ablation and summer balance

The summer balance was greater than the 1981-2010 average for all seven reference glaciers. Gråsubreen had the greatest relative summer balance with 169 % of the reference period average.

Annual balance

The annual balance was negative for all six reference glaciers in southern Norway, and of these, Ålfotbreen had the greatest deficit with −2.4 m w.e. Hansebreen had the greatest deficit of all measured glaciers with −3.0 m w.e. Hellstugubreen and Gråsubreen had the third greatest deficit since measurements started in 1962. Engabreen had a positive mass balance at 0.8 m w.e.

The results from the mass balance measurements in Norway in 2019 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, winter and annual balance of the northernmost glaciers, Langfjordjøkelen and Engabreen, are better correlated with AO than NAO (Andreassen et al., 2020). For the glaciers in southern Norway, the correlations are similar for NAO and AO, and reduced with distance to the coast (Rasmussen, 2007; Andreassen et al., 2020).

In winter 2018/2019 (December-March) NAO and AO were positive (0.574 and 0.243 calculated from monthly means, source: http://www.cpc.ncep.noaa.gov/). Comparing the period 1989-2019 (31 years) shows that the most positive NAO and AO years were in the period with mass surplus from 1989 to 1995 and also several recent years, in particular 2012, 2014 and 2015 (Fig. 1-3).

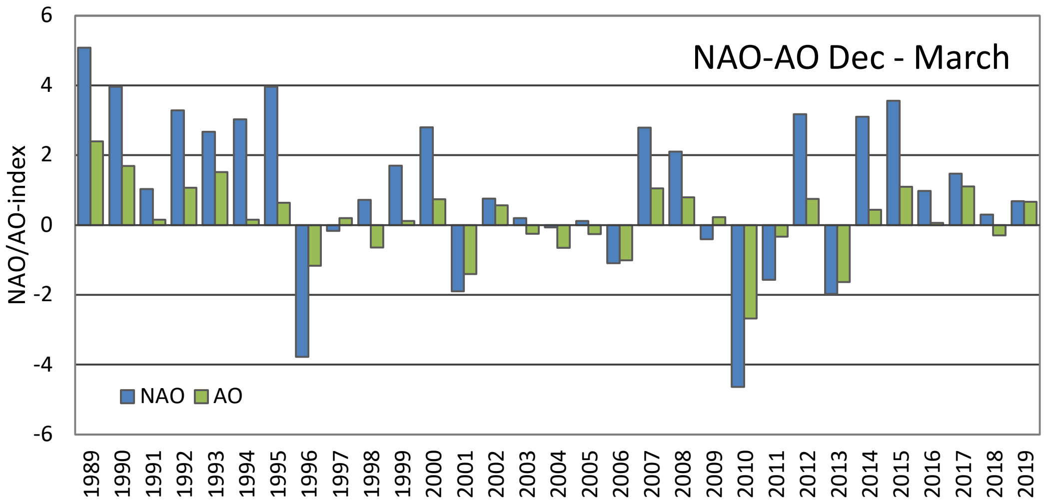


Figure 1-3
NAO and AO index for December–March for 1989–2019. NAO and AO data were downloaded from the NOAA Center for Weather and Climate Prediction (http://www.cpc.ncep.noaa.gov/). Figure updated and modified from Andreassen et al. (2020). The large-scale circulation indices NAO and AO are in units 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 2019. 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	1963-19	4.0	890-1368	2.38	64	−4.82	126	−2.44	−0.08	>1368	0
Hansebreen	1986-19	2.8	927-1310	2.04	[1)]60	−5.05	[1)]124	−3.01	[1)]−0.67	>1310	0
Nigardsbreen	1962-19	46.6	330-1952	2.04	91	−2.31	105	−0.27	0.06	1580	62
Austdalsbreen	1988-19	10.1	1200-1740	1.58	[2)]72	[3)]−2.87	[2)]105	−1.29	[2)]−0.55	>1740	0
Rembesdalskåka	1963-19	17.3	1066-1854	1.78	83	−2.61	121	−0.82	−0.02	1761	39
Storbreen	1949-19	4.9	1420-2091	1.02	69	−2.54	139	−1.52	−0.33	2005	3
Juvfonne[4)]	2010-19	0.1	1852-1985	1.31		−1.53		−0.22			
Hellstugubreen	1962-19	2.7	1487-2213	0.60	54	−2.47	163	−1.87	−0.39	>2213	0
Gråsubreen	1962-19	1.7	1854-2277	0.27	34	−1.96	169	−1.69	−0.37	undef.	
Engabreen	1970-19	36.2	111-1544	3.45	134	−2.66	103	0.79	−0.01	1091	76
Langfjordjøkelen	1989-93 1996-19	3.7 2.6	280-1050 338-1043	2.51	[5)]122	−2.89	[5)]96	−0.38	[5)]−0.96	undef.	

[1)]Calculated for the measured period 1986-2018
[2)]Calculated for the measured period 1988-2018
[3)]Contribution from calving amounts to −0.21 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 1996-2018

Figure 1-4 presents the mass balance results in southern Norway for 2019. The west-east gradient is evident for both winter and summer balances. The results for 2019 show a negative mass balance for all eleven measured glaciers in Norway.

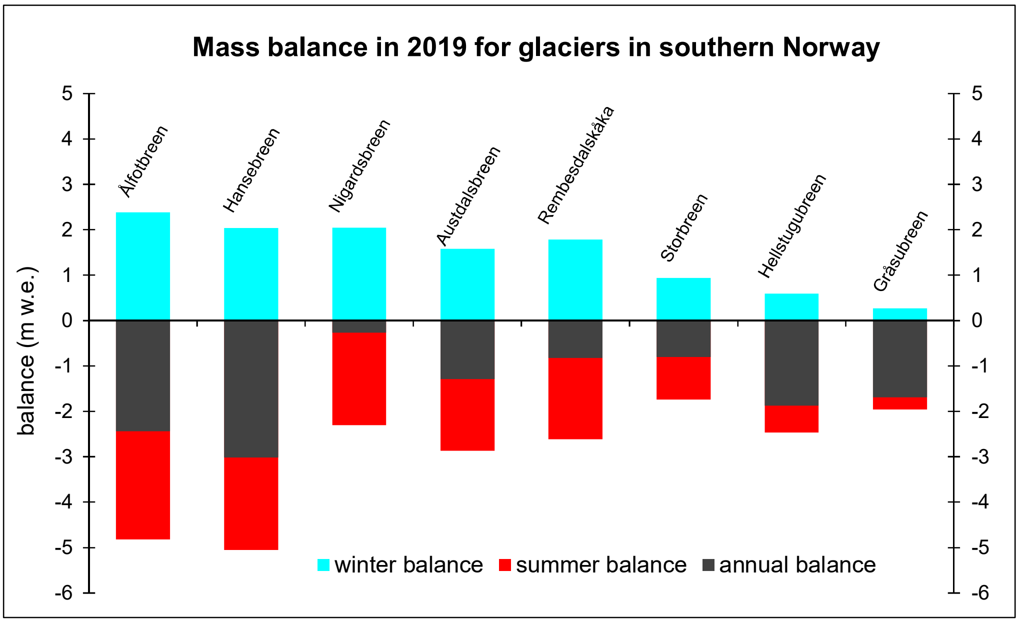


Figure 1-4
Mass balance in 2019 in southern Norway. The glaciers are listed from west to east.

The cumulative annual balance for the six reference glaciers in southern Norway for the period 1963-2019 is shown in Figure 1-5. 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 1963-2019.

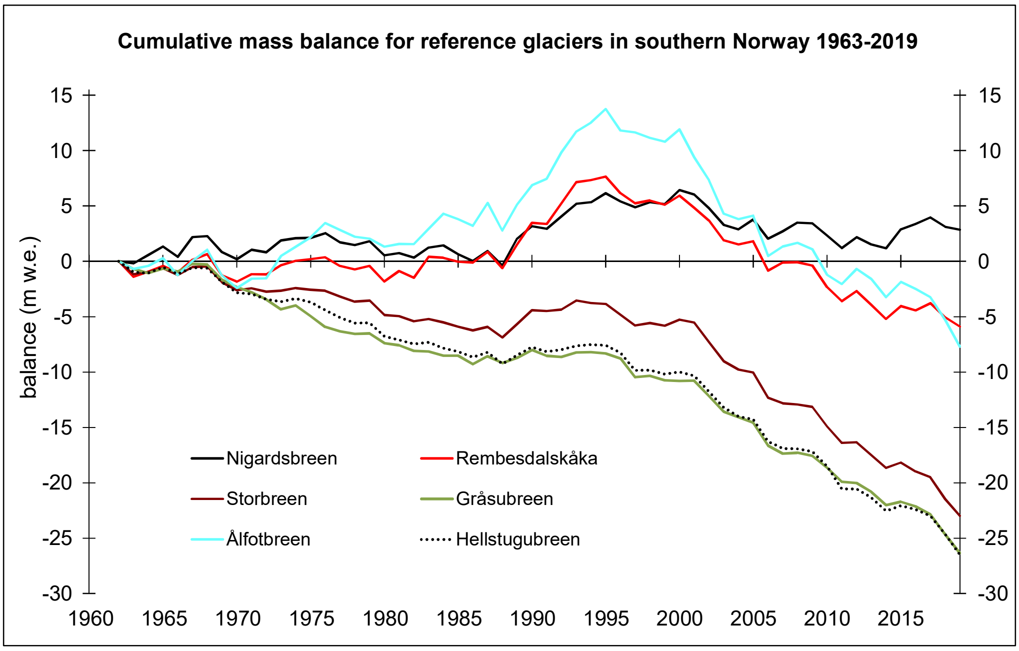


Figure 1-5
Cumulative mass balance for the six reference glaciers in southern Norway, Ålfotbreen, Nigardsbreen, Rembesdalskåka, Storbreen, Hellstugubreen and Gråsubreen, for the period 1963-2019.

1.2 Other investigations

Glacier length change measurements were performed at 36 glaciers in Norway in 2019. 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 2019. Glacier velocity was also measured at Ålfotbreen and Hansebreen (chap. 2), Nigardsbreen (chap. 3) and Langfjordjøkelen (chap. 11) for the period 2018-2019.

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). Pressure at the base of the glacier is measured but due to equipment malfunction there were limited data for 2019.

Some jøkulhlaups (glacier floods) have occurred in 2019 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 km^2 (2010) and is one of the westernmost and most maritime glaciers in Norway. Mass balance studies are performed on two adjacent north-facing outlet glaciers – Ålfotbreen (4.0 km^2,) and Hansebreen (2.8 km^2) (Fig. 1-2). The westernmost of these two has been the subject of mass balance investigations since 1963, and has always been reported as Ålfotbreen. The adjacent glacier east of Ålfotbreen has been given the name Hansebreen, and has been measured since 1986. None of the outlet glaciers from the icecap are given names on the official maps. Glaciological investigations in 2019 include mass balance and surface ice velocity.

Figure 2-1
Ålfotbreen (right) and Hansebreen (left) photographed on 25th September 2019. Photo: Bjarne Kjøllmoen.

2.1 Mass balance 2019

Fieldwork

Snow accumulation measurements were performed on 20th May and the calculation of winter balance was based on measurement of stakes in six different positions and 71 snow depth soundings on Ålfotbreen, and stakes in six different positions and 55 snow depth soundings on Hansebreen (Fig. 2-2). Comparison of stake readings and snow soundings indicated no significant melting after the ablation measurements in October 2018. The sounding conditions were good over the whole glacier and the summer surface could easily be detected. Generally, the snow depth varied between 3.5 and 5.0 m on Ålfotbreen, and between 2.5 and 4.5 m on Hansebreen. Snow density was measured in one location (pos. 28, 1200 m a.s.l.), applicable for both glaciers. The mean snow density of 3.9 m snow was 565 kg m^{-3}. The measured mean snow density for the twenty- year period 1999-2018 was 522 kg m^{-3}.

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

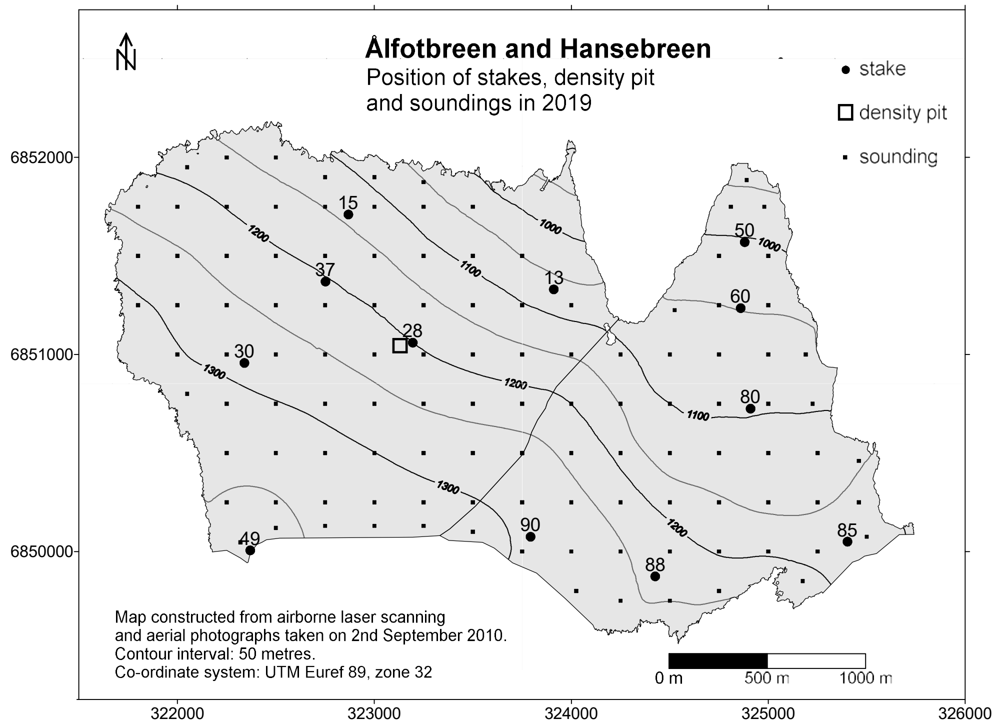


Figure 2-2
Location of stakes, soundings and snow pit at on Ålfotbreen (left) and Hansebreen (right) in 2019.

Ablation was measured on 25th September. The annual balance was measured at stakes in five positions on Ålfotbreen and six positions on Hansebreen (Fig. 2-2). At the time of the ablation measurements only a little (<10 cm) fresh snow had fallen.

Results

The calculations are based on the DTM from 2010.

All height intervals are represented with point measurements (b_w) for both glaciers. However, measurements below 1000 m a.s.l. on Hansebreen and 1050 m a.s.l. on Ålfotbreen are sparse.

The winter balance was calculated as a mean value for each 50- m height interval and was 2.4 ±0.2 m w.e. at Ålfotbreen, which is 64 % of the mean winter balance for the reference period 1981-2010. The winter balance on Hansebreen was calculated as 2.0 ±0.2 m w.e., which is 60 % of the mean winter balance for the measurement period 1986-2018. Spatial distribution of the winter balance at Ålfotbreen and Hansebreen is shown in Figure 2-3.

The density of melted firn was assumed to be 750 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 −4.8 ±0.3 m w.e. on Ålfotbreen, which is 126 % of the reference period. The summer balance on Hansebreen was −5.1 ±0.3 m w.e., which is 124 % of the mean winter balance for 1986-2018.

Hence, the annual balance was negative for both glaciers. Ålfotbreen had a deficit of 2.4 ±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 (2010-2019), the mean annual balance was −0.88 m w.e. and eight of those years had a negative annual balance. The annual balance at Hansebreen was −3.0 ±0.4 m w.e. The mean value for the measurement period 1986-2018 is −0.67 m w.e. Over the last ten years the mean annual balance was −1.39 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 2-4.

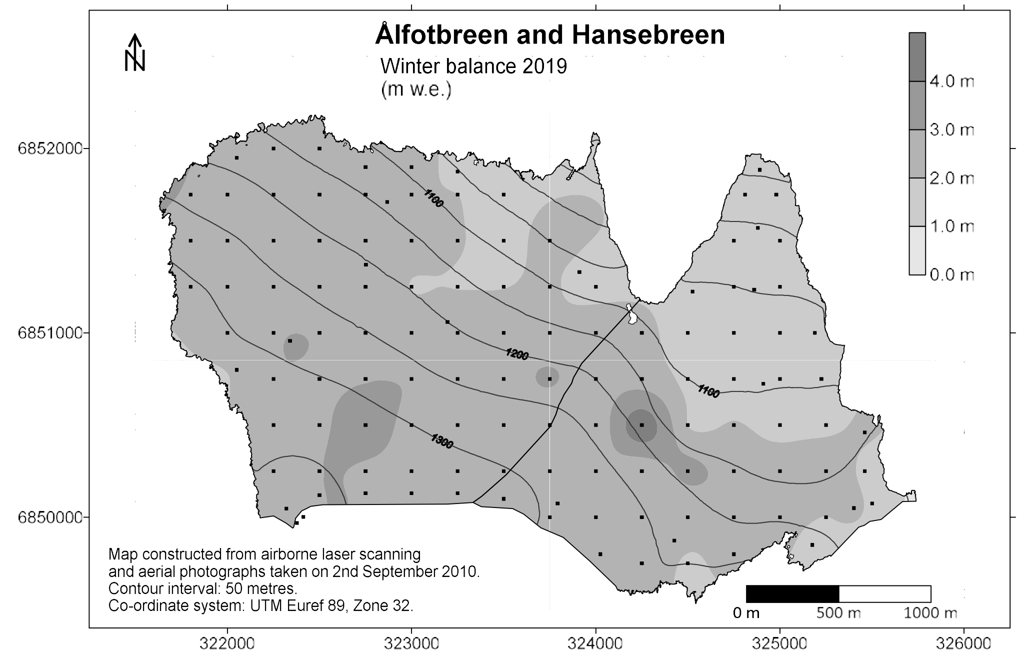


Figure 2-3
Spatial distribution of winter balance on Ålfotbreen (left) and Hansebreen (right) in 2019.

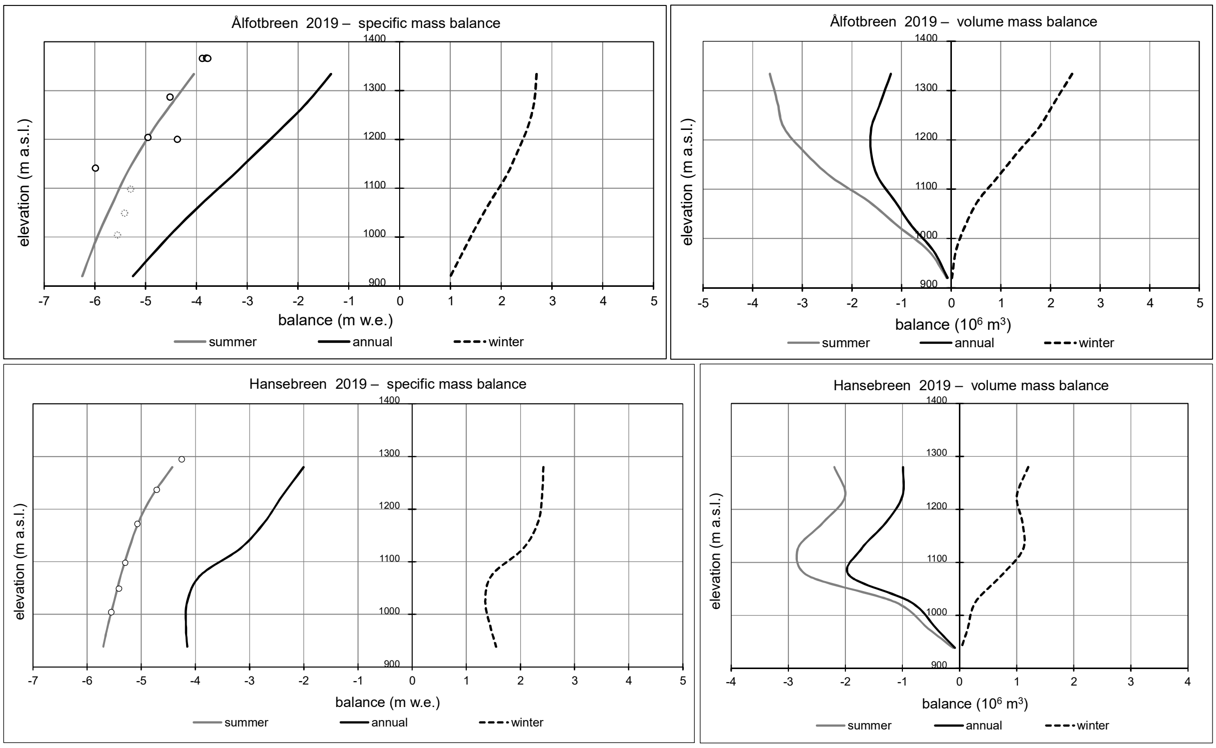


Figure 2-4
Mass balance diagram for Ålfotbreen (upper) and Hansebreen (lower) in 2019 showing altitudinal distribution of specific (left) and volumetric (right) winter, summer and annual balance. Specific summer balance at each stake is shown (○).

The summer balance for Ålfotbreen was calculated at seven stakes at five different altitudes. The balance values of the two lowest stakes (37, 1204 m a.s.l. and 15, 1141 m a.s.l.) differ significantly from the other stakes. Thus, stake values from the three lowest stakes at Hansebreen (○) were used to support the assessment of the summer balance curve in the lowermost part of Ålfotbreen (Fig. 2-4).

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

Table 2-1
Winter, summer and annual balance for Ålfotbreen (upper) and Hansebreen (lower) in 2019.

Mass balance Ålfotbreen 2018/19 – stratigraphic system

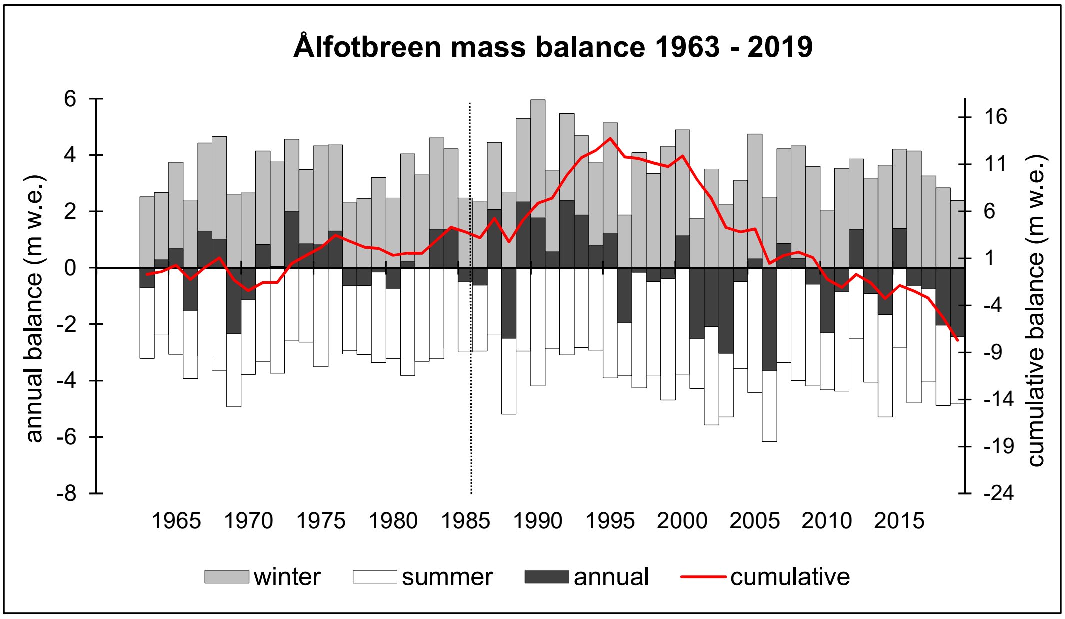
		Winter mass balance Measured 20th May 2019		Summer mass balance Measured 25th Sep 2019		Annual mass balance Summer surface 2018 - 2019	
Altitude (m a.s.l.)	Area (km²)	Specific (m w.e.)	Volume (10⁶ m³)	Specific (m w.e.)	Volume (10⁶ m³)	Specific (m w.e.)	Volume (10⁶ m³)
1300 - 1368	0.90	2.70	2.4	-4.05	-3.7	-1.35	-1.2
1250 - 1300	0.78	2.65	2.1	-4.48	-3.5	-1.83	-1.4
1200 - 1250	0.70	2.53	1.8	-4.83	-3.4	-2.30	-1.6
1150 - 1200	0.58	2.33	1.3	-5.13	-3.0	-2.80	-1.6
1100 - 1150	0.45	2.10	0.9	-5.40	-2.4	-3.30	-1.5
1050 - 1100	0.30	1.80	0.5	-5.63	-1.7	-3.83	-1.1
1000 - 1050	0.18	1.53	0.3	-5.85	-1.1	-4.33	-0.8
950 - 1000	0.08	1.28	0.1	-6.05	-0.5	-4.78	-0.4
890 - 950	0.01	1.00	0.0	-6.25	-0.1	-5.25	-0.1
890 - 1368	**3.98**	**2.38**	**9.5**	**-4.82**	**-19.2**	**-2.44**	**-9.7**

Mass balance Hansebreen 2018/19 – stratigraphic system

		Winter mass balance Measured 20th May 2019		Summer mass balance Measured 25th Sep 2019		Annual mass balance Summer surface 2018 - 2019	
Altitude (m a.s.l.)	Area (km²)	Specific (m w.e.)	Volume (10⁶ m³)	Specific (m w.e.)	Volume (10⁶ m³)	Specific (m w.e.)	Volume (10⁶ m³)
1250 - 1310	0.50	2.43	1.20	-4.43	-2.19	-2.00	-0.99
1200 - 1250	0.42	2.40	1.00	-4.80	-2.01	-2.40	-1.00
1150 - 1200	0.47	2.33	1.10	-5.05	-2.39	-2.73	-1.29
1100 - 1150	0.54	2.05	1.11	-5.23	-2.84	-3.18	-1.72
1050 - 1100	0.50	1.48	0.73	-5.38	-2.66	-3.90	-1.93
1000 - 1050	0.21	1.35	0.28	-5.50	-1.13	-4.15	-0.85
950 - 1000	0.10	1.45	0.14	-5.63	-0.55	-4.18	-0.41
927 - 950	0.02	1.55	0.03	-5.70	-0.11	-4.15	-0.08
927 - 1310	**2.75**	**2.04**	**5.6**	**-5.05**	**-13.9**	**-3.01**	**-8.3**

2.2 Mass balance 1963(86)-2019

The historical mass balance results for Ålfotbreen and Hansebreen are presented in Figure 2-5. The cumulative annual balance for Ålfotbreen for 1963-2019 is −7.7 m w.e., which gives a mean annual balance of −0.14 m w.e. a^{-1}. The cumulative annual balance for Hansebreen for 1986-2019 is −25.0 m w.e., which gives a mean annual balance of −0.74 m w.e. a^{-1}.



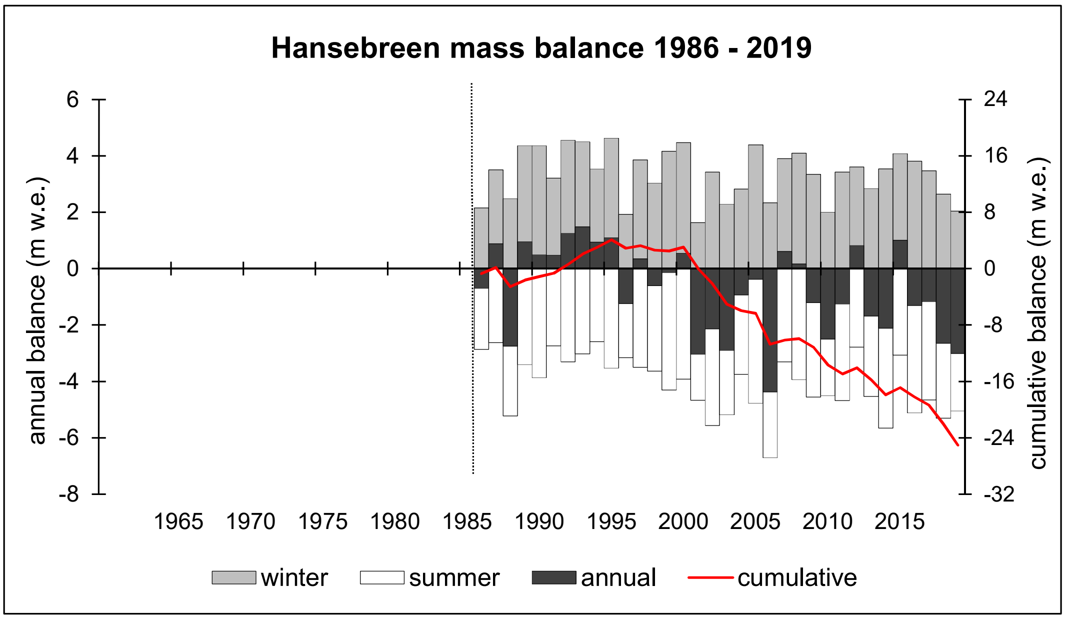


Figure 2-5
Mass balance at Ålfotbreen (upper) 1963-2019 and Hansebreen (lower) 1986-2019. Cumulative mass balance is given on the axis to the right.

2.3 Ice velocity

The surface ice velocity was calculated from repeated GNSS measurements of eleven stakes. The positions of the stakes were measured on 13th August and 11th October 2018, and 27th August and 25th September 2019.

The positions were measured using Topcon GR3 dual frequency GNSS receivers placed in the top of, or close to the stakes (Fig. 2-6). The GNSS data were post-processed using the software program "Topcon Tools". Data from the SATREF reference station Gloppen (30 km east of Ålfotbreen) was used for post-processing the GNSS data.

Figure 2-6
GNSS measurements on Ålfotbreen in August 2019. Photo: Hallgeir Elvehøy.

The calculated surface ice velocities show mean annual velocities between 0.4 m a^{-1} at the south-eastern edge of Hansebreen and 10.0 m a^{-1} in the middle of Ålfotbreen (Fig. 2-7). The uncertainty of the GNSS positioning is assumed to be ±0.5 m.

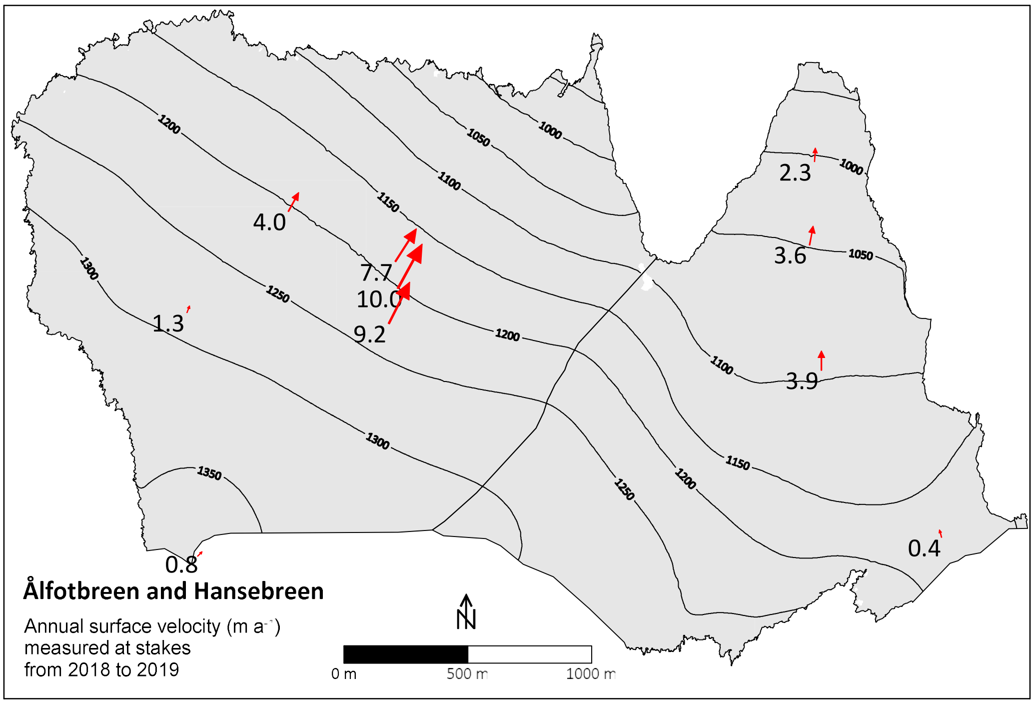


Figure 2-7
Map of Ålfotbreen and Hansebreen showing mean annual surface velocities calculated from stake position measurements in August and October 2018 and August and September 2019.

3. Nigardsbreen (Bjarne Kjøllmoen)

Nigardsbreen (61°42′N, 7°08′E) is one of the largest and best known outlet glaciers from Jostedalsbreen. It has an area of 46.6 km^2 (2013) and flows south-east from the centre of the ice cap. Nigardsbreen accounts for approximately 10 % of the total area of Jostedalsbreen, and extends from 1952 m a.s.l. down to 330 m a.s.l. (Fig. 3-1).

Glaciological investigations in 2019 include mass balance, glacier length change and surface ice velocity. Nigardsbreen has been the subject of mass balance investigations since 1962.

Figure 3-1
The glacier outlet Nigardsbreen photographed on 28th August 2019. Photo: Hallgeir Elvehøy.

3.1 Mass balance 2019

Fieldwork

Snow accumulation measurements were performed on 15th and 16th May and the calculation of winter balance is based on measurement of six stakes and 103 snow depth soundings (Fig. 3-2). Comparison of sounded snow depth and stake readings indicated no melting after the ablation measurements in October 2018. In spite of modest snow depths the sounding conditions were demanding and the summer surface was difficult to identify. The snow depth varied between 2.6 and 6.4 m on the plateau. On the glacier tongue, the snow depth was 0.6 m at stake position 1000 (961 m a.s.l.). Snow density was measured at stake position 94 (1682 m a.s.l.), and the mean density of 4.9 m snow was 479 kg m^{-3}.

Ablation was measured on 25th September. Measurements were made at stakes and towers in ten locations (Fig. 3-2). In the accumulation area there was between 0.1 and 3.0 m of snow remaining from winter 2018/19. At the time of measurement, there was between 0.5 and 1.0 m of fresh snow at stakes on the glacier plateau.

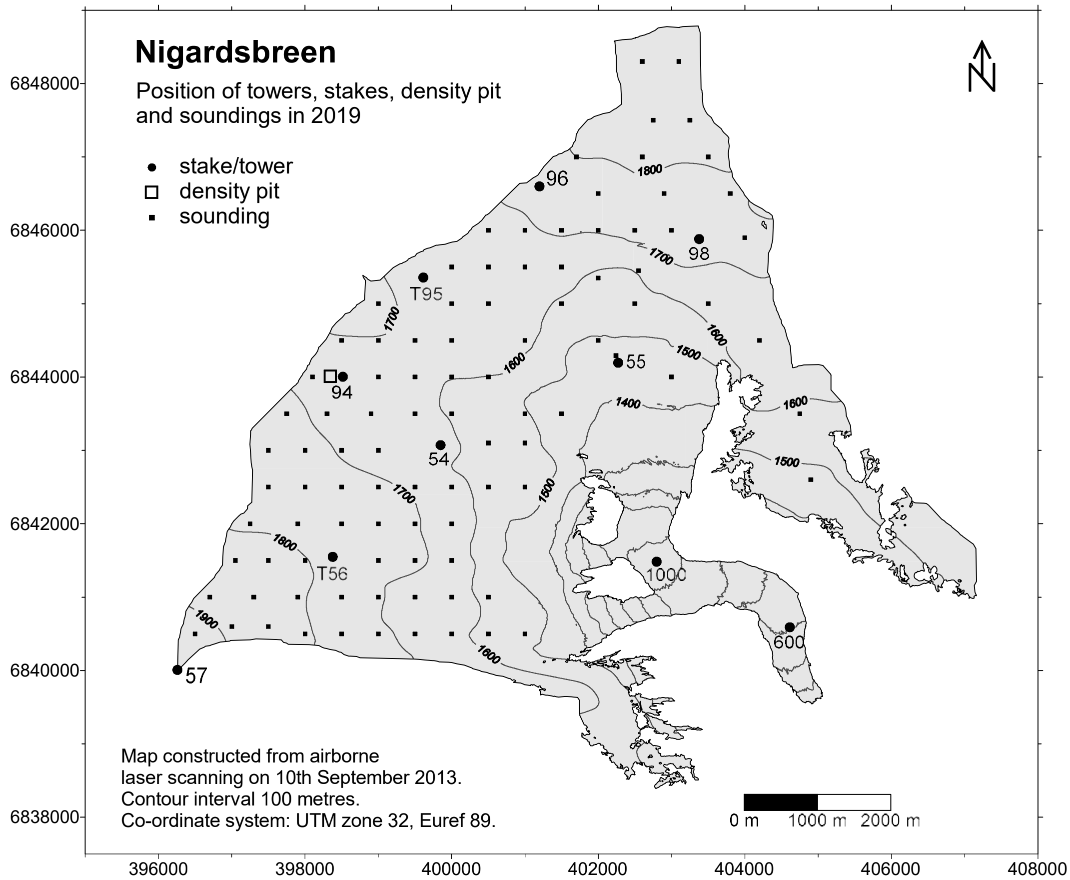


Figure 3-2
Location of towers, stakes, snow pit and soundings on Nigardsbreen in 2019.

Results

The calculations are based on the DTM from 2013.

The elevations above 1430 m a.s.l., which cover about 84 % of the catchment area, were well-represented with point measurements. Below this altitude the curve pattern was based on point measurements at 961 and 604 m elevation.

The winter balance was calculated as a mean value for each 100 m height interval and was 2.0 ±0.2 m w.e., which is 91 % 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 700 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 −2.3 ±0.3 m w.e., which is 105 % of the reference period.

Hence the annual balance was negative, at −0.3 m ±0.4 m w.e. The mean annual balance for the reference period 1981-2010 is +0.06 m w.e. Over the past ten years (2010-2019), the mean annual balance was −0.06 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.

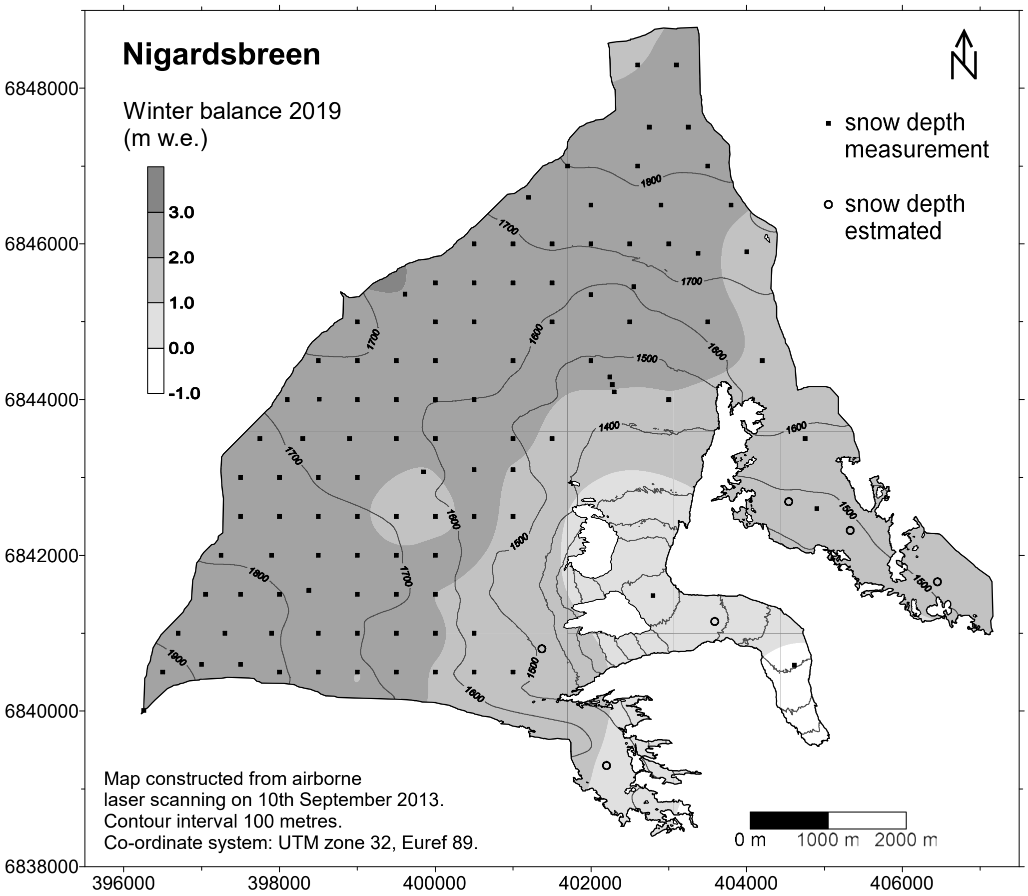
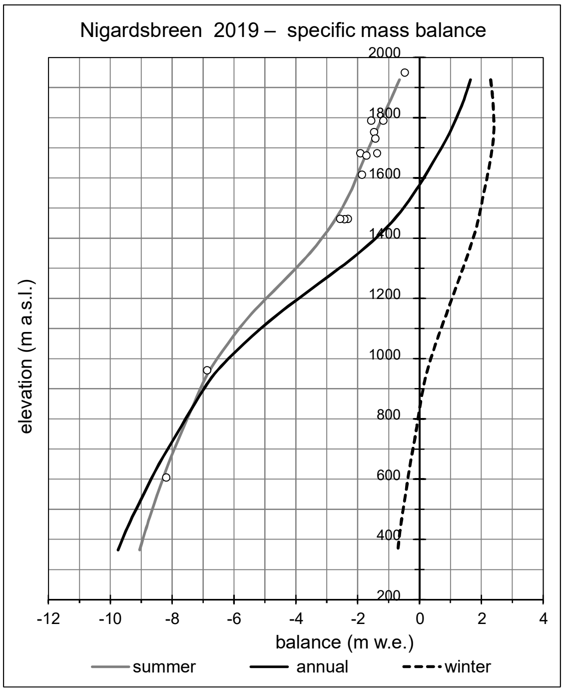


Figure 3-3
Spatial distribution of winter balance on Nigardsbreen in 2019. In areas with insufficient measurements six simulated values were used based on previous measurements.



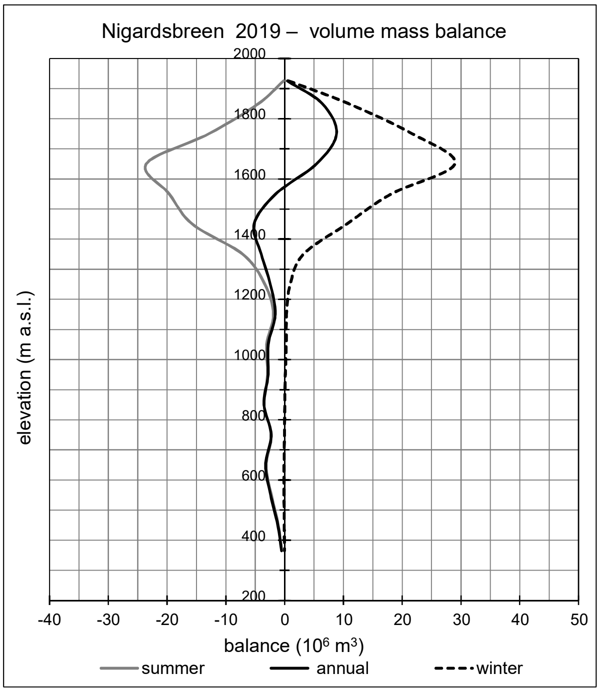


Figure 3-4
Mass balance diagram showing specific balance (left) and volume balance (right) for Nigardsbreen in 2019. Specific summer balance at ten different stake positions is shown as circles (○).

According to Figure 3-4, the Equilibrium Line Altitude was 1580 m a.s.l. Consequently the Accumulation Area Ratio was 62 %.

Table 3-1
The altitudinal distribution of winter, summer and annual balance in 100-m intervals for Nigardsbreen in 2019.

Mass balance Nigardsbreen 2018/19 – stratigraphic system

		Winter mass balance Measured 15th May 2019		Summer mass balance Measured 25th Sep 2019		Annual mass balance Summer surface 2018 - 2019	
Altitude (m a.s.l.)	Area (km^2)	Specific (m w.e.)	Volume (10^6 m^3)	Specific (m w.e.)	Volume (10^6 m^3)	Specific (m w.e.)	Volume (10^6 m^3)
1900 - 1952	0.28	2.30	0.6	-0.65	-0.2	1.65	0.5
1800 - 1900	4.58	2.38	10.9	-0.98	-4.5	1.40	6.4
1700 - 1800	9.05	2.40	21.7	-1.43	-12.9	0.98	8.8
1600 - 1700	12.72	2.28	28.9	-1.85	-23.5	0.43	5.4
1500 - 1600	8.72	2.08	18.1	-2.25	-19.6	-0.18	-1.5
1400 - 1500	5.61	1.88	10.5	-2.80	-15.7	-0.93	-5.2
1300 - 1400	2.02	1.58	3.2	-3.55	-7.2	-1.98	-4.0
1200 - 1300	0.75	1.23	0.9	-4.48	-3.4	-3.25	-2.4
1100 - 1200	0.35	0.88	0.3	-5.43	-1.9	-4.55	-1.6
1000 - 1100	0.50	0.53	0.3	-6.20	-3.1	-5.68	-2.8
900 - 1000	0.42	0.23	0.1	-6.85	-2.9	-6.63	-2.8
800 - 900	0.48	0.03	0.0	-7.30	-3.5	-7.28	-3.5
700 - 800	0.29	-0.13	0.0	-7.73	-2.3	-7.85	-2.3
600 - 700	0.39	-0.30	-0.1	-8.13	-3.1	-8.43	-3.2
500 - 600	0.27	-0.45	-0.1	-8.48	-2.3	-8.93	-2.4
400 - 500	0.12	-0.60	-0.1	-8.80	-1.1	-9.40	-1.2
330 - 400	0.06	-0.70	0.0	-9.05	-0.5	-9.75	-0.5
330 - 1952	**46.61**	**2.04**	**95.2**	**-2.31**	**-107.6**	**-0.27**	**-12.4**

3.2 Mass balance 1962-2019

The historical mass balance results for Nigardsbreen are presented in Figure 3-5. The cumulative annual balance for 1962-2019 is +5.1 m w.e., which gives a mean annual balance of +0.09 m w.e. a^{-1}.

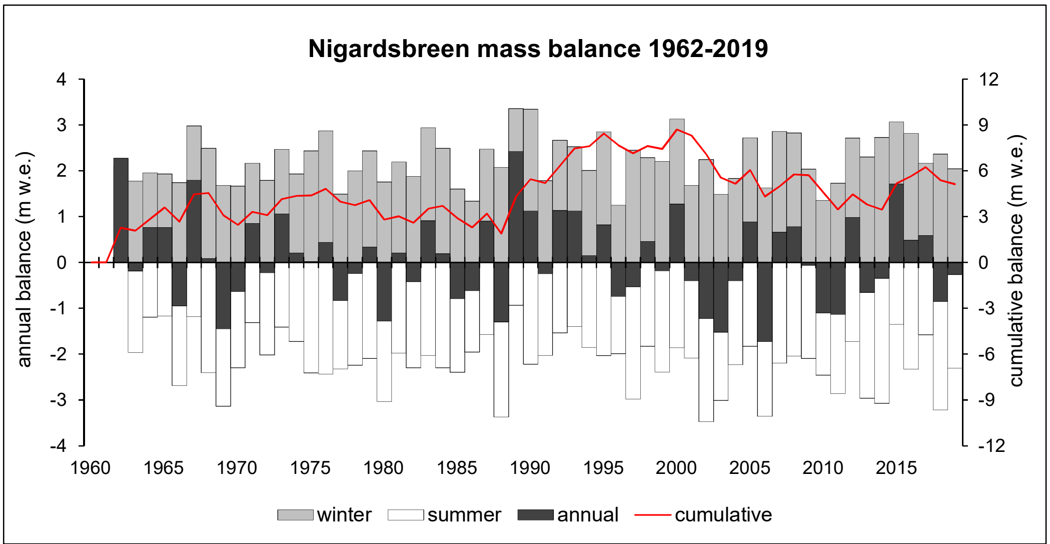


Figure 3-5
Winter, summer and annual balance at Nigardsbreen for 1962-2019. Cumulative mass balance is given on the right axis.

3.3 Ice velocity

The surface ice velocity was calculated from repeated GNSS measurements of five stakes. The positions of the stakes were measured on 26th October 2018 and 25th September 2019. For stake 1000, however, measurements represent a short period from 28th August 2019 to 25th September 2019.

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

The calculated surface ice velocities show mean annual velocities between 5 and 196 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 stakes on 25th September 2019. Photo: Hallgeir Elvehøy.

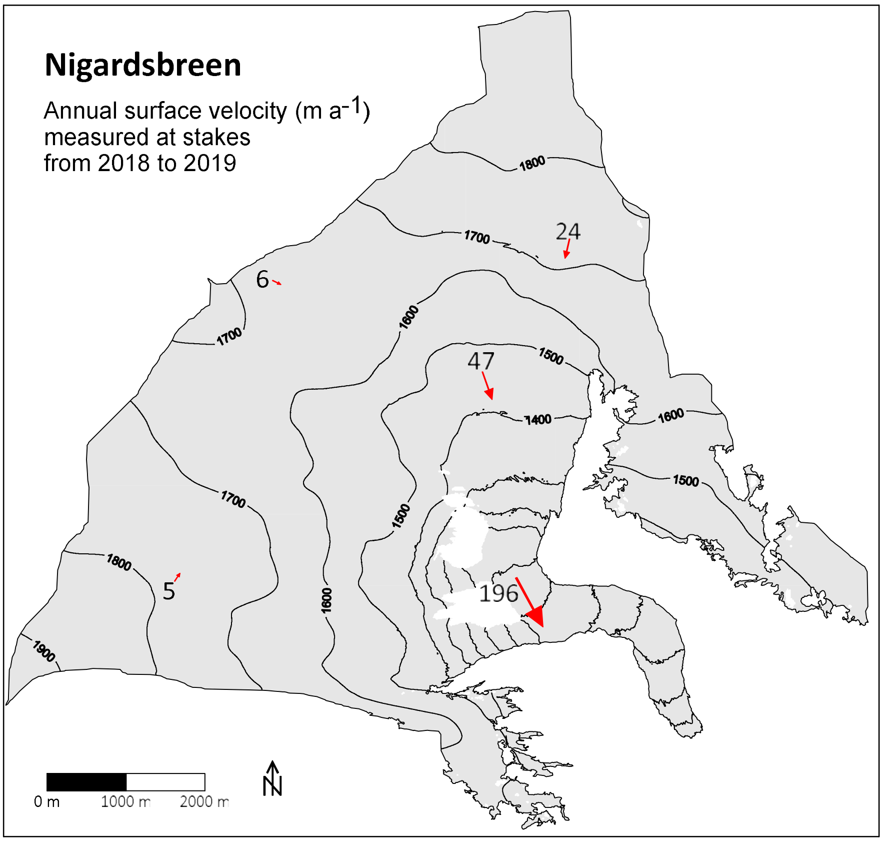


Figure 3-7
Map of Nigardsbreen showing mean annual surface velocities calculated from stake position measurements in October 2018 and September 2019. For stake 1000, (see Fig. 3-2) the velocity represents the period from 28th August 2019 to 25th September 2019.

4. Austdalsbreen (Hallgeir Elvehøy)

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

The glaciological investigations in 2019 included new mapping of the glacier, mapping of lake bathymetry in front of the glacier terminus, mass balance, front position change and glacier velocity. The mass balance has been measured at Austdalsbreen since 1988.

4.1 Mapping

Aerial photographs were taken, and airborne laser scanning (Lidar) was carried out on 27th August (Terratec AS, 2019). The mean point density was at least 1.5 points per m^2 (0.7 m^2 per point). Comparison of data from crossing flight lines shows that differences are generally less than 0.1 metre. The data set was compared with the data set from 2009 and adjusted 5 cm. A Digital Terrain Model (DTM) was processed based on the adjusted laser scanning data. The glacier outline was determined from the aerial photos.

Figure 4-1
Austdalsbreen on 28th August 2019. The lake level was 1191.6 m a.s.l., 8 metres below the highest regulated lake level. Photo: Jostein Aasen.

The glacier outline was digitised from the orthophotos. The ice divides were kept unchanged as defined from the DTM from 2009. Consequently, the drainage basin was defined from the outline and the ice divide defined from the DTM from 2009 (Kjøllmoen et al., 2010). The Area-altitude distribution for the drainage basin was calculated from the DTM (Tab. 4-1). Between 2009 and 2019 the glacier area decreased from 10.629 km² to 10.122 km² (−0.507 km²). The largest change in area occurred in the elevation band between 1550 and 1600 m a.s.l. (−0.308 km²). The elevation of the highest point decreased from 1747 to 1740 m a.s.l.

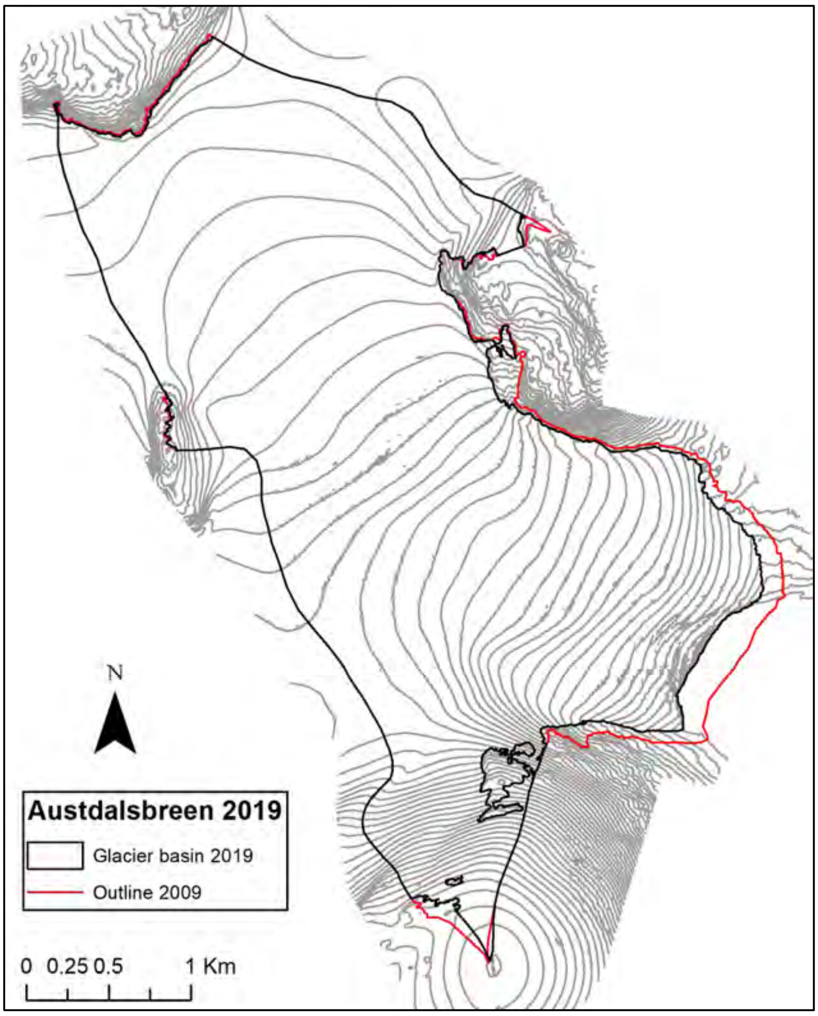


Figure 4-2
Map of Austdalsbreen on 27th August 2019. The glacier outline from 2009 is shown in red. The glacier terminus retreated approximately 220 metres between 2009 and 2019.

Table 4-1
The change in Area-altitude distribution between 2009 and 2019.

Altitude (m a.s.l.)		Area 2009 (km²)	Area 2019 (km²)	Area change (km²)	Change (%)
1700	1747/1740	0.126	0.090	−0.036	−29
1650	1700	0.139	0.119	−0.020	−14
1600	1650	0.182	0.172	−0.010	−5
1550	1600	1.892	1.584	−0.308	−16
1500	1550	2.792	2.748	−0.044	−2
1450	1500	1.604	1.503	−0.101	−6
1400	1450	1.378	1.594	0.216	16
1350	1400	0.931	0.952	0.021	2
1300	1350	0.821	0.721	−0.100	−12
1250	1300	0.536	0.457	−0.079	−15
1200	1250	0.228	0.182	−0.046	−20
1200	1740	10.629	10.122	−0.507	−4.8

4.2 Lake bathymetry

Glacier thickness is a parameter in the calculation of the contribution of calving volume to the summer mass balance. It has previously been calculated from a bottom topography map compiled from ice thickness measured using radar (1986), hot water drilling (1987), lake depth surveying (1988 and 1989), and lake outlines in orthophotos from 2010 and 2015. A new mapping of lake bottom elevation was performed on 10th September 2019 using a SonTek M9 Acoustic Doppler Profiler (ADP) positioned with a North Surveying GNSS. The lake level was 1191.6 m a.s.l., 8 metres below highest regulated lake level at 1200 m a.s.l. The measurements were processed with HydroSurveyer software. The water depth varied between 1 and 51 metres with an average of 29 metres. Comparisons of crossing profiles show that differences were typically less than two metres but up to 6 metres in some places. This is caused both from uncertainty in depth measurements and in the positioning.

From the measurements, 4900 point measurements within the outline of Austdalsbreen in 1966 were selected. In addition, results from previous measurements listed above as well as the lake outline in an orthophoto from 20th August 2015 (www.norgeibilder.no) when the lake level was 1173 m a.s.l., and the lake outline at 1191.4 m a.s.l. from 27th August 2019 were used. Based on these data a 20-metre bathymetry grid was interpolated using the kriging method. The results are shown in figure 4-3. The data coverage for the area between the 1988 and 2009 glacier outlines is good. However, close to the present ice cliff the coverage is sparse for obvious reasons.

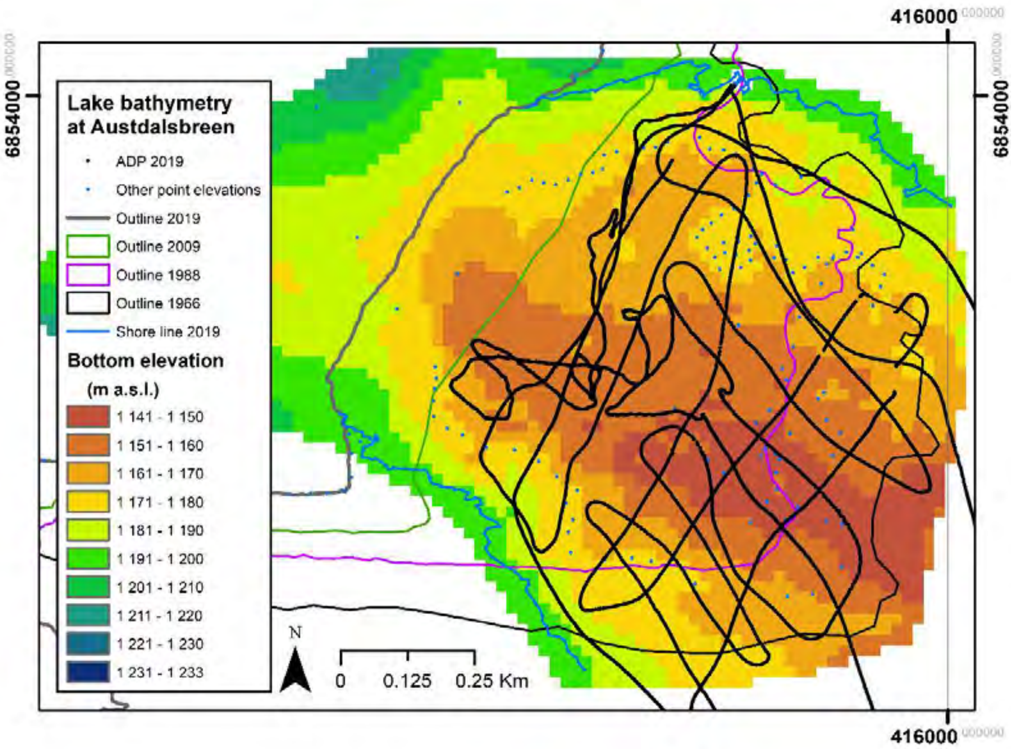


Figure 4-3
Lake bathymetry in Styggevatnet in front of Austdalsbreen based on water depth measurements on 10th September 2019 when lake level was 1191.4 m a.s.l. and older measurements (see text) is shown. Due to safety considerations there were no measurements closer than approximately 200 m to the glacier terminus in 2019.

4.3 Mass balance 2019

Fieldwork

Stakes were maintained throughout the winter in all stake locations except A80. Snow accumulation measurements were performed on 30th April. The calculation of winter balance was based on measurements in six stake locations and 40 out of 41 snow depth sounding locations (Fig. 4-4). Detecting the summer surface was relatively easy. The snow depth varied from 1.0 to 4.3 metres, and the average snow depth was 3.2 metres. Snow density was measured at stake A60 (1480 m a.s.l.). The mean density of 3.8 m snow was 489 kg m^{-3}.

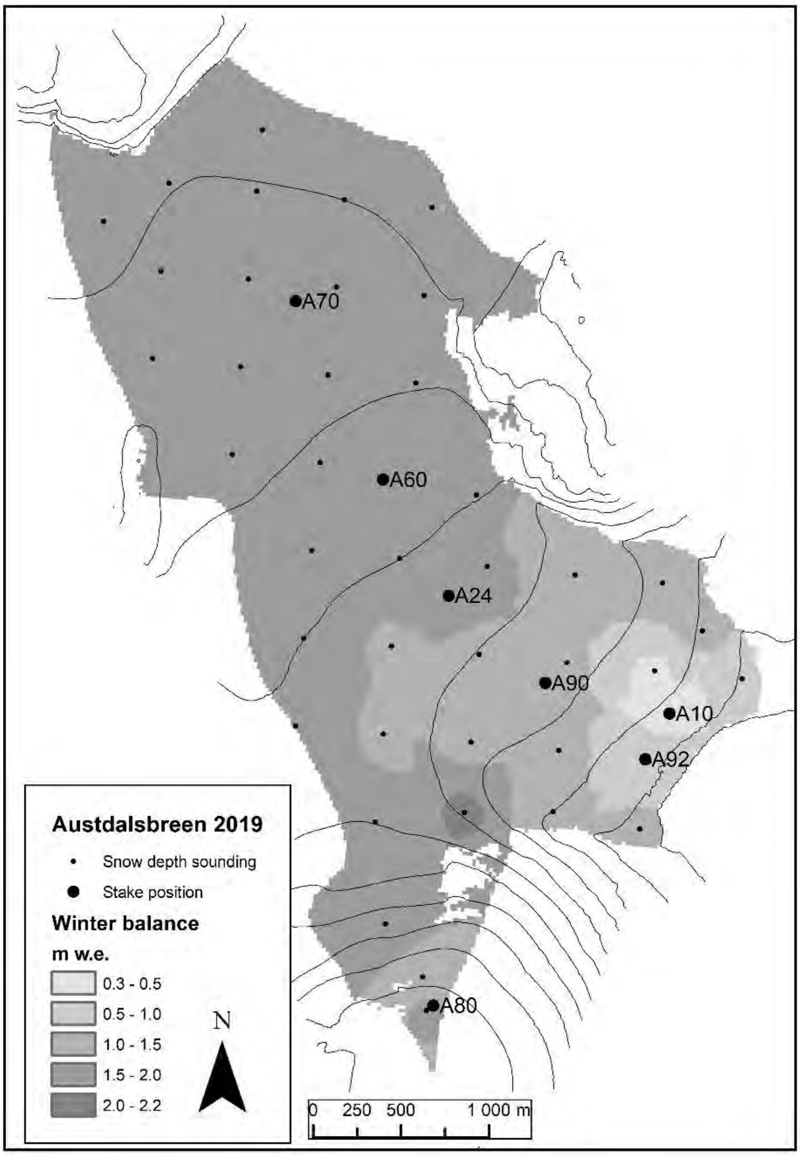


Figure 4-4
Location of stakes and snow depth soundings, and winter balance at Austdalsbreen in 2019 interpolated from 48 water equivalent values calculated from snow depth measurements.

The stake network was measured on 21st and 28th August. Stakes A92 and A10 had melted out. Between 4 and 5 metres of snow and ice had melted since 7th May. Only at A70 was there a small amount of winter snow remaining.

Summer and annual balance measurements were carried out on 25th September. There was up to 0.45 m of new snow on the glacier. Stakes were found in six locations. Based on stake observations, all the winter snow had melted, and consequently the ELA was above the top of the glacier (1740 m a.s.l.). In stake locations below 1400 m a.s.l., up to 4.25 metres of ice had melted. At stake locations above 1400 m a.s.l., up to 1.5 metres of firn had melted.

Results

The calculations are based on the new DTM from 27th August 2019. The winter balance was calculated from snow depth and snow density measurements on 30th April. A function correlating snow depth with water equivalent values was calculated based on snow density measurements at stake A60 (1490 m a.s.l.). Point winter balance values were calculated from the snow depth measurements using the water equivalent value function. Averages for 50-metre elevation intervals were calculated and plotted against altitude. the winter balance curve was then adjusted to the averages and interpolated where necessary (Fig. 4-5). The total winter balance was 16 ±2 mill. m^3 water or 1.6 ±0.2 m w.e., which is 73 % of the 1988-2018 average (2.18 m w.e.). In addition, the spatial distribution of the winter balance was interpolated from the point measurements using the Inverse Distance Weighting (IDW) method. The mean distributed winter balance was 1.61 m w.e (Fig. 4-4).

The summer balance was calculated directly for six stake locations between 1260 and 1720 m a.s.l. The summer balance curve was drawn from these six point values (Fig. 4-5).

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 (40 ±10 m a^{-1}), u_f is front position change averaged across the terminus (−22 ±5 m a^{-1}), W is terminus width (865 ±20 m) and H is mean ice thickness at the terminus (42 ±5 m). The mean ice thickness was calculated from mean surface elevations along the calving terminus surveyed on 26th October 2018 and 25th September 2019, and mean bottom elevation along the terminus calculated from the bathymetry map (Fig. 4-3) The resulting calving volume was 2.0 ±0.8 mill. m^3 water equivalent. The summer balance including calving was calculated as −28 ±3 mill. m^3 of water, which corresponds to −2.8 ±0.3 m w.e. The result is 103 % of the 1988-2018 average (−2.73 m w.e.). The calving volume was 7 % of the summer balance.

The annual balance at Austdalsbreen was calculated as −12 ±3 mill. m^3 water, corresponding to −1.2 ±0.3 m w.e. The average annual balance for the period 1988-2018 is −0.55 m w.e. The ELA in 2019 was above the summit at 1740 m a.s.l., and consequently the AAR was 0 %. The altitudinal distribution of winter, summer and annual balance is shown in Table 4-2 and Figure 4-5. Results from 1988-2019 are shown in Figure 4-6.

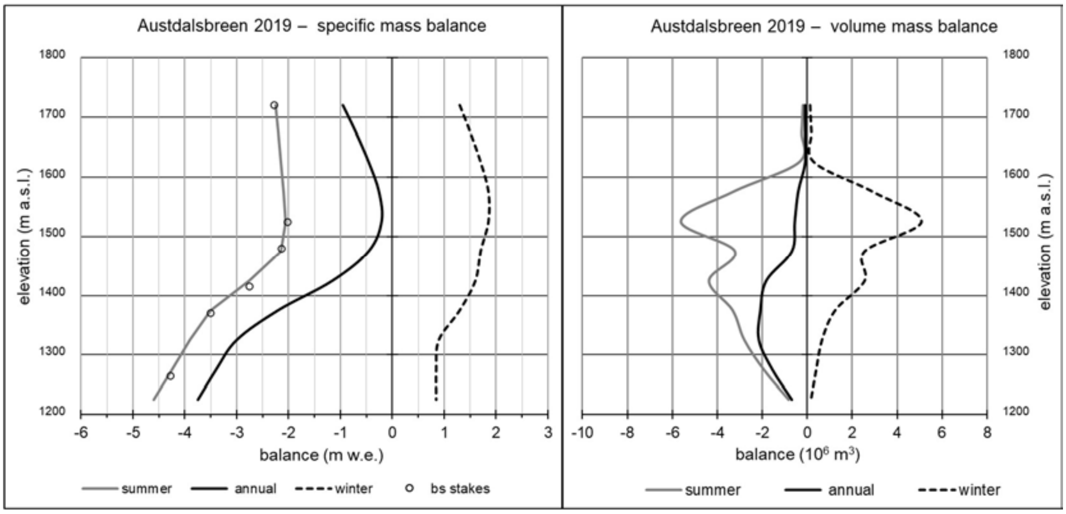


Figure 4-5
Altitudinal distribution of winter, summer and annual balance is shown as specific balance (left) and volume balance (right) at Austdalsbreen in 2019. Specific summer balance at six stake locations is shown (○).

Table 4-2
Altitudinal distribution of winter, summer and annual balances for Austdalsbreen in 2019.

Mass balance Austdalsbreen 2018/19 – stratigraphic system

		Winter mass balance Measured 30th April 2019		Summer mass balance Measured 25th Sep 2019		Annual mass balance Summer surface 2018 - 2019	
Altitude (m a.s.l.)	Area (km^2)	Specific (m w.e.)	Volume (10^6 m^3)	Specific (m w.e.)	Volume (10^6 m^3)	Specific (m w.e.)	Volume (10^6 m^3)
1700 - 1740	0.090	1.30	0.1	-2.25	-0.2	-0.95	-0.1
1650 - 1700	0.119	1.50	0.2	-2.20	-0.3	-0.70	-0.1
1600 - 1650	0.172	1.70	0.3	-2.15	-0.4	-0.45	-0.1
1550 - 1600	1.584	1.85	2.9	-2.10	-3.3	-0.25	-0.4
1500 - 1550	2.748	1.85	5.1	-2.05	-5.6	-0.20	-0.5
1450 - 1500	1.503	1.70	2.6	-2.15	-3.2	-0.45	-0.7
1400 - 1450	1.594	1.60	2.6	-2.75	-4.4	-1.15	-1.8
1350 - 1400	0.952	1.30	1.2	-3.50	-3.3	-2.20	-2.1
1300 - 1350	0.721	0.90	0.6	-3.90	-2.8	-3.00	-2.2
1250 - 1300	0.457	0.85	0.4	-4.25	-1.9	-3.40	-1.6
1200 - 1250	0.182	0.85	0.2	-4.60	-0.8	-3.75	-0.7
Calving					-2.0		-2.0
1200 - 1747	**10.122**	**1.59**	**16.1**	**-2.80**	**-28.4**	**-1.21**	**-12.2**

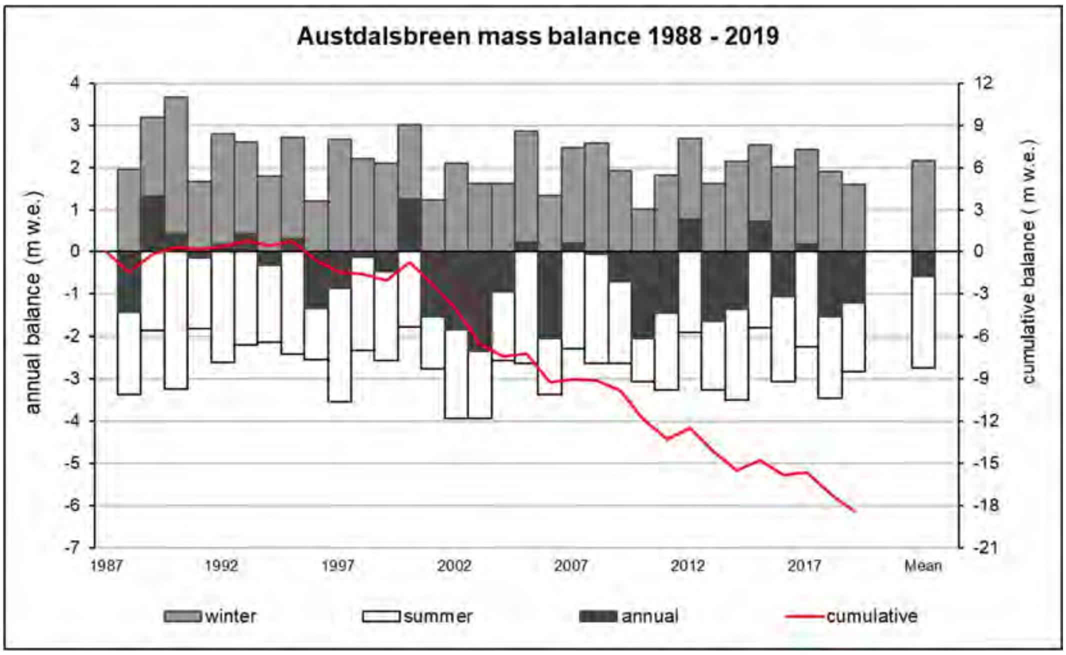


Figure 4-6
Winter, summer, annual and cumulative balance at Austdalsbreen during the period 1988-2019. Mean winter and summer balance is 2.16 and −2.73 m w.e., respectively. The cumulative mass balance is −18.4 m w.e.

4.4 Front position change

Nine points along the calving terminus were surveyed on 25th September 2019. The mean front position change was −22 ±5 m between 26th October 2018 and 25th September 2019 (Fig. 4-7). The width of the calving terminus was defined from the orthophoto from 27th August as 865 ±20 m. Since 1988 the glacier terminus has retreated about 740 m, and the lake area has increased 0.697 km^2.

4.5 Glacier dynamics

Glacier velocities are calculated from repeated surveys of stakes. The stake network was surveyed on 26th October 2018, 21st August and 25th September 2019. Annual velocities were calculated for four stake locations between 1350 and 1550 m a.s.l. for the period 26th October 2018 – 25th September 2019 (334 days). The annual results were similar to results from 2012-15 (Kjøllmoen et al., 2016).

Neither of the two frontal stake locations were maintained for the entire year. The winter velocity at A10 was calculated from a GNSS-position in October and a GPS navigator position in April. The summer velocity was estimated as like the summer velocity in 2018. The winter velocity at A92 was estimated as like the winter velocity in 2017/2018. The summer velocity was calculated from GNSS positions on 21st August and GPS navigator positions on 30th April and 25th September. The resulting annual velocities at stake locations close to the terminus were 64 m a^{-1} at A92 (61 m a^{-1} in 2018), and 52 m a^{-1} at A10 (43 m a^{-1} in 2018).

The glacier velocity averaged across the front width and thickness was estimated in order to calculate the calving volume. 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 2018/2019 is 40 ±10 m a^{-1}.

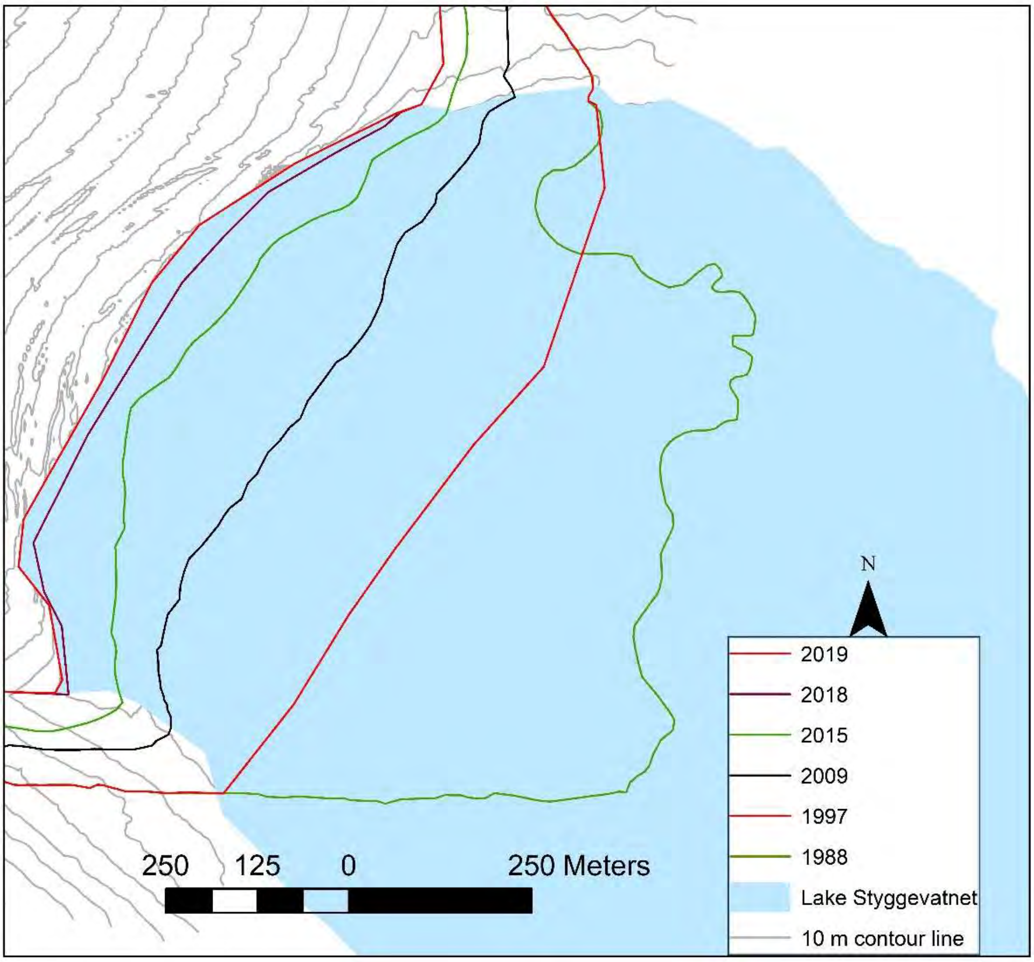


Figure 4-7
Surveyed front position of Austdalsbreen in 1988 when the lake was regulated, and in 1997, 2009 and 2015, 2018 and 2019. The front position change between 26th October 2018 and 25th September 2019 was −22 metres.

5. Rembesdalskåka (Hallgeir Elvehøy)

Rembesdalskåka (17 km^2, 60°32′N, 7°22′E) is a southwestern outlet glacier from Hardangerjøkulen, the sixth largest (73 km^2) glacier in Norway. Rembesdalskåka is situated on the main water divide between Hardangerfjorden and Hallingdalen valley and drains towards Simadalen valley and Hardangerfjorden. In the past Simadalen was flooded by jøkulhlaups from the glacier-dammed lake Demmevatnet (Fig. 5-1 and section 12.2). Since 2014 several jøkulhlaups have occurred, but they have been captured by the Rembesdalsvatnet reservoir, thus causing no damage. The most recent one occurred on 24th August 2019.

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 commissioned by Statkraft AS since 1985. The investigated basin covers the altitudinal range between 1066 and 1854 m a.s.l. as mapped in 2010.

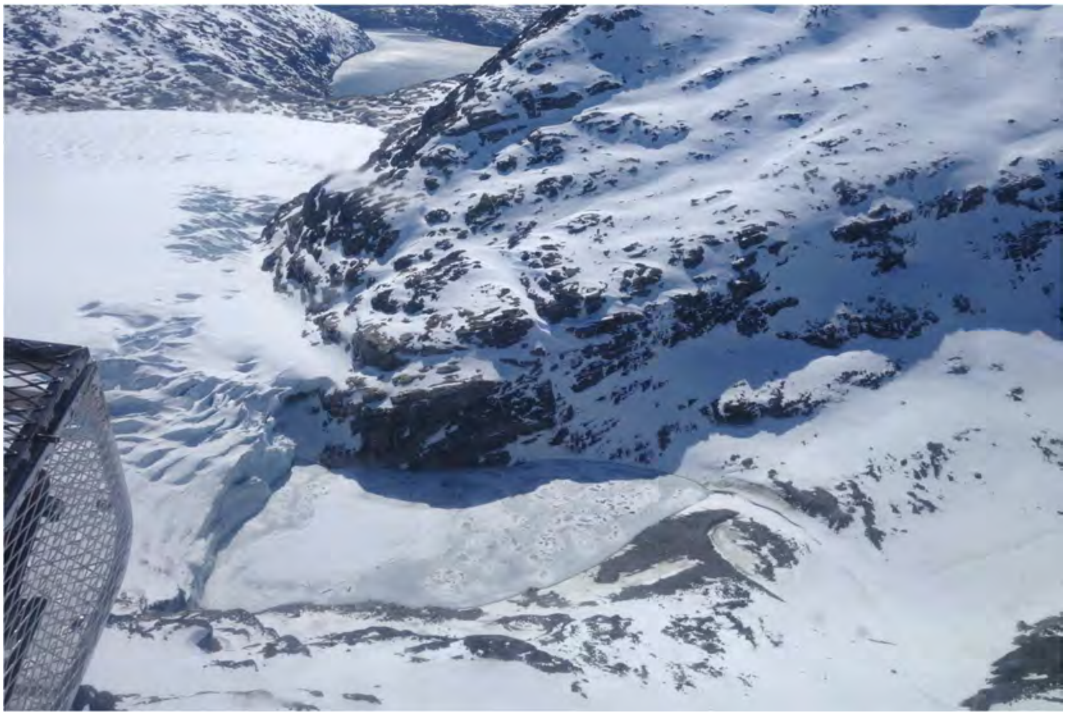


Figure 5-1
The lower part of Rembesdalskåka and Nedre Demmevatnet on 15th May 2019. The glacier drains to Rembesdalsvatnet (in the background) which is a reservoir for Sima Hydroelectric Power Station. Nedre Demmevatn seen in the forfield of the photo, was empty after a jøkulhlaup on 10th August 2018 and had started to re-fill. Photo: Hallgeir Elvehøy.

5.1 Mass balance 2019

Fieldwork

The autumn measurements in 2018 were performed on 22nd November. Comparison of snow depth sounding and stake measurement at stake H10 on 28th January 2019 indicated no ice melt after the autumn measurements.

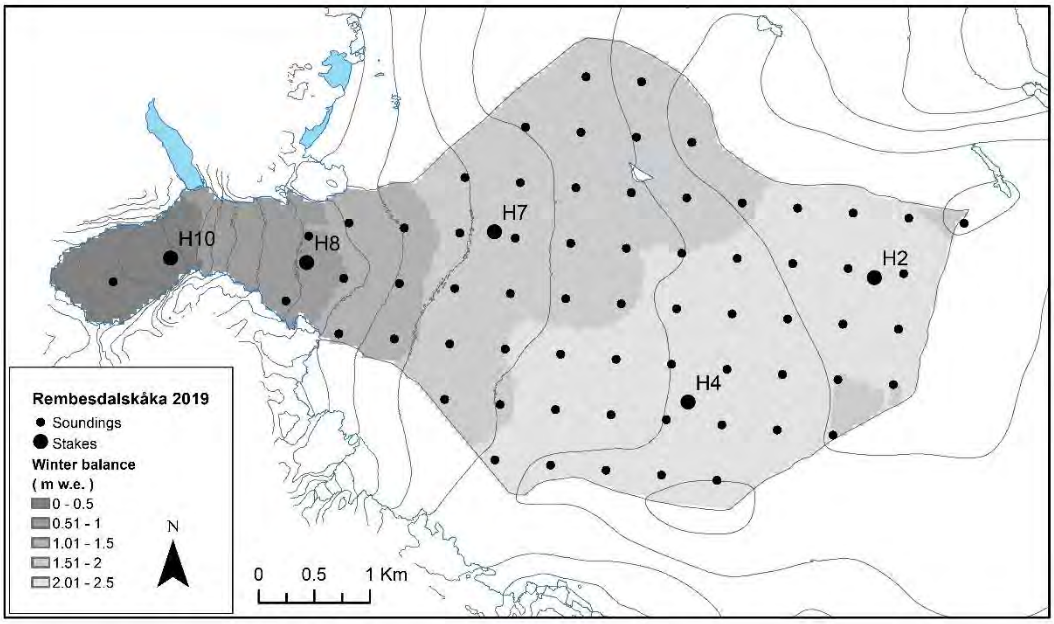


Figure 5-2
Winter balance at Rembesdalskåka interpolated from 64 snow depth soundings and five stake measurements of snow depth and one estimated point in the upper ice fall (1600 m a.s.l.).

The snow accumulation was measured on 15th May. Stakes were maintained in four locations. Snow depth was measured at 63 sounding locations in a 500 by 500 m grid on the glacier plateau above 1500 m a.s.l. (Fig. 5-2). The average snow depth on the plateau was 3.5 metres and varied between 0.8 and 4.6 metres. The summer surface (S.S.) was well defined. The mean snow density down to the summer surface at 3.05 m depth at stake H7 was 511 kg m^{-3}. On the lowest part of the glacier tongue most of the winter snow had already melted.

On 9th July all the winter snow had melted at stakes H10 and H8. All. By 24th September stake H10 had melted out, and new snow had started to accumulate on the glacier.

Summer and annual balance were measured on 5th November. There were up to 0.7 m of new snow at the stake locations. At H4 and H2 0.35 and 0.75 metres respectively of winter snow remained.

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 15th 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 m a.s.l. A value for each 50 m elevation was then determined from this curve. The resulting winter balance was 1.8 ±0.2 m w.e. or 31 ±3 mill. m^3 water. This is 83 % of the 1981-2010 average of 2.14 m w.e. a^{-1}.

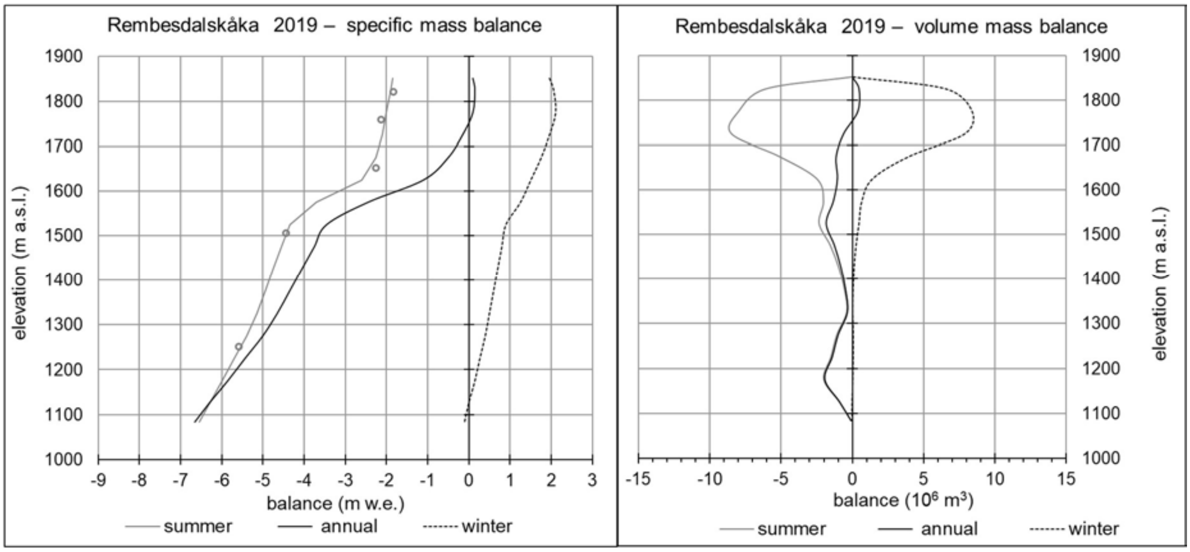


Figure 5-3
Altitudinal distribution of winter, summer and annual mass balance is shown as specific balance (left) and volume balance (right). Specific summer balance, b_s, at five stakes is shown (○).

Table 5-1
Altitudinal distribution of winter, summer and annual mass balance at Rembesdalskåka in 2019.

Mass balance Rembesdalskåka 2018/19 – stratigraphic system

Altitude (m a.s.l.)	Area (km²)	Winter mass balance Measured 15th May 2019 Specific (m w.e.)	Volume (10^6 m³)	Summer mass balance Measured 5th Nov 2019 Specific (m w.e.)	Volume (10^6 m³)	Annual mass balance Summer surface 2018 - 2019 Specific (m w.e.)	Volume (10^6 m³)
1850 - 1854	0.03	1.95	0.1	-1.85	-0.1	0.10	0.0
1800 - 1850	3.21	2.05	6.6	-1.90	-6.1	0.15	0.5
1750 - 1800	3.99	2.10	8.4	-2.00	-8.0	0.10	0.4
1700 - 1750	4.05	1.95	7.9	-2.10	-8.5	-0.15	-0.6
1650 - 1700	2.28	1.75	4.0	-2.25	-5.1	-0.50	-1.1
1600 - 1650	0.96	1.50	1.4	-2.60	-2.5	-1.10	-1.1
1550 - 1600	0.55	1.25	0.7	-3.70	-2.0	-2.45	-1.3
1500 - 1550	0.54	0.90	0.5	-4.35	-2.3	-3.45	-1.8
1450 - 1500	0.34	0.80	0.3	-4.55	-1.5	-3.75	-1.3
1400 - 1450	0.20	0.70	0.1	-4.75	-0.9	-4.05	-0.8
1350 - 1400	0.11	0.60	0.1	-4.95	-0.5	-4.35	-0.5
1300 - 1350	0.07	0.50	0.0	-5.15	-0.4	-4.65	-0.3
1250 - 1300	0.20	0.40	0.1	-5.40	-1.1	-5.00	-1.0
1200 - 1250	0.26	0.27	0.1	-5.70	-1.5	-5.43	-1.4
1150 - 1200	0.33	0.15	0.0	-6.00	-2.0	-5.85	-1.9
1100 - 1150	0.14	0.00	0.0	-6.30	-0.9	-6.30	-0.9
1066 - 1100	0.01	-0.10	0.0	-6.55	-0.1	-6.65	-0.1
1066 - 1854	**17.26**	**1.75**	**30.2**	**-2.52**	**-43.5**	**-0.77**	**-13.3**

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 1.76 m w.e.

The date of the 2019 mass balance minimum for Rembesdalskåka was assessed by studying 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 2nd September and on the glacier tongue on 30th September.

The summer balance was calculated directly at the four upper stake locations. Ice melting at H10 after 9th July was estimated as slightly higher than at H8.

The density of the remaining winter snow at H2 and H4 was set as 600 kg m^{-3}. At H7, the density of 0.9 m of firn from 2015 was set as 700 kg m^{-3}. The density of melted ice at H8 and H10 was set as 900 kg m^{-3}.

The summer balance curve in Figure 5-3 was drawn from five point values. The summer balance was calculated as −2.5 ±0.2 m w.e., corresponding to −44 ±3 mill. m^3 of water. This is 117 % of the 1981-2010 normal average, which is −2.16 m w.e. a^{-1}.

The annual balance at Rembesdalskåka was calculated as −0.8 ±0.3 m w.e. or −13 ±5 mill. m^3 water. The 1981-2010 normal average is -0.02 m w.e. a^{-1}. The ELA was 1755 m a.s.l. and the corresponding AAR was 40 %. The altitudinal distribution of winter, summer and annual balances is shown in Figure 5-3 and Table 5-1. Results from 1963-2019 are shown in Figure 5-4. The cumulative annual balance is −5.8 m w.e. Since 1995, the glacier has had a mass deficit of 234 mill. m^3 w.e. or −0.56 m w.e. a^{-1}.

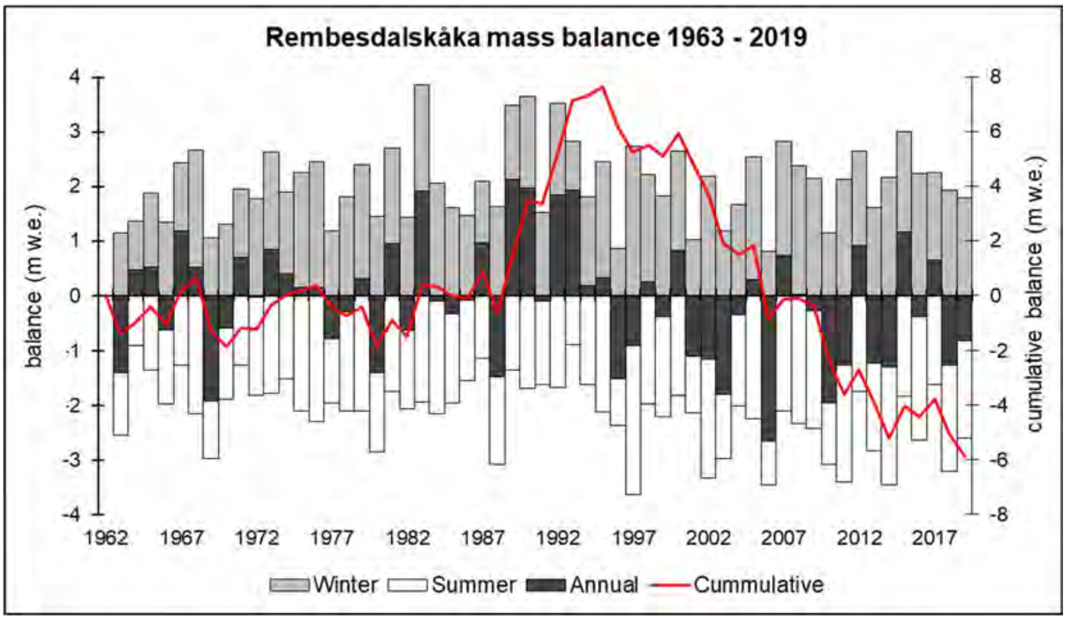


Figure 5-4
Winter, summer, annual and cumulative mass balance at Rembesdalskåka during the period 1963-2019. Mean values (1963-2019) are B_w=2.05 m w.e a^{-1} and B_s=−2.15 m w.e a^{-1}.

6. Storbreen (Liss M. Andreassen)

Storbreen (61°34′N, 8°8′E) (now written with –an ending on official maps: Storbrean) 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 km^2 and ranges in altitude from 1420 to 2091 m a.s.l. (map of 2019, Fig. 6-2). The mass balance for 2019 was calculated based on the DTM and glacier outline from 2019 (chap. 6.1).

Figure 6-1
Storbreen on 29th June 2019. Photo: Kjell Nøygard.

6.1 Survey 2019

The previous glacier survey used for glacier mass balance calculations was from 2009. To have an updated map of the glacier, laser scanning and aerial photography were conducted on 26th August 2019 by TerraTec AS (2019). The average point density of the laser point cloud was 2.0 points/m^2. The aerial photographs were used to create an orthophoto of 0.20 m resolution.

The glacier outline from the 2019 survey was digitised using the orthophotos, laser intensity values and a hillshade of the surface. A 5 m DTM was derived from the laser point cloud and used to calculate a new area-altitude distribution. The glacier area had decreased from 5.14 km^2 to 4.88 km^2, a reduction in area of 5 % (Fig. 6-2). The glacier tongues have retreated markedly, about 120 m at the northern tongue and 100 m at the southern tongue. The retreat of the southern tongue agrees well with the ground-based record of glacier length change, which gave a 99 m retreat from 2009 to 2019.

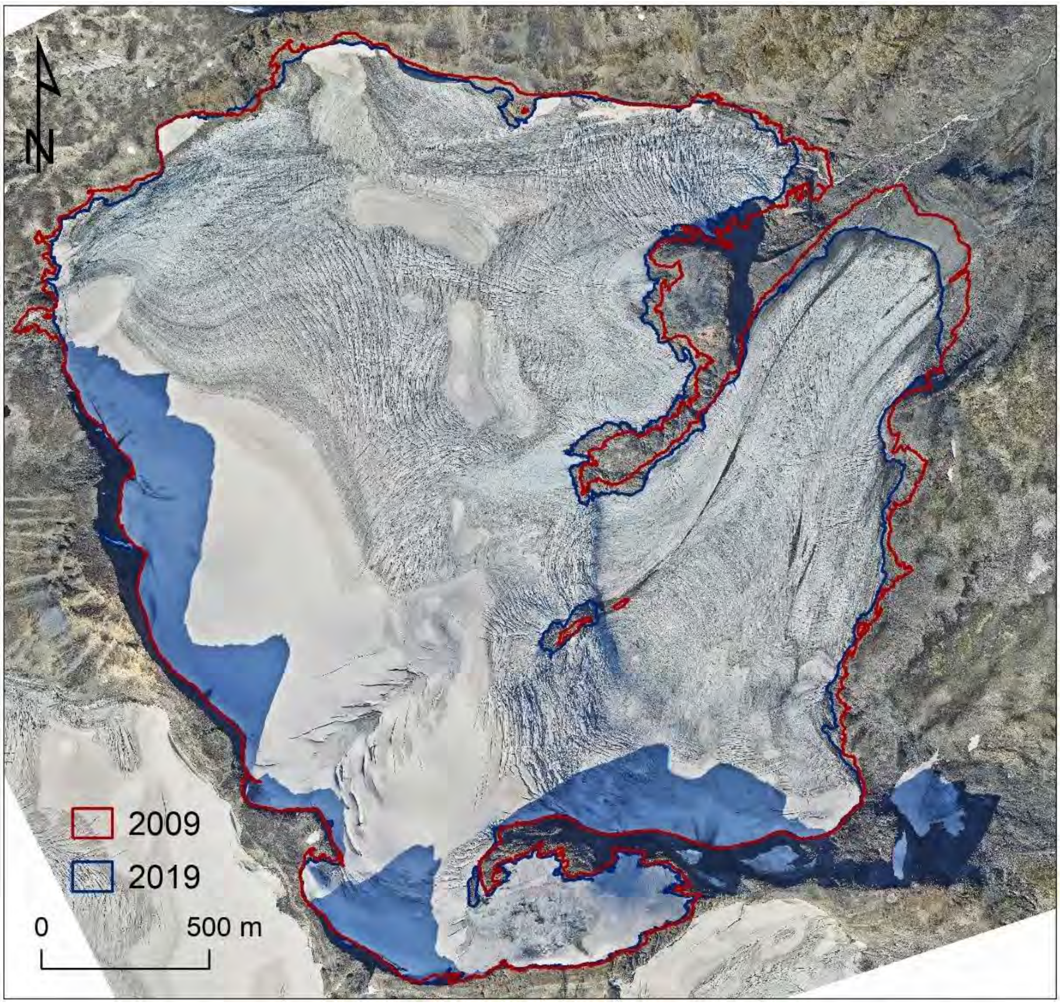


Figure 6-2
Orthophoto of Storbreen derived from aerial photos taken on 26th August 2019. The glacier outlines from 2009 and 2019 are shown. Orthophoto by TerraTec AS.

6.2 Mass balance 2019

Field work

Snow accumulation measurements were performed on 2nd May on the lower part and on 8th May on the upper part of the glacier. Stakes in 8 positions were visible. A total of 128 snow depth soundings between 1434 and 2015 m a.s.l. were made (Fig. 6-3). The snow depth varied between 0.3 and 4.3 m, the mean and median being 2.2 and 2.0 m respectively. Snow density was measured at the lower part (1537 m a.s.l.) where the total snow depth was 1.5 m and at the upper part (1715 m a.s.l.) where the total snow depth was 2.1 m. The average snow density measured was 414 kg m^{-3} at the lower location and 439 kg m^{-3} at the higher location. Ablation measurements were performed on 23rd September at stakes in all positions. The upper parts of the glacier were covered in snow.

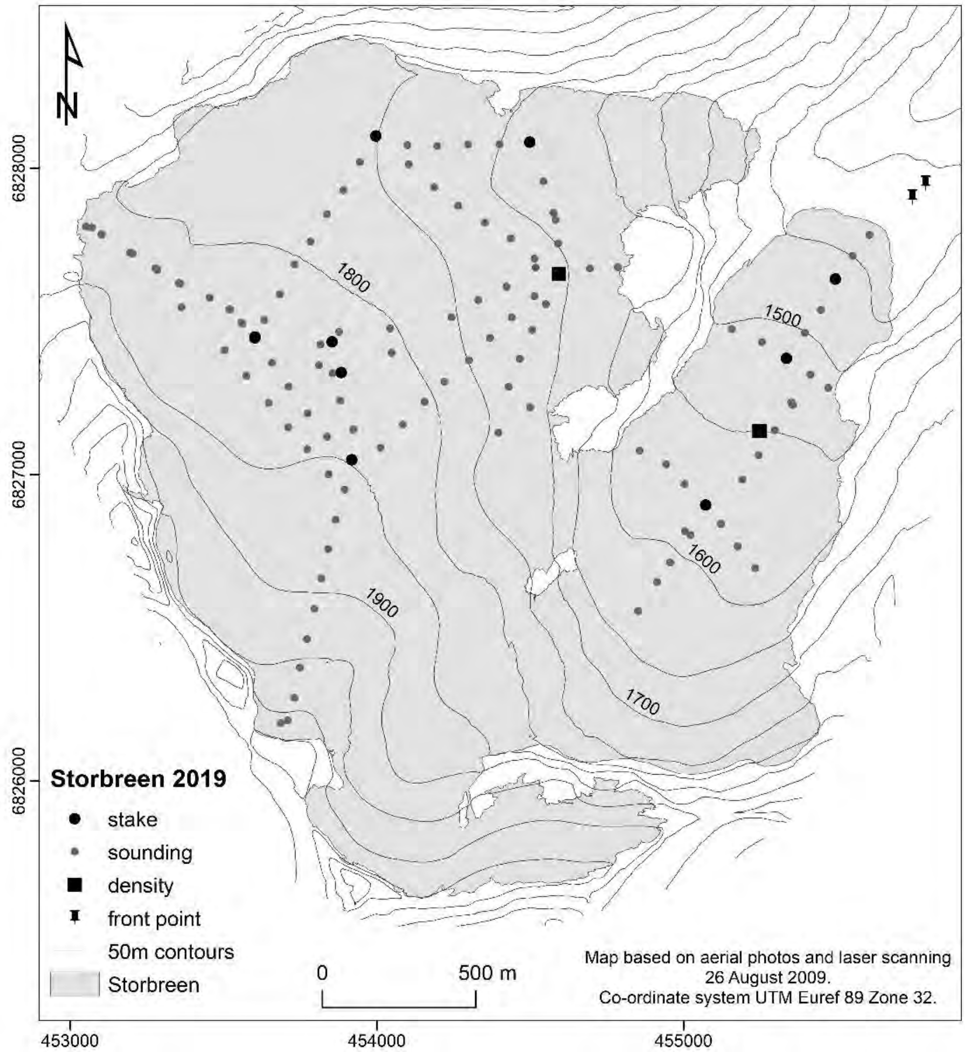


Figure 6-3
Location of stakes, soundings and density pits at Storbreen in 2019. The 50 m contours and the glacier outline are from aerial photos and laser scanning acquired on 26th August 2019.
Front point: reference points used for length change (glacier front) measurements (see chap. 12.1).

Results

The winter balance was calculated from the mean of the soundings within each 50-metre height interval and was 1.02 ±0.2 m w.e., which is 69 % of the mean winter balance for the reference period 1981-2010. Annual balance was calculated directly from stakes at ten locations. The summer balance was interpolated to 50 m height intervals based on the stake readings and was –2.54 ±0.3 m w.e., which is 139 % of the mean summer balance for the reference period 1981-2010. The annual balance of Storbreen was −1.52 ±0.3 m w.e. in 2020. The end-of-season snowline was not observed due to fresh snow and thus it is difficult to assess the equilibrium-line altitude (ELA). The orthophoto on 26th of August (Fig 6-1) and Sentinel-imagery on 27th August show that the snow line at that time was in the interval 1820-1850 m a.s.l. Several snowfall events followed before the minimum measurements. The annual balance curve from the annual balance diagram (Fig. 6-3) indicate an ELA of ~2005 m a.s.l. resulting in an estimated accumulation area ratio (AAR) of 3 %. However, the values are uncertain due to lack of observations at these elevations.

The mass balance results are shown in Table 6-1 and the corresponding curves for specific and volume balance are shown in Figure 6-4.

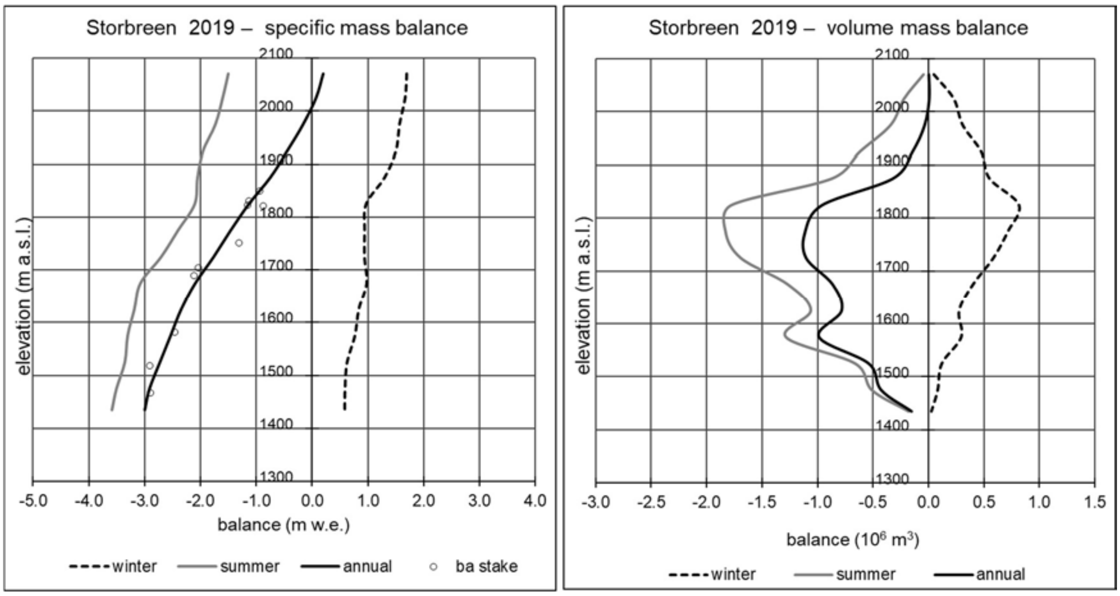


Figure 6-4
Mass balance versus altitude for Storbreen 2019, showing specific balance on the left and volume balance on the right. Annual balance at nine stakes is also shown.

Table 6-1
The distribution of winter, summer and annual balance in 50 m altitudinal intervals for Storbreen in 2019.

		Winter balance Measured 8th May		Summer balance Measured 23rd Sep.		Annual balance 2018 - 2019	
Altitude (m a.s.l.)	Area (km^2)	Specific (m w.e.)	Volume (10^6 m^3)	Specific (m w.e.)	Volume (10^6 m^3)	Specific (m w.e.)	Volume (10^6 m^3)
2050 - 2091	0.030	1.70	0.05	-1.50	-0.05	0.20	0.01
2000 - 2050	0.138	1.67	0.23	-1.60	-0.22	0.07	0.01
1950 - 2000	0.198	1.57	0.31	-1.73	-0.34	-0.16	-0.03
1900 - 1950	0.317	1.51	0.48	-1.95	-0.62	-0.44	-0.14
1850 - 1900	0.425	1.30	0.55	-2.05	-0.87	-0.75	-0.32
1800 - 1850	0.846	0.97	0.82	-2.10	-1.78	-1.13	-0.96
1750 - 1800	0.763	0.94	0.72	-2.40	-1.83	-1.46	-1.11
1700 - 1750	0.628	0.94	0.59	-2.70	-1.69	-1.76	-1.11
1650 - 1700	0.414	0.98	0.40	-3.07	-1.27	-2.09	-0.87
1600 - 1650	0.334	0.83	0.28	-3.18	-1.06	-2.35	-0.78
1550 - 1600	0.390	0.76	0.30	-3.30	-1.29	-2.54	-0.99
1500 - 1550	0.197	0.62	0.12	-3.35	-0.66	-2.73	-0.54
1450 - 1500	0.146	0.59	0.09	-3.50	-0.51	-2.91	-0.43
1420 - 1450	0.050	0.58	0.03	-3.58	-0.18	-3.00	-0.15
1420 - 2091	**4.876**	**1.02**	**4.97**	**-2.54**	**-12.37**	**-1.52**	**-7.41**

6.3 Mass balance 1949-2019

The cumulative balance for 1949-2019 is –28 m w.e. The mean annual balance for the period of 71 years is −0.39 m w.e. (Fig. 6-5). For the shorter period 2001-2019 (19 years) the mean annual balance is −0.94 m w.e.

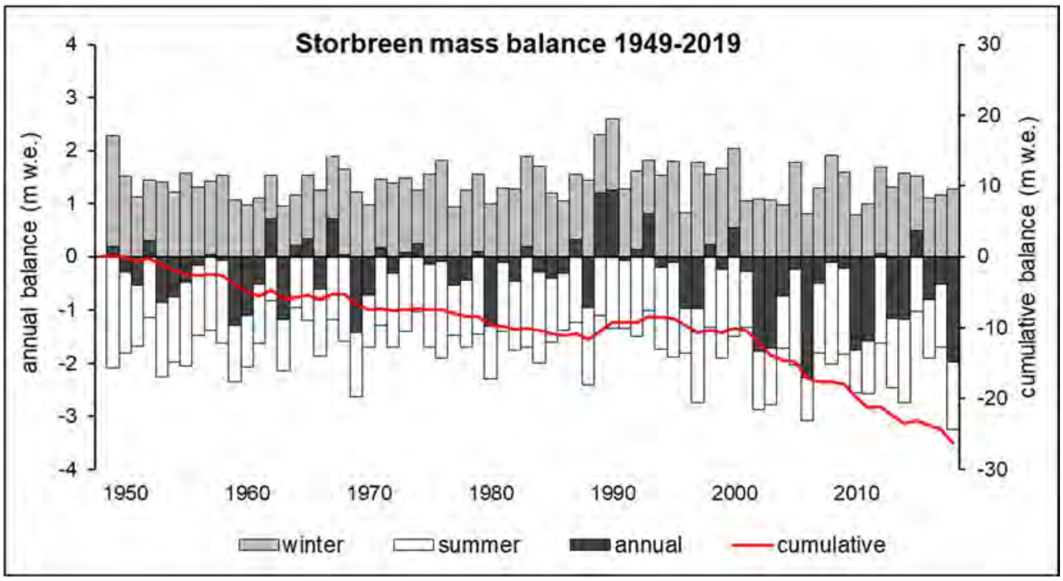


Figure 6-5
Winter, summer, annual and cumulative mass balance at Storbreen for the period 1949-2019.

Figure 6-6
Storbreen was also visited on 14th of August. Photos shows stake 7 after stake maintenance, looking up-glacier. Photo: Liss M. Andreassen.

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 are 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.). Juvfonne has an area of 0.086 km^2 and altitudinal range from 1852 to 1985 m a.s.l. (map of 2019).

The observation programme of Juvfonne in 2019 consisted of accumulation measurements in spring, seasonal and annual balances measured in one stake position, front position (chap. 12.1) and survey of the surface elevation of the ice patch (chap. 7.1).

Figure 7-1
Juvfonne on 27th August 2019, the day after laser scanning was performed. Only a few areas had snow remaining at the time. Part of the lower ice patch is covered in white fabric to protect the tunnel roof from melting. Photo: Liss M. Andreassen.

7.1 Survey 2019

To have an updated map of the ice patch, laser scanning was conducted and aerial photos were taken on 26th August 2019 by TerraTec AS (2019). The average point density of the laser point cloud was 2.0 points/m^2. The aerial photographs were used to create an orthophoto of 0.20 m resolution (Fig. 7-2). The previous detailed laser scanning used for the mass balance investigations was from 2011. The glacier outline from the 2019 survey was digitised on screen using the orthophoto as aid. The ice patch area was reduced from 0.127 km^2 in 2011 to 0.086 km^2 in 2019 (Fig. 7-2).

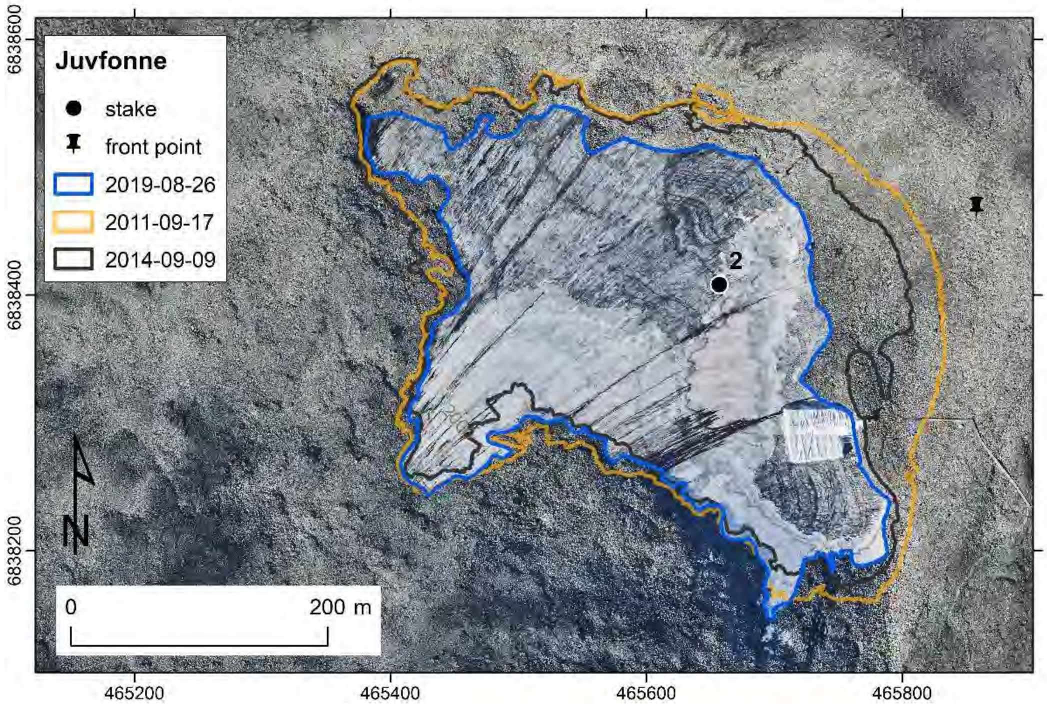


Figure 7-2
Orthophoto of Juvfonne on 26th August 2019 and previous extents from 2011 and 2014. See also Fig. 7-1. Orthophoto: TerraTec AS.

7.2 Mass balance 2019

Field work

The accumulation measurements on Juvfonne were carried out on 29th April. A total of 41 snow depth soundings were made, whereof 26 were within the new 2019 outline of 26th August (Fig. 7-3). The snow depths taken within the 2019 outline varied between 1.42 and 3.55 m with a mean and median of 2.50 and 2.55 m respectively. For all soundings including those outside the present ice patch extent, the snow depths varied between 0.42 and 3.8 m with a mean and median of 2.39 and 2.60 m. The snow density was measured in a pit down to the previous summer surface near stake 2 (the only stake now maintained on the ice patch), where the depth to the 2018 summer surface was 2.25 m. The resulting density was 503 kg m^{-3}. Ablation measurements were carried out on 23rd September at stake 2. A layer of fresh snow covered the ice patch.

Results

Seasonal surface mass balances have been measured since 2010 at stake 2 (Fig. 7-3). In 2019 the point winter balance was 1.31 ±0.15 m w.e., the point summer balance was –1.53 ±0.15 m w.e and the annual balance was –0.22 ±0.15 m w.e. at this location. The cumulative mass balance for stake 2 over the 10 years of measurements is –11.7 m w.e., or –1.17 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.

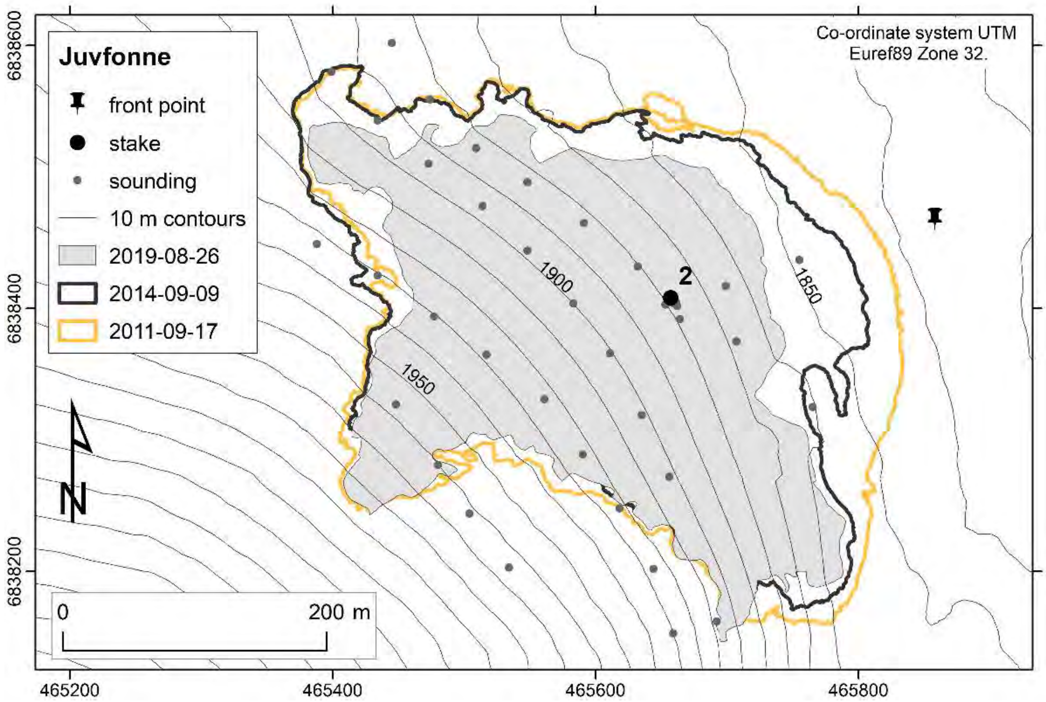


Figure 7-3
Location of snow depth soundings in 2019 and the position of stake 2 where density is measured. The ice patch extents in 2019 (orthophoto) and 2011 (orthophoto) are shown. "Front point" marks the reference point for front position and length change measurements (see chap. 12.1). The 10 m contours are derived from the 2019 DTM.

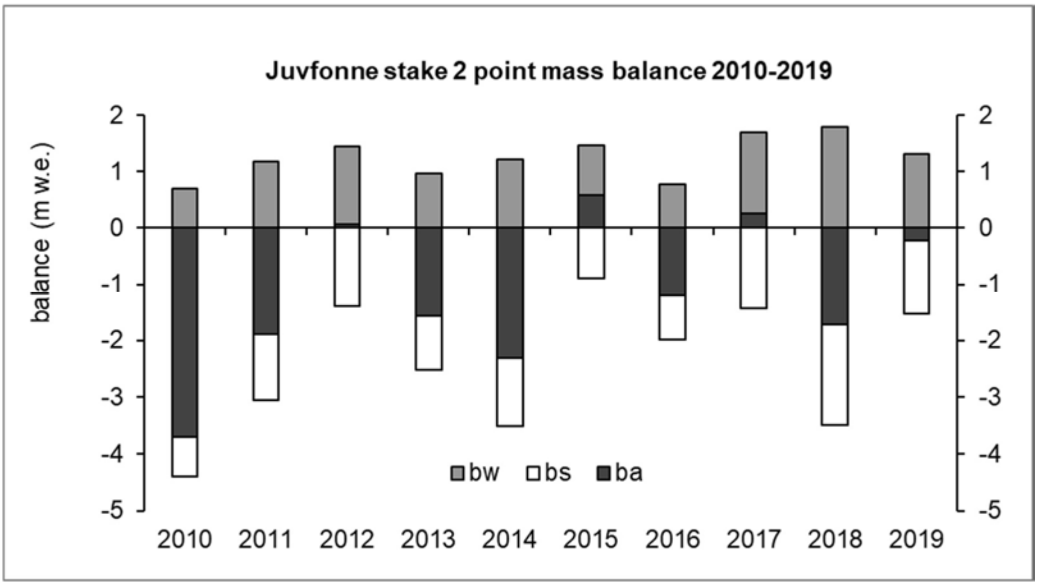


Figure 7-4
Point mass balance at stake 2 at Juvfonne 2010-2019, given as winter balance (b_w), summer balance (b_s) and annual balance (b_a).

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 (Fig. 8-2 and 8-3). Annual mass balance measurements began in 1962. The calculations presented here are based on a new survey of the glacier conducted in 2019 (chap. 8.1). According to this map, Hellstugubreen ranges in elevation from 1487 to 2213 m a.s.l. and has an area of 2.7 km^2.

Figure 8-1
Hellstugubreen on 23rd September 2019. Photo: Jostein Aasen.

8.1 Survey 2019

The previous detailed glacier survey used for glacier mass balance calculations was from 2009. To have an updated map of the glacier, laser scanning and orthophotos were taken on 26th August 2019 by TerraTec AS (2019). The average point density of the laser point cloud was 2.0 points/m^2. The aerial photographs were used to create an orthophoto of 0.20 m resolution. The glacier outline was digitised on screen using the orthophotos, hillshade and laser intensity values as aid. A 5 m DTM was derived from the laser point cloud and used to calculate a new area-altitude distribution. The new outline showed the glacier had shrunk in area from 2.9 km^2 to 2.7 km^2.

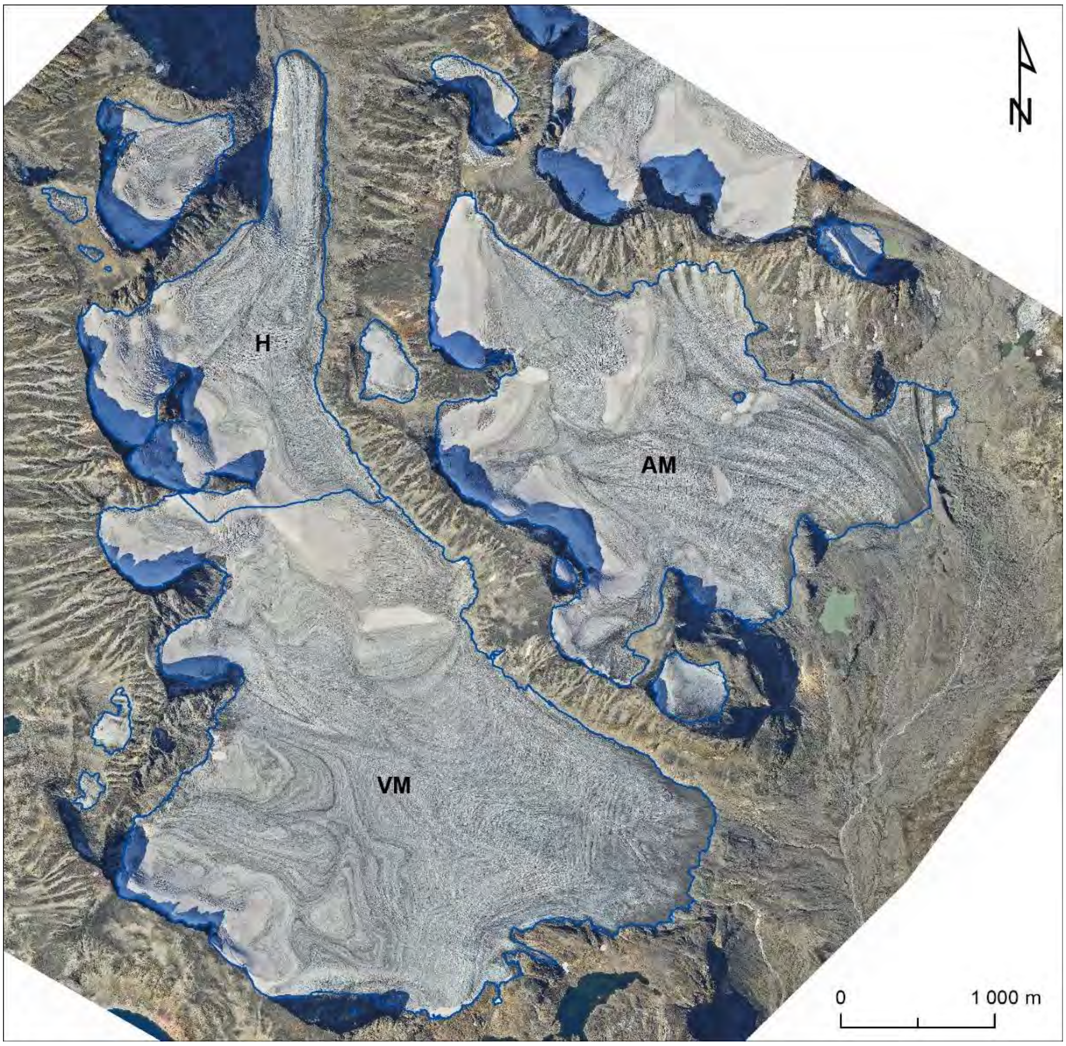


Figure 8-2
Orthophoto of Hellstugubreen (H), vestre Memurubre (VM), austre Memurubre (AM) and other nearby glaciers on 26th August 2019. See also Figure 8-3. Orthophoto: TerraTec AS.

8.2 Mass balance 2019

Field work

Accumulation measurements were performed on 30th April and 1st May. Snow depths were measured in 85 positions between 1511 and 2137 m a.s.l., covering most of the altitudinal range of the glacier (Fig. 8-3). The snow depth varied between 0.00 and 3.45 m, with a mean (median) of 1.22 (1.09) m. Snow density was measured in a density pit at 1945 m a.s.l. The total snow thickness measured was 1.5 m and the resulting density was 440 kg m^{-3}. Ablation measurements were carried out on 23rd when a layer of fresh snow covered much of the glacier, with the depth of new snow ranging from 1 cm at the lowest stakes to 47 cm at the highest located stake (Fig. 8-1).

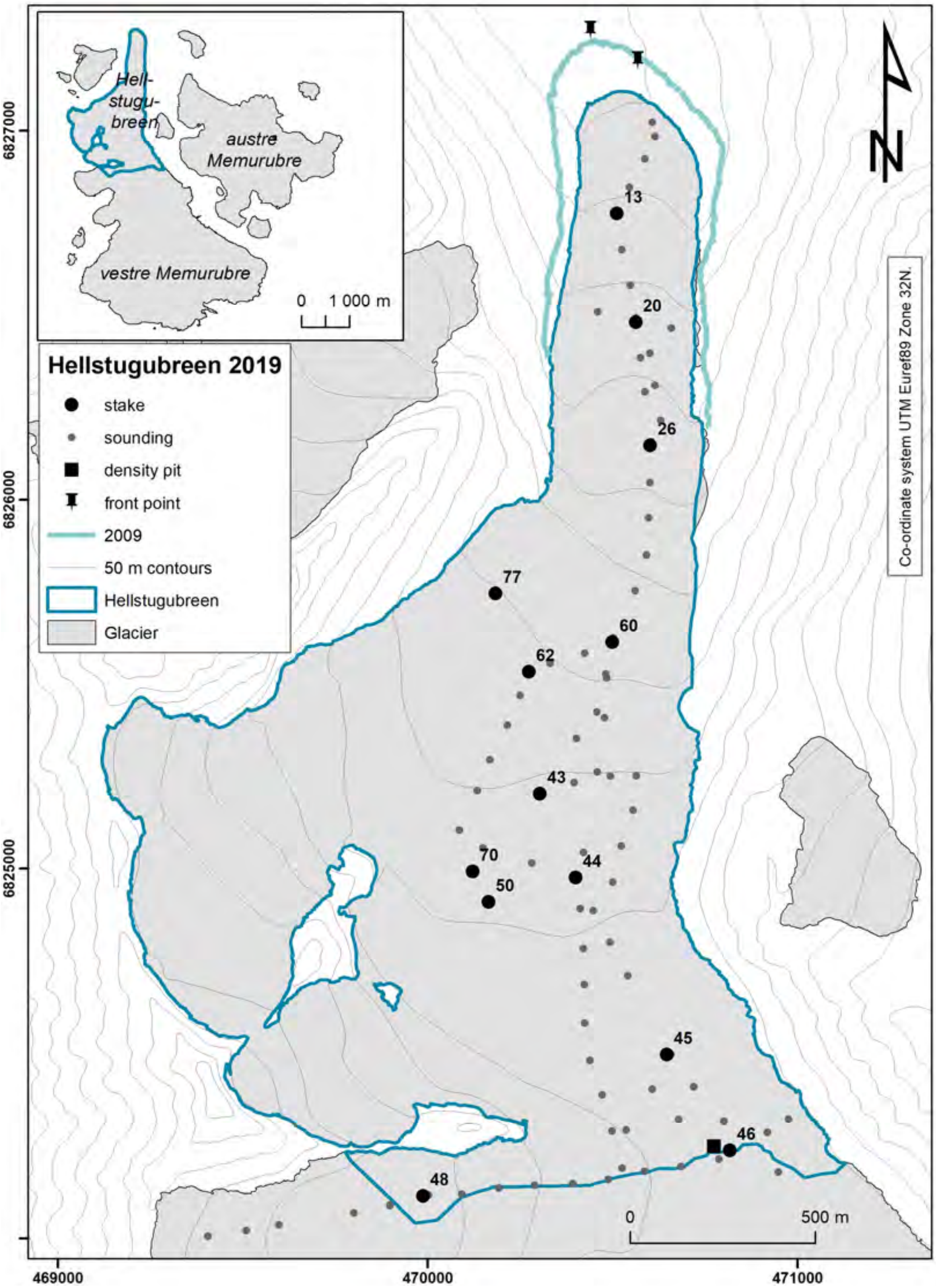


Figure 8-3
Map of Hellstugubreen showing the location of stakes, snow depth soundings and snow pit in 2019. Front point: reference points used for front position and length change measurements (chap. 12.1). The glacier retreated 80-150 m in this area between 2009 and 2019. Inset shows Hellstugubreen and surrounding glaciers.

Results

The calculations are based on the DTM from 2019. The winter balance was calculated as the mean of the soundings within each 50-metre height interval and was 0.60 ±0.2 m w.e., which is 54 % of the mean winter balance for the reference period 1981-2010, and the lowest winter balances on record. The summer balance was interpolated to 50 m height intervals based on the stake readings and was –2.47 ±0.3 m w.e., which is 163 % of the mean summer balance for the reference period 1981-2010. The annual balance of Hellstugubreen was −1.87 ±0.3 m w.e. The equilibrium line altitude (ELA) was above the highest stake at 2070 m a.s.l. and estimated to be above the highest point of the glacier. The ELA was not possible to observe in situ due to fresh snow (Fig. 8-1), but the orthophoto of 26th August 2019 reveals very little snow remaining already by the end of August (Fig. 8-2). The ELA was thus estimated to be >2213 m a.s.l., giving an accumulation area ratio (AAR) of 0 %. 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.

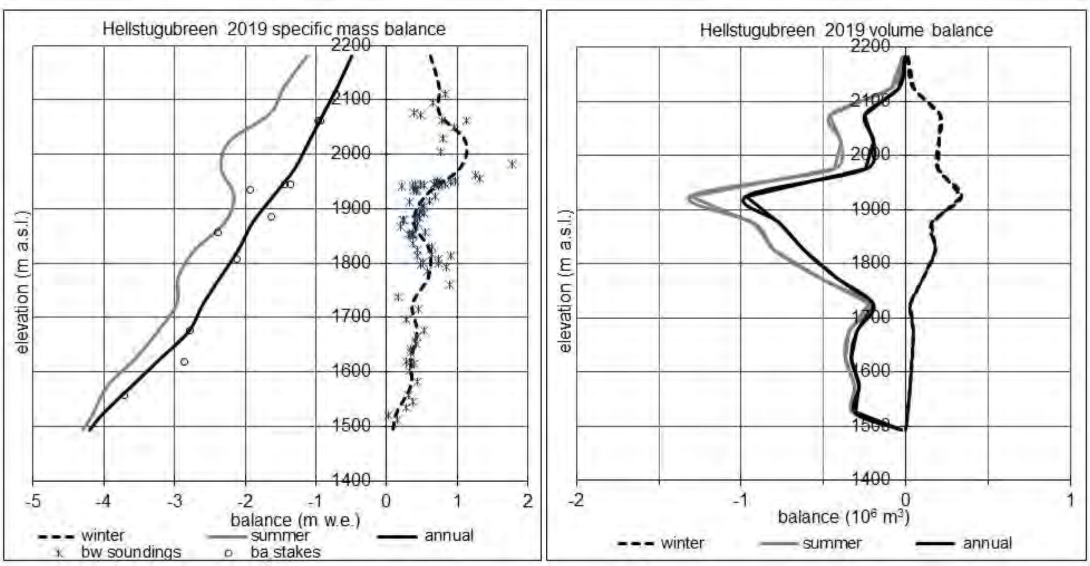


Figure 8-4
Mass balance diagram for Hellstugubreen in 2019, showing specific balance on the left and volume balance on the right. The winter balance soundings and annual balance at stakes are also shown.

Mass balance Hellstugubreen 2018/19							
		Winter balance Measured 30th April		Summer balance Measured 23rd Sep.		Annual balance 2018 - 2019	
Altitude (m a.s.l.)	Area (km^2)	Specific (m w.e.)	Volume (10^6 m^3)	Specific (m w.e.)	Volume (10^6 m^3)	Specific (m w.e.)	Volume (10^6 m^3)
2150 - 2213	0.017	0.62	0.01	-1.12	-0.02	-0.50	-0.01
2100 - 2150	0.060	0.74	0.04	-1.44	-0.09	-0.70	-0.04
2050 - 2100	0.278	0.75	0.21	-1.65	-0.46	-0.90	-0.25
2000 - 2050	0.178	1.11	0.20	-2.21	-0.39	-1.10	-0.20
1950 - 2000	0.186	1.04	0.19	-2.34	-0.43	-1.30	-0.24
1900 - 1950	0.607	0.56	0.34	-2.16	-1.31	-1.60	-0.97
1850 - 1900	0.404	0.38	0.15	-2.28	-0.92	-1.90	-0.77
1800 - 1850	0.295	0.61	0.18	-2.71	-0.80	-2.10	-0.62
1750 - 1800	0.181	0.59	0.11	-2.94	-0.53	-2.35	-0.43
1700 - 1750	0.076	0.36	0.03	-2.96	-0.23	-2.60	-0.20
1650 - 1700	0.107	0.43	0.05	-3.23	-0.35	-2.80	-0.30
1600 - 1650	0.104	0.35	0.04	-3.55	-0.37	-3.20	-0.33
1550 - 1600	0.079	0.34	0.03	-3.94	-0.31	-3.60	-0.28
1500 - 1550	0.077	0.14	0.01	-4.14	-0.32	-4.00	-0.31
1487 - 1500	0.007	0.09	0.00	-4.29	-0.03	-4.20	-0.03
1487 - 2213	**2.656**	**0.60**	**1.58**	**-2.47**	**-6.56**	**-1.87**	**-4.97**

Table 8-1
The distribution of winter, summer and annual balance in 50 m altitudinal intervals for Hellstugubreen in 2019.

8.3 Mass balance 1962-2019

The cumulative annual balance of Hellstugubreen since 1962 is –26 m w.e. (Fig. 8-5), giving a mean annual deficit of 0.44 m w.e. per year. The cumulative mass balance for the period 2009/2010 to 2018/2019 is –9.4 m w.e.

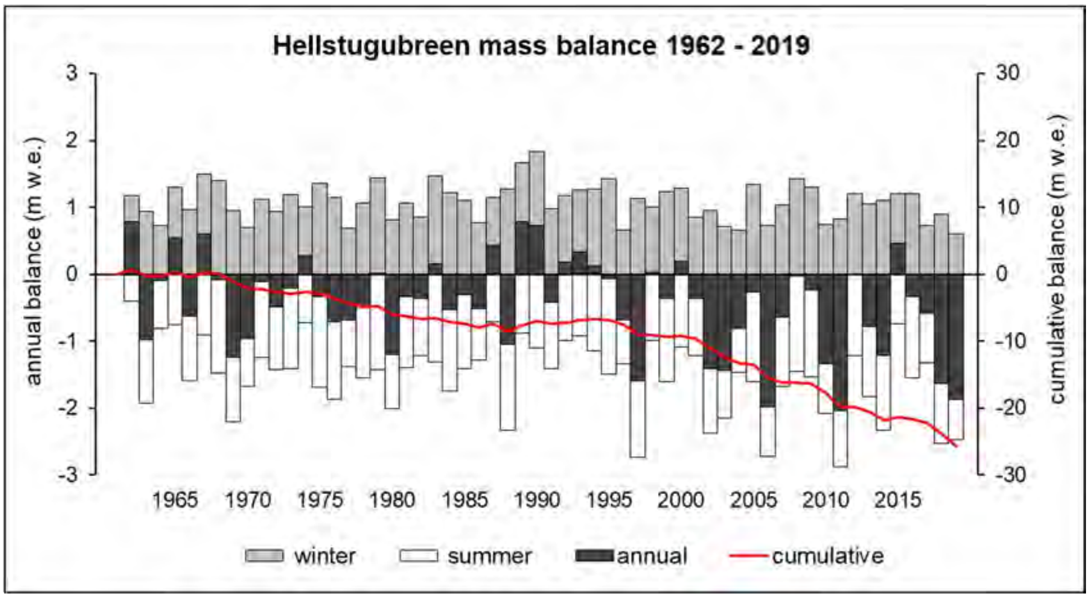


Figure 8-5
Winter, summer and annual balance at Hellstugubreen for 1962-2019, and cumulative mass balance for the whole period.

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 1.74 km^2 and ranges in elevation from 1854 to 2277 m a.s.l. (map of 2019). Mass balance investigations have been carried out annually since 1962.

Gråsubreen consists of relatively thin, cold ice which is underlain by a zone of temperate ice in the central, thicker part of the glacier. The distribution of accumulation and ablation at Gråsubreen is strongly dependent on the glacier geometry. In the central part of the glacier wind 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.

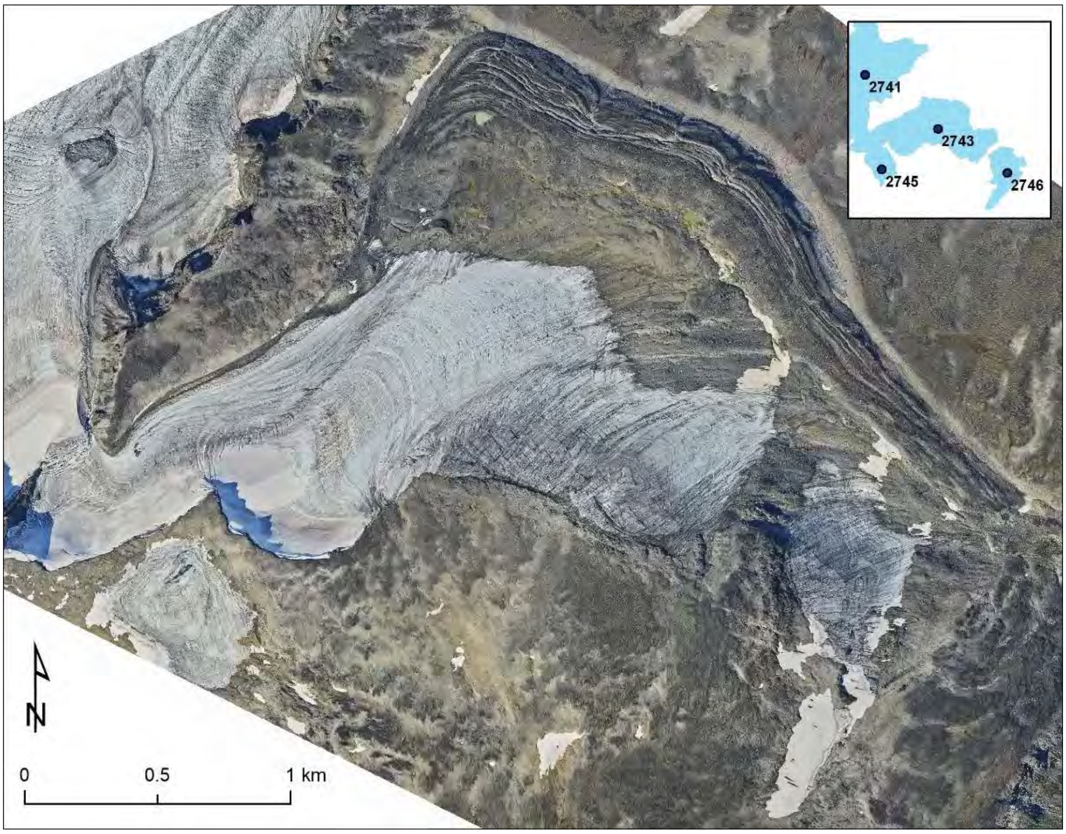


Figure 9-1
Orthohoto of Gråsubreen (ID 2743) and surrounding glaciers on 26th August 2019. Gråsubreen is attached to Austre Grotbrean (ID 2741) to the west. Note the well-defined ice-cored moraines to the northeast of the glacier marking its previous extent. The inset shows glacier ID numbers from the glacier inventory (Andreassen et al., 2012). Orthophoto: TerraTec AS.

9.1 Survey 2019

The previous detailed glacier survey used for glacier mass balance calculations was from 2009. To have an updated map of the glacier, laser scanning was conducted and aerial photographs were taken on 26th August 2019 by TerraTec AS (2019). The average point density of the laser point cloud was 2.0 points/m^2. The aerial photographs were used to create an orthophoto of 0.20 m resolution (Fig. 9-1).

The glacier outline from the 2019 survey was digitised on screen using the orthophotos, laser intensity values and a hillshade of the surface. A 5 m DTM was derived from the laser point cloud and used to calculate a new area-altitude distribution. The glacier area has reduced from 2.12 km^2 to 1.74 km^2 since 2009, a reduction of 17 %.

9.2 Mass balance 2019

Fieldwork

Accumulation measurements were performed on 11-12th June 2019. The calculation of winter balance is based on stake measurements and snow depth soundings in 88 positions between 1867 and 2270 m a.s.l. (Fig. 9-2). The snow depth varied between 0.00 and 2.60 with a mean and median of 0.54 and 0.44 m respectively. Much of the glacier had very little snow and the glacier melt season had already started at the time of measurement (Fig 9-2). The snow density was measured in a density pit near stake 5 (elevation 2102 m a.s.l.) where the total snow depth was 0.5 m and the mean density was 520 kg m^{-3}. Ablation measurements were carried out on 23rd September 2019, when all visible stakes were measured. A thin layer of snow covered parts of the glacier (Fig. 9-3). The calculation of annual balance was based on stakes in 7 different positions.

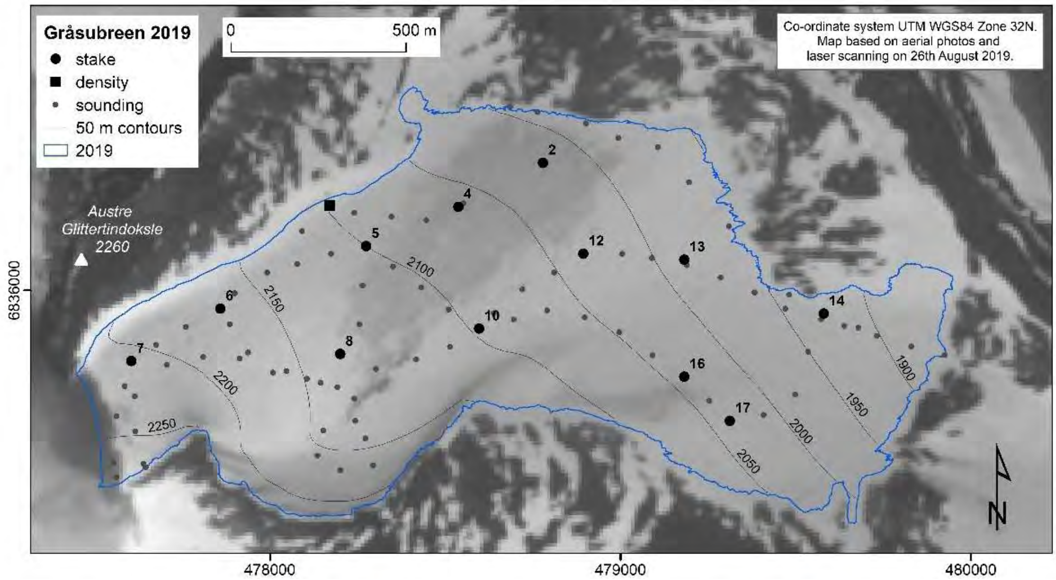


Figure 9-2
Map of Gråsubreen showing the location of stakes, density pit and soundings in 2019. The background image shows band 8 (Near-infrared (NIR) 0.78–0.90 µm) of a Sentinel 2 image taken on 10th June 2019, the day prior to the accumulation measurements. Part of the glacier, including stakes 2 and 4, had bare ice at the time of snow measurements. ***/Copernicus Sentinel data 2019/***

Figure 9-3
Measurement of stake 6 on 23rd September 2019. A thin layer of fresh snow covered part of the glacier at the time of the minimum measurements. Photo: Liss M. Andreassen.

Results

The winter balance was calculated as the mean of the soundings within each 50-metre height interval. This gave a winter balance of 0.27 ±0.1 m w.e., which is 34 % 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 −1.96 ±0.3 m w.e., which is 167 % of the mean summer balance for the reference period 1981-2010.

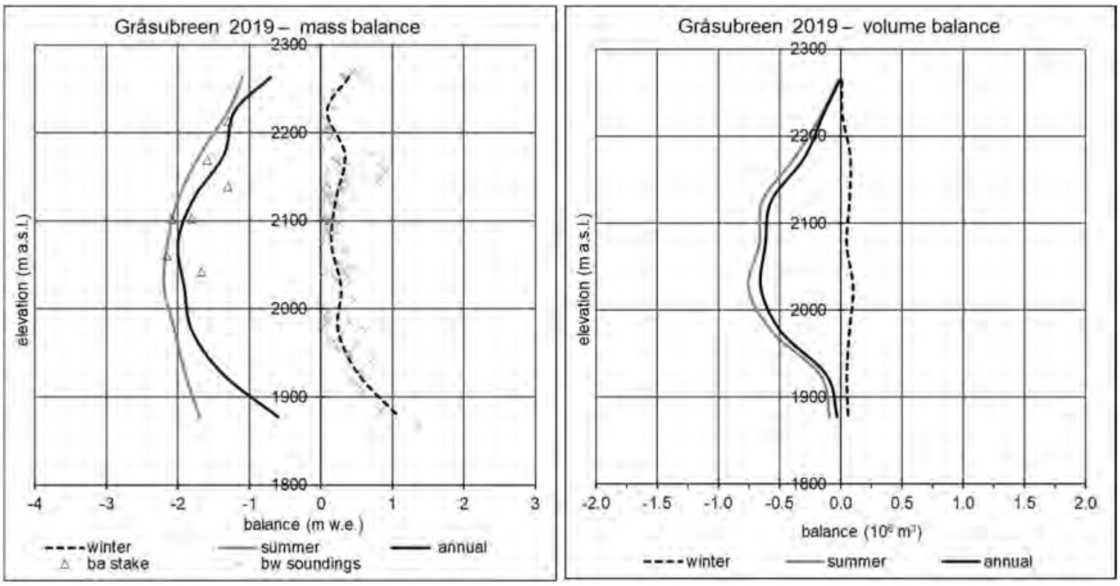


Figure 9-4
Mass balance diagram for Gråsubreen for 2019, showing specific balance on the left and volume balance on the right. Winter and summer balance at the stakes and individual snow depth soundings are also shown.

The annual balance of Gråsubreen was negative in 2019 at −1.69 ±0.3 m w.e. The ELA and AAR were not defined from the mass balance curve or in the field. However, only limited parts had snow remaining on 26th of August 2019 (Fig 9-1).

The mass balance results are shown in Table 9-1 and the corresponding curves for specific and volume balance are shown in Figure 9-4.

Mass balance Gråsubreen 2018/19

Altitude (m a.s.l.)	Area (km²)	Winter balance Measured 11th June		Summer balance Measured 23rd Sep.		Annual balance 2018 - 2019	
		Specific (m w.e.)	Volume (10^6 m³)	Specific (m w.e.)	Volume (10^6 m³)	Specific (m w.e.)	Volume (10^6 m³)
2250 - 2277	0.02	0.39	0.01	-1.10	-0.02	-0.71	-0.01
2200 - 2250	0.12	0.09	0.01	-1.30	-0.16	-1.21	-0.15
2150 - 2200	0.22	0.34	0.08	-1.70	-0.38	-1.36	-0.30
2100 - 2150	0.32	0.21	0.07	-2.00	-0.64	-1.79	-0.57
2050 - 2100	0.31	0.15	0.05	-2.15	-0.66	-2.00	-0.62
2000 - 2050	0.34	0.29	0.10	-2.20	-0.75	-1.91	-0.65
1950 - 2000	0.27	0.25	0.07	-2.05	-0.56	-1.80	-0.49
1900 - 1950	0.09	0.53	0.05	-1.90	-0.17	-1.37	-0.12
1854 - 1900	0.05	1.10	0.06	-1.70	-0.09	-0.60	-0.03
1854 - 2277	**1.74**	**0.27**	**0.48**	**-1.96**	**-3.42**	**-1.69**	**-2.95**

Table 9-1
The distribution of winter, summer and annual balance in 50 m altitudinal intervals for Gråsubreen in 2019.

9.3 Mass balance 1962-2019

The cumulative annual balance of Gråsubreen is –26 m w.e. since measurements began in 1962 (Fig. 9-5). The average annual balance is hence –0.44 m w.e. a^{-1}.

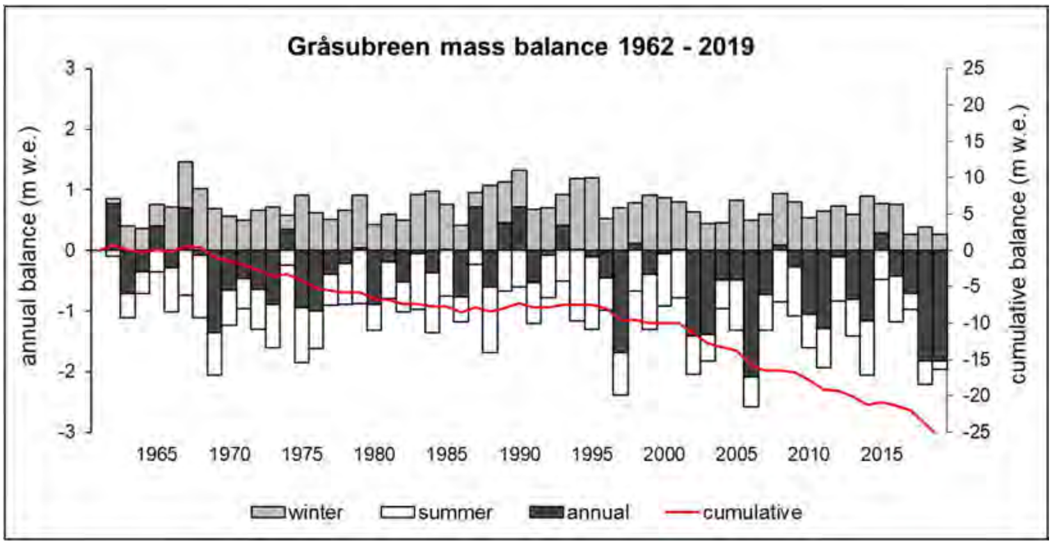


Figure 9-5
Winter, summer and annual balance for Gråsubreen for 1962-2019, and cumulative mass balance for the whole period.

10. Engabreen (Hallgeir Elvehøy and Miriam Jackson)

Engabreen (66°40′N, 13°45′E) is a 36 km^2 north-western outlet from the western Svartisen ice cap (Fig. 10-1). It covers an altitude range from 1544 m a.s.l. at Snøtinden 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 2019 are presented in chapter 10.3.

Figure 10-1
The terminus of Engabreen on 18th July 2019. The ice blocks in front of the glacier illustrate the potential danger for visitors who come too close. Photo: Miriam Jackson.

10.1 Mass balance 2019

Fieldwork

Stakes in four locations on the plateau were checked on 20th February and showed between 3.5 and 6.3 metres of snow.

The snow accumulation measurements were performed on 21st May. Four 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 3.8 and 8.8 metres. The summer surface was difficult to define in the upper part of the glacier. The mean snow density down to the summer surface at 7.0 m depth at stake E5 was 546 kg m^{-3}. At stake E17 on the glacier tongue 1.35 m of glacier ice had melted since 26th October 2018.

The stakes were checked on 31st July. The stakes on the glacier plateau were 2.9 to 4.2 metres longer than in May. On the glacier tongue 4.75 m of ice had melted, and the stake was re-drilled. Due to glacier recession the glacier tongue has become steeper, and access to the lowermost stake in location E17 has become more difficult. An alternative stake location about 150 m higher up on the glacier tongue was established to eventually replace E17.

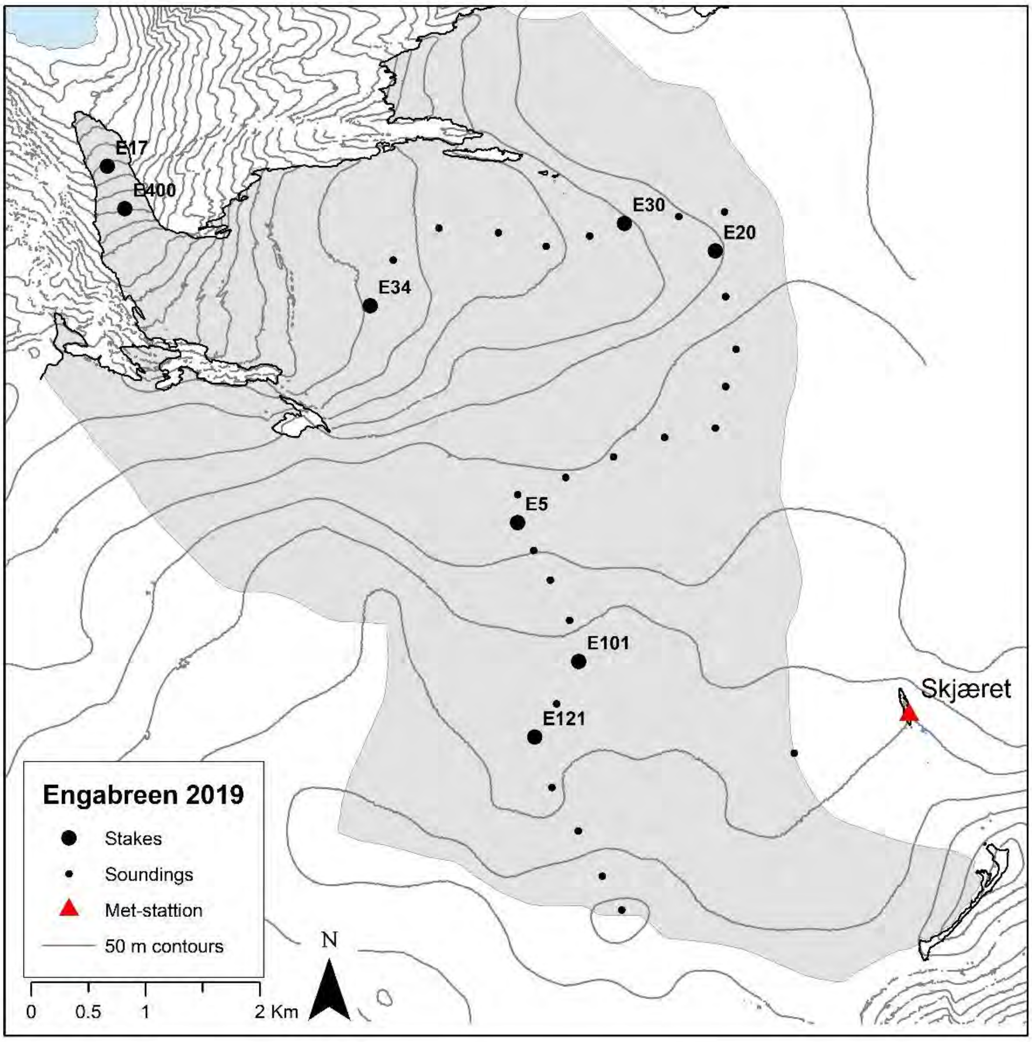


Figure 10-2
Location of stakes and soundings on Engabreen in 2019. The map is based on satellite imagery from 16th August 2016.

The summer ablation measurements were carried out on 27th September. There was up to 0.35 m of new snow at the stakes. Stakes were found in six locations on the plateau. Between 2 and 2.5 m of snow had melted since 31st July, and up to 3.5 metres remained at the uppermost stakes. From the stake measurements, the temporary snow line altitude at the end of the melt season was around 1100 m a.s.l. (Fig. 10-3). At stake E34, 960 m a.s.l., all the winter snow and 2.7 m of ice melted during the summer. At stakes E17 and E400 on the glacier tongue 3.5 and 3.45 metres of ice had melted since 31st July.

Results

The calculations are based on a DTM from 16th August 2016. The date of the 2019 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 glacier plateau on 17th September 2019.

The winter balance for 2019 was calculated from the snow depth and snow density measurements. The specific winter balance was calculated as 3.45 ±0.2 m w.e. This is 134 % of the average winter balance for the normal period 1981-2010 (2.58 m w.e. a^{-1}).

The point summer balance was calculated directly for seven stake locations between 290 and 1340 m a.s.l. The specific summer balance was calculated from the summer balance curve drawn from these seven point values (Fig. 10-4) as −2.7 ±0.2 m w.e. This is 103 % of the average summer balance for the normal period 1981-2010 (−2.60 m w.e. a^{-1}). The resulting annual balance was +0.8 ±0.3 m w.e. (Tab. 10-1). The ELA was 1090 m a.s.l. and consequently the AAR was 76 %.

Figure 10-3
Stake E20 on 27th September 2018. All the winter snow (5.25 m) and 10 cm of firn from 2017 had melted during the summer. The surface was covered with 15 cm of new snow. Photo: Hallgeir Elvehøy.

Table 10-1
Specific and volume winter, summer and annual balance calculated for 100 m elevation intervals at Engabreen in 2019.

Mass balance Engabreen 2018/19 – stratigraphic system

Altitude (m a.s.l.)	Area (km²)	Winter mass balance Measured 21. May 2019		Summer mass balance Measured 27. Sep 2019		Annual mass balance Summer surface 2018 - 2019	
		Specific (m w.e.)	Volume (10^6 m³)	Specific (m w.e.)	Volume (10^6 m³)	Specific (m w.e.)	Volume (10^6 m³)
1500 - 1544	0.05	4.00	0.2	-1.90	-0.1	2.10	0.1
1400 - 1500	2.13	4.70	10.0	-1.90	-4.0	2.80	6.0
1300 - 1400	9.24	4.50	41.6	-2.00	-18.5	2.50	23.1
1200 - 1300	8.04	3.70	29.8	-2.10	-16.9	1.60	12.9
1100 - 1200	7.57	3.00	22.7	-2.50	-18.9	0.50	3.8
1000 - 1100	4.61	2.85	13.1	-3.20	-14.7	-0.35	-1.6
900 - 1000	2.43	2.30	5.6	-4.50	-10.9	-2.20	-5.3
800 - 900	0.80	1.80	1.4	-4.90	-3.9	-3.10	-2.5
700 - 800	0.46	1.30	0.6	-5.30	-2.4	-4.00	-1.8
600 - 700	0.29	0.80	0.2	-5.65	-1.6	-4.85	-1.4
500 - 600	0.25	0.30	0.1	-6.00	-1.5	-5.70	-1.4
400 - 500	0.14	-0.30	0.0	-6.60	-1.0	-6.90	-1.0
300 - 400	0.10	-0.90	-0.1	-7.20	-0.7	-8.10	-0.8
200 - 300	0.12	-1.40	-0.2	-7.80	-0.9	-9.20	-1.1
111 - 200	0.04	-1.80	-0.1	-8.40	-0.3	-10.20	-0.4
111 - 1544	**36.25**	**3.45**	**125.0**	**-2.66**	**-96.4**	**0.79**	**28.6**

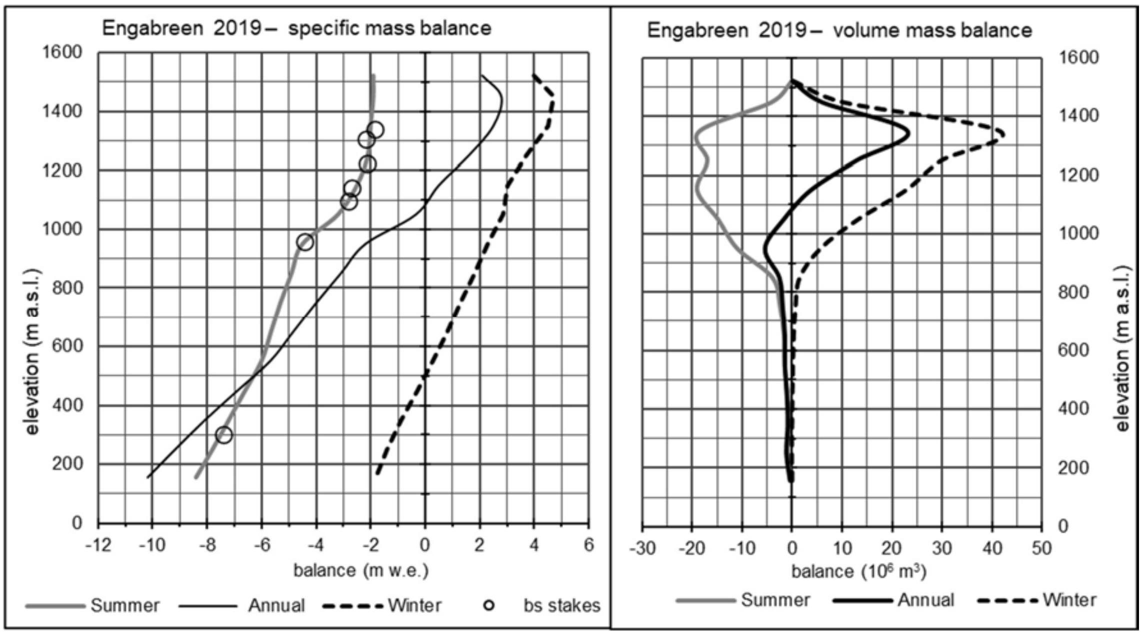


Figure 10-4
Mass balance diagram showing specific balance (left) and volume balance (right) for Engabreen in 2019. Summer balance at seven stake locations (○) is shown.

10.2 Mass balance 1970 - 2019

The annual surface mass balance at Engabreen for 1970-2019 is shown in Figure 10-4. The cumulative surface mass balance since the start of mass balance investigations at Engabreen is +0.1 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 22 years (1997-2019), the glacier volume has decreased by 7.3 m w.e., or 0.33 m w.e. a^{-1} (Fig. 10-5).

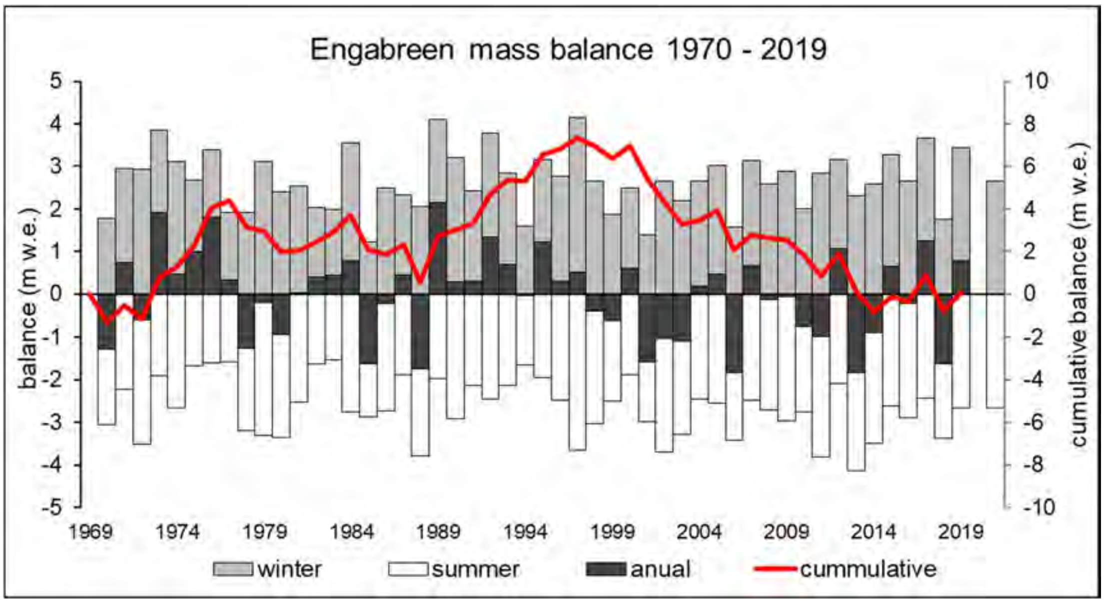


Figure 10-5
Mass balance at Engabreen during the period 1970-2019.Cumulative mass balance is given on the right axis. The average winter and summer balances are B_w =2.66 m w.e. and B_s =−2.66 m w.e.

10.3 Meteorological observations

A meteorological station recording air temperature and global radiation at 3 m above ground level is located on a the nunatak Skjæret (1364 m a.s.l.) close to the drainage divide between Engabreen and Storglombreen (Fig. 10-2). The station has been operating since 1995. Data were collected continously without gaps in 2019.

The mean summer temperature (1st June – 30th September) at Skjæret in 2019 was 3.8 °C. The average summer temperature for 19 years between 1995 and 2018 is 3.00 °C. The melt season on the upper part of the glacier plateau started on 17th May and probably lasted until 29th September. The period between 19th and 31st July was particularly warm with a mean daily temperature in this period of 10.8 °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).

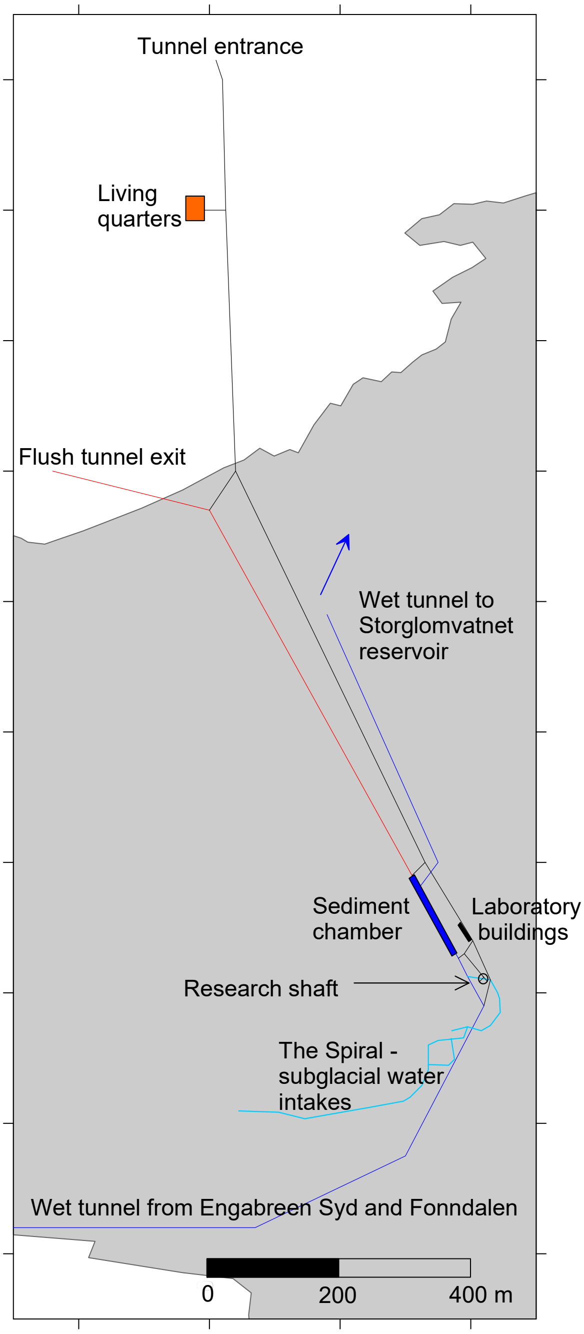


Figure 10-6
Map of tunnel system under Engabreen, showing research shaft and other facilities.

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. All load cells are installed at the glacier-bedrock interface within 20 m of each other. Four load cells are still in operation and recording data. The inter-annual variability of the load cells is examined in detail in Lefeuvre et al. (2015).

Due to equipment problems in 2019 and 2020, and limited access to the subglacial laboratory, there are very few data for 2019, and the first few months of 2020 are missing. Hence, 2019 and 2020 data will be combined and reported in the next annual glacier report. As always, these data are available for research on request.

Seismic data are also recorded in the subglacial tunnel.

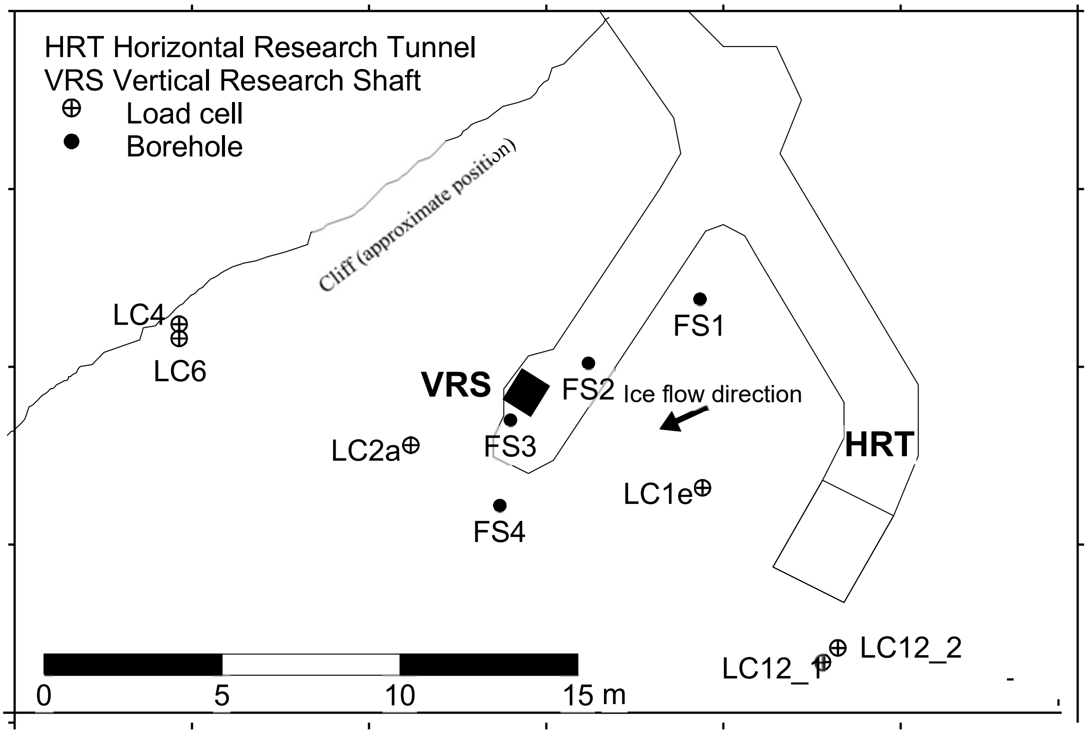


Figure 10-7
Research shaft showing locations of horizontal research tunnel (HRT), vertical research shaft (VRS) and load cells (LC). Boreholes from the tunnel to the glacier bed (FS) are also shown.

11. Langfjordjøkelen (Bjarne Kjøllmoen)

Langfjordjøkelen (70º10′N, 21º45′E) is a plateau glacier situated on the border of Troms and Finnmark counties, approximately 60 km northwest of the city of Alta. It has an area of about 6.2 km^2 (2018), and of this 2.6 km^2 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 2019 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 8th August 2019. Photo: Hallgeir Elvehøy.

11.1 Mass balance 2019

Fieldwork

Snow accumulation was measured on 23rd May and the calculation of winter balance was based on measurements of 60 snow depth soundings (Fig. 11-2). The snow depth varied between 0.3 and 6.0 m with an average of 4.1 m. Snow density was measured in position 25 (702 m a.s.l.) and the mean density of 3.9 m snow was 549 kg m^{-3}.

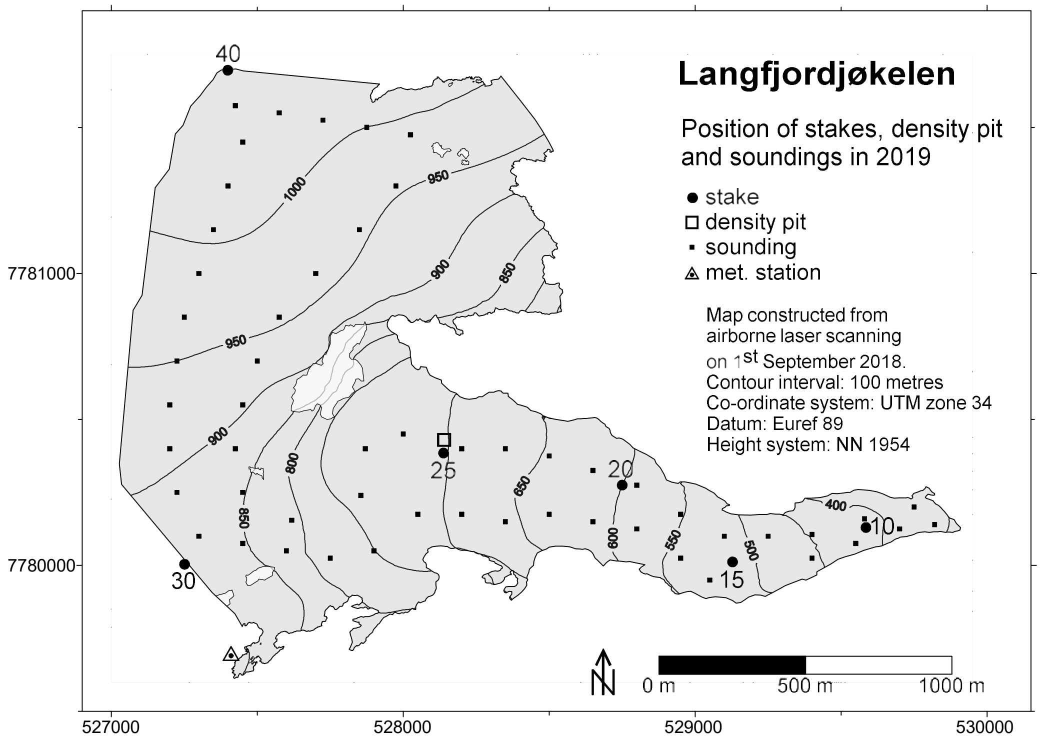


Figure 11-2
Location of stakes, soundings and snow pit at Langfjordjøkelen in 2019.

Ablation was measured on 27th September. The annual balance was measured at stakes in six locations (Fig. 11-2). There was no snow remaining on the glacier from the winter season 2018/19. At the time of measurement up to 40 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 2.5 ±0.2 m w.e., which is 122 % of the mean winter balance for the periods 1989-93 and 1996-2018. Spatial distribution of the winter balance is shown in Figure 11-3.

The ablation stakes cover elevations from the glacier summit to 412 m a.s.l. Based on estimated density and stake measurements the summer balance was also calculated as a mean value for each 50 m height interval and was −2.9 ±0.3 m w.e., which is 96 % of the mean summer balance for 1989-93 and 1996-2018.

Hence, the annual balance was negative, at −0.4 ±0.4 m w.e. The mean annual balance for 1989-93 and 1996-2018 is −0.96 m w.e. The mean annual balance for the past ten years (2010-19) is −1.06 m w.e.

The mass balance results are shown in Table 11-1 and the corresponding curves for specific and volume balance are shown in Figure 11-4.

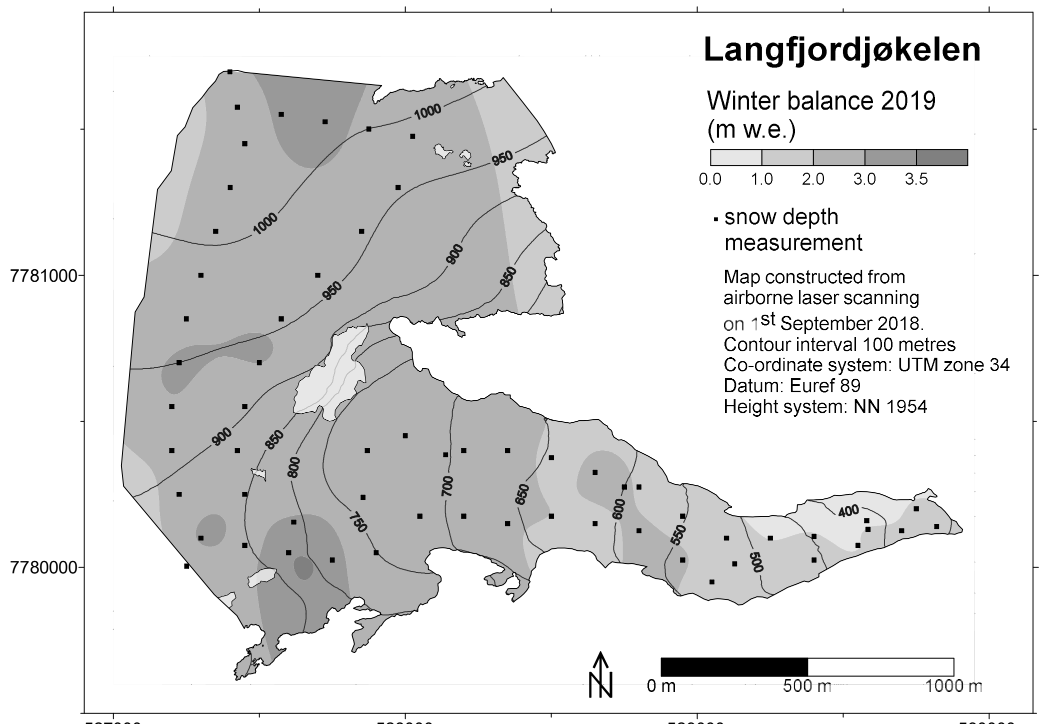


Figure 11-3
Spatial distribution of winter balance at Langfjordjøkelen in 2019.

The ELA and AAR could not be defined from the mass balance curve in Figure 11-4.

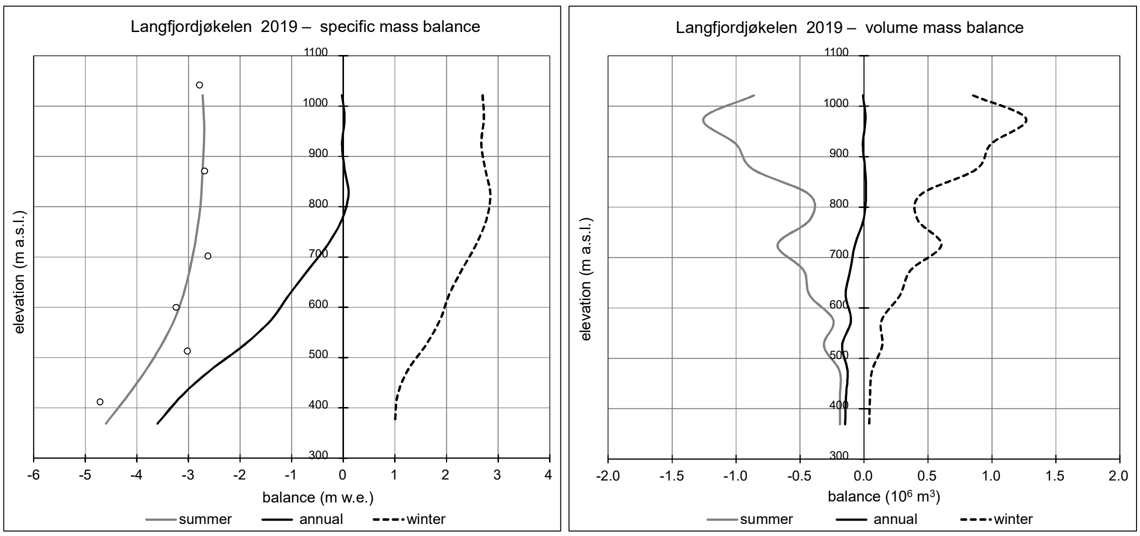


Figure 11-4
Mass balance diagram showing specific balance (left) and volume balance (right) for Langfjordjøkelen in 2019. Specific summer balance for six stakes is shown as circles (○).

Table 11-1
Winter, summer and annual balance for Langfjordjøkelen in 2019.

Mass balance Langfjordjøkelen 2018/19 – stratigraphic system

Altitude (m a.s.l.)	Area (km^2)	Winter mass balance Measured 23rd May 2019 Specific (m w.e.)	Volume (10^6 m^3)	Summer mass balance Measured 27th Sep 2019 Specific (m w.e.)	Volume (10^6 m^3)	Annual mass balance Summer surface 2018 - 2019 Specific (m w.e.)	Volume (10^6 m^3)
1000 - 1043	0.32	2.70	0.9	-2.73	-0.9	-0.02	0.0
950 - 1000	0.47	2.73	1.3	-2.70	-1.3	0.02	0.0
900 - 950	0.37	2.68	1.0	-2.70	-1.0	-0.03	0.0
850 - 900	0.32	2.75	0.9	-2.73	-0.9	0.02	0.0
800 - 850	0.16	2.85	0.4	-2.75	-0.4	0.10	0.0
750 - 800	0.15	2.78	0.4	-2.80	-0.4	-0.02	0.0
700 - 750	0.24	2.58	0.6	-2.88	-0.7	-0.30	-0.1
650 - 700	0.16	2.30	0.4	-2.98	-0.5	-0.68	-0.1
600 - 650	0.14	2.05	0.3	-3.10	-0.4	-1.05	-0.1
550 - 600	0.07	1.88	0.1	-3.28	-0.2	-1.40	-0.1
500 - 550	0.09	1.60	0.1	-3.53	-0.3	-1.93	-0.2
450 - 500	0.05	1.25	0.1	-3.83	-0.2	-2.58	-0.1
400 - 450	0.04	1.05	0.0	-4.18	-0.2	-3.13	-0.1
338 - 400	0.04	1.00	0.0	-4.60	-0.2	-3.60	-0.1
338 - 1043	**2.61**	**2.51**	**6.5**	**-2.89**	**-7.5**	**-0.38**	**-1.0**

11.2 Mass balance 1989-2019

The historical mass balance results for Langfjordjøkelen are presented in Figure 11-5. The cumulative annual balance for 1989-2019 (estimated values for 1994 and 1995 included) is –27.9 m w.e., which gives a mean annual balance of –0.90 m w.e. a^{-1}.

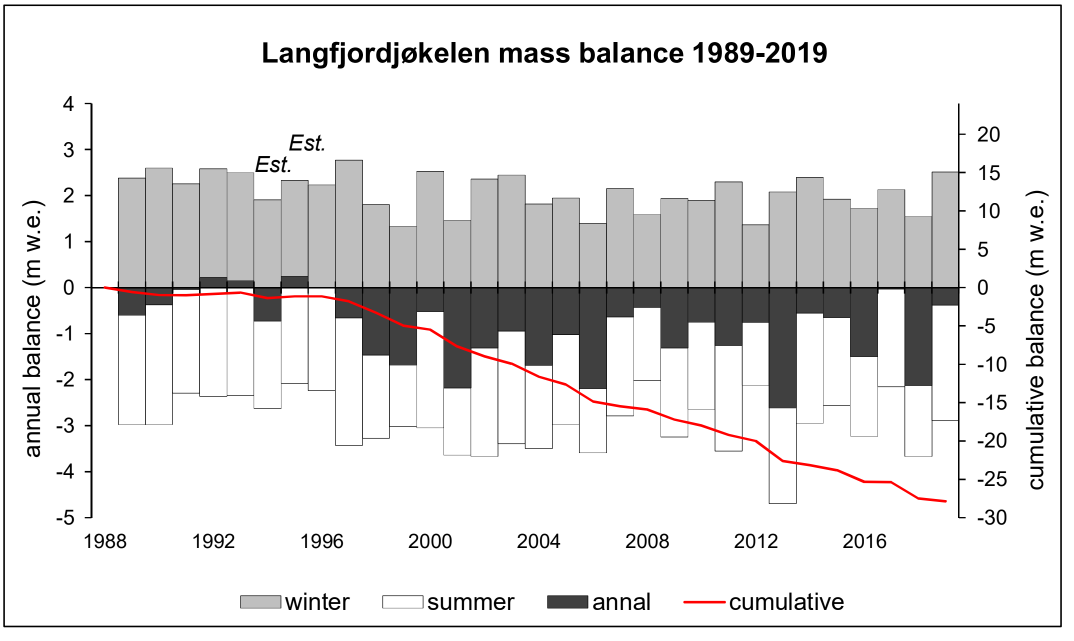


Figure 11-5
Mass balance at Langfjordjøkelen for the period 1989-2019. The total accumulated mass loss for 1989-2019 is 27.9 m w.e. (includes estimated values for 1994 and 1995).

11.3 Meteorological observations

A meteorological station (Langfjord Met) recording air temperature, global radiation, wind speed and wind direction at 3 m above ground level is located on rock south of the glacier (915 m a.s.l., Fig. 11-2) 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 2012-2019 only.

The mean summer temperature (1st June – 30th September) at Langfjord Met in 2019 was 5.5 °C. The mean summer temperature for 2009-10 and 2012-18 was 4.5 °C. The melt season on the upper part of the glacier (above 900 m a.s.l.) started about 27th May and lasted until about 16th September. A few days in July (20th-26th) were particularly warm with a mean daily temperature of 14.8 °C. The monthly summer temperatures were 3.4 °C (June), 8.6 °C (July), 7.3 °C (August) and 2.6 °C (September).

11.4 Ice velocity

The surface ice velocity was calculated from repeated GNSS measurements of six stakes. The positions of the stakes were measured on 12th October 2018, and 8th August and 27th September 2019.

The positions were measured using Topcon GR3 dual frequency GNSS receivers placed in the top of, or close to the stakes (Fig. 11-6). The GNSS data were post-processed using the software program "Topcon Tools" and data from the SATREF reference station Loppa.

Figure 11-6
GNSS measurements on Langfjordjøkelen in August 2019. Photo: Hallgeir Elvehøy.

The calculated surface ice velocities show mean annual velocities between 0.1 m a^{-1} at the top of the ice cap and 7.6 m a^{-1} in the middle of the glacier (Fig. 11-7). The uncertainty of the GNSS positioning is assumed to be ±0.5 m.

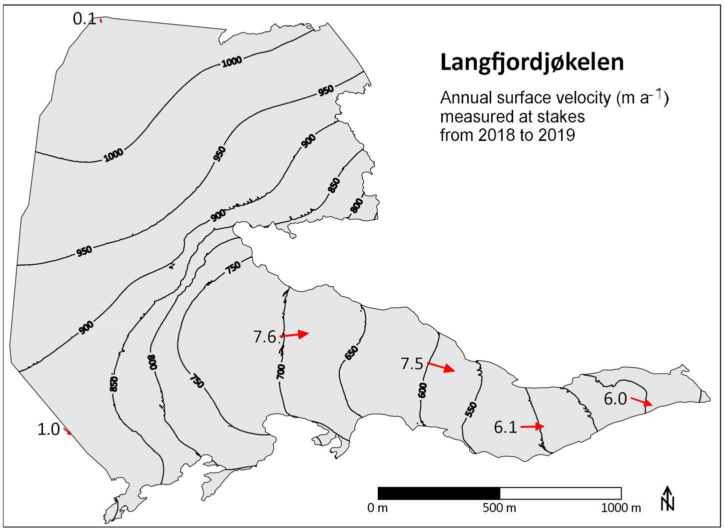


Figure 11-7
Map of Langfjordjøkelen showing mean annual surface velocities calculated from stake position measurements in October 2018 and August and September 2019.

12. Glacier monitoring

(Hallgeir Elvehøy and Miriam Jackson)

12.1 Glacier length change

Observations of glacier length change at Norwegian glaciers started in 1899 (Rekstad, 1902, Øyen 1906). Since then, glacier length change has been measured over several years at 73 glaciers. The total number of observations up to 2019 is 2795. The median and mean number of observations for a single glacier is 26 and 38, respectively, indicating many glaciers with few observations. The median and mean number of observations in one year is 21 and 23 glaciers, respectively. In 1911, 45 glaciers were measured, and in 1992 only 8 glaciers were measured.

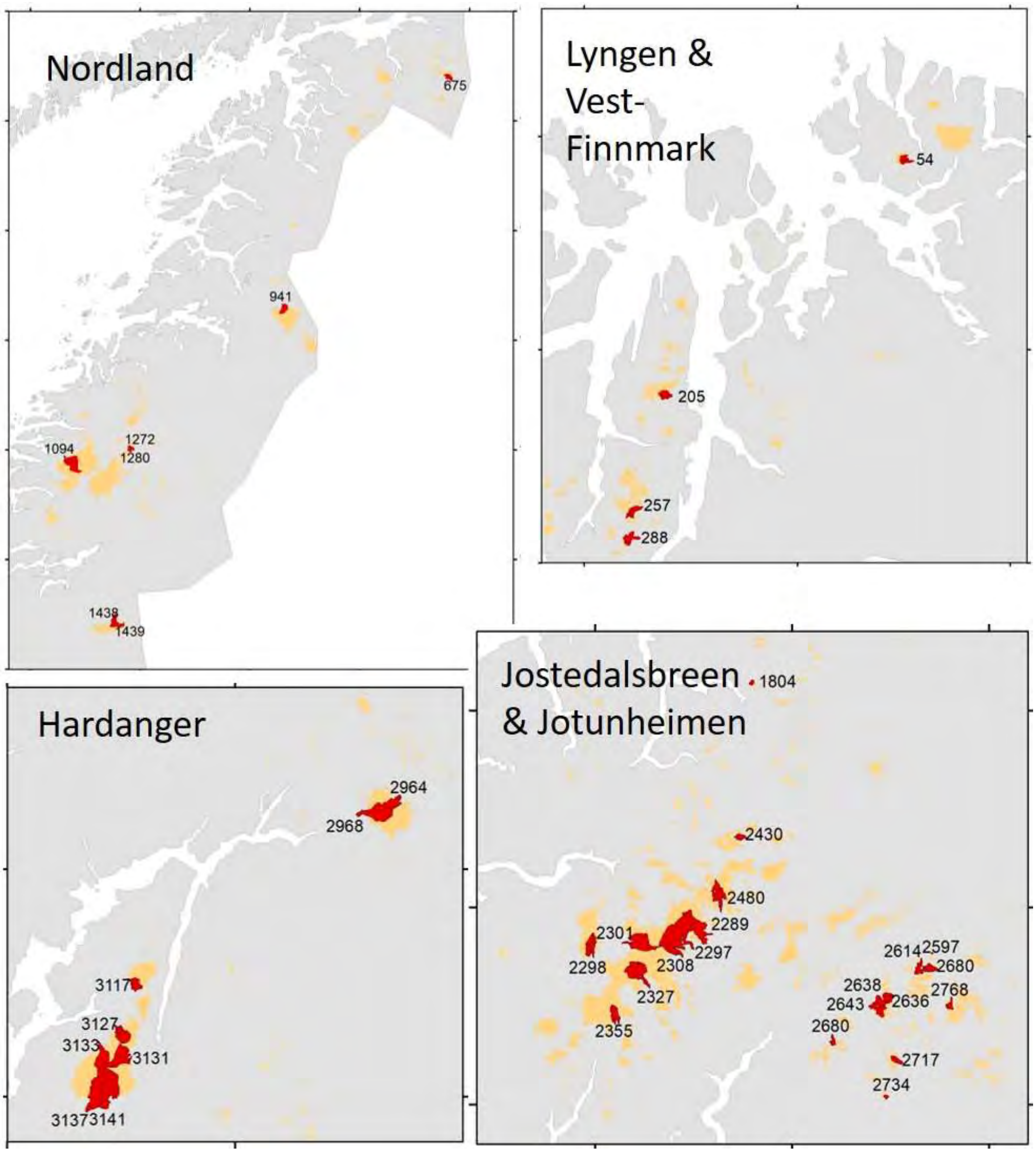


Figure 12-1
Map showing glaciers included in the length change monitoring programme (in red) with glacier IDs (Tab. 12-1). Note that the different glacier areas are not to the same scale.

Figure 12-2
Styggedalsbreen (Glacier ID 2680) on 23rd September 2019 seen from the reference point STYG2006. The reference point is located on the moraine ridge formed during an advance in the 1990s. The proglacial lake has formed as the glacier retreated 165 metres since 2000. Length change observations started in 1901 and the total retreat since 1901 is 614 metres. Photo: Jostein Aasen.

At Briksdalsbreen, the length change was measured 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. Styggedalsbreen in Jotunheimen (Fig. 12-2) has 98 observations. 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 87 measurements since 1903. 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 constitute about 14 % of the glacier area in Norway (Andreassen et al., 2012).

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. How representative a single distance measurement between one reference point to the generally irregular glacier front is questionable. However, when longer periods are considered the measurements give valuable information about glacier fluctuations, as well as regional tendencies and variations (Andreassen et al., 2020).

Table 12-1
Glacier length change measured in 2019. See Figure 12-1 for glacier locations.

	Glacier	Glacier-ID	2019	Observer	Period(s)	Number obs.
Finnmark & Troms	Langfjordjøkelen	54	-11	NVE	1998-	23
	Koppangsbreen	205	-13	NVE	1998-	20
	Sydbreen	257	-7	NVE	2007-	12
	Steindalsbreen	288	-48	NVE	1998-	27
Nordland	Storsteinsfjellbreen	675	-63*	NVE	2006-	15
	Rundvassbreen	941	-58	SISO	2011-	7
	Engabreen	1094	-61	S	1903-	87
	Skjelåtindbreen	1272	-14**	NVE	2014-	2
	Trollbergdalsbreen	1280	-49**	NVE	2010-	5
	Austre Okstindbreen	1438	-87**	NVE	1908-44, 2006-	27
	Corneliussenbreen	1439	NM	NVE	2006-	8
Sunnmøre & Breheimen	Trollkyrkjebreen	1804	-16	NVE	1944-74, 2008-	23
	Heimsta Mårådalsbreen	2430	NM	NVE	2002-	5
Jostedalsbreen	Fåbergstølsbreen	2289	-5	NVE	1899-	114
	Nigardsbreen	2297	-81	NVE	1899-	109
	Haugabreen	2298	-7	NBM	1933-41, 2013-	14
	Brenndalsbreen	2301	-10	NVE	1900-62, 1964-65, 1996-	82
	Tuftebreen	2308	-8	NVE	2007-	12
	Austerdalsbreen	2327	-30	NVE	1905-19, 1933-	100
	Vetle Supphellebreen	2355	-22	NBM	1899-44, 2011-	44
	Stigaholtbreen	2480	-18	NVE	1903-	113
Jotunheimen	Juvfonne	2597	-9	NVE	2010-	7
	Styggebrean	2608	-26	NFS	1951-63, 2011-	17
	Storjuvbrean	2614	-16	NVE	1901-07, 08-12, 33-61, 97-	59
	Storbreen	2636	-4	NVE	1902-	81
	Leirbrean	2638	--28	NVE	1907-77, 1979-	60
	Bøverbrean	2643	-10	NVE	1903-76, 1997-	46
	Styggedalsbreen	2680	-22	NVE	1901-	98
	Mjølkedalsbreen	2717	-31	BL	1978-	24
	Koldedalsbreen	2734	NM	BL	1978-	14
	Hellstugubreen	2768	-12	NVE	1901-	80
Hardanger	Midtdalsbreen	2964	-28	AN	1982-	37
	Rembesdalskåka	2968	-27	S	1917-	44
	Botnabrea	3117	-102*	GK	1996-	17
	Gråfjellsbrea	3127	-82	S	2002-	17
	Buerbreen	3131	-15	NVE	1900-	73
	Bondhusbrea	3133	-31	S	1902-	88
	Svelgjabreen	3137	-4	SKL	2007-	12
	Blomstølskardsbreen	3141	-40	SKL	1994-	20

* – two years, ** – three years,
NM – not measured in 2019

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

Results 2019

Thirty-six glaciers were measured - ten glaciers in northern Norway and 26 glaciers in southern Norway. The results for 2019, period(s) of measurements and number of observations (calculated length changes) are listed in Table 12-1. All 36 glaciers retreated in 2019. The annual length change varied from −4 m at Storbrean and Svelgjabreen to−81 m at Nigardsbreen and −82 m at Gråfjellsbrea. The average cumulative length change for the ten-year period 2009-19 for 29 glaciers is −197 metres, ranging from −584 metres at Gråfjellsbrea, and −39 metres at Svelgjabreen. Both glaciers are outlet glaciers from the southern part of Folgefonna. Three glaciers in the monitoring programme were not measured in 2019. Data are available at www.nve.no/glacier.

Revision of the length change record for Fåbergstølsbreen

Background

Fåbergstølsbreen is an eastern outlet from Jostedalsbreen. The glacier area is 20.3 km^2, the elevation interval from 720 to 1980 m a.s.l., and length is about 6.5 km (Andreassen et al., 2012). Glacier length change measurements at Fåbergstølsbreen started in 1899 (Rekstad, 1902; 1904). This record is one of the longest continuous records in Norway spanning 120 years. The original reference marks from 1899 were located in 2019 (Fig. 12-3).

In a length change record, cumulative glacier length change should agree with distance between mapped glacier termini, and the cumulative length change should be the same in years when the glacier terminus is 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). When Winsvold et al. (2014) compared glacier changes identified in Landsat satellite images to this length change record, the discrepancy was considerable. To resolve this, the supplementary information has been analysed, and the glacier length change record of Fåbergstølsbreen 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. In the reports, results are reported for the right and left side of the glacier, looking towards the glacier. The annual length change has been calculated as the average of the two from 1910 to 1951. In the observers notes, the observations are referred to the eastern (right) side or the western (left) side.

1899-1932: Two reference points (FAAB_M1 and FAAB_M2) were established in 1899, and the distance from FAAB_M1 on the western (left) side of the river was reported as 108 metres. In 1903, the glacier terminus had receded 49 metres from the line between the two reference marks (Fig. 12-5). For the same period, the retreat measured from FAAB_M1 was 22 metres (Rekstad, 1904). Between 1903 and 1907 the middle part of the terminus receded another 33 metres and the eastern (right) side receded 38 metres (Rekstad, 1910a). In 1908 the terminus advanced 11 metres on the eastern side (right side; Rekstad, 1910b). From 1908, the annual length change was reported for two lines, an eastern (right; probably not from FAAB_M2) and a western line (left, maybe from FAAB_M1) (Rekstad, 1910a).

According to the reports from Bergen Museum, the glacier front advanced 32 metres from 1907 to 1910 on the eastern side and 7.5 metres from 1908 to 1910 on the western side. From 1910 until 1922 the glacier retreated 96 metres, and advanced 100 metres from 1922 to 1930. The reported net change between 1910 and 1930 was an advance of 4 metres.

Figur 12-3
Fåbergstølsbreen seen from FAAB_M2 on 5th September 1903 (left) and the reference point FAAB_M2 31st May 2019 (right). The reference point FAAB_M1 is located within the red circle on the left photo. In 1899 the glacier tongue touched the line between FAAB_M1 and FAAB_M2. The cross carved into the rock at the foot of the cairn at FAAB_M2 lies inside the red circle on the right photo. Photos: J. Rekstad and Jostein Aasen, respectively.

1932-1999: Since 1932 the original observer`s reports have been available. No reference marks used in this period have been located. As the glacier retreated up-valley, new reference marks (probably cairns) were established on both sides of the river. The western line was abandoned in 1952 probably due to steep rocks between the river and the mountain. The cumulative length change from 1932 to 1999 is reported as −1021 metres. The retreat rate was slow between 1930 and 1936 (−6 m/year), faster between 1936 and 1951 (−34 m/year) and between 1951 and 1964 (-47 m/y), and even faster between 1964 and 1972 (109 m/year). Between 1972 and 1992 the retreat rate slowed again (−21 m/year). Between 1992 and 2000 the glacier advanced 190 metres.

1999-2019: The observer's notes and the reference marks are available for measurements since 1999. The advance of Fåbergstølsbreen culminated in 2000 without leaving a prominent end moraine. Between 2000 and 2019 the glacier front retreated 386 metres. Three reference points (FAAB99, FAAB02 and FAAB17) established in 1999, 2002 and 2017 have been used, and their locations are known (Fig. 12-4).

Available maps and aerial vertical photographs

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

1984: Mapped glacier terminus (Statkraftverkene).

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

2004: Orthophoto from 12th August 2004. (www.norgeibilder.no).

2010: Orthophoto from 29th September 2010 (www.norgeibilder.no).

2017: Orthophoto from 20th July 2017 (www.norgeibilder.no).

Method

Results reported in Bergen Museums Årbok (1908-1939) are checked against the known reference points, dated moraine ridges and observers' notes to identify discrepancies and suspected errors. Reports from the observers (1932 to present) and published results are checked against the length change record to identify discrepancies and suspected errors. The mapped moraines and front positions (1910, 1930, 1966, 1984, 1993, 2004, Fig 12-4) were then plotted on a line representing a central flow line close to 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 original cumulative length change.

Results

In the periods 1899-1903 and 1903-07 the observed retreat from the line between FAAB_M1 and FAAB_M2 was used, but the change for 1903-07 was adjusted so that the total change for 1899-1910 corresponds to the distance between the 1910-moraine and the line between FAAB_M1 and FAAB_M2 (50 metres). The advance between 1907 and 1910 recorded on the eastern side of the river was used.

According to the reported results in Bergen Museums Årbok (1911-1931) the distance between the front positions in 1910 and 1930 was only 4 metres). This is in contradiction to the distance between the moraine ridges 120-150 metres apart located upstream of FAAB_M1 and FAAB_M2 and lichenometrically dated to ca. 1910 and ca. 1930 (Bickerton and Matthews, 1993). As the reported distance from the western and eastern reference marks used in 1932 were 41 and 25 metres, respectively, the original reference marks from 1899 were no longer in use (the distance in 1899 from FAAB_M1 on the western side of the river was 108 metres). The annual results for 1922-23 show a marked advance (+69 m and +93 m on the eastern and western sides of the river, respectively) in between annual results for 1921-22 (−4 m and −5 m) and 1923-24 (−14 m and −12 m) (Rekstad, 1922; 1923; 1924). This behaviour is unexpected at that time even though several other outlet glaciers from Jostedalsbreen advanced in 1922-23. The numbers for 1922-23 are revised so that the change between 1910 and 1930 agrees with the distance between the moraines on both sides of the river (120 metres).

The observer´s notes and the reported results for 1931-99 have been compared and checked. In 1937 the observer seems to have given an erroneous distance from the eastern mark, 177 metres, which possibly should have been 77 metres. In the previous and following years, 1936 and 1938, the distance was reported as 52 and 125 metres, respectively. Due to the noted distance in 1937, the observer recorded that the glacier advanced 52 metres on the eastern side between 1937 and 1938. This was reported as a retreat of 52 metres (Fægri, 1940). On the western side of the river the glacier retreated in these years. In 1943/44, both lines showed a small advance. This advance is unexpected, but there are no indications of error.

As the western line was abandoned in 1951, the revised series for 1931-51 are based on the eastern line. The measurements between 1930 and 1938 were referenced to the same reference mark and the retreat rate was moderate (13 m/year). Hence, the record between 1930 and 1938 is assumed to be correct. The distance from the 1930-moraine to the mapped outline from 1966 is 995 metres, which isin contrast to the cumulative length change from 1930 to 1966 of 1526 metres. Consequently, the period 1938-66 was calibrated (Tab. 12-

2). The distance between the mapped outlines from 1966 and 1984 is 530 metres in contrast to the cumulative length change from 1966 to 1984 of 887 metres. A reference point established in 1972 (FAAB72) was used until 1981. The exact location of this reference point is unknown, but the annual length change between 1972 and 1984 is moderate (−21 m/year) compared to 1966-72 (-106 m/year), so the values recorded for the period 1972 – 1984 are assumed to be correct. Consequently, the period from 1966 to 1972 was calibrated (Tab. 12-2). Between 1984 and 2004 the glacier retreated until 1992, advanced until 2000, and then retreated again. The terminus position was mapped in 1984, 1993 and 2004. The annual results were adjusted to fit the mapped terminus positions and to the measurement in 1999 when FAAB99 was established (Tab. 12-2).

The distance from FAAB02 to the surveyed and mapped terminus positions from 2017 corresponds to distances measured on the ground within acceptable limits when differences in dates of observation are considered. Hence, the record between 2004 and 2017 is probably correct.

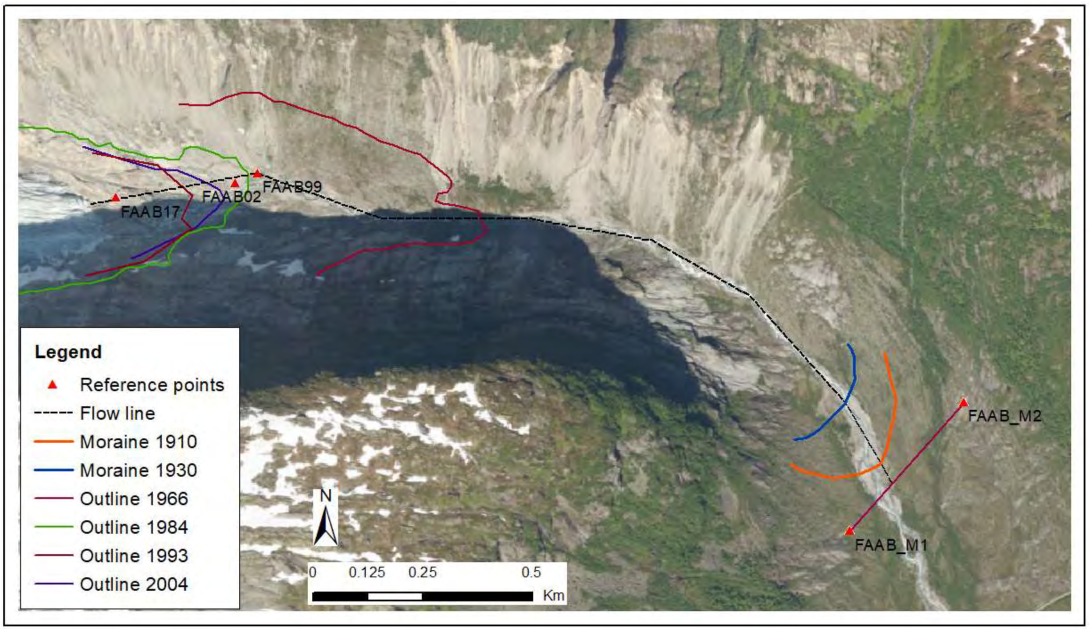


Figure 12-4
Orthophoto from September 2017 showing the positions of terminal moraines from ca. 1910 and 1930, glacier front positions mapped in 1966, 1984, 1993 and 2004, and known reference points. The distance from the line between FAAB_M1 and FAAB_M2 to the glacier terminus in 2017 was ca. 2100 metres. Orthophoto: www.norgeibilder.no.

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
1930 – 1966	−1526	−995	419	1936 - 1966
1966 – 1984	−887	−530	357	1966 - 1972
1984 – 1993	−152	−130	22	1984 - 1993
1993 – 1999	+155	+100	−55	1993 - 1999

The original and revised cumulative glacier length change is shown in Figure 12-5. The advancing and retreating periods are unchanged, but the amount of change has been adjusted to match the distance between mapped or otherwise known terminus positions. The revised length change record is available at www.nve.no/glacier.

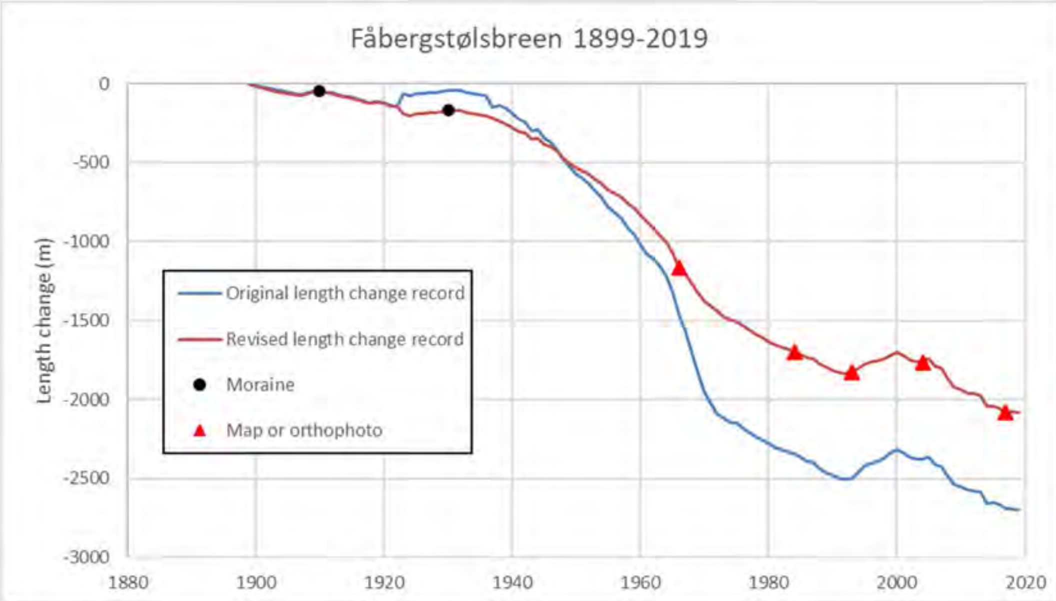


Figure 12-5
Original and revised glacier length change record for Fåbergstølsbreen between 1899 and 2019.

12.2 Jøkulhlaups

Jøkulhlaups, also known as Glacier Lake Outburst Floods (GLOFs), were registered at five glaciers in Norway in 2019. However, two of the events were observed on satellite images only and would not have been observed by conventional means. Hence, the relatively high number of events this year is because of these two extra reports.

Events were observed at Rundvassbreen, Rembesdalskåka, and Nupsfonn, which lies just south of Hardangervidda mountain plateau. This is the first known event from Nupsfonn, but there have been several registered events from both Rundvassbreen and Rembsedalskåka, with ten events from Rundvassbreen since 2001, and six events from Rembesdalskåka since 2014.

Inspection of glacier-dammed lakes on Sentinel 2 imagery showed that there probably were outburst events from Sandåbreen, a small glacier northeast of Jostedalsbreen, in August and from Fortundalsbreen, northeast of Harbardsbreen, in early July.

Rundvassbreen (Blåmannsisen)

In mid-September a jøkulhlaup occurred at Rundvassbreen, a northern outlet glacier of the Blåmannsisen icecap east of Fauske in northern Norway (Fig. 12-6). About 10 million cubic metres of water drained under the glacier in less than two days (Fig. 12-7). This is just one year after the previous event, and the third time that the subglacial lake has drained after an interval of only one year.

Several previous events of a similar magnitude or greater have been recorded from this glacier (Jackson and Ragulina, 2014). The first 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, Lake Sisovatnet. Previously the water had drained over a rock sill and flowed into a river in Sweden (Engeset et al., 2005). The event in 2019 was the tenth, and the interval between events has varied from one year to four years. 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.

Year	Date	Water volume	Water level before event
2001	5th – 7th September	35 mill. m^3	full (1053 m a.s.l.)
2005	27th – 29th August	35 mill. m^3	full (1053 m a.s.l.)
2007	29th August	20 mill. m^3	~ half-full
2009	6th – 7th September	20 mill. m^3	~ half-full
2010	8th – 17th September	11 mill. m^3	< half-full
2011	22nd September	12 mill. m^3	< half-full (ca. 1029 m a.s.l.)
2014	10th – 12th August	35 mill. m^3	full (probably 1053 m a.s.l.)
2016	28th – 29th September	26 mill. m^3	> half-full (ca. 1040.7 m a.s.l.)
2018	25th – 26th August	22 mill. m^3	> half-full (ca. 1039.8 m a.s.l.)
2019	9th – 10th September	10 mill. m^3	< half-full (ca. 1027 m a.s.l.)

The water level in the glacier-dammed lake before the most recent event was about 1027 m a.s.l. Two contractors were near the hydropower reservoir, Lake Sisovatnet, on the evening of 9th September and noted nothing unusual. However, when two employees from the hydropower plant were there the following morning, it was clear from the high discharge in the glacier river that a jøkulhlaup was taking place. The discharge in the river soon normalised, so it is presumed that the event started late on the 9th September or shortly after midnight on 10th September.

Figure 12-6
Photo showing the almost-emptied glacier-dammed lake on 17th September and approximate route taking by water that drained under the glacier, to the lake Rundvatnet and subsequently to the hydropower reservoir Sisovatnet. Photo: Cecilie Amundsen, Siso Energi AS.

Figure 12-7
The site where the glacier-dammed lake drained under the glacier, taken on 17th September 2019, one week after the event. Photo: Miriam Jackson.

Rembesdalskåka (Hardangerjøkulen)

Rembesdalskåka, an outlet glacier of Hardangerjøkulen, dams a lake called Demmevatnet (literally "dammed lake"). There have been many previous events recorded from Demmevatnet, the earliest in 1736 (Liestøl, 1956). In the years leading up to 1893 the lake emptied almost every year, usually taking two to three weeks to drain. However, individual events without damage were not recorded. During the event in 1893, the lake drained in just 24 hours.

A new event occurred from the glacier-dammed lake, Demmevatnet on 24th August 2019. A total of 1.8 million m^3 water drained under Rembesdalskåka and subsequently to the hydropower reservoir Rembesdalsvatn (Tab. 12-4). The hydropower company reported a maximum discharge into the reservoir of 170 m^3/s.

Table 12-4
Dates and approximate volumes of jøkulhlaups from Demmevatnet. Construction of drainage tunnels meant there were no events for over 75 years.

Year	Date	Water volume	Comment
1736	unknown	unknown	Earliest record of flood from Demmevatnet
1813	unknown	unknown	Flood damages.
1842	unknown	unknown	Flood damages.
1861	17th September	unknown	Damage, including two bridges.
1893	Late August	35 mill. m^3	Catastrophic flood. Lake drained in 24 hours.
1897	17th August	35 mill. m^3	Water flowed over glacier surface, lasted 24 hrs.
1937	10th August	12 mill. m^3	Drained in 3.5 hours.
1938	23rd August	10 mill. m^3	Flood before new drainage tunnel completed
2014	25th August	1.9 mill. m^3	Event occurred over ~3 hours.
2016	~25th January	1.44 mill. m^3	Lake observed full 24 January; empty 30 January
2016	6th September	1.87 mill. m^3	Event occurred over ~4 hours.
2017	27th October	1.85 mill. m^3	Event occurred over ~22 hours.
2018	10th August	unknown	
2019	24th August	1.8 mill. m^3	Event occurred over ~3 hours

Nupsfonn (BreID: 3075)

The first recorded event from Nupsfonn (also called Nupsfonn West) occurred from 24th to 25th August 2019 (Fig. 12-8). Drainage of a glacier-dammed lake caused high discharge in the river Nupselva and into the hydropower reservoir Ulevåvatnet/Ståvatn. The volume of the flood was calculated by the hydropower company as approximately 10 million m^3 water.

The water in the dammed lakes Ulevåvatnet and Ståvatn was observed to be very cloudy on 25th August, and water discharge in the river Nupselva was unusually large on 24th and 25th August (Fig. 12-9). A short helicopter overflight on 27th August showed that the lake level in the glacier-dammed lake had dropped about 10 m. The form of the ice tongue and surface crevasses with water in suggest that the part of the glacier closest to the lake could be floating. Interpolated meteorological data from senorge.no shows that there were several days of rain immediately before the event and it was especially heavy on 20th and 23rd August. This may have triggered the event.

Figure 12-8
Orthophoto showing the glacier-dammed lake on 22nd September, four weeks after the event. Photo from norgeibilder.no.

The glacier itself has an area of 1.15 km^2, so such a large volume of water from a small glacier was somewhat surprising. Nupsfonn Vest (Nupsfonn West) is one of three ice masses, the other two being Store Nupsfonn (Greater Nupsfonn) and Nupsfonn Øst (Nupsfonn East). Previously this was a contiguous ice mass, but the different parts have become separated from one another over the last few decades due to continuous glacier shrinkage.

Figure 12-9
Nupselva on 24th August at the beginning of the event and 29th August, four days after the event was over. Photos: Nils-Ove Hauge (left) and Torleif Fresvik (right).

Events observed on satellite images only:

Sandåbreen (BreID: 2434)

Sandåbreen is a glacier with an area of 5 km^2 that lies southwest of the ridge Skridulaupen, in the municipality of Skjåk (Fig. 12-10). Examination of Sentinel images from 2nd and 5th August 2019 suggest that a glacier-dammed lake emptied in this period (Fig. 12-11).

Figure 12-10
Sandåbreen as seen from the air on 20th September 2016. The glacier-dammed lake is located within the red ellipse. Photo: Hallgeir Elvehøy.

Subsequent inspection of Sentinel satellite images from previous years suggest that there could also have been events in 2016, 2017 and 2018. Images from 23rd July and 22nd August 2016 suggest that the glacier-dammed lake may have decreased in size between these two dates, but the images are somewhat indistinct and there are not clear images within this period. Again, images from 23rd July and 22nd August 2017 suggest a possible event but the images are indistinct and there are no better images within the period. Images from 2018 are quite clear and more frequent and suggest a drainage event between 20th July and either 23rd July or 26th July 2018, as reported in Kjøllmoen et al. (2019). There is no record of increased discharge downstream of the glacier during any of these periods.

Figure 12-11
Sentinel satellite images of the glacier-dammed lake on 2nd August (left) and 5th August (right).

Fortundalsbreen (BreID: 2509)

At Fortundalsbreen there is a glacier-dammed lake called "Heksegryta" (witch's cauldron) that lies northwest of the peak Sveinkollen (Fig. 12-12). It was identified as a potential source of jøkulhaups in Jackson and Ragulina (2014) but no events have been directly observed. However, Sentinel satellite images from 28th June and 10th July 2019 suggest that the marginal lake decreased significantly in area during this period, probably when water drained under the glacier (Fig. 12-13). Water from the lake could have drained either north to Styggvatnet and thence to Tverrådalen or south and joined the main glacier drainage and drained eventually into the hydropower dam Fivlemyrane.

Figure 12-12
Heksegryta observed in 2001. Photo: Leif Edvin Wærstad.

A probable event in 2018 between 13th and 26th June was documented in Kjøllmoen et al. (2019), but observations of satellite images from 2017 strongly suggest that a drainage event also occurred between 20th July and 22nd August 2017.

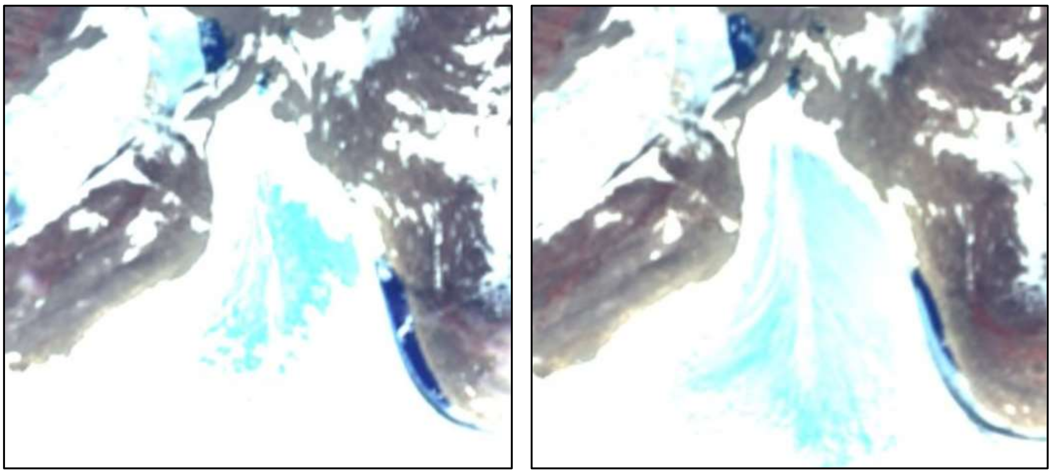


Figure 12-13
Sentinel satellite images of Heksegryta at Fortundalsbreen on 28th June (left) and 10th July (right) 2019.

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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 46 Norwegian glaciers during the period 1949-2019. The table lists characteristic data for the investigated glaciers. The Glacier ID refers to ID in the glacier inventory of Norway (Andreassen et al., 2012).

Area/ No. Glacier	Glacier ID	Lat., Long.	Area (km^2)	Altitude (m a.s.l.)	Mapping year	Period	No. of years
Ålfotbreen							
1 Ålfotbreen	2078	61°45', 5°38'	4.0	890-1368	2010	1963-	57
2 Hansebreen	2085	61°44', 5°40'	2.8	927-1310	2010	1986-	34
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 Møsevassbreen	3138	59°59', 6°16'	15.5	873-1617	2017	2017	1
6 Bondhusbrea	3133	60°02', 6°20'	10.7	477-1636	1979	1977-81	5
7 Breidablikkbrea	3128	60°03', 6°22'	3.9	1217-1660	1959	1963-68	6
			3.2	1232-1648	2013	2003-13	11
8 Gråfjellsbrea	3127	60°04', 6°24'	9.7	1034-1656	1959	64-68, 74-75	7
			8.1	1049-1647	2013	2003-13	11
9 Blåbreen	3126	60°05', 6°26'	2.3	1060-1602	1959	1963-68	6
10 Ruklebreen	3129	60°04', 6°26'	1.8	1603-1235	1959	1964-68	5
11 Midtre Folgefonna	2)	60°08', 6°28'	8.6	1100-1570	1959	1970-71	2
Jostedalsbreen							
12 Jostefonn	3)	61°25', 6°33'	3.8	960-1622	1993	1996-2000	5
13 Vesledalsbreen	2474	61°50', 7°16'	4.1	1126-1745	1966	1967-72	6
14 Tunsbergdalsbreen	2320	61°36', 7°02'	52.2	536-1942	1964	1966-72	7
15 Nigardsbreen	2297	61°42', 7°08'	46.6	330-1952	2013	1962-	58
16 Store Supphellebreen	2352	61°31', 6°48'	12.0	80-300/ 720-1740	1966	1964-67, 73-75, 79-82	11
17 Austdalsbreen	2478	61°45', 7°20'	10.0	1200-1740	2019	1988-	32
18 Spørteggbreen	4)	61°36', 7°28'	27.9	1260-1770	1988	1988-91	4
19 Harbardsbreen	2514	61°41', 7°40'	13.2	1242-1978	1996	1997-2001	5
Hardangerjøkulen							
20 Rembesdalskåka	2968	60°32', 7°22'	17.3	1066-1854	2010	1963-	57
21 Midtdalsbreen	2964	60°33', 7°26'	6.7	1380-1862	1995	2000-2001	2
22 Omnsbreen	2919	60°39', 7°28'	1.5	1460-1570	1969	1966-70	5
Jotunheimen							
23 Tverråbreen	2632	61°35', 8°17'	5.9	1415-2200		1962-63	2
24 Blåbreen	2770	61°33', 8°34'	3.6	1550-2150	1961	1962-63	2
25 Storbreen	2636	61°34', 8°08'	4.9	1420-2091	2019	1949-	71
26 Vestre Memurubre	2772	61°31', 8°27'	9.2	1565-2270	1966	1968-72	5
27 Austre Memurubre	2769	61°33', 8°29'	8.7	1627-2277	1966	1968-72	5
28 Juvfonne	2597	61°40', 8°21'	0.1	1852-1985	2019	2010-	10
29 Hellstugubreen	2768	61°34', 8°26'	2.7	1487-2213	2019	1962-	58
30 Gråsubreen	2743	61°39', 8°37'	1.7	1854-2277	2019	1962-	58
Okstindbreene							
31 Charles Rabot Bre	1434	66°00', 14°21'	1.1	1090-1760	1965	1970-73	4
32 Austre Okstindbre	1438	66°00', 14°17'	14.0	730-1750	1962	1987-96	10
Svartisen							
33 Høgtuvbreen	1144	66°27', 13°38'	2.6	588-1162	1972	1971-77	7
34 Svartisheibreen	1135	66°33', 13°46'	5.7	765-1424	1995	1988-94	7
35 Engabreen	1094	66°40', 13°45'	36.2	111-1544	2016	1970-	50
36 Storglombreen	5)	66°40', 13°59'	59.2	520-1580	1968	1985-88	4
			62.4	520-1580		2000-05	6
37 Tretten-null-tobreen	1084	66°43', 14°01'	4.3	580-1260	1968	1985-86	2
38 Glombreen	1052	66°51', 13°57'	2.2	870-1110	1953	1954-56	3
39 Kjølbreen	1093	66°40', 14°05'	3.9	850-1250	1953	1954-56	3
40 Trollbergdalsbreen	1280	66°42', 14°26'	2.0	907-1366	1968	1970-75	6
			1.8	907-1369	1998	1990-94	5
Blåmannsisen							
41 Rundvassbreen	941	67°17', 16°03'	11.7	788-1533	1998	2002-04	3
			10.8	853-1527	2017	2011-17	7
Skjomen							
42 Blåisen	596	68°20', 17°51'	2.2	860-1204	1959	1963-68	6
43 Storsteinsfjellbreen	675	68°13', 17°54'	6.2	926-1846	1960	1964-68	5
			5.9	969-1852	1993	1991-95	5
44 Cainhavarre	703	68°06', 17°59'	0.7	1214-1538	1960	1965-68	4
Vest-Finnmark							
45 Svartfjelljøkelen	26	70°14', 21°57'	2.7	500-1080	1966	1978-79	2
46 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

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