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Glaciological investigations in Norway 2020

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Frontpage photo: The glacier snout of Austre Okstindbreen in Nordland, northern Norway. The photo was taken on 29th August 2020 by Kjell Harald Nerengmo.

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Abstract: Results of glaciological investigations performed at Norwegian glaciers in 2020 are presented in this report. The main part concerns mass balance investigations. Results from investigations of glacier length changes are discussed in a separate chapter.

Keywords: Glaciology, Mass balance, Glacier length change, Glacier dynamics, Ice velocity, Meteorology, Jøkulhlaup.

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Preface

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

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

The report is published in English with a summary in Norwegian. The purpose of this report is to provide a joint presentation of the glacier investigations and calculations made mainly by NVE’s Section for Glaciers, Ice and Snow during 2020. 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 George Stanley Cowie made many corrections and improvements to the text.

Oslo, November 2021

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Summary

Mass balance

Mass balance investigations were performed on eleven glaciers in Norway in 2020 – two in northern Norway and nine in southern Norway.

The winter balance was greater than the 1981-2010 average for six of the seven reference glaciers (mass balance series back to at least 1981). Only Gråsubreen in Jotunheimen had lower winter balance with 91 % of the reference period average. Nigardsbreen had the greatest relative winter balance with 156 % of the 1981-2010 average.

The summer balance was greater than the 1981-2010 average for five of the seven reference glaciers. Hellstugubreen had the greatest relative summer balance with 120 % of the reference period average, while Nigardsbreen had the lowest relative summer balance with 85 % of the 1981-2010 average.

The annual balance was positive for four of the reference glaciers, and of these four, Nigardsbreen had the greatest surplus with 1.7 m w.e. For the three reference glaciers in Jotunheimen the annual balance was negative.

Glacier length change

Glacier length changes were measured at 23 glaciers in southern Norway and 7 glaciers in northern Norway. Twenty-three of the 30 measured glacier outlets showed a decrease in length. The greatest retreats were observed at Gråfjellsbrea on Folgefonna (47 m) and at Engabreen on Svartisen (46 m).

Sammendrag

Massebalanse

I 2020 ble det utført massebalansemålinger på 11 breer i Norge – to i Nord-Norge og ni i Sør-Norge.

For seks av de sju referansebreene (de breene som har massebalanseserie tilbake til 1981 eller lengre) ble vinterbalansen større enn gjennomsnittet for referanseperioden 1981-2010. Bare Gråsubreen i Jotunheimen hadde mindre vinterbalanse med 91 % av referanse-perioden. Nigardsbreen fikk den relativt største vinterbalansen med 156 % av referanseperioden.

For fem av de sju referansebreene ble sommerbalansen større enn gjennomsnittet for referanseperioden. Hellstugubreen hadde relativt størst sommerbalanse med 120 % av referanseperioden, mens Nigardsbreen hadde relativt minst med 85 % av gjennomsnittet for perioden 1981-2010.

Årlig balanse ble positiv for fire av referansebreene, og av disse fire breene hadde Nigardsbreen størst overskudd med 1,7 m v.ekv. De tre referansebreene i Jotunheimen fikk alle negativ balanse.

Lengdeendringer

Lengdeendringer ble målt på 23 breer i Sør-Norge og 7 breer i Nord-Norge. Tjuetre av de 30 målte breutløperne hadde tilbakegang. Størst tilbakegang ble målt på Gråfjellsbrea ved Folgefonna (47 m) og Engabreen ved Svartisen (46 m).

1. Glacier investigations in Norway 2020

1.1 Mass balance

Surface mass balance is the sum of surface accumulation and surface ablation and includes loss due to calving. The surface mass-balance series of the Norwegian Water Resources and Energy Directorate (NVE) include annual (net), winter, and summer balances. If the winter balance is greater than the summer balance, the annual balance is positive and the glacier increases in volume. Alternatively, if the melting of snow and ice during the summer is larger than the winter balance, the annual balance is negative and the ice volume decreases.

Acronyms and terminology

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

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

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

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

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

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

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

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

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

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

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

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

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

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.

GPR
Ground Penetrating Radar. A geophysical method that uses high-frequency radar waves to image the subsurface.

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*. 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 that is covered by the first snow of the new balance year.

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.

Summer and annual balance

Summer and annual balances are obtained from measurements of stakes and towers (Fig. 1-1), usually performed in September or October. Below the 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}.

Figure 1-1
Measurement of stakes and fresh snow at Engabreen on 1st October 2020. Photo: Håvard Toft Larsen.

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 2020 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 58 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 72 years of measurements, while Engabreen at Svartisen has the longest series (51 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 2020 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. (2020b).

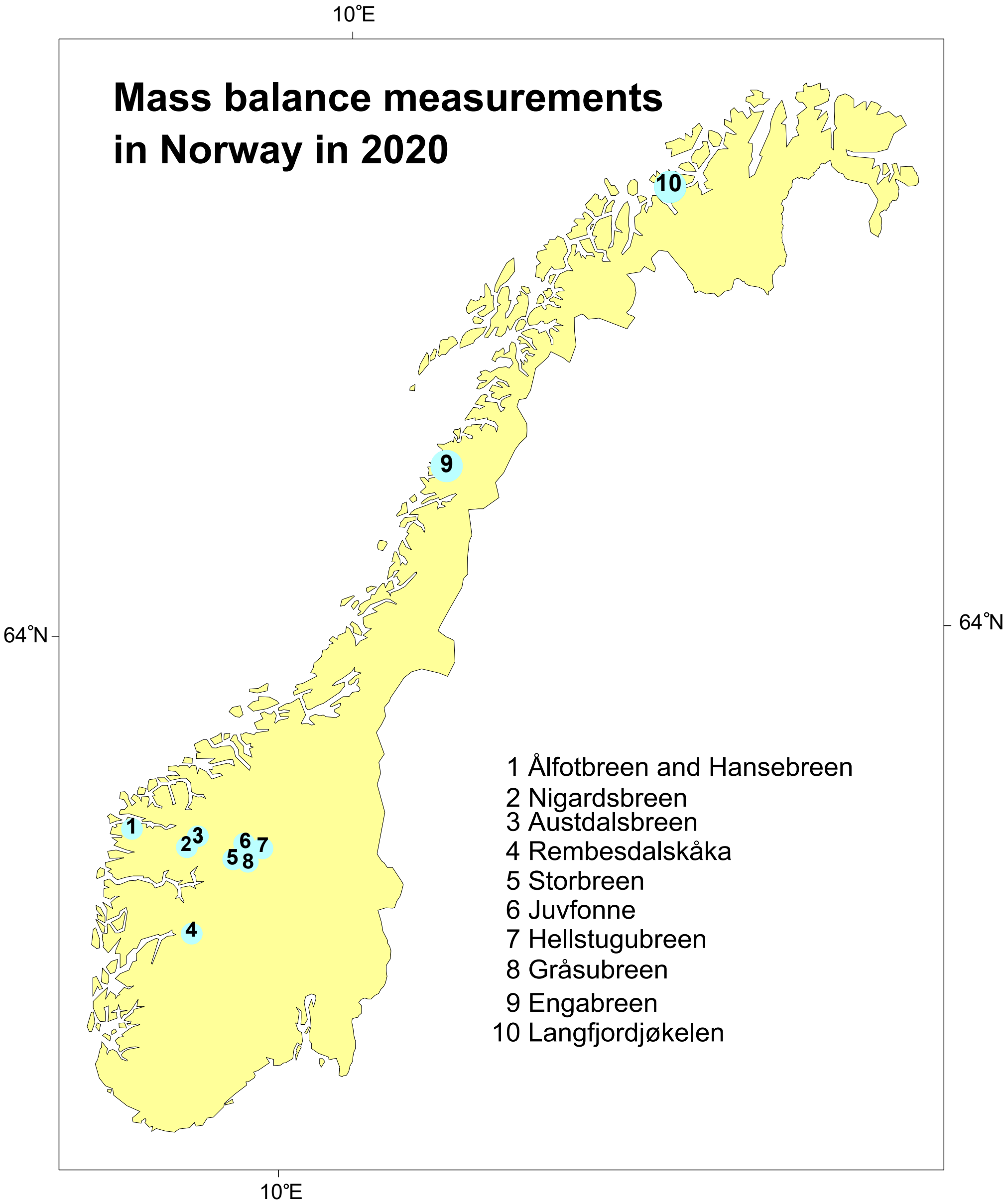


Figure 1-2
Location of the glaciers at which mass balance studies were performed in 2020.

Mass balance studies performed on Norwegian glaciers in 2020 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 2019/20 started with cold and dry weather in October and November all over the country. The following winter months however, were mild and snow-rich over most of the country.

Snow accumulation and winter balance

The winter balance for five of the six reference glaciers in southern Norway was greater than the average of the reference period 1981-2010. Nigardsbreen had the greatest relative winter balance with 156 % of the 1981-2010 average. Only Gråsubreen in Jotunheimen had lower winter balance with 91 % of the reference period average. Engabreen in northern Norway had a greater winter balance than average with 144 %.

Summer weather

The summer season was warm in June, August and September over most of the country. July however, was rather cool in southern Norway.

Ablation and summer balance

The summer balance for five of the six reference glaciers in southern Norway was greater than the 1981-2010 average. Hellstugubreen had the greatest relative summer balance with 120 % of the reference period average. Only Nigardsbreen had lower summer balance with 85 % of the 1981-2010 average. Engabreen had 99 % of the reference period average.

Annual balance

The annual balance was positive for three of the six reference glaciers in southern Norway, and of these, Nigardsbreen had the greatest surplus with 1.7 m w.e. For the three reference glaciers in Jotunheimen the annual balance was significantly negative for Gråsubreen (−0.6 m w.e.) and Hellstugubreen (−0.4 m w.e.). Storbreen was about in balance (−0.05 m w.e.). Engabreen had a positive mass balance at 1.2 m w.e.

The results from the mass balance measurements in Norway in 2020 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., 2020b). 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., 2020b).

In winter 2019/2020 (December-March) NAO and AO indexes were positive in all months with a mean of 1.20 and 2.22 respectively for December-March 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).

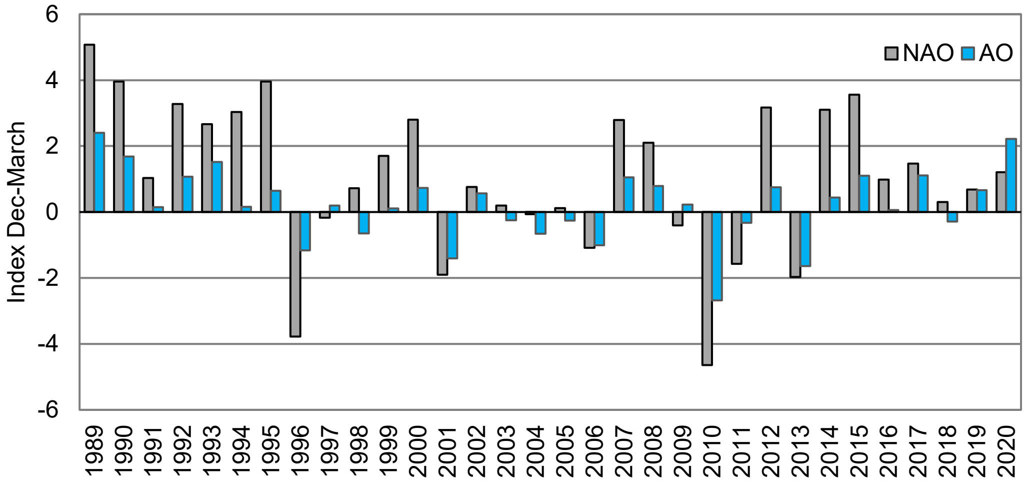


Figure 1-3
NAO and AO index for December–March for 1989–2020. NAO and AO data were downloaded from the NOAA Center for Weather and Climate Prediction (http://www.cpc.ncep.noaa.gov/). Figure updated and modified from Andreassen et al. (2020). The large-scale circulation indices NAO and AO are in units 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 2020. 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	1963-20	3.5	1000-1360	4.99	133	−3.99	104	1.00	−0.08	<1000	100
Hansebreen	1986-20	2.5	927-1303	4.59	1)136	−4.10	1)100	0.49	1)−0.74	1065	80
Nigardsbreen	1962-20	44.9	389-1955	3.51	156	−1.86	85	1.65	0.06	1285	93
Austdalsbreen	1988-20	10.1	1200-1740	2.91	2)135	3)−2.13	2)78	0.78	2)−0.57	1375	82
Rembesdalskåka	1963-20	17.1	1085-1851	3.05	142	−2.41	112	0.64	−0.02	1579	86
Storbreen	1949-20	4.9	1420-2091	1.93	130	−1.98	109	−0.05	−0.33	1760	53
Juvfonne4)	2010-20	0.1	1852-1985	1.75		−1.39		0.36			
Hellstugubreen	1962-20	2.7	1487-2213	1.38	123	−1.82	120	−0.44	−0.39	1935	33
Gråsubreen	1962-20	1.7	1854-2277	0.72	91	−1.34	115	−0.62	−0.37	>2270	0
Engabreen	1970-20	36.2	111-1544	3.72	144	−2.55	99	1.17	−0.01	1017	85
Langfjordjøkelen	1989-93 1996-20	3.7 2.6	280-1050 338-1043	2.74	5)133	−2.76	5)92	−0.02	5)−0.94	830	59

1)Calculated for the measured period 1986-2019
2)Calculated for the measured period 1988-2019
3)Contribution from calving amounts to −0.27 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 1996-2019

Figure 1-4 presents the mass balance results in southern Norway for 2020. The west-east gradient is evident for both winter and summer balances. The results for 2020 show a positive mass balance for five of the measured glaciers in southern Norway.

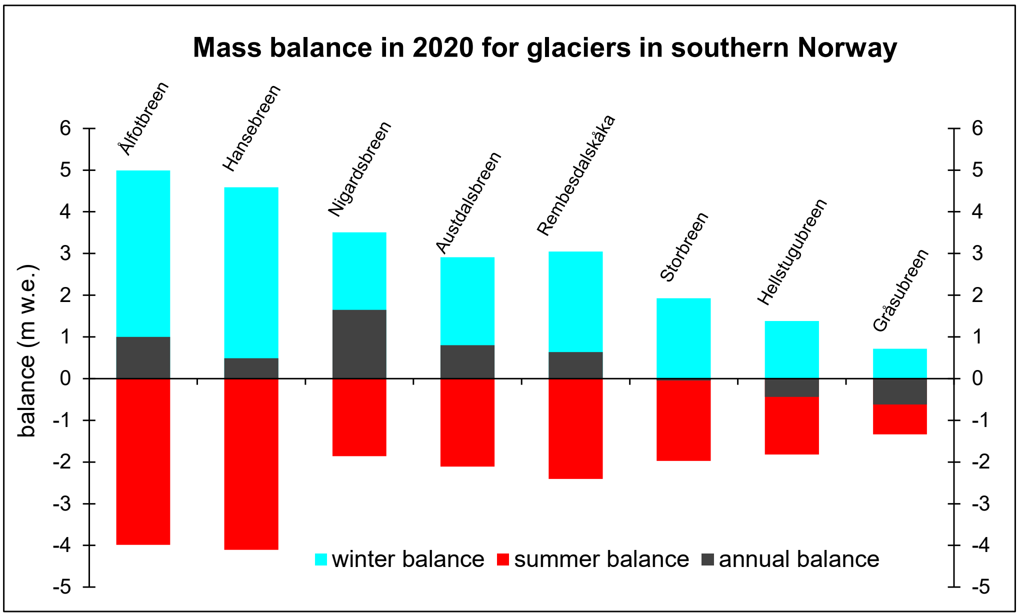


Figure 1-4
Mass balance in 2020 in southern Norway. The glaciers are listed from west to east.

The cumulative annual balance for the six reference glaciers in southern Norway for the period 1963-2020 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 1963-2020.

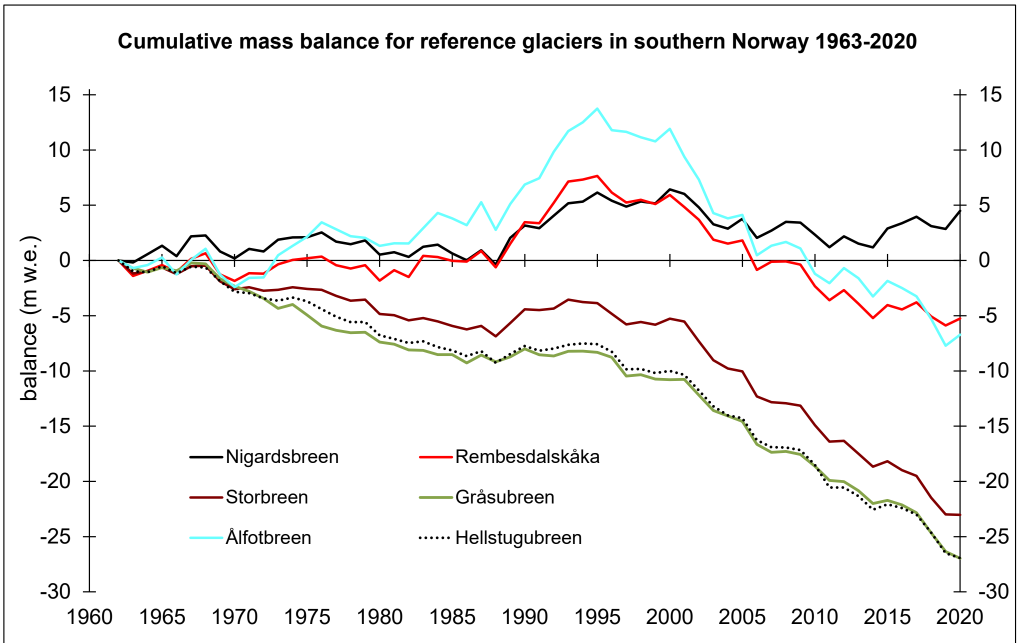


Figure 1-5
Cumulative mass balance for the six reference glaciers in southern Norway, Ålfotbreen, Nigardsbreen, Rembesdalskåka, Storbreen, Hellstugubreen and Gråsubreen, for the period 1963-2020.

1.2 Other investigations

Glacier length change measurements were performed at 30 glaciers in Norway in 2020. 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) has been studied at Austdalsbreen since 1987 (chap. 4). The measurements continued in 2020. Glacier velocity was also measured at Ålfotbreen and Hansebreen (chap. 2) and Nigardsbreen (chap. 3) for the period 2019-2020.

Meteorological observations were performed at Engabreen (chap. 10) and Langfjord-jøkelen (chap. 11).

Some jøkulhlaups (glacier floods) have occurred in 2020 and these are 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 (3.5 km^2, 2019) and Hansebreen (2.5 km^2, 2019) (Fig. 2-1). 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 ice cap are given names on the official maps. Glaciological investigations in 2020 include mass balance and surface ice velocity.

Figure 2-1
Ålfotbreen (right) and Hansebreen (left) photographed on 6th October 2020. Photo: Bjarne Kjøllmoen.

2.1 Mapping

A new survey of Ålfotbreen and Hansebreen was performed in 2019. LIDAR data was recorded on 22nd September 2019 by Terratec AS (Terratec AS, 2020) as a part of the national laser scanning program initiated by the Norwegian Mapping Authority. The data set produced by Terratec AS was point clouds (laz). Aerial photos were not taken.

A Digital Terrain Model (DTM) was generated based on the laser scanning data (x, y and z). As orthophotos were not available, the glacier outlines were digitised using the shaded relief of the DTM_{2019} (Fig. 2-2). The ice divides were calculated using GIS and compared with the ice divides from 2010. The ice divides from 2019 were similar to the 2010 divides and hence, the 2010 ice divides are continued in the following work.

All data was referred to the UTM co-ordinate system zone 32, Euref 89 datum and the Norwegian height system NN2000.

The mapping from 2019 showed quite large glacier changes compared with the previous mapping in 2010. The area for Ålfotbreen and Hansebreen together had shrunk from 6.73

to 5.96 km^2, an area decrease of 0.77 km^2 or 11 % (Fig. 2-2). Most of this area decrease (0.50 km^2) was related to Ålfotbreen.

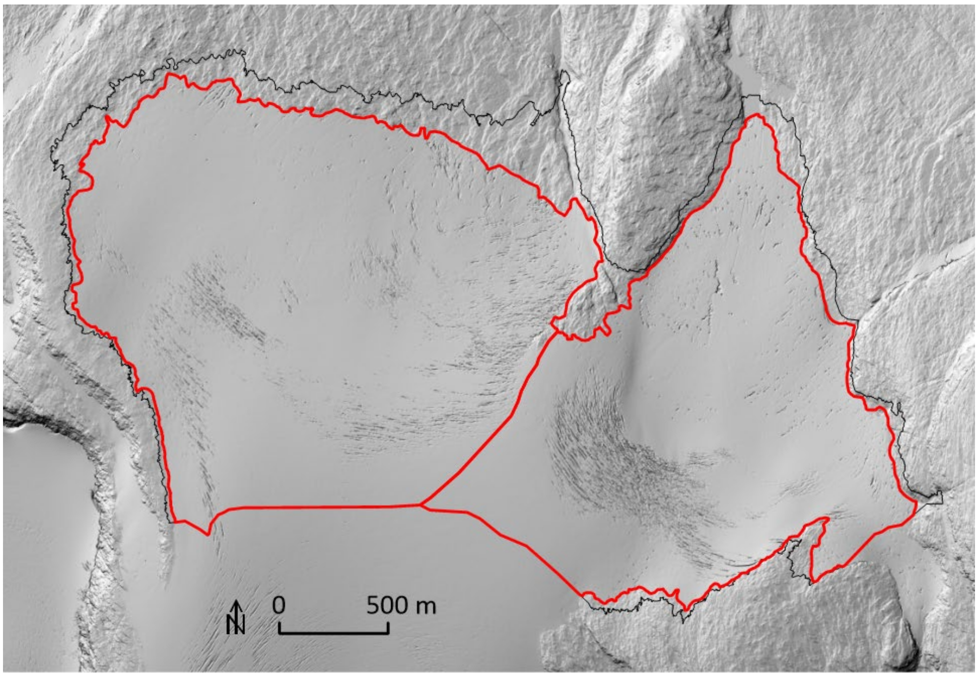


Figure 2-2
Shaded relief map of Ålfotbreen and Hansebreen based on the DTM 2019. Glacier boundaries for 2019 in red and for 2010 in black.

Based on the new DTM from 2019 the area-altitude distribution was changed from the 2010 DTM (Fig. 2-3). As shown in Figure 2-3 the area for Ålfotbreen was reduced in all height intervals. The area for Hansebreen was also reduced in most height intervals, but was increased in the two intervals between 1000 and 1100 m a.s.l.

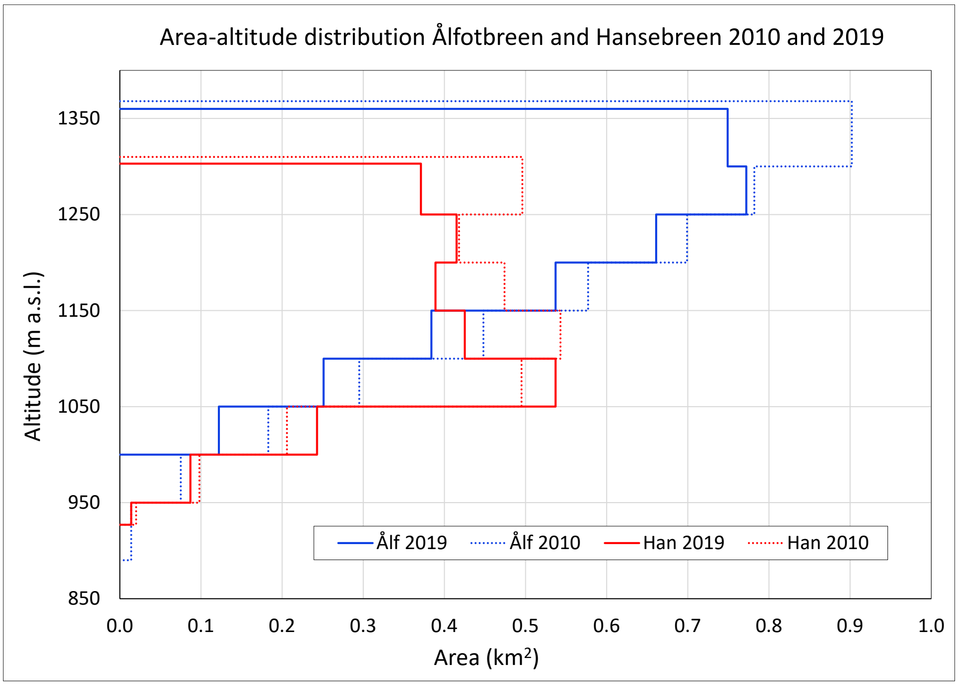


Figure 2-3
Area-altitude distribution for Ålfotbreen (blue) and Hansebreen (red).

2.1 Mass balance 2020

Fieldwork

Snow accumulation measurements were performed on 28th April. Due to restrictions associated to the corona pandemic the field work program was reduced by about 50 percent. The calculation of winter balance was based on 35 and 34 snow depth soundings on Ålfotbreen and Hansebreen, respectively, and on measurement of stakes in two different positions on both glaciers (Fig. 2-4). Comparison of stake readings and snow soundings indicated no significant melting after the ablation measurements in September 2019. Despite of great snow depths the sounding conditions were good over the whole glacier and the summer surface could easily be detected. Generally, the snow depth varied between 8 and 11 m on Ålfotbreen, and between 7 and 12 m on Hansebreen. Snow density was measured in one location (pos. 28, 1203 m a.s.l.), applicable for both glaciers. The mean snow density of 9.1 m snow was 509 kg m^{-3}. The measured mean snow density for the twenty- year period 2000-2019 was 522 kg m^{-3}.

The locations of stakes, snow pit and soundings are shown in Figure 2-4.

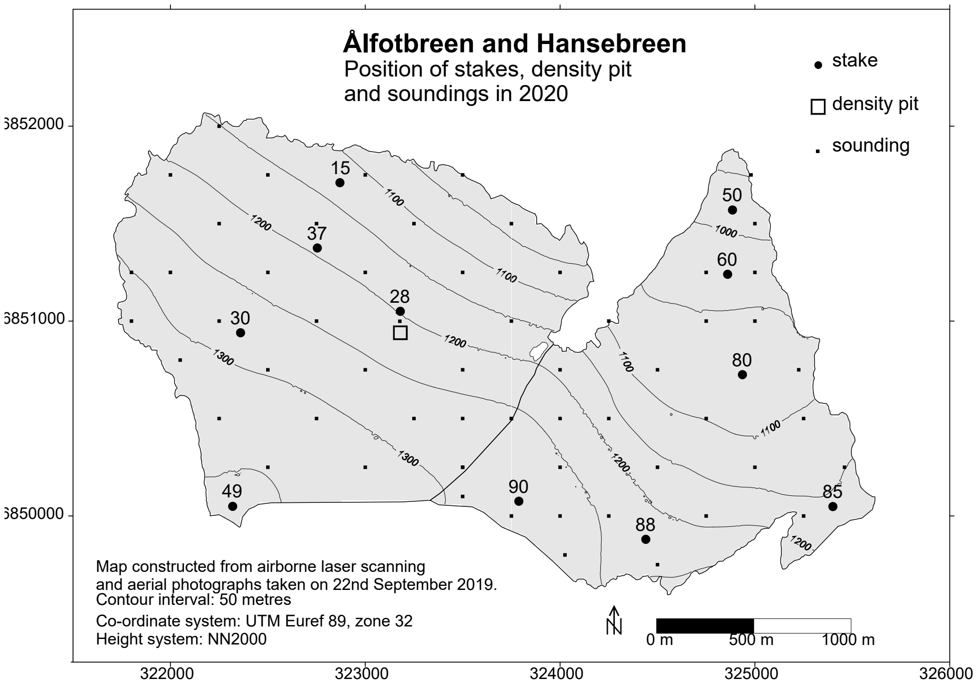


Figure 2-4
Location of stakes, soundings and snow pit on Ålfotbreen (left) and Hansebreen (right) in 2020.

Ablation was measured on 6th October. The annual balance was measured at stakes in five positions on Ålfotbreen and six positions on Hansebreen (Fig. 2-4). At the time of the ablation measurements no fresh snow had fallen.

Results

The calculations are based on the DTM from 2019.

All height intervals are represented with point measurements (b_w) for both glaciers. However, measurements below 1000 m a.s.l. on Hansebreen and 1100 m a.s.l. on Ålfot-breen are sparse.

The winter balance was calculated as a mean value for each 50-m height interval and was 5.0 ±0.2 m w.e. at Ålfotbreen, which is 133 % of the mean winter balance for the reference period 1981-2010. The winter balance on Hansebreen was calculated as 4.6 ±0.2 m w.e., which is 136 % of the mean winter balance for the measurement period 1986-2019. Spatial distribution of the winter balance at Ålfotbreen and Hansebreen is shown in Figure 2-5.

The density of remaining snow was assumed to be 600 kg m^{-3}, and the density of melted ice was set as 900 kg m^{-3}. The summer balance for Ålfotbreen was calculated at stakes at five different altitudes and it was no stake measurement below 1128 m a.s.l. 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. 2-6).

Based on estimated density and stake measurements the summer balance was also calculated as a mean value for each 50 m height interval and was −4.0 ±0.3 m w.e. on Ålfotbreen, which is 104 % of the reference period. The summer balance on Hansebreen was −4.1 ±0.3 m w.e., which is 100 % of the mean summer balance for 1986-2019.

Hence, the annual balance was positive for both glaciers. Ålfotbreen had a surplus of 1.0 ±0.4 m w.e. The mean annual balance for the reference period 1981-2010 is −0.08 m w.e. However, over the last ten years (2011-2020), the mean annual balance was −0.55 m w.e. and seven of those years had a negative annual balance. The annual balance at Hansebreen was +0.5 ±0.4 m w.e. The mean value for the measurement period 1986-2019 is −0.74 m w.e. Over the last ten years the mean annual balance was −1.09 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 2-6.

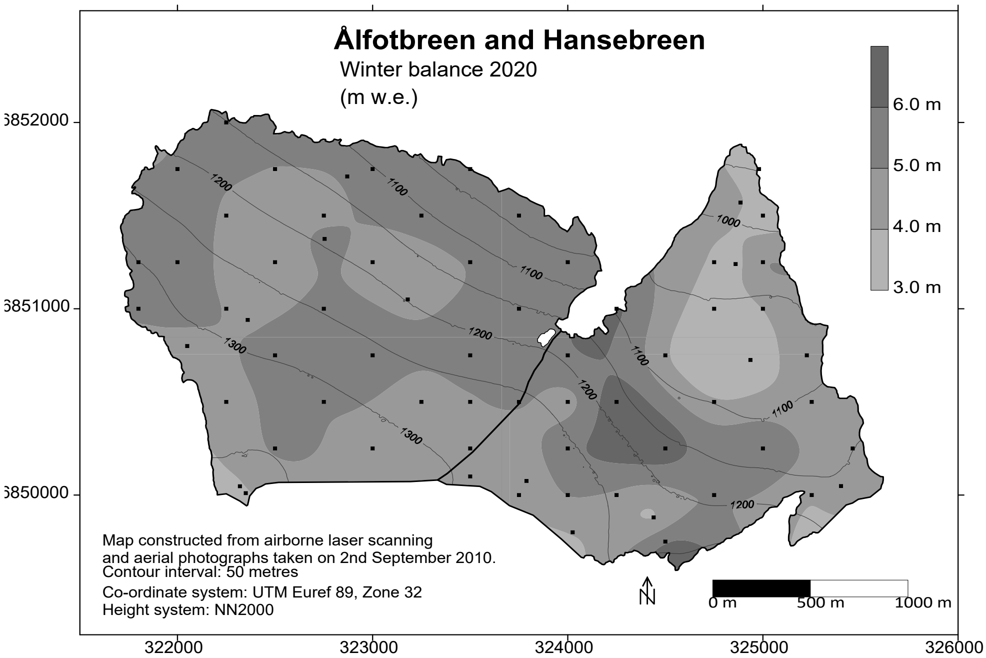


Figure 2-5
Spatial distribution of winter balance on Ålfotbreen (left) and Hansebreen (right) in 2020.

According to Figure 2-6 the ELA lies at 1065 m a.s.l. on Hansebreen and below the lowest point on Ålfotbreen. Consequently the AAR is 80 % for Hansebreen and 100 % for Ålfotbreen.

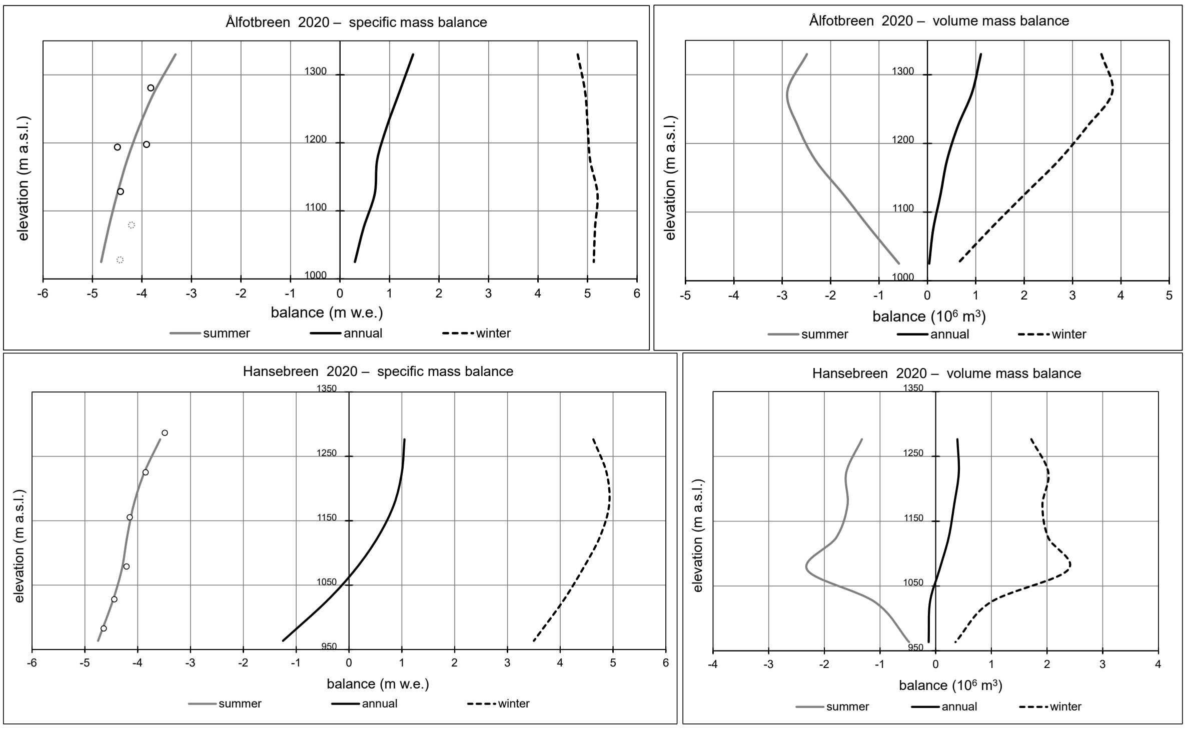


Figure 2-6
Mass balance diagram for Ålfotbreen (upper) and Hansebreen (lower) in 2020 showing altitudinal distribution of specific (left) and volumetric (right) winter, summer and annual balance. Specific summer balance at each stake is shown (○).

Table 2-1
Winter, summer and annual balance for Ålfotbreen (upper) and Hansebreen (lower) in 2020.

Mass balance Ålfotbreen 2019/20 – stratigraphic system

Altitude (m a.s.l.)	Area (km^2)	Winter mass balance Measured 28th Apr 2020		Summer mass balance Measured 6th Oct 2020		Annual mass balance Summer surface 2019 - 2020	
		Specific (m w.e.)	Volume (10^6 m^3)	Specific (m w.e.)	Volume (10^6 m^3)	Specific (m w.e.)	Volume (10^6 m^3)
1300 - 1360	0.75	4.80	3.6	-3.33	-2.5	1.48	1.1
1250 - 1300	0.77	4.95	3.8	-3.75	-2.9	1.20	0.9
1200 - 1250	0.66	5.00	3.3	-4.05	-2.7	0.95	0.6
1150 - 1200	0.54	5.05	2.7	-4.30	-2.3	0.75	0.4
1100 - 1150	0.38	5.20	2.0	-4.50	-1.7	0.70	0.3
1050 - 1100	0.25	5.15	1.3	-4.68	-1.2	0.48	0.1
1000 - 1050	0.12	5.13	0.6	-4.83	-0.6	0.30	0.0
1000 - 1360	**3.48**	**4.991**	**17.3**	**-3.988**	**-13.9**	**1.003**	**3.5**

Mass balance Hansebreen 2019/20 – stratigraphic system

Altitude (m a.s.l.)	Area (km^2)	Winter mass balance Measured 28th Apr 2020		Summer mass balance Measured 6th Oct 2020		Annual mass balance Summer surface 2019 - 2020	
		Specific (m w.e.)	Volume (10^6 m^3)	Specific (m w.e.)	Volume (10^6 m^3)	Specific (m w.e.)	Volume (10^6 m^3)
1250 - 1303	0.37	4.63	1.72	-3.58	-1.33	1.05	0.39
1200 - 1250	0.42	4.88	2.02	-3.88	-1.61	1.00	0.42
1150 - 1200	0.39	4.93	1.92	-4.08	-1.59	0.85	0.33
1100 - 1150	0.43	4.75	2.02	-4.20	-1.79	0.55	0.23
1050 - 1100	0.54	4.43	2.38	-4.30	-2.31	0.13	0.07
1000 - 1050	0.24	4.05	0.98	-4.48	-1.09	-0.43	-0.10
927 - 1000	0.10	3.50	0.35	-4.75	-0.48	-1.25	-0.13
927 - 1303	**2.48**	**4.590**	**11.4**	**-4.104**	**-10.2**	**0.486**	**1.2**

2.2 Mass balance 1963(86)-2020

After four successive years with deficits the mass balance was positive at both glaciers in 2020. The historical mass balance results for Ålfotbreen and Hansebreen are presented in Figure 2-7. The cumulative annual balance for Ålfotbreen for 1963-2020 is −6.7 m w.e., which gives a mean annual balance of −0.12 m w.e. a^{-1}. The cumulative annual balance for Hansebreen for 1986-2020 is −24.5 m w.e., which gives a mean annual balance of −0.70 m w.e. a^{-1}.

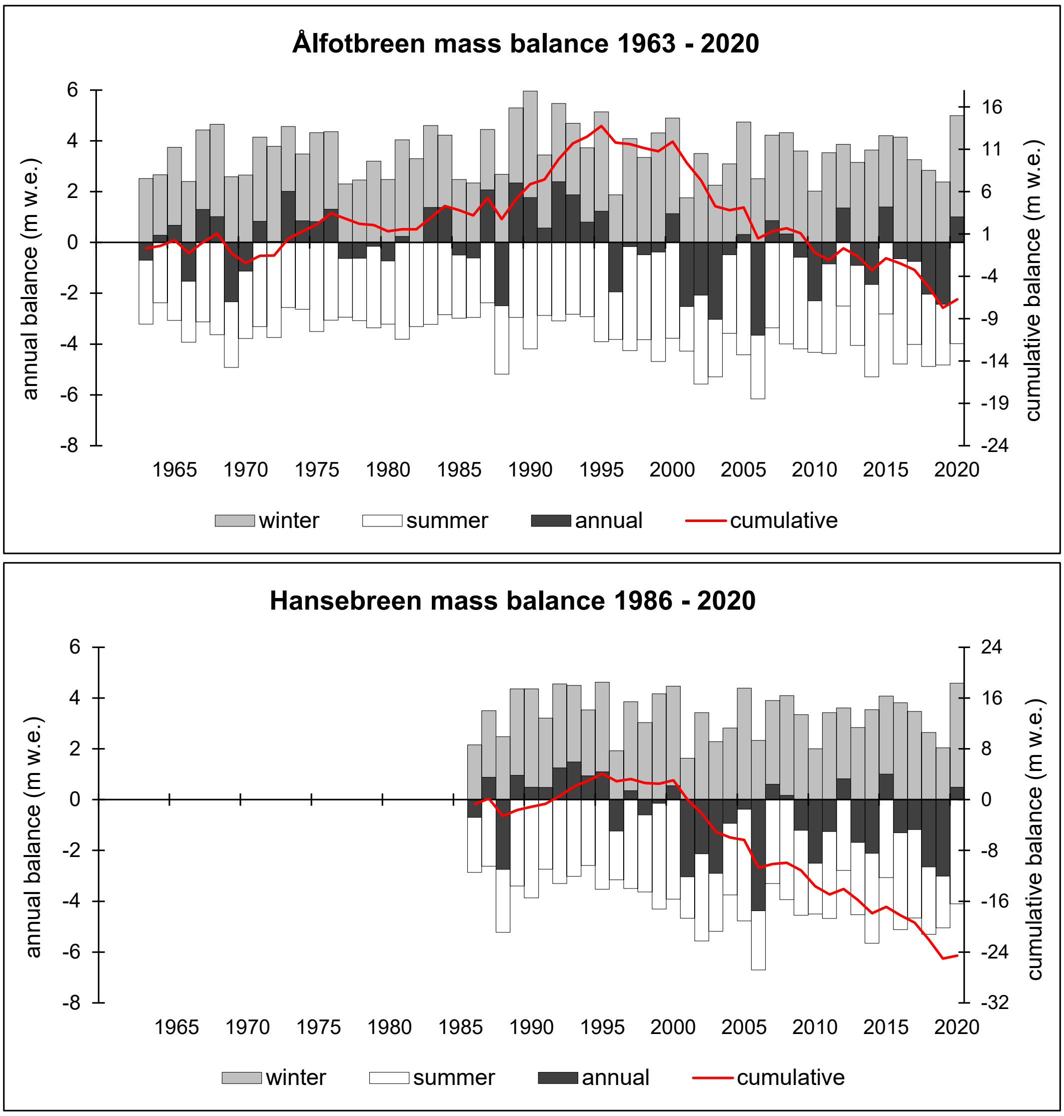


Figure 2-7
Mass balance at Ålfotbreen (upper) 1963-2020 and Hansebreen (lower) 1986-2020. Cumulative mass balance is given on the axis to the right.

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 27th August and 25th September 2019, and 28th April and 6th October 2020.

The positions were measured using Topcon GR-3 and Topcon Legacy E+ dual frequency GNSS receivers placed in the top of, or close to the stakes. 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.

The calculated surface ice velocities show mean annual velocities between 0.9 m a^{-1} and 12.5 m a^{-1} at Ålfotbreen and between 1.4 m a^{-1} and 3.5 m a^{-1} at Hansebreen (Fig. 2-8). The uncertainty of the GNSS positioning is assumed to be ±0.5 m.

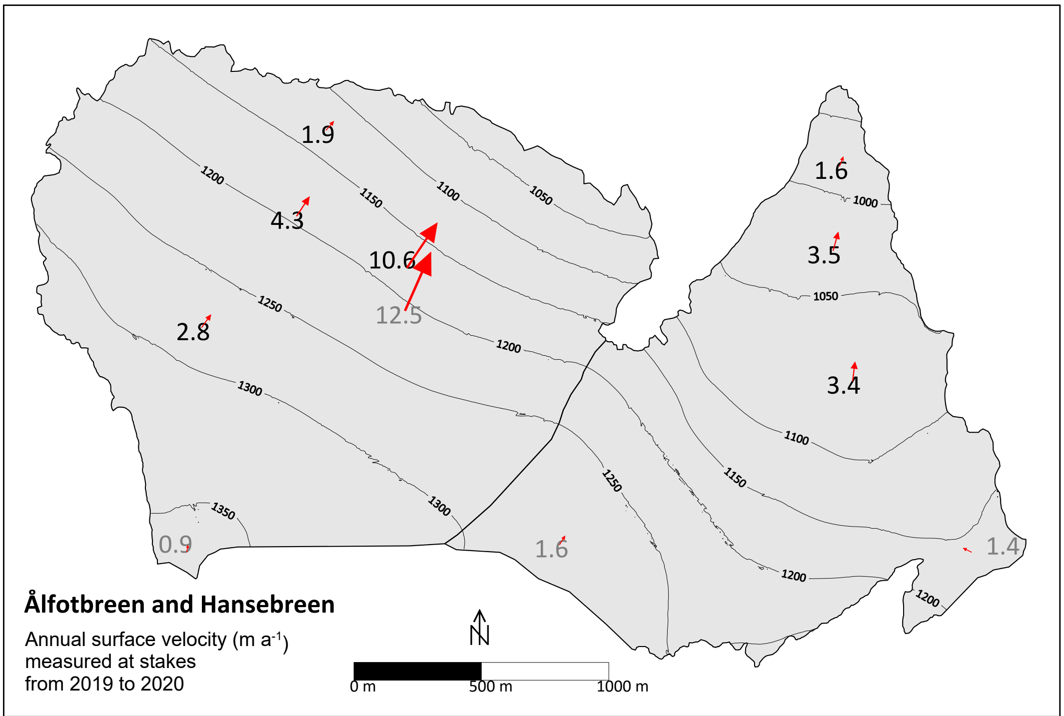


Figure 2-8
Map of Ålfotbreen and Hansebreen showing mean annual surface velocities calculated from stake position measurements in August and September 2019 and April and October 2020. The black values indicate mean annual surface velocities from August or September 2019 to October 2020, and the grey values represent the period from April to October 2020.

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 44.9 km^2 (2020) 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 1955 m a.s.l. down to 389 m a.s.l.

Glaciological investigations in 2020 include mass balance, glacier length change and surface ice velocity. Nigardsbreen has been the subject of mass balance investigations since 1962.

2.1 Mapping

A new survey of Nigardsbreen was performed in 2020. LIDAR data were recorded on 9th and 15th August 2020 by Terratec AS (Terratec AS, 2020a) as a part of the national laser scanning program initiated by the Norwegian Mapping Authority. Most of the glacier was covered by the first flight on 9th August. The glacier tongue below 1000 m altitude and some small areas in south-east was covered by the flight on 15th August. The data set produced by Terratec AS was point clouds (laz). Aerial photos were not taken.

A Digital Terrain Model (DTM) was generated based on the laser scanning data (x, y and z). As orthophoto was not available, the glacier outlines were digitised using the shaded relief of the DTM$_{2020}$ (Fig. 3-1) supported by orthophoto from 11th July 2019 and from satellite imagery from 27th August 2019. The ice divides calculated from laser DTM$_{2009}$ were used in the following work.

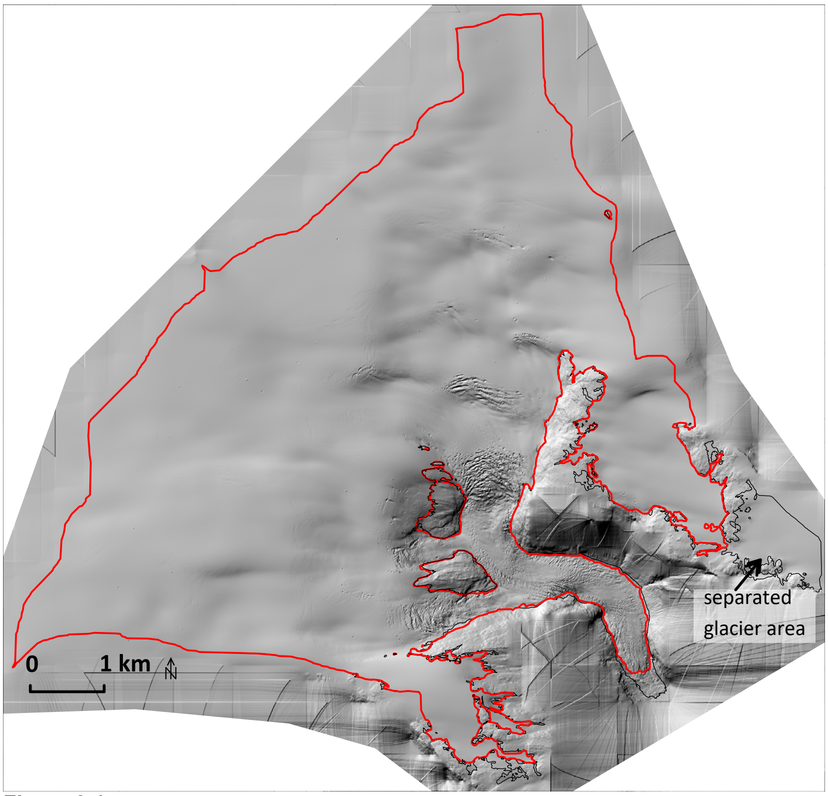


Figure 3-1
Shaded relief map of Nigardsbreen based on the DTM 2020. Glacier boundaries for 2020 in red and for 2013 in black.

All data was referred to the UTM co-ordinate system zone 32, Euref 89 datum and the Norwegian height system NN2000.

The mapping from 2020 showed some glacier changes compared with the previous mapping in 2013. The contiguous glacier area was reduced from 46.6 to 44.9 km^2, an area reduction of 1.7 km^2 or 4 %. This area correction was mainly related to separation of glacier cover in the eastern part of Nigardsbreen (Fig. 3-1). The recession of the glacier tongue from 2013 to 2020 was between 350 and 400 metres (Fig. 3-1).

Based on the new DTM from 2020 the area-altitude distribution was changed from the 2013 DTM (Fig. 3-2). Due to the separation of the glacier cover in east the area was considerably reduced between 1400 and 1600 m a.s.l.

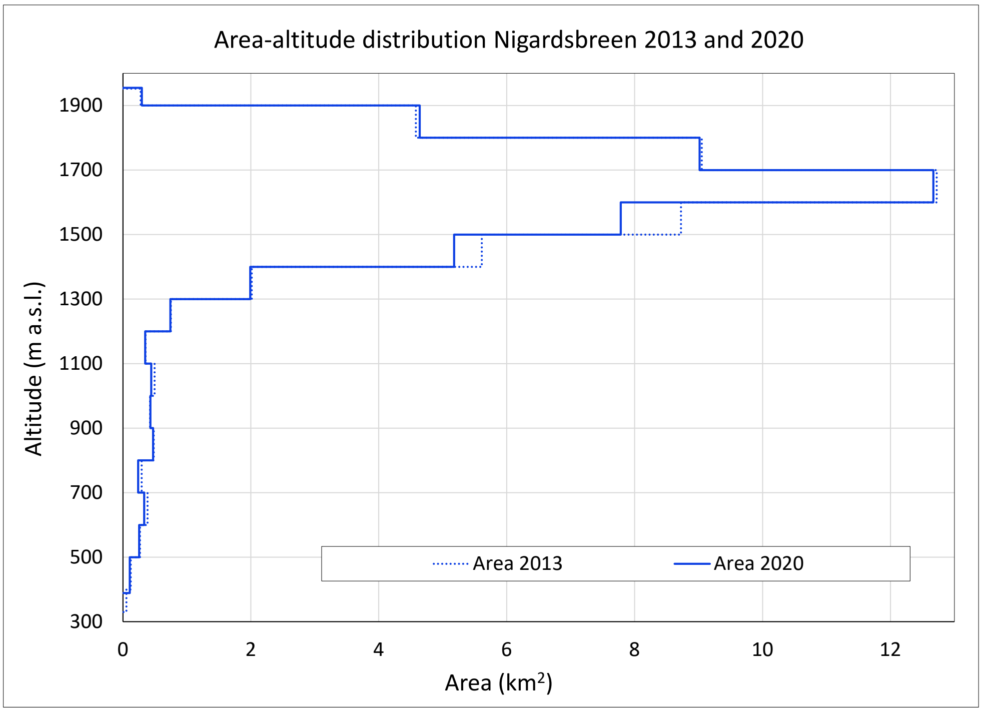


Figure 3-2
Area-altitude distribution for Nigardsbreen in 2013 (dotted line) and 2020 (solid line), respectively.

3.1 Mass balance 2020

Fieldwork

Snow accumulation measurements were performed on 19th and 20th May and the calculation of winter balance is based on measurement of four stakes and 70 snow depth soundings (Fig. 3-3). Comparison of sounded snow depth and stake reading at the lowest stake (586 m a.s.l.) indicated 25 cm melting after the ablation measurements in September 2019. Generally the sounding conditions were good and the summer surface was detectable just below a loose snow layer. The snow depth varied between 4.3 and 11.0 m on the plateau. On the glacier tongue, the snow depth was 4.8 m at stake position 1000 (964 m a.s.l.) and 1.8 m at stake position 600 (586 m a.s.l.). Snow density was measured at stake position 94 (1683 m a.s.l.), and the mean density of 7.9 m snow was 467 kg m^{-3}.

Ablation was measured on 15th September. Measurements were made at stakes and towers in ten locations (Fig. 3-3). In the accumulation area there was between 2.2 and 5.1 m of snow remaining from winter 2019/20. At the time of measurement, there was between 5 and 25 cm of fresh snow at stakes on the glacier plateau.

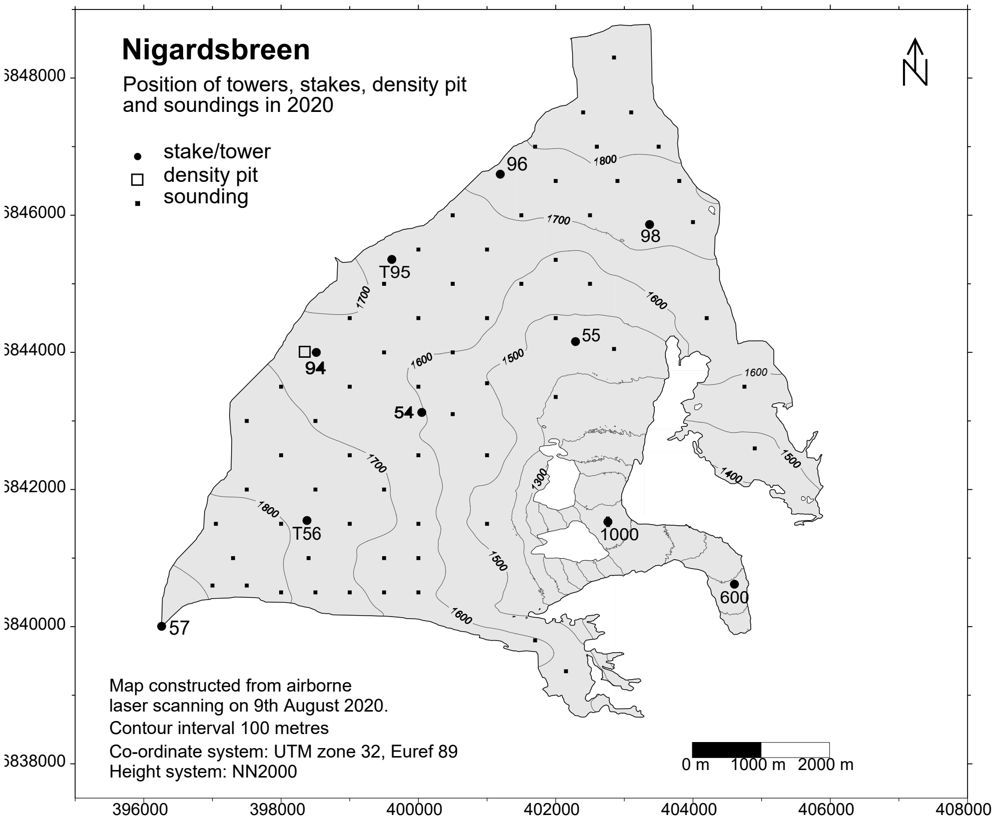


Figure 3-3
Location of towers, stakes, snow pit and soundings on Nigardsbreen in 2020.

Results

The calculations are based on the DTM from 2020.

The elevations above 1440 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 964, 956 and 586 m elevation.

The winter balance was calculated as a mean value for each 100 m height interval and was 3.5 ±0.2 m w.e., which is 156 % of the mean winter balance for the reference period 1981-2010. Spatial distribution of the winter balance is shown in Figure 3-4.

The density of remaining snow was assumed to be 600 kg m^{-3}. 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 −1.9 ±0.3 m w.e., which is 85 % of the reference period.

Hence the annual balance was positive, at +1.65 m ±0.40 m w.e. The mean annual balance for the reference period 1981-2010 is +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 3-5.

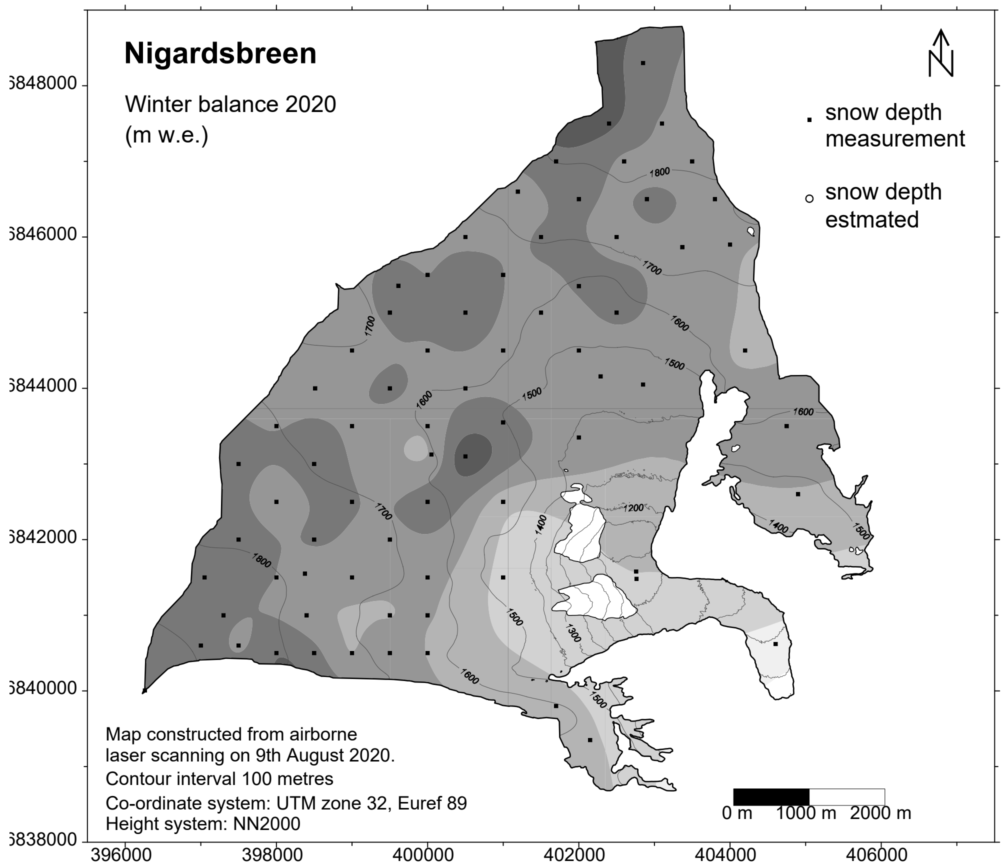


Figure 3-4
Spatial distribution of winter balance on Nigardsbreen in 2020.

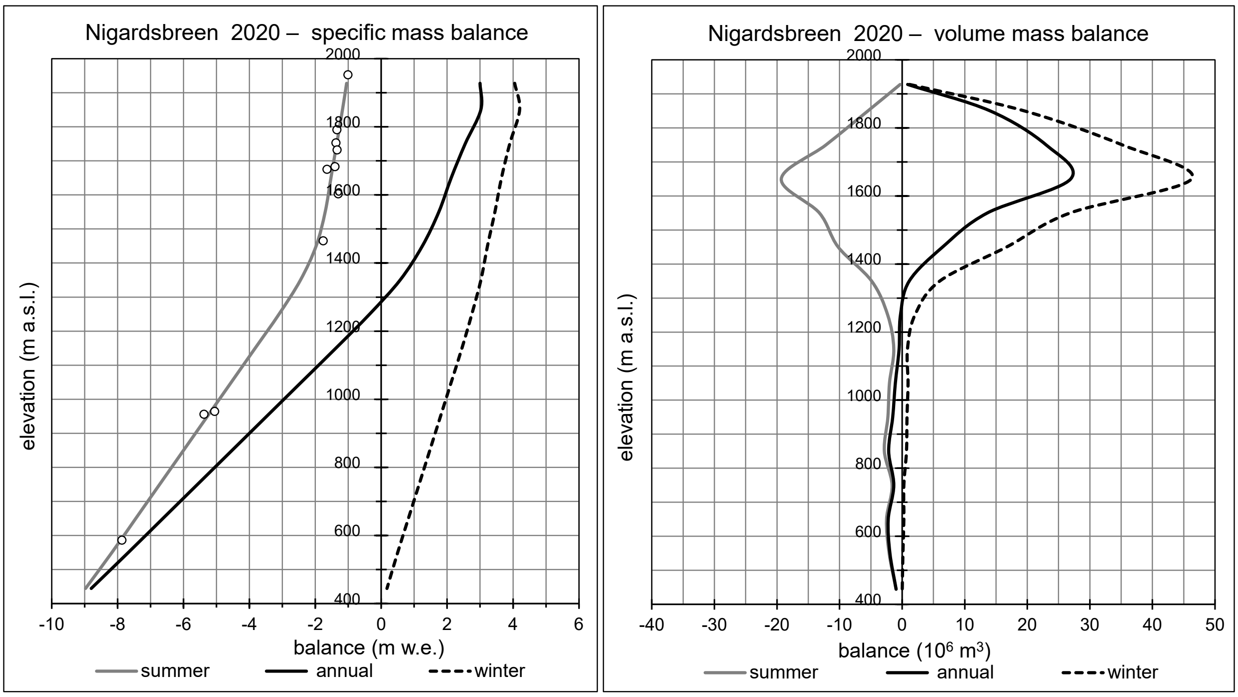


Figure 3-5
Mass balance diagram showing specific balance (left) and volume balance (right) for Nigardsbreen in 2020. Specific summer balance at eleven different stake positions is shown as circles (○).

According to Figure 3-5, the Equilibrium Line Altitude was 1285 m a.s.l. Consequently the Accumulation Area Ratio was 93 %.

Table 3-1
The altitudinal distribution of winter, summer and annual balance in 100-m intervals for Nigardsbreen in 2020.

Mass balance Nigardsbreen 2019/20 – stratigraphic system

Altitude (m a.s.l.)	Area (km^2)	Winter mass balance Measured 19th May 2020 Specific (m w.e.)	Volume (10^6 m^3)	Summer mass balance Measured 15th Oct 2020 Specific (m w.e.)	Volume (10^6 m^3)	Annual mass balance Summer surface 2019 – 2020 Specific (m w.e.)	Volume (10^6 m^3)
1900 - 1955	0.30	4.05	1.2	-1.05	-0.3	3.00	0.9
1800 - 1900	4.64	4.20	19.5	-1.18	-5.5	3.03	14.0
1700 - 1800	9.02	3.90	35.2	-1.35	-12.2	2.55	23.0
1600 - 1700	12.67	3.65	46.2	-1.53	-19.3	2.13	26.9
1500 - 1600	7.78	3.45	26.8	-1.70	-13.2	1.75	13.6
1400 - 1500	5.18	3.23	16.7	-1.98	-10.2	1.25	6.5
1300 - 1400	1.99	3.03	6.0	-2.45	-4.9	0.58	1.1
1200 - 1300	0.74	2.75	2.0	-3.10	-2.3	-0.35	-0.3
1100 - 1200	0.35	2.45	0.9	-3.83	-1.3	-1.38	-0.5
1000 - 1100	0.44	2.13	0.9	-4.55	-2.0	-2.43	-1.1
900 - 1000	0.43	1.80	0.8	-5.28	-2.3	-3.48	-1.5
800 - 900	0.47	1.48	0.7	-6.00	-2.8	-4.53	-2.1
700 - 800	0.24	1.15	0.3	-6.73	-1.6	-5.58	-1.3
600 - 700	0.33	0.83	0.3	-7.45	-2.5	-6.63	-2.2
500 - 600	0.25	0.50	0.1	-8.18	-2.1	-7.68	-1.9
389 - 500	0.11	0.18	0.0	-8.98	-1.0	-8.80	-1.0
389 - 1955	**44.95**	**3.508**	**157.7**	**-1.857**	**-83.5**	**1.651**	**74.2**

3.2 Mass balance 1962-2020

The historical mass balance results for Nigardsbreen are presented in Figure 3-6. The cumulative annual balance for 1962-2020 is +6.8 m w.e., which gives a mean annual balance of +0.11 m w.e. a^{-1}. Over the past ten years (2011-2020), the mean annual balance was +0.22 m w.e.

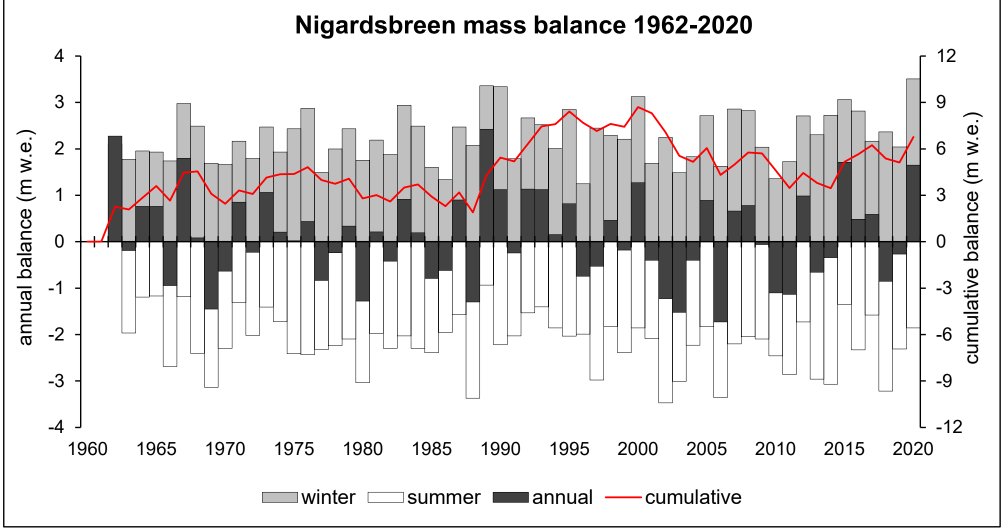


Figure 3-6
Winter, summer and annual balance at Nigardsbreen for 1962-2020. Cumulative mass balance is given on the right axis.

3.3 Ice velocity

The surface ice velocity was calculated from repeated GNSS measurements of four stakes. The positions of the stakes were measured on 25th September 2019 and 13th October 2020. For stake 55 (48 m a^{-1}), however, measurements represent the period from 25th September 2019 to 20th August 2020.

The positions were measured by using Topcon GR-3 dual frequency GNSS receivers placed on top of, or close to the stakes (Fig. 3-7). 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 4 and 207 m a^{-1} (Fig. 3-8). The uncertainty of the GNSS positioning is assumed to be ±0.5 m.

Figure 3-7
GNSS positioning of stakes on 20th August 2020.
Photo: Even Loe.

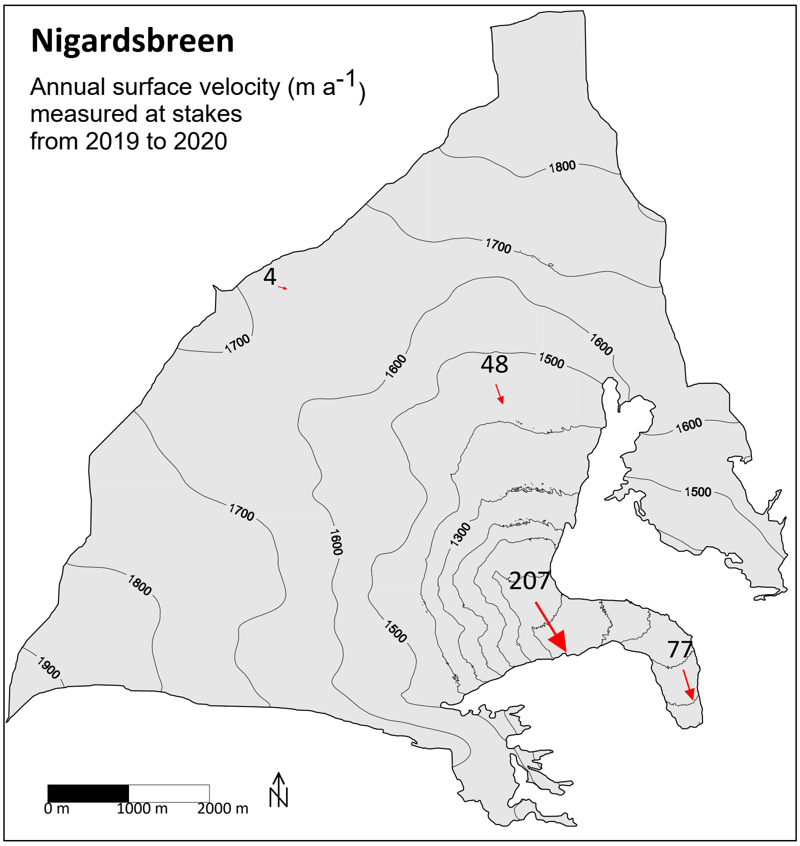


Figure 3-8
Map of Nigardsbreen showing mean annual surface velocities calculated from stake position measurements in September 2019 and October 2020. For stake 55, (see position in Fig. 3-3) the velocity represents the period from September 2019 to August 2020.

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 1740 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 2020 included mass balance, front position change and glacier velocity. The mass balance has been measured at Austdalsbreen since 1988.

Figure 4-1
Stake A10 on 13th October 2020. The stake position was surveyed using a GNSS-receiver for glacier velocity calculations. Photo: Hallgeir Elvehøy.

Mass balance 2020

Fieldwork

Only one stake location at A70 was maintained through the winter. Snow accumulation measurements were performed on 21st April. The calculation of the winter balance was based on measurements in eight stake locations and 39 snow depth sounding locations (Fig. 4-2). Detecting the summer surface was relatively easy. The snow depth varied between 4 and 8 metres, and the average snow depth was 6.3 metres. The mean density of 6.5 m snow at stake A60 (1480 m a.s.l.) was 446 kg m^{-3}.

The stake network was measured on 20th August. Between 3.5 and 5 metres of snow and ice had melted since 21st April. The transient snow line was around 1300 m a.s.l.

Summer and annual balance measurements were carried out on 13th October (Fig. 4-1). There was up to 0.2 m of new snow on the glacier. Stakes were found in all the eight stake locations.

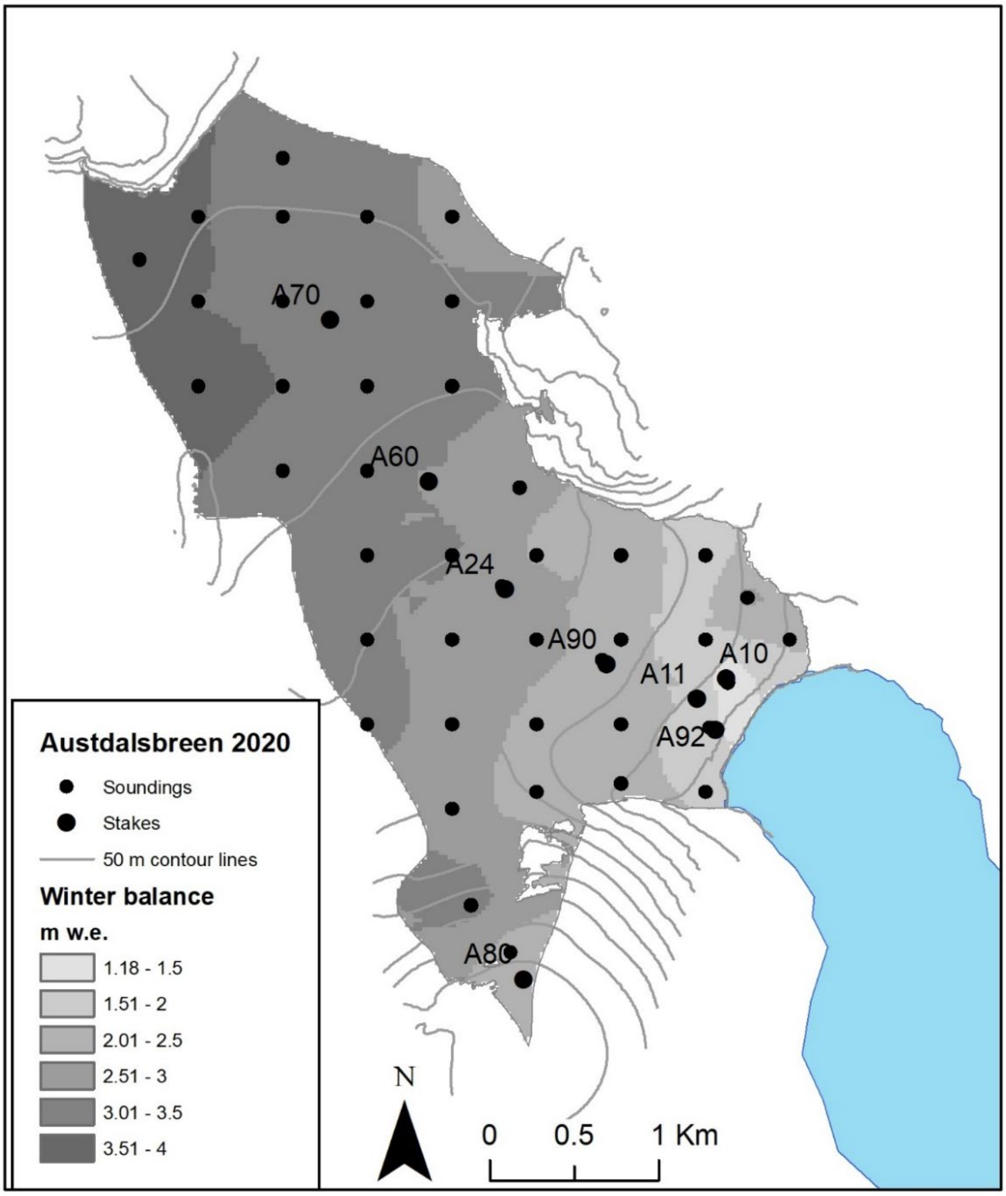


Figure 4-2
Location of stakes and snow depth soundings, and winter balance at Austdalsbreen in 2020 interpolated from 47 water equivalent values calculated from snow depth measurements.

Based on stake observations, the snow line altitude was around 1375 m a.s.l. Close to the glacier terminus between 1 and 3 metres of ice had melted. Above 1400 m a.s.l. up to 2.5 metres of snow remained.

Results

The calculations are based on a DEM from 27th August 2019. The winter balance was calculated from snow depth and snow density measurements on 24th April. A function correlating snow depth with water equivalent values was calculated based on snow density measurements at stake A60 (1480 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. 4-3). The total winter balance was 29 ±2 mill. m^3 water or 2.9 ±0.2 m w.e., which is 135 % of the 1988-2019 average (2.16 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 2.89 m w.e (Fig. 4-2).

The summer balance was calculated for eight stake locations between 1250 and 1715 m a.s.l. The summer balance curve was drawn from these eight point values (Fig. 4-3).

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

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

where ρ_{ice} is 900 kg m^{-3}, u_{ice} is annual glacier velocity (37 ±10 m a^{-1}), u_f is front position change averaged across the terminus (+27 ±5 m a^{-1}), W is terminus width (865 ±20 m) and H is mean ice thickness at the terminus (38 ±5 m). The mean ice thickness was calculated from mean surface elevations along the calving terminus surveyed on 25th September 2019 and 13th October 2020, and mean bottom elevation along the terminuses calculated from a bathymetry map (Kjøllmoen and others, 2020). The resulting calving volume was 0.3 ±0.8 mill. m^3 water equivalent. The summer balance including calving was calculated as −21 ±3 mill. m^3 of water, which corresponds to −2.1 ±0.3 m w.e. The result is 78 % of the 1988-2019 average (−2.73 m w.e.). The calving volume was 1 % of the summer balance.

The annual balance at Austdalsbreen was calculated as +8 ±3 mill. m^3 water, corresponding to +0.8 ±0.3 m w.e. The average annual balance for the period 1988-2019 is −0.57 m w.e. The ELA in 2020 was at 1375 m a.s.l., and the AAR was 82 %. The altitudinal distribution of winter, summer and annual balance is shown in Table 4-1 and Figure 4-3. Results from 1988-2020 are shown in Figure 4-4.

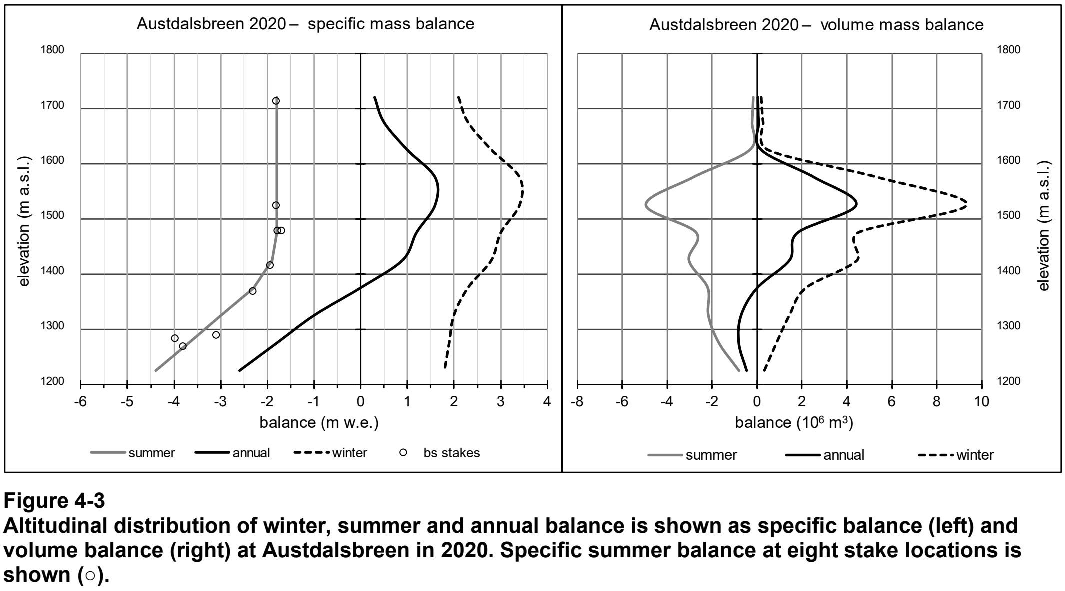


Figure 4-3
Altitudinal distribution of winter, summer and annual balance is shown as specific balance (left) and volume balance (right) at Austdalsbreen in 2020. Specific summer balance at eight stake locations is shown (○).

Table 4-1
Altitudinal distribution of winter, summer, and annual balances for Austdalsbreen in 2020.

Mass balance Austdalsbreen 2019/20 – stratigraphic system

		Winter mass balance Measured 21st April 2020		Summer mass balance Measured 13th Oct 2020		Annual mass balance Summer surface 2019 – 2020	
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	2.10	0.2	-1.80	-0.2	0.30	0.0
1650 - 1700	0.119	2.30	0.3	-1.80	-0.2	0.50	0.1
1600 - 1650	0.172	2.80	0.5	-1.80	-0.3	1.00	0.2
1550 - 1600	1.584	3.40	5.4	-1.80	-2.9	1.60	2.5
1500 - 1550	2.748	3.40	9.3	-1.80	-4.9	1.60	4.4
1450 - 1500	1.503	3.00	4.5	-1.80	-2.7	1.20	1.8
1400 - 1450	1.594	2.80	4.5	-1.90	-3.0	0.90	1.4
1350 - 1400	0.952	2.30	2.2	-2.30	-2.2	0.00	0.0
1300 - 1350	0.721	2.00	1.4	-3.00	-2.2	-1.00	-0.7
1250 - 1300	0.457	1.90	0.9	-3.70	-1.7	-1.80	-0.8
1200 - 1250	0.182	1.80	0.3	-4.40	-0.8	-2.60	-0.5
Calving					-0.3		-0.3
1200 - 1740	**10.122**	**2.912**	**29.5**	**-2.110**	**-21.4**	**0.802**	**8.1**

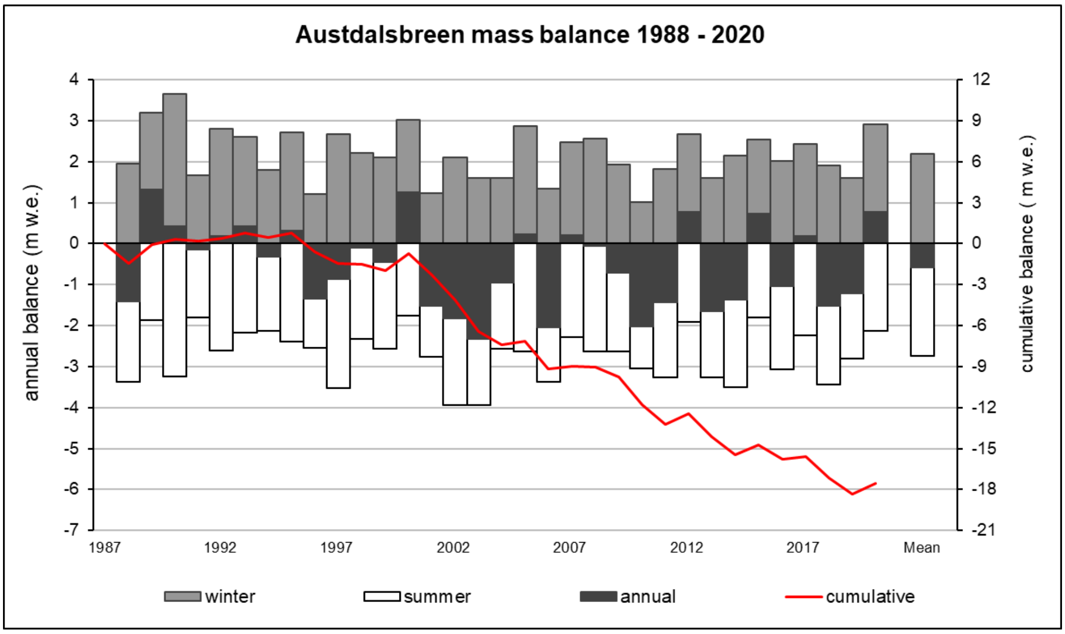


Figure 4-4
Winter, summer, annual and cumulative balance at Austdalsbreen during the period 1988-2020. Mean winter and summer balance is 2.18 and −2.73 m w.e., respectively. The cumulative mass balance is −17.6 m w.e.

Front position change

Two points on the calving terminus were surveyed on 13th October 2020. In addition, Sentinel 2 satellite images from 15th October were used to determine the terminus position (www.xgeo.no). The mean front position change was +27 ±5 m between 25th September 2019 and 13th October 2020 (Fig. 4-5). The width of the calving terminus was defined from an orthophoto from 27th August 2019 as 865 ±20 m. Since 1988 the glacier terminus has retreated about 710 m, and the lake area has increased 0.674 km^2.

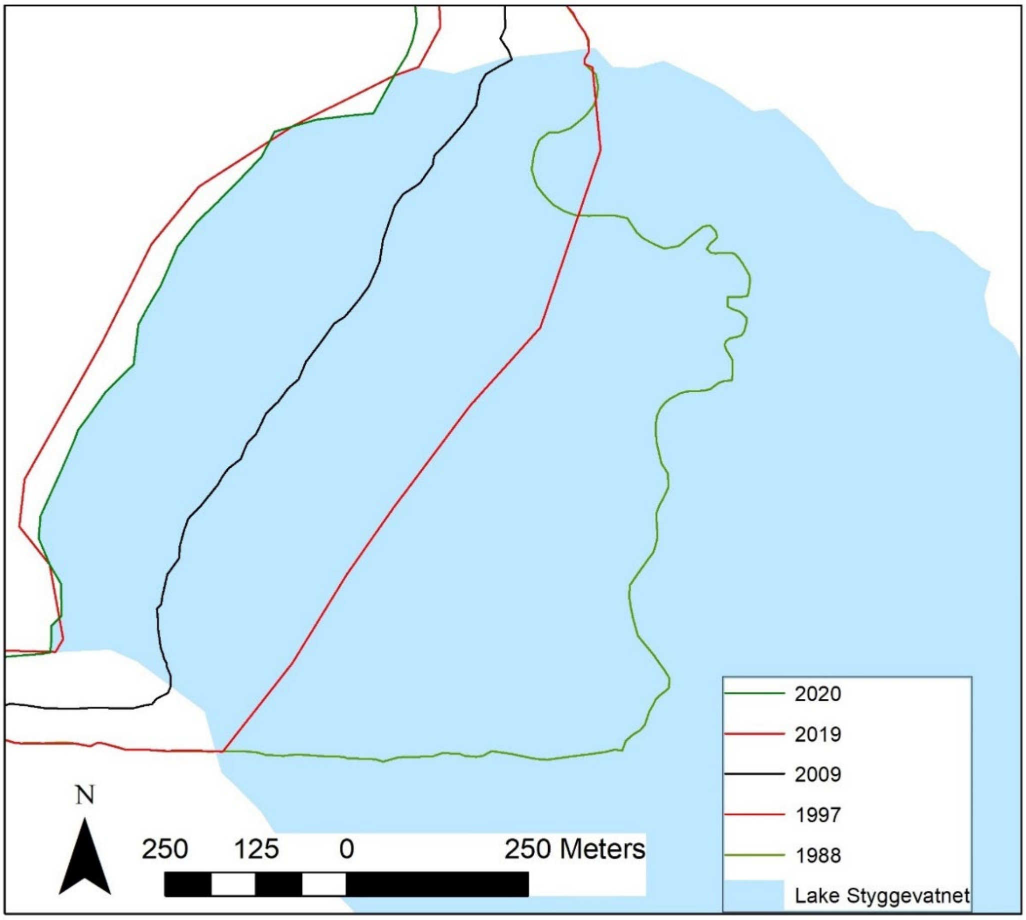


Figure 4-5
Surveyed front position of Austdalsbreen in 1988 when the lake was regulated, and in 1997, 2009, 2019 and 2020. The glacier terminus advanced 27 metres between 25th September 2019 and 13th October 2020.

Glacier dynamics

Glacier velocities are calculated from repeated surveys of stakes. The stake network was surveyed on 21st August and 25th September 2019, and 21st April, 20th August and 13th October 2020. Annual velocities were calculated for four stake locations between 1350 and 1550 m a.s.l. for the period 25th September 2019 – 13th October 2020 (373 days). The annual results were similar to results from 2012-15 (Kjøllmoen and others, 2016).

The two frontal stakes A10 and A92 were not measured on 25th September 2019. Consequently, the annual velocities were calculated from positions on 21st August 2019 and 13th October 2020. The resulting annual velocities at stake locations close to the terminus was 63 m a^{-1} at A92 (64 m a^{-1} in 2019) and 42 m a^{-1} at A10 (52 m a^{-1} in 2019).

The glacier velocity averaged across the front width and thickness was estimated 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 calculated as 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 2019/2020 is 37 ±10 m a^{-1}.

5. Rembesdalskåka (Hallgeir Elvehøy)

Rembesdalskåka (17 km^2, 60°32′N, 7°22′E) is a southwestern outlet glacier from Hardangerjøkulen (Fig. 5-1), 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. 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 6th September 2020 (see section 12.2).

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 1085 and 1851 m a.s.l. as mapped in 2020.

Figure 5-1
The lower part of Rembesdalskåka on 14th October 2020. The nunatak Olavvarden (1765 m a.s.l.) is seen in the background. Photo: Hallgeir Elvehøy.

5.1 Mapping

Aerial photographs were taken, and airborne laser scanning (Lidar) was carried out on 16th August (Terratec AS, 2020b). The mean point density was 2.8 points per m^2 (0.36 m^2 per point). Comparison of data from crossing flight lines shows that differences are generally less than 0.1 metres. A larger data set from the same flight was adjusted 5 cm after comparison with reference areas, and this dataset was adjusted likewise. A Digital Elevation Model (DEM) was processed based on the adjusted laser scanning data.

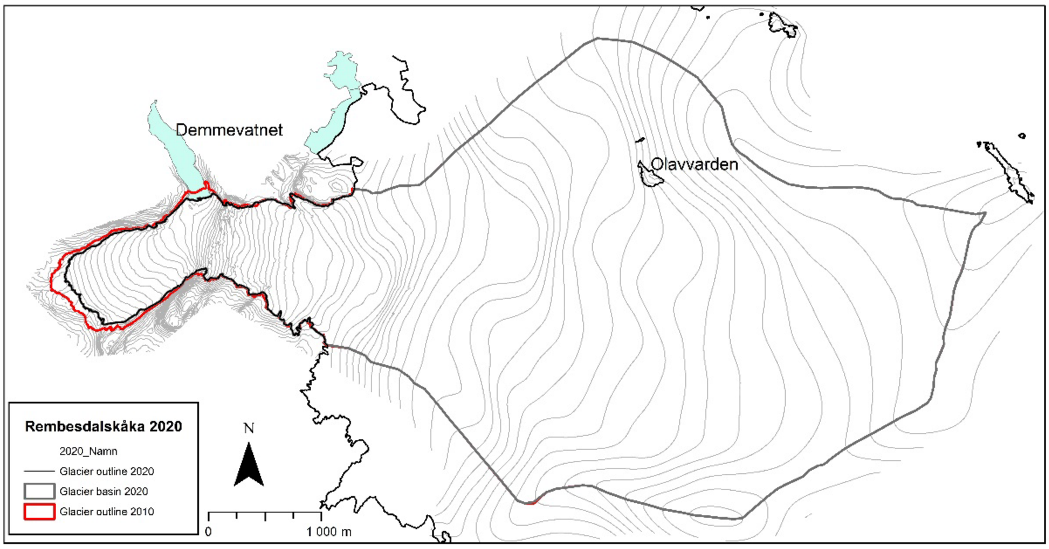


Figure 5-2
Map of Rembesdalskåka on 16th August 2020. The glacier terminus retreated 85 metres between 2010 and 2020, and the glacier edge in Demmevatnet retreated 75 metres.

Table 5-1
The change in Area-Altitude-Distribution between 2010 and 2020.

		Area 2010 km²	Area 2020 km²	Area change km²	Change %
1850	1854/1851	0.029	0.002	−0.027	−93
1800	1850	3.213	2.823	−0.390	−12
1750	1800	3.992	4.059	+0.067	+2
1700	1750	4.048	4.130	+0.082	+2
1650	1700	2.281	2.267	−0.014	−1
1600	1650	0.957	1.167	+0.210	+22
1550	1600	0.545	0.534	−0.011	−2
1500	1550	0.535	0.523	−0.012	−2
1450	1500	0.336	0.381	+0.045	+13
1400	1450	0.197	0.201	+0.004	+2
1350	1400	0.108	0.107	−0.001	−1
1300	1350	0.074	0.071	−0.003	−4
1250	1300	0.199	0.126	−0.077	−39
1200	1250	0.262	0.202	−0.060	−23
1150	1200	0.333	0.289	−0.044	−13
1100	1150	0.143	0.194	+0.051	+36
1066/1085	1100	0.012	0.010	−0.002	−17
Total area		17.264	17.086	−0.178	−1.0

The glacier outline was digitized from the orthophotos. The ice divides were kept unchanged as defined from the DEM from 2010. Consequently, the drainage basin was defined from the outline and the ice divide defined from the DEM from 2010 (Kjøllmoen et al. 2011). The Area-altitude distribution for the drainage basin was calculated from the DEM (Tab. 5-1). Between 2010 and 2020 the glacier area decreased from 17.264 km² to

17.086 km² (−0.178 km²). The largest change in area occurred in the elevation band between 1800 and 1850 m a.s.l. (−0.390 km²). The elevation of the highest point decreased from 1854 to 1851 m a.s.l.

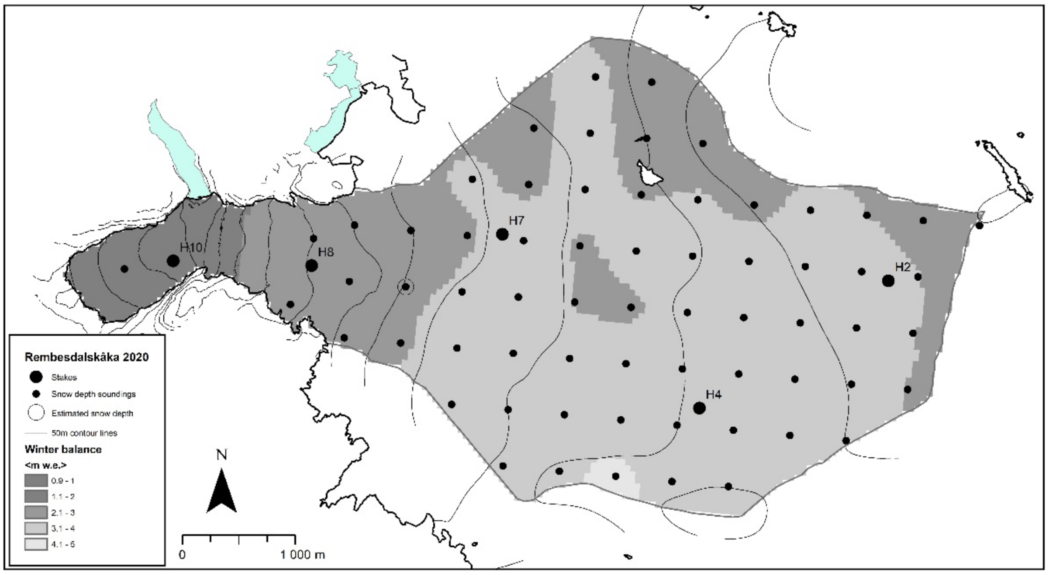


Figure 5-3
Winter balance at Rembesdalskåka interpolated from five stake measurements of snow depth, 65 snow depth soundings, and one estimated point in the upper ice fall (1600 m a.s.l.).

5.2 Mass balance 2020

Fieldwork

The snow accumulation was measured on 20th May. Stakes were maintained in four locations. Snow depth was measured in 64 sounding locations in a 500 by 500 m grid on the glacier plateau above 1500 m a.s.l. (Fig. 5-3). The average snow depth on the plateau was 7.15 m and varied between 4.8 and 8.8 m. The summer surface (SS) was well defined. The mean snow density down to the summer surface at 7.5 m depth at stake H7 was 457 kg m^{-3}.

Summer and annual balances were measured on 14th October. There were up to 0.5 m of new snow at the stake locations. At H7, H4 and H2 between 2.4 and 2.8 m of winter snow remained. At H8 and H10 all the winter snow and 0.35 and 5.0 m of ice, respectively, had melted. Stake measurement and snow depth sounding at H10 on 27th November revealed that an additional 1.05 m of ice had melted between 14th October and 27th November.

Results

The calculation of the mass balance is based on a DEM from 2020. The winter balance was calculated from the snow depth and snow density measurements on 20th 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. 5-4). Below 1500 m a.s.l. the winter balance curve was interpolated 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 3.0 ±0.2 m w.e. or 52 ±3 mill. m³ water. This is 142 % of the 1981-2010 average of 2.14 m w.e. a^{-1}.

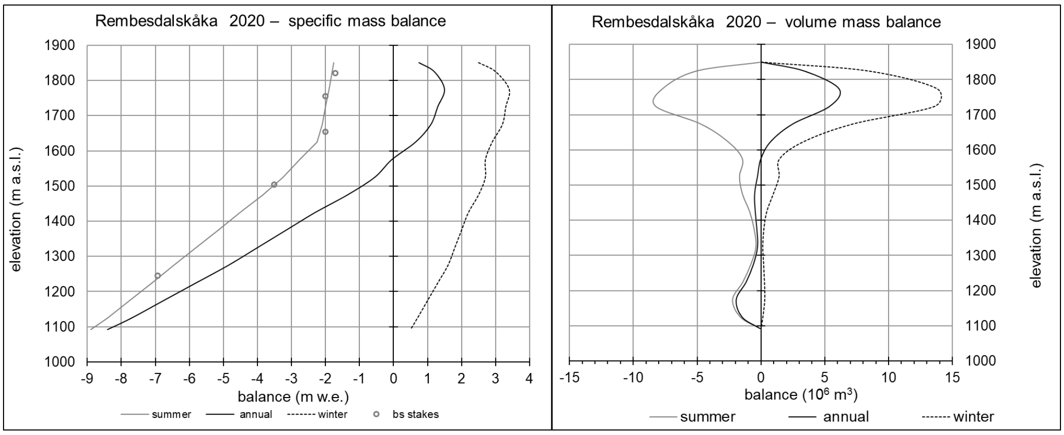


Figure 5-4
Altitudinal distribution of winter, summer and annual mass balance is shown as specific balance (left) and volume balance (right). Specific summer balance, b_s, at five stakes is shown (○).

Table 5-2
Altitudinal distribution of winter, summer and annual mass balance at Rembesdalskåka in 2020.

Mass balance Rembesdalskåka 2019/20 – stratigraphic system

Altitude	Area	Winter mass balance Measured 20th May 2020		Summer mass balance Measured 14th Oct 2020		Annual mass balance Summer surface 2019 - 2020	
(m a.s.l.)	(km²)	Specific (m w.e.)	Volume (10^6 m³)	Specific (m w.e.)	Volume (10^6 m³)	Specific (m w.e.)	Volume (10^6 m³)
1850 - 1851	0.002	2.50	0.0	-1.75	0.0	0.75	0.0
1800 - 1850	2.823	3.00	8.5	-1.80	-5.1	1.20	3.4
1750 - 1800	4.059	3.40	13.8	-1.90	-7.7	1.50	6.1
1700 - 1750	4.130	3.30	13.6	-2.00	-8.3	1.30	5.4
1650 - 1700	2.267	3.20	7.3	-2.10	-4.8	1.10	2.5
1600 - 1650	1.167	2.90	3.4	-2.25	-2.6	0.65	0.8
1550 - 1600	0.534	2.70	1.4	-2.75	-1.5	-0.05	0.0
1500 - 1550	0.523	2.70	1.4	-3.25	-1.7	-0.55	-0.3
1450 - 1500	0.381	2.50	1.0	-3.85	-1.5	-1.35	-0.5
1400 - 1450	0.201	2.20	0.4	-4.50	-0.9	-2.30	-0.5
1350 - 1400	0.107	2.00	0.2	-5.15	-0.6	-3.15	-0.3
1300 - 1350	0.071	1.80	0.1	-5.80	-0.4	-4.00	-0.3
1250 - 1300	0.126	1.60	0.2	-6.45	-0.8	-4.85	-0.6
1200 - 1250	0.202	1.30	0.3	-7.10	-1.4	-5.80	-1.2
1150 - 1200	0.289	1.00	0.3	-7.75	-2.2	-6.75	-2.0
1100 - 1150	0.194	0.70	0.1	-8.40	-1.6	-7.70	-1.5
1085 - 1100	0.010	0.50	0.0	-8.90	-0.1	-8.40	-0.1
1085 - 1851	**17.086**	**3.045**	**52.0**	**-2.408**	**-41.2**	**0.637**	**10.9**

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 5-3, and the mean winter balance was 3.08 m w.e.

The date of the 2020 mass balance minimum on the glacier plateau above 1500 m a.s.l. was assessed as the 8th of October based on the daily gridded data of temperature and new snow from www.senorge.no. On the glacier tongue the melting persisted until 19th November.

The summer balance was calculated directly at the five stake locations. The density of the remaining winter snow at H7, H4 and H2 was set as 600 kg m^{-3}, and the density of melted ice at H8 and H10 was set as 900 kg m^{-3}. The summer balance curve in Figure 5-4 was drawn from five point values. The summer balance was calculated as −2.4 ±0.2 m w.e., corresponding to −41 ±3 mill. m^3 of water. This is 112 % of the 1981-2010 normal average, which is −2.16 m w.e. a^{-1}. The annual balance at Rembesdalskåka was calculated as +0.6 ±0.3 m w.e. or +11 ±5 mill. m^3 water. The 1981-2010 normal average is -0.02 m w.e. a^{-1}. The ELA in 2020 was 1575 m a.s.l. and the corresponding AAR was 86%. The altitudinal distribution of winter, summer and annual balances is shown in Figure 5-4 and Table 5-2. Results from 1963-2020 are shown in Figure 5-5. The cumulative annual balance is −5.3 m w.e. Since 1995 the glacier has had a mass deficit of −13.0 m w.e. or −0.52 m w.e. a^{-1}.

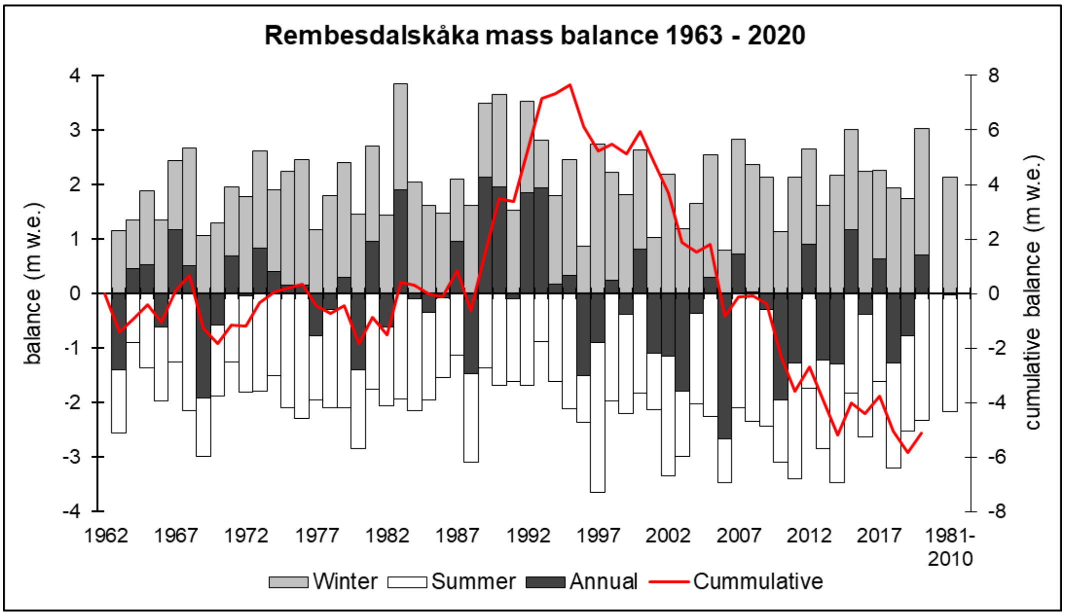


Figure 5-5
Winter, summer, annual and cumulative mass balance at Rembesdalskåka during the period 1963-2020. Mean values (1963-2020) are B_w=2.07 m w.e a^{-1} and B_s=−2.16 m w.e a^{-1}.

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 4.9 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 (section 6-1).

Figure 6-1
Storbreen on 12th August 2020. Photo: Liss M. Andreassen.

6.1 Mass balance 2020

Field work

Snow accumulation measurements were performed on 21st of April on the lower part and on 22nd – 23rd April on the upper part of the glacier. Stakes were only visible in one position were visible. A total of 94 snow depth soundings between 1433 and 2023 m a.s.l. were made (Fig. 6-2). The snow depth varied between 2.44 and 6.50 m, the mean and median being 4.3 and 4.1 m respectively. Snow density was measured at stake 4 (1703 m a.s.l.) where the total snow depth was 3.86 m. The average snow density measured was 441 kg m^{-3}. Ablation measurements were performed on 18th September at all stake positions.

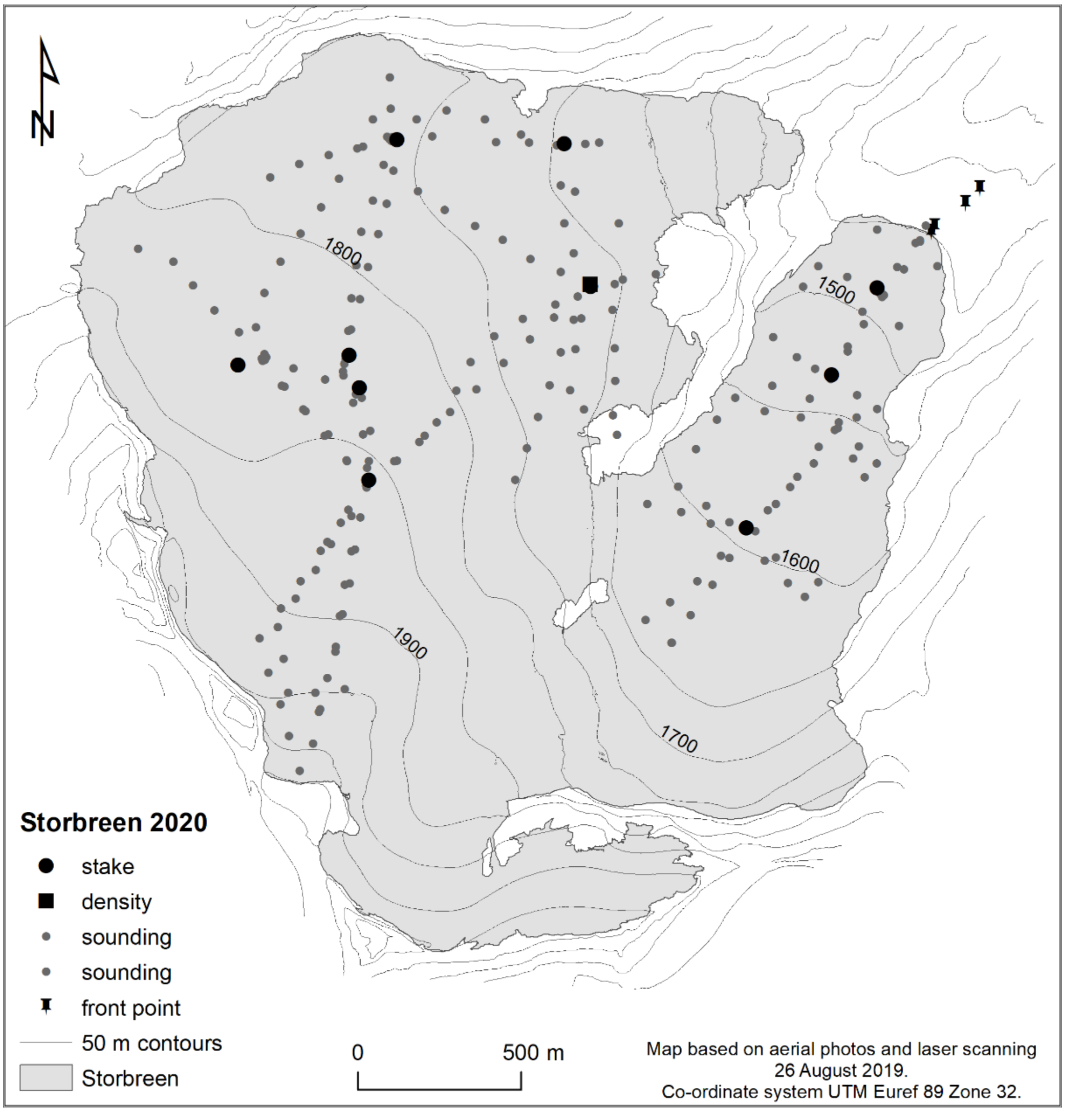


Figure 6-2
Location of stakes, soundings and density pits at Storbreen in 2020.
Front point: reference points used for length change (glacier front) measurements (see chap. 12.1).

Results

The winter balance was calculated from the mean of the soundings within each 50-metre height interval and was 1.93 ± 0.2 m w.e., which is 130 % 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 –1.98 ± 0.3 m w.e., which is 109 % of the mean summer balance for the reference period 1981-2010. The annual balance of Storbreen was –0.05 ± 0.3 m w.e. in 2020. The annual balance curve from the annual balance diagram (Fig. 6-3) indicates an ELA of ~1760 m a.s.l. resulting in an estimated accumulation area ratio (AAR) of 53 %.

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

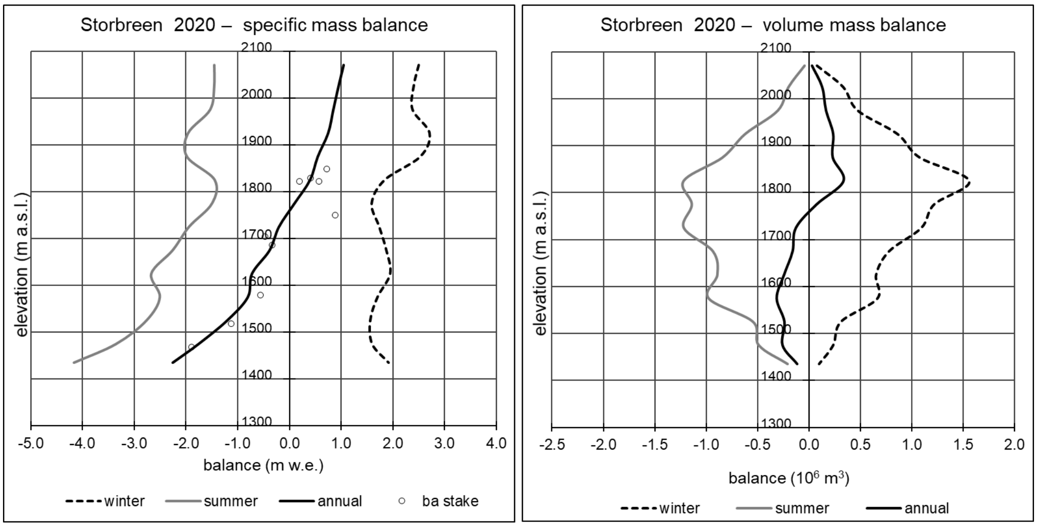


Figure 6-3
Mass balance versus altitude for Storbreen 2020, showing specific balance on the left and volume balance on the right. Annual balance at nine stakes is also shown.

Table 6-1
The distribution of winter, summer and annual balance in 50 m altitudinal intervals for Storbreen in 2020.

Mass balance Storbreen 2019/20

Altitude (m a.s.l.)	Area (km^2)	Winter balance Measured 21-23 April Specific (m w.e.)	Winter Volume (10^6 m^3)	Summer balance Measured 28 Sep. Specific (m w.e.)	Summer Volume (10^6 m^3)	Annual balance 2019 - 2020 Specific (m w.e.)	Annual Volume (10^6 m^3)
2050 - 2091	0.030	2.50	0.08	-1.45	-0.04	1.05	0.03
2000 - 2050	0.138	2.40	0.33	-1.45	-0.20	0.95	0.13
1950 - 2000	0.198	2.38	0.47	-1.53	-0.30	0.85	0.17
1900 - 1950	0.317	2.71	0.86	-1.96	-0.62	0.75	0.24
1850 - 1900	0.425	2.53	1.07	-1.98	-0.84	0.55	0.23
1800 - 1850	0.846	1.84	1.56	-1.44	-1.22	0.40	0.34
1750 - 1800	0.763	1.59	1.22	-1.49	-1.14	0.10	0.08
1700 - 1750	0.628	1.74	1.09	-1.94	-1.22	-0.20	-0.13
1650 - 1700	0.414	1.88	0.78	-2.26	-0.93	-0.38	-0.16
1600 - 1650	0.334	1.95	0.65	-2.67	-0.89	-0.72	-0.24
1550 - 1600	0.390	1.71	0.67	-2.51	-0.98	-0.80	-0.31
1500 - 1550	0.197	1.57	0.31	-2.77	-0.55	-1.20	-0.24
1450 - 1500	0.146	1.60	0.23	-3.35	-0.49	-1.75	-0.26
1420 - 1450	0.050	1.92	0.10	-4.17	-0.21	-2.25	-0.11
1420 - 2091	**4.876**	**1.93**	**9.41**	**-1.98**	**-9.64**	**-0.05**	**-0.22**

6.3 Mass balance 1949-2020

The cumulative balance for 1949-2020 is –28 m w.e. The mean annual balance for the period of 72 years is −0.39 m w.e. (Fig. 6-4). For the shorter period 2001-2020 (20 years) the mean annual balance is −0.89 m w.e.

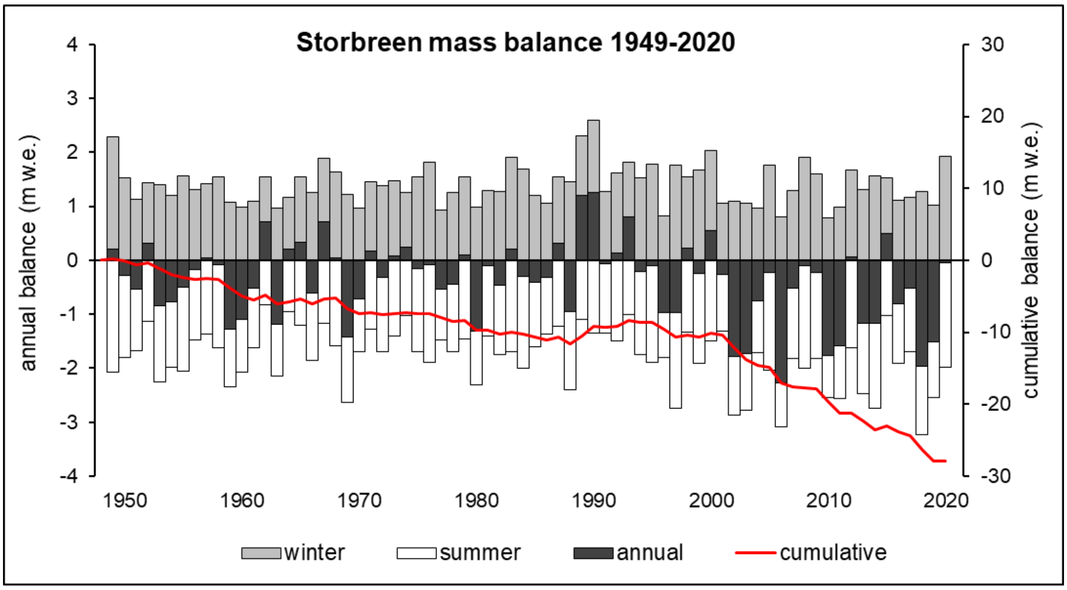


Figure 6-4
Winter, summer, annual and cumulative mass balance at Storbreen for the period 1949-2020.

Figure 6-5
Storbreen was also visited on 29th of July to maintain the stake network. Only stake 1 needed redrilling due to much remaining snow at that time. 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 2020 consisted of accumulation measurements in spring, seasonal and annual balances measured in one stake position, front position and survey of the ice patch extent (section 7-1).

Figure 7-1
Juvfonne on 19th September 2020. Part of the lower ice patch is covered in white fabric to protect the tunnel roof from melting. Only small parts of the ice patch had bare ice in 2020.
Photo: Liss M. Andreassen.

7.1 Survey 2020

The extent of Juvfonne has been measured every year since 2010 (Fig. 7.2). The ice patch outline was still covered in snow at the minimum measurements. Only the lower part of the ice patch was measured with handheld GPS and differential GNSS (Fig. 7-2).

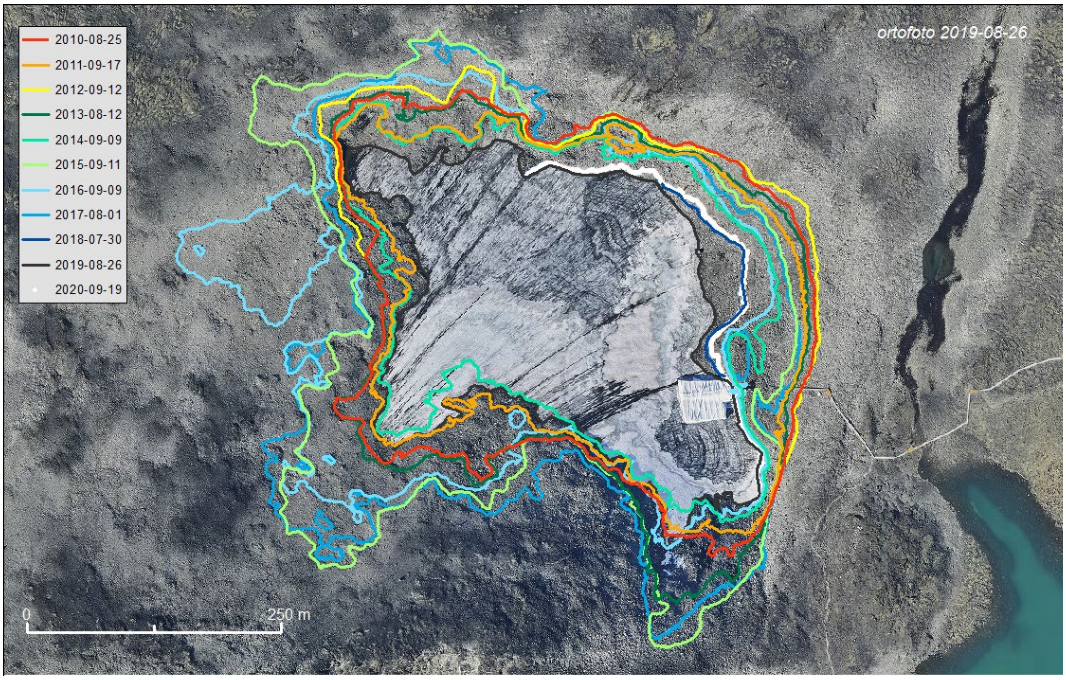


Figure 7-2
The ice extent of Juvfonne from 2010 to 2020. Background orthophoto of 26 August 2019 by TerraTec AS. The walking path to the ice patch and the fabric covered ice tunnel is visible in the photo. See also Fig. 7-1. The extent outlines are measured by foot (2010, 2012, 2013, 2014, 2018 and 2020) and from orthophotos (2011, 2016, 2017 and 2019). Figure from Andreassen et al. (2020a).

7.2 Mass balance 2020

Field work

The accumulation measurements on Juvfonne were carried out on 19th May (Fig. 7-3). The snow varied between 3.77 and > 5.8 m. The sounding conditions were very challenging with hard wind packed snow and many layers. The snow density was measured in a pit near stake 2 (the only stake now maintained on the ice patch), where the depth to the 2019 summer surface was 4.1 m. Only the upper 1.5 m of the snowpack was possible to measure due to the unusual hard and compact snowpack this year. The resulting density was estimated to be 400 kg m^{-3}. Ablation measurements were carried out on 19th September at stake 2. Only a small part of the ice patch was snow free (Fig. 7-1). A layer of 60 cm snow was remaining at stake 2.

Results

Seasonal surface mass balances have been measured since 2010 at stake 2 (Fig. 7-3). In 2020 the point winter balance was 1.75 ±0.15 m w.e., the point summer balance was –1.39 ±0.15 m w.e and the annual balance was 0.36 ±0.15 m w.e. at this location. The cumulative mass balance for stake 2 over the 11 years of measurements is –11.3 m w.e., or –1.03 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.

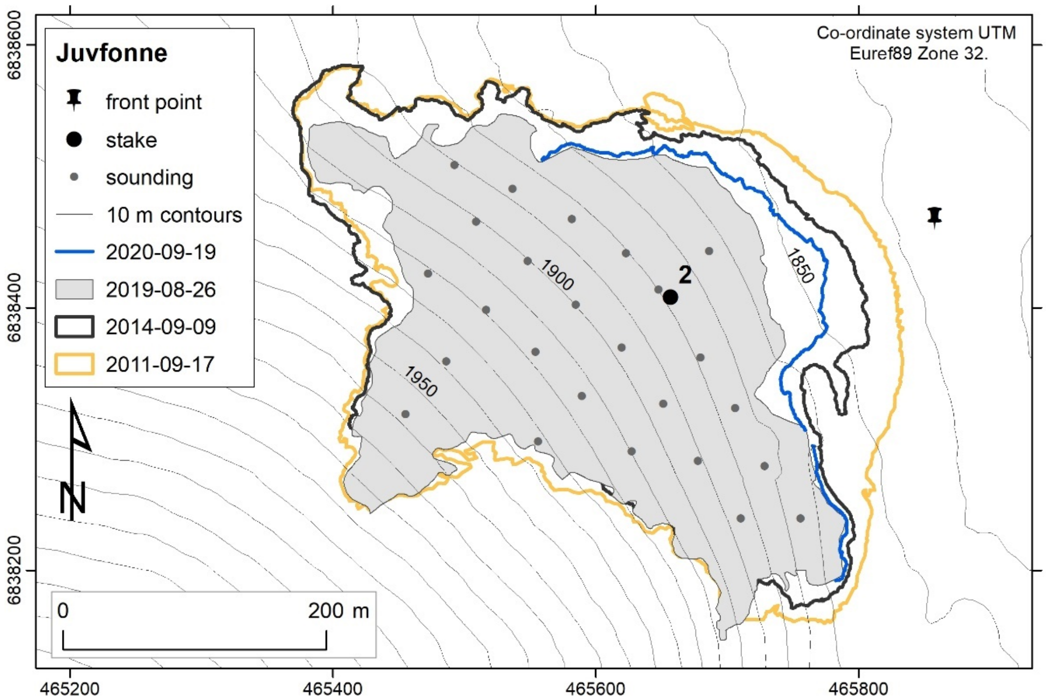


Figure 7-3
Location of snow depth soundings in 2020 and the position of stake 2 where density is measured. The ice patch extent in 2020 (snow covered - survey by GNSS), 2019 (orthophoto) and 2011 (orthophoto) are shown. "Front point" marks the reference point for front position and length change measurements (see chap. 12.1). The 10 m contours are derived from the 2019 DTM.

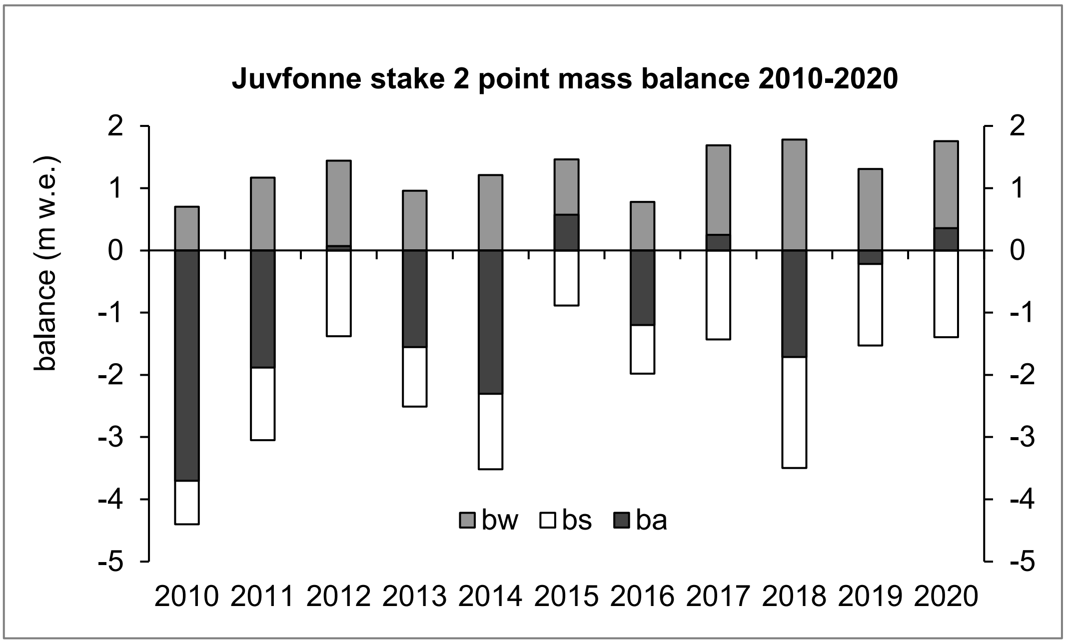


Figure 7-4
Point mass balance at stake 2 at Juvfonne 2010-2020, given as winter balance (b_w), summer balance (b_s) and annual balance (b_a).

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). Annual mass balance measurements began in 1962. Hellstugubreen ranges in elevation from 1487 to 2213 m a.s.l. and has an area of 2.7 km^2 (map of 2019).

Figure 8-1
Hellstugubreen on 28th September 2020. Photo: Liss M. Andreassen.

8.2 Mass balance 2020

Field work

Accumulation measurements were performed on 21st April. Snow depths were measured in 64 positions between 1498 and 2165 m a.s.l., covering most of the altitudinal range of the glacier (Fig. 8-2). The snow depth varied between 1.19 and 4.4 m, with a mean (median) of 2.89 (2.79) m. Snow density was measured in a density pit at 1946 m a.s.l. The total snow thickness measured was m and the resulting density was 453 kg m^{-3}. Ablation measurements were carried out on 28th September. There was remaining snow at most of the stakes above 1900 m asl. (Fig. 8-3).

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 1.38 ±0.2 m w.e., which is 123 % of the mean winter balance for the reference period 1981-2010. The summer balance was interpolated to 50 m height intervals based on the stake readings and was –1.82 ±0.3 m w.e., which is 120 % of the mean summer balance for the reference period 1981-2010. The annual balance of Hellstugubreen was −0.44 ±0.3 m w.e. The equilibrium line altitude (ELA) was estimated to be 1935 m a.s.l., giving an accumulation area ratio (AAR) of 33 %. 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.

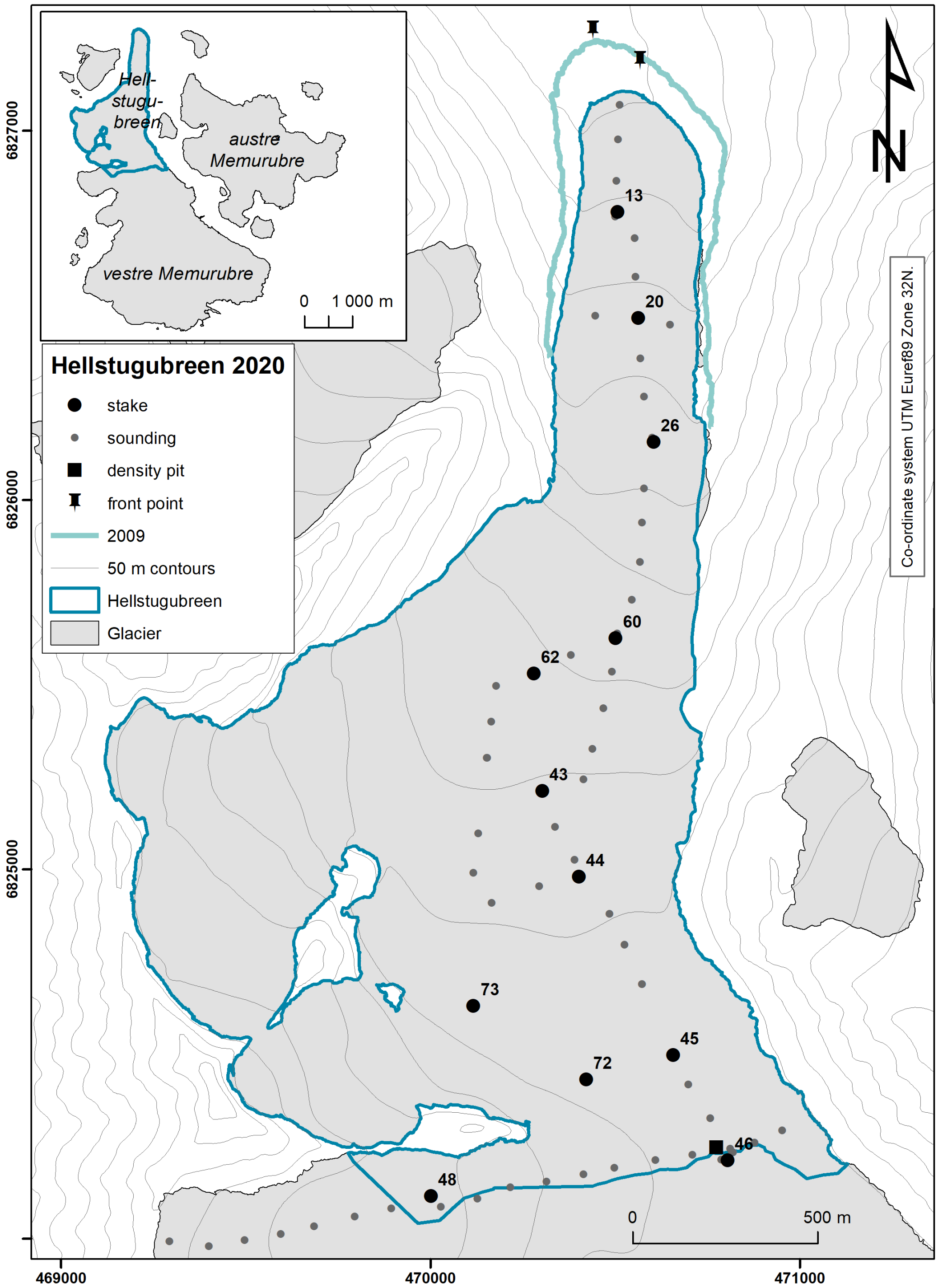


Figure 8-2
Map of Hellstugubreen showing the location of stakes, snow depth soundings and snow pit in 2020. Front point: reference points used for front position and length change measurements (chap. 12-1). Inset shows Hellstugubreen and surrounding glaciers.

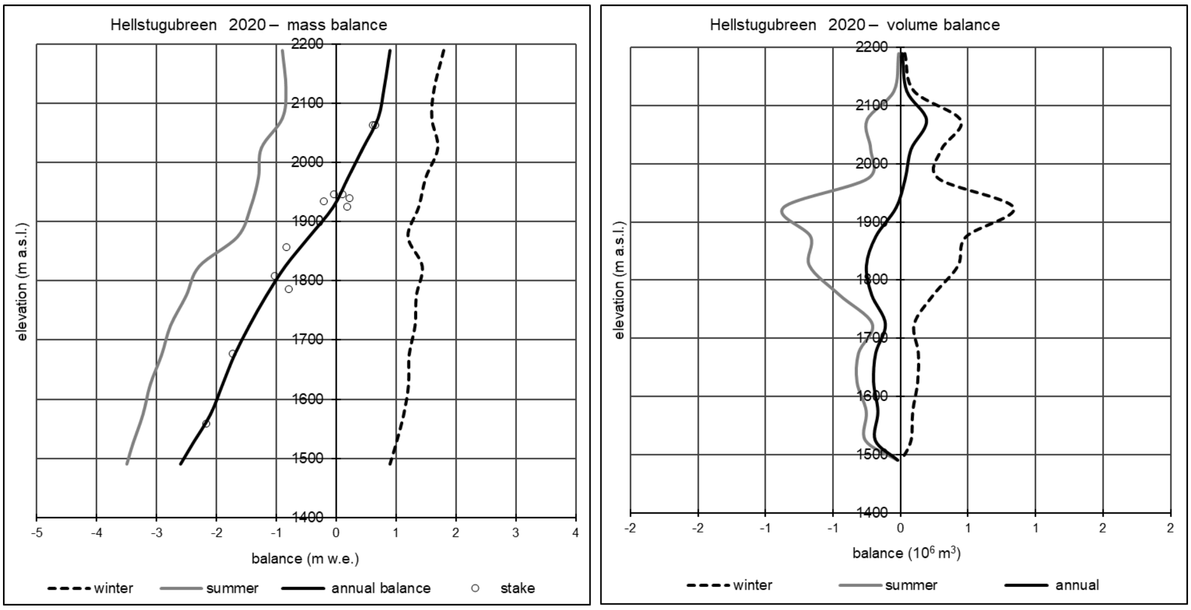


Figure 8-3
Mass balance diagram for Hellstugubreen in 2020, showing specific balance on the left and volume balance on the right. The winter balance soundings and annual balance at stakes are also shown.

Table 8-1
The distribution of winter, summer and annual balance in 50 m altitudinal intervals for Hellstugubreen in 2020.

Mass balance Hellstugubreen 2019/20

Altitude (m a.s.l.)	Area (km^2)	Winter balance Measured 21 April 2020		Summer balance Measured 28 Sep 2020		Annual balance 2019-2020	
		Specific (m w.e.)	Volume (10^6 m^3)	Specific (m w.e.)	Volume (10^6 m^3)	Specific (m w.e.)	Volume (10^6 m^3)
2150 - 2229	0.017	1.80	0.03	-0.90	-0.02	0.90	0.02
2100 - 2150	0.060	1.64	0.10	-0.84	-0.05	0.80	0.05
2050 - 2100	0.278	1.60	0.44	-0.90	-0.25	0.70	0.19
2000 - 2050	0.178	1.70	0.30	-1.25	-0.22	0.45	0.08
1950 - 2000	0.186	1.50	0.28	-1.30	-0.24	0.20	0.04
1900 - 1950	0.607	1.38	0.84	-1.43	-0.87	-0.05	-0.03
1850 - 1900	0.404	1.20	0.48	-1.65	-0.67	-0.45	-0.18
1800 - 1850	0.295	1.44	0.42	-2.29	-0.68	-0.85	-0.25
1750 - 1800	0.181	1.34	0.24	-2.51	-0.45	-1.17	-0.21
1700 - 1750	0.076	1.32	0.10	-2.77	-0.21	-1.45	-0.11
1650 - 1700	0.107	1.22	0.13	-2.92	-0.31	-1.70	-0.18
1600 - 1650	0.104	1.21	0.13	-3.11	-0.32	-1.90	-0.20
1550 - 1600	0.079	1.13	0.09	-3.23	-0.26	-2.10	-0.17
1500 - 1550	0.077	1.00	0.08	-3.40	-0.26	-2.40	-0.18
1482 - 1500	0.007	0.90	0.01	-3.50	-0.02	-2.60	-0.02
1482 - 2229	**2.656**	**1.38**	**3.67**	**-1.82**	**-4.83**	**-0.44**	**-1.16**

8.3 Mass balance 1962-2020

The cumulative annual balance of Hellstugubreen since 1962 is –26 m w.e. (Fig. 8-4), giving a mean annual deficit of 0.45 m w.e. per year. The cumulative mass balance for the period 2000/2001 to 2019/2020 (20 years) is –17 m w.e. or –0.85 m w.e./a.

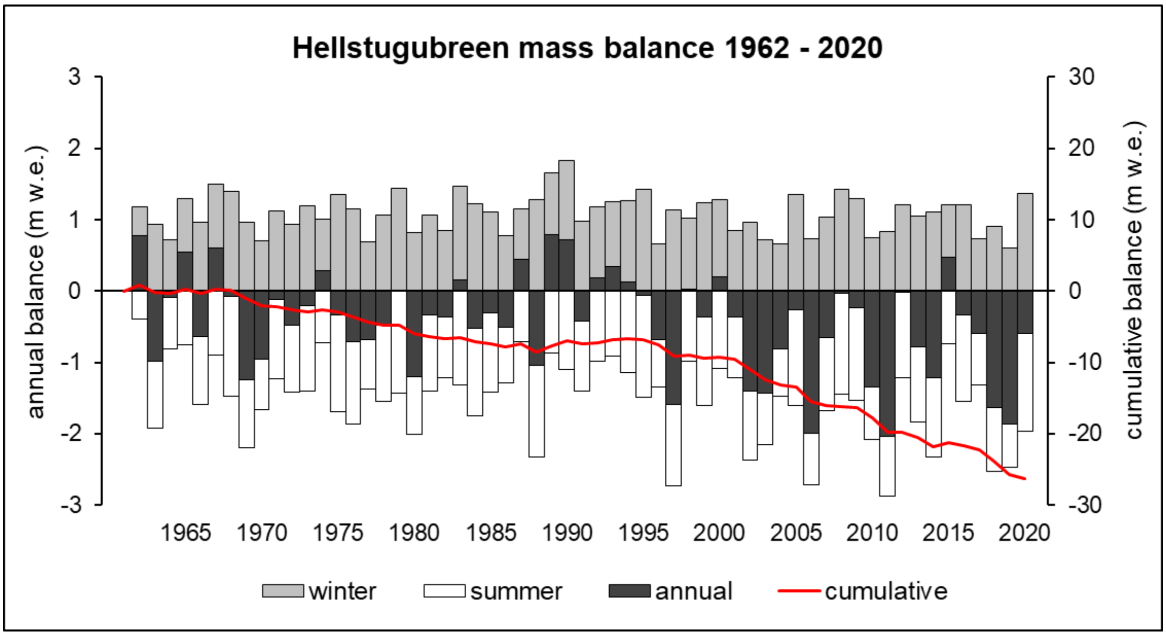


Figure 8-4
Winter, summer and annual balance at Hellstugubreen for 1962-2020, and cumulative mass balance for the whole period.

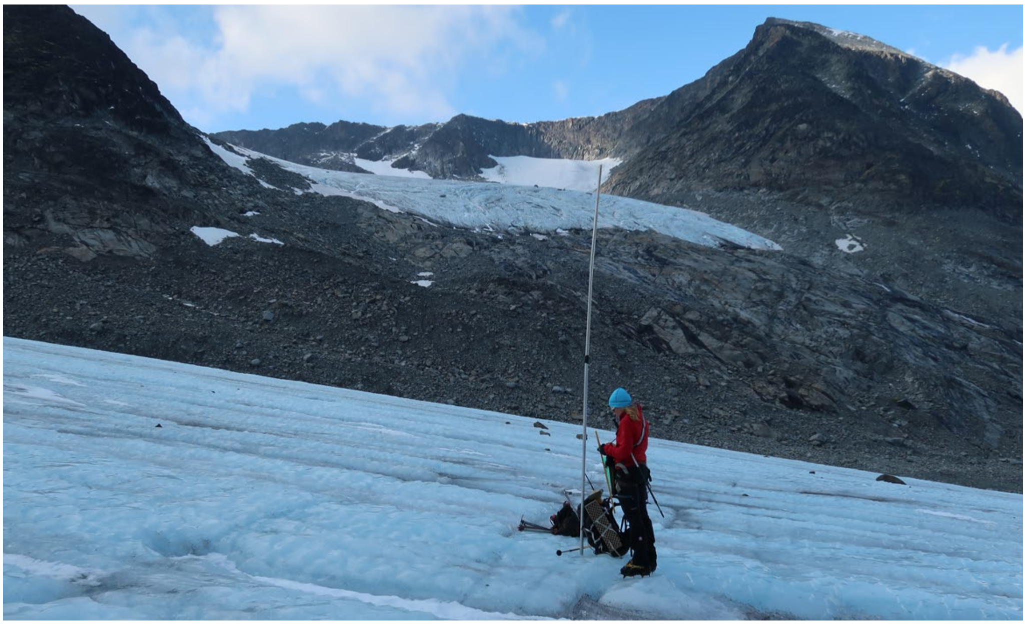


Figure 8-5
Field work on 28 September 2020 on the lower part of the glacier. View from stake 20 towards west and the detached glacier that was connected to the main glacier until the 1960s. See also Figure 8-1 and 8-2. Photo: Jostein Aasen.

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 snowpack, whereas snow accumulates in sheltered areas at lower elevations. The ELA and AAR are therefore 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
Part of Gråsubreen on 17th September 2020. View towards East with the peak Nautgardstinden in the background. Photo: Kjetil Melvold.

9.1 Mass balance 2020

Fieldwork

Accumulation measurements were performed on 20th April 2020. The calculation of winter balance is based on stake measurements and snow depth soundings in 96 positions between 1872 and 2271 m a.s.l. (Fig. 9-2). The snow depth varied between 0.05 and 3.55 with a mean and median of 1.73 and 1.70 m respectively. The surface was clearly wind-blown at the time of measurements (Fig. 9-3). The snow density was measured in a density pit near stake 8 (elevation 2140 m a.s.l.) where the total snow depth was 1.57 m and the mean density was 377 kg m^{-3}. Ablation measurements were carried out on 17th September 2020, when all visible stakes were measured. The glacier had a partial thin layer of fresh snow after snowfalls prior to the measurements (Fig. 9-3). The calculation of annual balance was based on stakes in 10 different positions.

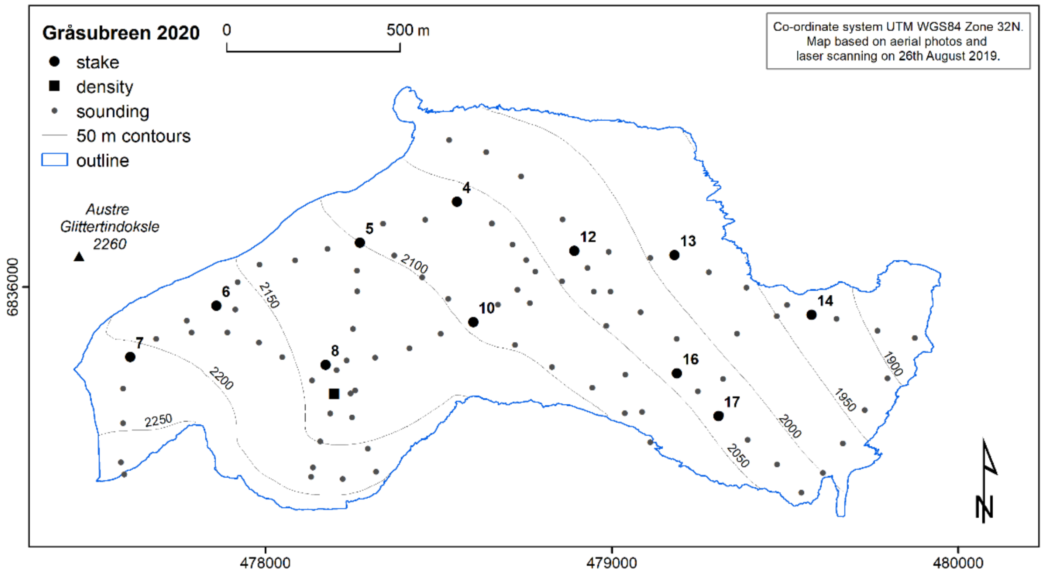


Figure 9-2
Map of Gråsubreen showing the location of stakes, density pit and soundings in 2020.

Figure 9-3
Wind-blown snow surface at the winter accumulation measurements on 20th April after a windy winter. View from upper parts looking towards northwest and stake 7. 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 ±0.72 m w.e., which is 91 % 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 −1.34 ±0.3 m w.e., which is 115 % of the mean summer balance for the reference period 1981-

2010. The annual balance of Gråsubreen was negative in 2020 at −0.62 ±0.3 m w.e. The ELA and AAR were not defined from the mass balance curve or in the field. There was some snow remaining in the cirque above stake 8. The mass balance results are shown in Table 9-1 and the corresponding curves for specific and volume balance are shown in Figure 9-4.

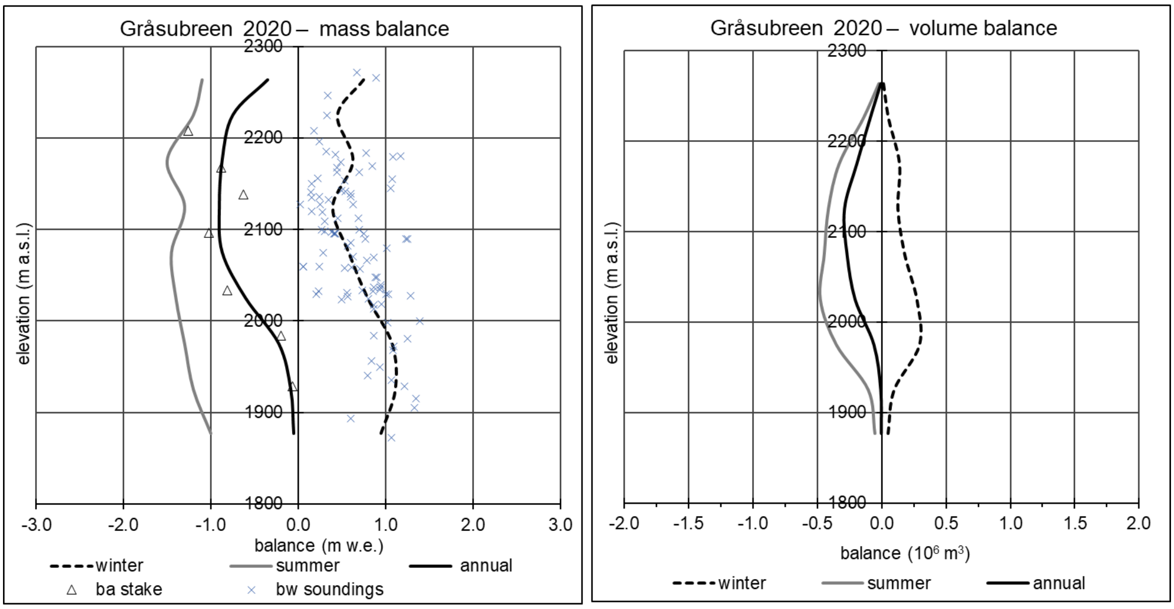


Figure 9-4
Mass balance diagram for Gråsubreen for 2020, showing specific balance on the left and volume balance on the right. Winter and summer balance at the stakes and individual snow depth soundings are also shown.

Table 9-1
The distribution of winter, summer and annual balance in 50 m altitudinal intervals for Gråsubreen in 2020.

Mass balance Gråsubreen 2019/20

		Winter balance Measured 20th April		Summer balance Measured 17th Sep.		Annual balance 2019 - 2020	
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)
2250 - 2277	0.031	0.75	0.02	-1.10	-0.03	-0.35	-0.01
2200 - 2250	0.153	0.45	0.07	-1.20	-0.18	-0.75	-0.11
2150 - 2200	0.255	0.63	0.16	-1.50	-0.38	-0.87	-0.22
2100 - 2150	0.353	0.40	0.14	-1.30	-0.46	-0.90	-0.32
2050 - 2100	0.362	0.58	0.21	-1.45	-0.52	-0.87	-0.32
2000 - 2050	0.405	0.80	0.32	-1.40	-0.57	-0.60	-0.24
1950 - 2000	0.320	1.08	0.35	-1.30	-0.42	-0.22	-0.07
1900 - 1950	0.127	1.12	0.14	-1.20	-0.15	-0.08	-0.01
1854 - 1900	0.113	0.95	0.11	-1.00	-0.11	-0.05	-0.01
1854 - 2277	**1.744**	**0.72**	**1.52**	**-1.34**	**-2.83**	**-0.62**	**-1.31**

9.3 Mass balance 1962-2020

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}. Gråsubreen has had a negative mass balance in all years since 2001, except for slight surpluses in 2008 and 2015.

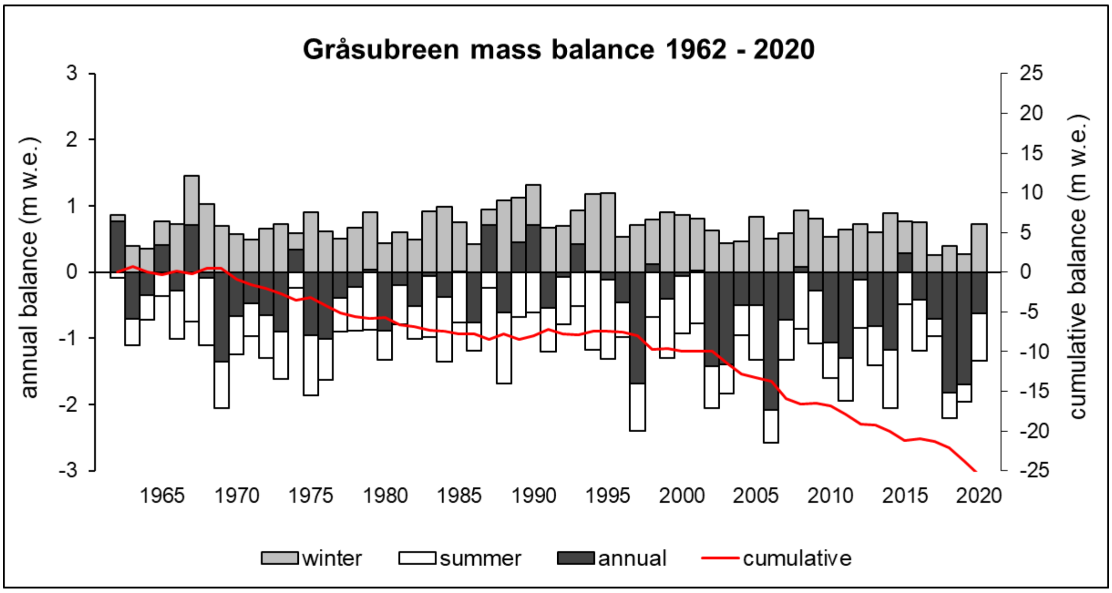


Figure 9-5
Winter, summer and annual balance for Gråsubreen for 1962-2019, and cumulative mass balance for the whole period.

Figure 9-6
The mass balance year 2019/2020 was another year of mass deficit for Gråsubreen. Bare ground is getting exposed in upper parts due the mass loss over years. Photo taken on 17th September at the minimum measurements. View towards west from the mid part. Photo: Liss M. Andreassen.

10. Engabreen (Hallgeir Elvehøy)

Engabreen (66°40′N, 13°45′E) is a 36 km^2 north-western outlet from the western Svartisen ice cap (Fig. 10-1). In 2016 it covered an altitude range from 1544 m a.s.l. at Snøtinden down to 111 m a.s.l. Length change observations started in 1903 (chap. 12) and mass balance measurements have been performed annually since 1970.

Figure 10-1
Engabreen on 10th June 2020. Photo: Hallgeir Elvehøy.

10.1 Mass balance 2020

Fieldwork

Stakes in three locations on the plateau were checked on 25th February and showed between 3.7 and 6.9 metres of snow.

The snow accumulation measurements were performed on 10th June (Fig 10-1). Three 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 4.75 m at stake E5 was 488 kg m^{-3}. At stake E17 on the glacier tongue 1.15 m of glacier ice had melted since 27th September 2019.

The stakes on the glacier tongue were checked on 4th August. At stake E400 and E17 5.1 and 4,55 m of ice had melted, respectively, since 10th June. The stakes were re-drilled. Stake E34 was checked on 28th August. All the winter snow (4.75 m) and 0.25 m of ice had melted since 10th June.

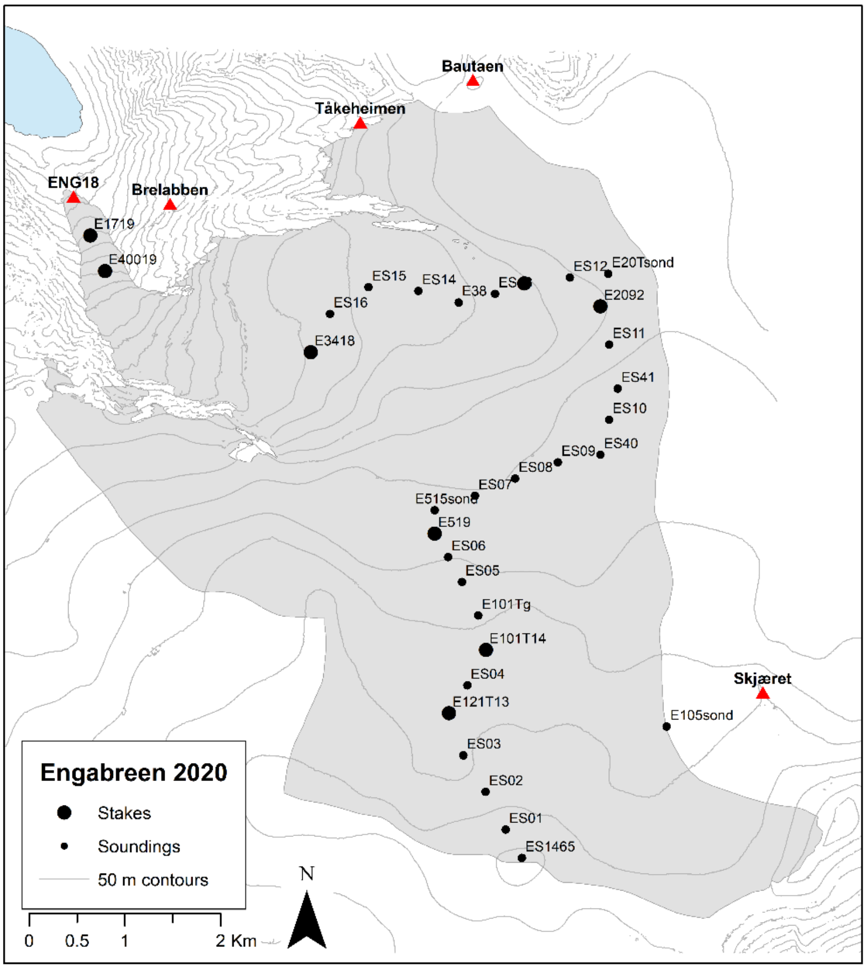


Figure 10-2
Location of stakes and soundings on Engabreen in 2020. The map is based on satellite imagery from 16th August 2016.

The summer ablation measurements were carried out on 1st October. There was up to 1.05 m of new snow at the stakes above 1000 m a.sl. Stakes were found in six locations on the plateau. Between 4.75 and 6.2 m of snow and ice had melted since 10th June, and up to 4.5 metres remained at the uppermost stake. From the stake measurements, the temporary snow line altitude at the end of the melt season was around 1000 m a.s.l. (Fig. 10-3). At stake E34, 960 m a.s.l., all the winter snow and 1.1 m of ice melted during the summer. At stakes E17 and E400 on the glacier tongue 3.95 and 3.15 metres of ice, respectively, had melted since 4th August.

Results

The calculations are based on a DEM from 16th August 2016. The date of the 2020 mass balance minimum at Engabreen was assessed by visual inspection of the daily changes in gridded data of temperature and snow amount from www.senorge.no (Saloranta, 2014). The snow accumulation on the glacier plateau probably started above 1200 m a.s.l. on 9th September 2020, and on 13th October below 1200 m a.s.l.

Table 10-1
Specific and volume winter, summer and annual balance calculated for 100 m elevation intervals at Engabreen in 2020.

Mass balance Engabreen 2019/20 – stratigraphic system

		Winter mass balance		Summer mass balance		Annual mass balance	
		Measured 21. May 2020		Measured 27. Sep 2020		Summer surface 2019 - 2020	
Altitude	Area	Specific	Volume	Specific	Volume	Specific	Volume
(m a.s.l.)	(km^2)	(m w.e.)	(10^6 m^3)	(m w.e.)	(10^6 m^3)	(m w.e.)	(10^6 m^3)
1500 - 1544	0.05	4.50	0.2	-2.00	-0.1	2.50	0.1
1400 - 1500	2.13	4.75	10.1	-2.10	-4.5	2.65	5.6
1300 - 1400	9.24	4.75	43.9	-2.20	-20.3	2.55	23.6
1200 - 1300	8.04	4.10	33.0	-2.30	-18.5	1.80	14.5
1100 - 1200	7.57	3.30	25.0	-2.35	-17.8	0.95	7.2
1000 - 1100	4.61	3.10	14.3	-2.70	-12.4	0.40	1.8
900 - 1000	2.43	2.50	6.1	-3.30	-8.0	-0.80	-1.9
800 - 900	0.80	2.00	1.6	-3.90	-3.1	-1.90	-1.5
700 - 800	0.46	1.50	0.7	-4.50	-2.0	-3.00	-1.4
600 - 700	0.29	1.00	0.3	-5.10	-1.5	-4.10	-1.2
500 - 600	0.25	0.50	0.1	-5.75	-1.4	-5.25	-1.3
400 - 500	0.14	-0.15	0.0	-6.40	-0.9	-6.55	-0.9
300 - 400	0.10	-0.70	-0.1	-7.10	-0.7	-7.80	-0.8
200 - 300	0.12	-1.30	-0.2	-7.80	-0.9	-9.10	-1.1
111 - 200	0.04	-1.90	-0.1	-8.50	-0.3	-10.40	-0.4
111 - 1544	**36.25**	**3.72**	**134.9**	**-2.55**	**-92.5**	**1.17**	**42.4**

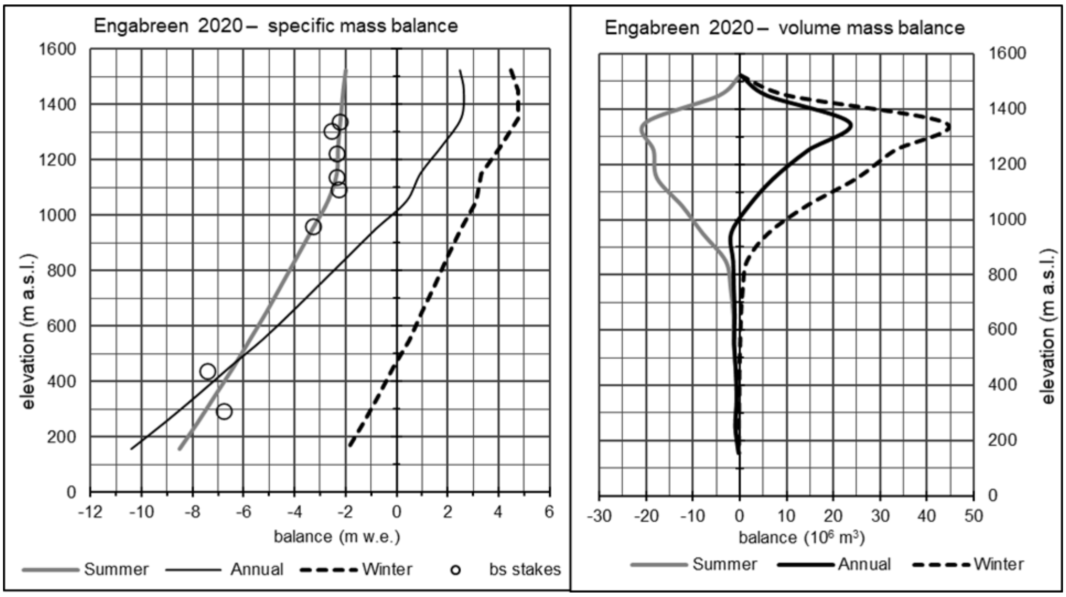


Figure 10-3
Mass balance diagram showing specific balance (left) and volume balance (right) for Engabreen in 2020. Summer balance at eight stake locations (○) is shown.

The winter balance for 2020 was calculated from the snow depth and snow density measurements. The specific winter balance was calculated as 3.7 ±0.2 m w.e. This is 144 % 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 eight stake locations between 290 and 1340 m a.s.l. The specific summer balance was calculated from the summer balance curve drawn from these eight point values (Fig. 10-3) as −2.6 ±0.2 m w.e. This is 99 % of the average summer balance for the normal period 1981-2010 (−2.60 m w.e. a^{-1}). The resulting annual balance was +1.2 ±0.3 m w.e. (Tab. 10-1). The ELA was 1017 m a.s.l. and the AAR was 85 %.

The annual surface mass balance at Engabreen for 1970-2020 is shown in Figure 10-4. The cumulative surface mass balance since the start of mass balance investigations at Engabreen is +1.2 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}. Between 1997 and 2014 (17 years) the glacier volume decreased by −8.2 m w.e., or −0.48 m w.e. a^{-1} (Fig. 10-4). After 2014 the glacier volume has increased by 2.0 m w.e. or 0.33 m w.e. a^{-1}.

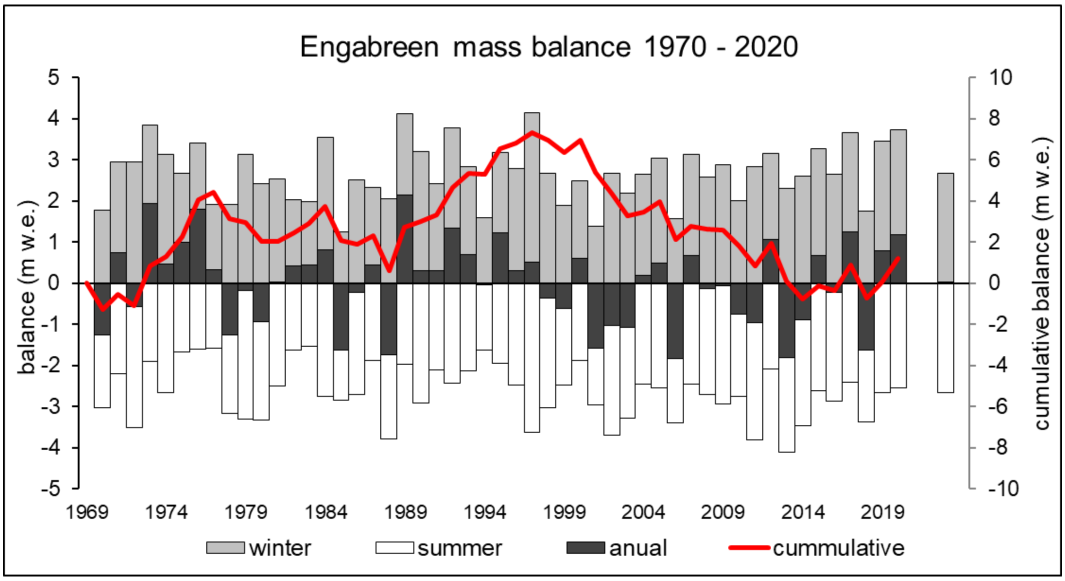


Figure 10-4
Mass balance at Engabreen during the period 1970-2020. Cumulative mass balance is given on the right axis. The average winter and summer balances are Bw =2.68 m w.e. and Bs =−2.66 m w.e.

10.2 Meteorological observations

A meteorological station recording air temperature and global radiation at 3 m above ground level is located on a 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. In 2020 data were collected between 1st January and 1st October with a gap in the record between 4th February and 18th May.

The mean summer temperature (1st June – 30th September) at Skjæret in 2020 was 3.4 °C. The average summer temperature for 20 years between 1995 and 2019 is 3.04 °C. The melt season on the upper part of the glacier plateau started on 30th May and probably lasted until 12th October. In the warmest period from 17th to 30th June the average temperature was 9.2 °C.

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 2020 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 29th September 2020. Photo: Bjarne Kjøllmoen.

11.1 Mass balance 2020

Fieldwork

Snow accumulation was measured on 26th May and the calculation of winter balance was based on measurements of 61 snow depth soundings (Fig. 11-2). The snow depth varied between 3.3 and 7.4 m with an average of 5.3 m. Snow density was measured in position 25 (702 m a.s.l.) and the mean density of 4.7 m snow was 467 kg m^{-3}.

Ablation was measured on 29th September. The annual balance was measured at stakes in six locations (Fig. 11-2). There was up to 70 cm of snow remaining in the upper parts of the glacier from the winter season 2019/20. At the time of measurement up to 80 cm of fresh snow had fallen on the glacier.

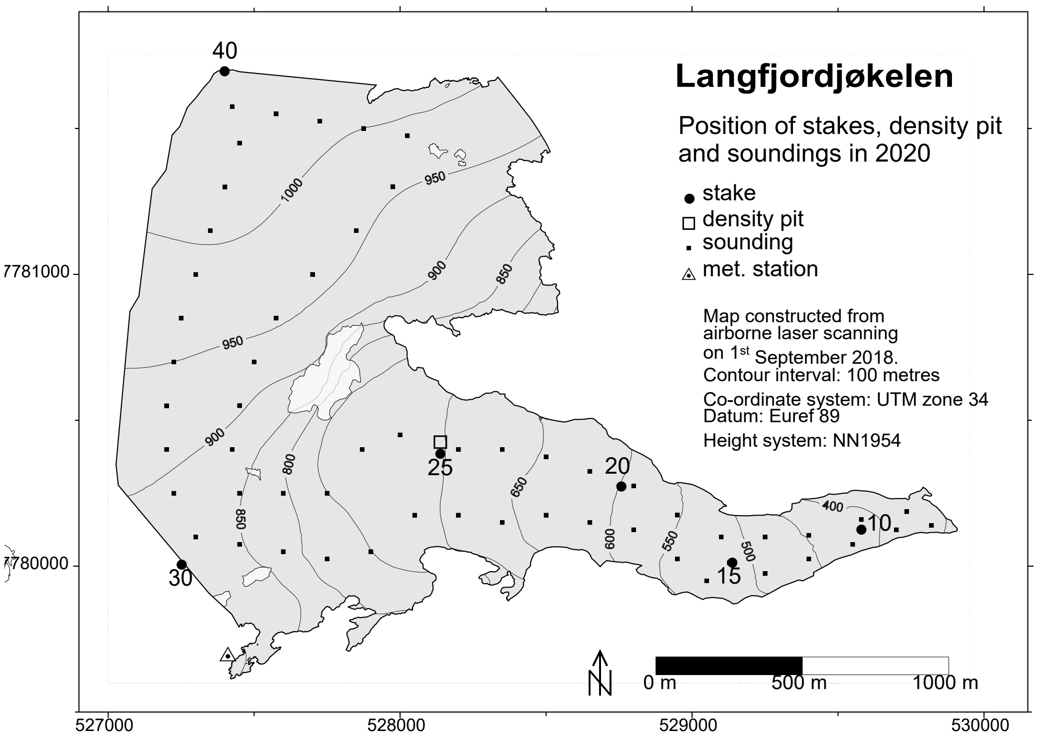


Figure 11-2
Location of stakes, soundings and snow pit at Langfjordjøkelen in 2020.

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 2.7 ±0.2 m w.e., which is 133 % of the mean winter balance for the periods 1989-93 and 1996-2019. 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 −2.8 ±0.3 m w.e., which is 92 % of the mean summer balance for 1989-93 and 1996-2019.

Hence, the annual balance was slightly negative at −0.02 ±0.40 m w.e. The mean annual balance for 1989-93 and 1996-2019 is −0.94 m w.e. The mean annual balance for the past ten years (2011-20) is −0.99 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.

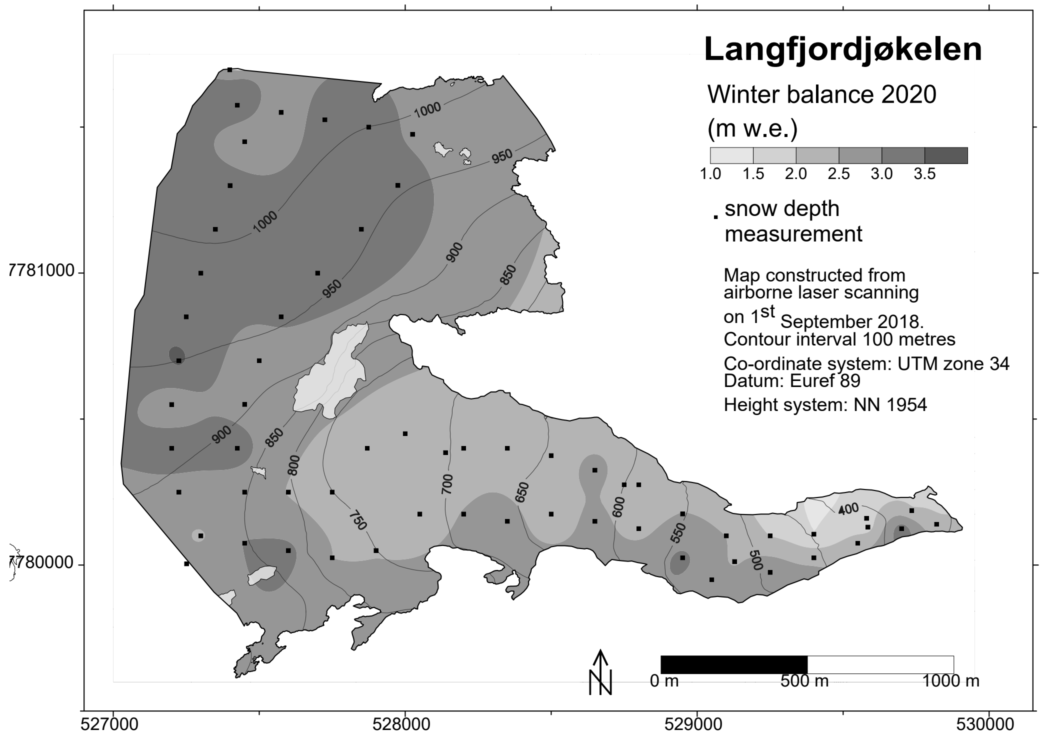


Figure 11-3
Spatial distribution of winter balance at Langfjordjøkelen in 2020.

According to Figure 11-4, the Equilibrium Line Altitude was 830 m a.s.l. Consequently the Accumulation Area Ratio was 59 %.

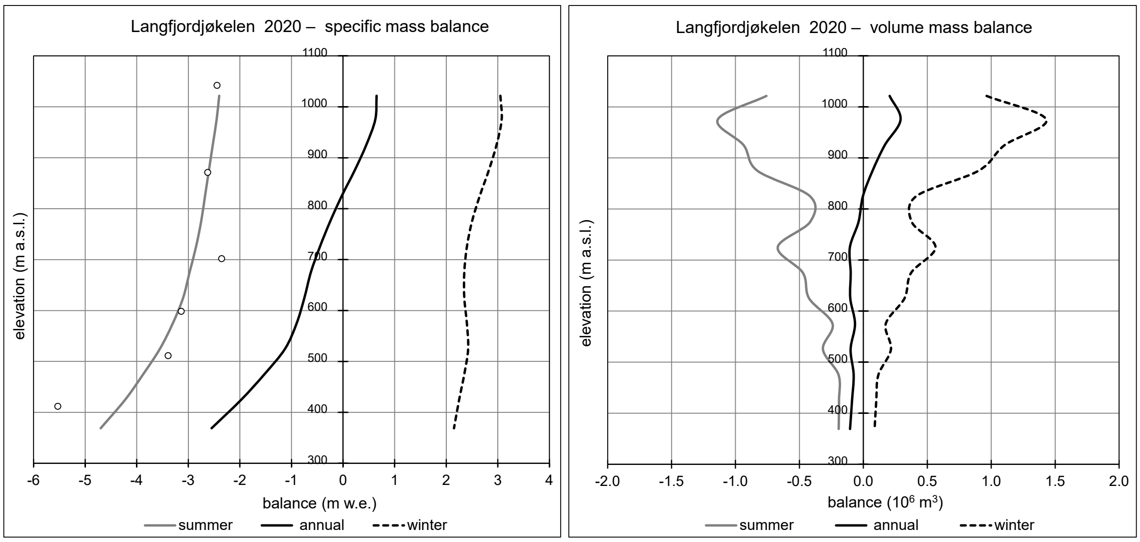


Figure 11-4
Mass balance diagram showing specific balance (left) and volume balance (right) for Langfjordjøkelen in 2020. Specific summer balance for six stakes is shown as circles (○).

Table 11-1
Winter, summer and annual balance for Langfjordjøkelen in 2020.

Mass balance Langfjordjøkelen 2019/20 – stratigraphic system

Altitude (m a.s.l.)	Area (km²)	Winter mass balance Measured 26th May 2020 Specific (m w.e.)	Winter Volume (10^6 m^3)	Summer mass balance Measured 29th Sep 2020 Specific (m w.e.)	Summer Volume (10^6 m^3)	Annual mass balance Summer surface 2019 - 2020 Specific (m w.e.)	Annual Volume (10^6 m^3)
1000 - 1043	0.32	3.05	1.0	-2.40	-0.8	0.65	0.2
950 - 1000	0.47	3.08	1.4	-2.45	-1.1	0.63	0.3
900 - 950	0.37	2.98	1.1	-2.53	-0.9	0.45	0.2
850 - 900	0.32	2.83	0.9	-2.60	-0.8	0.23	0.1
800 - 850	0.16	2.65	0.4	-2.68	-0.4	-0.02	0.0
750 - 800	0.15	2.50	0.4	-2.75	-0.4	-0.25	0.0
700 - 750	0.24	2.40	0.6	-2.85	-0.7	-0.45	-0.1
650 - 700	0.16	2.35	0.4	-2.98	-0.5	-0.63	-0.1
600 - 650	0.14	2.35	0.3	-3.10	-0.4	-0.75	-0.1
550 - 600	0.07	2.40	0.2	-3.30	-0.2	-0.90	-0.1
500 - 550	0.09	2.43	0.2	-3.55	-0.3	-1.13	-0.1
450 - 500	0.05	2.35	0.1	-3.88	-0.2	-1.53	-0.1
400 - 450	0.04	2.25	0.1	-4.23	-0.2	-1.98	-0.1
338 - 400	0.04	2.15	0.1	-4.70	-0.2	-2.55	-0.1
338 - 1043	**2.61**	**2.741**	**7.1**	**-2.761**	**-7.2**	**-0.019**	**-0.1**

11.2 Mass balance 1989-2020

The historical mass balance results for Langfjordjøkelen are presented in Figure 11-5. The cumulative annual balance for 1989-2020 (estimated values for 1994 and 1995 included) is –27.9 m w.e., which gives a mean annual balance of –0.87 m w.e. a^{-1}.

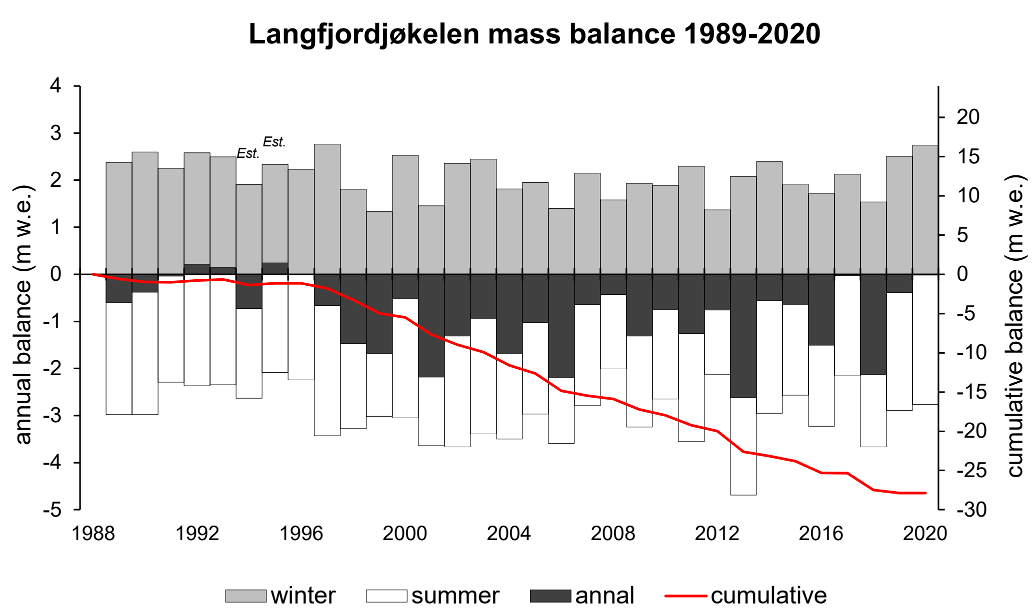


Figure 11-5
Mass balance at Langfjordjøkelen for the period 1989-2020. The total accumulated mass loss for 1989-2020 is 27.9 m w.e. (includes estimated values for 1994 and 1995).

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 (Fig. 11-6) 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 2012-2020.

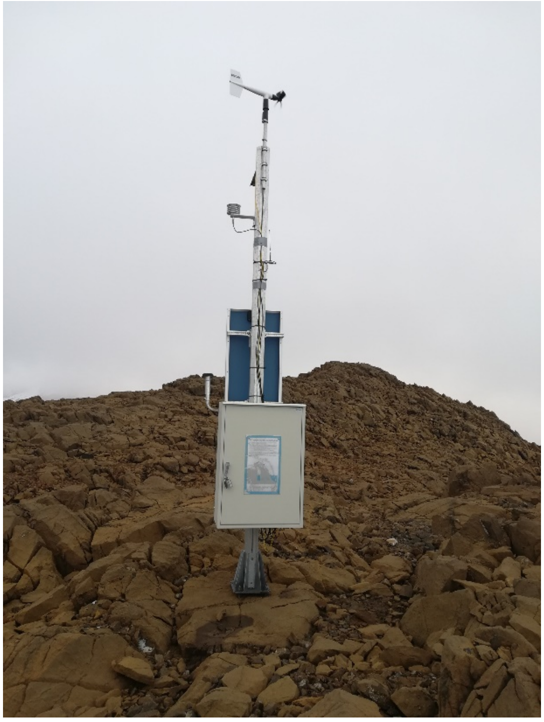


Figure 11-6
The meteorological station, Langfjord Met. Photo: Solveig Winsvold.

The mean summer temperature (1st June – 30th September) at Langfjord Met in 2020 was 6.1 °C. The mean summer temperature for 2009-10 and 2012-19 was 4.6 °C. The melt season on the upper part of the glacier (above 900 m a.s.l.) started around the 23rd May and lasted until about 18th September. The period from 28th September to 10th October was relatively warm and some melting could have occurred during these two weeks. The monthly summer temperatures were 5.6 °C (June), 9.5 °C (July), 6.2 °C (August) and 2.9 °C (September).

12. Glacier monitoring

(Hallgeir Elvehøy and Bjarne Kjøllmoen)

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 74 glaciers. The total number of observations up to 2020 is 2745. In addition, 88 measurements of length change based on maps, reconstructions from photos, moraines etc., and combinations of methods are included in the database. The median and mean number of observations for a single glacier is 26 and 39, respectively, indicating many glaciers with few observations. The median and mean number of observations in one year is 22 and 24 glaciers, respectively. In 1911, 45 glaciers were measured, and in 1992 only 8 glaciers were measured.

At Fåbergstølsbreen the length change observations started in 1899, and measurements have been conducted every year since 1907 resulting in 115 observations. Stigaholtbreen, Nigardsbreen and Austerdalsbreen also have more than 100 observations each. Styggedalsbreen in Jotunheimen has 99 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 88 measurements since 1903. The present monitoring programme for glacier length change includes 40 glaciers, 29 glaciers in southern Norway and 11 glaciers in northern Norway (Fig. 12-1 for location). The area of the monitored glaciers is 381 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. 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).

Results 2020

Thirty-one glaciers were measured - seven glaciers in northern Norway and twenty-four glaciers in southern Norway. The results for 2020, period(s) of measurements and number of observations (calculated length changes) are listed in Table 12-1. Twenty-three glaciers retreated in 2020. Six glaciers showed no change, and two glaciers showed a small advance. The annual length change varied from +7 m at Koppangsbreen to −45 m at Engabreen and −47 m at Gråfjellsbrea. Vinnufonna in Sunndal municipality in Møre and Romsdal county (Fig. 12-2 and 12-3) was measured for the first time, showing no change.

The average cumulative length change for the ten-year period 2010-20 for 25 glaciers is −193 metres, ranging from −610 metres at Gråfjellsbrea to −41 metres at Svelgjabreen. Both glaciers are outlet glaciers from the southern part of Folgefonna. Nine glaciers in the monitoring programme were not measured in 2020. Data are available at www.nve.no/glacier.

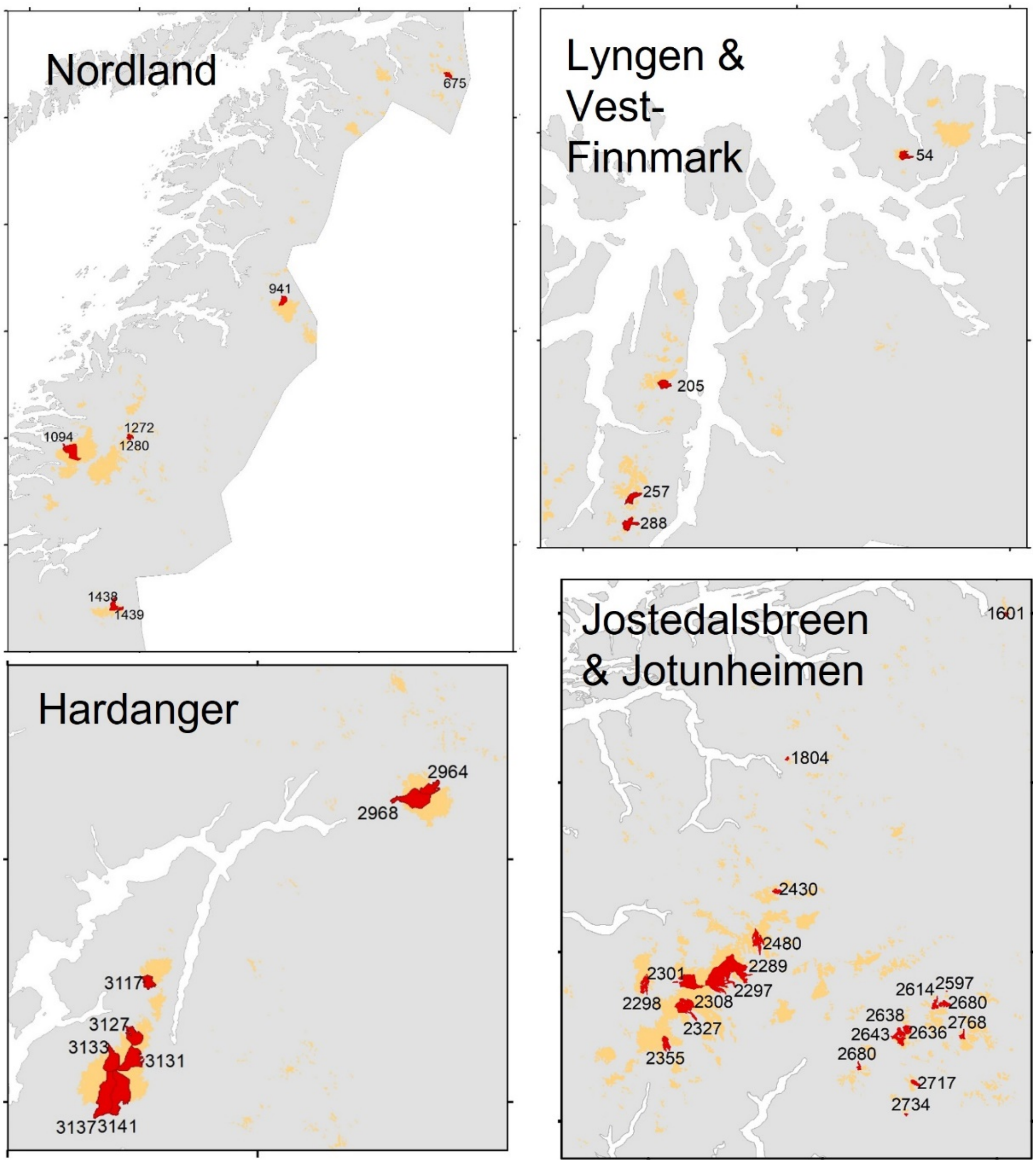


Figure 12-1
Map showing glaciers included in the length change monitoring programme (in red) with glacier IDs (Tab. 12-1). Note that the different glacier areas are not to the same scale.

Figure 12-2
Vinnufonna (Glacier ID 1601) situated on the southern flank of Kongskrona (1814 m a.s.l.) was photographed on 20th September 2016. Length change observations started in 2019.
Photo: Hallgeir Elvehøy.

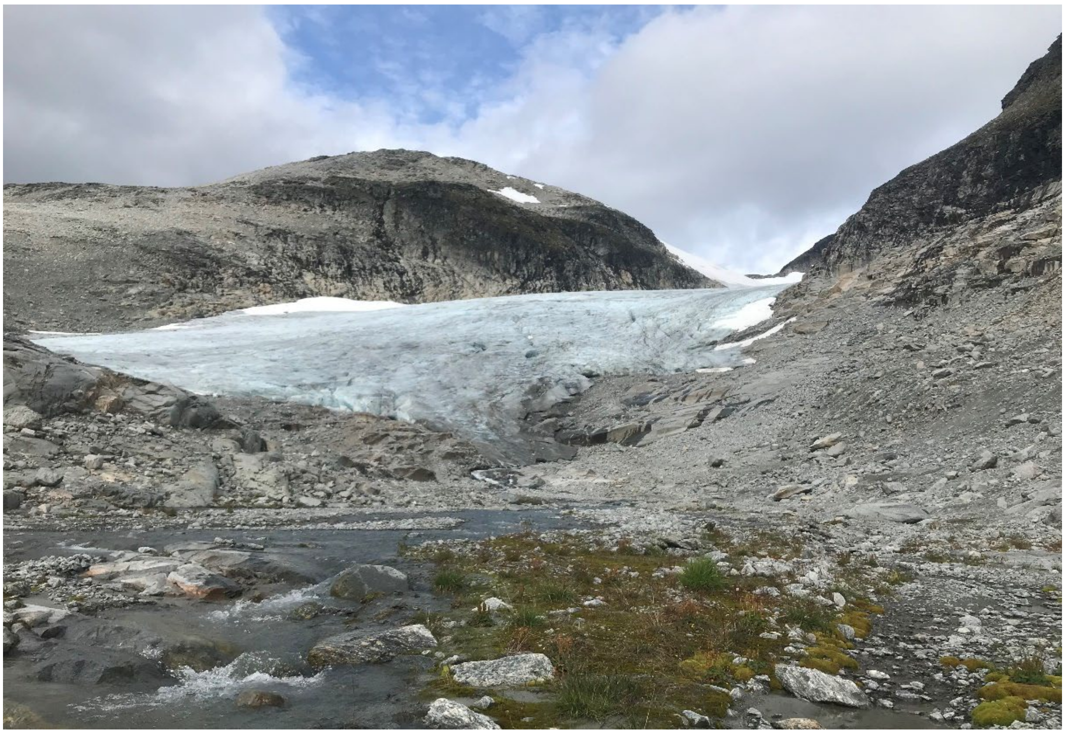


Figure 12-3
Vinnufonna (Glacier ID 1601) on 29th August 2019. The reference point is located on the ridge to the left of the river outlet. Photo: Hallgeir Elvehøy.

Table 12-1
Glacier length change from autumn 2019 to autumn 2020 (2019-20). See Figure 12-1 for glacier locations.

	Glacier	Glacier-ID	2019-20 (m)	Observer	Period(s)	Number of obs. years
Finnmark & Troms	Langfjordjøkelen	54	-15	NVE	1998-	24
	Koppangsbreen	205	7	NVE	1998-	21
	Sydbreen	257	NM	NVE	2007-	12
	Steindalsbreen	288	-18	NVE	1978-	28
Nordland	Storsteinsfjellbreen	675	-3	NVE	2006-	16
	Rundvassbreen	941	-20	SISO	2011-	10
	Engabreen	1094	-45	S	1903-	88
	Skjelåtindbreen	1272	NM	NVE	2014-	2
	Trollbergdalsbreen	1280	NM	NVE	2010-	5
	Austre Okstindbreen	1438	-24	NVE	1908-44, 2006-	28
	Corneliussenbreen	1439	NM	NVE	2006-	8
Sunnmøre & Breheimen	Vinnufonna	1601	0	NVE	2019-	1
	Trollkyrkjebreen	1804	0	NVE	1944-74, 2008-	25
	Heimsta Mårådalsbreen	2430	-37*	NVE	2002-	6
Jostedalsbreen	Fåbergstølsbreen	2289	-4	NVE	1899-	115
	Nigardsbreen	2297	-4	NVE	1899-	110
	Haugabreen	2298	-8	NBM	1933-41, 2013-	15
	Brenndalsbreen	2301	NM	NVE	1900-62, 1964-65, 1996-	82
	Tuftebreen	2308	-20	NVE	2007-	13
	Austerdalsbreen	2327	0	NVE	1905-19, 1933-	100
	Vetle Supphellebreen	2355	-6	NBM	1899-44, 2011-	45
	Stigaholtbreen	2480	-26	NVE	1903-	107
Jotunheimen	Juvfonne	2597	NM	NVE	2010-	7
	Styggebrean	2608	NM	NFS	1951-63, 2011-	17
	Storjuvbrean	2614	-56**	NVE	1901-07, 08-12, 33-61, 97-	60
	Storbreen	2636	-7	NVE	1902-	82
	Leirbrean	2638	-15	NVE	1907-77, 1979-	61
	Bøverbrean	2643	2	NVE	1903-76, 1997-	47
	Styggedalsbreen	2680	-16	NVE	1901-	99
	Mjølkedalsbreen	2717	-4	BL	1978-	25
	Koldedalsbreen	2734	NM	BL	1978-	14
	Hellstugubreen	2768	-12	NVE	1901-	81
Hardanger	Midtdalsbreen	2964	3	AN	1982-	38
	Rembesdalskåka	2968	-8	S	1917-	45
	Botnabrea	3117	NM	GK	1996-	17
	Gråfjellsbrea	3127	-47	S	2002-	18
	Buerbreen	3131	-10	NVE	1900-	74
	Bondhusbrea	3133	-23	S	1902-	89
	Svelgjabreen	3137	-1	SKL	2007-	13
	Blomstølskardsbreen	3141	-1	SKL	1994-	21

* – three years,
** the measurement in the defined direction hit the glacier river outlet
NM – not measured in 2020

Observers other than NVE:

SISO	Siso Energi
S	Statkraft
NBM	Norsk Bremuseum & Ulltveit-Moe senter for klimaviten, Fjærland
BL	Birger Løvland, Eidsbugarden
AN	Prof. Atle Nesje, University of Bergen
GK	Geir Knudsen, Tyssedal
SKL	Sunnhordland Kraftlag
NFS	Norsk fjellsenter, Lom

Figure 12-4
Bødalsbreen seen from the reference point BODA_M1 (the large boulder) on 11th July 2019. Lake Bødalsvatnet is visible to right of the boulder. Photo: Atle Nesje.

Revision of the length change record for Bødalsbreen

Background

Bødalsbreen is a western outlet from Jostedalsbreen in Lodalen, Stryn municipality. The glacier area is 8.4 km^2, the elevation interval from 652 to 1923 m a.s.l., and the length is about 6.0 km (Andreassen et al., 2012). Glacier length change measurements at Bødalsbreen started in 1900 (Rekstad, 1902) and were conducted from 1900 to 1953. The observations were resumed in 1996 (Winkler et al. 2009). In 2015 the measurements had to be stopped due to unfavourable conditions at the glacier terminus situated at the top of high cliffs. In 2019 Rekstad's original reference point from 1900 was located by Atle Nesje (Fig. 12-4). Here we check the original records and fill the gap between the two observation periods using mapped terminus positions and the reference points.

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 later an electronic distance meter in defined directions to the glacier boundary. In the official reports, results were reported for the right (western) and left (eastern) side of the glacier, looking towards the glacier. The annual length change has been calculated as the average of the two from 1909 to 1953. In the observers' notes, available from the period between 1932 and 1953, the observations are referred to the eastern (left) or the western (right) side.

1900-1936

John Bernhard Rekstad established a reference point on the eastern (left) side of the outlet river in 1900, and the direction to the glacier snout was measured (Rekstad, 1902). Between 1900 and 1907 the glacier advanced 30 metres. A second reference point was established on the western (right) side of the river in 1907, and annual changes for 1907-08 were reported for the central part and right side of the terminus independently. After

1908 the annual changes were reported for the right and left side separately for most years (Rekstad, 1910). According to the annual reports from Bergen Museum the glacier advanced 48 metres from 1900 to 1912. From 1912 until 1922 the glacier retreated 143 metres and then advanced 62 metres from 1922 to 1930. The net reported frontal change between 1900 and 1930 was a retreat of 33 metres. Between 1930 and 1936 the reported terminus retreat was 62 metres.

In the observer's notes from 1932 the reference marks were referred to as "the eastern carved cross from 1930 in a large rock" and "the western carved cross in a large stone". The directions were noted as "straight south" and "10 degrees east of south", respectively. The original reference point from 1900 was a cairn on top of a large boulder. As the glacier advanced both prior to 1910 and prior to 1930, new marks located in more favourable positions to the glacier terminus were probably established.

1937-1953: On 13th September 1936 the observer, Simon Raudi, was one of the many who was killed in the second large rockslide from Ramnefjellet in Loen. The new observer, Torvald Hogrenning, was not able to locate the old reference marks, and new marks were established. Consequently, there is a gap in the record. 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, but the reported distance was referred to the reference points from 1937. The cumulative length change from 1937 to 1953 calculated from the observer's notes is −699 metres on the western side and −597 metres on the eastern side. The reported length change from 1937 to 1953 is −648 metres, corresponding to a retreat rate of −34 m/year.

1996-2015: Stefan Winkler established reference points in front of Bødalsbreen in 1996, and new marks were established as the glacier advanced and subsequently receded (Fig. 12-5). The advance of Bødalsbreen culminated in 2001, forming an end moraine and trimline. In 2010 the responsibility for the measurements were transferred to NVE, and Erling Briksdal was hired to perform the measurements. In 2014 the lower part of the glacier tongue was separated from the rest of the glacier (Fig 12-6). The terminus was then located on top of high cliffs, and the length change observations were aborted in 2015.

Available maps and aerial vertical photographs/orthophotos

1938: Orthophoto from 22nd July 1938. (Widerøes Flyveselskap AS, mission no.50).

1967: Orthophoto from 20th July 1967. (www.norgeibilder.no).

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

2005: Orthophoto from 10th September 2005. (www.norgeibilder.no).

2010: Orthophoto from 7th September 2010 (www.norgeibilder.no).

2015: Orthophoto from 20th August 2015 (www.norgeibilder.no).

Figure 12-5
Bødalsbreen on 26th June 2010. The reference point BODAX11 is a cairn located on the large boulder in front of the glacier. See Fig. 12-6 for location. Photo: Hallgeir Elvehøy.

Figure 12-6
Bødalsbreen on 28th June 2014. The lower tongue disintegrated during the summer of 2014. Photo: Erling Briksdal.

Methods

A vertical aerial photo from 1938 (frame I 087) covering the glacier terminus and glacier forefield was scanned and the image was geo-rectified using four reference points (Fig. 12-7). The glacier terminus was then digitized. A central flow line was drawn from a point at the river outlet in lake Bødalsvatnet representing the glacier terminus in 1900 to the terminus position in 2015 as shown on an orthophoto from 2015 (Fig. 12-8). The distance from the river outlet in 1900 along this flow line is ca. 1600 metres. The mapped front positions from 1938, 1967, 1993, 2000, 2010 and 2015 were plotted on this flow line, and the distance between the different terminus positions were measured. Results reported in Bergens Museums Årbok (1908-1939), and Fluctuations of Glaciers (Mercanton 1948, 1950, 1953) were checked against the observers' notes to identify discrepancies and errors, and annual results were adjusted for rounding errors. For some years (1914, 1927 and1928) only one number is given without specification for left or right side. The result is assumed representative for both measuring lines. The gap between 1936 and 1937 was estimated as the mean of annual retreats for 1934/35, 1935/36, 1937/38 and 1938/39 (4 years). In the period 1996-2012, one to three reference points on the western side of the river were used to calculate the annual change. We reduced the record to rely on one reference point at a time.

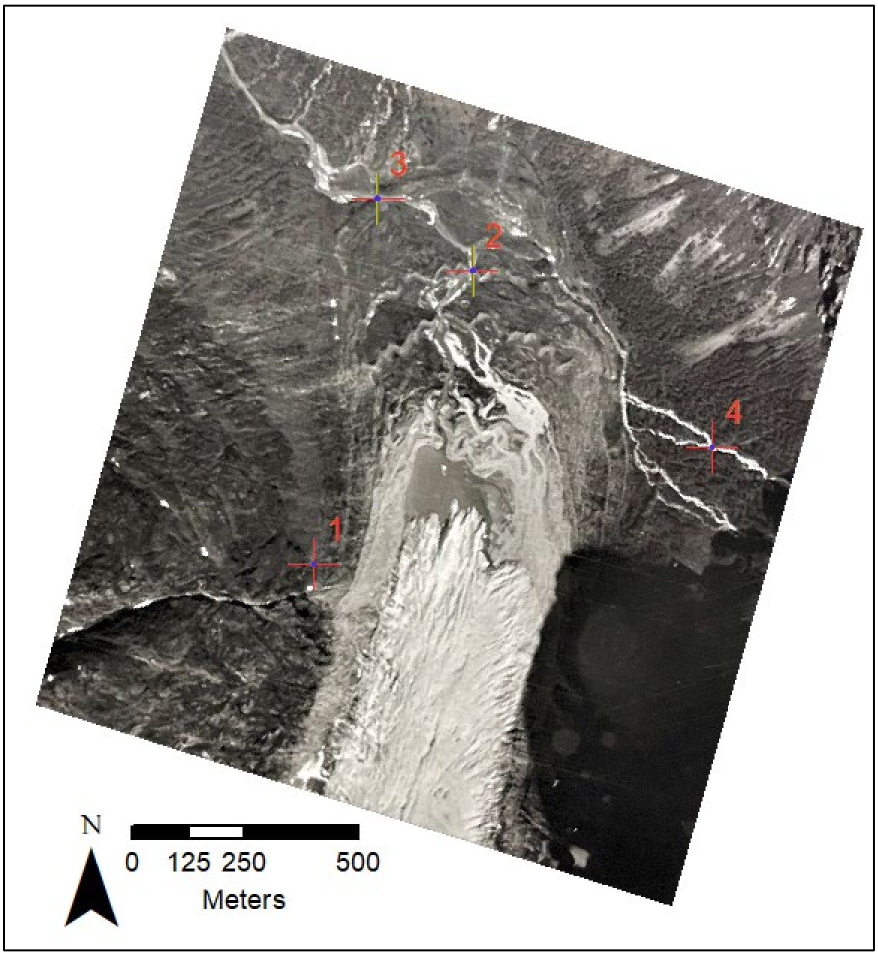


Figure 12-7
Bødalsbreen on 22nd July 1938. Four reference points used for the georeferencing is shown as crosses. Photo: Widerøes Flyveselskap AS (Mission no. 50, frame I 087).

Results

In the periods 1900-1936 and 1937-53 the original results were used but adjusted for rounding errors. The retreat between 1936 and 1937 was estimated as the mean of annual retreats for 1934/35, 1935/36, 1937/38 and 1938/39 (4 years) as −20 metres. The assumed uncertainty in this estimate is ±10 metres.

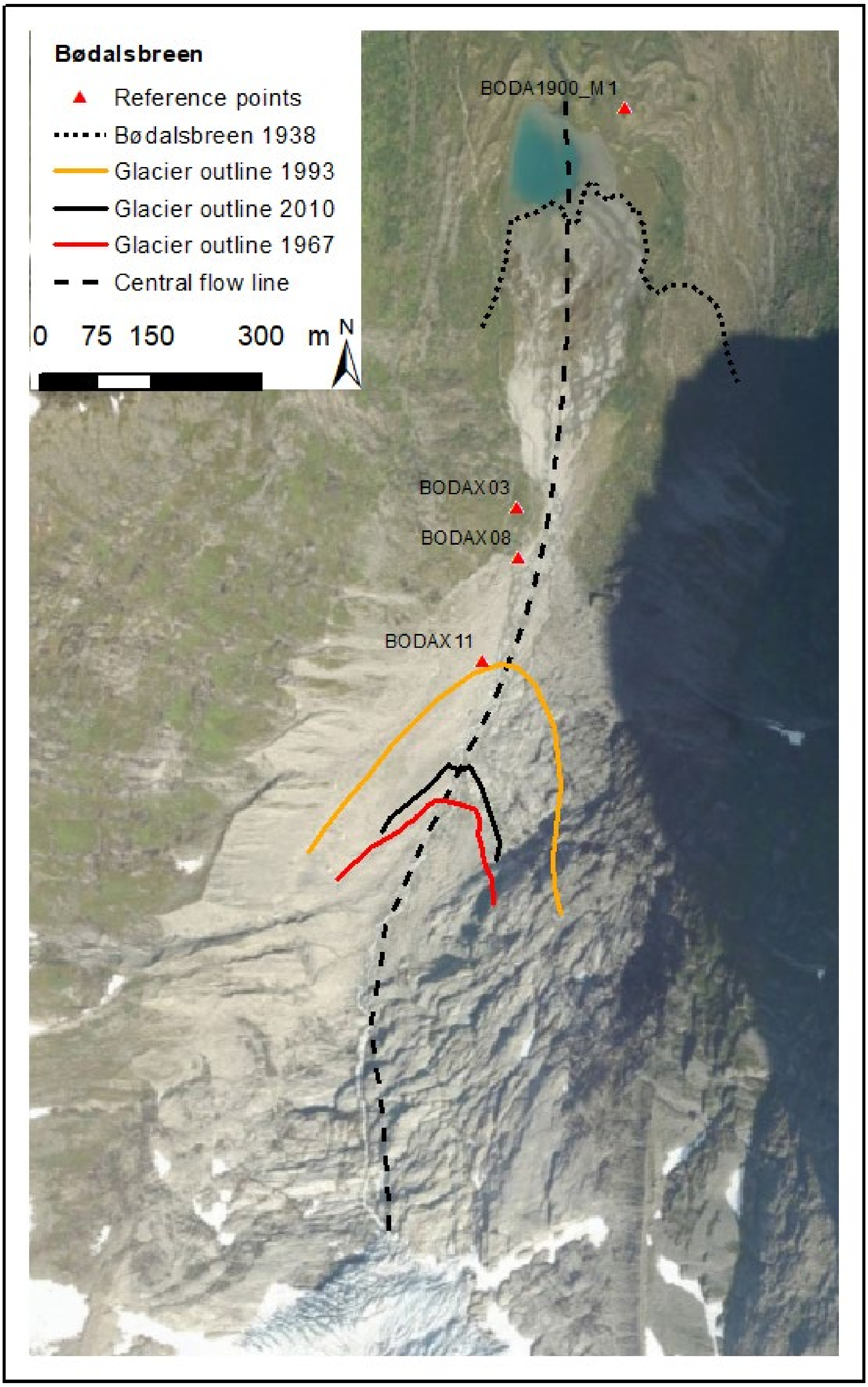


Figure 12-8
Orthophoto from August 2015 showing known reference points, the trimline and moraine formed during the advance culminating in 2000-2001 close to the reference point BODAX08, and glacier front positions mapped in 1938, 1967, 1993 and 2010. The distance along the flow line from the river outlet close to the reference point BODA1900_M1 to the glacier terminus in 2015 is ca. 1600 metres.
Orthophoto: www.norgeibilder.no

The distance along the central flow line from the river outlet to the terminus position in 1967 is 980 metres. As the cumulative length change from 1900 to 1953 is −763 metres, the length change between 1953 and 1967 is estimated as −217 metres (−15 metres pr. year). The glacier tongue in 1967 as seen on the orthophoto probably continued to retreat for some more years before it started to advance. Briksdalsbreen in Olden, 19 km south-west of Bødalsbreen, advanced 200 metres between 1973 and 1980, suggesting that Bødalsbreen probably reached its minimum length in the 1970-ies. The terminus position in 1993 implies a net advance of 200 metres between 1967 and 1993. The distance between the 1993 terminus position and the trimline from 2000-2001 shows an additional advance of 165 metres. The length change measurements show an advance of 61 metres between 1996 and 2000, implying that the glacier advanced 104 metres between 1993 and 1996.

In the period 1996-2012, one to three reference points on the western side of the river were used to calculate the annual change. We reduced the record to rely on one reference point at a time. The net change between 1996 and 2012 was −406 metres.

The lower tongue disintegrated in 2014 (Fig 12-6). The distance along the central flow line between the terminus in 2010 and the terminus in 2015 is 680 metres. Between 2010 and 2012 the measured retreat was 178 metres. Inspection of photographs taken from the valley indicates no change between 2014 and 2015. Consequently, the retreat along the flow line between 2012 and 2014 was 502 metres.

The adjusted length change record for Bødalsbreen is available at www.nve.no/glacier.

12.2 Jøkulhlaups

Jøkulhlaups, also known as Glacier Lake Outburst Floods (GLOFs), were registered at five glaciers in Norway in 2020. However, two of the events were observed on photographs and satellite images only and would not have been observed by conventional means.

Events were observed at Rundvassbreen (Blåmannsisen), Rembesdalskåka (Hardanger-jøkulen), and Storbreen in Jotunheimen. This is the first known event from Storbreen, but there have been several registered events from both Rundvassbreen and Rembsedalskåka, with eleven events from Rundvassbreen since 2001, and seven events from Rembesdal-skåka since 2014.

Inspection of glacier-dammed lakes on photographs and Sentinel-2 imagery showed that there were probably outburst events from Harbardsbreen in Breheimen, east of Jostedals-breen, and from Svartisheibreen, south-west of the western Svartisen.

Rundvassbreen (Blåmannsisen)

The lake Øvre Messingmalmvatnet is adjacent to and dammed by the glacier Rundvass-breen, a northern outlet glacier of the Blåmannsisen icecap in northern Norway (Fig. 12-9).

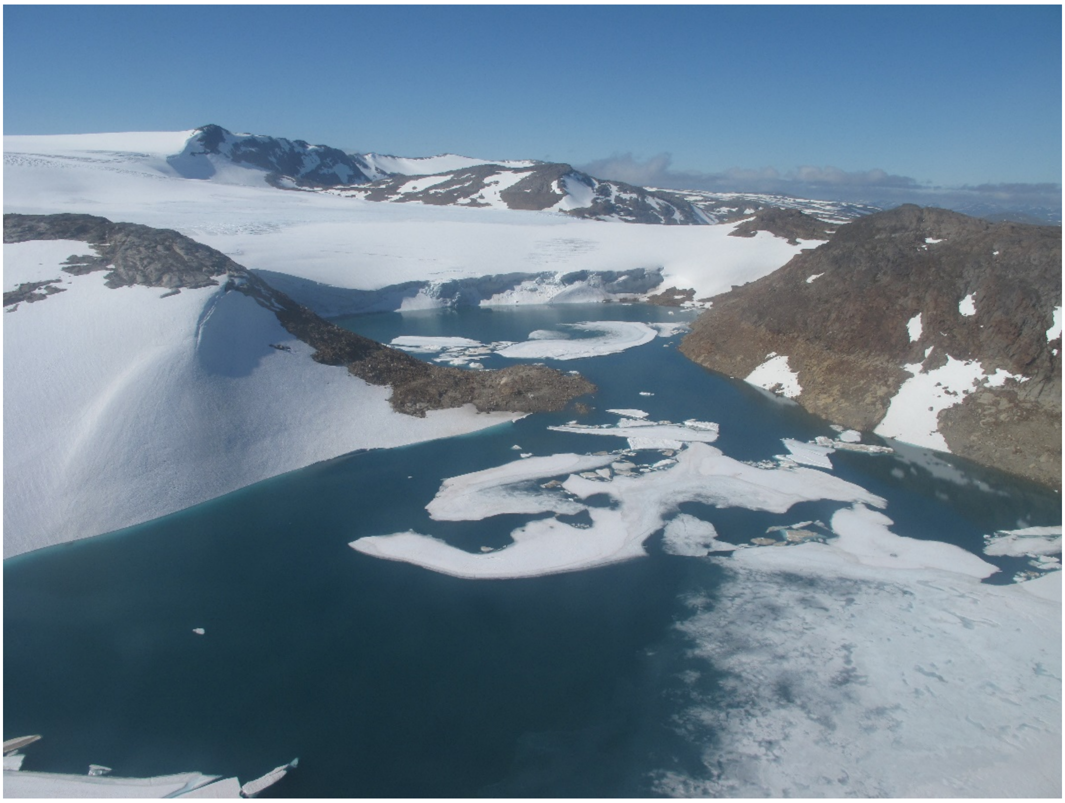


Figure 12-9
The lake Øvre Messingmalmvatnet is dammed by the ice-barrier at Rundvassbreen.
Photo: Hans Martin Hjemaas, SISO Energi AS.

Jøkulhlaup 2020

Between 3rd and 4th September a new jøkulhlaup occurred at Rundvassbreen. About 10 million cubic metres of water drained under the glacier in less than two days. This is just one year after the previous event, and the third successive year that the subglacial lake has drained. Satellite images from 21st August and 4th October show the lake before and after the jøkulhlaups (Fig. 12-10).

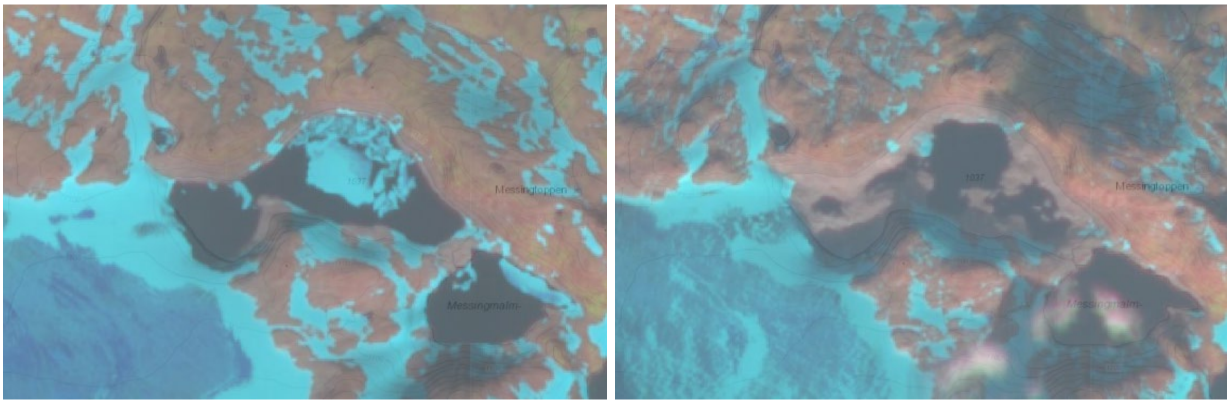


Figure 12-10
Satellite images (Sentinel-2) taken before and after the event. The left image was taken on 21st August and the right image on 4th October 2020. Source: Varsom Xgeo.

The water level in Øvre Messingmalmvatnet before the most recent event was 1025.4 m a.s.l. Two employees from the hydropower plant were near the snout of Rundvassbreen on mid-day of 3rd September and noted increased discharge in the glacier river. The next morning, employees from the hydropower plant observed a considerable increase in the discharge, and could ascertain that a jøkulhlaup was taking place (Fig. 12-11). During the afternoon the discharge in the river was normalised.

Figure 12-11
High discharge in the glacier river from Rundvassbreen at the end of the jøkulhlaup in the morning on 4th September 2020. Photo: Cecilie Amundsen, Siso Energi AS.

Several previous events of a similar magnitude or greater have been recorded from Rundvassbreen (Jackson and Ragulina, 2014). The first was in September 2001, when 35 mill. m^3 of water suddenly drained 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, 2005). The event in 2020 was the eleventh, and the interval between events has varied from one year to four years. All recorded events from Rundvassbreen have been in late summer, i.e. August or September (Tab. 12-2).

Revision of the correlation between water level and water volume

In order to calculate the water volume of the lake before and after a jøkulhlaup, a correlation between the water level and the water volume was described in Engeset (2002) and Engeset (2003). The correlation was based on mapping (aerial photos) from 1998 and adjusted for the glacier retreat between 1998 and 2001. After 2001 the recession of the ice-barrier has continued. The latest orthophoto was taken in 2017, and from 1998 to 2017 the glacier retreat released an area of 83750 m^2 (Fig. 12-12). Thus, the water volume of the lake has increased correspondingly.

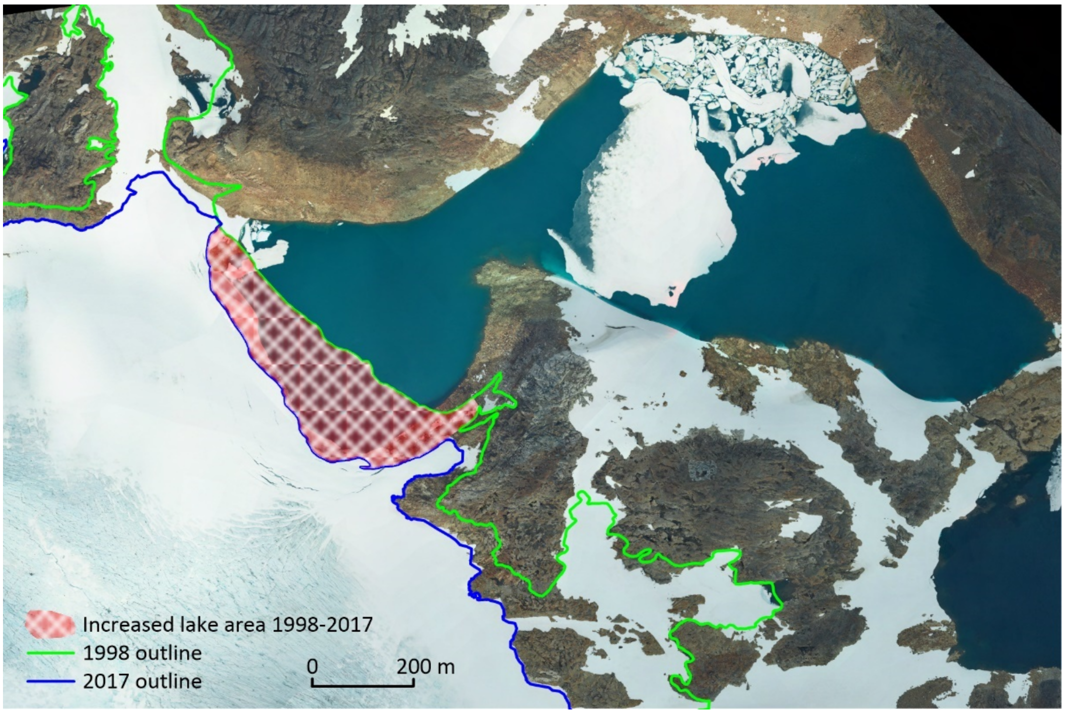


Figure 12-12
The recession of the ice-barrier from 1998 to 2017 has increased the area of the lake by 0.084 km^2. Source: norgeibilder.no.

Based on the increased water volume in the lake a revised correlation curve between the water level and the water volume was calculated (Fig. 12-13). The revised correlation curve was used to re-calculate the water volumes from jøkulhlaups back to 2011. Updated water volumes are shown in table 12-2.

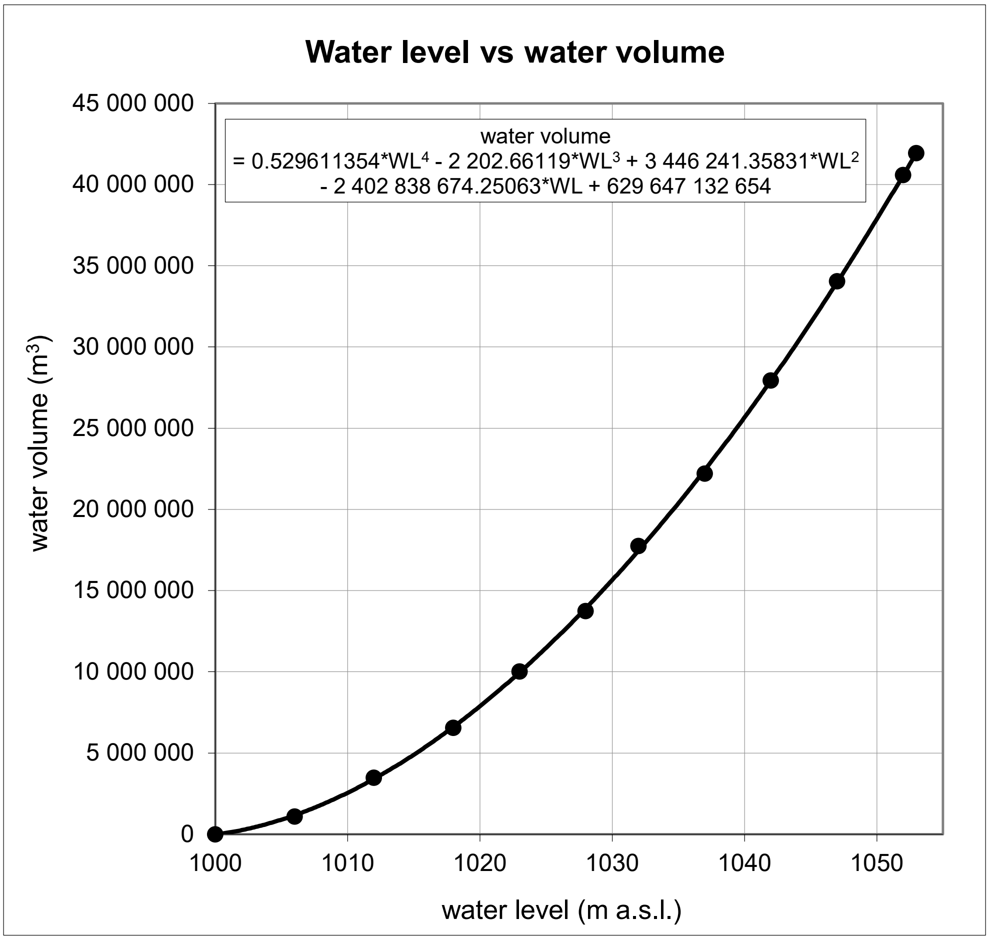


Figure 12-13
The revised correlation curve for water level vs water volume for Øvre Messingmalmvatnet. The revised correlation curve is used to re-calculate water volumes back to 2011.

Table 12-2
Dates, water level before and after the drainages and approximate water volumes of jøkulhlaups from Øvre Messingmalmvatnet 2001-2020.

Year	Date	Water level (m a.s.l.) Before	Water level (m a.s.l.) After	Comment	Water volume (mill. m^3)
2001	5th – 7th September	~1051	~1007	WL estimated	35
2005	27th – 29th August	~1051	~1007	WL estimated	35
2007	29th August	~1040	~1007	WL estimated	20
2009	6th - 7th September	~1040	~1007	WL estimated	20
2010	8th - 17th September	~1028	~1007	WL estimated	11
2011	22nd September	1029	1007.5	WL measured	13
2014	10th - 12th August	1050	1007.3	WL measured	36
2016	28th - 29th September	1040.7	~1007	WL measured/estimated	25
2018	25th - 26th August	1039.8	1007.3	WL measured	24
2019	9th - 10th September	1026.2	1007.2	WL measured	11
2020	3rd - 4th September	1025.4	1007.0	WL measured	10

Rembesdalskåka (Hardangerjøkulen)

Rembesdalskåka, an outlet glacier of Hardangerjøkulen, dambs a lake called Nedre Demmevatnet (Fig. 12-14). There have been many previous events recorded from Nedre 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.

Figure 12-14
The lake Nedre Demmevatnet is dammed by the ice-barrier at Rembesdalskåka.
Photo: Anders Ekanger, NRK.

Jøkulhlaup 2020

A new event occurred from the glacier-dammed lake, Nedre Demmevatnet on 6th September 2020 (Fig. 12-15). Over 5-6 hours a total of 2.3 million m^3 water drained under Rembesdalskåka and subsequently to the hydropower reservoir Rembesdalsvatn. This is the greatest volume measured in a jøkulhlaup from Nedre Demmevatnet since 1938 (Tab. 12-3).

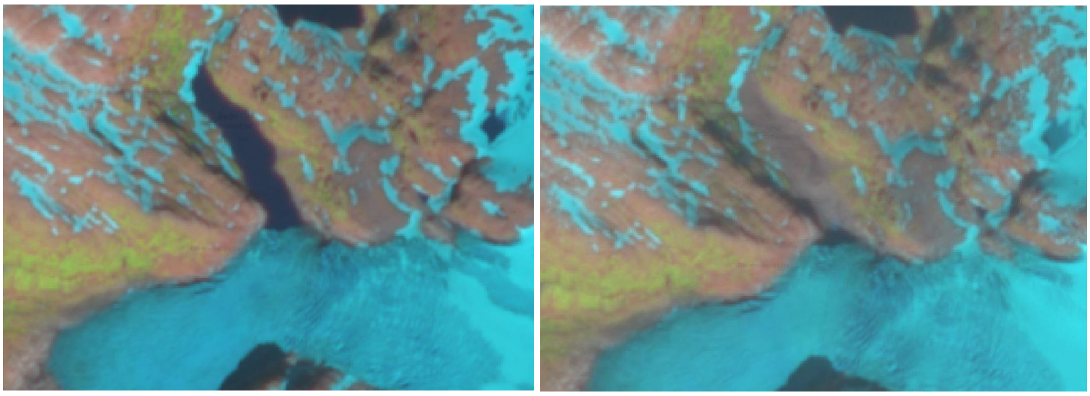


Figure 12-15
Satellite images of the glacier lake Nedre Demmevatnet taken before (2nd September, left) and after (17th September, right) the jøkulhlaup on 6th September 2020. Source: Varsom Xgeo.

Table 12-3
Dates and approximate volumes of jøkulhlaups from Nedre Demmevatnet.

Year	Date	Comment	Water volume (mill. m^3)
1736	unknown	Earliest record of flood from Demmevatnet	unknown
1813	unknown	Flood damages	unknown
1842	unknown	Flood damages	unknown
1861	17th September	Damage, including two bridges	unknown
1893	Late August	Catastrophic flood, lake drained in 24 hours	35
1897	17th August	Water flowed over glacier surface, lasted 24 hours	35
1937	10th August	Drained in 3.5 hours	12
1938	23rd August	Flood before new drainage tunnel completed	10
2014	24th August	Event occurred over ~3 hours	1.9
2016	~25th January	Lake observed full 24th January and empty 30th January	1.44
2016	6th September	Event occurred over ~4 hours	1.87
2017	27th October	Event occurred over ~22 hours	1.85
2018	10th August		unknown
2019	24th August	Event occurred over ~3 hours	1.8
2020	6th September	Event occurred over 5-6 hours	2.3

Storbreen (Jotunheimen)

Over the past years a small lake has appeared in front of the southern outlet of Storbreen. As the glacier tongue has melted back the lake has grown, and in August 2019 the lake had an area of 0.002 km^2 (Fig. 12-16).

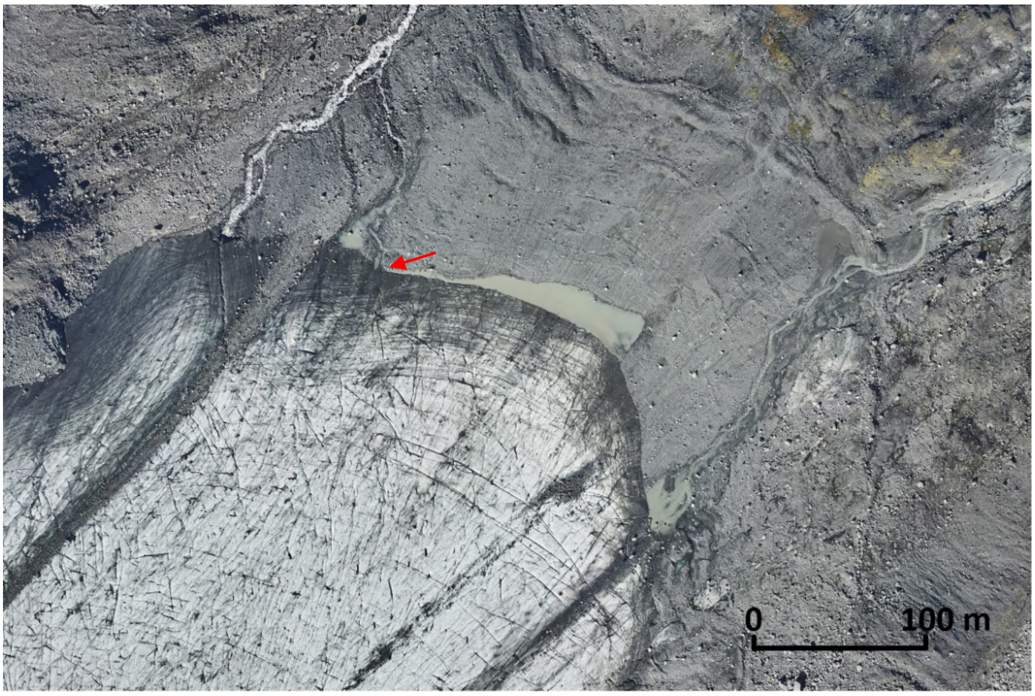


Figure 12-16
Orthophoto showing the glacier-dammed lake in front of Storbreen on 26th August 2019. The drainage outflow is indicated with the red arrow. Photo: Terratec AS.

Jøkulhlaup 2020

Field visits during the summer 2020 showed that the lake was emptied between 11th August and 18th September (Fig. 12-17). The water volume of the drainage is estimated to be approximately 10 000 m^3. It was supposed that the water drained at the western side of the glacier snout (Figs. 12-13 and 12-14).

Figure 12-17
During the field visit on 18th September the lake was emptied. The drainage outflow is indicated with the red arrow. Photo: Liss M. Andreassen.

Events observed on photography and satellite images only:

Svartisheibreen (Vestre Svartisen)

Svartisheibreen is a small valley glacier south-west of the western Svartisen ice cap that calves into a recently formed proglacial lake, here called Heiavatnet. Several previous events have occurred at Svartisheibreen, the last one in August or September 2016. Although rather than being directly observed, most of the events were registered due to the water level being lower than normal and the presence of stranded ice blocks around the lake.

Jøkulhlaup 2020

Photographs taken from a light aircraft show that the water level in Heiavatnet is quite low in August 2020 (Fig. 12-18), with many stranded ice blocks around the lake (Fig. 12-18). Photographs taken the previous year (Fig. 12-18) show a higher water level.

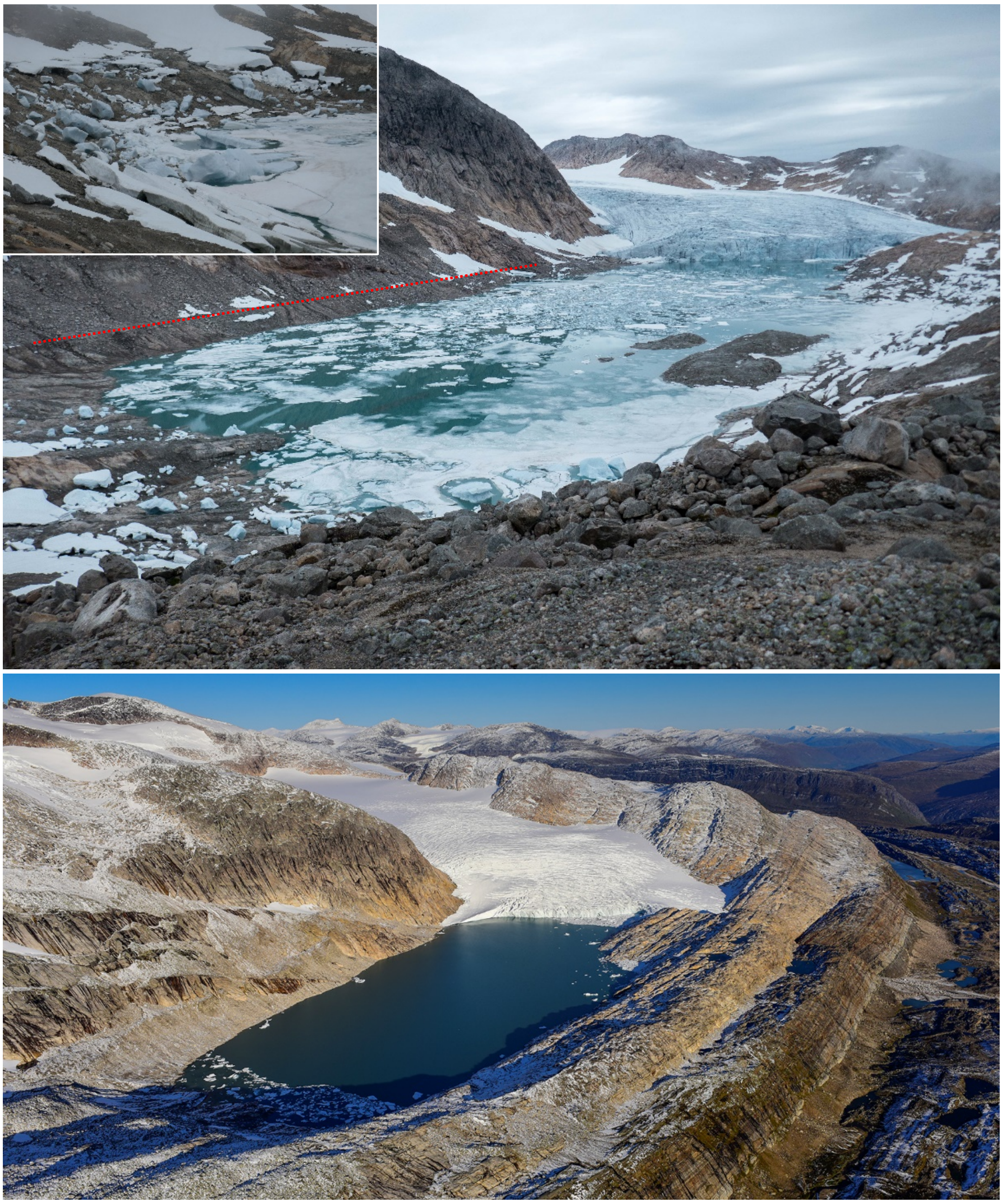


Figure 12-18
Heiavatnet photographed on 20th August 2020 (upper) and 22nd September 2019 (lower). Stranded ice blocks are visible in the upper left inset photo from 2020. Assumed water level prior to the jøkulhlaup is indicated with the red dotted line. Photos: Mark Reysoo (2020) and Lars Westvig (2019).

Satellite images confirm that the water level was lower in August 2020 than it was in September 2019 (Fig. 12-19). Thus photographs and satellite images from 2019 and 2020 highly indicate that the dammed lake was drained, probably in late July or early August 2020. As there were no measurements or observations, the water volume of the drainage was not estimated.

Figure 12-19
Satellite images (Sentinel-2) of Heiavatnet on 26th September 2019 (left) and 18th August 2020 (right). Source: Varsom Xgeo.

Harbardsbreen (Breheimen)

Harbardsbreen is a plateau glacier in the Breheimen area with an area of about 25 km^2. In the central part the glacier dams two unnamed lakes (Fig. 12-20).

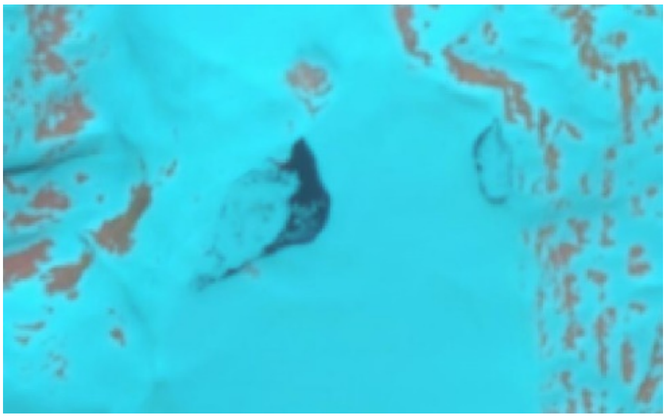
Figure 12-20
The western glacier-dammed lake on Harbardsbreen photographed on 2nd September 2020, just over two months after the jøkulhlaup. Photo: Thorben Dunse.

Several previous jøkulhlaups have occurred at Harbardsbreen, the last one in August 2015. Over the period 1996-2001 there were almost annual jøkulhlaups from the glacier-dammed lake on the western margin of Harbardsbreen, in 1996, 1997, 1998, 2000 and

2001 (Jackson and Ragulina, 2014). The next jøkulhlaup didn't occur until nine years later in 2010 and was followed by events in 2012 and 2015. In 2010 and 2015 the water volumes were estimated to 5.5 mill.m^3, respectively.

Jøkulhlaup 2020

The event in 2020 was not observed directly, but is based on satellite images from June and July (Fig. 12-21). A satellite image from 19th June shows water in both lakes. The next image from 24th June shows that the western lake was empty, while the water level in the eastern lake had increased. A Sentinel-2 image from 24th July shows that both lakes were empty. Thus the satellite images indicated that a new event occurred in late June. As there were no measurements or observations, the water volume of the drainage was not estimated.



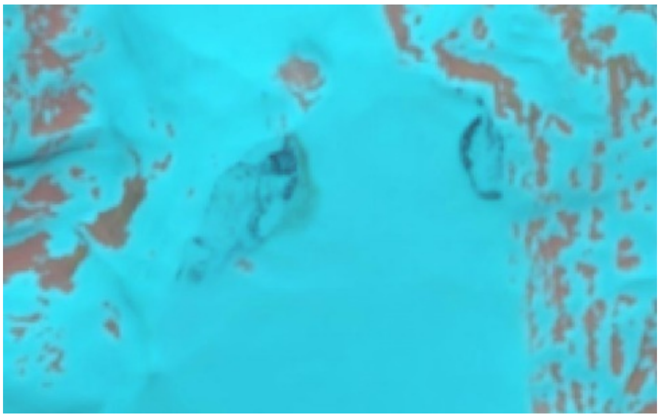


Figure 12-21
Sentinel-2 images of Harbardsbreen from 19th June (upper left), 24th June (upper right) and 24th July (lower right) 2020. On 19th June both lakes were filled with water. On 24th June the western lake was almost emptied, while the eastern lake was still filled. On 24th July both lakes were completely emptied. Source: Varsom Xgeo.

Oksfjellbreen (Okstindbreen)

Oksfjellbreen is a southern outlet from the ice cap Okstindbreen in Nordland county. In the northern part of the glacier outlet a small ice-dammed lake is located (Fig. 12-22). No previous jøkulhlaup from Oksfjellbreen has been registered.

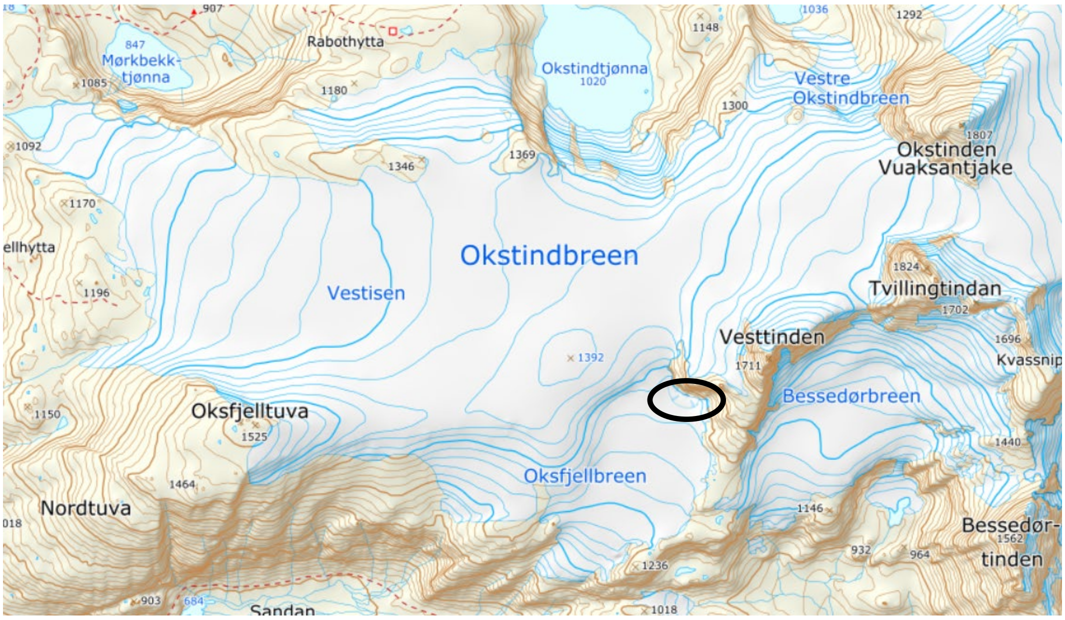


Figure 12-22
Oksfjellbreen is a southern outlet from the ice cap Okstindbreen. A glacier-dammed lake is located in the northern part of the outlet. Map source: norgeskart.no.

Jøkulhlaup 2020

The event in 2020 was not observed directly, but is solely based on Sentinel-2 satellite images. Comparison of images from 27th June and 4th July 2020 suggest that the glacier-dammed lake emptied during this period (Fig. 12-23). The image from 27th June shows water in the lake, while the image from 4th July shows that the lake was empty and it also shows traces of running water.

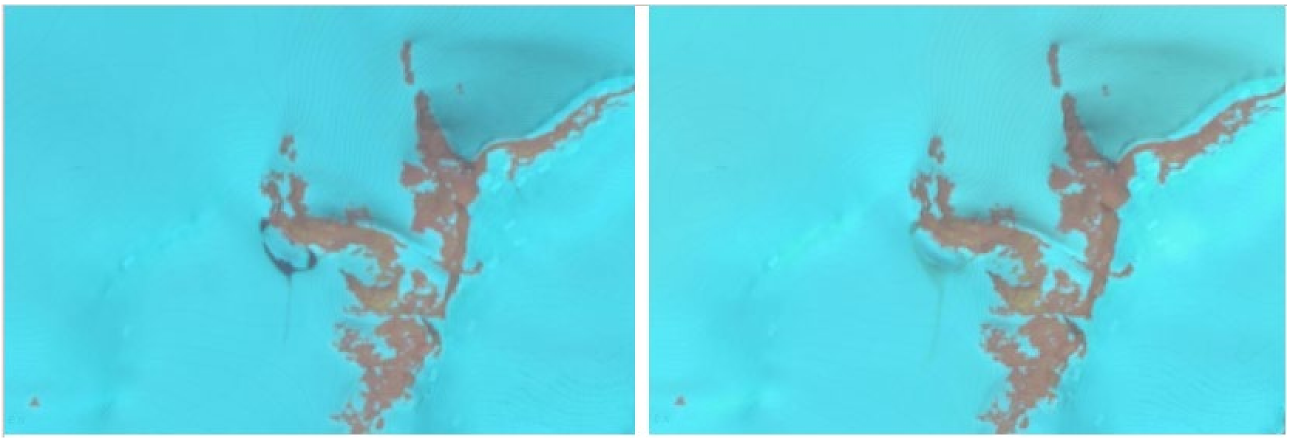


Figure 12-23
Sentinel-2 images showing part of Oksfjellbreen and the glacier-dammed lake. The left image is from 27th June and the right from 4th July 2020. On 27th June the lake was filled with water and on 4th July the lake was emptied. Source: Varsom Xgeo.

13. Glittertinden (Kjetil Melvold and Liss M. Andreassen)

Glittertinden (61°40′N, 8°21′E) in Jotunheimen is Norway's second highest peak (2452 m a.s.l.) (Fig. 13-1). It's peak is covered by a snow and ice pack that varies in thickness. Historical photos from 1910 show a thick ice and snow layer (NRK 2020, NVE 2021). In the past, the surface elevation of Glittertinden's ice covered peak was higher than Galdhøgpiggen (2469 m asl), but with recent thinning of the ice this is no longer the case.

Figure 13-1
Glittertinden is Norway's second highest peak and had in 2020 a thin snow and ice layer covering the upper parts. Photo Kjetil Melvold.

To determine the snow and ice thickness and the current surface elevation of Glittertinden, NVE and Kartverket (the Norwegian mapping authorities) conducted a Ground Penetrating Radar (GPR) and GNSS survey and ice coring at two sites on 17 September 2020.

13.1 Field work

The GPR survey consisted of several relatively short transects (30 – 75 metres) collected on the highest ice-covered part of Glittertinden (Fig. 13-2). Two manual ice core drillings were also done to validate the GPR survey (Fig. 13-2). The timing of the survey was chosen to be close to maximum snow melt. A fresh snow layer of about 6 cm covered the surface. The snowpack was frozen at the time of the survey.

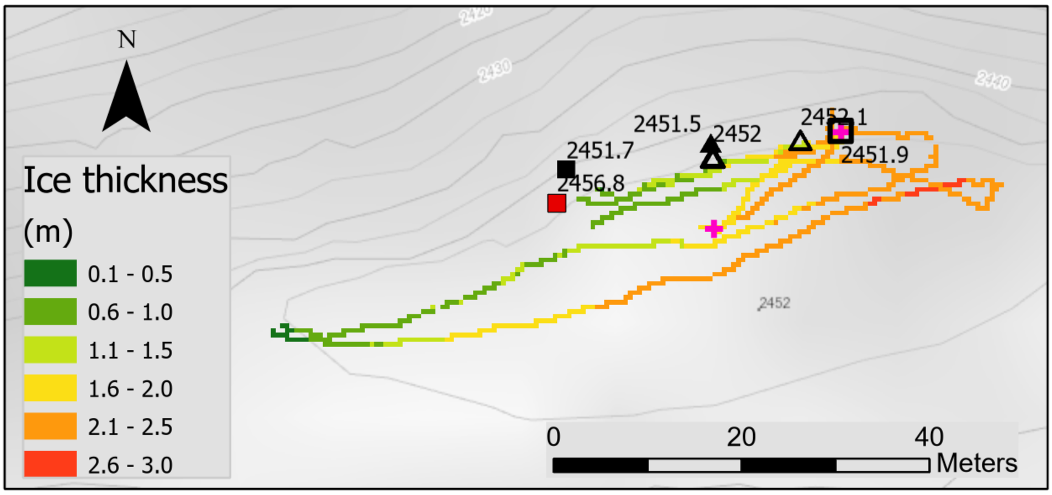


Figure 13-2
Map of the study area. Squares and triangles are surface elevation measured by Kartverket and NVE respectively. Open square and triangle are measured on the snow- and ice-covered part whereas filled are measured on bedrock outcrops. Red squares are old surface elevation measured in September 2017 by Kartverket. Magenta crosses are ice drilling sites where ice thickness was measured. Drill site A to the west and B to the east. The coloured lines show the radar survey transect and ice thickness along these lines.

Instrument and field setup

The GPR survey was conducted with a 350 MHZ antenna from Radarteam and a SIR-3000 control unit to display and collect data in the field. The 350 MHz antenna was dragged along the snow surface and data was collected using a time trigger (16 traces per second) (Fig. 13-3). The GPR data were collected along straight lines and position were captured with one second interval using the Garmin GPSMap 66i unit. We used a traditional manual stake drill for drilling down to the interface between ice/snow and bedrock.

To determine the surface elevation of Glittertinden point measurements were carried out using a Spectral geospatial SP20 handheld GNSS unit from NVE and Altus APS-3G GNSS Unit from Kartverket. Measurements were carried out both on the ice and on exposed bedrock outcrops along of the northern cliff. The GNSS antennas were placed directly on top of snow cover or bedrock. The Altus APS-3G was logging raw GNSS data for at least 30-45 min on each site. The SP20 GNSS unit was set up to perform Real-time kinematic (RTK) measurements. The unit received corrections for the GNSS data over cellular network.

Figure 13-3
Radar survey setup. The red box is the GPR antenna, the control unit is carried by the rearmost operator. In background ice drilling at site A. Photo: Even Lusæter/NRK innlandet.

Post processing GPR and GNSS

The geo-coding (to resolve the longitudinal and latitudinal position of the GPR trace) was determined from the GPS survey data, since data from both the GPR and GPS were collected at fixed time increments. When GPR samples were not collected simultaneously (at the same time) with the GPS data, positions were linearly interpolated between GPS positions.

The GPR data were processed using the commercial software packages, Reflex-Win version 8.5 by (Sandmeier geophysical research). Due to the shallow snow and ice thickness the only processing steps applied was dewow, a time zero correction. The data was dewow filtered to eliminate possible low frequency parts. A static-correction was also performed to correct the time zero of the trace. Figure 13-4 shows a typical result of the GPR survey (radargram) collected on Glittertinden. Ice thickness less than about 0.25 m could not be determined with the 350 MHz antenna since it was masked by the direct wave between the transmitter and receiver antennas. The ice and bedrock interface was easy to detect in the radar diagram (Fig. 13-4). From the processed radar data, the two wave travel-time (TWT, time difference between first in the arrivals and the bed reflector) was determined for the ice bedrock reflector. The reflector was digitised manually. Ice thickness was readily computed from the TWT, assuming a homogeneous radio wave velocity of 168 m μs^{-1}.

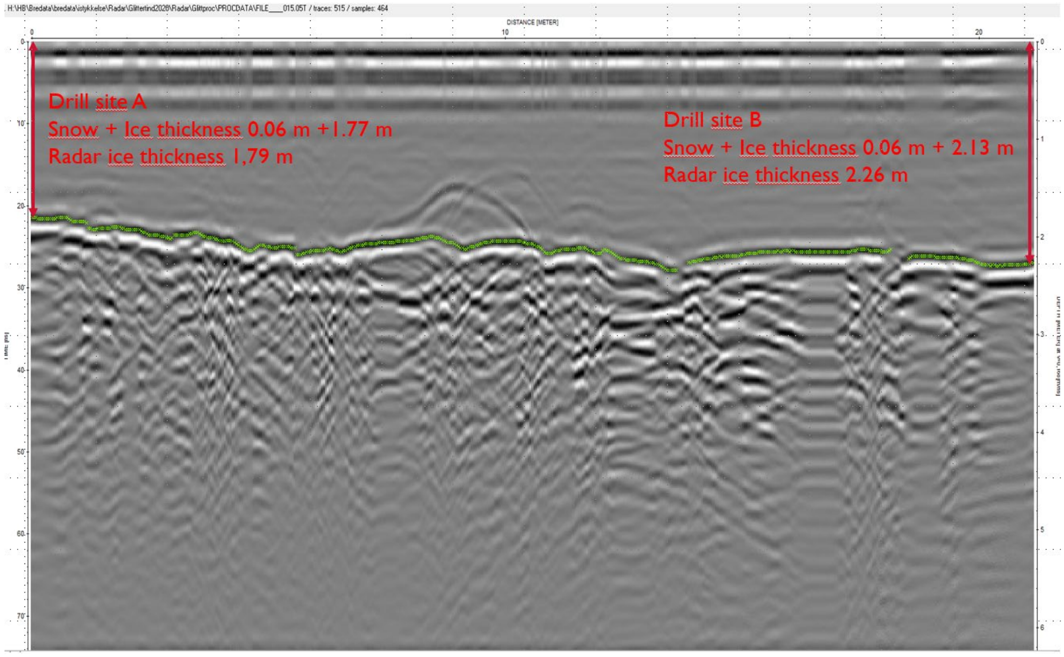


Figure 13-4
Example of radar data collected from drill site A to B. Green crosses show digitized bedrock interface along the profile. Text indicates the snow and ice thickness at the two drill sites based on drilling and radar. Length of profile about 32 m.

In total, 5600 GPR data points were collected along 7 transects with a total length of about 350 m on the uppermost part of the ice patch still remaining on Glittertinden.

The Topcon GNSS data was post processed by Kartverket and the result from the RTK unit was downloaded at NVE and post processed.

13.2 Error in ice thickness and volume

Measurement's error

Uncertainties in the calculation of ice thickness arise from uncertainties in Radio Wave Velocity (RWV) of the electromagnetic wave in ice, inaccuracies when picking reflectors (inaccurate travel time determination), and the resolution of the radar system and influence of snow cover. The ice thickness values will also be affected by a horizontal positioning error due to both GPS uncertainty and interpolation errors of trace location along the radar train. A more fully discussion ofboth errors related to GPR measurement could be found in Lapazaran (2016). A short description with relevant values for our radar systems will be given here.

The wave speed through the glacier has not been measured, but a constant RWV of 169 or 168 m µs-1 has been used. These are typical values previously used for temperate glaciers in Norway by NVE. It is based on a suggested value by Robin et al. (1969) for pure crystalline ice. These values might be too high but to be consistent with previous studies it was not corrected. Our measurements were carried out in September after days with sub-zero temperatures and we assume that the snow was relatively dry at the time of the survey, which minimises the spatial variation in RWV. The snow cover was only 6 cm thick so no adjustment was made for snow depth. The point data was interpolated into 50 cm grid cells.

The maximum resolutions that can be achieved correspond to ¼ of the used wavelength, However in this study we have used a more conservative value of ½ of a wavelength which gives respectively ±28 cm in ice for our 350MHz radar. The vertical resolution is also dependent on the digital sampling of the GPR system. The picking (interpretation error) of the ice-base reflections will depend on the quality of the bed reflector and the expertise of the operator. In some cases, the bed echo could be easily misinterpreted especially in case with a lot of internal backscatter in the ice. Based on our one experience we have found the picking error to be about ±1.0 ns (travel time) corresponds to an error of ±17 cm in the ice thickness.

The accuracy of the bedrock elevation is also affected by inaccurate positioning of the radar traces. The GPS measurements were carried out by code measurement with a somewhat limited accuracy, ±5 m making the final position for the sounding lines accurate within ±5 m. As a result, some of the lines were overlapping even though it should be some distance between the lines (Fig. 13-2). This is due to the inaccuracy in the GPS data. Based on our survey setup it is not possible to determine the positioning error effect one our ice thickness data. But both the study area and the variation in ice thickness are small and we therefore assume an error in bed elevation of maximum ±50 cm.

13.3 Results

The two ice coring's gave ice thicknesses of 1.77 m (site A) and 2.13 m (site B) below the 6 cm snow layer. The GPR measured snow+ice thickness varied between 0.0 and 2.7 m along the profiles with a mean (median) of 1.7 m (1.9 m). The thickest ice was found in the south-eastern corner of the mapped areas (Fig. 13-2). The surface elevation in this part is lower (based on visual inspection) than in the most northern GPR survey line. The ice thickness along the northernmost profile, close to the exposed bedrock and the bedrock cliff, increases from west toward east. The surface elevation also increases slightly along the profile up to 2452.1 m a.s.l. and then decrease down to 2451.9 m a.s.l. at drill site B and even more further east (Fig. 13-2).

The GNSS survey shows that the highest part of Glittertind is still ice coved (2452.1 m a.s.l.) (Fig. 13-2), but the exposed bedrock outcrops along the northern cliff wall are only 40 cm lower than the highest part of the ice. The highest part of bedrock has an elevation 2451.7 m a.s.l. At drill site B the GNSS data shows an ice surface elevation 2451.9 m a.s.l. subtracting 6 cm of snow, the radar measured snow + ice thickness was 2.26 m at this site. Using the ice thickness from the drilling of 2.13 m gives a bedrock elevation of 2449.7 m a.s.l. well below the highest bedrock outcrop.

Based on the surface elevation data the bedrock beneath the ice must be lower than the exposed bedrock. The radar data indicates that the bedrock beneath the ice covered part of Glittertinden has a gently dipping surface toward south-southeast.

Based on this survey and the general shape of the snow/ice patch we are relatively sure that the highest point of bedrock on Glittertinden is not hidden below the ice snow patch, and is on the northern side of the central peak area.

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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 1949-2020. 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'	3.5	1000-1360	2019	1963-	58
2 Hansebreen	2085	61°44', 5°40'	2.5	927-1303	2019	1986-	35
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'	44.9	389-1955	2020	1962-	59
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-	33
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'	17.1	1085-1851	2020	1963-	58
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-	72
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-	11
29 Hellstugubreen	2768	61°34', 8°26'	2.7	1487-2213	2019	1962-	59
30 Gråsubreen	2743	61°39', 8°37'	1.7	1854-2277	2019	1962-	59
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-	51
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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