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Glaciological investigations in Norway

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Cover photo: The glacier snout of Steindalsbreen in Lyngen, northern Norway.
The photo was taken on 30th August 2021, by David Skirnisson

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Summary: Results of glaciological investigations performed at Norwegian glaciers in 2021 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.

Subject terms: 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 2021. 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 some corrections and improvements to the text.

Oslo, September 2022

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This document is sent without signature. The content is approved according to internal routines.

Summary

Mass balance

Mass balance investigations were performed on eleven glaciers in Norway in 2021 – two in northern Norway and nine in southern Norway.

The winter balance was lower than the 1991-2020 average for five of the seven reference glaciers (continuous mass balance series back to at least 1991). Hellstugubreen in Jotunheimen and Engabreen in northern Norway had greater winter balances with 105 and 106 % of the reference period averages. Rembesdalskåka had the lowest relative winter balance with 84 % of the 1991-2020 average.

The summer balance was greater than the 1991-2020 average for all seven reference glaciers. The three glaciers in Jotunheimen had the greatest relative summer balances with 161 % (Gråsubreen), 151 % (Storbreen) and 140 % (Hellstugubreen) of the reference period averages.

The annual balance was negative for all seven reference glaciers, and of these seven, Ålfotbreen and Storbreen had the greatest deficits with −1.7 m w.e. Hansebreen, the adjacent glacier to Ålfotbreen, had the greatest deficit of all measured glaciers in Norway with −2.3 m w.e.

Glacier length change

Glacier length changes were measured at 26 glaciers in southern Norway and 10 glaciers in northern Norway. Thirty-four of the 36 measured glacier outlets showed a decrease in length. The greatest retreats were observed at Austerdalsbreen on the southern side of Jostedalsbreen (130 m), at Gråfjellsbrea on Folgefonna (66 m) and at Austre Okstindbreen in Nordland (59 m).

Sammendrag

Massebalanse

I 2021 ble det utført massebalansemålinger på 11 breer i Norge – to i Nord-Norge og ni i Sør-Norge.

For fem av de sju referansebreene (breer som har sammenhengende massebalanseserie tilbake til 1991 eller lengre) ble vinterbalansen mindre enn gjennomsnittet for referanseperioden 1991-2020. Hellstugubreen i Jotunheimen og Engabreen i Nord-Norge hadde større vinterbalanse med hhv. 105 % og 106 % av referanseperioden. Rembesdalskåka fikk den relativt minste vinterbalansen med 84 % av referanseperioden.

Sommerbalansen ble større enn gjennomsnittet for alle sju referansebreene. De tre breene i Jotunheimen hadde relativt størst sommerbalanse med 161 % (Gråsubreen), 151 % (Storbreen) og 140 % (Hellstugubreen) av referanseperioden.

Årlig balanse ble negativ for alle sju referansebreene, og Ålfotbreen og Storbreen hadde størst underskudd, begge med −1,7 m v.ekv. Hansebreen, som er nabobreen til Ålfotbreen, hadde det største underskuddet av alle de målte breene i Norge med −2,3 m v.ekv.

Lengdeendringer

Lengdeendringer ble målt på 26 breer i Sør-Norge og 10 breer i Nord-Norge. Trettifire av de 36 målte breutløperne hadde tilbakegang. Størst tilbakegang ble målt på Austerdalsbreen på sørsiden av Jostedalsbreen (130 m), på Gråfjellsbrea ved Folgefonna (66 m) og på Austre Okstindbreen i Nordland (59 m).

1. Glacier investigations in Norway 2021

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.

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

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

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

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

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

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

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

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

Stratigraphic 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.

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

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

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

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

Method

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

Winter balance

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

Summer and annual balance

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

Figure 1-1
Snow density measurement at Storbreen on 27th April 2021. Photo: Liss M. Andreassen.

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 is 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 2021 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 59 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 73 years of measurements, while Engabreen at Svartisen has the longest series (52 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 30-year reference period (1991-2020) is defined and the balance values for 2021 are compared with the average of the reference period. A comprehensive review of the glacier mass balance and length measurements in Norway is given in Andreassen et al. (2020).

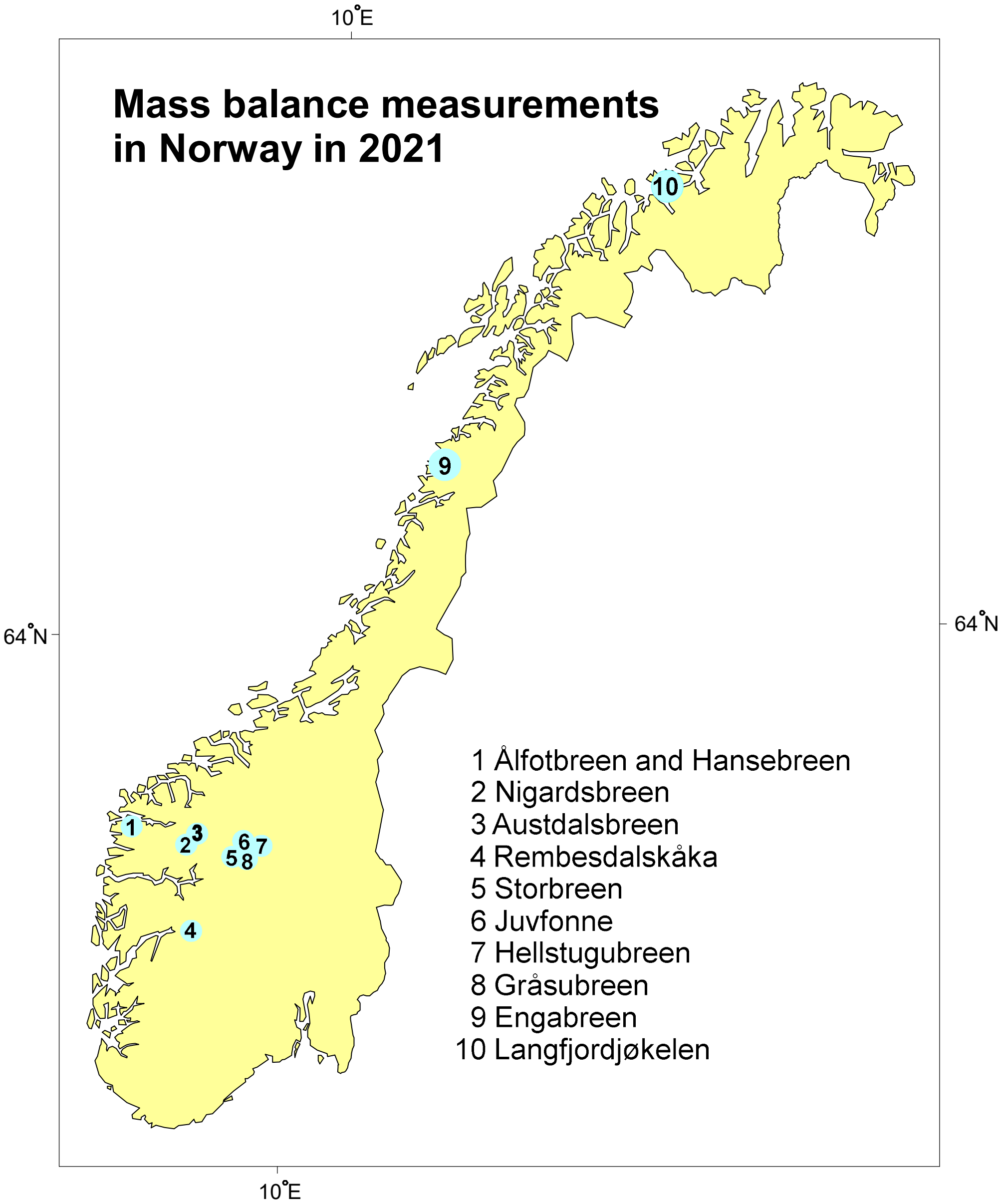


Figure 1-2
Location of the glaciers at which mass balance studies were performed in 2021.

Mass balance studies performed on Norwegian glaciers in 2021 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 2020/21 started with mild and dry weather in October. The mild weather continued in November and December all over the country. The following two winter months, January and February however, were cold all over the country. February and March were snow-rich in northern Norway and quite normal in southern Norway.

Snow accumulation and winter balance

The winter balance was lower than the 1991-2020 average for five of the seven reference glaciers (continuous mass balance series back to at least 1991). Hellstugubreen in Jotunheimen and Engabreen in northern Norway had greater winter balance with 105 and 106 % of the reference period average. Rembesdalskåka had the lowest relative winter balance with 84 % of the 1991-2020 average.

Summer weather

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

Ablation and summer balance

The summer balance was greater than the 1991-2020 average for all seven reference glaciers. The three measured glaciers in Jotunheimen had the greatest relative summer balances with 161 % (Gråsubreen), 151 % (Storbreen) and 140 % (Hellstugubreen) of the reference period averages.

Annual balance

The annual balance was negative for all seven reference glaciers, and of these seven, Ålfotbreen and Storbreen had the greatest deficits, both with −1.7 m w.e. Hansebreen, the adjacent glacier to Ålfotbreen, had the greatest deficit of all measured glaciers in Norway with −2.3 m w.e.

The results from the mass balance measurements in Norway in 2021 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 1991-2020. The annual balance results are compared with the mean annual balance in the same way. ELA is the equilibrium line altitude (m a.s.l.) and AAR is the accumulation area ratio (%).

Circulation patterns AO and NAO

Norway's climate is strongly influenced by large-scale circulation patterns and westerly winds are dominant. Much of the variation in weather from year to year, in particular the winter precipitation, may be attributed to variations in circulation and wind patterns in the North Atlantic Ocean. Indices such as the North Atlantic Oscillation (NAO) and the Arctic Oscillation (AO) are used to describe the variation in the pressure gradients in the northern latitudes, and the resulting effects on temperature and storm tracks. When the NAO or AO is positive, the coast of Norway experiences warm and wet winters resulting in high winter precipitation on the glaciers. When the NAO or AO is negative, the winters are colder and drier with less precipitation on the glaciers

(Hanssen-Bauer and Førland, 1998; Nesje et al., 2000). Although NAO is more commonly used, winter and annual balance of the northernmost glaciers, Langfjordjøkelen and Engabreen, are better correlated with AO than NAO (Andreassen et al., 2020). For the glaciers in southern Norway, the correlations are similar for NAO and AO, and reduced with distance to the coast (Rasmussen, 2007; Andreassen et al., 2020).

In winter 2020/2021 (December-March) NAO and AO indexes were negative in December and January (NAO) and December, January and February (AO). The NAO and AO mean was −0.14 and −0.83 respectively for December-March calculated from the monthly means, source: http://www.cpc.ncep.noaa.gov/). Over the period 1989-2021 the most positive NAO and AO years were in the period with mass surplus from 1989 to 1995 and also in several recent years, in particular 2012, 2014 and 2015 (Fig. 1-3).

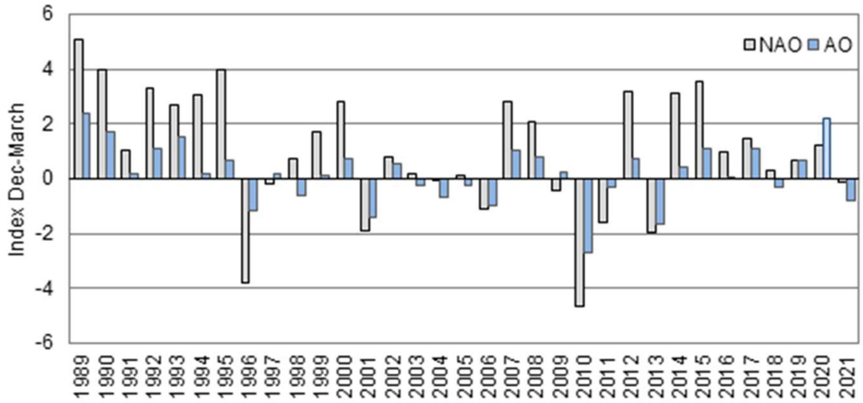


Figure 1-3
NAO and AO index for December–March for 1989–2021. NAO and AO data were downloaded from the NOAA Center for Weather and Climate Prediction (http://www.cpc.ncep.noaa.gov/). Figure updated and modified from Andreassen et al. (2020). The large-scale circulation indices NAO and AO are in units 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 2021. 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 1991-2020.

Glacier	*Period*	*Area* *(km²)*	*Altitude* *(m a.s.l.)*	*B_w* *(m)*	*% of ref.*	*B_s* *(m)*	*% of ref.*	*B_a* *(m)*	*B_a ref.*	*ELA* *(m a.s.l.)*	*AAR* *(%)*
Ålfotbreen	1963-21	3.5	1000-1360	3.16	87	−4.87	120	−1.71	−0.42	>1360	0
Hansebreen	1986-21	2.5	927-1303	2.92	84	−5.26	128	−2.33	−0.66	>1303	0
Nigardsbreen	1962-21	44.9	389-1955	1.93	85	−2.49	108	−0.57	−0.05	1645	46
Austdalsbreen	1988-21	10.1	1200-1740	1.61	76	[1]−3.31	123	−1.70	−0.60	>1740	0
Rembesdalskåka	1963-21	17.1	1085-1851	1.76	84	−3.24	135	−1.48	−0.29	>1851	0
Storbreen	1949-21	4.9	1420-2091	1.37	98	−3.04	151	−1.67	−0.62	2015	2
Juvfonne[2]	2010-21	0.1	1852-1985	1.49		−2.71		−1.22			
Hellstugubreen	1962-21	2.7	1482-2229	1.10	105	−2.37	140	−1.26	−0.64	2155	1
Gråsubreen	1962-21	1.7	1854-2277	0.61	87	−2.15	161	−1.54	−0.63	>2277	0
Engabreen	1970-21	36.0	177-1532	2.88	106	−3.40	123	−0.52	−0.06	1236	46
Langfjordjøkelen	1989-93 1996-21	3.7 2.6	280-1050 338-1043	2.20	[3]106	−2.40	[3]80	−0.20	−0.13 [3]−0.91	780	65

[1])Contribution from calving amounts to −0.17 m for B_s
[2])Calculated for a point only, b_w, b_s and b_a
[3])Calculated for the measured periods 1989-93 and 1996-2020

Figure 1-4 presents the mass balance results in southern Norway for 2021. The west-east gradient is evident for both winter and summer balances. The results for 2021 show a negative mass balance for all eight measured glaciers in southern Norway.

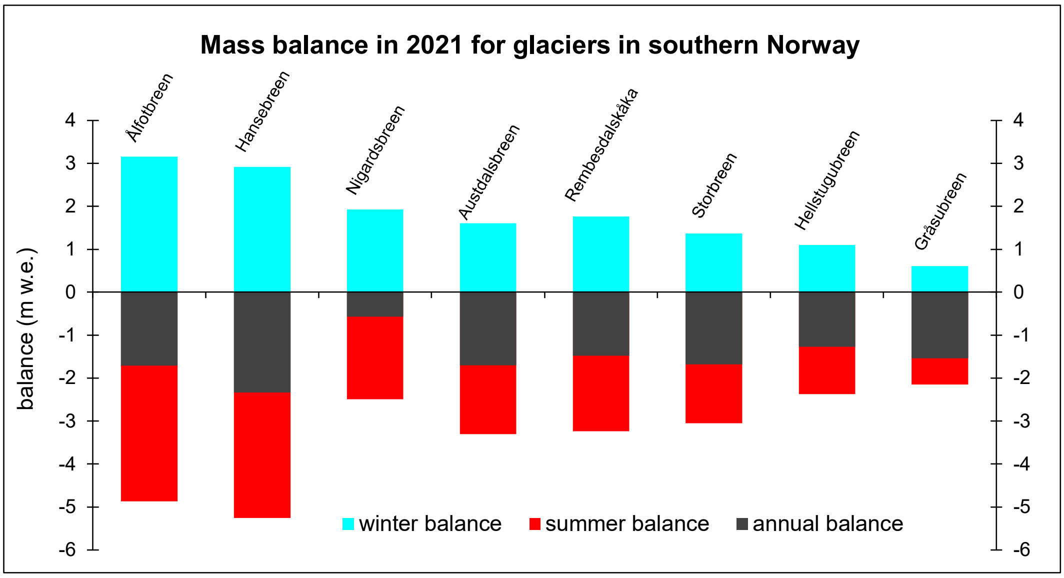


Figure 1-4
Mass balance in 2021 in southern Norway. The glaciers are listed from west to east.

The cumulative annual balance for the six reference glaciers in southern Norway for the period 1963-2021 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 1963-2021.

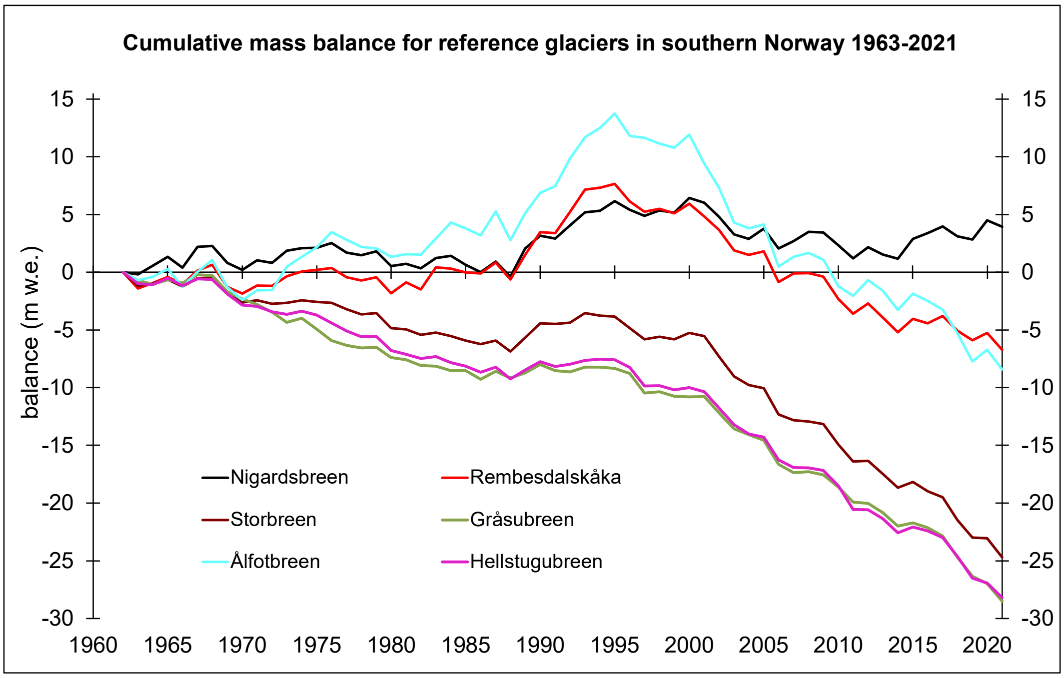


Figure 1-5
Cumulative mass balance for the six reference glaciers in southern Norway, Ålfotbreen, Nigardsbreen, Rembesdalskåka, Storbreen, Hellstugubreen and Gråsubreen, for the period 1963-2021.

1.2 Homogenisation and revision of mass balance series

Whereas the glaciological method measures the surface mass balance, the geodetic method measures the sum of surface, internal and basal mass balances. In order to make a direct comparison of glaciological and geodetic balances, the methodological differences, such as differences in survey dates (accounts for ablation or accumulation between the survey dates) and surveyed areas (using the same area and ice divides in both methods) must be considered. In addition, the effects of changes in density profiles between the geodetic surveys must be accounted for.

A joint paper from the workshop on “Measurement and Uncertainty Assessment of Glacier Mass Balance” at the Tarfala Research Station in northern Sweden in 2012 describes a standard procedure for reanalysing mass balance series (Zemp et al., 2013), based on best practices. It recommended that mass balance series longer than 20 years should always be reanalysed.

Two new NVE reports give details on four glaciers analysed; Nigardsbreen (Kjøllmoen, 2022a), and Ålfotbreen and Hansebreen (Kjøllmoen, 2022b). The reanalysis included (i) homogenisation of both glaciological and geodetic observation series, (ii) uncertainty assessment and, (iii) estimates of generic differences including estimates of internal and basal melt, (iv) validation, and for some glaciers, (v) calibration of the mass balance series. In total, three periods of data were compared and the results show discrepancies between the glaciological and geodetic methods for some glaciers, which are attributed partly to internal and basal ablation and partly to inhomogeneity in the data processing.

Homogenised glaciological and geodetic results were in overall agreement for Ålfotbreen 2011-2019 and Hansebreen 2011-2019, but they differed for Nigardsbreen 2013-2020. The 2013-2020 period for Nigardsbreen were calibrated by applying an annual correction factor (the annual difference between the homogenised geodetic and glaciological mass balance) to the summer and winter balances according to their relative size.

The reanalysis processes have revised seasonal, annual, and cumulative values as well as ELA and AAR values for the four glaciers. The mass balance series are categorised as ‘original’ (as published in ‘Glasiologiske undersøkelser i Norge/Glaciological investigations in Norway), ‘homogenised’ (for selected or all years) or ‘calibrated’ (periods are calibrated with geodetic observations) in the NVE databases. The new reanalysed and thus “official” values are available for download from NVE’s website: http://glacier.nve.no/viewer/CI/en/.

1.3 Other investigations

Glacier length change measurements were performed at 36 glaciers in Norway in 2021. 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 2021.

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

Some jøkulhlaups (glacier floods) have occurred in 2021 and these are described in chapter 12.

Ingenmannsland (No man's land) – an abbreviated version of a study of NVE's photographic documentation of Norwegian glacier measurements 1949-1979 is presented in chapter 13.

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.

Figure 2-1
Ålfotbreen (right) and Hansebreen (left) photographed on 28th August 2021. Photo: Hallgeir Elvehøy.

2.1 Mass balance 2021

Fieldwork

Snow accumulation measurements were performed on 28th April. The calculation of winter balance was based on 63 and 47 snow depth soundings on Ålfotbreen and Hansebreen, respectively, and on measurement of stakes in two different positions on Ålfotbreen and four different positions on Hansebreen (Fig. 2-2). Comparison of stake readings and snow soundings indicated no significant melting after the ablation measurements in October 2020. The sounding conditions were good over the whole glacier and the summer surface could easily be detected. Generally, the snow depth varied between 6 and 8 m on Ålfotbreen, and between 5 and 7 m on Hansebreen. Snow density was measured in one location (pos. 28, 1204 m a.s.l.), applicable for both glaciers. The mean snow density of 6.2 m snow was 469 kg m^{-3}. The measured mean snow density for the twenty- year period 2001-2020 was 520 kg m^{-3}.

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

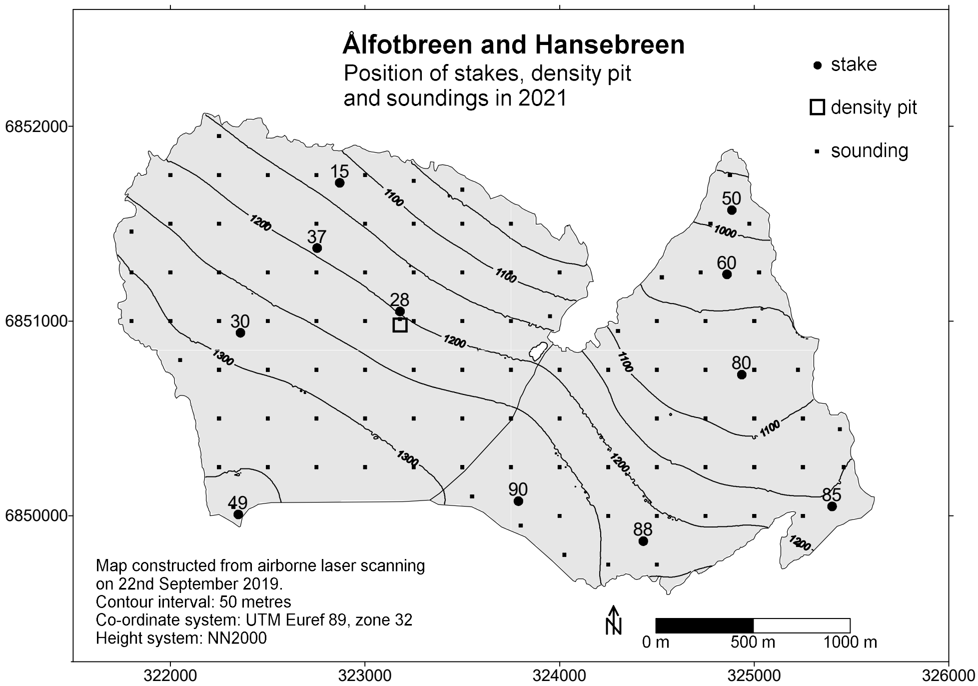


Figure 2-2
Location of stakes, soundings and snow pit on Ålfotbreen (left) and Hansebreen (right) in 2021.

Ablation was measured on 8th and 13th November. The annual balance was measured at stakes in five positions on Ålfotbreen and six positions on Hansebreen (Fig. 2-2). At the time of the ablation measurements between 40 and 75 cm fresh snow had fallen (Fig. 2-3).

Figure 2-3
At the time of ablation measurements on 13th November, 75 cm of fresh snow had fallen at stake position 49 on top of Ålfotbreen. Note the icy summer surface.

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 1050 m a.s.l. on Ålfotbreen are sparse.

The winter balance was calculated as a mean value for each 50-m height interval and was 3.2 ±0.2 m w.e. at Ålfotbreen, which is 87 % of the mean winter balance for the reference period 1991-2020. The winter balance on Hansebreen was calculated as 2.9

±0.2 m w.e., which is 84 % of the mean winter balance for the reference period 1991-2020. Spatial distribution of the winter balance at Ålfotbreen and Hansebreen is shown in Figure 2-4.

The density of melted firn was assumed to be 650 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, but there were no stake measurements below 1129 m a.s.l. Thus, stake values from the two lowest stakes at Hansebreen (○) were used to support the assessment of the summer balance curve in the lowermost part of Ålfotbreen (Fig. 2-5).

Based on estimated density and stake measurements the summer balance was also calculated as a mean value for each 50 m height interval and was −4.9 ±0.3 m w.e. on Ålfotbreen, which is 120 % of the reference period. The summer balance on Hansebreen was −5.3 ±0.3 m w.e., which is 128 % of the mean summer balance for the reference period 1991-2020.

Hence, the annual balance was negative for both glaciers. Ålfotbreen had a deficit of −1.7 ±0.4 m w.e. The mean annual balance for the reference period 1991-2020 is −0.42 m w.e.

The annual balance at Hansebreen was −2.3 ±0.4 m w.e. The mean value for the reference period 1991-2020 is −0.66 m w.e.

The mass balance results are shown in Table 2-1 and the corresponding curves for specific and volume balance are shown in Figure 2-5.

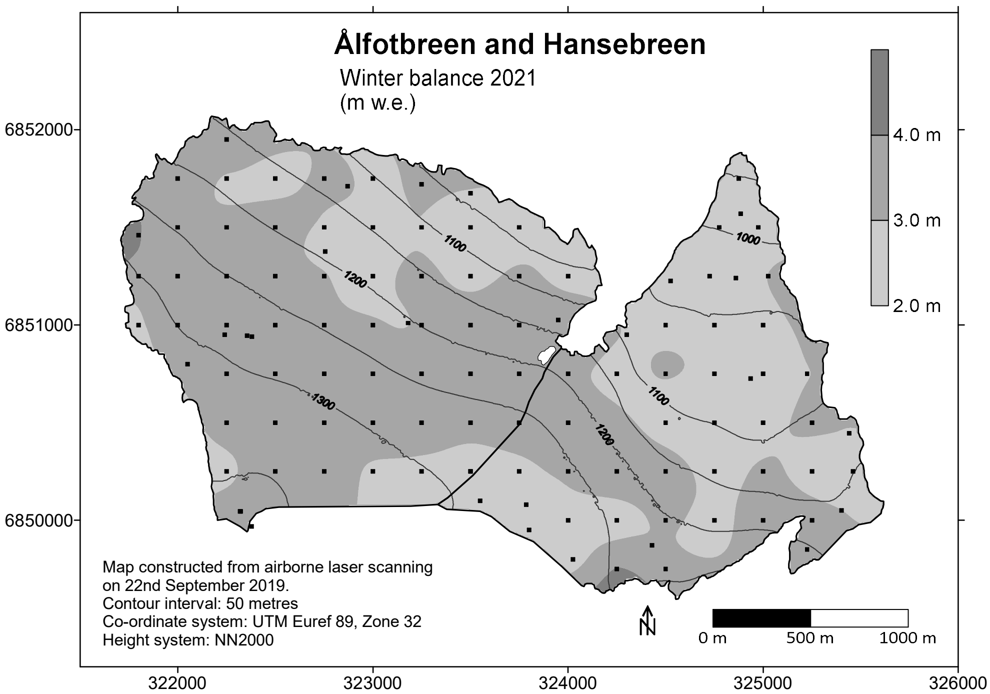


Figure 2-4
Spatial distribution of the winter balance on Ålfotbreen (left) and Hansebreen (right) in 2021.

According to Figure 2-4 the ELA lies above the highest point on both glaciers, and consequently the AAR is 0 %.

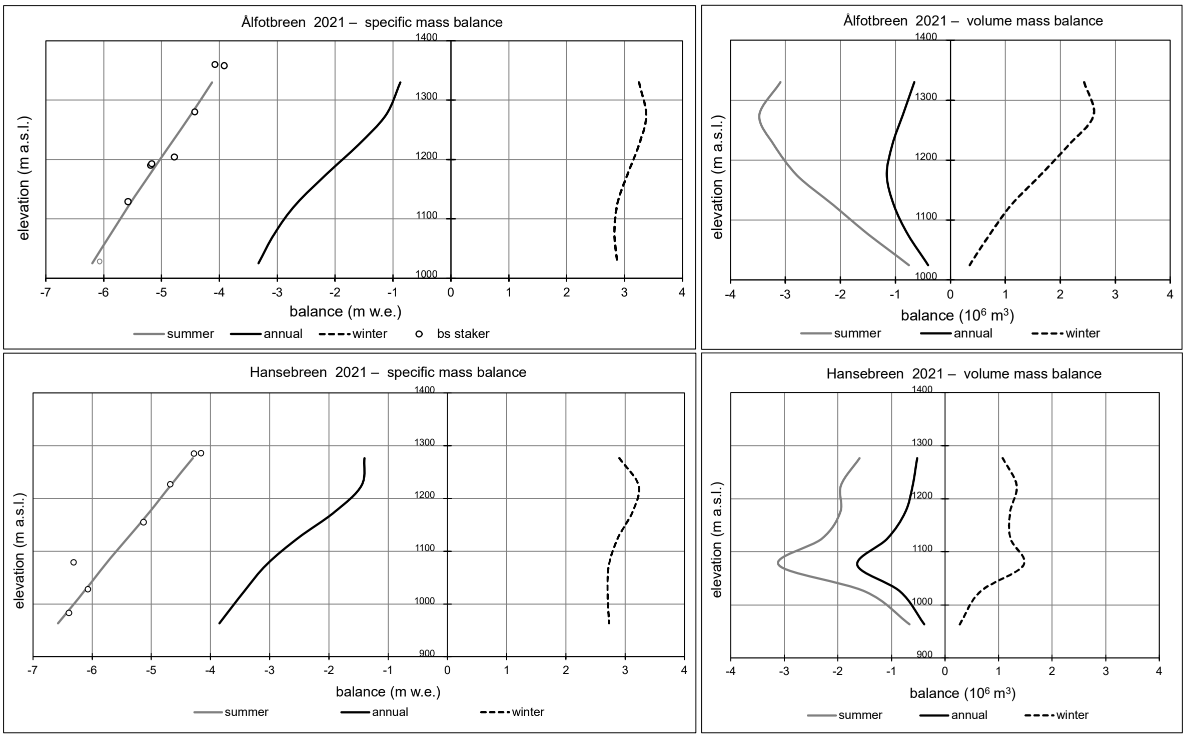


Figure 2-5
Mass balance diagram for Ålfotbreen (upper) and Hansebreen (lower) in 2021 showing altitudinal distribution of specific (left) and volumetric (right) winter, summer and annual balance. Specific summer balance at each stake is shown (○).

Table 2-1
Winter, summer and annual balance for Ålfotbreen (upper) and Hansebreen (lower) in 2021.

Mass balance Ålfotbreen 2020/21 – stratigraphic system

		Winter mass balance		Summer mass balance		Annual mass balance	
		Measured 28th Apr 2021		Measured 13th Nov 2021		Summer surface 2020 - 2021	
Altitude (m a.s.l.)	Area (km^2)	Specific (m w.e.)	Volume (10^6 m^3)	Specific (m w.e.)	Volume (10^6 m^3)	Specific (m w.e.)	Volume (10^6 m^3)
1300 - 1360	0.75	3.25	2.4	-4.13	-3.1	-0.88	-0.7
1250 - 1300	0.77	3.38	2.6	-4.50	-3.5	-1.13	-0.9
1200 - 1250	0.66	3.25	2.1	-4.85	-3.2	-1.60	-1.1
1150 - 1200	0.54	3.05	1.6	-5.20	-2.8	-2.15	-1.2
1100 - 1150	0.38	2.88	1.1	-5.55	-2.1	-2.68	-1.0
1050 - 1100	0.25	2.83	0.7	-5.88	-1.5	-3.05	-0.8
1000 - 1050	0.12	2.88	0.4	-6.20	-0.8	-3.33	-0.4
1000 - 1360	**3.48**	**3.162**	**11.0**	**-4.869**	**-16.9**	**-1.707**	**-5.9**

Mass balance Hansebreen 2020/21 – stratigraphic system

		Winter mass balance		Summer mass balance		Annual mass balance	
		Measured 28th Apr 2021		Measured 13th Nov 2021		Summer surface 2020 - 2021	
Altitude (m a.s.l.)	Area (km^2)	Specific (m w.e.)	Volume (10^6 m^3)	Specific (m w.e.)	Volume (10^6 m^3)	Specific (m w.e.)	Volume (10^6 m^3)
1250 - 1303	0.37	2.90	1.08	-4.30	-1.60	-1.40	-0.52
1200 - 1250	0.42	3.23	1.34	-4.68	-1.94	-1.45	-0.60
1150 - 1200	0.39	3.13	1.22	-5.03	-1.95	-1.90	-0.74
1100 - 1150	0.43	2.88	1.22	-5.40	-2.30	-2.53	-1.07
1050 - 1100	0.54	2.73	1.46	-5.78	-3.10	-3.05	-1.64
1000 - 1050	0.24	2.70	0.66	-6.13	-1.49	-3.43	-0.83
927 - 1000	0.10	2.73	0.28	-6.58	-0.66	-3.85	-0.39
927 - 1303	**2.48**	**2.921**	**7.2**	**-5.255**	**-13.0**	**-2.335**	**-5.8**

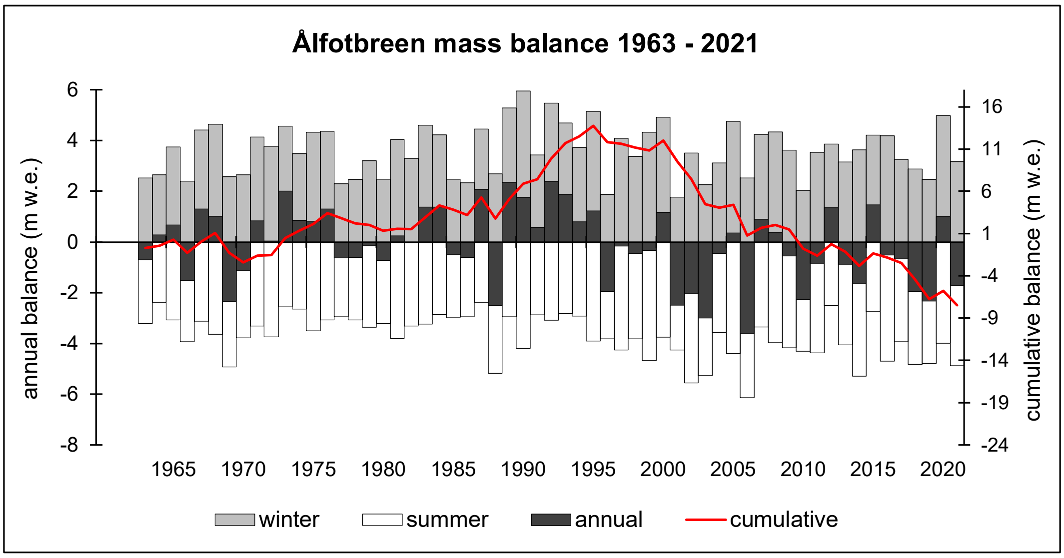
2.2 Mass balance 1963(86)-2021

The original mass balance series for Ålfotbreen and Hansebreen were reported previously in the series “Glaciological investigations in Norway (e.g. Kjøllmoen et al., 2020). Recently the mass balance series for the period 2011-2020 have been homogenized (Kjøllmoen, 2022b). The homogenization procedure is described in chapter 1.2. The period of homogenized data sets was compared with the corresponding geodetic mass balance and the results did not show significant discrepancies for the period 2011-2019 and hence, a calibration was not required for any of the glaciers.

In the reanalysis of Ålfotbreen and Hansebreen for 1998-2010 (Kjøllmoen, 2016b) the specified mapping date for 2010 was incorrect. The original given date was 2nd September, but the correct date was 29th September. The consequence of the corrected mapping date was that calibration for Hansebreen was not necessary and the calibration for Ålfotbreen was slightly changed compared with the reanalysis in Kjøllmoen (2016).

The mass balance series for Ålfotbreen (1963-2020) and Hansebreen (1986-2020) were updated with respect to the homogenisation 2011-2020 and to the consequence of the correction of mapping date in 2010.

After a year with surplus, the mass balance was negative again at both glaciers in 2021. The historical mass balance results for Ålfotbreen and Hansebreen are presented in Figure 2-6. The cumulative annual balance for Ålfotbreen for 1963-2021 is −7.5 m w.e., which gives a mean annual balance of −0.13 m w.e. a^{-1}. Over the last ten years (2012-2021), the mean annual balance was −0.59 m w.e. The cumulative annual balance for Hansebreen for 1986-2021 is −23.2 m w.e., which gives a mean annual balance of −0.64 m w.e. a^{-1}. Over the last ten years the mean annual balance was −1.20 m w.e.



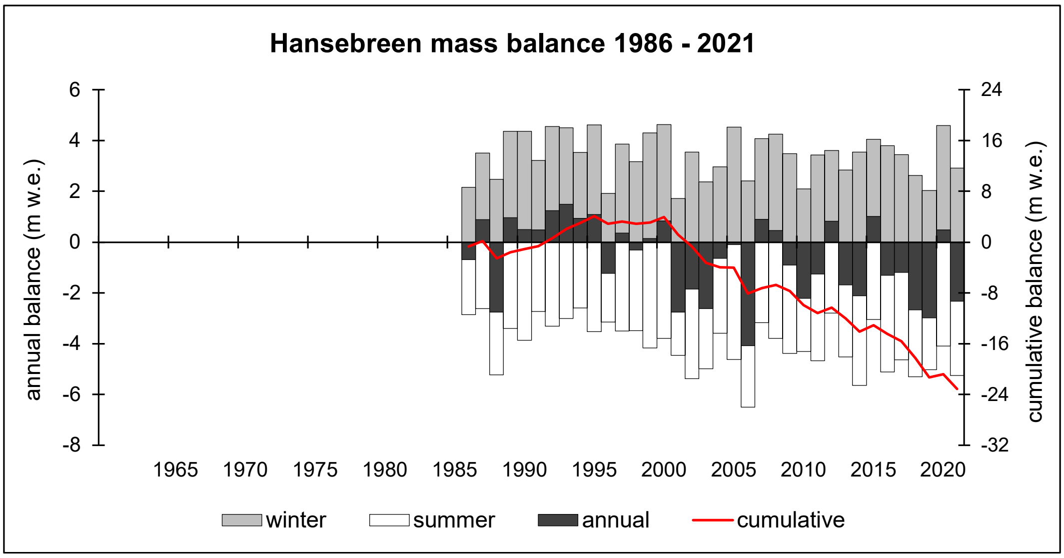


Figure 2-6
Mass balance at Ålfotbreen (upper) 1963-2021 and Hansebreen (lower) 1986-2021. Cumulative mass balance is given on the axis to the right.

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 2021 include mass balance and glacier length change. Nigardsbreen has been the subject of mass balance investigations since 1962.

3.1 Mass balance 2021

Fieldwork

Snow density was measured on 14th April 2021 while snow depths were measured on 29th and 30th April. The calculation of winter balance is based on measurements of eight stakes and towers (Fig. 3-1), and 123 snow depth soundings (Fig. 3-2). Comparison of sounded snow depth and stake reading at the lowest stake (589 m a.s.l.) indicated no melting after the ablation measurements in October 2020. Generally, the sounding conditions were good and the summer surface was detectable all over the glacier. The snow depth varied between 3.3 and 6.8 m on the plateau. On the glacier tongue, the snow depth was 3.1 m at stake position 1000 (954 m a.s.l.) and 1.2 m at stake position 600 (589 m a.s.l.). Snow density was measured at position T56 (1791 m a.s.l.), and the mean density of 5.5 m snow was 404 kg m^{-3}.

Figure 3-1
Measurement of the tower T56 on 29th April 2021. Photo: Jostein Aasen.

Ablation was measured on 14th September. Measurements were made at stakes and towers in ten locations (Fig. 3-2). In the accumulation area there was up to 1.2 m of snow remaining from winter 2020/21. At the time of measurement, no fresh snow had fallen.

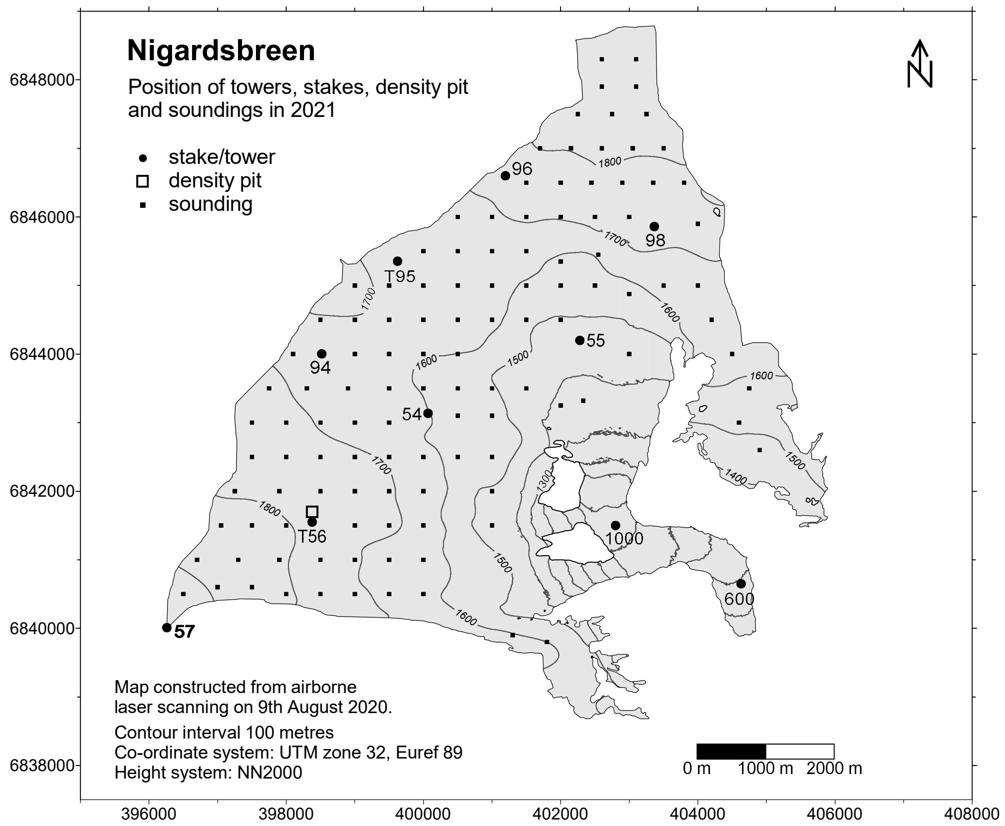


Figure 3-2
Location of towers, stakes, snow pit and soundings on Nigardsbreen in 2021.

Results

The calculations are based on the DTM from 2020.

The elevations above 1450 m a.s.l., which cover about 83 % of the catchment area, were well-represented with point measurements. Below this altitude the curve pattern was based on point measurements at 954 and 589 m elevation.

The winter balance was calculated as a mean value for each 100 m height interval and was 1.9 ±0.2 m w.e., which is 85 % of the mean winter balance for the reference period 1991-2020. Spatial distribution of the winter balance is shown in Figure 3-3.

The density of remaining snow was assumed to be 600 kg m^{-3}. The density of melted firn was assumed to be 650-700 kg m^{-3}, and the density of melted ice was set as 900 kg m^{-3}. Based on the estimated density and stake measurements the summer balance was also calculated as a mean value for each 100 m height interval and was −2.5 ±0.3 m w.e., which is 108 % of the reference period.

Hence, the annual balance was negative, at −0.57 m ±0.40 m w.e. The mean annual balance for the reference period 1991-2020 is −0.05 m w.e.

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

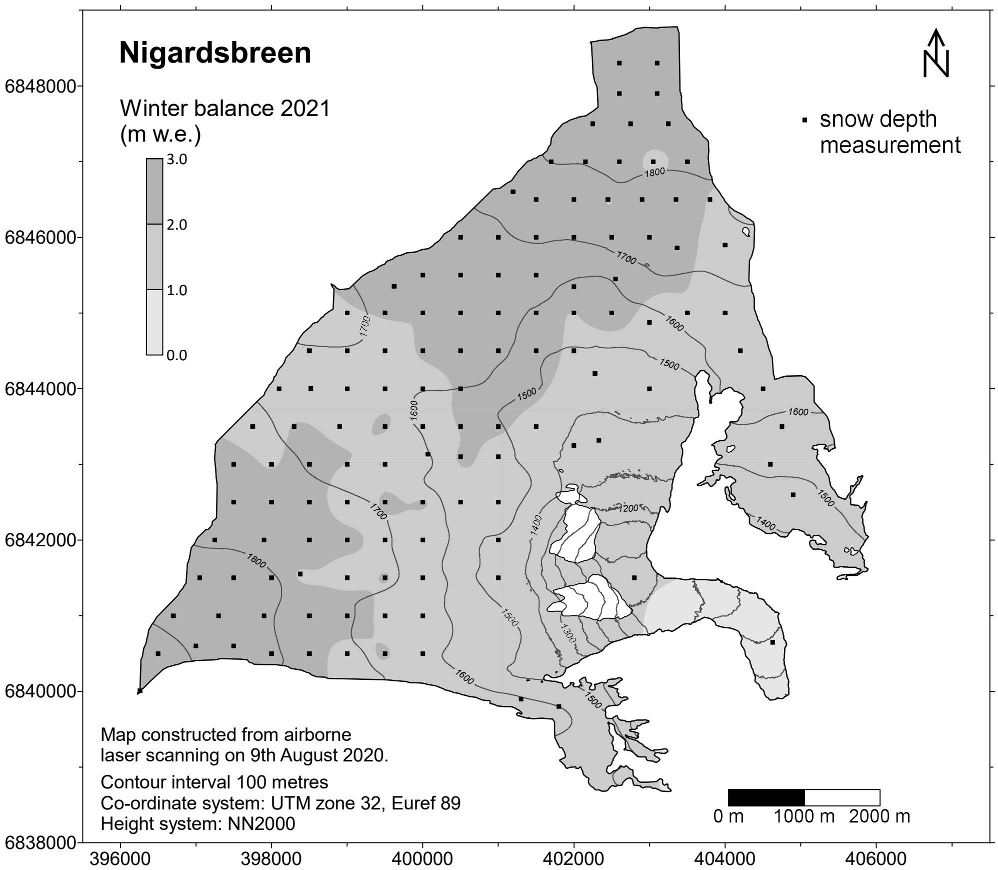


Figure 3-3
Spatial distribution of winter balance on Nigardsbreen in 2021.

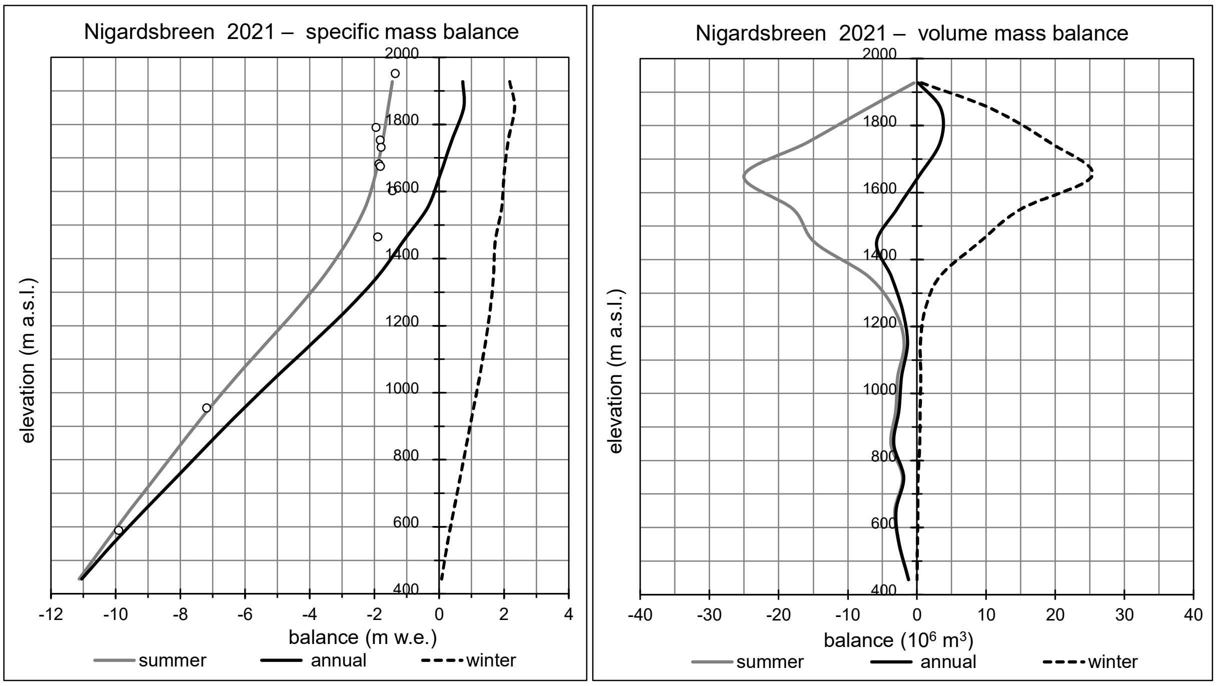


Figure 3-4
Mass balance diagram showing specific balance (left) and volume balance (right) for Nigardsbreen in 2021. Specific summer balance at 11 different stake positions is shown as circles (○).

According to Figure 3-4, the equilibrium line altitude was 1645 m a.s.l. Consequently the accumulation area ratio was 46 %.

Table 3-1
The altitudinal distribution of winter, summer and annual balance in 100-m intervals for Nigardsbreen in 2021.

Mass balance Nigardsbreen 2020/21 – stratigraphic system

		Winter mass balance Measured 29th April 2021		Summer mass balance Measured 14th Oct 2021		Annual mass balance Summer surface 2020 - 2021	
Altitude (m a.s.l.)	Area (km^2)	Specific (m w.e.)	Volume (10^6 m^3)	Specific (m w.e.)	Volume (10^6 m^3)	Specific (m w.e.)	Volume (10^6 m^3)
1900 - 1955	0.30	2.18	0.6	-1.45	-0.4	0.73	0.2
1800 - 1900	4.64	2.33	10.8	-1.58	-7.3	0.75	3.5
1700 - 1800	9.02	2.13	19.2	-1.75	-15.8	0.38	3.4
1600 - 1700	12.67	2.00	25.3	-1.98	-25.0	0.02	0.3
1500 - 1600	7.78	1.93	15.0	-2.30	-17.9	-0.38	-2.9
1400 - 1500	5.18	1.73	8.9	-2.85	-14.8	-1.13	-5.8
1300 - 1400	1.99	1.68	3.3	-3.55	-7.1	-1.88	-3.7
1200 - 1300	0.74	1.58	1.2	-4.40	-3.3	-2.83	-2.1
1100 - 1200	0.35	1.43	0.5	-5.33	-1.9	-3.90	-1.4
1000 - 1100	0.44	1.25	0.6	-6.25	-2.8	-5.00	-2.2
900 - 1000	0.43	1.05	0.5	-7.13	-3.1	-6.08	-2.6
800 - 900	0.47	0.85	0.4	-7.95	-3.8	-7.10	-3.4
700 - 800	0.24	0.65	0.2	-8.75	-2.1	-8.10	-1.9
600 - 700	0.33	0.45	0.2	-9.55	-3.2	-9.10	-3.0
500 - 600	0.25	0.25	0.1	-10.33	-2.6	-10.08	-2.5
389 - 500	0.11	0.08	0.0	-11.13	-1.2	-11.05	-1.2
389 - 1955	**44.95**	**1.927**	**86.6**	**-2.494**	**-112.1**	**-0.566**	**-25.4**

3.2 Mass balance 1962-2021

The mass balance series for Nigardsbreen has been reported in the series “Glaciological investigations in Norway” (e.g. Kjøllmoen et al., 2020). Subsequently the mass balance series for the period 2014-2020 has been homogenized and calibrated (Kjøllmoen, 2022a). The homogenization and calibration procedures are described in chapter 1.2. The period of the homogenized data set was compared with the corresponding geodetic mass balance. The results showed a significant discrepancy and hence, a calibration was required.

The mass balance series for Nigardsbreen was updated with respect to the homogenization and calibration for the period 2014-2020.

The historical mass balance results for Nigardsbreen 1962-2021 are presented in Figure 3-5. The cumulative annual balance for 1962-2021 is +3.5 m w.e., which gives a mean annual balance of +0.06 m w.e. a^{-1}. Over the past ten years (2012-2021), the mean annual balance was +0.005 m w.e.

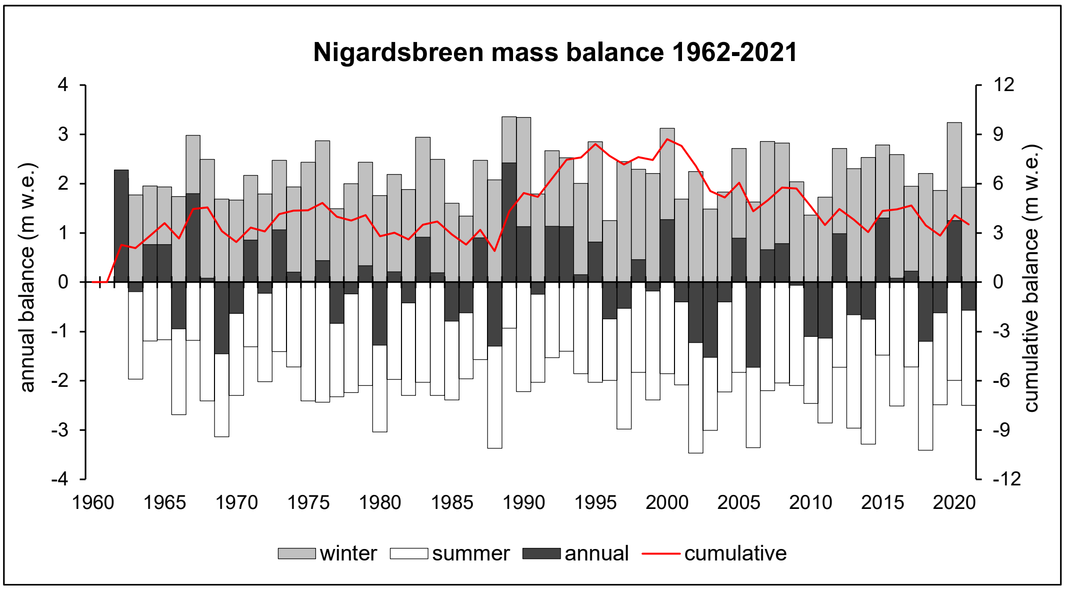


Figure 3-5
Winter, summer and annual balance at Nigardsbreen for 1962-2021. Cumulative mass balance is given on the right axis.

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 2021 included mass balance, front position change and glacier velocity. The mass balance has been measured at Austdalsbreen since 1988.

Figure 4-1
The firn line close to stake A60 on Austdalsbreen on 28th September 2021 seen from stake A80 (see fig. 4-2 for location). All the 2019/2020 winter snow had melted. Photo: Jostein Aasen.

4.1 Mass balance 2021

Fieldwork

Stakes were maintained through the winter in all the stake locations except stake A80 (1715 m a.s.l.). Snow accumulation measurements were performed on 16th April. The calculation of the winter balance was based on measurements in eight stake locations and 37 snow depth sounding locations (Fig. 4-4). Detecting the summer surface was fairly easy. The snow depth varied between 1.5 and 4.8 metres, and the average snow depth was 3.8 metres. The mean density of 4.1 m snow at stake A60 (1480 m a.s.l.) was 397 kg m^{-3}.

The stake network was measured on 27th August. Between 4.3 and 6.1 metres of snow and ice had melted since 16th April. All the winter snow had melted at the stake locations.

Summer and annual balance measurements were carried out on 28th September. Stakes were found in all the seven stake locations. Close to the glacier terminus 3 to 5 metres of ice had melted. Above 1400 m a.s.l. up to 1.5 metres of firn from 2019/2020 had melted.

The stakes were re-measured on 10th December showing up to 0.3 metres of additional melting after 28th September in all stake locations.

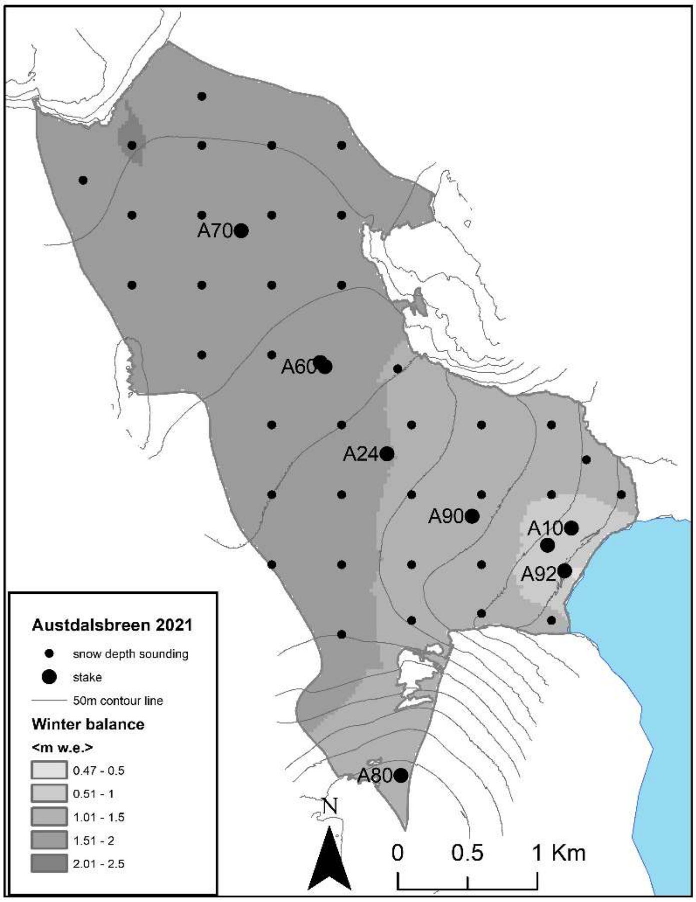


Figure 4-2
Location of stakes and snow depth soundings, and winter balance for Austdalsbreen in 2021 interpolated from 45 water equivalent values calculated from snow depth measurements.

Results

The calculations are based on a DTM from 27th August 2019. The winter balance was calculated from snow depth and snow density measurements on 16th 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 16 ±2 mill. m^3 water or 1.6 ±0.2 m w.e., which is 75 % of the 1991-2020 average (2.10 m w.e.). In addition, the spatial distribution of the winter balance was interpolated from the point measurements using the Inverse Distance Weighting (IDW) method. The mean distributed winter balance was 1.57 m w.e (Fig. 4-4).

The summer balance was calculated for seven stake locations between 1280 and 1715 m a.s.l. The density of firn from 2019/20 and melted ice at stakes above 1400 m a.sl. was set as 650 and 850 kg/m^3, respectively. The summer balance curve was drawn from these seven 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 (chapter 4.2 and 4.3). The calving 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 (30 ±10 m a^{-1}), u_f is front position change averaged across the terminus (−25 ±5 m a^{-1}), W is terminus width (865 ±20 m) and H is mean ice thickness at the terminus (40 ±5 m). The mean ice thickness was calculated from mean surface elevations along the calving terminus surveyed on 13th October 2020 and 28th September 2021, and mean bottom elevation along the terminuses calculated from a bathymetry map (Kjøllmoen and others, 2020). The resulting calving volume was 1.7 ±0.8 mill. m^3 water equivalent. The summer balance including calving was calculated as −34 ±3 mill. m^3 of water, which corresponds to −3.4 ±0.3 m w.e. The result is 124 % of the 1991-2021 average (−2.70 m w.e.). The calving volume was 5 % of the summer balance.

The annual balance at Austdalsbreen was calculated as −18 ±3 mill. m^3 water, corresponding to −1.8 ±0.3 m w.e. The average annual balance for the period 1991-2020 is −0.60 m w.e. The ELA in 2021 was above the top of the glacier at 1740 m a.s.l., and consequently the AAR was 0 %. The altitudinal distribution of winter, summer and annual balance is shown in Table 4-2 and Figure 4-5. Results from 1988-2021 are shown in Figure 4-6.

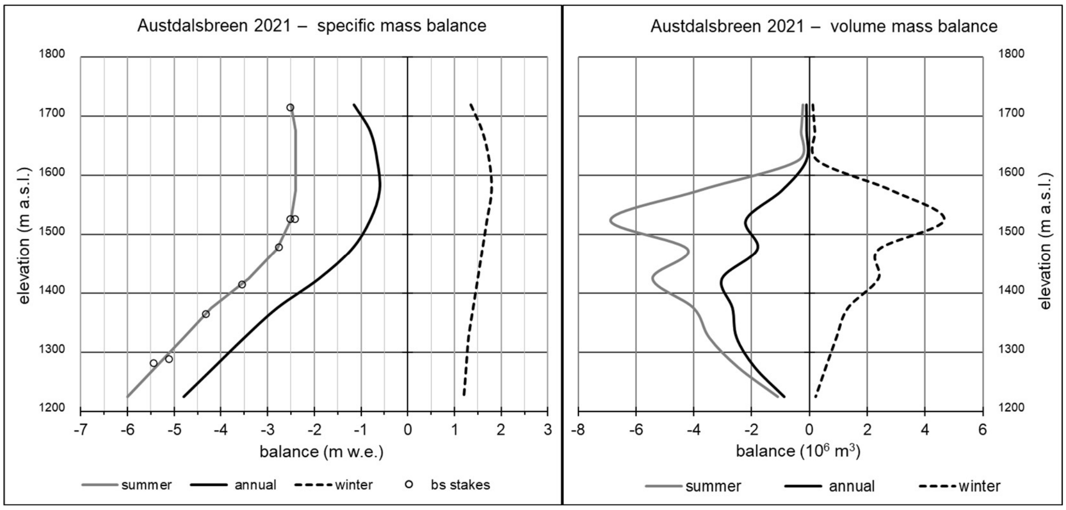


Figure 4-3
Altitudinal distribution of specific winter, summer and annual balance for Austdalsbreen in 2021. Specific summer balance at seven stake locations is shown (○).

Table 4-1
Altitudinal distribution of winter, summer, and annual balances for Austdalsbreen in 2021.

Mass balance Austdalsbreen 2020/21 – stratigraphic system

		Winter mass balance Measured 16th April 2021		Summer mass balance Measured 28th Sep 2021		Annual mass balance Summer surface 2020 - 2021	
Altitude (m a.s.l.)	Area (km^2)	Specific (m w.e.)	Volume (10^6 m^3)	Specific (m w.e.)	Volume (10^6 m^3)	Specific (m w.e.)	Volume (10^6 m^3)
1700 - 1740	0.090	1.35	0.1	-2.50	-0.2	-1.15	-0.1
1650 - 1700	0.119	1.60	0.2	-2.40	-0.3	-0.80	-0.1
1600 - 1650	0.172	1.75	0.3	-2.40	-0.4	-0.65	-0.1
1550 - 1600	1.584	1.80	2.9	-2.40	-3.8	-0.60	-1.0
1500 - 1550	2.748	1.70	4.7	-2.50	-6.9	-0.80	-2.2
1450 - 1500	1.503	1.60	2.4	-2.80	-4.2	-1.20	-1.8
1400 - 1450	1.594	1.50	2.4	-3.40	-5.4	-1.90	-3.0
1350 - 1400	0.952	1.40	1.3	-4.20	-4.0	-2.80	-2.7
1300 - 1350	0.721	1.30	0.9	-4.80	-3.5	-3.50	-2.5
1250 - 1300	0.457	1.25	0.6	-5.40	-2.5	-4.15	-1.9
1200 - 1250	0.182	1.20	0.2	-6.00	-1.1	-4.80	-0.9
Calving					-1.7		-1.7
1200 - 1740	**10.122**	**1.580**	**16.0**	**-3.355**	**-34.0**	**-1.775**	**-18.0**

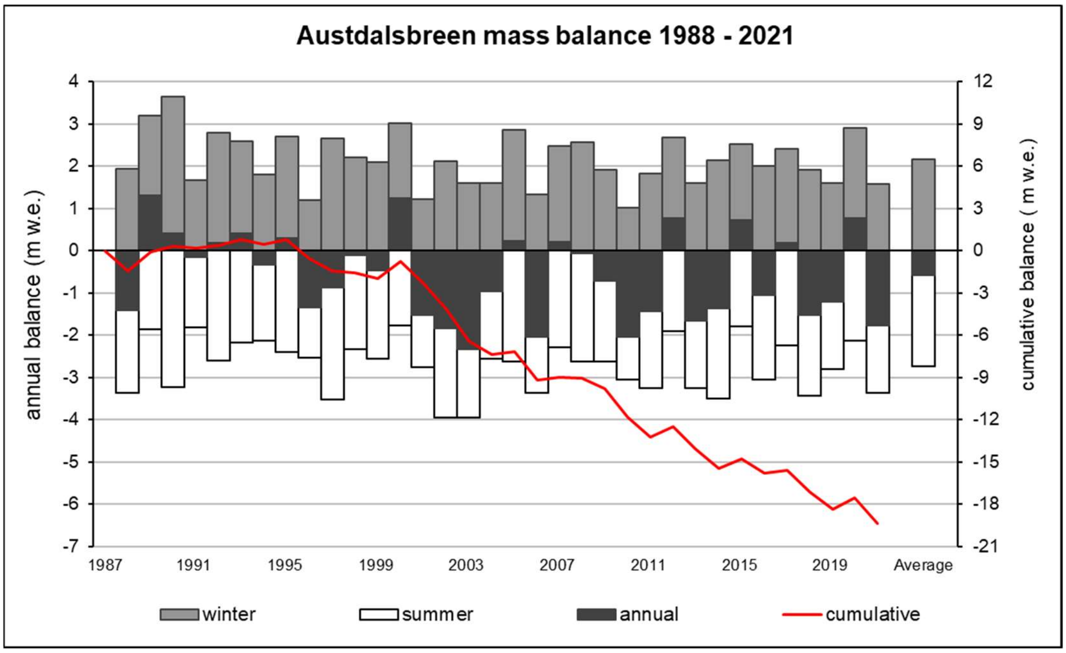


Figure 4-4
Winter, summer, annual and cumulative balance at Austdalsbreen during the period 1988-2021. Mean winter and summer balance is 2.16 and −2.73 m w.e., respectively. The cumulative mass balance is −19.4 m w.e.

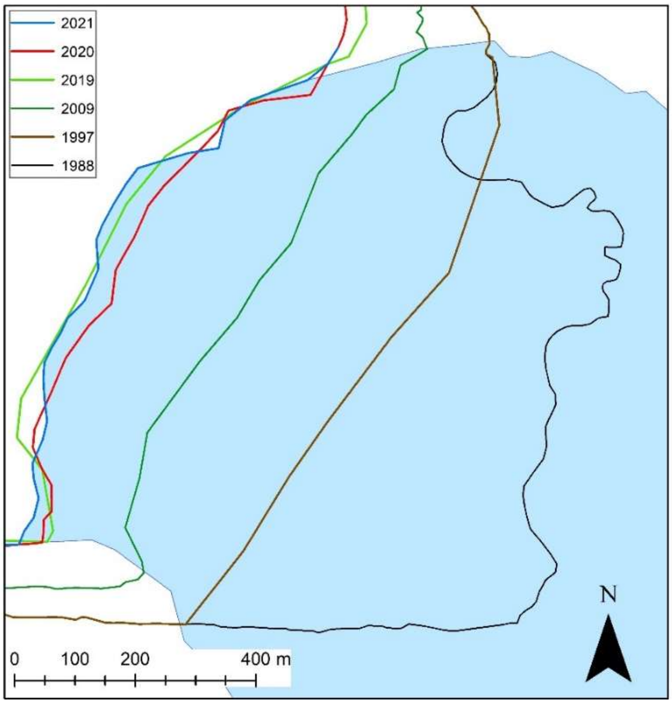


Figure 4-5
Surveyed front positions of Austdalsbreen in 1988 when the lake was regulated, and in 1997, 2009, 2019, 2020 and 2021. The glacier terminus retreated 25 metres between 13th October 2020 and 28th September 2021.

4-2 Front position change

Sentinel-2 satellite images from 13th and 28th September were used to determine the terminus position for 2021 (www.xgeo.no). The average front position change was −25 ±5 m between 13th October 2020 and 28th September 2021. Between 2019 and 2020 the glacier advanced 27 metres, and consequently the change between 2019 and 2021 is small (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 740 m, and the lake area has increased by 0.696 km^2.

4.3 Glacier dynamics

Glacier velocities are calculated from repeated surveys of stakes. The stake network was surveyed on 13th October 2020 and 17th April and 27th August 2021. Annual velocities were calculated for six stake locations between 1280 and 1525 m a.s.l. for the period 13th October 2020 – 28th September 2021 (318 days). The annual results were similar to results from 2011-15 (Kjøllmoen and others, 2016a).

The glacier velocity averaged across the front width and thickness was estimated to calculate the calving volume. The annual velocities at stake locations close to the terminus was 39 m a^{-1} at A10 and 47 m a^{-1} at A11. We assume the average of A10 and A11 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 2020/2021 is 30 ±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, 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 13th July 2021 (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 28th September 2021. Photo: Hallgeir Elvehøy.

5.1 Mass balance 2021

Fieldwork

Stakes were maintained through the winter in all stake locations but H7. The snow accumulation was measured on 28th May. Snow depth was measured in 62 sounding locations in a 500 by 500 m grid on the glacier plateau above 1500 m a.s.l. (Fig. 5-2). The average snow depth on the plateau was 3.5 meters and varied between 2.1 and 4.2 meters. The summer surface (S.S.) was well defined. The mean snow density down to the summer surface at 3.0 m depth at stake H7 was 522 kg m^{-3}.

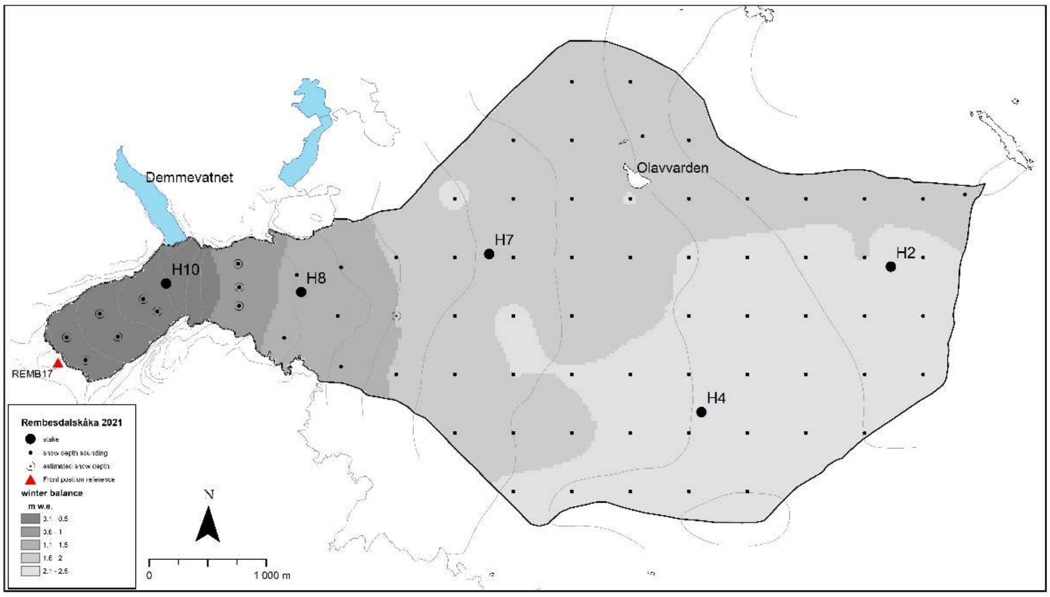


Figure 5-2
Winter balance at Rembesdalskåka in 2021 interpolated from five stake measurements of snow depth, 62 snow depth soundings, and one estimated point in the upper ice fall (1600 m a.s.l.).

Stake H10 melted out between 6th and 23rd June and was replaced on 10th September. Summer and annual balances were measured on 28th September. There were up to 0.2 m of new snow at the stake locations above 1700 m a.s.l. All the winter snow had melted. At H8 3.7 m of ice had melted. At stake H7 1.95 m of old firn had melted. At stakes H4 and H2 1.15 and 0.9 m of firn from 2019/20 had melted, respectively.

Results

The calculation of the mass balance is based on a DTM from 2020. The winter balance was calculated from the snow depth and snow density measurements on 28th May. A function correlating snow depth and water equivalent values was calculated based on snow density measurements at location H7 (1655 m a.s.l.). Point winter balance values were calculated from snow depth observations using this function. From the calculated water equivalent values, averages for 50 m elevation bands were calculated and plotted against altitude. An altitudinal winter balance curve was drawn from these averages (Fig. 5-3). Below 1500 m a.s.l. the winter balance curve was interpolated from the measurements at stakes H8 (1510 m a.s.l.) and H10 (1250 m a.s.l.). A value for each 50 m elevation was then determined from this curve. The resulting winter balance was 1.8 $\pm$0.2 m w.e. or 30 $\pm$3 mill. m^3 water. This is 84 % of the 1991-2020 average of 2.10 m w.e. a^{-1}.

Based on the snow depth measurements the spatial distribution of the winter balance was interpolated using the kriging method. Six winter balance points based on the specific winter balance curve were added in the ice fall and on the lower glacier tongue to support the interpolation below 1500 m a.s.l. The distributed winter balance is shown in Figure 5-2, and the mean winter balance was 1.76 m w.e.

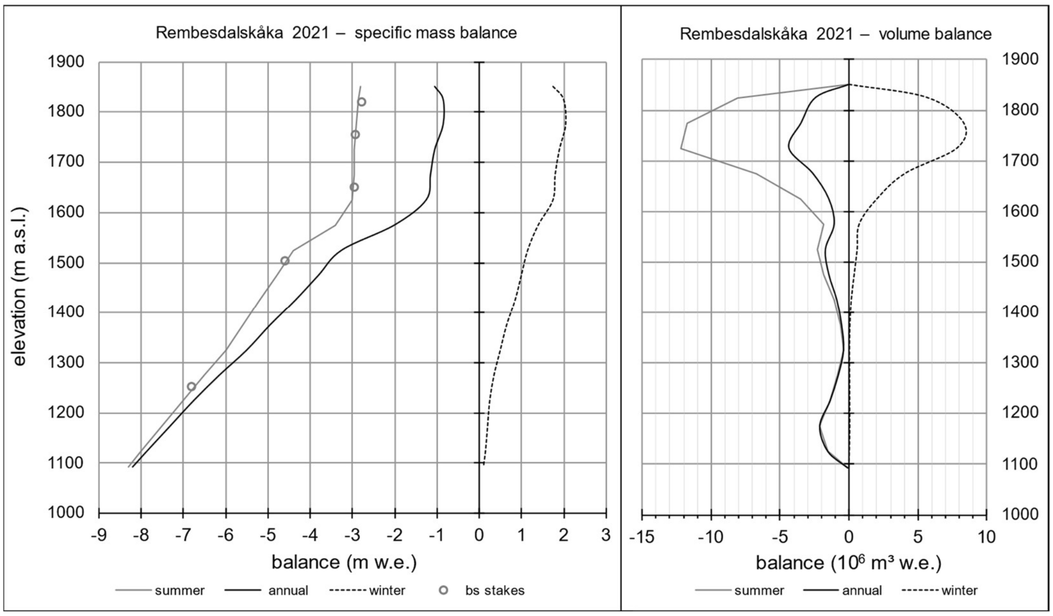


Figure 5-3
Altitudinal distribution of specific winter, summer and annual mass balance in 2021. Specific summer balance, b_s, at five stakes is shown (○).

Table 5-1
Altitudinal distribution of winter, summer and annual mass balance at Rembesdalskåka in 2021.

Mass balance Rembesdalskåka 2020/21 – stratigraphic system

		Winter mass balance Measured 28th May 2021		Summer mass balance Measured 28th Sep 2021		Annual mass balance Summer surface 2020 - 2021	
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)
1850 - 1851	0.002	1.75	0.0	-2.80	0.0	-1.05	0.0
1800 - 1850	2.823	2.00	5.6	-2.85	-8.0	-0.85	-2.4
1750 - 1800	4.059	2.05	8.3	-2.90	-11.8	-0.85	-3.5
1700 - 1750	4.130	1.90	7.8	-2.95	-12.2	-1.05	-4.3
1650 - 1700	2.267	1.80	4.1	-2.95	-6.7	-1.15	-2.6
1600 - 1650	1.167	1.75	2.0	-3.00	-3.5	-1.25	-1.5
1550 - 1600	0.534	1.40	0.7	-3.40	-1.8	-2.00	-1.1
1500 - 1550	0.523	1.15	0.6	-4.40	-2.3	-3.25	-1.7
1450 - 1500	0.381	1.00	0.4	-4.80	-1.8	-3.80	-1.4
1400 - 1450	0.201	0.85	0.2	-5.20	-1.0	-4.35	-0.9
1350 - 1400	0.107	0.65	0.1	-5.60	-0.6	-4.95	-0.5
1300 - 1350	0.071	0.50	0.0	-6.00	-0.4	-5.50	-0.4
1250 - 1300	0.126	0.35	0.0	-6.50	-0.8	-6.15	-0.8
1200 - 1250	0.202	0.25	0.1	-7.00	-1.4	-6.75	-1.4
1150 - 1200	0.289	0.20	0.1	-7.50	-2.2	-7.30	-2.1
1100 - 1150	0.194	0.15	0.0	-8.00	-1.6	-7.85	-1.5
1085 - 1100	0.010	0.10	0.0	-8.30	-0.1	-8.20	-0.1
1085 - 1851	**17.086**	**1.763**	**30.1**	**-3.292**	**-56.2**	**-1.529**	**-26.1**

The date of the 2021 mass balance minimum on the glacier plateau was assessed from the daily gridded data of temperature and new snow at 1200 m a.s.l. from www.senorge.no as 23rd September above 1700 m a.s.l, and 10th October between 1500 and 1700 m a.s.l. On the glacier tongue the melting probably persisted until 5th November. The additional ice melt at H10 and H8 after 28th September was modelled as 0.65 and 0.2 meters of ice, respectively, and is included in the summer balance. At H7 the melting after 28th September probably was negligible.

The summer balance was calculated directly at four stake locations. The ice melt at H10 between 6th June and 10th September was modelled with daily temperature 1200 m a.sl. from www.senorge.no using a positive degree-day factor. The resulting ice melt for this period was 6.2 metres of ice.

The density of the melted firn from 2019/2020 at H4 and H2 and older melted firn at H7 was set as 650 and 700 kg m^{-3}, respectively, and the density of melted ice at H8 and H10 was set as 900 kg m^{-3}. The summer balance curve in Figure 5-3 was drawn from the five point values. The summer balance was calculated as −3.2 ±0.2 m w.e., corresponding to −56 ±3 mill. m^3 of water. This is 135 % of the 1991-2020 average of −2.40 m w.e. a^{-1}. The annual balance at Rembesdalskåka was calculated as −1.5 ±0.3 m w.e. or −25 ±5 mill. m^3 water. The 1991-2020 average is −0.29 m w.e. a^{-1}. The ELA in 2021 was higher than the top of the glacier at 1851 m a.s.l., and consequently the AAR was 0 %. The altitudinal distribution of winter, summer and annual balances is shown in Figure 5-3 and Table 5-1. Results from 1963-2021 are shown in Figure 5-4. The cumulative annual balance is −6.8 m w.e. Since 1995 the glacier has had a mass deficit of −14.5 m w.e. or −0.58 m w.e. a^{-1}.

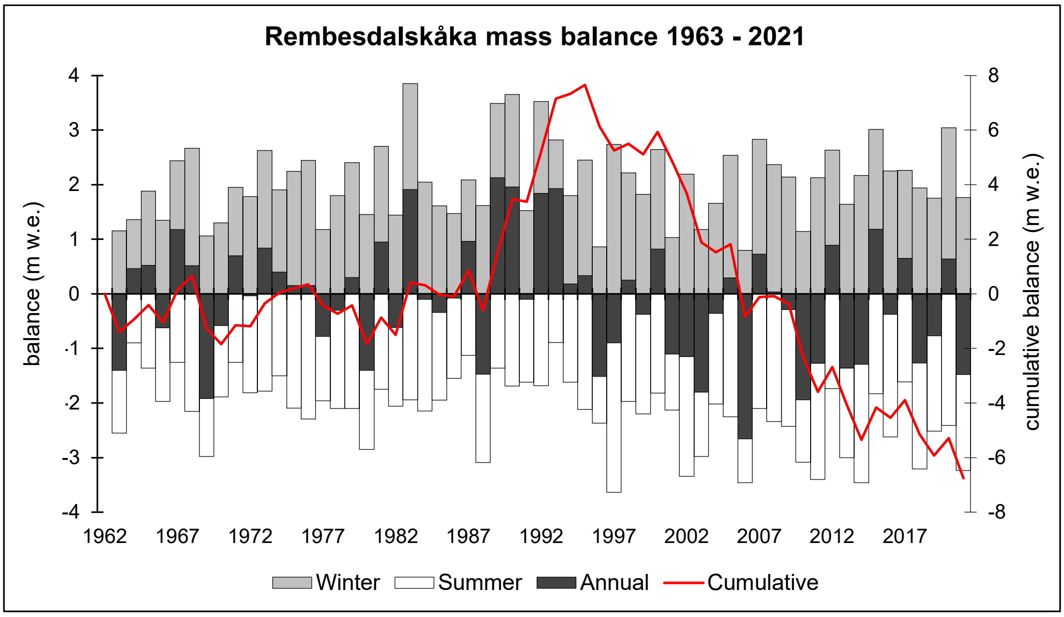


Figure 5-4
Winter, summer, annual and cumulative mass balance at Rembesdalskåka during the period 1963-2021. Mean values (1963-2021) are B_w=2.07 m w.e a^{-1} and B_s=−2.18 m w.e a^{-1}.

6. Storbreen (Liss M. Andreassen)

Storbreen (61°34′N, 8°8′E) (now written as "Storbrean" 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 km² 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 26th September 2021 at the ablation measurements. The glacier was partly covered in a thin layer of fresh snow. Photo: Jan T. Espedal, Aftenposten.

6.1 Mass balance 2020

Field work

Snow accumulation measurements were performed on 27th April. Stakes were visible in six positions. A total of 89 snow depth soundings between 1449 and 2005 m a.s.l. were made (Fig. 6-2). The snow depth varied between 2.28 and 4.15 m, the mean and median being 3.03 and 3.05 m respectively. Snow density was measured at stake 4 (1704 m a.s.l.) where the total snow depth was 2.9 m. The average snow density measured was 408 kg m^{-3}. Ablation measurements were performed on 18th September at all stake positions. Part of the terminus position was measured on 2nd September 2021 by differential GNSS (Fig. 6-2).

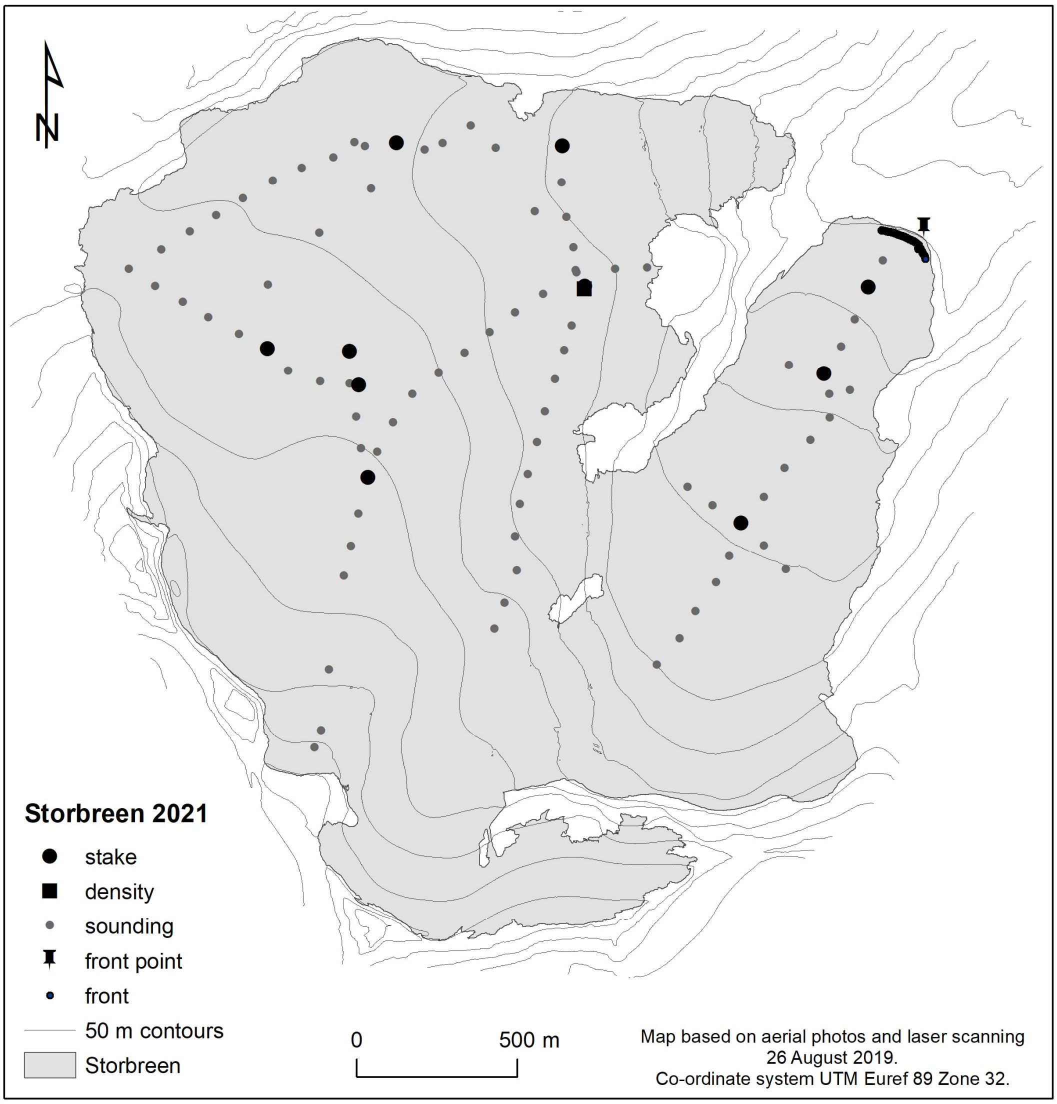


Figure 6-2
Location of stakes, soundings and density pits at Storbreen in 2021. Front: part of terminus measured by GNSS on 2nd September. Front point: reference points used for length change (glacier front) measurements (see chap. 12.1).

Results

The winter balance was calculated from the mean of the soundings within each 50 m height interval and was 1.37 ±0.2 m w.e., which is 98 % of the mean winter balance for the reference period 1991-2020. 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 –3.05 ±0.3 m w.e., which is 151 % of the mean summer balance for the reference period 1991-2020. The annual balance of Storbreen was –1.67 ±0.3 m w.e. in 2020. The ELA was above the highest stake in 2021 and is therefore uncertain. The annual balance curve from the annual balance diagram (Fig. 6-3) indicates an ELA of ~2015 m a.s.l. resulting in an estimated accumulation area ratio (AAR) of ~3 %.

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

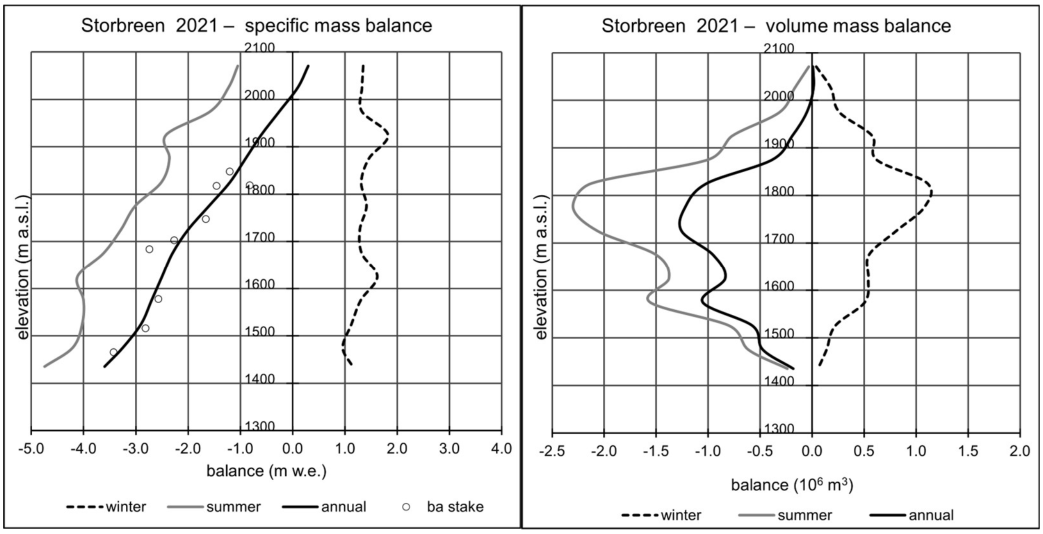


Figure 6-3
Mass balance versus altitude for Storbreen 2021, showing specific balance on the left and volume balance on the right. Annual balance at nine stakes is also shown.

Table 6-1
The distribution of winter, summer and annual balance in 50 m altitudinal intervals for Storbreen in 2021.

Mass balance Storbreen 2020/21

Altitude (m a.s.l.)	Area (km^2)	Winter balance Measured 27 April: Specific (m w.e.)	Winter balance Measured 27 April: Volume (10^6 m^3)	Summer balance Measured 26 Sep.: Specific (m w.e.)	Summer balance Measured 26 Sep.: Volume (10^6 m^3)	Annual balance 2020 - 2021: Specific (m w.e.)	Annual balance 2020 - 2021: Volume (10^6 m^3)
2050 - 2091	0.030	1.35	0.04	-1.05	-0.03	0.30	0.01
2000 - 2050	0.138	1.33	0.18	-1.23	-0.17	0.10	0.01
1950 - 2000	0.198	1.32	0.26	-1.57	-0.31	-0.25	-0.05
1900 - 1950	0.317	1.82	0.58	-2.42	-0.77	-0.60	-0.19
1850 - 1900	0.425	1.46	0.62	-2.36	-1.00	-0.90	-0.38
1800 - 1850	0.846	1.31	1.11	-2.51	-2.13	-1.20	-1.02
1750 - 1800	0.763	1.41	1.08	-3.01	-2.30	-1.60	-1.22
1700 - 1750	0.628	1.29	0.81	-3.29	-2.06	-2.00	-1.26
1650 - 1700	0.414	1.32	0.55	-3.62	-1.50	-2.30	-0.95
1600 - 1650	0.334	1.62	0.54	-4.12	-1.38	-2.50	-0.84
1550 - 1600	0.390	1.30	0.51	-4.00	-1.56	-2.70	-1.05
1500 - 1550	0.197	1.13	0.22	-4.03	-0.79	-2.90	-0.57
1450 - 1500	0.146	0.96	0.14	-4.21	-0.61	-3.25	-0.47
1420 - 1450	0.050	1.15	0.06	-4.75	-0.24	-3.60	-0.18
1420 - 2091	**4.876**	**1.37**	**6.70**	**-3.05**	**-14.85**	**-1.67**	**-8.16**

6.3 Mass balance 1949-2021

The cumulative balance for 1949-2021 is –30 m w.e. The mean annual balance for the period of 73 years is −0.41 m w.e. (Fig. 6-4). For the period 1949-2000 (52 years) the mean annual balance is −0.19 m w.e., whereas for the period 2001-2021 (21 years) the mean annual balance is −0.93 m w.e.

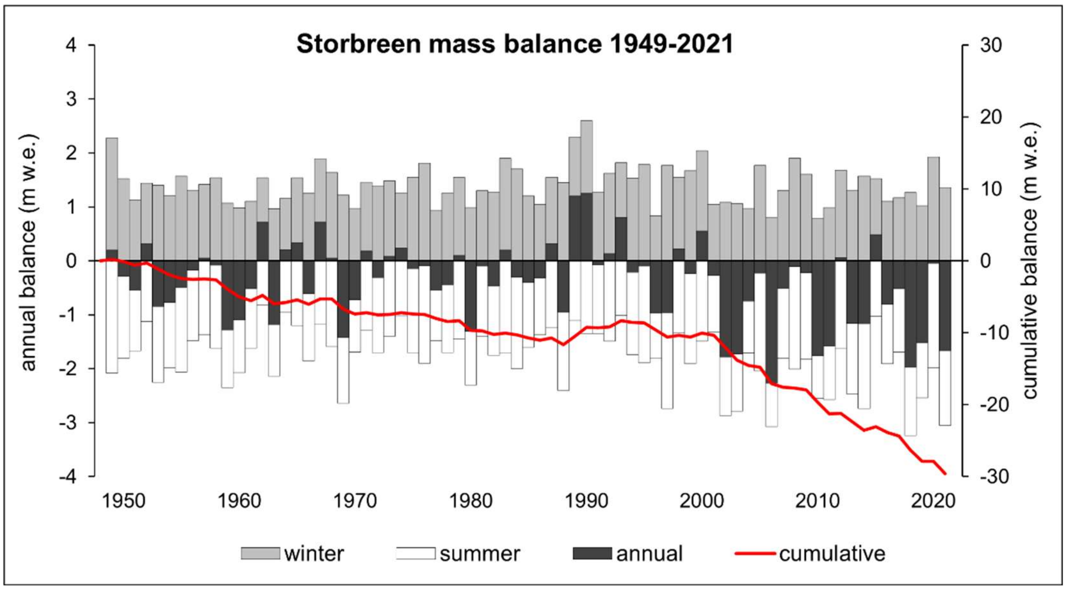


Figure 6-4
Winter, summer, annual and cumulative mass balance at Storbreen for the period 1949-2021.

Figure 6-5
A layer of fresh snow covered the glacier at the ablation measurements on 26th September 2021.
Photo: Jan T. Espedal, Aftenposten.

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 2021 consisted of accumulation measurements in spring, seasonal and annual balances measured in one stake position, front position and ice patch extent and drone survey (section 7.1).

Figure 7-1
Juvfonne on 28th September 2021. Part of the lower ice patch is covered in white fabric to protect the tunnel roof from melting. Most of the ice patch had bare ice exposed at the time of the ablation measurements.
Photo: Liss M. Andreassen.

7.1 Survey 2021

The extent of Juvfonne has been regularly measured since 2010 by digitising the outline by differential GNSS or handheld GPS by foot. Several outlines are available from digitising outlines from orthophotos taken by drone or by airplanes. In 2021 the ice patch was surveyed by drone and differential GNSS on 31st August (Fig. 7-2). In addition, part of the extent was measured by handheld GPS on 28th September revealing retreat of the margin compared to the 31st August survey, but the 2019 extent was smaller (Fig. 7-2). The glacier area from the 31st of August 2021 GNSS measurements was 0.100 km^2. The extent of Juvfonne grows and shrinks along the whole margin from year to year.

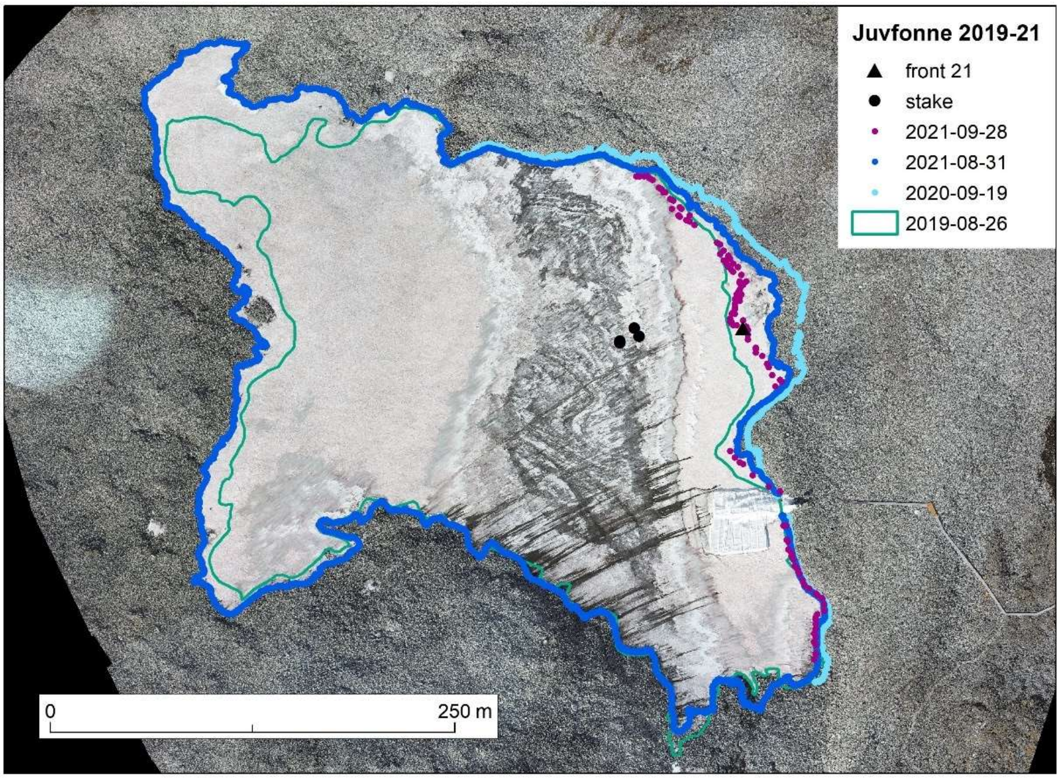


Figure 7-2
Variation of the ice extent of Juvfonne from 2019 to 2021. Background orthophoto of 31st August 2021 by NVE (Simon Oldani). The walking path to the ice patch and the fabric covered ice tunnel is visible in the photo. See also Fig. 7-1. The extent outlines are measured by orthophoto (2019) and differential GNSS and handheld GPS.

7.2 Mass balance 2021

Field work

The accumulation measurements on Juvfonne were carried out on 12th May (Fig. 7-3). Snow depth was measured in 32 positions from 1862 to 1956 m a.s.l. The snow varied between 1.1 and 3.4 m. 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 3.2 m. The resulting density was estimated to be 467 kg m^{-3}. Ablation measurements were carried out on 28th September at stake 2. Most of ice patch had bare ice exposed (Fig. 7-1).

Results

Seasonal surface mass balances have been measured since 2010 at stake 2 (Fig. 7-3). In 2021 the point winter balance was 1.49 ±0.15 m w.e., the point summer balance was −2.71 ±0.15 m w.e and the annual balance was −1.22 ±0.15 m w.e. at this location. The cumulative mass balance for stake 2 over the 12 years of measurements is −12.5 m w.e., or −1.04 m w.e. a^{-1} (Fig. 7-4). Glacier-wide mass balance was not calculated; this was calculated only for the first year of measurements in 2009/2010 when more stakes were measured.

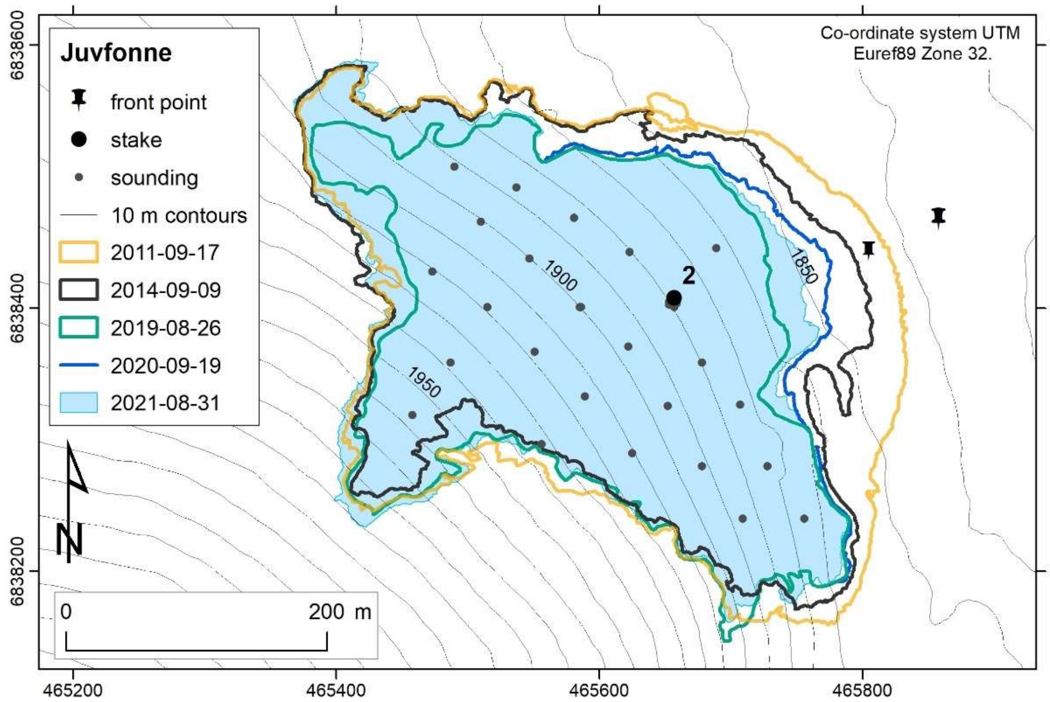


Figure 7-3
Location of snow depth soundings in 2021 and the position of stake 2 where density is measured. The ice patch extent in 2021 (orthophoto), 2019 (orthophoto) and 2011 (orthophoto) are shown. "front point" marks the reference point for front position and length change measurements (see chap. 12.1). The 10 m contours are derived from the 2019 DTM.

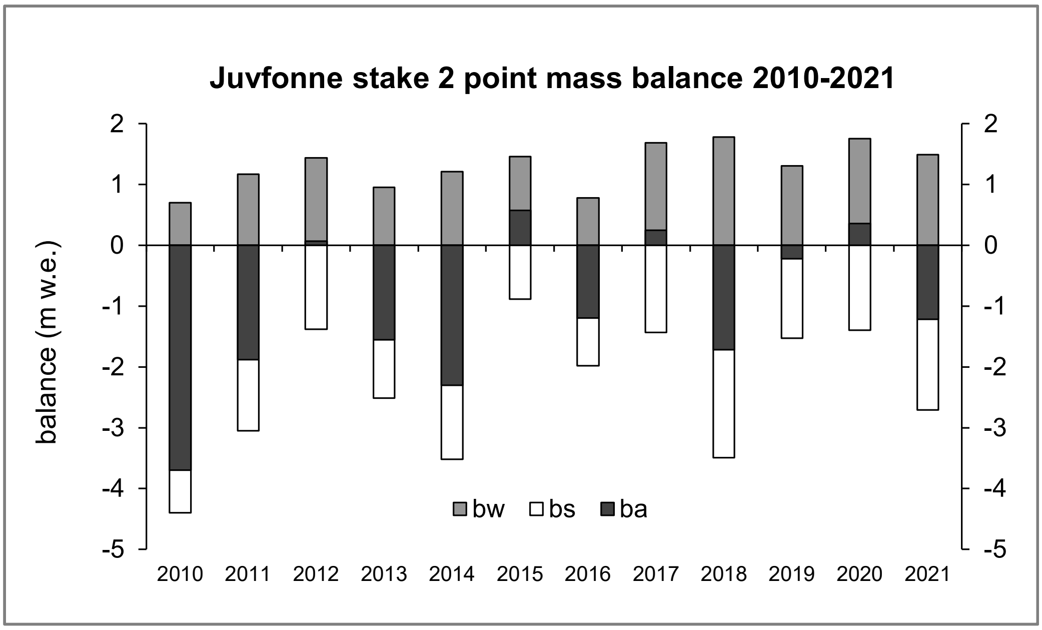


Figure 7-4
Point mass balance at stake 2 at Juvfonne 2010-2021, given as winter balance (b_w), summer balance (b_s) and annual balance (b_a).

8. Hellstugubreen (Liss M. Andreassen)

Hellstugubreen (61°34′N, 8° 26′E) (now written as “Hellstugubrean” on official maps) 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 26th September 2021. Photo: Jan Tomas Espedal, Aftenposten.

8.2 Mass balance 2021

Field work

Accumulation measurements were performed on 29th April. Snow depths were measured in 73 positions between 1559 and 2138 m a.s.l., covering most of the altitudinal range of the glacier (Fig. 8-2). The snow depth varied between 1.70 and 4.42 m, with a mean (median) of 2.50 (2.37) m. Snow density was measured in a density pit at 1945 m a.s.l. The total snow thickness measured was m and the resulting density was 443 kg m^{-3}. Ablation measurements were carried out on 26th and 27th September (Fig. 8-5).

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 1.10 ±0.2 m w.e., which is 105 % of the mean winter balance for the reference period 1991-2020. The summer balance was interpolated to 50 m height intervals based on the stake readings and was –2.38 ±0.3 m w.e., which is 141 % of the mean summer balance for the reference period 1991-2020. The annual balance of Hellstugubreen was −1.28 ±0.3 m w.e. The equilibrium line altitude (ELA) was above the highest stake at 2060 m a.s.l. and estimated to be 2155 m a.s.l., giving an accumulation area ratio (AAR) of 1 %. The mass balance results are shown in Table 8-1 and the corresponding curves for specific and volume balance are shown in Figure 8-3.

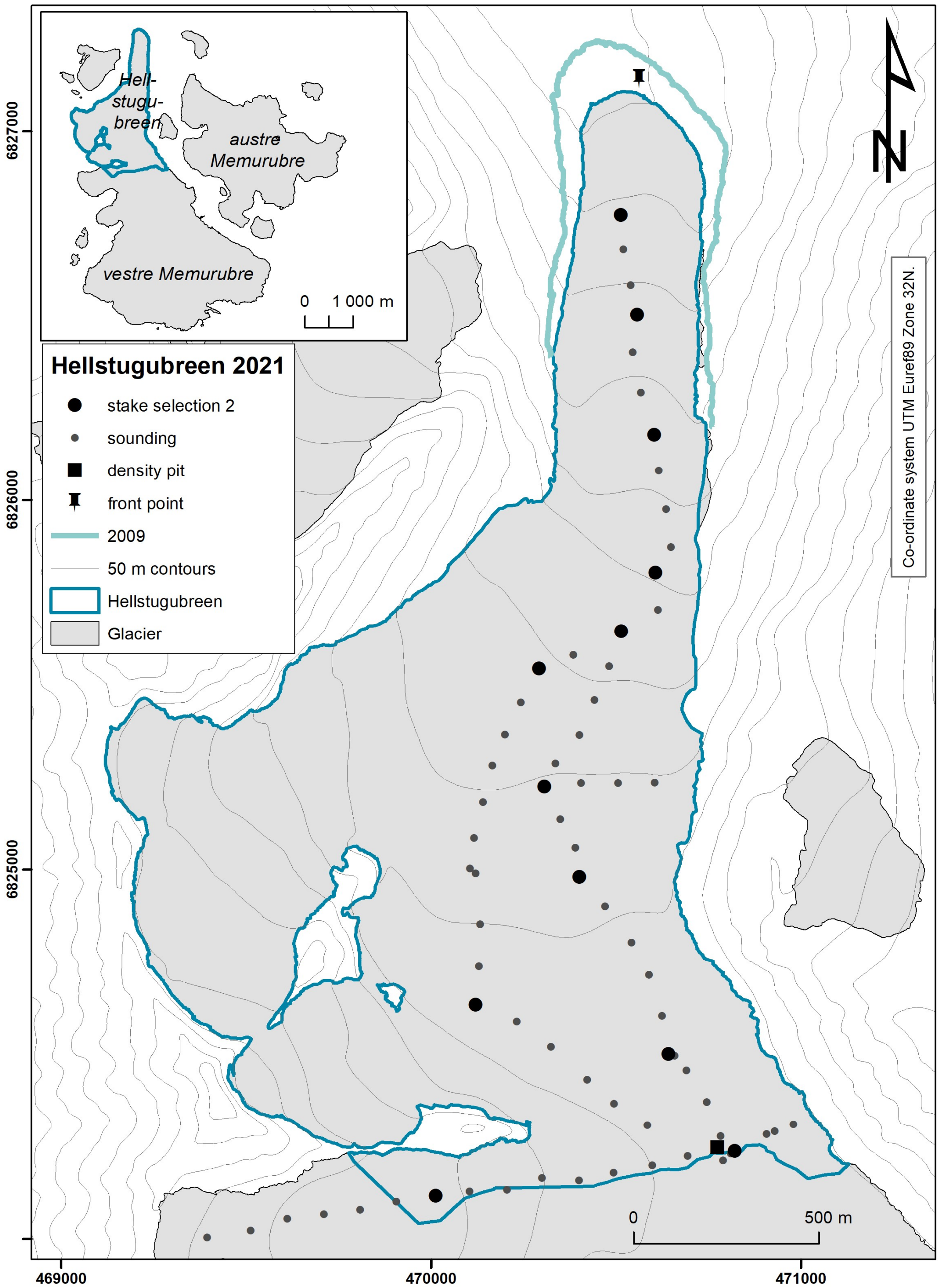


Figure 8-2
Map of Hellstugubreen showing the location of stakes, snow depth soundings and snow pit in 2021. Front point: reference points used for front position and length change measurements (chap. 12-1).
Inset shows Hellstugubreen and surrounding glaciers.

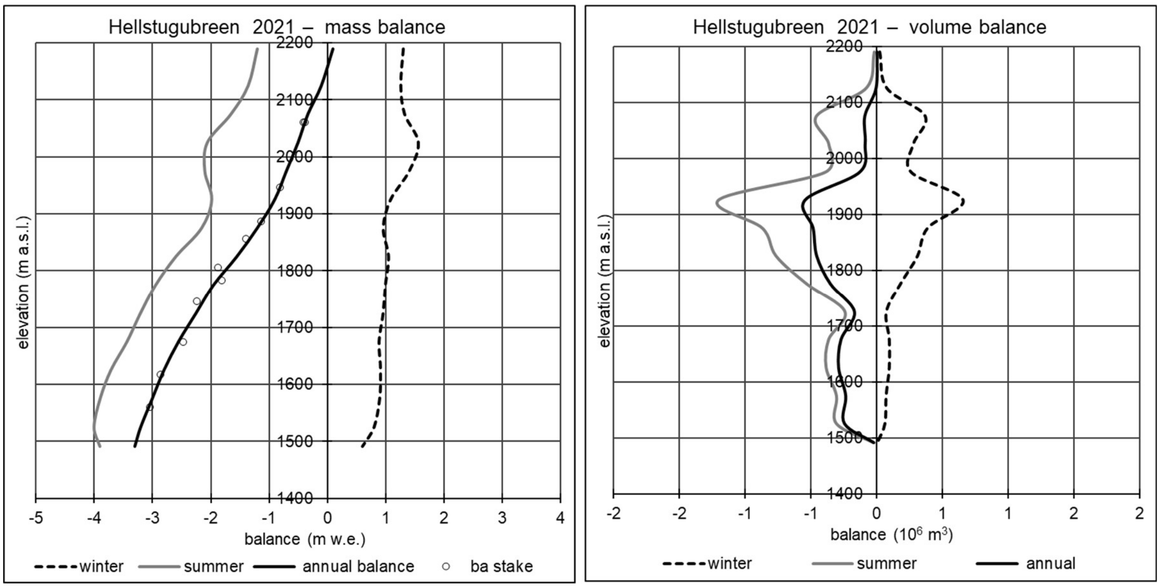


Figure 8-3
Mass balance diagram for Hellstugubreen in 2021, showing specific balance on the left and volume balance on the right. The winter balance soundings and annual balance at stakes are also shown.

Table 8-1
The distribution of winter, summer and annual balance in 50 m altitudinal intervals for Hellstugubreen in 2021.

Mass balance Hellstugubreen 2020/21

Altitude (m a.s.l.)	Area (km2)	Winter balance Measured 29 Apr 2021		Summer balance Measured 26 Sep 2021		Annual balance Summer surfaces 2020 - 2021	
		Specific (m w.e.)	Volume (106 m3)	Specific (m w.e.)	Volume (106 m3)	Specific (m w.e.)	Volume (106 m3)
2150 - 2229	0.017	1.30	0.02	-1.20	-0.02	0.10	0.00
2100 - 2150	0.060	1.26	0.08	-1.36	-0.08	-0.10	-0.01
2050 - 2100	0.278	1.32	0.37	-1.65	-0.46	-0.33	-0.09
2000 - 2050	0.178	1.56	0.28	-2.06	-0.37	-0.50	-0.09
1950 - 2000	0.186	1.40	0.26	-2.10	-0.39	-0.70	-0.13
1900 - 1950	0.607	1.08	0.66	-1.98	-1.20	-0.90	-0.55
1850 - 1900	0.404	0.96	0.39	-2.16	-0.87	-1.20	-0.48
1800 - 1850	0.295	1.05	0.31	-2.60	-0.77	-1.55	-0.46
1750 - 1800	0.181	0.99	0.18	-2.94	-0.53	-1.95	-0.35
1700 - 1750	0.076	0.95	0.07	-3.20	-0.24	-2.25	-0.17
1650 - 1700	0.107	0.88	0.09	-3.43	-0.37	-2.55	-0.27
1600 - 1650	0.104	0.91	0.09	-3.71	-0.39	-2.80	-0.29
1550 - 1600	0.079	0.90	0.07	-3.90	-0.31	-3.00	-0.24
1500 - 1550	0.077	0.80	0.06	-4.00	-0.31	-3.20	-0.25
1482 - 1500	0.007	0.60	0.00	-3.90	-0.03	-3.30	-0.02
1482 - 2229	**2.656**	**1.10**	**2.93**	**-2.38**	**-6.33**	**-1.28**	**-3.40**

8.3 Mass balance 1962-2021

The cumulative annual balance of Hellstugubreen since 1962 is –27 m w.e. (Fig. 8-4), giving a mean annual deficit of 0.46 m w.e. per year. The cumulative mass balance for the period 2000/2001 to 2019/2021 (21 years) is –18 m w.e. or –0.87 m w.e./a.

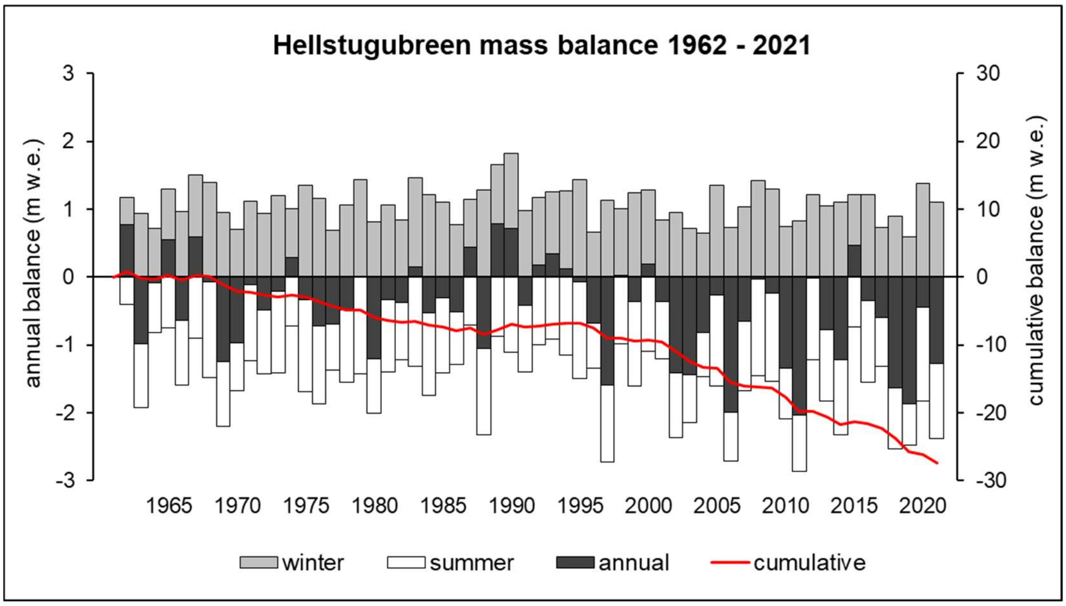


Figure 8-4
Winter, summer and annual balance at Hellstugubreen for 1962-2021, and cumulative mass balance for the whole period.

Figure 8-5
Field work on 26 September 2021 measuring stake 46 at the glacier divide towards Vestre Memurubre. At this location snow density is measured in April. See also Figure 8-2. Photo: Jan Tomas Espedal, Aftenposten.

9. Gråsubreen (Liss M. Andreassen)

Gråsubreen (61°39′N, 8°37′E) (now written as "Gråsubrean" on official maps) 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 26th September 2021 at the ablation measurements. All winter snow was gone, and bare ice was exposed. In this central part of the glacier bare ground has appeared in recent years due to the mass loss of the glacier. View towards northeast from stake 8. Photo: Liss M. Andreassen.

9.1 Mass balance 2021

Fieldwork

Accumulation measurements were performed on 28th April 2021. The calculation of winter balance is based on stake measurements and snow depth soundings in 59 positions between 1871 and 2259 m a.s.l. (Fig. 9-2). The snow depth varied between 0.23 and 2.92 with a mean and median of 1.61 and 1.62 m, respectively. The snow density was measured in a density pit near stake 8 (elevation 2140 m a.s.l.) where the total snow depth was 2.05 m and the mean density was 381 kg m^{-3}. Ablation measurements were carried out on 26th September 2021, when all visible stakes were measured. The winter snow was gone at all stake positions (Fig. 9-3). The calculation of annual balance was based on stakes in 6 different positions.

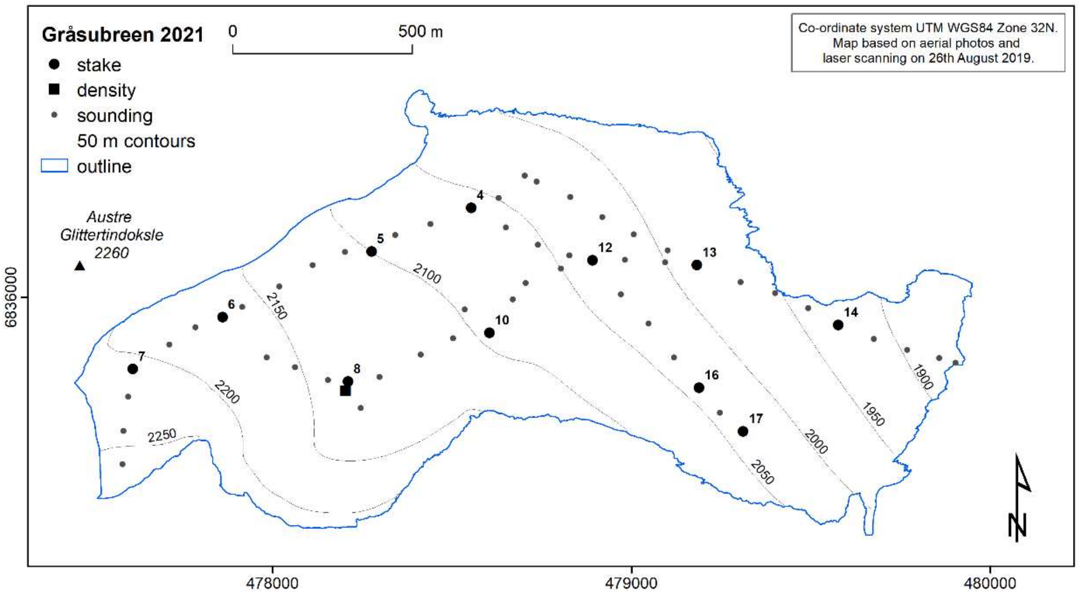


Figure 9-2
Map of Gråsubreen showing the location of stakes, density pit and soundings in 2021.

Figure 9-3
The winter snow was gone at all stake positions at the ablation measurements on 26th September 2021. The snow on the picture is remnants from an autumn snow fall prior to the measurements.
Photo: Eilev Hellekveen.

Results

The winter balance was calculated as the mean of the soundings within each 50-metre height interval. This gave a winter balance of ±0.61 m w.e., which is 87 % of the mean winter balance for the reference period 1991-2020. Summer and annual balance were calculated from direct measurements of 6 stakes. The resulting summer balance was −2.15 ±0.3 m w.e., which is 169 % of the mean summer balance for the reference period 1981-2010. The annual balance of Gråsubreen was negative in 2021 at −1.54 ±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.

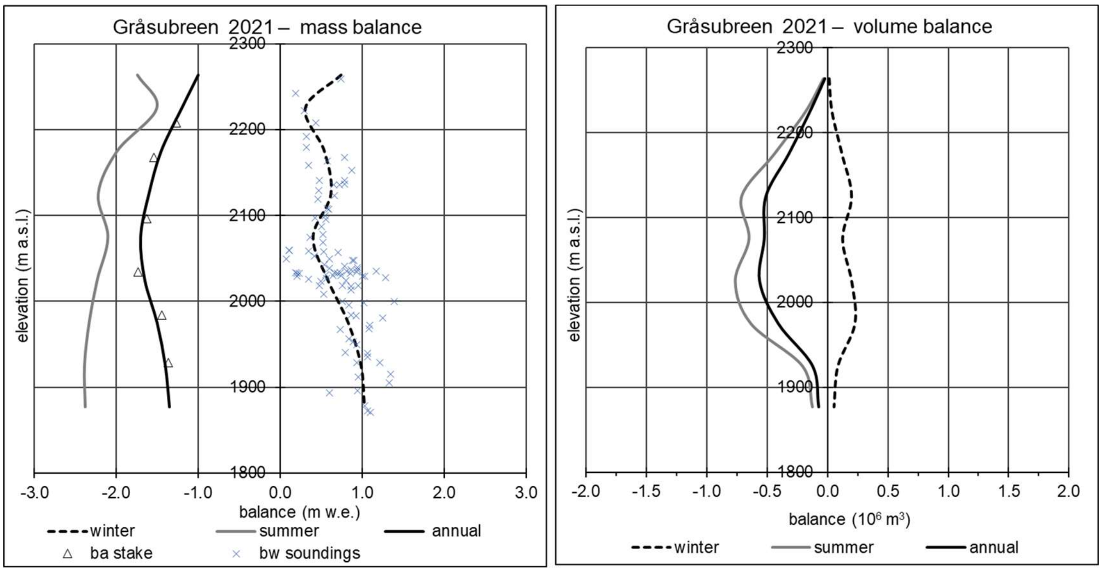


Figure 9-4
Mass balance diagram for Gråsubreen for 2021, showing specific balance on the left and volume balance on the right. Winter and summer balance at the stakes and individual snow depth soundings are also shown.

Mass balance Gråsubreen 2020/21

Altitude (m a.s.l.)	Area (km²)	Winter balance Measured 20th April		Summer balance Measured 17th Sep.		Annual balance 2020 - 2021	
		Specific (m w.e.)	Volume (10^6 m³)	Specific (m w.e.)	Volume (10^6 m³)	Specific (m w.e.)	Volume (10^6 m³)
2250 - 2277	0.020	0.74	0.01	-1.74	-0.03	-1.00	-0.02
2200 - 2250	0.120	0.31	0.04	-1.51	-0.18	-1.20	-0.14
2150 - 2200	0.221	0.54	0.12	-1.99	-0.44	-1.45	-0.32
2100 - 2150	0.320	0.62	0.20	-2.22	-0.71	-1.60	-0.51
2050 - 2100	0.309	0.40	0.12	-2.10	-0.65	-1.70	-0.53
2000 - 2050	0.342	0.58	0.20	-2.23	-0.76	-1.65	-0.56
1950 - 2000	0.272	0.83	0.23	-2.33	-0.63	-1.50	-0.41
1900 - 1950	0.087	0.99	0.09	-2.39	-0.21	-1.40	-0.12
1854 - 1900	0.053	1.03	0.05	-2.38	-0.13	-1.35	-0.07
1854 - 2277	**1.744**	**0.61**	**1.06**	**-2.15**	**-3.75**	**-1.54**	**-2.69**

Table 9-1
The distribution of winter, summer and annual balance in 50 m altitudinal intervals for Gråsubreen in 2021.

9.3 Mass balance 1962-2021

The cumulative annual balance of Gråsubreen is –28 m w.e. since measurements began in 1962 (Fig. 9-5). The average annual balance is hence –0.46 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.

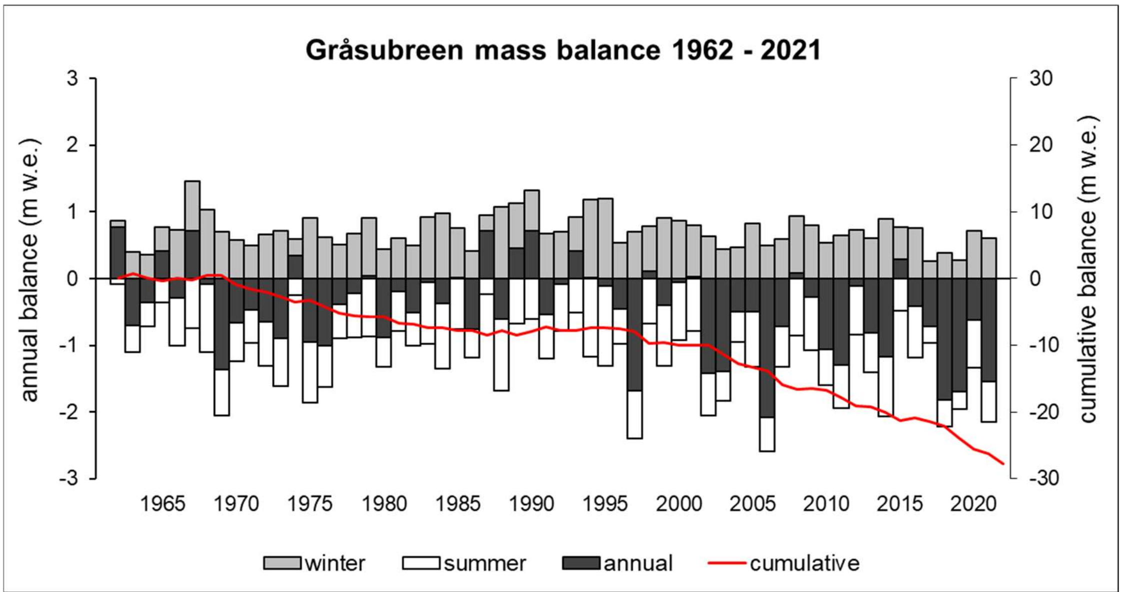


Figure 9-5
Winter, summer and annual balance for Gråsubreen for 1962-2021, and cumulative mass balance for the whole period.

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. In 2020 it covered an altitude range from 1531 m a.s.l. at Snøtinden down to 176 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
On 4th August 2021 stake E3420 was replaced with a new stake E3421 in the position E3420 had in August 2020. The annual velocity in this stake position is 76 m/a. Photo: Hallgeir Elvehøy.

10.1 New DTM

As part of an initiative from Statens Kartverk to construct a new digital elevation model for all of Norway, large parts of western Svartisen (Vestisen) were mapped on 10th August 2020 (Terratec AS, Oslo, Norway). Based on the LIDAR point elevation data a 10 x 10 m DTM covering Engabreen was constructed.

The glacier outline was mapped using a combination of laser intensity values and terrain relief. The drainage basin for calculation of the mass balance at Engabreen was updated using the ice divide from 2008 and the new glacier outline. The area of the drainage basin reduced from 36.255 km² in 2016 to 35.960 km² in 2020. The elevation distribution was calculated by counting grid cells within 100 metre elevation bins, each grid cell representing 100 m². The elevation interval reduced from 111 - 1544 m a.s.l to 177 - 1532 m a.s.l.

10.2 Mass balance 2021

Fieldwork

Stakes in four locations on the glacier plateau were checked on 9th March and showed between 3.7 and 6.9 metres of snow.

The snow accumulation measurements were performed on 26th May. Four stakes on the glacier plateau were located and used to validate the snow depth soundings. Snow depth was measured at 24 sounding locations along the profile from the summit at 1464 m a.s.l. to E34 (Fig. 10-2). The snow depth was between 2.7 and 7.9 metres. The summer surface was easy to define. The mean snow density down to 5.3 m at stake E5 was 520 kg m^{-3}. At stake E17 and E400 on the glacier tongue 1.45 and 1.2 m of glacier ice had melted, respectively, since 1st October 2020.

The stake network was checked on 4th August. Stake E17 and E400 on the glacier tongue melted out prior to 4th August. Stake E400 was photographed by a glacier guide on 17th and 27th July, documenting 5.15 m of ice melt between 26th May and 27th July. The stakes were re-drilled. At stake E34 all the winter snow (2.7 m) and 1.6 m of ice had melted since 26th May. The stake was re-drilled (Fig. 10-1). Higher up on the glacier plateau 3 to 4 metres of snow had melted.

Some of the stakes were checked on 27th August showing around 1 meter of snow and ice melt on the glacier plateau since 4th August.

The summer ablation measurements were carried out on 23rd October. Unfortunately, only the four stake locations below 1100 m a.s.l. could be visited. At stake E17 and E400 on the glacier tongue, 3.4 and 3.65 metres of ice had melted, respectively. At E34, 2.0 m of ice had melted, and at E30 0.4 m of snow and 1.55 m of ice had melted.

On 22nd February 2022 snow depth and stake length were measured at stake E34, E20 and E101T. From these observations the early autumn melting after 27th August at E20 was verified as 0.1 m of snow and 1.45 m of firn from 2019/20, and the early autumn melting at E5, E101 and E121 was limited to between 0.8 and 0.6 metres of snow and firn.

Results

The calculations are based on a DTM from 10th August 2020. All the stake and sounding locations are appointed elevations from the 2020 DTM.

The winter balance for 2021 was calculated from the snow depth and snow density measurements. The specific winter balance was calculated as 2.9 ±0.2 m w.e. This is 106 % of the average winter balance for the normal period 1991-2020 (2.71 m w.e. a^{-1}).

The date of the 2021 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 on 10th -11th October 2021. On the glacier tongue the summer season probably ended on 18th November.

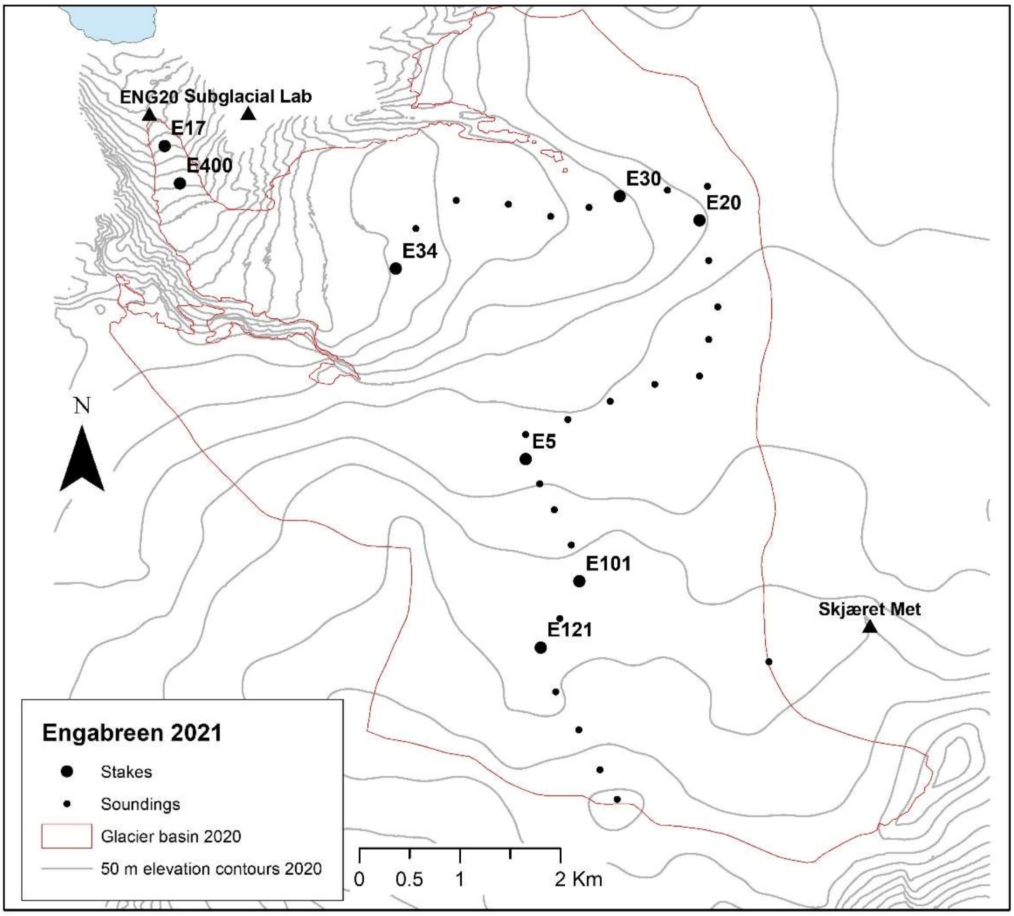


Figure 10-2
Location of stakes and soundings on Engabreen in 2021. The map is based on airborne laser scanning (LIDAR) data from 10th August 2020.

The point summer balance was calculated directly for stake locations E34 and E30 at 960 and 1090 m a.s.l., respectively. The ice melt at E400 between 27th July and 4th August was estimated as 0.64 m of ice using the melt rate calculated for 17th to 27th July (8 cm/d). Stake E17 was not observed prior to 4th August. The ice melt between 27th May and 4th August was estimated as 5.4 metres from the calculated melt at E400 and the fraction of melt at E17 and E400 between 4th August and 23rd October.

The snow and ice melt after 4th August at stake location E20 was assessed as 0.1 m of snow and 1.45 of firn from 2019/20 based on the measurements at E20 on 22nd February 2022.

The snow melt after 27th August at stake locations E5, E101 and E121 was estimated as 0.7 m of snow based on measurements at E101 on 22nd February 2022.

The specific summer balance was calculated from the summer balance curve drawn from these eight point values (Fig. 10-3) as −3.4 ±0.2 m w.e. This is 123 % of the average summer balance for the normal period 1991-2020 (−2.77 m w.e. a^{-1}). The resulting annual balance was −0.5 ±0.3 m w.e. (Tab. 10-1). The ELA was 1236 m a.s.l. and the AAR was 46 %.

Table 10-1
Specific and volume winter, summer and annual balance calculated for 100 m elevation intervals at Engabreen in 2021.

Mass balance Engabreen 2020/21 – stratigraphic system

		Winter mass balance		Summer mass balance		Annual mass balance	
		Measured 26. May 2021		Measured 23. Oct 2021		Summer surface 2020 - 2021	
Altitude (m a.s.l.)	Area (km²)	Specific (m w.e.)	Volume (10^6 m³)	Specific (m w.e.)	Volume (10^6 m³)	Specific (m w.e.)	Volume (10^6 m³)
1500 - 1532	0.046	4.00	0.2	-2.60	-0.1	1.40	0.1
1400 - 1500	2.199	4.30	9.5	-2.70	-5.9	1.60	3.5
1300 - 1400	9.228	3.85	35.5	-2.80	-25.8	1.05	9.7
1200 - 1300	8.041	3.15	25.3	-3.00	-24.1	0.15	1.2
1100 - 1200	7.487	2.40	18.0	-3.20	-24.0	-0.80	-6.0
1000 - 1100	4.552	2.25	10.2	-3.90	-17.8	-1.65	-7.5
900 - 1000	2.373	1.60	3.8	-4.80	-11.4	-3.20	-7.6
800 - 900	0.773	1.25	1.0	-5.30	-4.1	-4.05	-3.1
700 - 800	0.439	0.90	0.4	-5.80	-2.5	-4.90	-2.2
600 - 700	0.270	0.40	0.1	-6.30	-1.7	-5.90	-1.6
500 - 600	0.249	-0.10	0.0	-6.90	-1.7	-7.00	-1.7
400 - 500	0.137	-0.60	-0.1	-7.60	-1.0	-8.20	-1.1
300 - 400	0.089	-1.10	-0.1	-8.20	-0.7	-9.30	-0.8
200 - 300	0.071	-1.40	-0.1	-8.80	-0.6	-10.20	-0.7
177 - 200	0.006	-1.70	0.0	-9.30	-0.1	-11.00	-0.1
177 - 1532	**35.960**	**2.88**	**103.7**	**-3.38**	**-121.6**	**-0.50**	**-18.0**

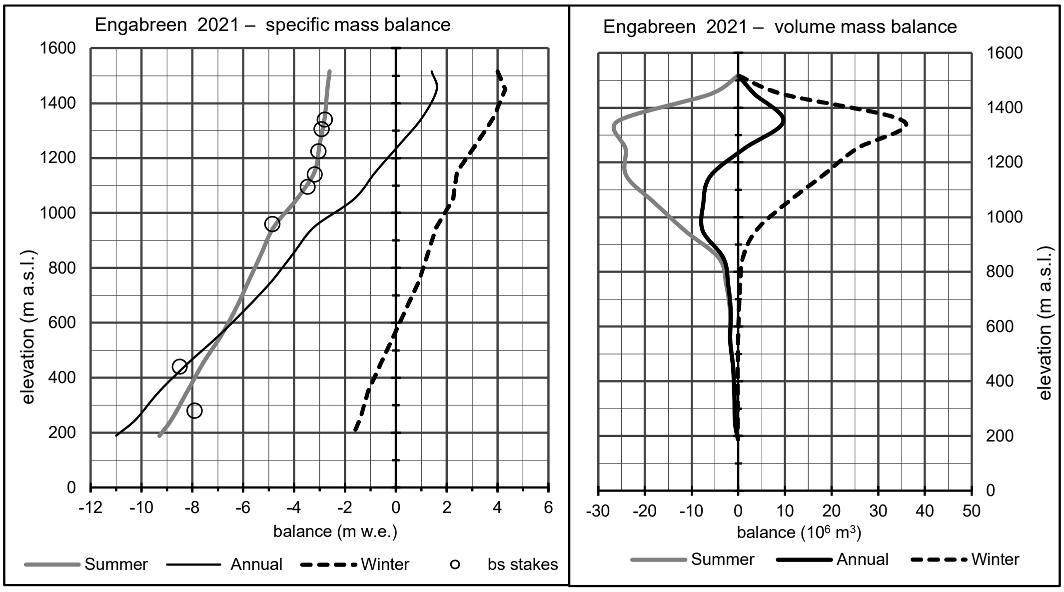


Figure 10-3
Mass balance diagram showing specific balance (left) and volume balance (right) for Engabreen in 2021. Summer balance at eight stake locations (○) is shown.

The annual surface mass balance at Engabreen for 1970-2021 is shown in Figure 10-4. The cumulative surface mass balance since the start of mass balance investigations at Engabreen is +0.8 m w.e., showing that the long-term change in glacier volume has been small.

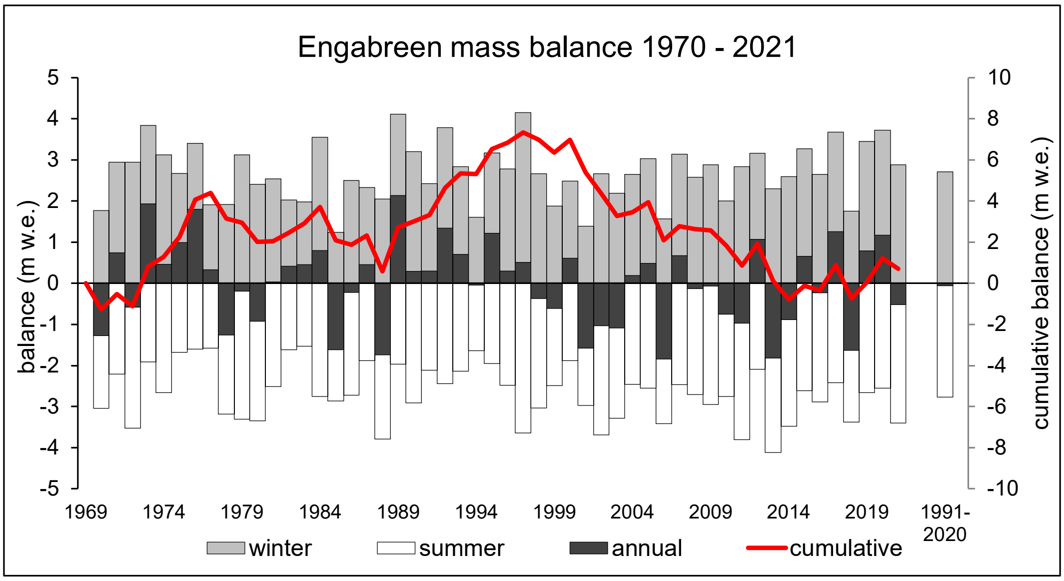


Figure 10-4
Mass balance at Engabreen during the period 1970-2021. Cumulative mass balance is given on the right axis. The average winter and summer balances are B_w =2.69 m w.e. and B_s =−2.67 m w.e.

10.3 Meteorological observations

A meteorological station recording air temperature and global radiation at 3 m above ground level is located on a nunatak (1364 m a.s.l.) close to the drainage divide between Engabreen and Storglombreen (Fig 10-2, Skjæret Met). The station has been operating since 1995. There is a gap in the data record between 1st October 2019 and 27th August 2021. The temperature record indicate that on the upper part of the glacier plateau the melt season ended around 11th October 2021.

11. Langfjordjøkelen (Bjarne Kjøllmoen)

Langfjordjøkelen (70°10′N, 21°45′E) is a plateau glacier situated on the border of the 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), where the glacier ranges in elevation from 338 to 1043 m a.s.l.

The glaciological investigations in 2021 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.

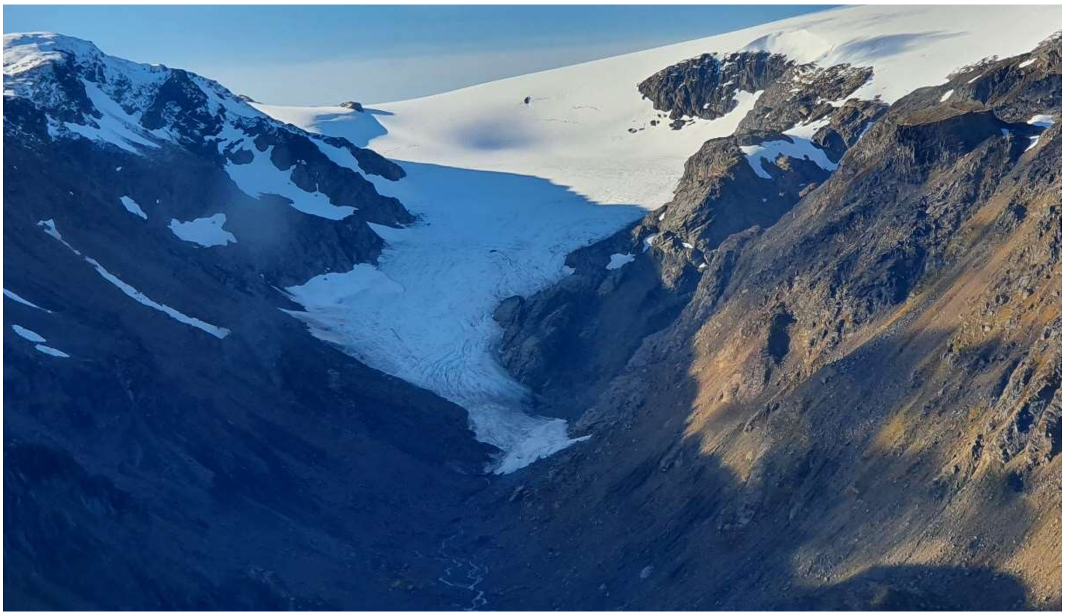


Figure 11-1
The east-facing outlet of Langfjordjøkelen photographed on 18th September 2021. Photo: Bjarne Kjøllmoen.

11.1 Mass balance 2021

Fieldwork

Snow accumulation was measured on 4th May and the calculation of winter balance was based on measurements of 61 snow depth soundings (Fig. 11-2). The snow depth varied between 2.6 and 6.8 m with an average of 5.2 m. Snow density was measured in position 25 (709 m a.s.l.) and the mean density of 5.5 m snow was 399 kg m^{-3}.

Ablation was measured on 18th September. The annual balance was measured at stakes in six locations (Fig. 11-2). There was 75 cm of snow remaining at the topmost stake position (pos. 40, 1042 m a.s.l.) from the winter season 2020/21. At the time of measurement up to 35 cm of fresh snow had fallen on the glacier.

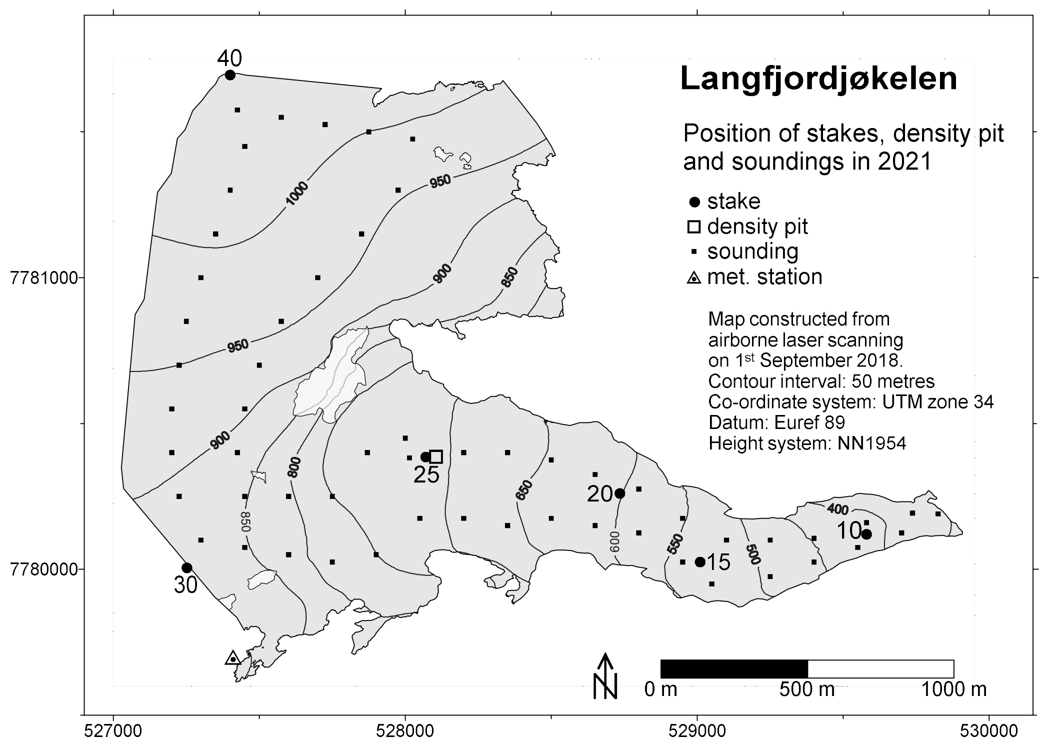


Figure 11-2
Location of stakes, soundings and snow pit at Langfjordjøkelen in 2021.

Results

The calculations are based on the 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 2.2 ±0.2 m w.e., which is 106 % of the mean winter balance for the periods 1989-93 and 1996-2020. The spatial distribution of the winter balance is shown in Figure 11-3.

The ablation stakes cover elevations from the glacier summit (1042 m a.s.l.) to 413 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 −2.4 ±0.3 m w.e., which is 80 % of the mean summer balance for 1989-93 and 1996-2020.

Hence, the annual balance was slightly negative at −0.20 ±0.40 m w.e. The mean annual balance for 1989-93 and 1996-2020 is −0.91 m w.e. The mean annual balance for the past ten years (2012-21) is −0.89 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.

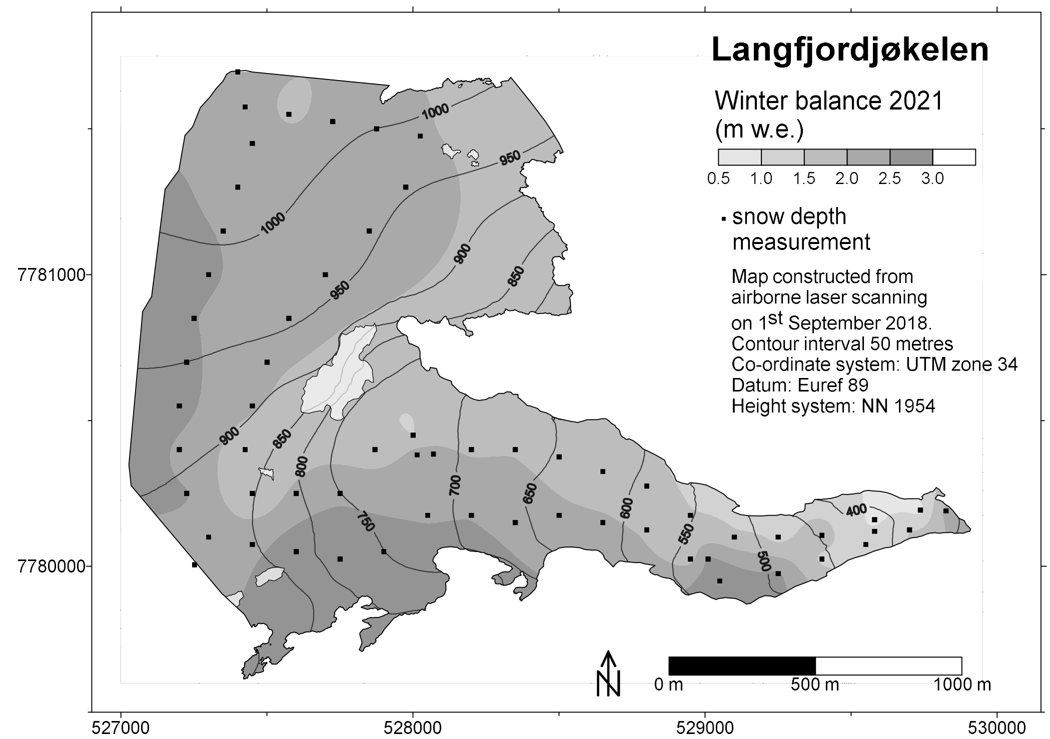


Figure 11-3
Spatial distribution of winter balance at Langfjordjøkelen in 2021.

According to Figure 11-4, the equilibrium line altitude was 780 m a.s.l. Consequently the accumulation area ratio was 65 %.

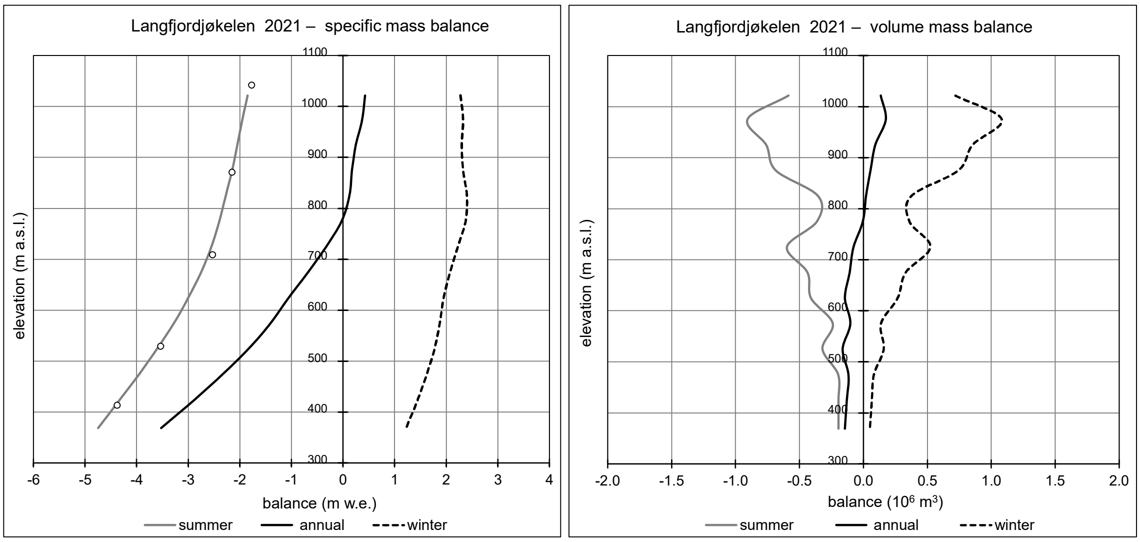


Figure 11-4
Mass balance diagram showing specific balance (left) and volume balance (right) for Langfjordjøkelen in 2021. Specific summer balance for six stakes is shown as circles (○).

Table 11-1
Winter, summer and annual balance for Langfjordjøkelen in 2021.

Mass balance Langfjordjøkelen 2020/21 – stratigraphic system

Altitude (m a.s.l.)	Area (km^2)	Winter mass balance Measured 4th May 2021		Summer mass balance Measured 18th Sep 2021		Annual mass balance Summer surface 2020 - 2021	
		Specific (m w.e.)	Volume (10^6 m^3)	Specific (m w.e.)	Volume (10^6 m^3)	Specific (m w.e.)	Volume (10^6 m^3)
1000 - 1043	0.32	2.28	0.7	-1.85	-0.6	0.43	0.1
950 - 1000	0.47	2.33	1.1	-1.95	-0.9	0.38	0.2
900 - 950	0.37	2.30	0.9	-2.05	-0.8	0.25	0.1
850 - 900	0.32	2.33	0.7	-2.15	-0.7	0.18	0.1
800 - 850	0.16	2.40	0.4	-2.28	-0.4	0.13	0.0
750 - 800	0.15	2.38	0.4	-2.40	-0.4	-0.02	0.0
700 - 750	0.24	2.23	0.5	-2.55	-0.6	-0.33	-0.1
650 - 700	0.16	2.08	0.3	-2.75	-0.4	-0.68	-0.1
600 - 650	0.14	1.95	0.3	-3.00	-0.4	-1.05	-0.1
550 - 600	0.07	1.88	0.1	-3.28	-0.2	-1.40	-0.1
500 - 550	0.09	1.78	0.2	-3.60	-0.3	-1.83	-0.2
450 - 500	0.05	1.63	0.1	-3.95	-0.2	-2.33	-0.1
400 - 450	0.04	1.45	0.1	-4.33	-0.2	-2.88	-0.1
338 - 400	0.04	1.23	0.1	-4.75	-0.2	-3.53	-0.1
338 - 1043	**2.61**	**2.202**	**5.7**	**-2.397**	**-6.2**	**-0.195**	**-0.5**

11.2 Mass balance 1989-2021

The historical mass balance results for Langfjordjøkelen are presented in Figure 11-5. The cumulative annual balance for 1989-2021 (estimated values for 1994 and 1995 included) is –28.1 m w.e., which gives a mean annual balance of –0.85 m w.e. a^{-1}.

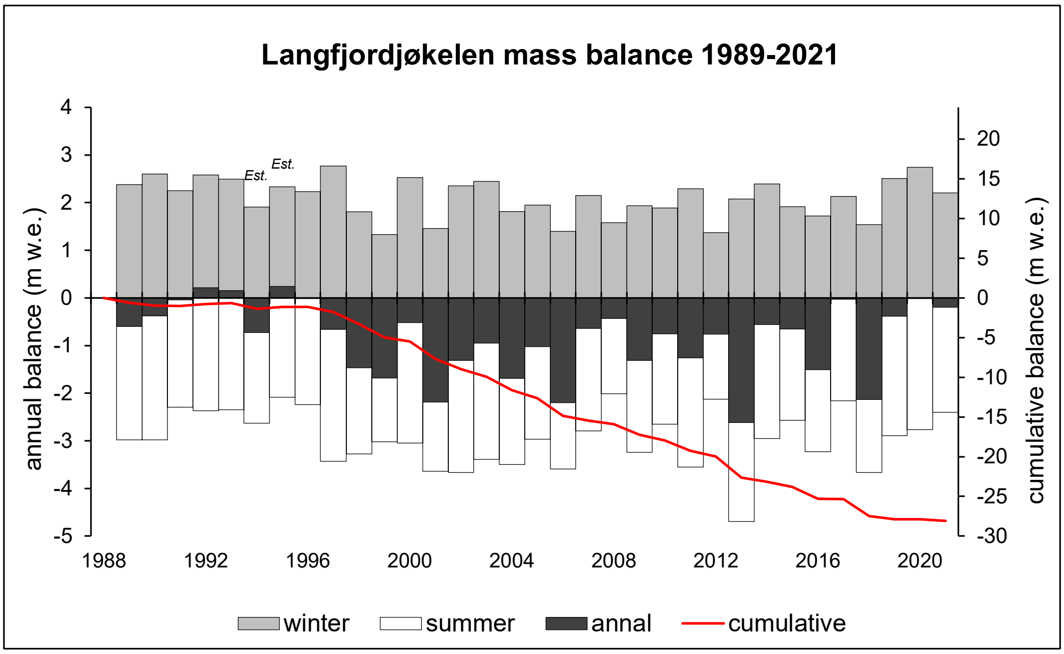


Figure 11-5
Mass balance at Langfjordjøkelen for the period 1989-2021. The total accumulated mass loss for 1989-2021 is 28.1 m w.e. (includes estimated values for 1994 and 1995).

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 only exist for the periods 2009-2010 and 2012-2021.

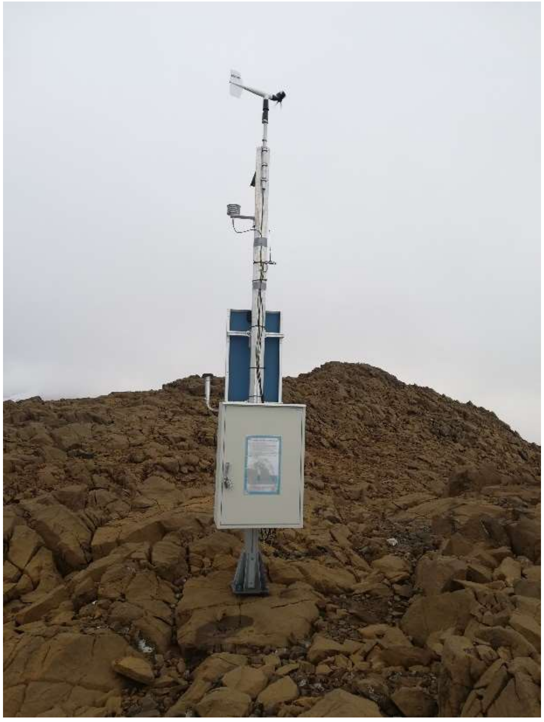


Figure 11-6
The meteorological station, Langfjord Met.
Photo: Solveig Winsvold.

The mean summer temperature (1st June – 30th September) at Langfjord Met in 2021 was 4.7 °C. The mean summer temperature for 2009-10 and 2012-20 was also 4.7 °C. The melt season on the upper part of the glacier (above 900 m a.s.l.) started around 1st June and lasted until about 5th October. The period from 1st to 24th September was relatively cold and hence, the melting was probably quite modest during these two and a half weeks. The monthly summer temperatures were 4.2 °C (June), 7.3 °C (July), 5.1 °C (August) and 2.0 °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 for at least 74 glaciers. The total number of observations in our database up to 2021 is 2869, including 88 measurements of length change based on maps, reconstructions from photos, moraines etc., or combinations of methods. 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.

The longest and most complete record is for Fåbergstølsbreen. The length change observations started there in 1899, and measurements have been conducted every year since 1907 resulting in 116 observations. Stigaholtbreen, Nigardsbreen and Austerdalsbreen, and Styggedalsbreen in Jotunheimen have 100 or more observations each. Fifteen glaciers have between 50 and 99 observations, and an additional eleven glaciers have between 30 and 49 observations. The longest record in northern Norway is Engabreen with 89 measurements since 1903. The present monitoring programme for glacier length change includes 39 glaciers, 28 glaciers in southern Norway and 11 glaciers in northern Norway (Fig. 12-1 for location). The area of the monitored glaciers is 371 km^2, and they constitute about 16 % of the glacier area in Norway (Andreassen et al. 2022).

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).

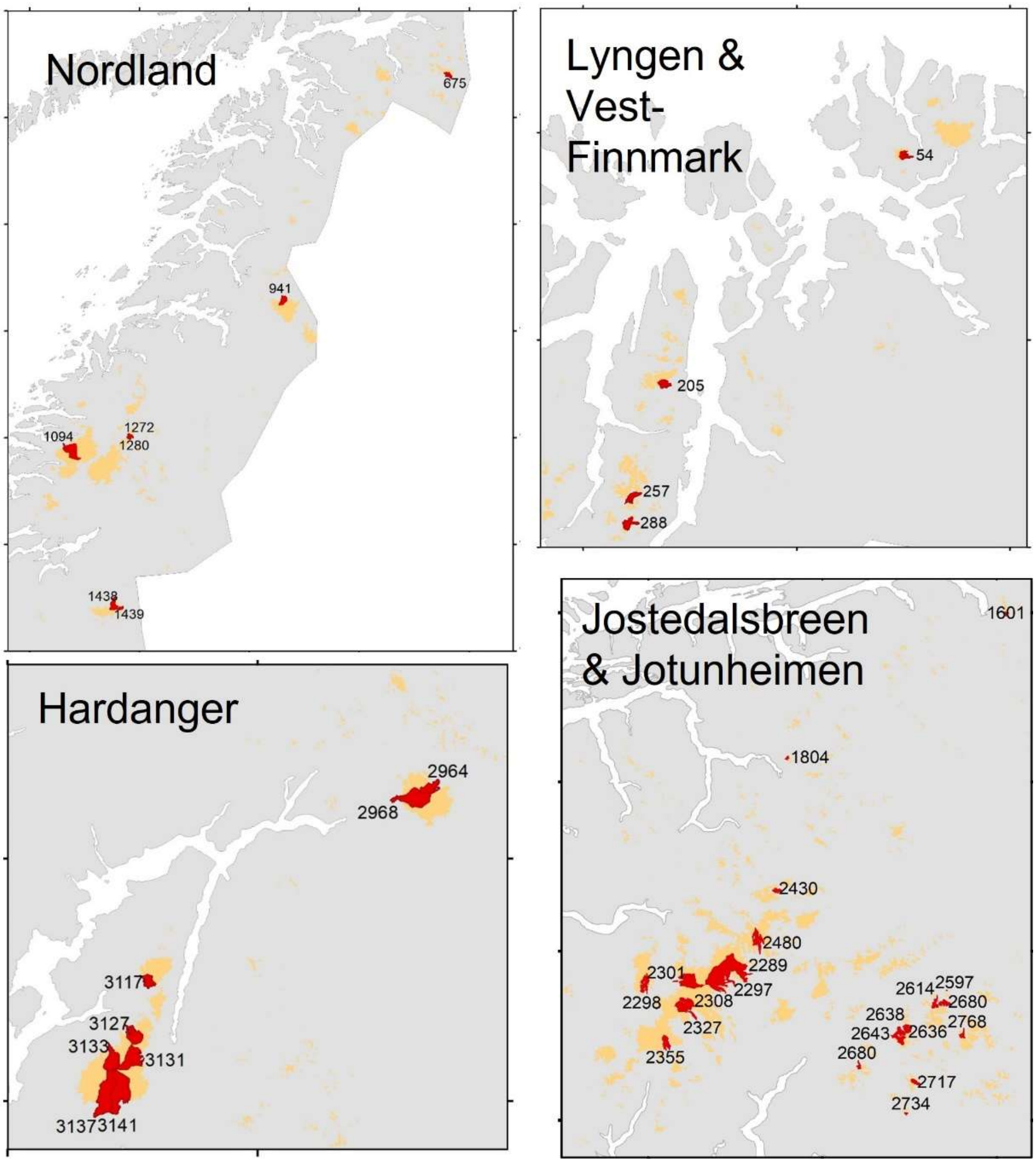


Figure 12-1
Map showing glaciers included in the length change monitoring programme (in red) with glacier IDs (Tab. 12-1). Note that the different glacier areas are not to the same scale.

Results 2021

Thirty-six glaciers were measured - ten glaciers in northern Norway and twenty-six glaciers in southern Norway. The results for 2021, period(s) of measurements and number of observations (calculated length changes) are listed in Table 12-1. Thirty-two glaciers retreated in 2021, and two glaciers showed no change. The annual length change varied from 0 m for Koppangsbreen (no change) to −130 m for Austerdalsbreen.

The average cumulative length change for the ten-year period 2011-21 for 25 glaciers is −192 metres, ranging from −610 metres at Gråfjellsbrea to −41 metres at Svelgjabreen. Both glaciers are outlet glaciers from the southern part of Folgefonna. Three glaciers in the monitoring programme were not measured in 2021. Data are available at www.nve.no/glacier.

Figure 12-2
Haugabreen (Glacier ID 2298), a southern outlet from Myklebustbreen (45 km²), an icecap north-west of Jostedalsbreen was photographed on 6th October 2021. Length change measurements were conducted from 1933 to 1941 and were resumed in 2013 by Norsk Bremuseum & Ulltveit-Moe climate centre. The terminus has retreated 89 meters since 2013. Photo: Pål Hage Kielland.

Figure 12-3
Leirbrean (Glacier ID 2638), a north-facing part of Smørstabbrean in Jotunheimen, was photographed on 7th October 2021. Length change measurements were initiated by P.A. Øyen (Oslo University) in 1907 and by NVE in 1998. The terminus has retreated ca. 1 km since 1909. The pro-glacial lake appeared in the 1990s.
Photo: Dag Inge Bakke.

Table 12-1
Glacier length change measured in 2021. See Figure 12-1 for glacier locations.

	Glacier	Glacier-ID	2020	Observer	Period(s)	Number obs.
Finnmark & Troms	Langfjordjøkelen	54	−19	NVE	1998-	25
	Koppangsbreen	205	−15	NVE	1998-	22
	Sydbreen	257	*−23	NVE	2007-	13
	Steindalsbreen	288	−45	NVE	1978-	29
Nordland	Storsteinsfjellbreen	675	NM	NVE	2006-	16
	Rundvassbreen	941	−14	SISO	2011-	11
	Engabreen	1094	−26	S	1903-	89
	Skjelåtindbreen	1272	*−14	NVE	2014-	3
	Trollbergdalsbreen	1280	*−26	NVE	2010-	6
	Austre Okstindbreen	1438	−59	NVE	1908-44, 2006-	29
	Corneliussenbreen	1439	[5]−26	NVE	2006-	10
Sunnmøre & Breheimen	Vinnufonna	1601	−24	NVE	2019-	2
	Trollkyrkjebreen	1804	−16	NVE	1944-74, 2008-	26
	Heimsta Mårådalsbreen	2430	NM	NVE	2002-	6
Jostedalsbreen	Fåbergstølsbreen	2289	−12	NVE	1899-	116
	Nigardsbreen	2297	−17	NVE	1899-	111
	Haugabreen	2298	−5	NBM	1933-41, 2013-	16
	Brenndalsbreen	2301	−15	NVE	1900-62, 1964-65, 1996-	83
	Tuftebreen	2308	−14	NVE	2007-	14
	Austerdalsbreen	2327	−130	NVE	1905-19, 1933-	101
	Vetle Supphellebreen	2355	−2	NBM	1899-44, 2011-	46
	Stigaholtbreen	2480	−14	NVE	1903-	108
Jotunheimen	Styggebrean	2608	−23	NFS	1951-63, 2011-	18
	Storjuvbrean	2614	−33	NVE	1901-07, 08-12, 33-61, 97-	61
	Storbreen	2636	−24	NVE	1902-	83
	Leirbrean	2638	−23	NVE	1907-77, 1979-	62
	Bøverbrean	2643	−18	NVE	1903-76, 1997-	48
	Styggedalsbreen	2680	−37	NVE	1901-	100
	Mjølkedalsbreen	2717	−5	NVE	1978-	26
	Koldedalsbreen	2734	NM	NVE	1978-	14
	Hellstugubreen	2768	−20	NVE	1901-	82
Hardanger	Midtdalsbreen	2964	−24	AN	1982-	39
	Rembesdalskåka	2968	−17	S	1917-	46
	Botnabrea	3117	*−19	GK	1996-	18
	Gråfjellsbrea	3127	−59	S	2002-	19
	Buerbreen	3131	−45	NVE	1900-	75
	Bondhusbrea	3133	−46	S	1902-	90
	Svelgjabreen	3137	0	SKL	2007-	14
	Blomstølskardsbreen	3141	−17	SKL	1994-	22

* – two years
[5] – five years
NM – not measured in 2021

Observers other than NVE:

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

12.2 Jøkulhlaups

Jøkulhlaups, also known as Glacier Lake Outburst Floods (GLOFs), were registered at four glaciers in Norway in 2021. However, three of the events were observed on photographs and satellite images only and were not observed by conventional means.

One event was observed at Demmevatnet, a glacier dammed lake at Rembesdalskåka, a western outlet of Hardangerjøkulen. There have been eight outburst events from Demmevatnet since 2014.

Inspection of glacier-dammed lakes on photographs and Sentinel-2 imagery showed that there were probably outburst events at Svartisheibreen, south-west of the western Svartisen, at Oksfjellbreen, a southern outlet in the Okstindan mountain massif and at Sandåbreen, a small glacier northeast of Jostedalsbreen.

Rembesdalskåka

Rembesdalskåka, an outlet glacier of Hardangerjøkulen, dams a lake called Nedre Demmevatnet (Fig. 12-4). There have been many previous events recorded from Nedre Demmevatnet (Tab. 12-2), 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 12-4
The lake Nedre Demmevatnet is dammed by the ice-barrier at Rembesdalskåka. The area of the water-filled lake was approximately 0.14 km^2. Photo: Orthophoto from norgeibilder.no.

Jøkulhlaup 2021

A new event occurred from the glacier-dammed lake, Nedre Demmevatnet on 13th July 2021 (Fig. 12-5). Over 3-4 hours, a total of 1.5-2.0 million m^3 water drained under Rembesdalskåka and subsequently to the hydropower reservoir Rembesdalsvatn.

Figure 12-5
The "lake" Nedre Demmevatnet photographed on 22nd August, almost six weeks after the jøkulhlaup on 13th July 2021. Photo: Liss M. Andreassen.

Table 12-2
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
2021	13th July	Event occurred over 3-4 hours	1.75

Events observed by photography and satellite images only:

Svartisheibreen

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 at the end of July 2020 (Tab. 12-3). 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 2021

Photograph taken from a light aircraft shows that the water level in Heiavatnet was quite low in August 2021 (Fig. 12-6), with many stranded ice blocks around the lake.

Figure 12-6
Heiavatnet photographed on 7th August 2021. Stranded ice blocks are visible around the lake. Photo: Lars Westvig.

Satellite images confirm that the water level was lower on 6th August than it was on 26th July (Fig. 12-7). Thus, the photograph and satellite images from 2021 suggest that the dammed lake drained between 26th July and 6th August.

Figure 12-7
Satellite images (Sentinel-2) of Heiavatnet on 26th July 2021 (left) and 6th August 2021 (right). The area of the water-filled lake was approximately 0.5 km^2. Source: Varsom Xgeo.

The water flood from the jøkulhlaups at Heiavatnet drains into the river Tverråga and further into Glomåga (Fig. 12-8). Close to Glomåga there is a hydrometric station (Berget, 61 m a.s.l.) recording water level, water discharge and air temperature (Fig. 12-8). The diagrams in Figure 12-9 show water discharge and air temperature at Berget during the period 26th-31st July 2021. The water discharge curve shows a distinct increase over 4-5 hours in the evening on 28th July (Fig. 12-9). The air temperature curve shows high temperature (up to 25 °C) for several days in the same period and consequently, snow and ice melting rates from the glacier was probably high. No precipitation was observed in the area in the days before 28th July. Thus, the sudden increase in water discharge on 28th July was most probably a result of the jøkulhlaup from Heiavatnet.

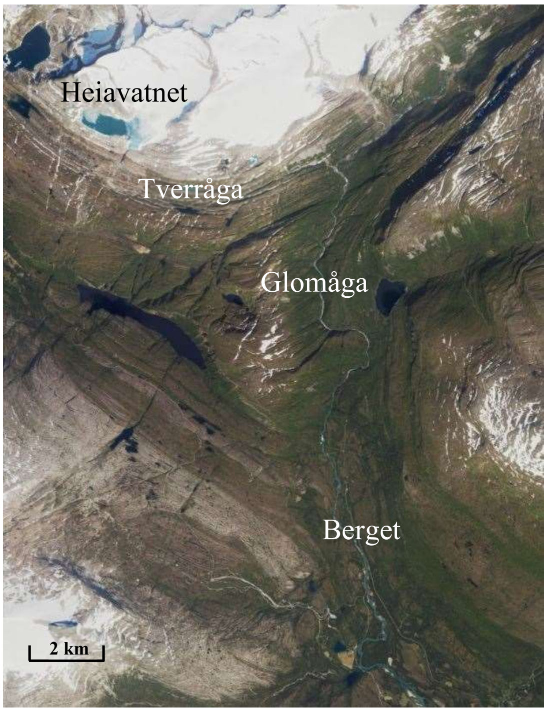


Figure 12-8
Water from Heivatnet drains into the river Tverråga and Glomåga. The hydrometric station Berget is located downstream from Heiavatnet close to Glomåga. Photo: Orthophoto from norgeibilder.no.

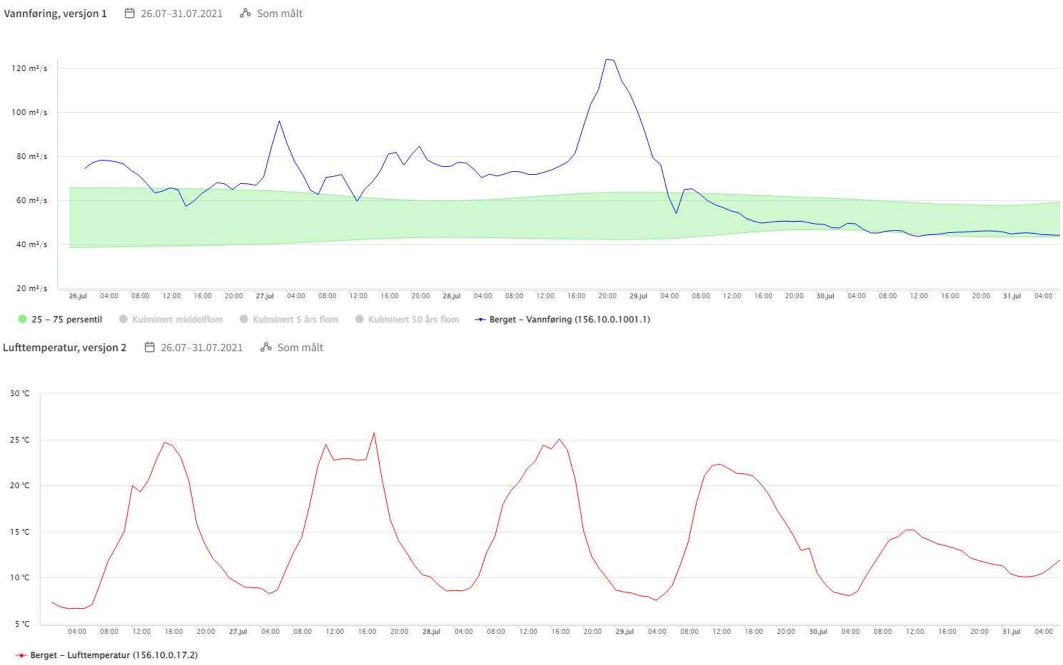


Figure 12-9
Water discharge (upper) and air temperature (below) at the hydrometric station Berget from 26th to 31st July 2021. Note the sudden increase in water discharge in the evening on 28th July and the high temperature during the days before.

Table 12-3
An overview of jøkulhlaups from Heiavatnet since 1989.

Year	Date	Comment
1989	unknown	P Low water level observed in August
1991	7th-15th April	Water level recordings. Water volume estimated to 1.8 mill.m^3
1999	unknown	P Low water level observed in September
2000	unknown	P Low water level and stranded icebergs observed in September
2014	late summer	P Low water level and stranded icebergs observed in September
2016	late summer	P Low water level and stranded icebergs observed in September
2020	late July	P/S Low water level and stranded icebergs observed in August
2021	July/August	P/S Low water level and stranded icebergs observed in August

P Photograph
S Sentinel image

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. 12-10). The first jøkulhlaup from Oksfjellbreen was registered in 2020.

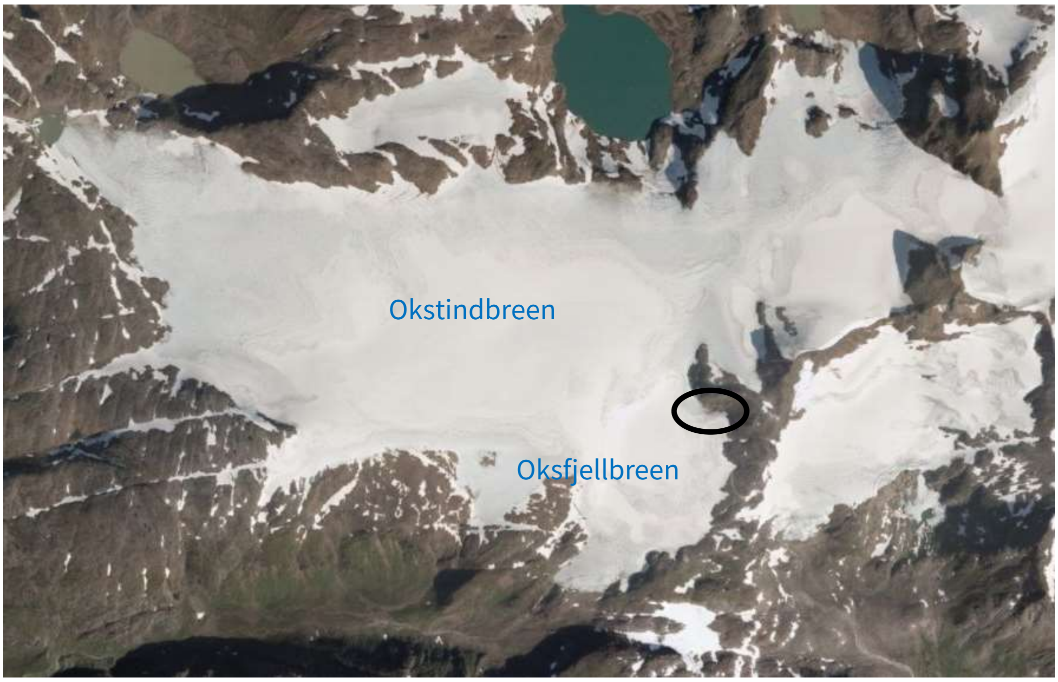


Figure 12-10
Oksfjellbreen is a southern outlet from the ice cap Okstindbreen. The glacier-dammed lake is located in the northern part of the Oksfjellbreen outlet, indicated by the black ellipse.
Photo: Orthophoto from norgeibilder.no.

Jøkulhlaup 2021

The event in 2021 is based on Sentinel-2 satellite images. A comparison of the images from 9th and 26th June 2021 suggest that the glacier-dammed lake emptied during this period (Fig. 12-11). The image from 9th June shows water in the lake, while the image from 26th June shows that the lake was empty. The last image also shows dirty snow in the lake indicating a decreased water level.

Figure 12-11
Sentinel-2 images showing the glacier-dammed lake at Oksfjellbreen. The left image is from 9th June and the right from 26th June 2021. On 9th June the lake was filled with water and on 26th June the lake was emptied. The area of the water-filled lake before the event was approximately 0.013 km^2. Source: Varsom Xgeo.

Sandåbreen (BreID: 2434)

Sandåbreen is a glacier with an area of 5 km^2 that lies southwest of the ridge Skridulaupen, in the municipality of Skjåk (Fig. 12-12). In the northern part of the glacier a small ice-dammed lake is located (Fig. 12-12). Two previous events have occurred at Sandåbreen, in July 2018 and August 2019. Subsequent inspection of Sentinel satellite images from even two more years suggest that there could also have been events in 2016 and 2017, but the images are somewhat indistinct and hence, indication of jøkulhlaups are rather uncertain.

Figure 12-12
Sandåbreen and the glacier-dammed lake at the northern ice edge as seen from the air on 19th August 2015. Photo: Orthophoto from norgeibilder.no.

Jøkulhlaup 2021

Examination of Sentinel images from 13th and 28th September 2021 suggest that the glacier-dammed lake emptied in this period (Fig. 12-13). The image from 13th September shows water in the lake, while the image from 28th September shows that the lake was almost empty.

Figure 12-13
Sentinel satellite images of the glacier-dammed lake at Sandåbreen from 13th (left) and 28th September (right) 2021. On 13th September the lake was filled with water and on 28th September the lake was almost emptied. The area of the water-filled lake before the event was approximately 0.025 km^2. Source: Varsom Xgeo.

13. No Man’s Land – Glacier photographs, science and materiality

(Stig Storheil)

As part of the national research project "Norwegian Photographic History 1940 - 2011", I look at documentation of Norwegian glaciers from 1949 to 1979. Monitoring and measuring of glaciers were from the early 1960s initiated based on the potential for hydropower development, and from day one photography was used for documentation, analysis, and dissemination. In the review of this material, combined with archival studies and interviews, there are clear indications that the photographic media quickly gained more uses than purely scientific ones. It seems that the use of photography in a scientific context had freed itself from its role as “primary metaphor for objective truth”, and that non-scientific aspects of the medium voluntarily or involuntarily became part of intention and use.

Figure 13-1
Vestre Memurubre in 1973. Photo: Nils Haakensen/NVE.

The close relationship between photography and science has characterized most of the age of photography from 1839 to the present. The relationship has been characterized by an expectation that the inherent properties of the photographic media would support and underpin science's principles of objective, clear and provable data. The close and undoubted connection of photography to sensible reality, together with opportunities to show sharpness and accuracy, formed a solid foundation for the natural sciences to be excited about the potential of the medium.

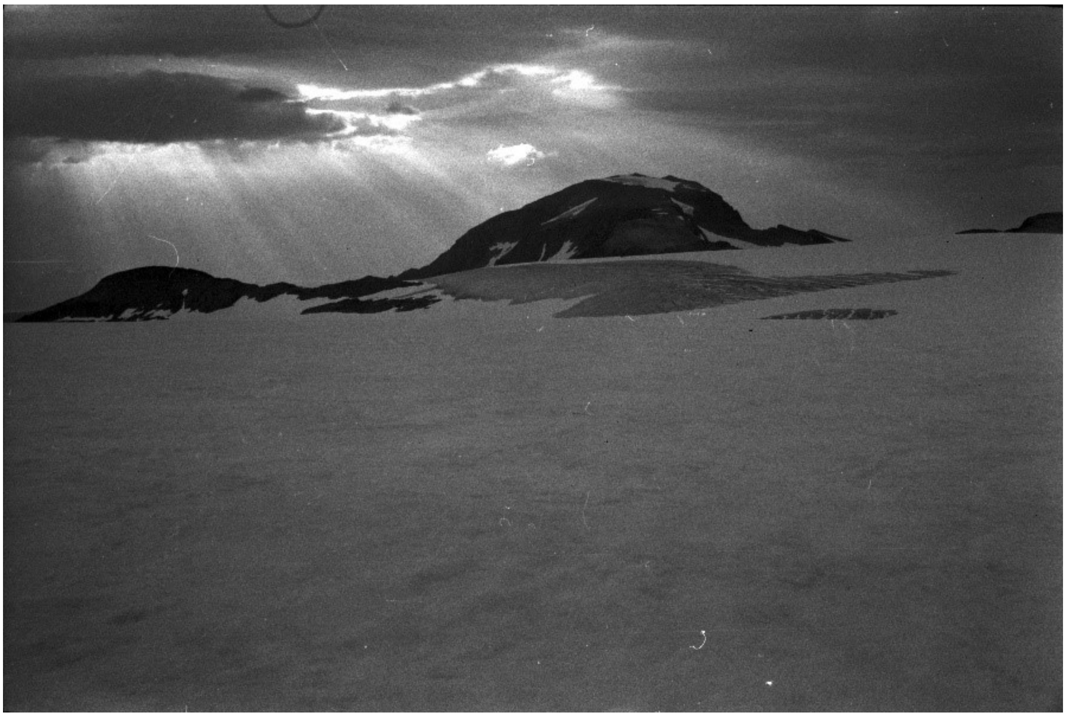


Figure 13-2
Engabreen in 1970. Photo: Øyvind Skaugrud/NVE.

However, it was not long after the invention of photography that this enthusiasm was supplemented with a gradual recognition that the photo medium was more multifaceted than first thought. The early application of photography in art and as art quickly freed itself from the bonds of painting art and reinforced the independence of the media and its connection to subjective addictions.

The strive for scientific objectivity depends on the actor demonstrating a conscious and knowledge-based relationship with photography. This was arguably not the case with these glacier photographs, where the choice of recording medium, the facilitation of photographic practice on the glaciers and the use of amateurs in the photographic sense reinforce the basic subjective nature of the photographic medium. Dust, fingerprints, scratches along with aesthetics, associations and humour are archived as physical and emotional traces of human activity, at the same time challenging the natural science's ideal of exact, detailed, and realistic imaging.

It is possible to claim that these glacier photographs find themselves in a no man's land where science's demands for objectivity meets the subjective potential of both the photographic medium and how humans act.

Figure 13-3
Ålfotbreen in 1966. Photo: NVE.

From a photo-historical point of view, it is interesting to analyse this type of photographic collection. Photographs taken in a scientific context can be "translated" as cultural-historical documentation and thus have added value. When digitized files can now be placed in new contexts 50 - 60 years later, it can provide new opportunities to see where the No man's land is located and how the connection between photography and science can be.

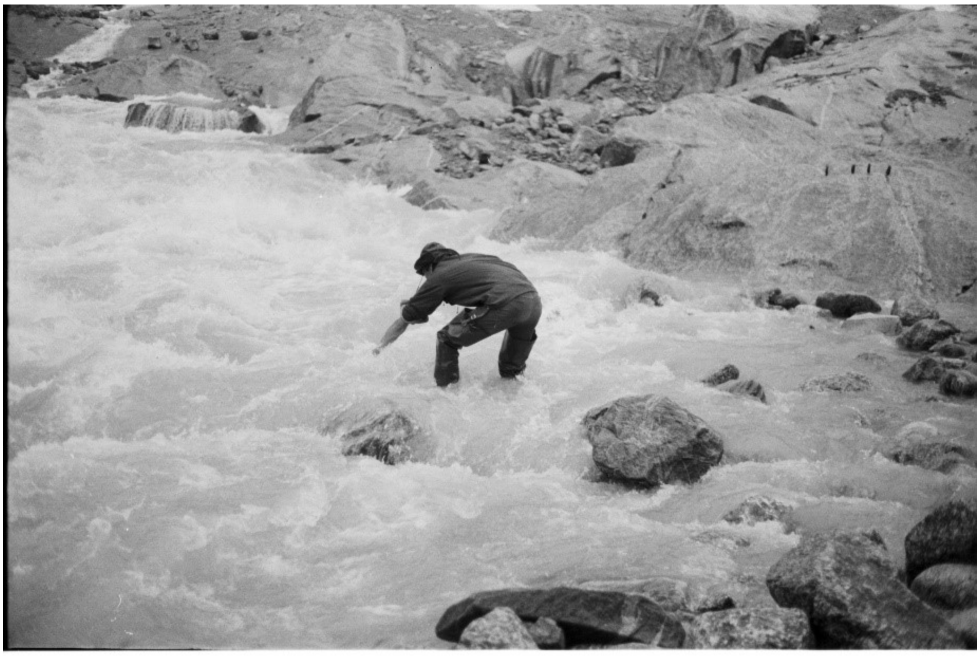


Figure 13-4
Nigardsvatnet in 1970. Photo: Per Hagen/NVE.

My contribution here is based on a peer-reviewed article entitled “Ingenmannsland - brefotografier, vitenskap og materialist”, published in Mediehistorisk tidsskrift, No 2, 2021.

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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 1949-2021. The table lists characteristic data for the investigated glaciers. The Glacier ID refers to ID in the glacier inventory of Norway (Andreassen et al., 2022).

Area/ No. Glacier	Glacier ID	Lat., Long.	Area (km²)	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-	59
2 Hansebreen	2085	61°44', 5°40'	2.5	927-1303	2019	1986-	36
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-	60
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-	34
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-	59
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-	73
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-	12
29 Hellstugubreen	2768	61°34', 8°26'	2.7	1487-2213	2019	1962-	60
30 Gråsubreen	2743	61°39', 8°37'	1.7	1854-2277	2019	1962-	60
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'	36.0	176-1532	2020	1970-	52
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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