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Glaciological investigations in Norway 2024

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Cover photo: Langfjordjøkelen, an ice cap in Troms and Finnmark counties in northern Norway. The photo was taken on 29 August 2024, by Flytjenesten i Tromsø.

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Abstract: Results of glaciological investigations performed at Norwegian glaciers in 2024 are presented in this report. The main part concerns mass balance investigations. Results from investigations of glacier length changes are discussed in a separate chapter.

Key words: Glaciology, Mass balance, Glacier front variations, 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. From 1963 to 2021 the report was published as a printed edition. From 2022, however, the report will only be published as a digital edition.

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 2024. The chapters are written by different authors, but are presented in a similar 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 of the report.

Oslo, October 2025

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

In memory of Randi Pytte Asvall
(1939-2025)



Randi Pytte Asvall in front of Nigardsbreen in spring 1962. Photo: NVE.

Randi Pytte Asvall (1939-2025)

We in NVE are proud and grateful to have had Randi Pytte Asvall as colleague over several decades.

This issue of the “Glasiologiske undersøkelser i Norge/ Glaciological Investigations in Norway” report series is dedicated to Randi.



Randi Pytte Asvall doing fieldwork at Folgefonna in the 1960s. Photo: NVE.

Randi Pytte Asvall combined her interest in nature with her intellectual capacity and became the first woman to study glaciology in Norway. Throughout her professional life, she worked with glaciers and ice in rivers at the Norwegian Water Resources and Energy Directorate (NVE). She distinguished herself as a tough woman in a male-dominated environment in the 1960s and has left a strong legacy. She was awarded the King's Medal of Merit in 2008.

Randi was born in Kongsberg on 28 May 1939, and on 8 February 2025, at an age of 85, she left three sons behind.

In the early 1960s, she combined her main fieldwork on Hellstugubreen with glacier guiding as Norway's first female glacier guide. In 1962, she started at NVE as a glaciologist and carried out a unique mapping of Folgefonna from 1963–1971, as preliminary studies for hydropower development in Mauranger, and worked with mass balance measurements and annual reports. From 1970, she worked with ice conditions in rivers and fjords, as well as impact assessments. From 1991, environmental and ice problems in the Alta watercourse, Barduelva, Otta, and Upper Glomma were her focus, and she concluded with a guide on ice problems in rivers.

Randi used the triangular huts on Folgefonna for glacier measurements (further reading on [Kraftlandet: Iskald overnatting](#), in Norwegian). These “Pyttebuene” are named after her and were restored with authentic items from the 1960s. Perhaps one of the world's smallest museums?

Randi was an important driving force and inspired others to pursue technical and natural science education. On behalf of colleagues at NVE, we are very grateful for her efforts and commitment throughout her long life.

Rest in peace, Randi.

Summary

Mass balance

Mass balance investigations were performed on ten glaciers in Norway in 2024 – two in northern Norway and eight in southern Norway. In this report we refer to the nine mass balance reference glaciers that include Langfjordjøkelen and Engabreen in northern Norway and Ålfotbreen, Hansebreen, Nigardsbreen, Rembesdalskåka, Storbreen, Hellstugubreen and Gråsubreen in southern Norway, according to the Norwegian hydrological reference dataset for climate change studies (Fleig et al., 2013; Andreassen and Elvehøy, 2021). In addition, mass balance on a small ice patch in Jotunheimen was measured.

The winter balance was lower than the 1991-2020 average for eight of the nine reference glaciers. Only Storbreen in Jotunheimen had a greater winter balance than the average at 103 %. Rembesdalskåka on Hardangerjøkulen and Engabreen on Svartisen had the lowest relative winter balances with 62 % and 64 % of the 1991-2020 averages, respectively.

The summer balance was greater than the 1991-2020 average for all nine reference glaciers. Engabreen and Langfjordjøkelen in western Finnmark had the greatest relative summer balances with 203 % and 188 % of the reference period averages, respectively. This is the greatest summer balances measured on these two glaciers since measurements started in 1970 and 1989, respectively. Rembesdalskåka had the lowest relative summer balance with 103 % of the reference period average.

The annual balance thus was negative for all nine reference glaciers. Langfjordjøkelen and Engabreen had the greatest deficits with -4.1 m w.e. and -3.9 m w.e., respectively, and these are the greatest deficits ever measured on both glaciers.

Glacier front variations

Glacier front variations were measured at 26 glaciers in southern Norway and 9 glaciers in northern Norway. Thirty-four of the 35 measured glacier outlets showed a decrease in length. The greatest retreats were observed at Engabreen (83 m), at Austre Okstindbreen (80 m) and at Steindalsbreen (75 m), all located in northern Norway.

Sammendrag

Massebalanse

I 2024 ble det utført massebalansemålinger på 10 breer i Norge – to i Nord-Norge og åtte i Sør-Norge. I henhold til det norske hydrologiske referansedatasettet for klima-endringsstudier (Fleig et al., 2013; Andreassen og Elvehøy, 2021) refererer vi i denne rapporten til de ni referansebreene for massebalanse som inkluderer Langfjordjøkelen og Engabreen i Nord-Norge og Ålfotbreen, Hansebreen, Nigardsbreen, Rembesdalskåka, Storbreen, Hellstugubreen og Gråsubreen i Sør-Norge. I tillegg ble det målt massebalanse på en isfonn i Jotunheimen.

For åtte av de ni referansebreene ble vinterbalansen mindre enn gjennomsnittet for referanseperioden 1991-2020. Bare Storbreen i Jotunheimen fikk større vinterbalanse enn gjennomsnittet med 103 %. Rembesdalskåka på Hardangerjøkulen og Engabreen på Svartisen fikk den relativt minste vinterbalansen med hhv. 62 % og 64 % av referanseperioden.

Sommerbalansen ble større enn gjennomsnittet for alle ni referansebreene. Engabreen og Langfjordjøkelen i Vest-Finnmark hadde relativt størst sommerbalanse med hhv. 203 % og 188 % av referanseperioden. Det er den største sommerbalansen som er målt på disse to breene siden målingene startet i hhv. 1970 og 1989. Rembesdalskåka fikk den relativt minste sommerbalansen med 103 % av referanseperioden.

Årlig balanse ble dermed negativ for alle ni referansebreene. Langfjordjøkelen og Engabreen hadde de største underskuddene med hhv. -4,1 m v.ekv. og -3,9 m v.ekv. og det er de største underskuddene som er målt på begge disse breene.

Lengdeendringer

Lengdeendringer ble målt på 26 breer i Sør-Norge og 9 breer i Nord-Norge. Trettifire av de 35 målte breutløperne hadde tilbakegang. Størst tilbakegang ble målt på Engabreen (83 m), på Austre Okstindbreen (80 m) og på Steindalsbreen (75 m), alle i Nord-Norge.

1. Glacier investigations in Norway 2024

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.

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/DEM

Digital terrain/elevation 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.

GOTHECA

Glacier impacts On The Hydrological systems in Europe and Central Asia. A research project about climate change and its impact to increasing meltwater from glaciers.

GPR

Ground-Penetrating Radar. A geophysical instrument that uses radar pulses to image the subsurface.

Jökulhlaup

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

LIA

Little Ice Age. A period of regional cooling, often defined as extending from the 16th to the 19th centuries.

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.

RCP4.5

Representative Concentration Pathway 4.5 is a climate scenario.

Reference glacier

The nine mass balance reference glaciers that include Ålfotbreen, Hansebreen, Nigardsbreen, Rembesdalskåka, Storbreen, Hellstugubreen, Gråsubreen, Engabreen and Langfjordjøkelen, according to the Norwegian hydrological reference dataset for climate change studies (Fleig et al., 2013; Andreassen and Elvehøy, 2021).

Reference period

The 30 year mass balance reference period 1991-2020 is used as standard normal period.

Sentinel satellite data

Sentinel-1 is a polar-orbiting, all-weather, day-and-night radar imaging mission. Sentinel-2 is a polar-orbiting, multispectral high-resolution imaging mission.

SMB

Surface Mass Balance is the difference between snow accumulation and surface ablation of snow, firn and ice.

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*.

UAV

Unmanned Aerial Vehicle. An aircraft, commonly known as a drone, without any human pilot, crew or passengers on board, operated remotely or pre-programmed.

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.norgebilder.no

An open web portal showing new, as well as a selection of historical orthophotos in Norway.

www.senorge.no

An open web portal showing daily updated maps of snow, weather and water conditions, and climate for Norway as well as Sentinel satellite images.

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 in grids. Stake readings are used to verify the soundings where possible (Fig. 1-1). Since the stakes can disappear during particularly snow-rich winters, and since it is often difficult to distinguish the summer surface (S.S.) by sounding alone, snow coring is also used to confirm the sounding results. Snow density is usually measured in one pit on each glacier.



Figure 1-1
Snow depth sounding and stake reading at Hellstugubreen on 26 April 2024. Photo: Liss M. Andreassen.

Summer and annual balance

Summer and annual balances are obtained from measurements of stakes and towers, usually performed in September or October (Fig. 1-2). Below the elevation of a glacier's equilibrium line the annual balance is negative, meaning that more snow and ice melts during the 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 1-2
Stake reading on Hellstugubreen on 31 July 2024. 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 2024 mass balance measurements were performed on eleven glaciers in Norway - nine in southern Norway and two in northern Norway (Fig. 1-3). Included in this total is one small ice mass, Juvfonne, which can be characterised as an ice patch rather than a glacier (chap. 7).

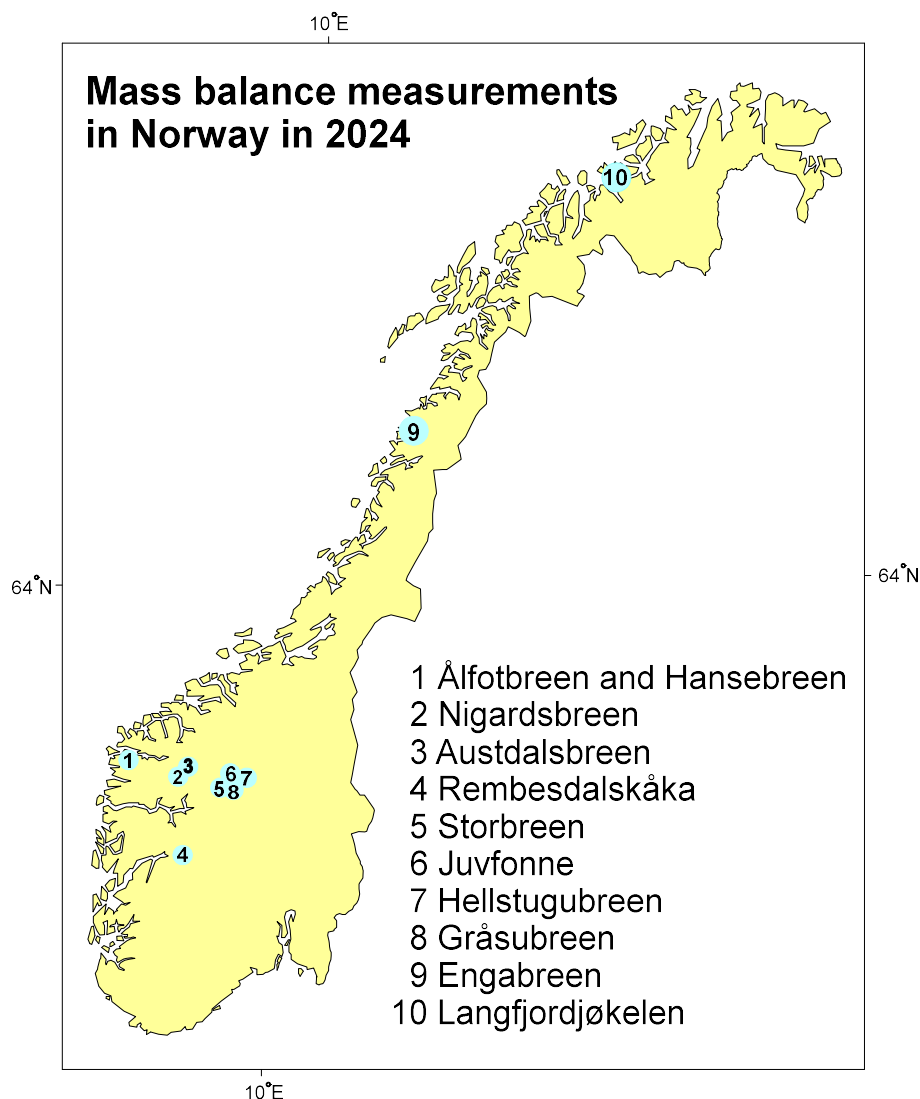


Figure 1-3
Location of the glaciers at which mass balance studies were performed in 2024.

In southern Norway, six of the glaciers (Ålfotbreen, Nigardsbreen, Rembesdalskåka, Storbreen, Hellstugubreen and Gråsubreen) have been measured for 62 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. (using the reference period 1991-2020). Storbreen in Jotunheimen has the longest series of all glaciers in Norway with 76 years of measurements, while Engabreen at Svartisen has the longest series (55 years) in northern Norway. The six glaciers measured for 62 consecutive years or more, together with Hansebreen in southern Norway and Langfjordjøkelen and Engabreen in northern Norway, are selected to be included in the

Norwegian Hydrological Reference Dataset (Fleig et al., 2013; Andreassen and Elvehøy, 2021). These nine glaciers constitute the so-called mass balance reference glaciers. Austdalsbreen was excluded because it is calving into a hydro-power reservoir, and consequently the glacier is influenced by the lake level regulations. For eight of the reference glaciers, a 30-year reference period (1991-2020) is defined and the balance values for 2024 are compared with the average of the reference period. Langfjordjøkelen was not measured in 1994 and 1995 and thus, the reference period 1991-2020 can not be defined. A comprehensive review of the glacier mass balance and length measurements in Norway is given in Andreassen et al. (2020).

Mass balance studies performed on Norwegian glaciers in 2024 are reported in detail for each glacier in the following chapters (chap. 2-11).

The mass balance (winter, summer and annual balance) is given in 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 2023/24 started with dry and cold weather in October, November and December over most of the country. January was more normal, and February was quite snow-rich in southern Norway, but rather snow-poor in northern Norway. The end of the winter season was fairly snow-poor in March and April over most of the country, however quite normal in Jotunheimen.

Snow accumulation and winter balance

The winter balance was lower than the 1991-2020 average for eight of the nine reference glaciers. Only Storbreen in Jotunheimen had a greater winter balance (103 %) than the average. Rembesdalskåka on Hardangerjøkulen and Engabreen on Svartisen had the lowest relative winter balances with 62 % and 64 % of the 1991-2020 averages, respectively.

Summer weather

The summer season can be briefly described as dry and very hot in northern Norway and quite normal in southern Norway.

Ablation and summer balance

The summer balance was greater than the 1991-2020 average for all nine reference glaciers. Engabreen and Langfjordjøkelen in western Finnmark had the greatest relative summer balances with 203 % and 188 % of the reference period averages, respectively. This is the greatest summer balances measured on these two glaciers since measurements started in 1970 and 1989, respectively. Rembesdalskåka had the lowest relative summer balance with 103 % of the reference period average.

Annual balance

The annual balance thus was negative for all nine reference glaciers. Langfjordjøkelen and Engabreen had the greatest deficits with -4.1 m w.e. and -3.9 m w.e., respectively, and these are the greatest deficits ever measured on both glaciers.

The results from the mass balance measurements in Norway in 2024 are shown in Table 1-1. Winter (B_w), summer (B_s) and annual balance (B_a) are given in 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 2023/2024 (December-March) the NAO index was positive in December, January and February, and the AO index was only positive in February. The resulting NAO and AO mean was 0.75 and -0.10 respectively for December-March calculated from the monthly means, source: <http://www.cpc.ncep.noaa.gov/>. The NAO and AO indexes vary from year to year (Fig. 1-4). Over the period 1989-2024 the most positive NAO and AO years were in the period with mass surplus from 1989 to 1995 and in some more recent years, e.g., 2012, 2014 and 2015 and 2020.

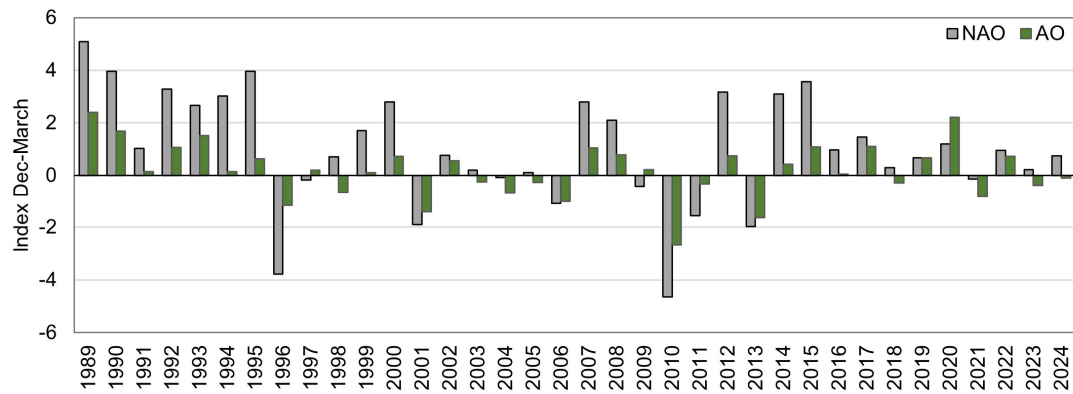


Figure 1-4
NAO and AO index for December–March for 1989–2024. NAO and AO data were downloaded from the NOAA Center for Weather and Climate Prediction (<http://www.cpc.ncep.noaa.gov/>). Figure updated and modified from Andreassen et al. (2020). The large-scale circulation indices NAO and AO are in units 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 2024. 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 reference period 1991-2020. Glacier IDs from the Inventory of Norwegian Glaciers (Andreassen and Winsvold, 2012).

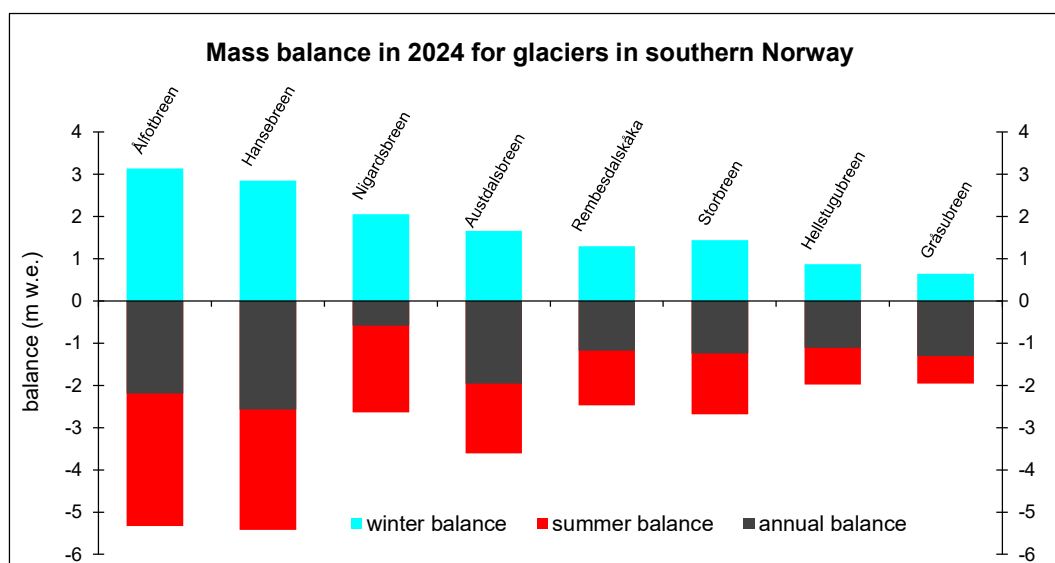
Glacier name	Glacier ID	Period	Area (km ²)	Altitude (m a.s.l.)	B_w (m)	% of ref.	B_s (m)	% of ref.	B_o (m)	B_o ref.	ELA (m a.s.l.)	AAR (%)
Ålfotbreen	2078	1963-24	3.5	1000-1360	3.14	86	-5.33	131	-2.19	-0.42	>1360	0
Hansebreen	2085	1986-24	2.5	927-1303	2.85	83	-5.42	132	-2.57	-0.66	>1303	0
Nigardsbreen	2297	1962-24	44.9	389-1955	2.06	91	-2.64	115	-0.58	-0.05	1680	36
Austdalsbreen	2478	1988-24	10.1	1200-1740	1.66	79	¹⁾ -3.61	134	-1.95	-0.60	>1740	0
Rembesdalskåka	2968	1963-24	17.1	1085-1851	1.30	62	-2.48	103	-1.18	-0.29	>1851	0
Storbreen	2636	1949-24	4.9	1420-2091	1.44	103	-2.68	133	-1.24	-0.62	1920	11
Juvfonne ²⁾	2597	2010-24	0.1	1852-1985	1.80		-2.82		-1.02			
Hellstugubreen	2768	1962-24	2.7	1482-2229	0.87	83	-1.98	117	-1.11	-0.64	2015	18
Gråsubreen	2743	1962-24	1.7	1854-2277	0.65	93	-1.95	146	-1.30	-0.63	>2277	0
Engabreen	1094	1970-24	36.0	177-1532	1.74	64	-5.62	203	-3.88	-0.06	>1532	0
Langfjordjøkelen	54	1989-93	3.7	280-1050						-0.13		
		1996-24	2.6	338-1043	1.70	³⁾ 80	-5.76	³⁾ 188	-4.06	³⁾ -0.94	>1043	0

¹⁾Contribution from calving amounts to -0.19 m for B_s

²⁾Calculated for a point only, b_w , b_s and b_o

³⁾Calculated for the measured periods 1989-93 and 1996-2023

Figure 1-5 presents the mass balance results eight glaciers in southern Norway for 2024. The west-east gradient is evident for both winter and summer balances.

**Figure 1-5**

Mass balance in 2024 in southern Norway. The glaciers are listed from west to east.

The cumulative annual balance for the six long-term glaciers (measured for 62 consecutive years or more) in southern Norway for the period 1963-2024 is shown in Figure 1-6. The maritime glaciers, Ålfotbreen, Nigardsbreen and Rembesdalskåka, showed a marked surplus 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 1963-2024. Note that several of the series have been calibrated (Andreassen et al., 2016).

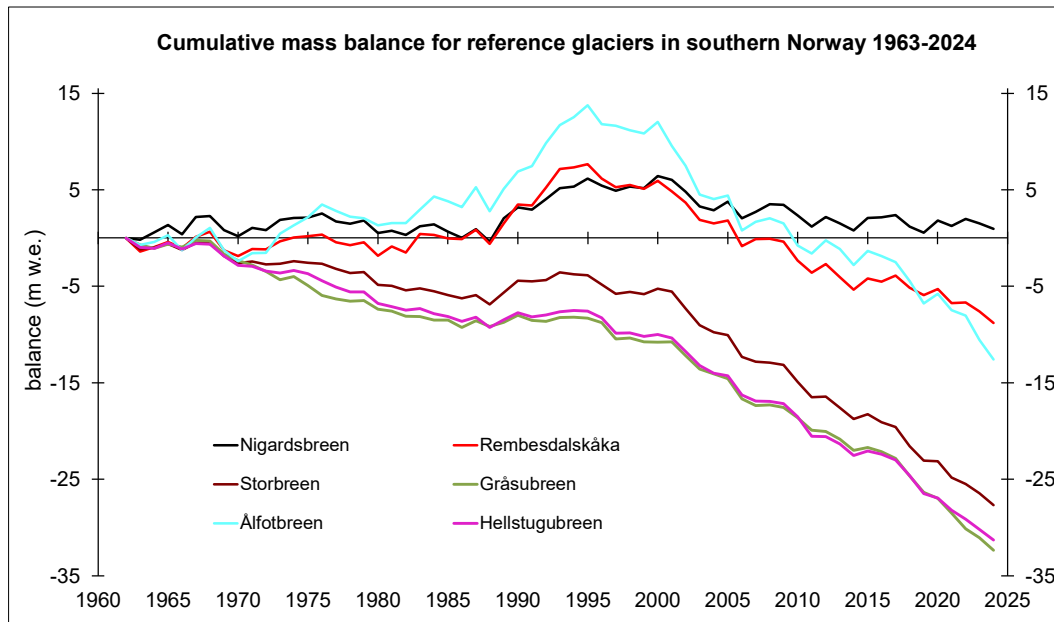


Figure 1-6
Cumulative mass balance for the six long-term glaciers in southern Norway for the period 1963-2024.

1.2 Other investigations

Glacier front change measurements were performed at 35 glaciers in Norway in 2024. Some of the glaciers have record going back to about 1900. The front variations are summarised in chapter 12.

Glacier dynamics (surface velocity) has been studied at Austdalsbreen since 1987 (chap. 4). The measurements continued in 2024.

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

Some jøkulhlaups and runoffs from glacier lakes have occurred in 2024 and these are described in chapter 13.

The research project “JOSTICE” which includes natural and societal consequences of climate-forced changes of the Jostedalsbreen ice cap has been run over the period 2020-2025. Some results are summarized in chapter 14.

2. Ålfotbreen (Bjarne Kjøllmoen)

The Ålfotbreen ice cap (61°45'N, 5°40'E) has an area of 9.3 km² (2019) 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 km², 2019) and Hansebreen (2.5 km², 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 of the ice cap are named on official maps.



Figure 2-1
Ålfotbreen (right) and Hansebreen (left) photographed on 20 September 2024. Photo: Bjarne Kjøllmoen.

2.1 Mass balance 2024

Fieldwork

Snow accumulation measurements were performed on 2 May. The calculation of winter balance was based on 59 and 46 snow depth soundings on Ålfotbreen and Hansebreen, respectively. The sounding conditions were good on both glaciers and the summer surface could easily be detected. Generally, the snow depth varied between 5 and 7 m on Ålfotbreen, and between 5 and 6 m on Hansebreen. Snow density was measured in one location (pos. 28, 1224 m a.s.l.), assumed to be representative for both glaciers (Fig. 2-2). The mean density of the snow pack in position 28 was 526 kg m⁻³. The measured mean snow density for the twenty- year period 2004-2023 is 516 kg m⁻³.

The location of stakes, density pit and soundings are shown in Figure 2-2.

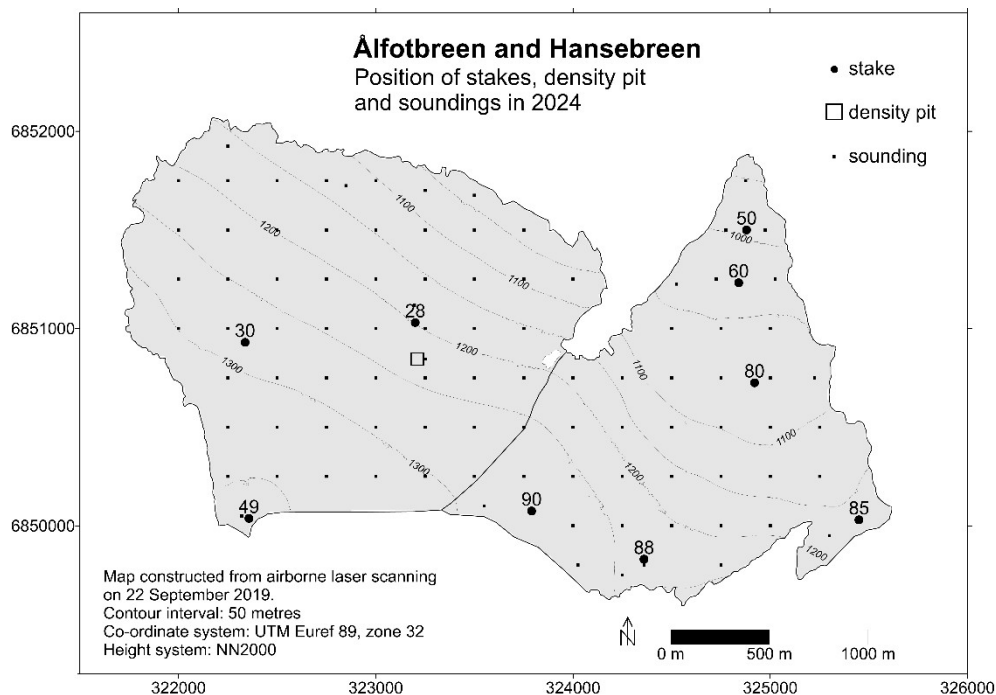


Figure 2-2
Location of stakes, soundings and snow pit on Ålfotbreen (left) and Hansebreen (right) in 2024.

Ablation was measured on 20 September. The annual balance was measured at stakes in three positions on Ålfotbreen and six positions on Hansebreen (Fig. 2-2). At the time of the ablation measurements no fresh snow had fallen. Comparison of stake measurements and snow depth soundings in April 2025 indicated that some melting occurred after the ablation measurements on 20 September 2024. This additional melting is included in the calculation of the mass balance for 2024.

Results

The calculations are based on the DTM from 2019.

All height intervals are represented with point measurements (bw) for both glaciers. However, there are no stake measurements below 1198 m a.s.l. on Ålfotbreen.

The winter balance was calculated as a mean value for each 50-m height interval and was 3.1 ± 0.2 m w.e. on Ålfotbreen, which is 86 % 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 83 % of the mean winter balance for the reference period 1991-2020. Spatial distribution of the winter balance on Ålfotbreen and Hansebreen is shown in Figure 2-3.

The density of melted ice was set as 900 kg m^{-3} . The summer balance for Ålfotbreen was calculated at stakes at three different altitudes, and there were no stake measurements below 1198 m a.s.l. Thus, stake values from the two lowest stakes on Hansebreen (○) were used to support the assessment of the summer balance curve in the lowermost part of Ålfotbreen (Fig. 2-4). The summer balance for Hansebreen was calculated at stakes at six different altitudes.

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 -5.3 ± 0.3 m w.e. on

Ålfotbreen, which is 131 % of the reference period. The summer balance on Hansebreen was -5.4 ± 0.3 m w.e., which is 132 % 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 -2.2 ± 0.4 m w.e. The mean annual balance for the reference period 1991-2020 is -0.42 m w.e.

The annual balance on Hansebreen was -2.6 ± 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 2-4.

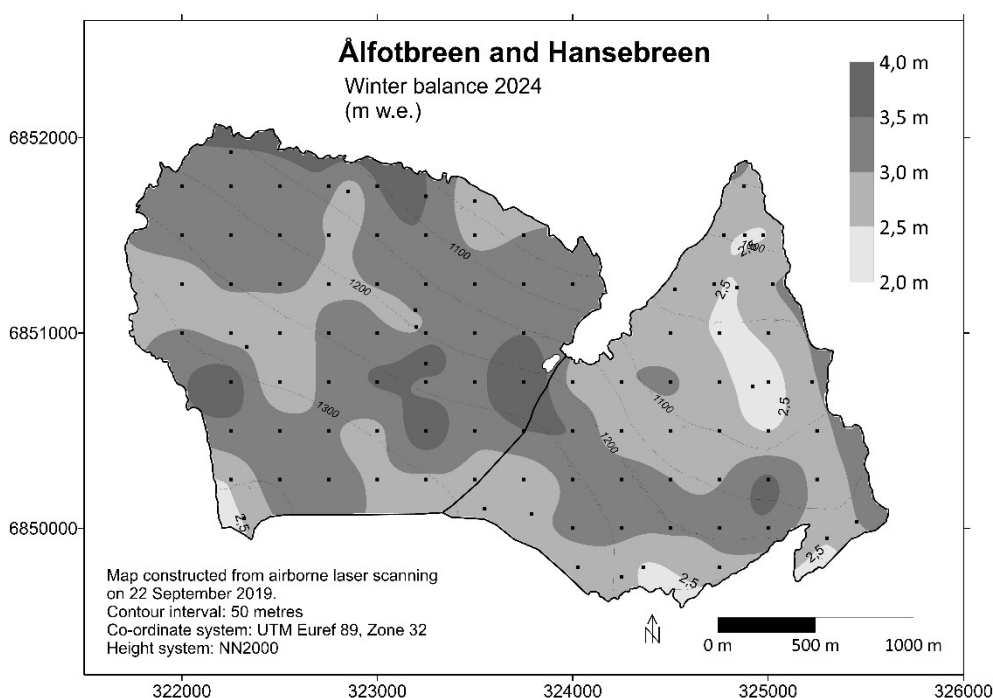


Figure 2-3
Spatial distribution of the winter balance on Ålfotbreen (left) and Hansebreen (right) in 2024.

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

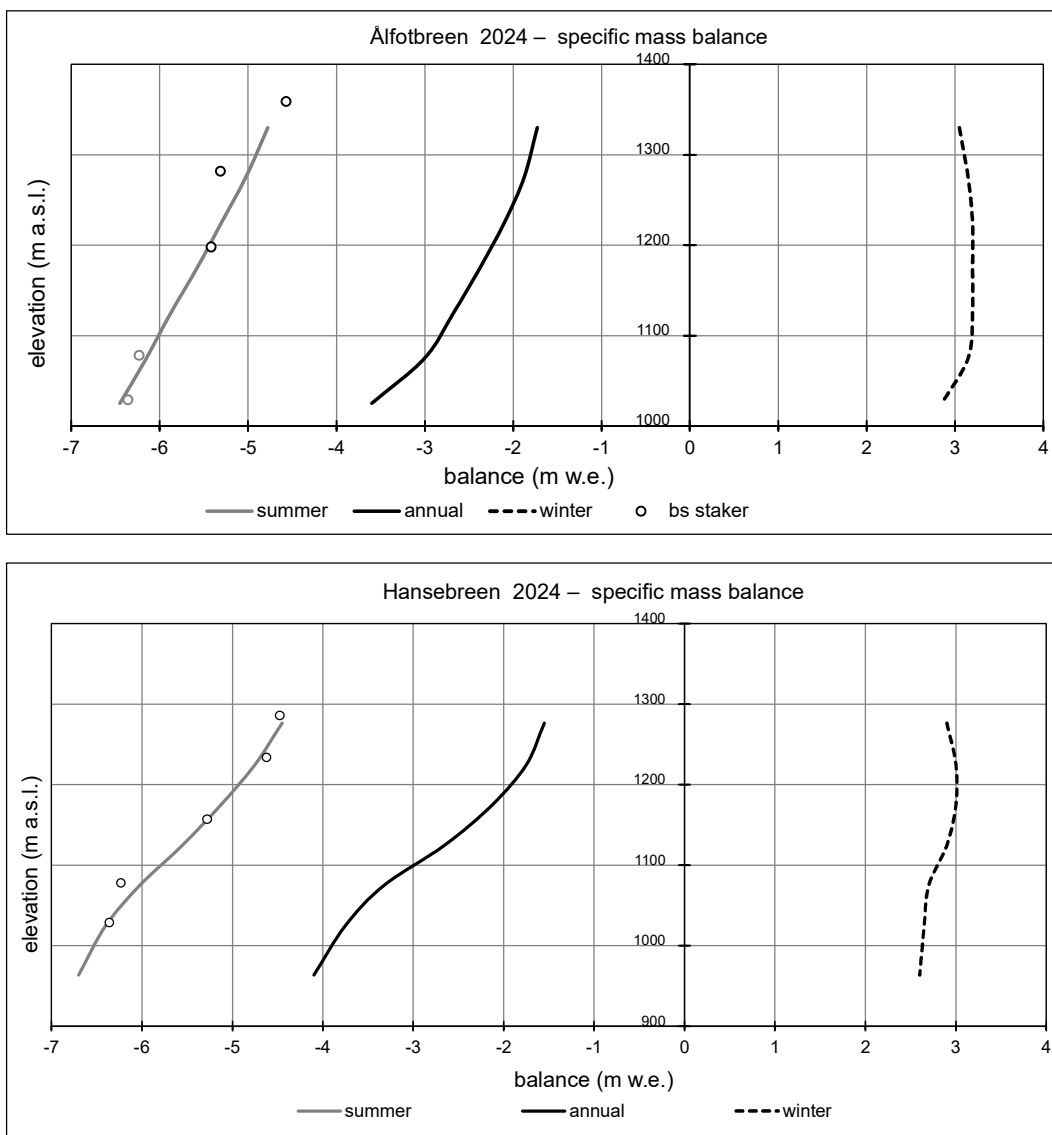


Figure 2-4
Mass balance diagram for Ålfotbreen (upper) and Hansebreen (lower) in 2024 showing altitudinal distribution of specific winter, summer and annual balance. Specific summer balance at each stake is shown (○).

Table 2-1

Winter, summer and annual balance for Ålfotbreen (upper) and Hansebreen (lower) in 2024.

Mass balance Ålfotbreen 2023/24 – stratigraphic system				
Altitude (m a.s.l.)	Area (km ²)	Winter balance Measured 2 May (m w.e.)	Summer balance Measured 20 Sep (m w.e.)	Annual balance S.S. 2023-2024 (m w.e.)
1300 - 1360	0.901	3.050	-4.775	-1.725
1250 - 1300	0.782	3.150	-5.025	-1.875
1200 - 1250	0.699	3.200	-5.300	-2.100
1150 - 1200	0.577	3.200	-5.575	-2.375
1100 - 1150	0.449	3.200	-5.875	-2.675
1050 - 1100	0.296	3.150	-6.150	-3.000
1000 - 1050	0.183	2.850	-6.450	-3.600
Specific mass balance				
1000-1360	3.476	3.141	-5.334	-2.193

Mass balance Hansebreen 2023/24 – stratigraphic system				
Altitude (m a.s.l.)	Area (km ²)	Winter balance Measured 2 May (m w.e.)	Summer balance Measured 20 Sep (m w.e.)	Annual balance S.S. 2023-2024 (m w.e.)
1250 - 1303	0.371	2.900	-4.450	-1.550
1200 - 1250	0.415	3.000	-4.750	-1.750
1150 - 1200	0.389	3.000	-5.125	-2.125
1100 - 1150	0.425	2.900	-5.550	-2.650
1050 - 1100	0.537	2.700	-6.025	-3.325
1000 - 1050	0.243	2.650	-6.400	-3.750
927 - 1000	0.101	2.600	-6.700	-4.100
Specific balance				
927-1303	2.481	2.852	-5.418	-2.566

2.2 Mass balance 1963(86)-2024

The mass balance in 2024 was negative on both glaciers in 2024, -2.2 m w.e. on Ålfotbreen and -2.6 m w.e. on Hansebreen. The historical mass balance results for Ålfotbreen and Hansebreen are presented in Figure 2-5. The cumulative annual balance for Ålfotbreen for 1963-2024 is -12.7 m w.e., which gives a mean annual balance of -0.21 m w.e. a⁻¹. Over the last ten years (2015-2024), the mean annual balance was -0.99 m w.e. The cumulative annual balance for Hansebreen for 1986-2024 is -29.8 m w.e., which gives a mean annual balance of -0.76 m w.e. a⁻¹. Over the last ten years (2015-2024) the mean annual balance was -1.56 m w.e.

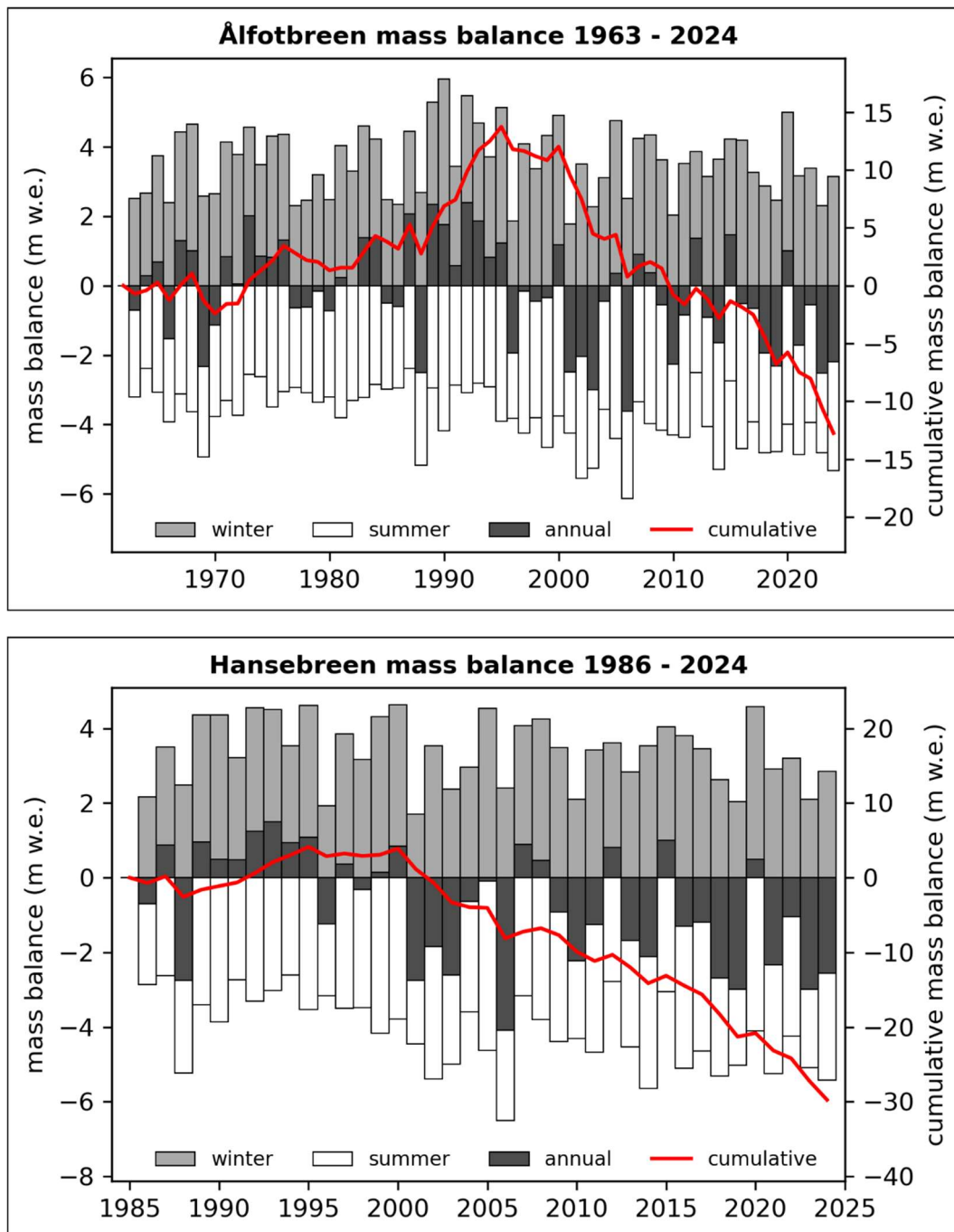


Figure 2-5
Mass balance on Ålfotbreen (upper) 1963-2024 and Hansebreen (lower) 1986-2024. Cumulative mass balance is given on the axis to the right.

3. Nigardsbreen (Bjarne Kjøllmoen)

Nigardsbreen (61°42'N, 7°08'E) is one of the largest and best-known outlet glaciers from Jostedalsgreen. It has an area of 44.9 km² (2020) and flows south-east from the centre of the ice cap (Fig. 3-1). Nigardsbreen accounts for approximately 10 % of the total area of Jostedalsgreen, and extends from 1955 m a.s.l. down to 389 m a.s.l.

Glaciological investigations in 2024 include mass balance and glacier front variations. Nigardsbreen has been the subject of mass balance investigations since 1962.

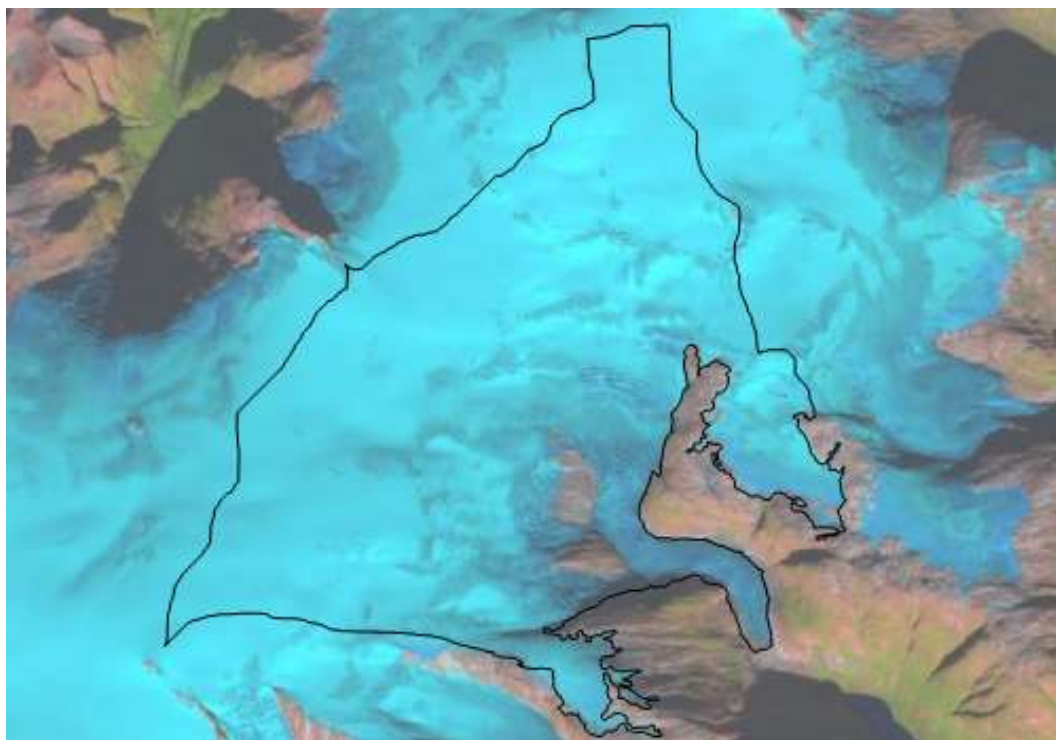


Figure 3-1
Satellite image showing Nigardsbreen on 19 September 2024. Source: senorge.no.

3.1 Mass balance 2024

Fieldwork

Snow accumulation was measured on 14 and 15 May and the calculation of winter balance is based on measurements of stakes and towers in six different positions, and 124 snow depth soundings (Fig. 3-2). Comparison of sounded snow depths and stake readings at the two lowest stakes, 1000 (959 m a.s.l.) and 600 (579 m a.s.l.), indicated 0.25 m melting at both stakes after the ablation measurements on 22 September 2023. This extra melting was taken into account in the winter balance calculations. The sounding conditions were good and the summer surface was easy to identify. On the plateau the snow depth varied between 2.5 and 6.0 m with a mean snow depth of 4.3 m. On the glacier tongue, the snow depth was 2.0 m at stake position 1000 (959 m a.s.l.) and 0.6 m at stake position 600 (579 m a.s.l.). Snow density was measured at position 94 (1682 m a.s.l.), and the mean density of the snowpack was 512 kg m⁻³.

Ablation was measured on 1 October. Measurements were made at stakes and towers in ten locations (Fig. 3-2). In the accumulation area there was up to 2.1 m of snow remaining from winter 2023/24.

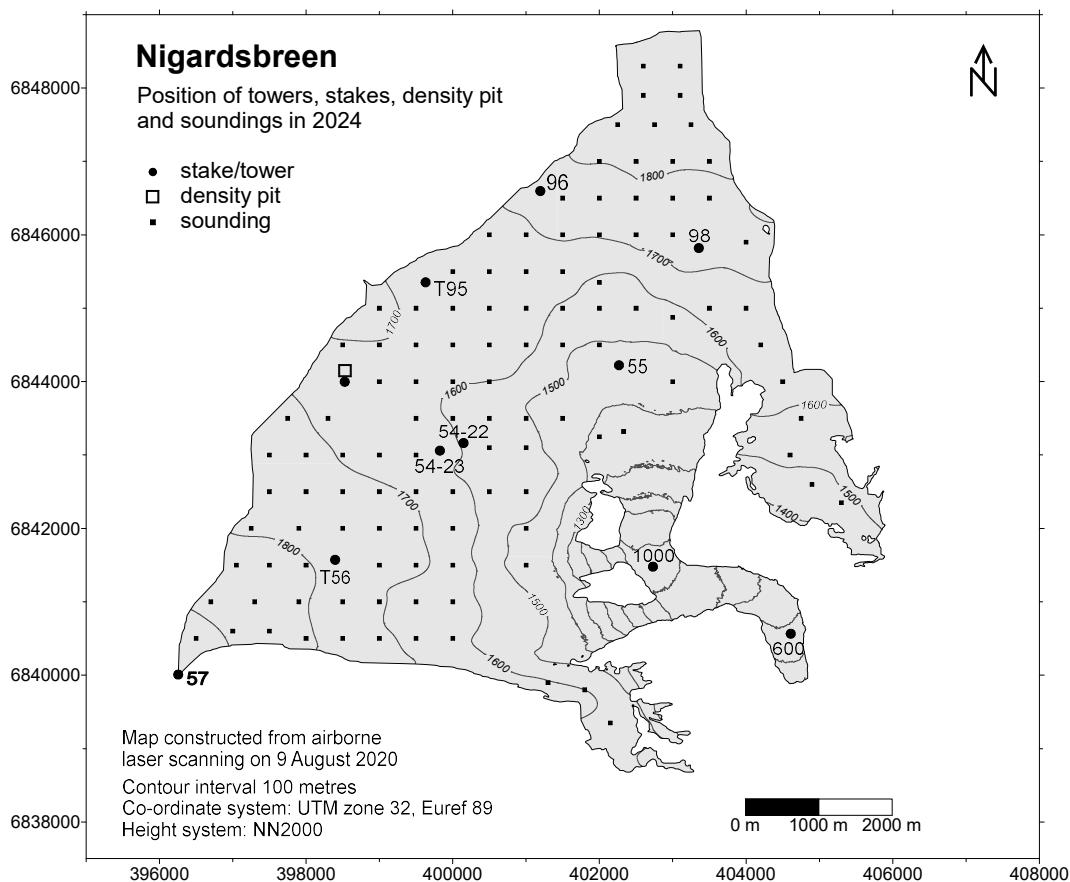


Figure 3-2
Location of towers, stakes, snow pit and soundings on Nigardsbreen in 2024.

Results

The calculations are based on a DTM from 2020.

The areas 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 959 and 579 m elevation.

The winter balance was calculated from mean values for each 100 m height interval and was 2.1 ± 0.2 m w.e., which is 91 % 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 the ice before melting was assumed to be 900 kg m^{-3} . Based on the estimated density and stake measurements the summer balance was calculated for each 100 m height interval and was -2.6 ± 0.3 m w.e., which is 115 % of the reference period.

Hence, the annual balance was negative, at $-0.58 \text{ m} \pm 0.40 \text{ m w.e.}$ 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 balances are shown in Figure 3-4.

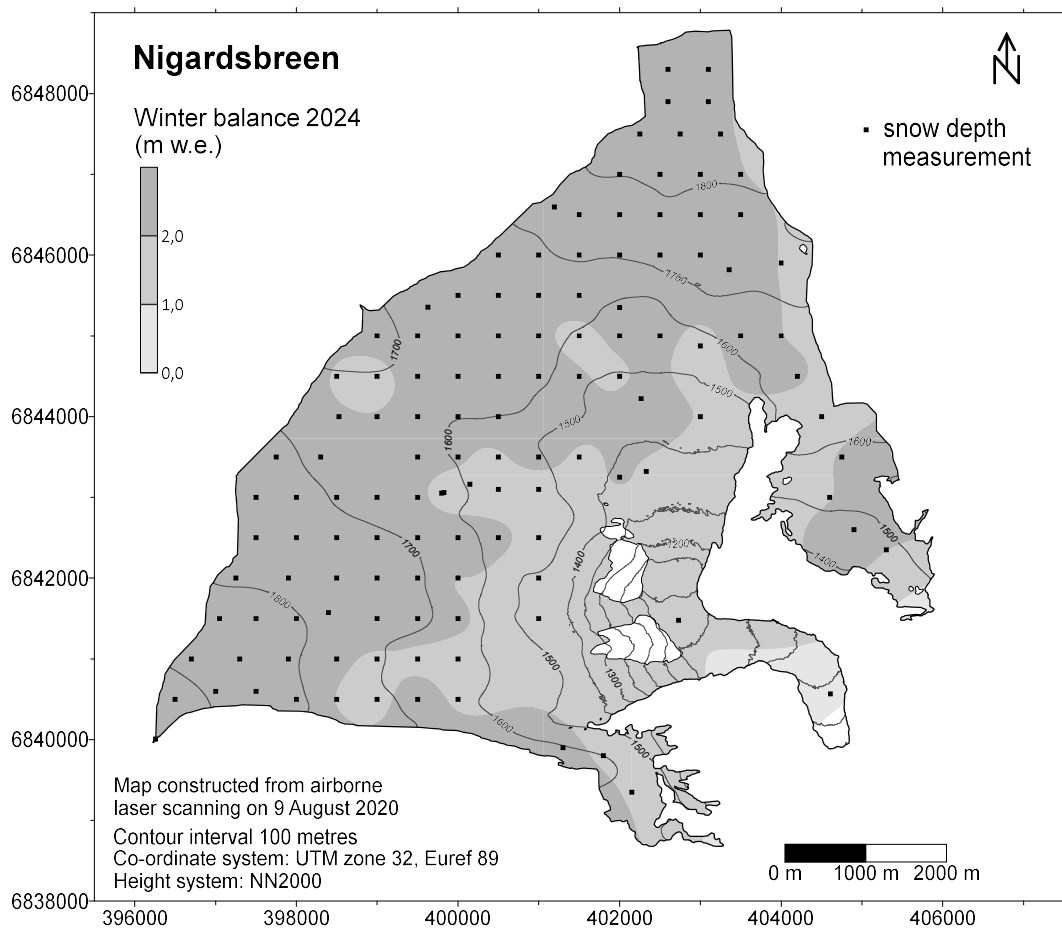


Figure 3-3
Spatial distribution of winter balance on Nigardsbreen in 2024.

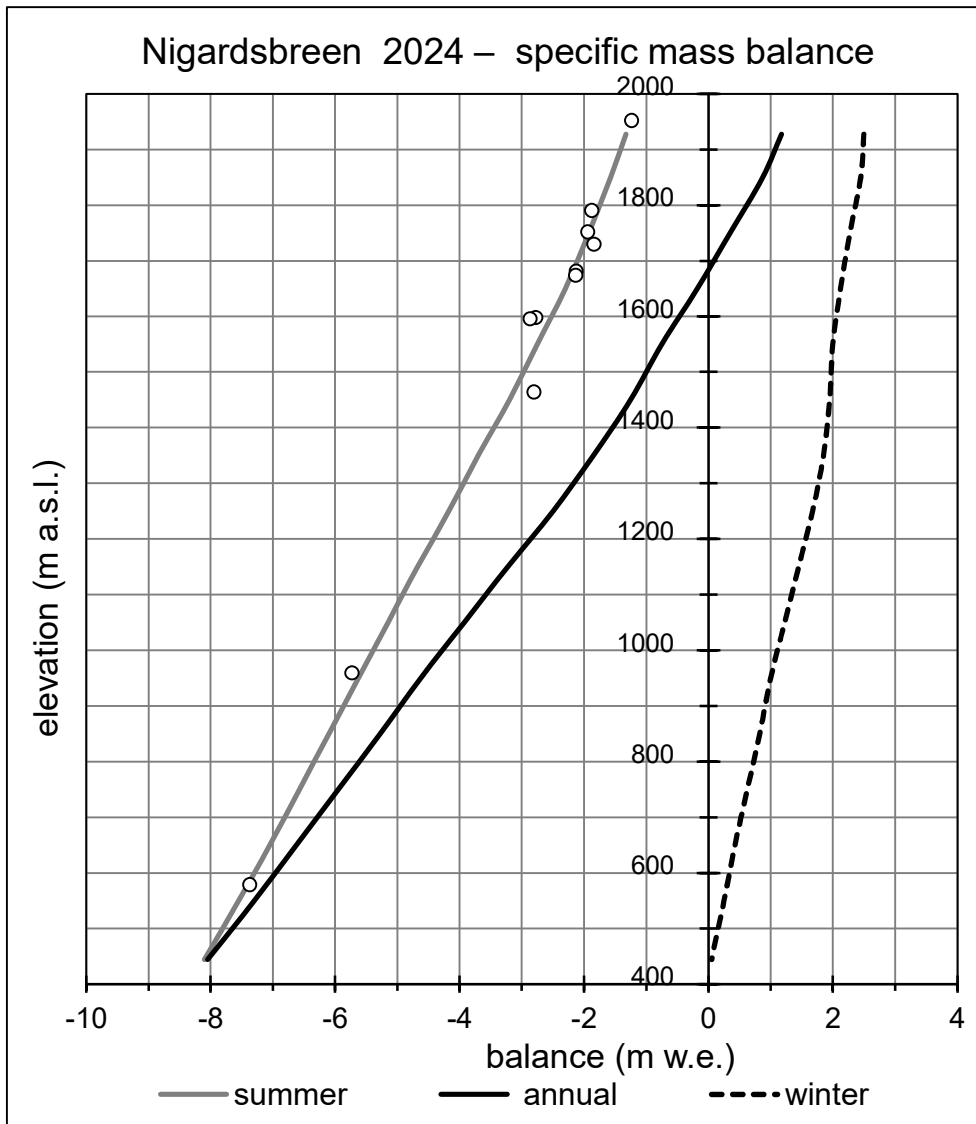


Figure 3-4
Mass balance diagram showing specific balance for Nigardsbreen in 2024. Specific summer balance at 10 different stake locations is shown as circles (○).

According to Figure 3-4, the equilibrium line altitude was 1680 m a.s.l. Consequently, the accumulation area ratio (AAR) was 36 %.

Table 3-1

The altitudinal distribution of winter, summer and annual balance in 100-m intervals for Nigardsbreen in 2024.

Mass balance Nigardsbreen 2023/24 – stratigraphic system				
Altitude (m a.s.l.)	Area (km ²)	Winter balance Measured 4 May (m w.e.)	Summer balance Measured 22 Sep (m w.e.)	Annual balance S.S. 2022-2023 (m w.e.)
1900 - 1955	0.310	2.500	-1.325	1.18
1800 - 1900	4.056	2.450	-1.575	0.88
1700 - 1800	9.194	2.275	-1.925	0.35
1600 - 1700	12.738	2.125	-2.300	-0.18
1500 - 1600	8.938	2.000	-2.750	-0.75
1400 - 1500	5.921	1.950	-3.200	-1.25
1300 - 1400	2.082	1.850	-3.700	-1.85
1200 - 1300	0.787	1.675	-4.175	-2.50
1100 - 1200	0.390	1.450	-4.675	-3.23
1000 - 1100	0.580	1.225	-5.150	-3.93
900 - 1000	0.456	1.000	-5.625	-4.63
800 - 900	0.471	0.825	-6.100	-5.28
700 - 800	0.321	0.625	-6.575	-5.95
600 - 700	0.405	0.425	-7.050	-6.63
500 - 600	0.261	0.250	-7.550	-7.30
389 - 500	0.157	0.050	-8.100	-8.05
Specific mass balance				
389-1955	44.945	2.055	-2.638	-0.583

3.2 Mass balance 1962-2024

The historical mass balance results for Nigardsbreen 1962-2024 are presented in Figure 3-5. The cumulative annual balance for 1962-2024 is +3.2 m w.e., which gives a mean annual balance of +0.06 m w.e. a⁻¹. Over the past ten years (2015-2024), the mean annual balance was +0.02 m w.e.

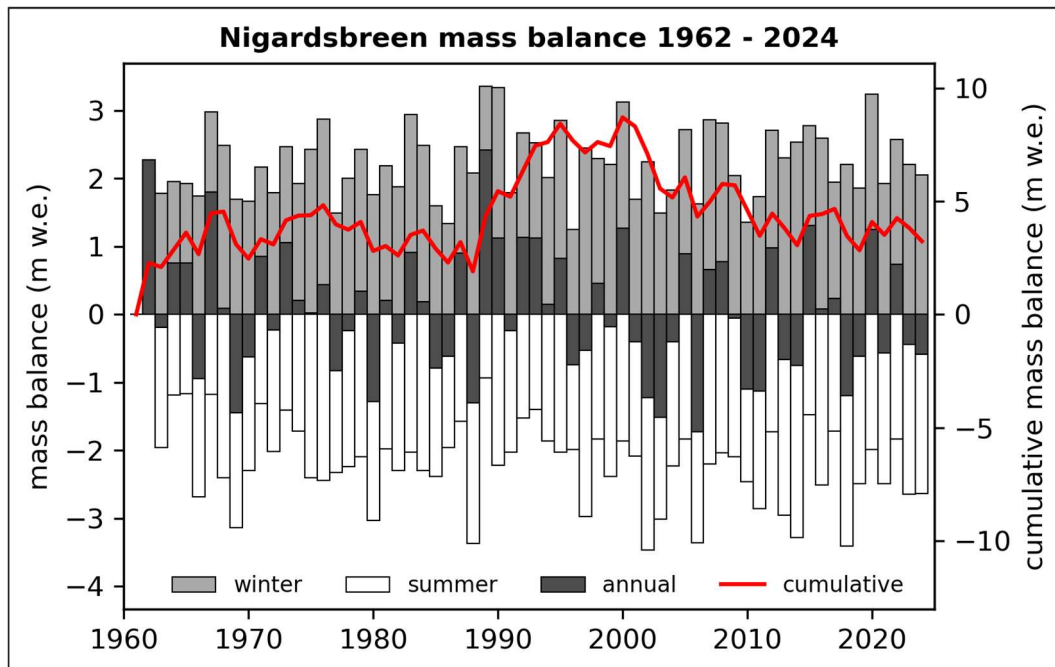


Figure 3-5
Winter, summer and annual balance on Nigardsbreen for 1962-2024. Cumulative mass balance is given on the right axis.

4. Austdalsbreen (Hallgeir Elvehøy)

Austdalsbreen (61°45'N, 7°20'E) is an eastern outlet of the northern part of Jostedalsglacier, 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 on Austdalsbreen started in 1986 in connection with the construction of the hydropower reservoir. The glaciological investigations in 2024 included mass balance, front position change and glacier velocity. The mass balance has been measured on Austdalsbreen since 1988.



Figure 4-1
Austdalsbreen on 6 September 2024. The lake level was 1195 m a.s.l., 5 meters below the highest regulated lake level at 1200 m a.s.l. Photo: Jostein Aasen.

4.1 Mass balance 2024

Fieldwork

Stakes were maintained through the winter in five stake locations. Snow accumulation measurements were performed on 14 May. The calculation of the winter balance was based on measurements in seven stake locations and 41 snow depth sounding locations (Fig. 4-2). Detecting the summer surface was easy. Most of the snow depth measurements were between 2.8 and 4 meters, and the average snow depth was 3.4 meters. The mean density of the snowpack down to 3.2 meters at stake A60 (1480 m a.s.l.) was 474 kg m^{-3} . Here the summer surface was at 3.35 m depth.

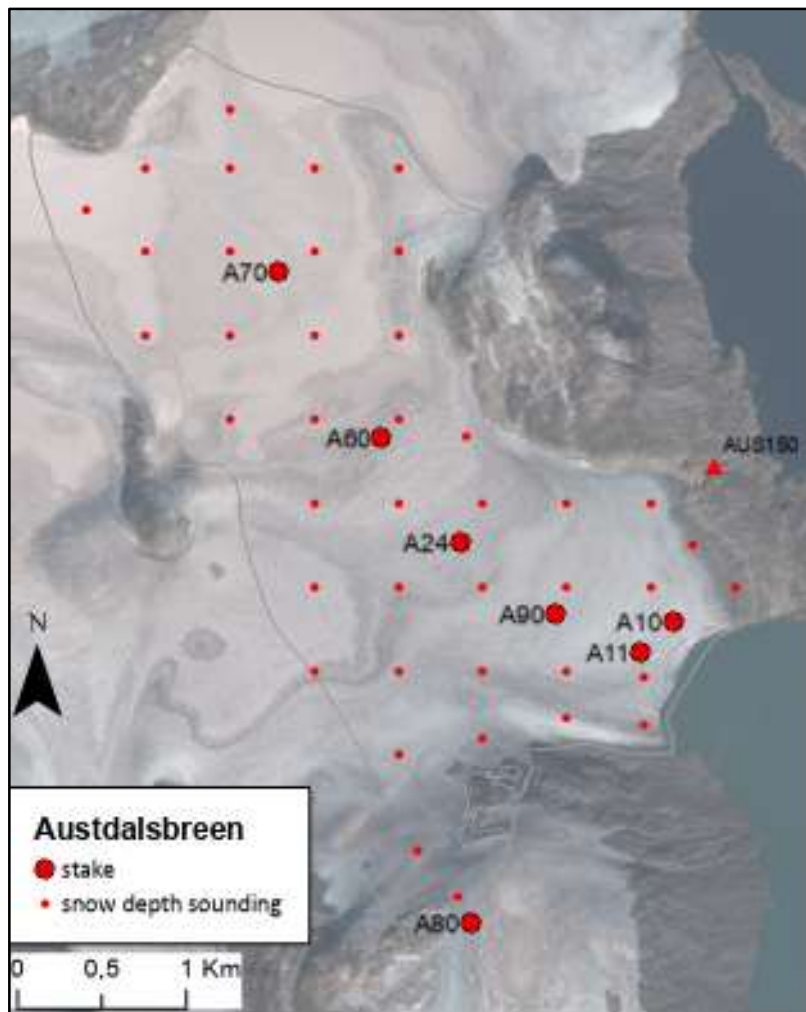


Figure 4-2
 Location of stakes and snow depth soundings on a true-colour satellite image from 19 September 2024. All the winter snow had melted. The 2019 basin outline and terminus position is shown in grey.
 Source: Copernicus Sentinel-2 (2024).

Summer and annual balance measurements were carried out on 1 October. Stakes were found in all the seven stake locations. All the winter snow had melted in all stake locations. In addition, between 0.95 and 4.6 meters of firn and ice had melted during the summer at the stake locations (Fig. 4-3).

The stakes on the lower part of the glacier were re-measured and snow depth sounded on 8 December 2024, indicating no additional melt after 1 October.



Figure 4-3

The southern, steep part of Austdalsbreen on Austdalsnosi as seen from stake A24 on 6 September 2024. Stake A80 is located close to the summit (see Fig. 4-2 for location). Photo: Jostein Aasen.

Results

The calculations are based on a DEM from 27 August 2019. The winter balance was calculated from snow depth and snow density measurements on 14 May. 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. 4-4). The total winter balance was 17 ± 2 mill. m^3 water or 1.7 ± 0.2 m w.e., which is 79 % of the 1991-2020 average (2.11 m w.e.).

The summer balance was calculated for all seven stake locations between 1280 and 1715 m a.s.l. The density of the melted firn from 2019/20 (at A70), melted older firn and melted ice was set as 850, 850 and 900 kg/m^3 , respectively. The summer balance curve was drawn from these seven point values (Fig. 4-4).

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:

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

where ρ_{ice} is 900 kg m^{-3} , u_{ice} is annual glacier velocity ($23 \pm 10 \text{ m a}^{-1}$), u_f is front position change averaged across the terminus ($-34 \pm 5 \text{ m a}^{-1}$), W is terminus width ($865 \pm 20 \text{ m}$)

and H is mean ice thickness at the terminus (42 ± 5 m). The width of the calving terminus was defined from an orthophoto from 27 August 2019. The mean ice thickness was calculated from the mean surface elevation along the calving terminus on 22 September 2023 and 1 October 2024, and mean bottom elevation along the termini calculated from a bathymetry map (Kjøllmoen and others, 2020). The resulting calving volume was 1.9 ± 0.8 mill. m³ water equivalent. The summer balance including calving was calculated as -37 ± 3 mill. m³ of water, and corresponds to -3.6 ± 0.3 m w.e. The result is 134 % of the 1991-2020 average (-2.70 m w.e.). The calving volume was 5 % of the summer balance.

The annual balance on Austdalsbreen was calculated as -20 ± 3 mill. m³ water, corresponding to -2.0 ± 0.3 m w.e. The average annual balance for the period 1991-2020 is -0.60 m w.e. The ELA in 2024 was above the summit at 1740 m a.s.l., and consequently the AAR was 0 %. The altitudinal distribution of winter, summer and annual balance is shown in Table 4-1 and Figure 4-4. Results from 1988-2024 are shown in Figure 4-5.

Table 4-1
Altitudinal distribution of specific winter, summer, and annual balances for Austdalsbreen in 2024.

Mass balance Austdalsbreen 2023/24 - stratigraphic system				
Altitude (m a.s.l.)	Area (km ²)	Winter balance Measured 14 May (m w.e.)	Summer balance Measured 1 Oct (m w.e.)	Annual balance Summer surface 2023 - 2024 (m w.e.)
1700 - 1740	0.09	1,50	-2,65	-1,15
1650 - 1700	0.119	1,65	-2,70	-1,05
1600 - 1650	0.172	1,75	-2,75	-1,00
1550 - 1600	1.584	1,90	-2,80	-0,90
1500 - 1550	2.748	1,90	-2,85	-0,95
1450 - 1500	1.503	1,60	-3,30	-1,70
1400 - 1450	1.594	1,60	-3,70	-2,10
1350 - 1400	0.952	1,40	-4,15	-2,75
1300 - 1350	0.721	1,20	-4,60	-3,40
1250 - 1300	0.457	1,20	-5,00	-3,80
1200 - 1250	0.182	1,25	-5,45	-4,20
Calving			-1,873 mill m ³	-1,873 mill m ³
Specific mass balance including calving				
1200 - 1740	10,121	1,659	-3,613	-1,954

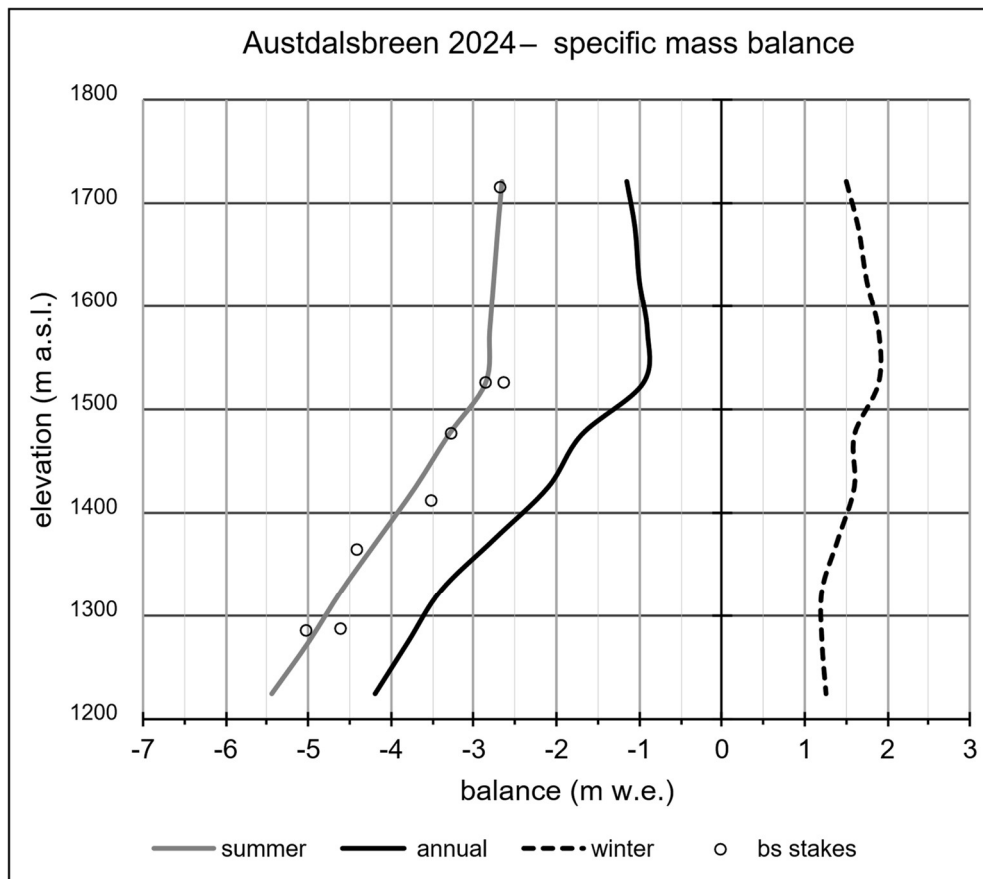


Figure 4-4
Hypsometric areal distribution (grey bars) and altitudinal distribution of specific winter, summer, and annual balance on Austdalsbreen in 2024. Specific summer balance in seven stake locations is shown.

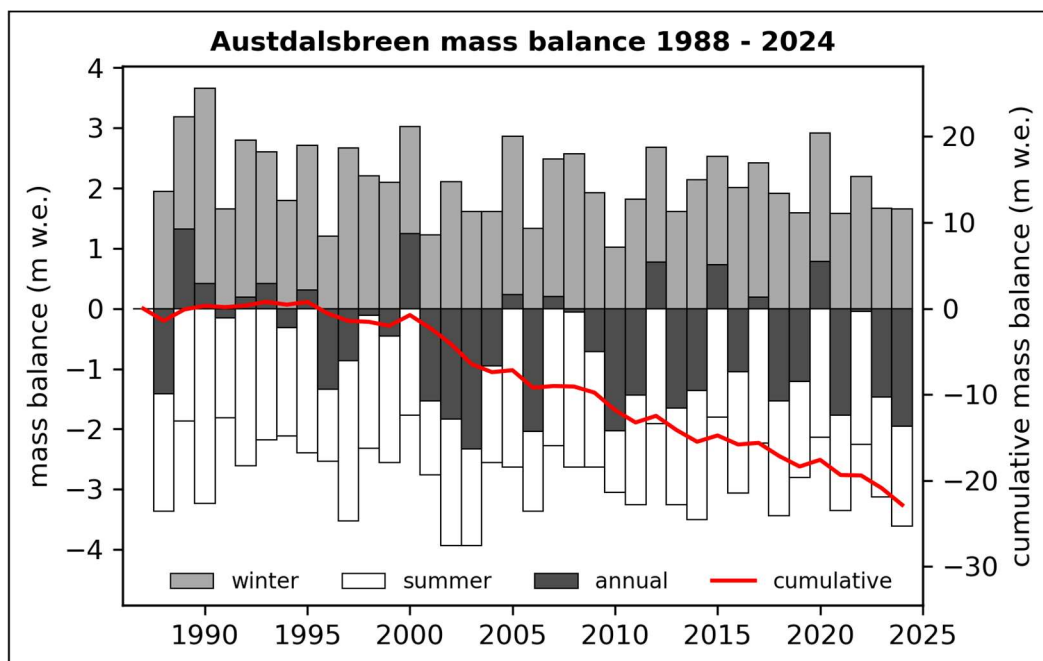


Figure 4-5
Winter, summer, annual and cumulative balance on Austdalsbreen during the period 1988-2024. Mean winter and summer balance is 2.14 and -2.76 m w.e., respectively. The cumulative mass balance is -22.9 m w.e.

4.2 Front position change

The terminus position and elevation were surveyed using GNSS from a helicopter on 1 October. The average front position change between 22 September 2023 and 1 October 2024 was -34 ± 5 m (Fig. 4-6). The glacier terminus had retreated 744 m since 1988, and the lake area had increased by 0.748 km^2 .

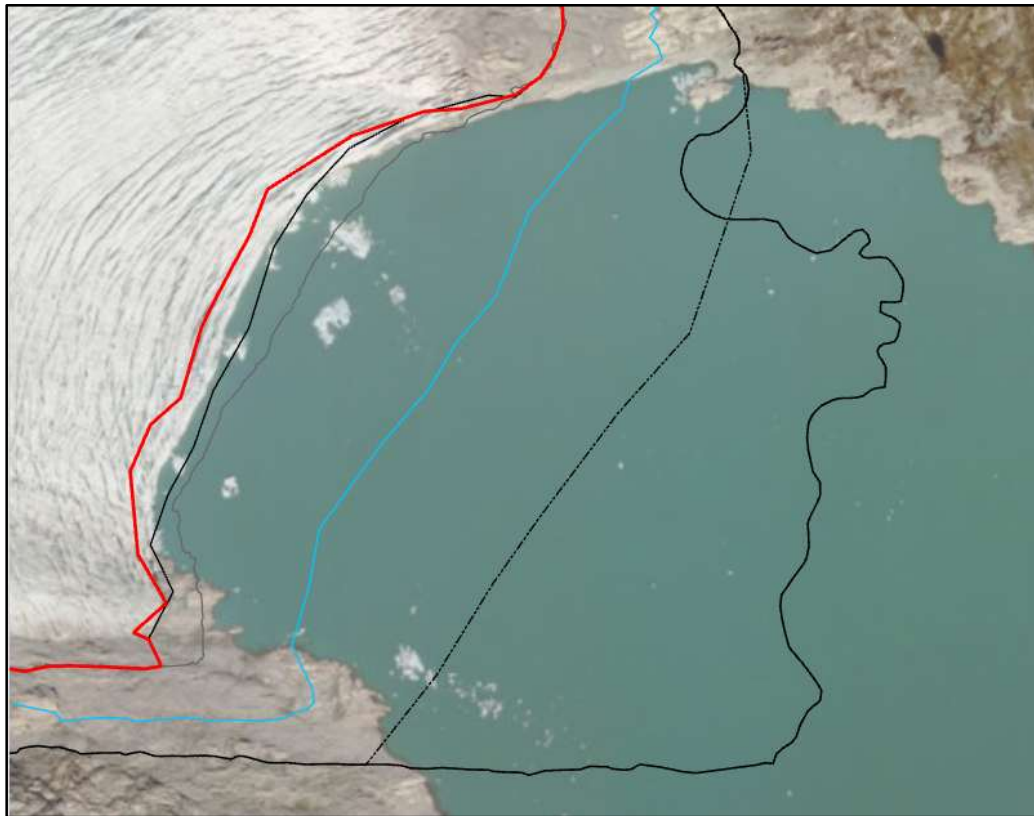


Figure 4-6
Surveyed front positions of Austdalsbreen in Styggevatnet on 1 October 2024 (red), 22 September 2023 (black), 2019 (grey), 20019 (blue) and in 1988 (largest) and in 1997 (dotted line). The background is an orthophoto from 1 September 2024 from www.norgebilder.no.

4.3 Glacier dynamics

Glacier velocities are calculated from repeated surveys of stakes. The stake network was surveyed on 31 August and 22 September 2023, and on 14 May, 21 August, 6 September and 1 October 2024. Annual velocities were calculated for five stake locations between 1250 and 1500 m a.s.l. for periods between August 2023 and September 2024 (ca. 360 days). The annual results are comparable to results from 2011-15 (Kjøllmoen and others, 2016).

The glacier velocity averaged across the front width and thickness was estimated to calculate the calving volume. We assume the average of A10 and A11 is representative for the centre line surface velocity. The annual velocity at stake A10 and A11 between 31 August 2023 and 21 August 2024 was 31 and 40 m a^{-1} , respectively. The glacier velocity averaged over the cross-section is calculated as 70 % of the central surface velocity based on earlier measurements and estimates of the amount of glacier sliding at the bed. The resulting cross-sectional mean velocity for 2023/24 is $23 \pm 10 \text{ m a}^{-1}$.

5. Rembesdalskåka (Hallgeir Elvehøy)

Rembesdalskåka (17 km², 60°32'N, 7°22'E) is a southwestern outlet glacier from Hardangerjøkulen (Fig. 5-1), the sixth largest (64 km²) 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 annual jøkulhlaups have occurred, but they have been captured by the Rembesdalsvatnet reservoir, thus causing no damage. In 2024 a jøkulhlaup occurred on 3 June 2024 (chap. 13).

Front variations have been measured annually since 1995. After an advance culminating in 2000, measurements show a frontal retreat of 461 metres (chap. 12).

Mass balance measurements were initiated on Rembesdalskåka in 1963 by Norwegian Polar Institute. 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
Rembesdalskåka on 18 September 2024. Photo: Hallgeir Elvehøy.

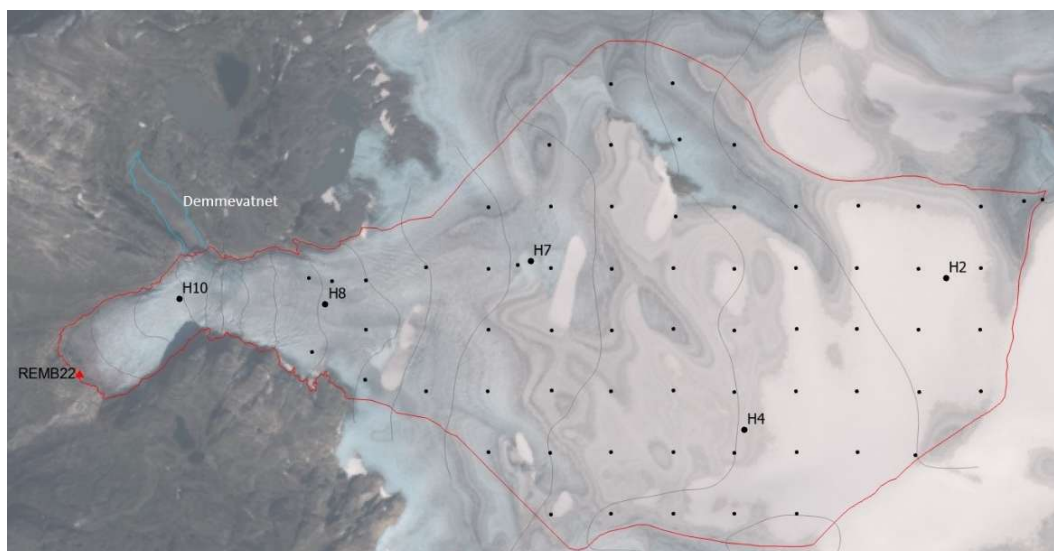


Figure 5-2
Location of stakes and snow depth soundings on Rembesdalskåka in 2024. The background is a true-colour image from 6 September 2024. The brightest snow between H4 and H2 is firn from 2022. Source: Copernicus Sentinel-2 (2024).

Mass balance 2024

Fieldwork

Stakes in locations H2, H4 and H10 were maintained through the winter (Fig. 5-2). The snow accumulation was measured on 11 June. Snow depth was measured in 63 sounding locations in a 500 by 500 m grid on the glacier plateau above 1490 m a.s.l. The average snow depth on the plateau was 2.6 meters and varied between 0.4 and 3.9 meters. The summer surface (S.S.) was well defined. The mean snow density down to the summer surface at 2.3 meters depth at stake H7 (1650 m a.s.l.) was 528 kg m^{-3} .

Summer and annual balances were measured on 18 September. All the winter snow had melted at the stake locations (Fig. 5-2). Up to 0.55 meters of additional ice melting was measured on 8 November. At stake H10 (1245 m a.s.l.) all the winter snow and 5.7 meters of ice had melted (Fig. 5-3). At the upper-most stake H2 (1820 m a.s.l.) 3.45 m of winter snow and 0.25 m of firn from 2022 had melted.

Results

The calculation of the mass balance is based on a DEM from 2020. The winter balance was calculated from the snow depth and snow density measurements on 11 June. A function correlating snow depth and water equivalent values was calculated based on the snow density measurement. 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. 5-4). Below 1500 m a.s.l. the winter balance curve was interpolated from the measurements at stakes H8 (1510 m a.s.l.) and H10 (1250 m a.s.l.). A value for each 50 m elevation was then determined from this curve. The resulting winter balance was $1.3 \pm 0.2 \text{ m w.e.}$ corresponding to $22 \pm 3 \text{ mill. m}^3 \text{ water}$. This is 62 % of the 1991-2020 average of $2.10 \text{ m w.e. a}^{-1}$.

The date of the 2024 mass balance minimum on the glacier plateau and on the glacier tongue was assessed from the daily gridded data of temperature and new snow from www.senorge.no as 15 September above 1700 m a.s.l. and 21 October below 1700 m a.s.l.

The summer balance was calculated directly at all five stake locations. The density of the melted firn at H2, H4 and H7 was set as 600, 650 and 700 kg m⁻³, respectively, and the density of the ice that melted at H10 and H8 was set as 900 kg m⁻³.

The summer balance curve in Figure 5-4 was drawn from five point values. The summer balance was calculated as -2.5 ± 0.2 m w.e., corresponding to -42 ± 3 mill. m³ of water. This is 103 % of the 1991-2020 average of -2.40 m w.e. a⁻¹. The annual balance on Rembesdalskåka was calculated as -1.2 ± 0.3 m w.e. or -20 ± 5 mill. m³ water. The 1991-2020 average is -0.29 m w.e. a⁻¹. The ELA in 2024 was above the summit of Hardangerjøkulen 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 5-4 and Table 5-1. The cumulative annual balance over the measurement period 1963-2024 is -8.8 m w.e. (Fig. 5-5). However, since 1995 the glacier has had a mass deficit of -16.5 m w.e. or -0.57 m w.e. a⁻¹.



Figure 5-3

Stake H10 was re-drilled using a Heucke steam drill on 18 September 2024. The stake was surveyed using a GNSS. The old cabin Demmevasshytta is visible in the upper right corner. Photo: Hallgeir Elvehøy.

Table 5-1

Altitudinal distribution of winter, summer, and annual mass balance on Rembesdalskåka in 2024. All values are in meter water equivalents.

Mass balance Rembesdalskåka 2023/24 – stratigraphic system				
Altitude (m a.s.l.)	Area (km ²)	Winter balance	Summer balance	Annual balance
		Measured 11 June (m w.e.)	Measured 8 November (m w.e.)	Summer surfaces 2023 - 2024 (m w.e.)
1800 - 1851	2,825	1,60	-2,05	-0,45
1750 - 1800	4,059	1,65	-2,10	-0,45
1700 - 1750	4,130	1,55	-2,10	-0,55
1650 - 1700	2,267	1,20	-2,10	-0,90
1600 - 1650	1,167	0,95	-2,30	-1,35
1550 - 1600	0,534	0,80	-3,20	-2,40
1500 - 1550	0,523	0,65	-4,10	-3,45
1450 - 1500	0,381	0,50	-4,40	-3,90
1400 - 1450	0,201	0,35	-4,60	-4,25
1350 - 1400	0,107	0,20	-4,80	-4,60
1300 - 1350	0,071	0,05	-5,00	-4,95
1250 - 1300	0,126	-0,10	-5,20	-5,30
1200 - 1250	0,202	-0,25	-5,40	-5,65
1150 - 1200	0,289	-0,40	-5,60	-6,00
1100 - 1150	0,194	-0,55	-5,80	-6,35
1085 - 1100	0,010	-0,65	-5,95	-6,60
Specific mass balance				
1085 - 1851	17,086	1,300	-2,476	-1,176

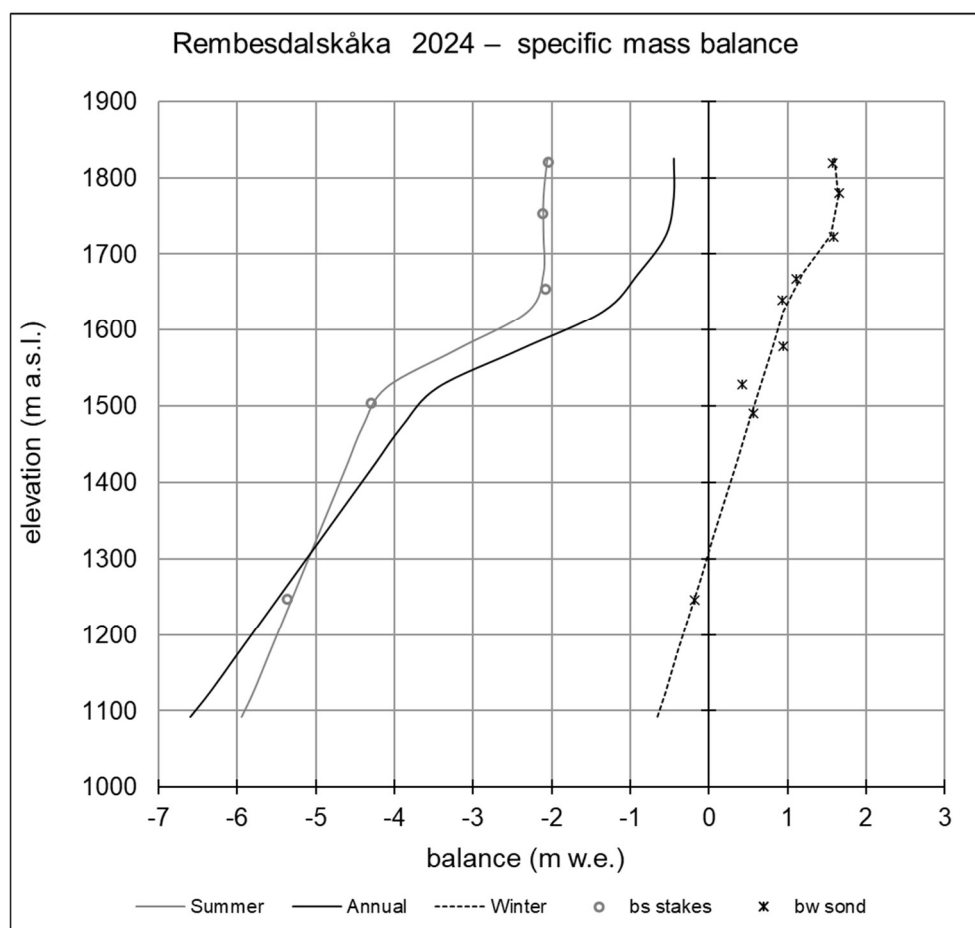


Figure 5-4

Altitudinal distribution of specific winter, summer, and annual mass balance in 2024. Average specific winter balance for snow depth soundings in 50-meter elevation bins (x) and specific summer balance, b_s, in five stake locations (o) is shown.

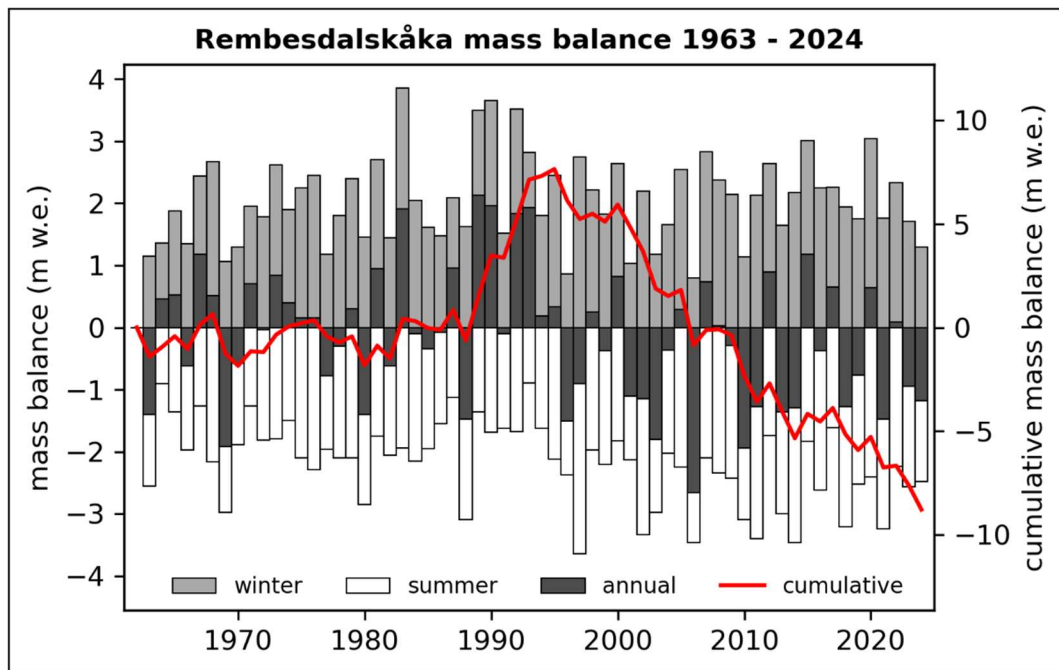


Figure 5-5
Winter, summer, annual and cumulative mass balance on Rembesdalskåka during the period 1963-2024. Mean values (1963-2024) are $B_w=2.05 \text{ m w.e a}^{-1}$ and $B_s=-2.19 \text{ m w.e a}^{-1}$.



Figure 5-6
Stake H721B was surveyed using a GNSS on 18 September 2024. All the winter snow had melted. The nunatak Olavvarden is in the background. Photo: Hallgeir Elvehøy.

6. Storbreen (Liss M. Andreassen)

Storbreen (61°34'N, 8°8'E) (now written as “Storbreen” on official maps) 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).

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 2024 was calculated based on the DTM and glacier outline from 2019.

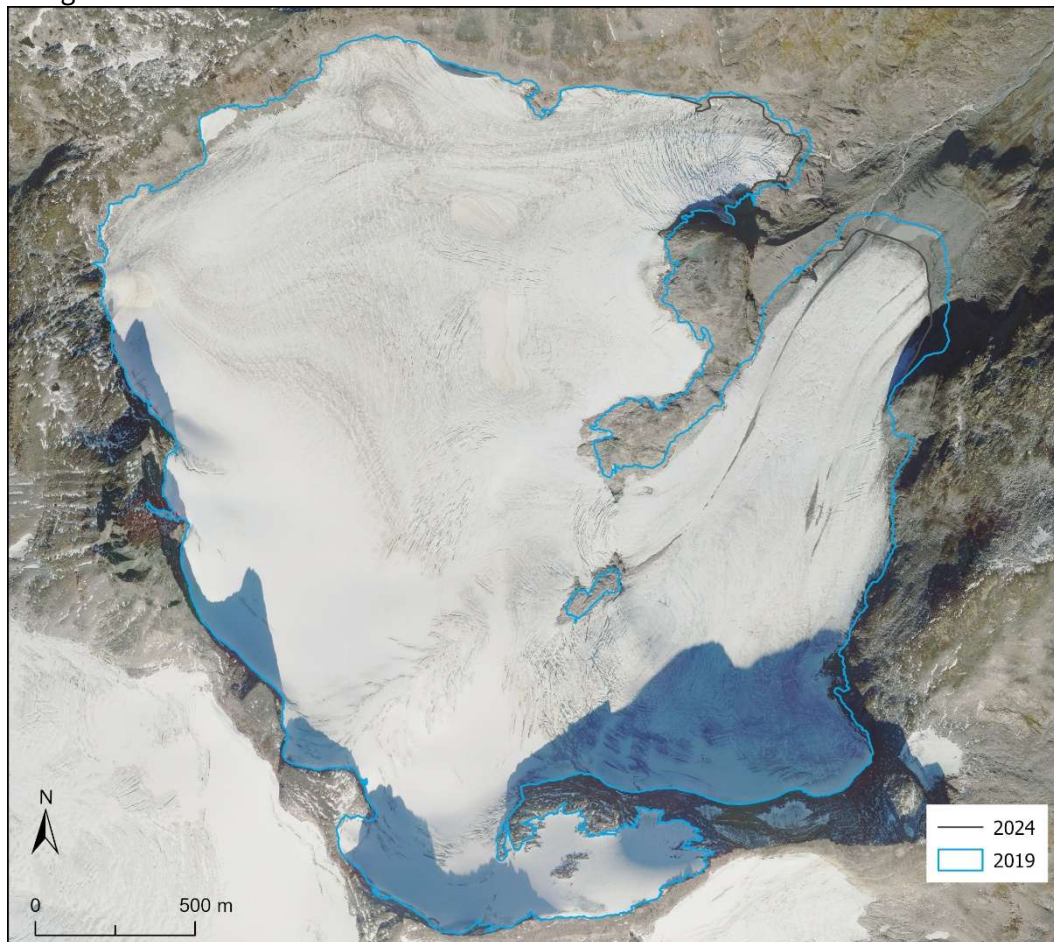


Figure 6-1
Orthophoto of Storbreen on 18 September 2024. The 2019 outline and part of 2024 terminus extent are shown to illustrate the retreat between 2019 and 2024. Orthophoto from [Norgebilder.no](https://norgebilder.no/)/Norwegian Mapping Authority.
© Statens kartverk, Geovekst og kommunene, Innlandet NV 2024.

6.1 Mass balance 2024

Field work

Snow accumulation measurements were performed on 2 May on the lower tongue (stake 1-3) and on 3 May on the upper part (stakes 4-9) (Fig. 6-2). Stakes were visible in six positions. A total of 86 snow depth soundings between 1449 and 2012 m a.s.l. were made (Fig. 6-2). The snow depth varied between 2.00 and 5.60 m, the mean and median

being 3.11 and 3.00 m, respectively. Snow density was measured at stake 4 (1703 m a.s.l.) where the total snow depth was 2.9 m. The average snow density measured was 430 kg m^{-3} . Extra field visits were done in July to drill stakes. Ablation measurements were performed on 18 September at all stake positions.

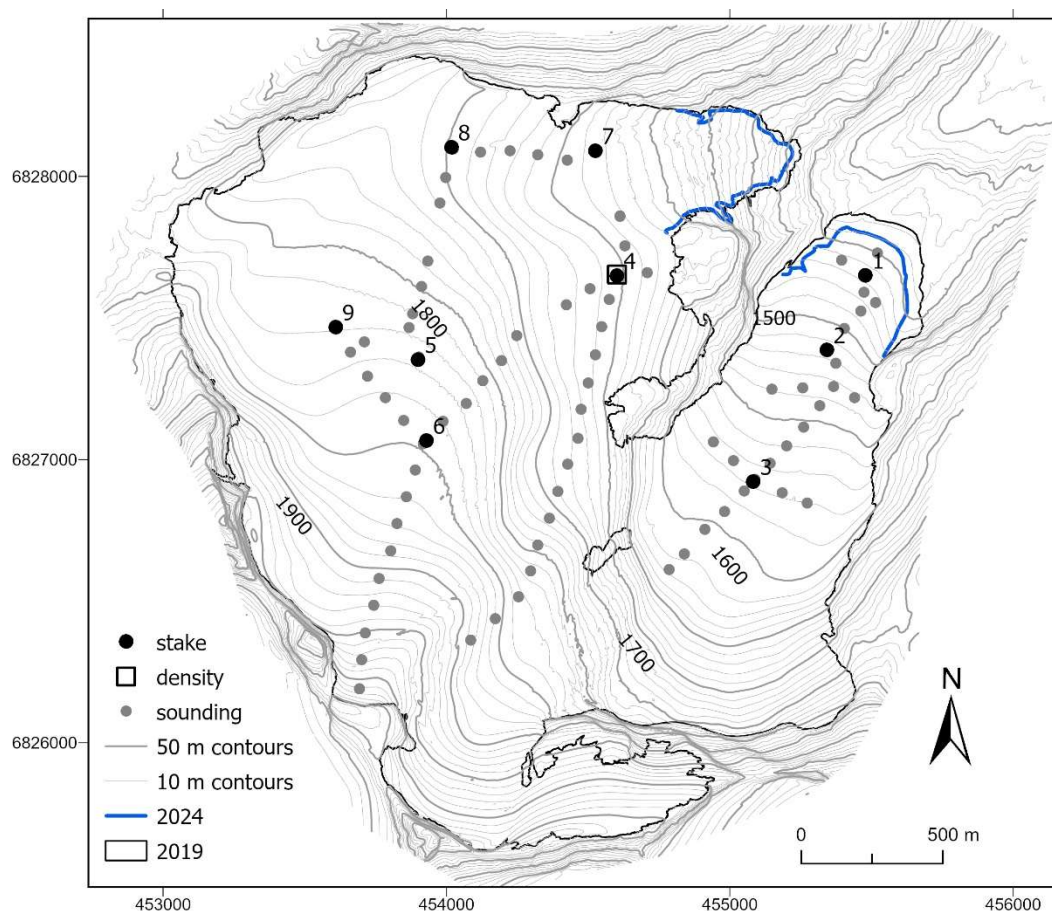


Figure 6-2
Location of stakes, soundings and density pit on Storbreven in 2024. Outline from 2019 and terminus outline from 2024 (see Fig. 6-1).

Results

The winter balance was calculated from the mean of the soundings within each 50 m height interval and was $1.44 \pm 0.2 \text{ m w.e.}$, which is 103 % of the mean winter balance for the reference period 1991-2020. Annual balance was calculated directly from stakes at six locations. The annual balance of Storbreven was $-1.24 \pm 0.3 \text{ m w.e.}$ in 2024. The resulting summer balance was $-2.68 \pm 0.3 \text{ m w.e.}$, which is 133 % of the mean summer balance for the reference period 1991-2020. The ELA was above the highest stake in 2024 and is therefore uncertain. The annual balance curve from the annual balance diagram (Fig. 6-3) indicates an ELA of $\sim 1920 \text{ m a.s.l.}$ resulting in an estimated accumulation area ratio (AAR) of $\sim 11 \%$.

The mass balance results are shown in Table 6-1 and in Figure 6-3.

Table 6-1
The distribution of winter, summer and annual balance in 50 m altitudinal intervals for Storbreen in 2024.

Mass balance Storbreen 2023/24				
Altitude (m a.s.l.)	Area (km ²)	Winter (m w.e.)	Summer (m w.e.)	Annual (m w.e.)
2050 - 2091	0.030	1.80	-1.30	0.50
2000 - 2050	0.138	1.24	-0.84	0.40
1950 - 2000	0.198	1.45	-1.25	0.20
1900 - 1950	0.317	1.88	-1.88	0.00
1850 - 1900	0.425	1.62	-1.92	-0.30
1800 - 1850	0.846	1.37	-1.97	-0.60
1750 - 1800	0.763	1.58	-2.58	-1.00
1700 - 1750	0.628	1.44	-2.94	-1.50
1650 - 1700	0.414	1.27	-3.22	-1.95
1600 - 1650	0.334	1.55	-3.75	-2.20
1550 - 1600	0.390	1.26	-3.76	-2.50
1500 - 1550	0.197	1.15	-4.15	-3.00
1450 - 1500	0.146	1.06	-4.46	-3.40
1420 - 1450	0.050	1.20	-5.00	-3.80
1420 - 2091	4.876	1.44	-2.68	-1.24

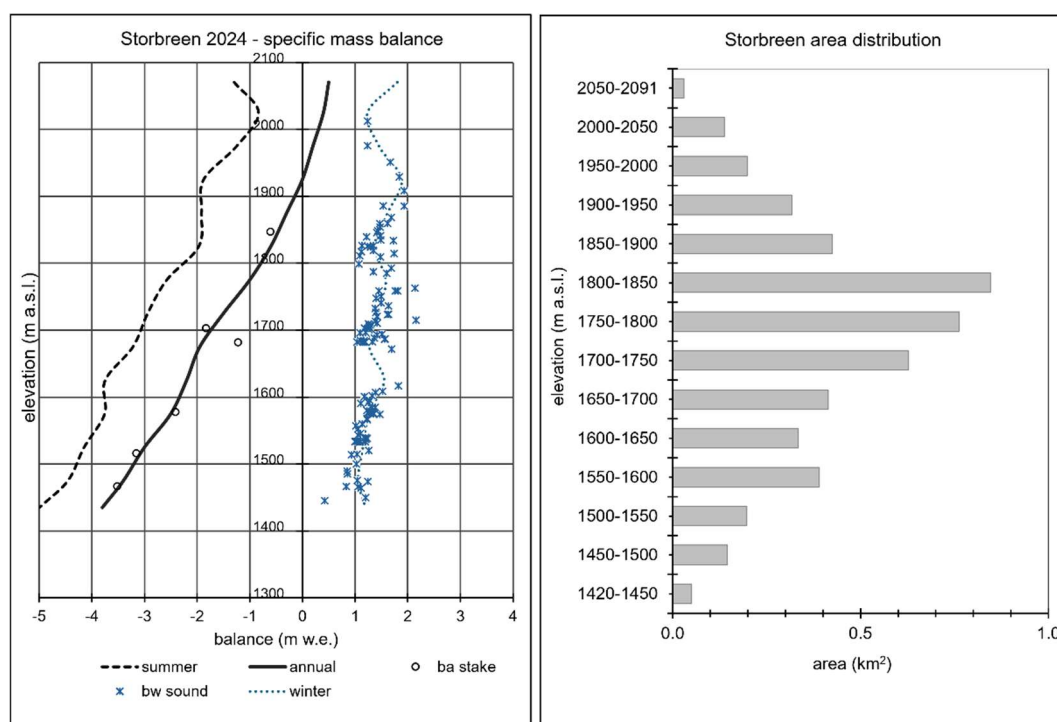


Figure 6-3
Left: Mass balance diagram for Storbreen for 2024. Right: The area-elevation distribution of Storbreen from the map survey of 2019.

6.3 Mass balance 1949-2024

The cumulative balance for 1949-2024 is -32.4 m w.e. (Fig. 6-4). The mean annual balance for the period of 76 years is -0.43 m w.e. For the period 1949-2000 (52 years) the mean annual balance is -0.19 m w.e., whereas for the period 2001-2024 (24 years) the mean annual balance is -0.93 m w.e.

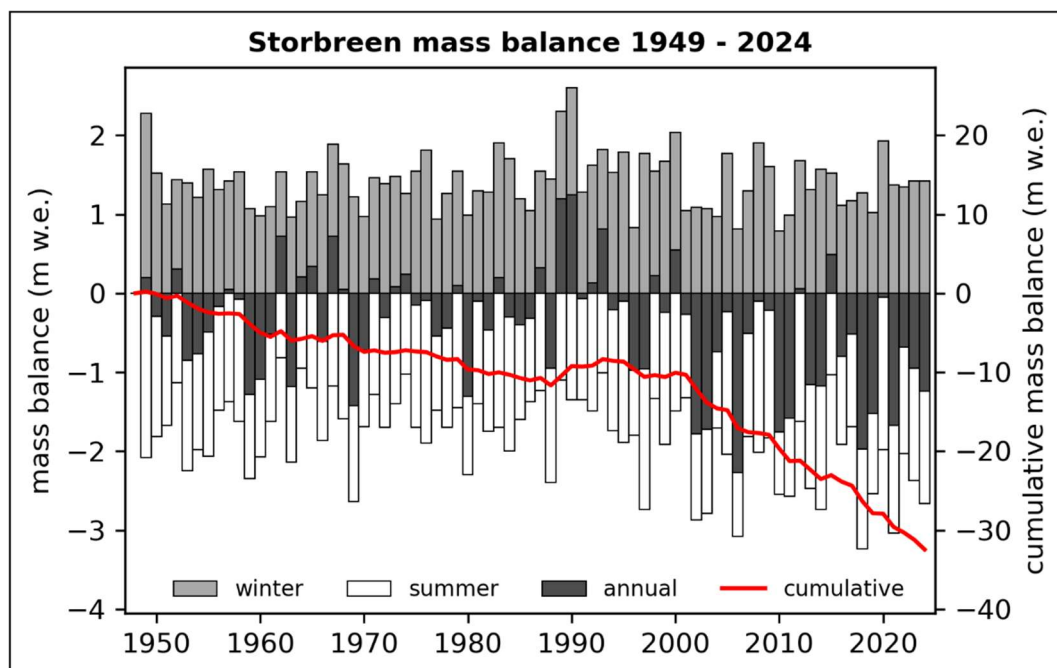


Figure 6-4

Winter, summer, annual and cumulative mass balance on Storbreen for the period 1949-2024.



Figure 6-5

The point used for measuring the front variation of Storbreen. Note the small lake in the foreground that has formed in recent years and had a small outburst flood in 2020. Photo: Liss M. Andreassen, 18 September 2024.

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 km² and altitudinal range from 1852 to 1985 m a.s.l. (map of 2019).

The observation programme of Juvfonne in 2024 consisted of accumulation measurements in May, seasonal and annual balances measured in one stake position and front variation measurement in September. In addition, the surface extent and ice patch elevation were mapped by uncrewed aerial vehicle (UAV) in September (Fig. 7-2).



Figure 7-1

Juvfonne on 17 September 2024 at the time of the ablation measurements. Most of the surface was snow free at the time of survey. Note the tunnel covered in white geotextiles. Photo: Liss M. Andreassen.

7.1 Survey 2024

The extent of Juvfonne has been regularly measured since 2010 using differential GNSS or by digitising extents from orthophotos. The surface extent and ice patch elevation were mapped by uncrewed aerial vehicle (UAV) on 2 September. At that time most of the surface had bare ice exposed (Fig. 7-2). The ice patch extent was digitised from this orthophoto and revealed an area of 0.081 km². This is the smallest area of Juvfonne registered since measurements began in 2010.

7.2 Mass balance 2024

Field work

The accumulation measurements on Juvfonne were carried out on 2 May (Fig. 7-3). Snow depth was measured in 26 positions from 1865 to 1957 m a.s.l. The snow depth varied between 2.05 and 4.69 m with a mean (median) of 3.50 (3.38) m. The measurements were partly influenced by the redistribution of snow prior to the measurements (Fig. 7-3). 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 2023 summer surface

was 3.88 m. The resulting density was calculated to be 463 kg m^{-3} . Ablation measurements were carried out on 17 September at stake 2 (Fig 7-5).

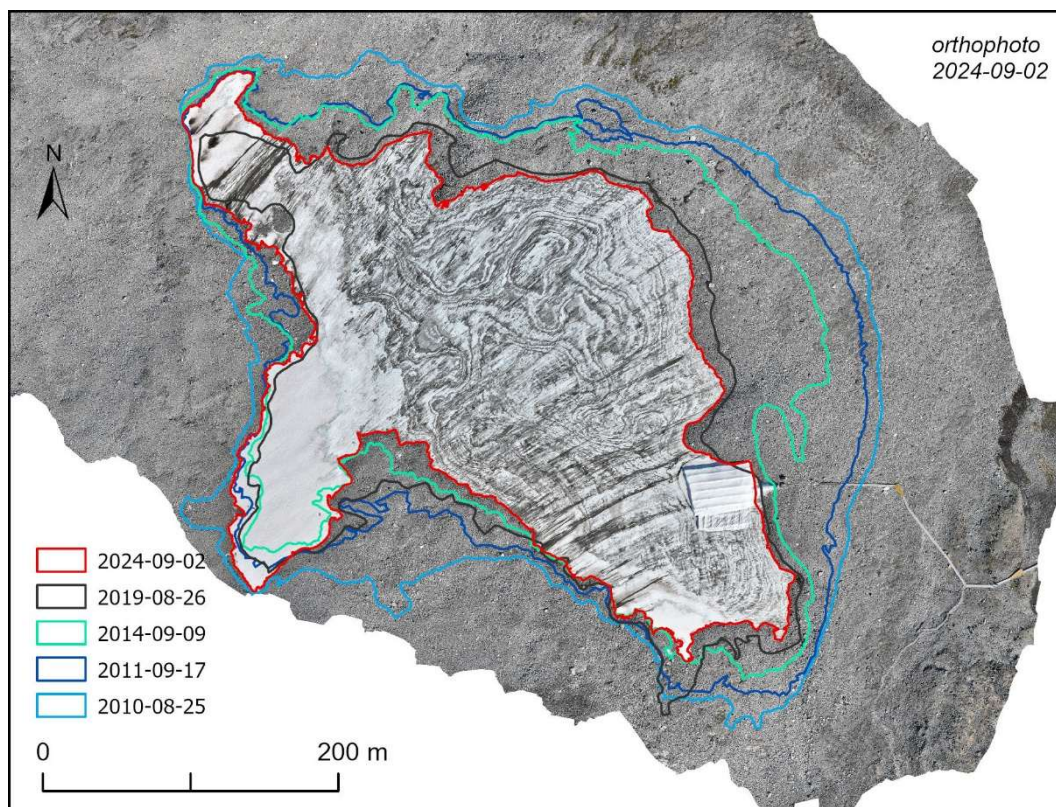


Figure 7-2
Orthophoto of Juvfonne from uncrewed aerial vehicle on 2 September 2024. Outlines from 2010 (GNSS), 2011 (orthophoto), 2014 (GNSS), 2019 (orthophoto) and 2024 (orthophoto). Background orthophoto of 2024 provided by Simon Oldani, NVE. Note the tunnel covered in white geotextiles.



Figure 7-3
In 2024 redistribution of snow to protect the ice tunnel was done prior to the accumulation measurements on Juvfonne. The photo is taken on the arrival on 2 May at the time of the snow measurements. Photo: Liss M. Andreassen.

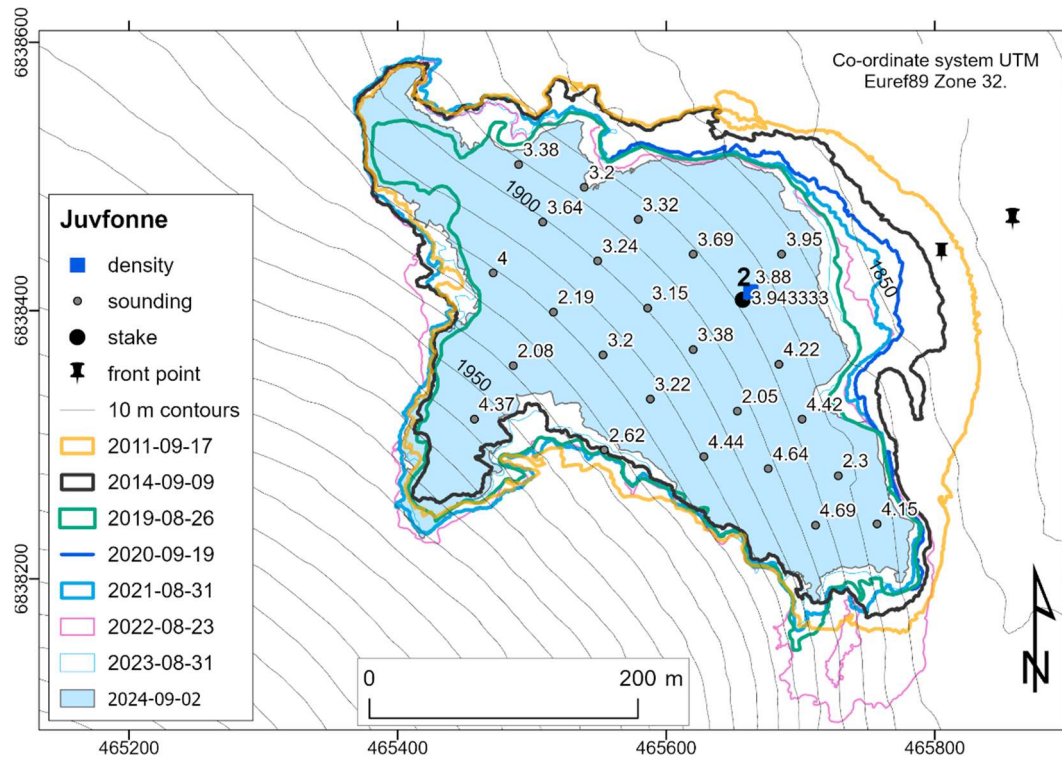


Figure 7-4

Location of snow depth soundings in 2024 and the position of stake 2 where density was measured. Selected ice patch extents from 2011 to 2024 measured using orthophoto) or GNSS are shown. “front point” marks the reference point for front variation measurements. The 10 m contours are derived from the 2019 DTM.



Figure 7-5

Measurements of stakes in position 2 on 17 September 2024 at the time of the ablation measurements.

A few centimetres of snow covered the surface. A total of 1.1 m of ice had melted since the ablation measurements on 16 September 2023.

Photo: Liss M. Andreassen.

Results

Seasonal surface mass balances have been measured since 2010 at stake 2 (Fig. 7-4). In 2024 the point winter balance was 1.80 ± 0.15 m w.e., the point summer balance was -2.82 ± 0.15 m w.e. and the annual balance was -1.02 ± 0.15 m w.e. at this location. The cumulative mass balance for stake 2 over the 14 years of measurements is -14.5 m w.e., or -0.97 m w.e. a^{-1} (Fig. 7-6). The mass balance of the entire ice patch was not calculated; this was calculated only for the first year of measurements in 2009/2010 when more stakes were measured. The mass balance of Juvfonne is likely influenced by the tunnel that is protected in fabric and by redistribution of snow (Fig. 7-7 and 7-3).

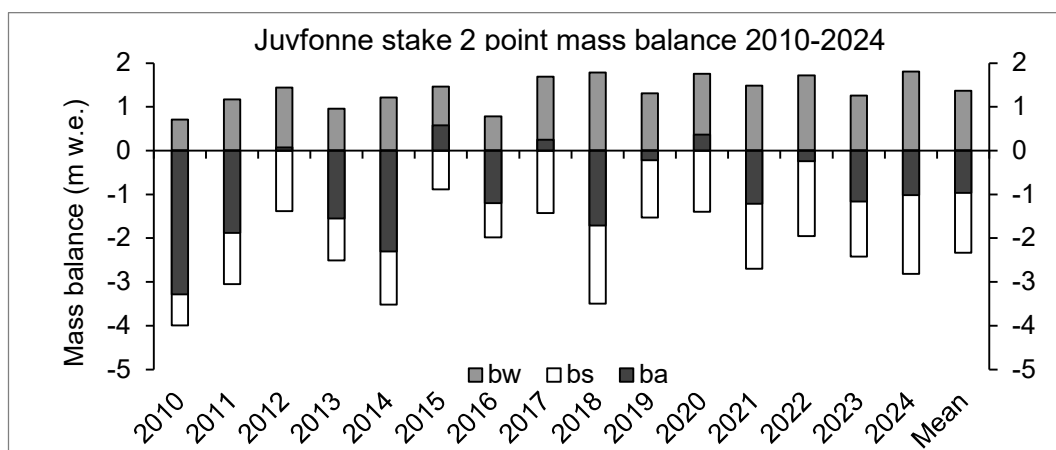


Figure 7-6
Point mass balance at stake 2 on Juvfonne 2010-2024, given as winter balance (bw), summer balance (bs) and annual balance (ba).

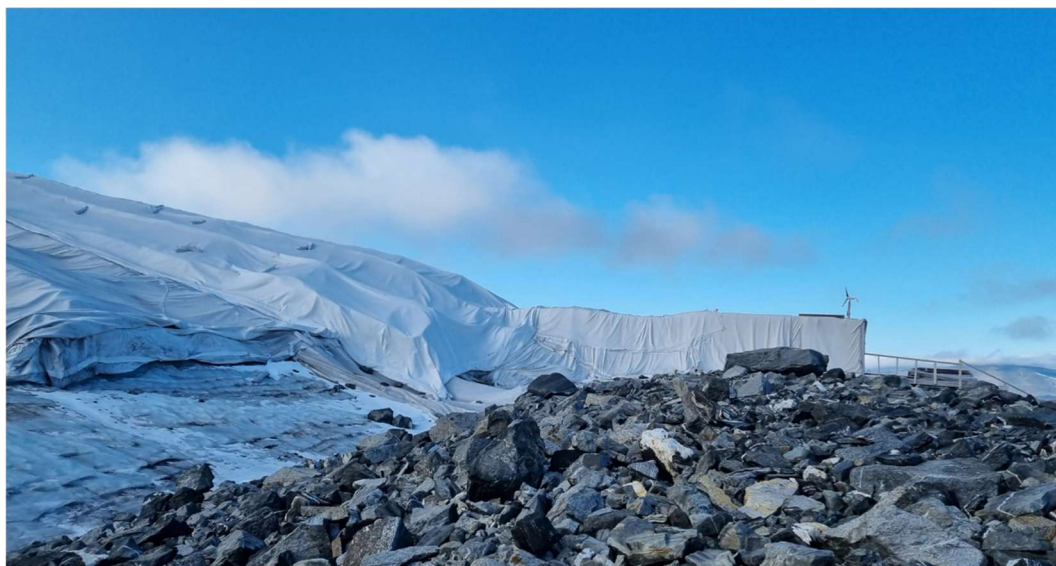


Figure 7-7
The ice tunnel at Juvfonne is covered in fabric that reduces the melting. View towards west.
Photo: Liss M. Andreassen, 17 September 2024.

8. Hellstugubreen (Liss M. Andreassen)

Hellstugubreen (61°34'N, 8° 26'E) (now written as “Hellstugubreen” on official maps) is a north-facing valley glacier situated in central Jotunheimen (Figs. 8-1, 8-2). The glacier shares a border with Vestre Memurubre glacier (Fig. 8-3). 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 km² (as of 2019). New orthophotos taken on 18 September 2024 reveal a terminus retreat of about 100 meter over the five years (Fig. 8-1).

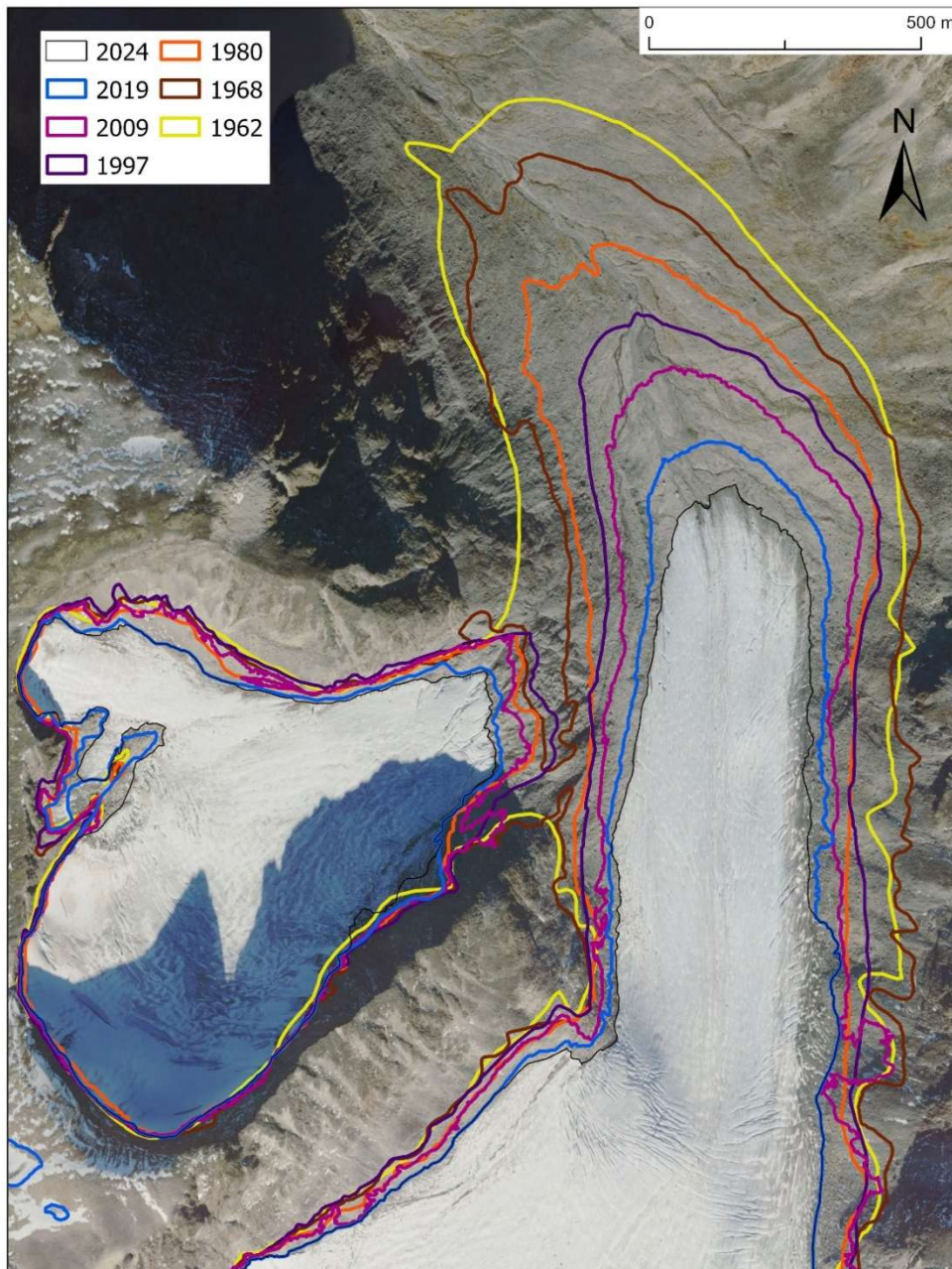


Figure 8-1
Orthophoto taken on 18 September 2024 showing the lower part of Hellstugubreen and the neighbouring glacier to the left that was detached from the main glacier in the 1960s. The glacier outlines are from a range of detailed glacier maps from 1941 to 2019. The 2024 outline is digitised from the orthophoto.
Orthophoto from Norgebilder.no/Norwegian Mapping Authority. © Statens kartverk, Geovekst og kommunene, Innlandet NV 2024.



Figure 8-2
Hellstugubreen on 29 July 2024. Photo: Liss M. Andreassen.

8.1 Mass balance 2024

Fieldwork

Accumulation measurements were performed on 26 April. Snow depths were measured in 73 positions between 1556 and 2124 m a.s.l., covering most of the altitudinal range of the glacier (Fig. 8-3). The snow depth varied between 0.99 and 4.34 m, with a mean (median) of 2.32 (2.27) m. Snow density was measured in a density pit at 1945 m a.s.l. The total snow thickness measured was 3.24 m and the resulting density was 374 kg m^{-3} . Ablation measurements were carried out on 19 September (Fig. 8-6).

Results

The calculations are based on the DTM from 2019. The winter balance was calculated as the mean of the soundings within each 50-metre height interval and was $0.87 \pm 0.2 \text{ m w.e.}$, which is 83 % of the mean winter balance for the reference period 1991-2020. The annual balance was interpolated to 50 m height intervals based on the stake readings and was $-1.11 \pm 0.3 \text{ m w.e.}$ The resulting summer balance was $-1.98 \pm 0.3 \text{ m w.e.}$, which is 117 % of the mean summer balance for the reference period 1991-2020. Sentinel-2 images revealed that most of the previous summer snow was gone on 6 September except from the uppermost stake, a snow fall covers the glacier on 14 September and images from 19 and 21 September reveals that this fresh snow was largely melted, but indicates remaining snow on the uppermost stake at 2055 m a.s.l. The equilibrium line altitude (ELA) was estimated from the images and the mass balance curve to be 2015 m a.s.l., giving an accumulation area ratio (AAR) of 18 %. The mass balance results are shown in Table 8-1 and Figure 8-4.

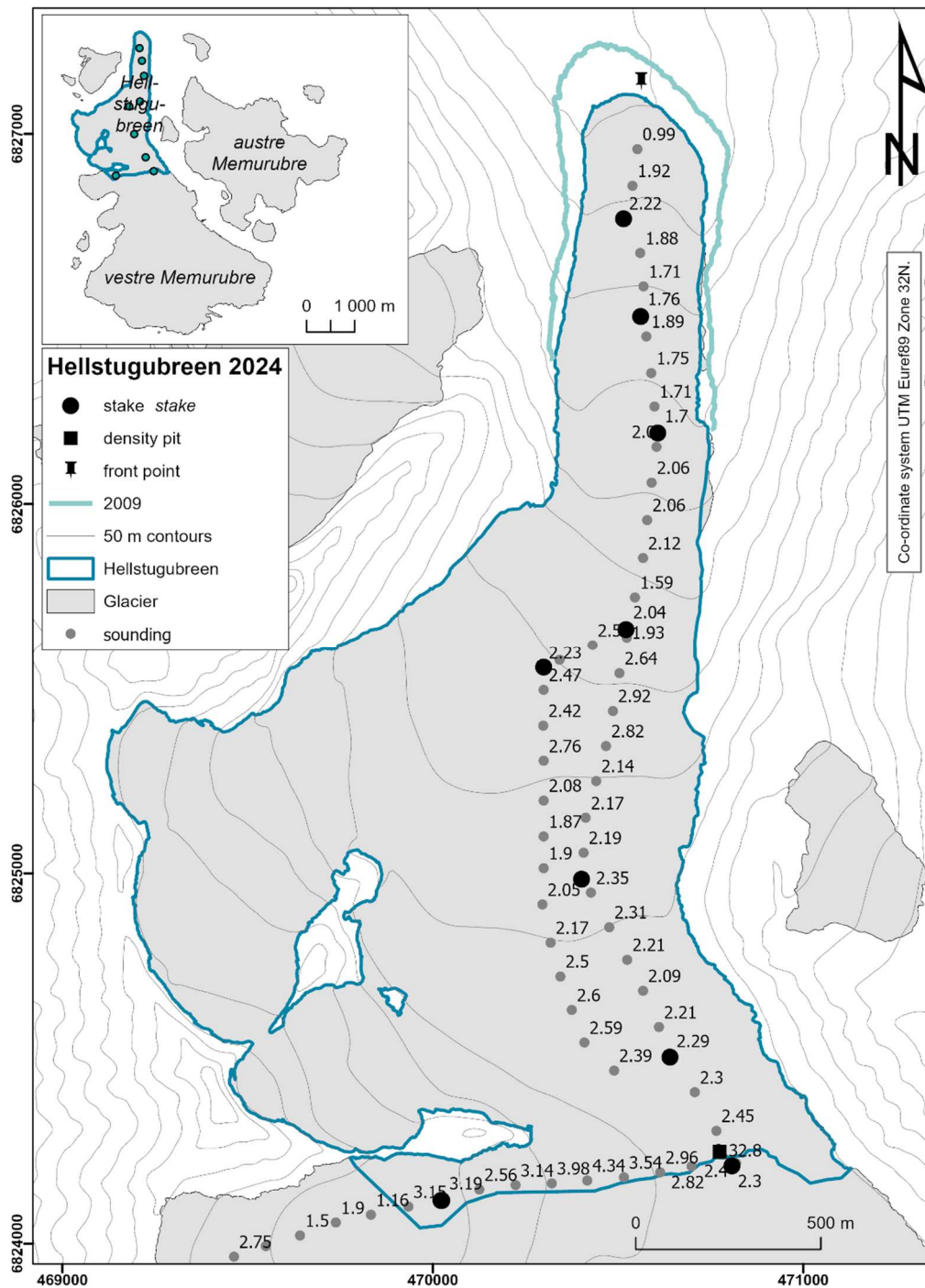


Figure 8-3
Map of Hellstugubreen showing the location of stakes, snow depth soundings (in meters) and snow pit in 2024.
Front point: reference points used for front position and length change measurements (chap. 12-1).
Inset shows Hellstugubreen and surrounding glaciers.

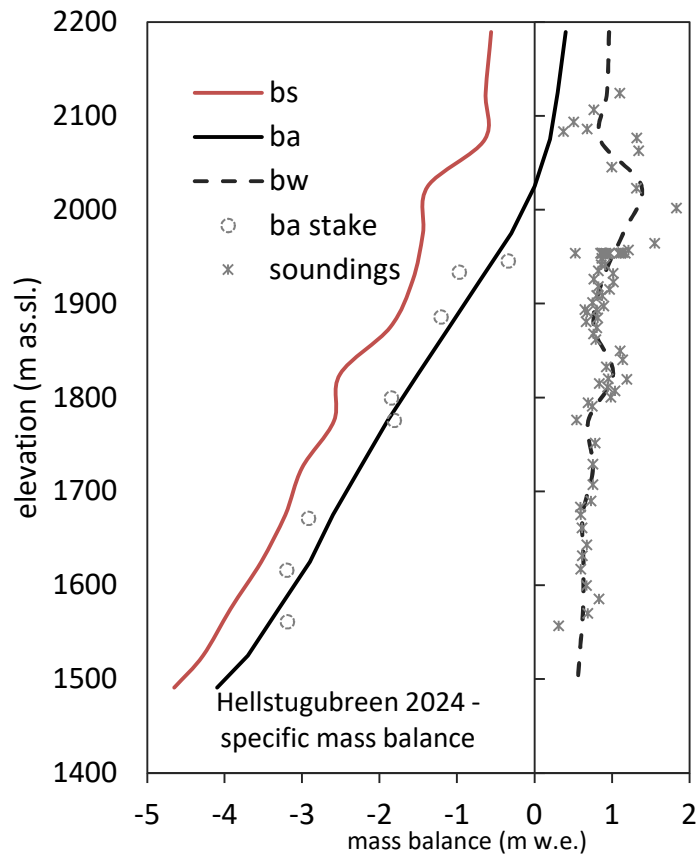


Figure 8-4
Mass balance diagram for Hellstugubreen in 2024 with winter (bw), summer (bs) and annual (ba) balance. Annual balance at stakes (ba stake) and soundings are also shown.

Mass balance Hellstugubreen 2023/24				
Altitude (m a.s.l.)	Area (km ²)	Winter (m w.e.)	Summer (m w.e.)	Annual (m w.e.)
2150 - 2229	0.017	0.96	-0.56	0.40
2100 - 2150	0.060	0.93	-0.63	0.30
2050 - 2100	0.278	0.85	-0.65	0.20
2000 - 2050	0.178	1.38	-1.38	0.00
1950 - 2000	0.186	1.14	-1.44	-0.30
1900 - 1950	0.607	0.87	-1.57	-0.70
1850 - 1900	0.404	0.76	-1.86	-1.10
1800 - 1850	0.295	1.01	-2.51	-1.50
1750 - 1800	0.181	0.69	-2.59	-1.90
1700 - 1750	0.076	0.75	-3.00	-2.25
1650 - 1700	0.107	0.62	-3.22	-2.60
1600 - 1650	0.104	0.63	-3.53	-2.90
1550 - 1600	0.079	0.63	-3.93	-3.30
1500 - 1550	0.077	0.58	-4.28	-3.70
1482 - 1500	0.007	0.55	-4.65	-4.10
1420 - 2091	2.656	0.87	-1.98	-1.11

Table 8-1
The distribution of winter, summer and annual balance in 50 m altitudinal intervals for Hellstugubreen in 2024.

8.2 Mass balance 1962-2024

The cumulative annual balance of Hellstugubreen since 1962 is -30.5 m w.e. (Fig. 8-5), giving a mean annual deficit of 0.48 m w.e. per year. The cumulative mass balance for the period 2000/2001 to 2022/2024 (24 years) is -21.3 m w.e. or -0.89 m w.e./a.

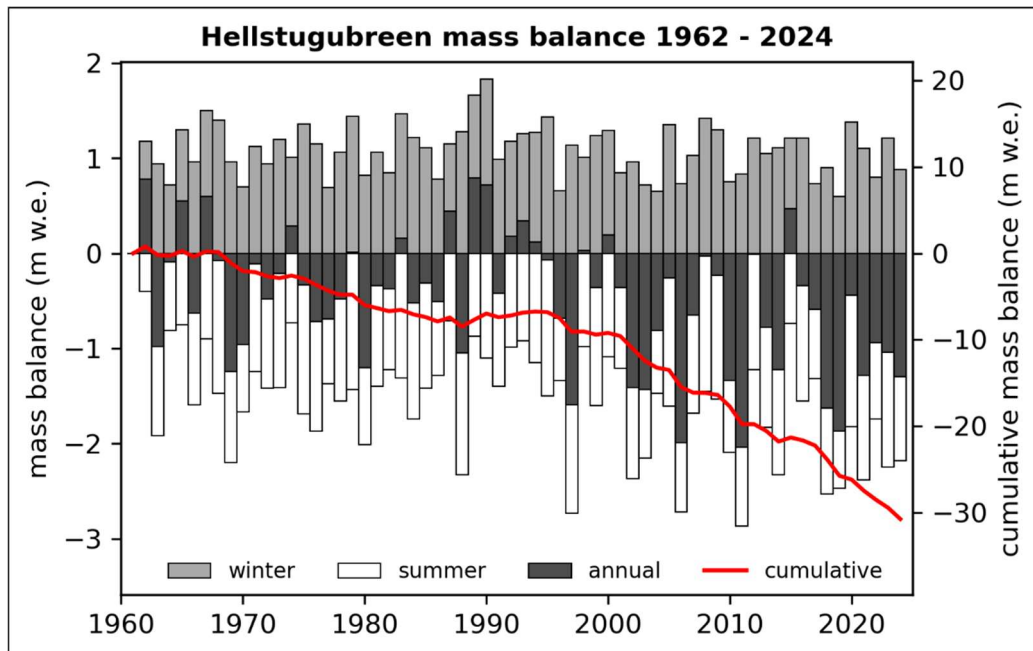


Figure 8-5

Winter, summer and annual balance at Hellstugubreen for 1962-2024, and cumulative mass balance for the whole period.



Figure 8-6

Field work. Ablation measurements on 19 September 2024.

Photo: Solveig H. Winsvold.

9. Gråsubreen (Liss M. Andreassen)

Gråsubreen (61°39'N, 8°37'E) (now written Gråsubreen 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 km² 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.

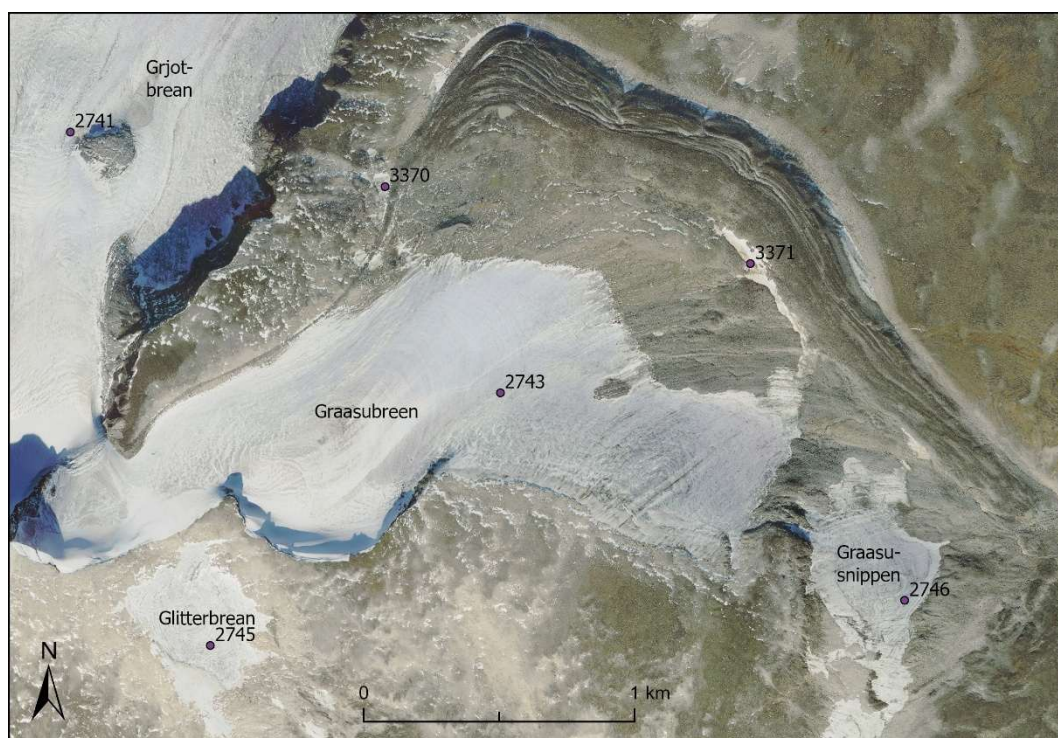


Figure 9-1
Orthophoto of Gråsubreen and surrounding glaciers taken on 18 September 2024. Glacier IDs from the Inventory of Norwegian Glaciers (Andreassen and others, 2022).
Orthophoto from Norgebilder.no/Norwegian Mapping Authority. © Statens kartverk, Geovekst og kommunene, Innlandet NV 2024.

9.1 Mass balance 2024

Fieldwork

Accumulation measurements were performed on 25 April 2024. The calculation of winter balance is based on stake measurements and snow depth soundings in 57 positions between 1892 and 2267 m a.s.l. (Fig. 9-2). The snow depth varied between 0.61 and 3.10 with a mean and median of 1.58 and 1.41 m respectively. The snow density was

measured in a density pit near stake 8 (elevation 2135 m a.s.l.) where the total snow depth was 1.6 m and the mean density was 345 kg m^{-3} (Fig. 9-3). Ablation measurements were carried out on 20 September 2024, when all visible stakes were measured. A layer of fresh snow covered the surface (Fig. 9-3). The winter snow was gone at all stake positions.

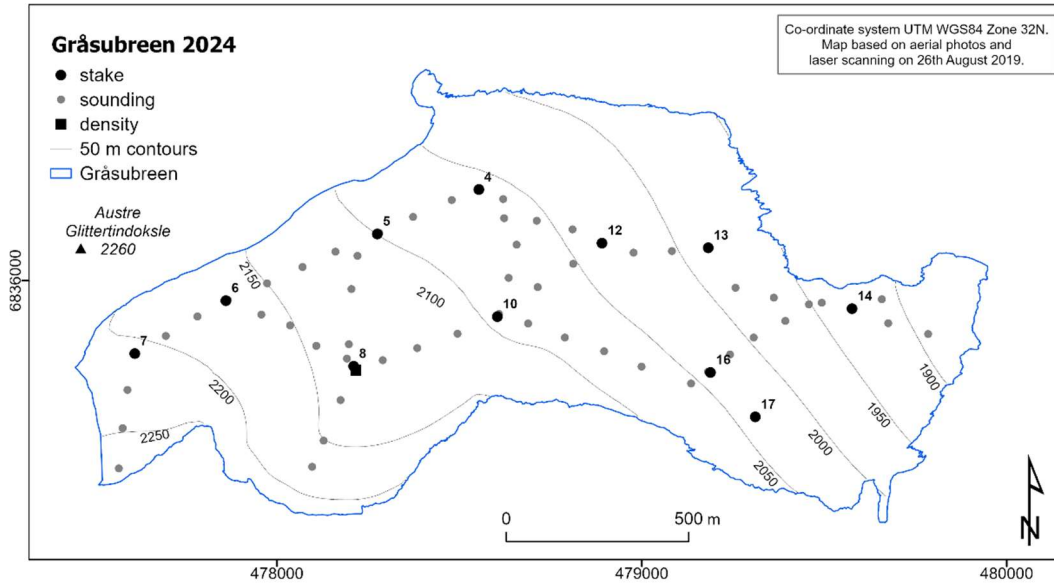


Figure 9-2
Map of Gråsubreen showing the location of stakes, density pit and soundings in 2024.

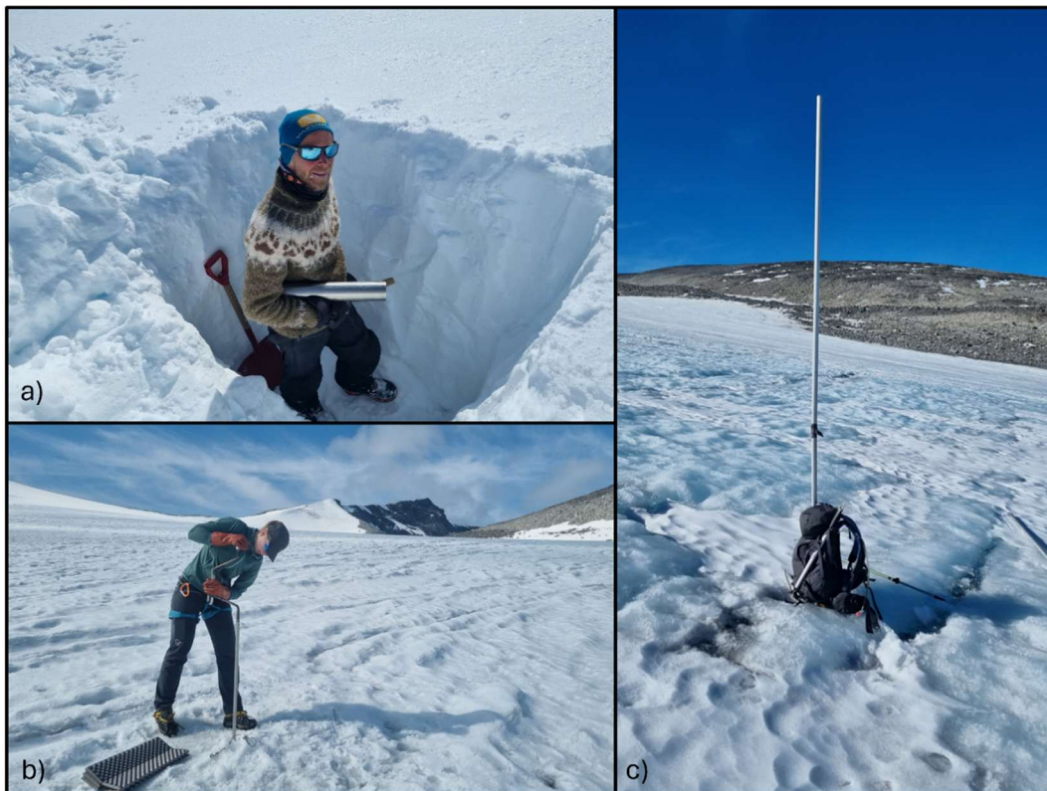


Figure 9-3
Field work: a) density was measured in a snow pit on 25 April 2024. The snow depth was 1.6 m to the previous summer surface of ice, b) stake drilling on 25 July 2024. The second highest peak in Norway, Glittertinden (2452 m asl.) in the background, c) stake measurements on 20 September 2024. Photos: Liss M. Andreassen.

Results

The winter balance was calculated as the mean of the soundings within each 50-metre height interval. This gave a winter balance of 0.65 ± 0.2 m w.e., which is 93 % of the mean winter balance for the reference period 1991-2020. Annual and summer balance were calculated from direct measurements of six stakes. The resulting summer balance was -1.95 ± 0.3 m w.e., which is 146 % of the mean summer balance for the reference period 1991-2020. The annual balance of Gråsubreen was negative in 2024 at -1.30 ± 0.3 m w.e. The ELA and AAR were not defined from the mass balance curve or in the field. The mass balance results are shown in Table 9-1 and Figure 9-4.

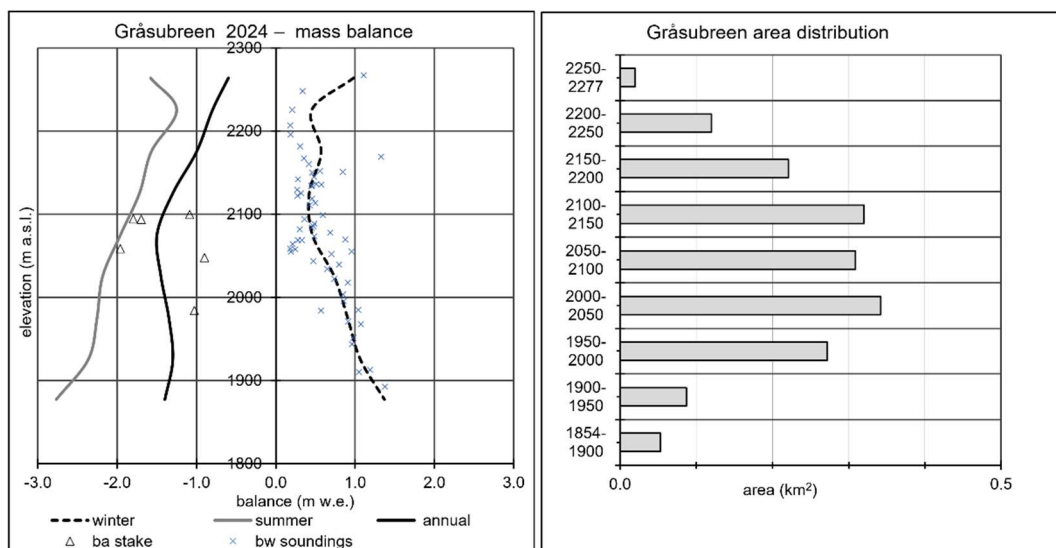


Figure 9-4

Mass balance diagram for Gråsubreen for 2024. The area-elevation distribution is from the map survey of 2019.

Table 9-1

The distribution of winter, summer and annual balance in 50 m altitudinal intervals for Gråsubreen in 2024.

Mass balance Gråsubreen 2023/24					
Altitude (m a.s.l.)	Area (km²)	Winter (m w.e.)	Summer (m w.e.)	Annual (m w.e.)	
2250 2277	0.020	0.98	-1.60	-0.62	
2200 2250	0.120	0.45	-1.20	-0.75	
2150 2200	0.221	0.57	-1.57	-1.00	
2100 2150	0.320	0.42	-1.72	-1.30	
2050 2100	0.309	0.46	-1.96	-1.50	
2000 2050	0.342	0.74	-2.19	-1.45	
1950 2000	0.272	0.91	-2.25	-1.35	
1900 1950	0.087	1.07	-2.37	-1.30	
1854 1900	0.053	1.37	-2.78	-1.41	
1854 - 2277	1.744	0.65	-1.95	-1.30	

9.3 Mass balance 1962-2024

The cumulative annual balance of Gråsubreen is -31.6 m w.e. since measurements began in 1962 (Fig. 9-5). The average annual balance is -0.52 m w.e. a^{-1} . Gråsubreen has had a negative mass balance every year since 2001, except for slight surpluses in 2008 and 2015.

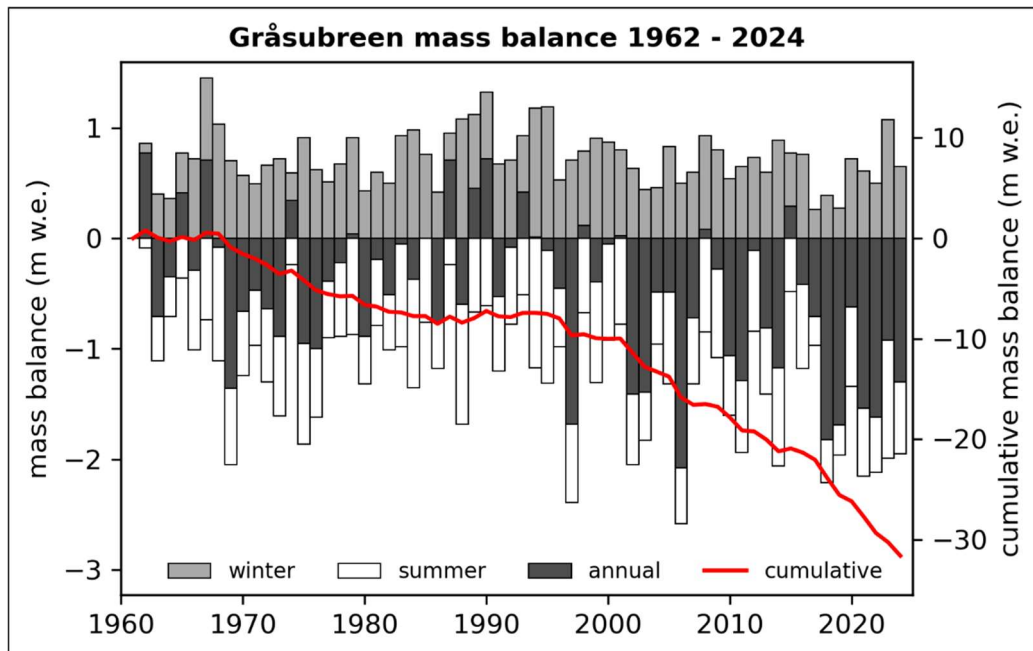


Figure 9-5
Winter, summer and annual balance on Gråsubreen for 1962-2024, and cumulative mass balance for the whole period.

10. Engabreen (Hallgeir Elvehøy)

Engabreen (66°40'N, 13°45'E) is a 36 km² north-western outlet from the western Svartisen ice cap. In 2020 it covered an altitude range from 1532 m a.s.l. at Snøtinden down to 176 m a.s.l. close to Engabrevatnet (Fig. 10-1). Front variation observations started in 1903 (chap. 12) and mass balance measurements have been performed annually since 1970.



Figure 10-1

Engabreen on 8 August 2024. Between 1999 when the glacier almost reached the lake, and 2024, the front variation measurements show a total retreat of 857 meters. Photo: Hallgeir Elvehøy.

10.1 Mass balance 2024

Fieldwork

Stakes in three locations on the glacier plateau were checked on 6 March and showed between 2 and 4.5 meters of snow on the plateau.

The snow accumulation measurements were performed on 7 May. Stakes were found in all stake positions, and they were used to validate the snow depth soundings. Snow depth was measured in 22 sounding locations along the profile from the summit (1460 m a.s.l.) to E34 (Fig. 10-2). The summer surface was easy to define in most sounding locations. The snow depth varied between 2 and 6 meters, and the mean snow depth was 3.7 meters. The mean snow density down to the previous summer surface at 3.6 m depth at stake E5 was 467 kg m⁻³. At stake E400 on the glacier tongue 1.35 m of glacier ice had melted since 18 October 2023.

Stake E400 on the glacier tongue was re-drilled on 2 July. Then the stake network was checked on 7 and 12 August. At stake E400 8 meters of ice had melted since 7 May, and the stake was re-drilled. Several stakes on the glacier plateau had melted out, and some old stakes from the 1980s had re-appeared. All the winter snow at the stakes had melted.

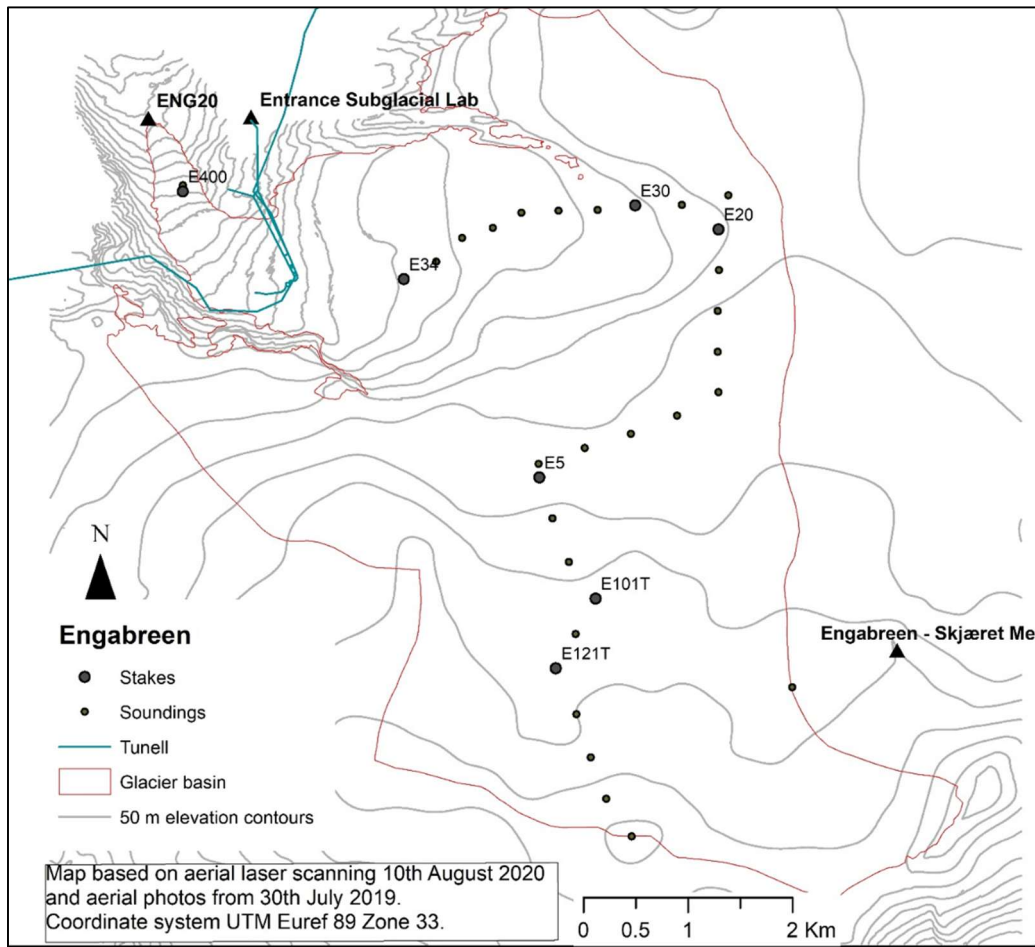


Figure 10-2

Location of stakes and soundings on Engabreen in 2024. Tunnel is the water collecting tunnel system for Svartisen Hydropower Station providing access to the Subglacial Lab (chap. 10-3). Engabreen - Skjæret Me is the location of the meteorological station, and ENG20 is a reference point for the front variation measurements (chap. 12).

The summer ablation measurements were carried out on 19 November. Up to 3 meters of new snow had accumulated at the stake locations, but the summer surface was easy to define. Up to 3 meters of firn and ice had melted at stakes on the glacier plateau since 7 August. The stake at the glacier tongue was covered with new snow but re-appeared between in May 2025. About 2.9 meters of ice had melted after 12 August.

Results

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

The winter balance on the glacier plateau was calculated from the snow depth and snow density measurements on 7 May. On the glacier tongue the point specific winter balance at E400 was calculated from measured ice melt between 18 October 2023 and 7 May 2024. The total specific winter balance was calculated as 1.7 ± 0.2 m w.e. This is 64 % of the average winter balance for the normal period 1991-2020 (2.71 m w.e. a^{-1}).

The date of the 2024 mass balance minimum on Engabreen was assessed from the daily changes in gridded data of temperature and snow amount from Senorge.no (Lussana et al., 2019) and the temperature record from the meteorological station Engabreen-

Skjæret (chap. 10-2). The snow accumulation on the glacier plateau above 950 m a.s.l. probably started on 21 September. On the glacier tongue most of the ice melt occurred before 28 October.

The point summer balance was calculated directly for three stake locations (E20, E101 and E121). The melting at stake E5 between 7 May and 7 August was estimated as 3.55 m of snow and 1.65 m of firn based on measured melting at stakes E20 and E101. The melting at stake E34 between 7 May and 7 August was estimated as 2.05 m of snow and 3.95 m of ice based on melting at E20 and E400. The ice melt at E400 after 12 August was estimated as 2.9 m based on stake lengths observed in June 2025.

The specific summer balance was calculated from the summer balance curve drawn from seven point-values (Fig. 10-4) as -5.6 ± 0.2 m w.e. This is 202 % of the average summer balance for the normal period 1991-2020 (-2.77 m w.e. a^{-1}). This is the largest summer balance measured at Engabreen since the measurements started in 1970. The second largest summer balance was -4.1 m w.e. in 2013.

The resulting annual balance for 2024 was -3.9 ± 0.3 m w.e. (Tab. 10-1). The ELA was above the top of the glacier, and consequently the AAR was 0 %. The annual surface mass balance on Engabreen for 1970-2024 is shown in Figure 10-5. The cumulative surface mass balance since the start of mass balance investigations on Engabreen is -4.1 m w.e.



Figure 10-3

Stake E5 (1225 m a.s.l.) was re-drilled after the old stake had melted out. All the winter snow had melted, and old firn from 2022 formed the surface. Photo: Hallgeir Elvehøy.

Table 10-1

Specific and volume winter, summer and annual balance calculated for 100 m elevation intervals on Engabreen in 2024.

Mass balance Engabreen 2023/24 – stratigraphic system				
Altitude (m a.s.l.)	Area (km ²)	Winter balance	Summer balance	Annual balance
		Measured 07.05.2024 (m w.e.)	Measured 19.11.2024 (m w.e.)	Summer surfaces 2023 - 2024 (m w.e.)
1500 - 1532	0,046	2,00	-4,90	-2,90
1400 - 1500	2,199	2,35	-4,90	-2,55
1300 - 1400	9,228	2,15	-5,00	-2,85
1200 - 1300	8,041	1,85	-5,10	-3,25
1100 - 1200	7,487	1,60	-5,30	-3,70
1000 - 1100	4,552	1,50	-6,30	-4,80
900 - 1000	2,373	1,20	-7,30	-6,10
800 - 900	0,773	0,90	-7,75	-6,85
700 - 800	0,439	0,60	-8,20	-7,60
600 - 700	0,270	0,30	-8,70	-8,40
500 - 600	0,249	0,00	-9,20	-9,20
400 - 500	0,137	-0,30	-9,70	-10,00
300 - 400	0,089	-0,60	-10,20	-10,80
200 - 300	0,071	-0,90	-10,70	-11,60
177 - 200	0,006	-1,10	-11,00	-12,10
Specific mass balance				
177 - 1532	35,960	1,738	-5,593	-3,855

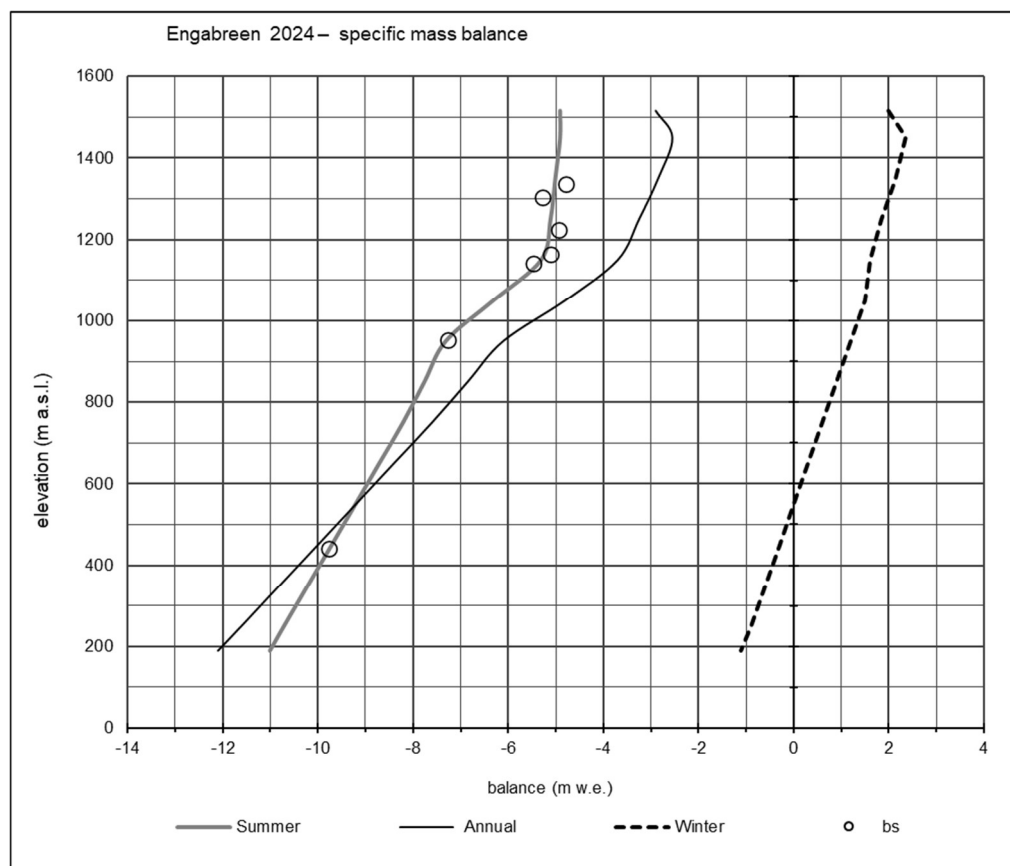


Figure 10-4

Altitudinal distribution of specific balance for Engabreen in 2024. Summer balance for seven stake locations is shown (o).

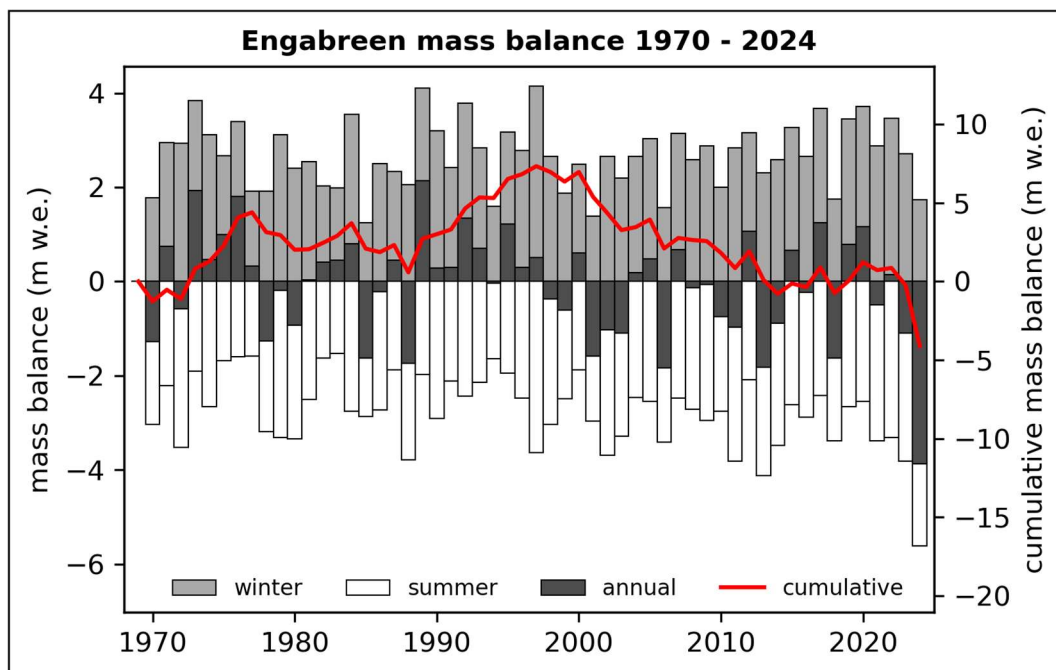


Figure 10-5
Mass balance on Engabreen during the period 1970-2024. Cumulative mass balance is given on the right axis. The average winter and summer balances are $B_w = 2.68$ m w.e. and $B_s = -2.76$ m w.e.

10.2 Meteorological observations

The meteorological station 159.20 Engabreen-Skjæret is recording air temperature and global radiation at 3 m above ground level. It is located on a nunatak at 1364 m a.s.l. close to the drainage divide between Engabreen and Storglombreen (Figs. 10-2, 10-6). The station has been operating since 1995.



Figure 10-6
The nunatak Skjæret (1364 m a.s.l.) where the meteorological station Engabreen-Skjæret is located, on 7 August 2024. Snøtinden (1593 m a.s.l.) is seen in the background. Photo: Hallgeir Elvehøy.

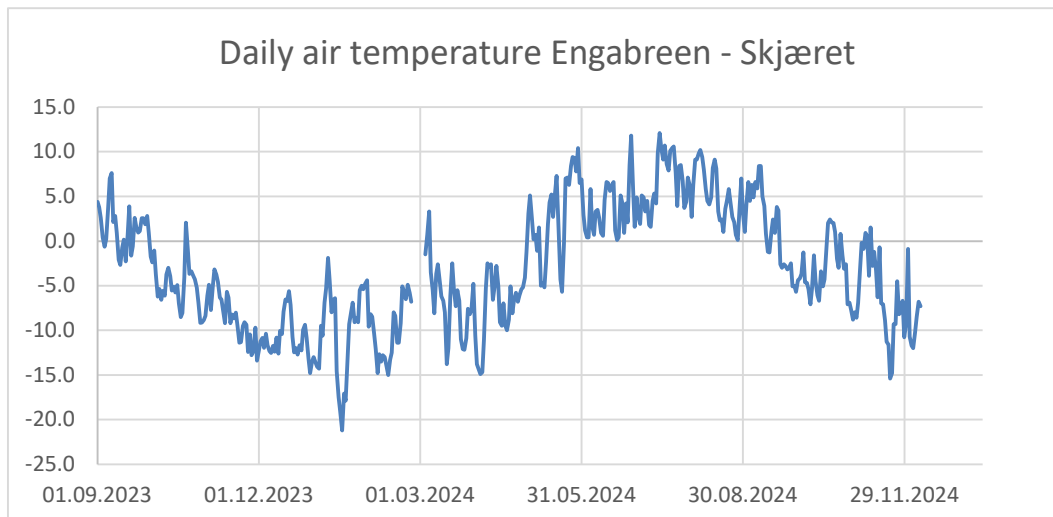


Figure 10-7

Air temperature at Engabreen-Skjæret (1364 m a.s.l.) from 1 September 2023 to 8 December 2024. The winter season lasted from 1 October 2023 to 11 May 2024, and the summer season ended on 19 September 2024.

The temperature record for 2024 is shown in Figure 10-7. A short data gap occurred between 25 February and 4 March due to power shortage. Based on the temperature record the melt season on the upper part of the glacier plateau started on 12 May and lasted until 19 September.

The mean summer temperature (1 June – 30 September) at Engabreen-Skjæret in 2024 was 4.1 °C. This is well above the average summer temperature for 23 years between 1995 and 2023 at 3.05 °C. However, both 2014 (5.7 °C) and 2023 (4.5 °C) had higher mean summer temperatures.

10.3 Svartisen Subglacial Observatory

Svartisen Subglacial Laboratory is situated under Engabreen. The laboratory buildings and research shaft are located about 1.5 km along a tunnel that is part of the water collecting tunnel system for Svartisen Kraftverk (hydropower development) (Fig. 10-2). The research shaft allows direct access to the bed of the glacier for measuring subglacial parameters, extracting samples and performing experiments (Jackson, 2000).

Load cells have been measuring variations in subglacial pressure at the glacier bed next to the research shaft since December 1992. The load cells are Geonor Earth Pressure Cells P-100 and P-105. Readings are made from the load cells at 15-minute intervals. The load cells were installed at the glacier-bedrock interface within 20 m of each other. Four load cells are still in operation and recording. The inter-annual variability of the load cells is examined in detail by Lefeuve and others (2015). After technical problems causing several data gaps between May 2018 and August 2021, the records of raw data from four load cells are complete up to 7 January 2025.

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 km² (2018), and of this, 2.6 km² 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 2024 include mass balance and front variations (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 29 August 2024. Photo: Flytjenesten i Tromsø.

11.1 Mass balance 2024

Fieldwork

Snow accumulation was measured on 25 April and the calculation of winter balance was based on measurements of 76 snow depth soundings (Fig. 11-2). Generally, the snow depth varied between 3 and 5 m. Snow density was measured in position 25 (708 m a.s.l.) and the mean density of the snow pack (3.85 m) was 425 kg m⁻³.

Ablation was measured on 25 September. The annual balance was measured at stakes in six locations (Fig. 11-2). There was no snow remaining on the glacier from the winter season 2023/24. At the time of measurement, up to 40 cm of fresh snow had fallen on the glacier.

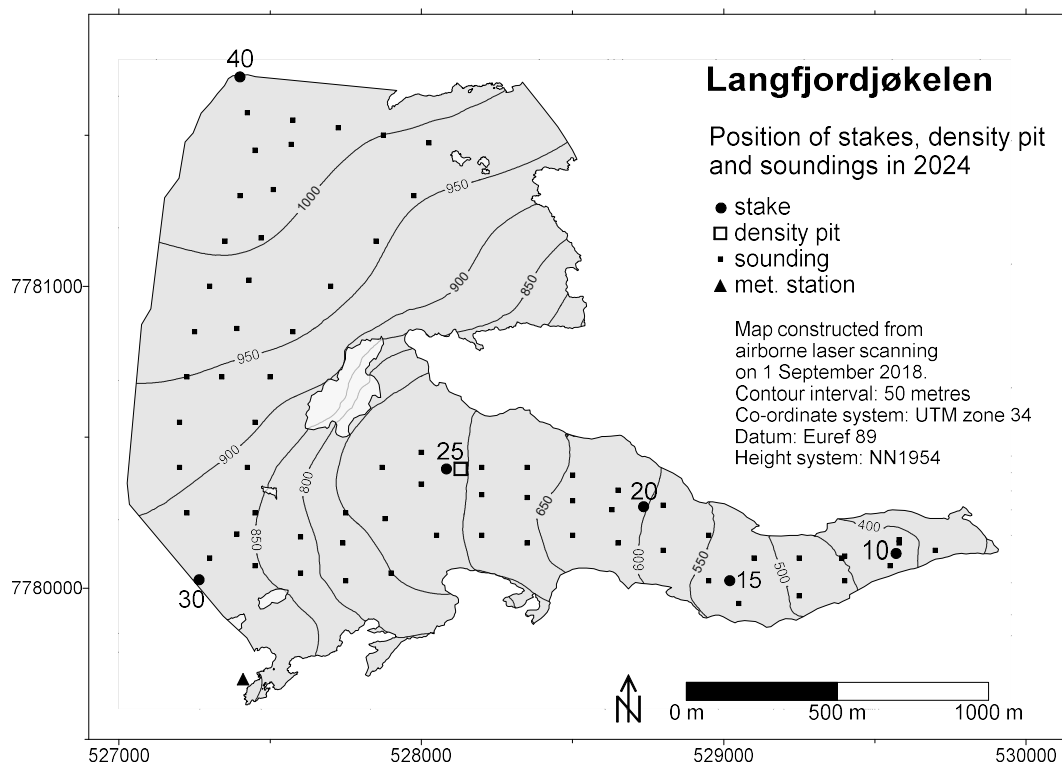


Figure 11-2
Location of stakes, soundings and snow pit on Langfjordjøkelen in 2024.

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 1.7 ± 0.2 m w.e., which is 82 % of the mean winter balance for the normal period 1991-2020 (except 1994 and 1995) (2.1 m w.e.). The interpolated 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. The density of the ice before melting was assumed to be 900 kg m^{-3} . Based on estimated density and stake measurements, the summer balance was also calculated as a mean value for each 50 m height interval and was -5.8 ± 0.3 m w.e., which is 195 % of the mean summer balance for the normal period 1991-2020 (-3.0 m w.e.). This is the greatest summer balance measured at Langfjordjøkelen since measurements started in 1989.

Hence, the annual balance was negative at -4.06 ± 0.40 m w.e. This is the greatest mass loss since 1989. The mean annual balance for 1991-2020 is -0.90 m w.e. The mean annual balance for the past ten years (2015-24) is -1.25 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.

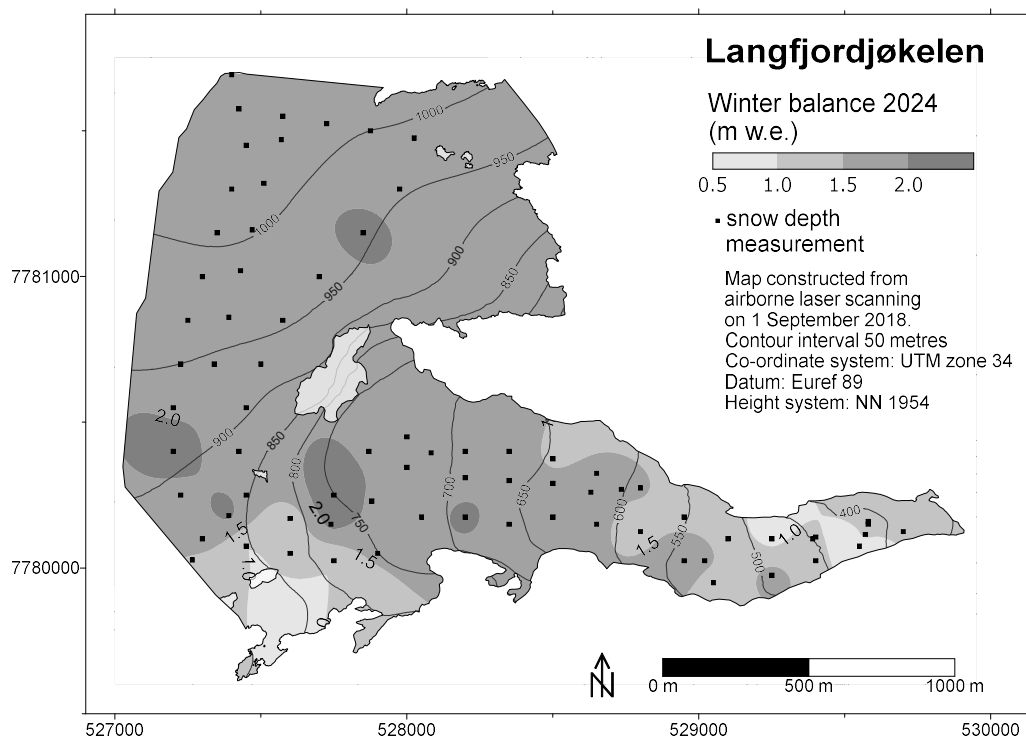


Figure 11-3
Spatial distribution of winter balance on Langfjordjøkelen in 2024.

According to Figure 11-4, the equilibrium line altitude was above the highest point of the glacier. Consequently, the accumulation area ratio was 0 %.

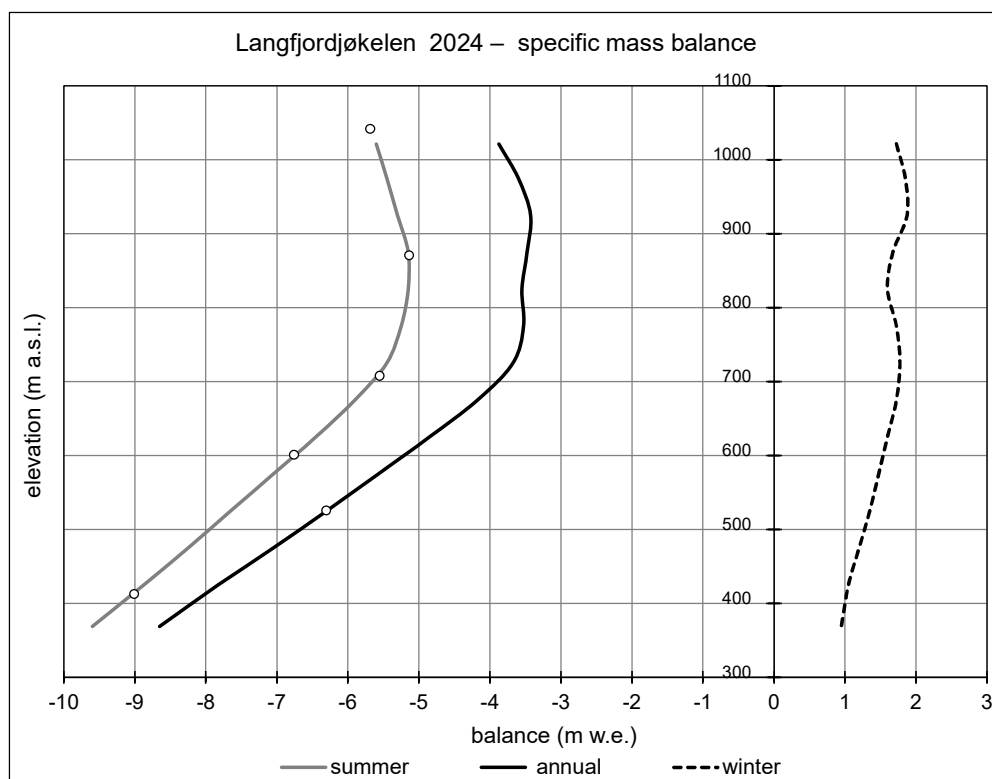


Figure 11-4
Mass balance diagram showing specific balance for Langfjordjøkelen in 2024. Specific summer balance for six stakes is shown as circles (○).

Table 11-1
Winter, summer and annual balance for Langfjordjøkelen in 2024.

Mass balance Langfjordjøkelen 2023/24 – stratigraphic system				
Altitude (m a.s.l.)	Area (km ²)	Winter balance Measured 18 June (m w.e.)	Summer balance Measured 15 Sep (m w.e.)	Annual balance S.S. 2021-2022 (m w.e.)
1000 - 1043	0.417	1.725	-5.600	-3.875
950 - 1000	0.467	1.850	-5.450	-3.600
900 - 950	0.376	1.875	-5.300	-3.425
850 - 900	0.362	1.675	-5.150	-3.475
800 - 850	0.232	1.600	-5.150	-3.550
750 - 800	0.217	1.725	-5.250	-3.525
700 - 750	0.267	1.775	-5.450	-3.675
650 - 700	0.203	1.725	-5.900	-4.175
600 - 650	0.168	1.600	-6.450	-4.850
550 - 600	0.128	1.475	-7.050	-5.575
500 - 550	0.121	1.350	-7.650	-6.300
450 - 500	0.095	1.200	-8.250	-7.050
400 - 450	0.096	1.050	-8.875	-7.825
338 - 400	0.049	0.950	-9.600	-8.650
Specific mass balance				
338-1043	2.61	1.70	-5.76	-4.06

11.2 Mass balance 1989-2024

The historical mass balance results for Langfjordjøkelen are presented in Figure 11-5. The cumulative annual balance for 1989-2024 (estimated values for 1994 and 1995 included) is -35.7 m w.e., which gives a mean annual balance of -0.99 m w.e. a⁻¹.

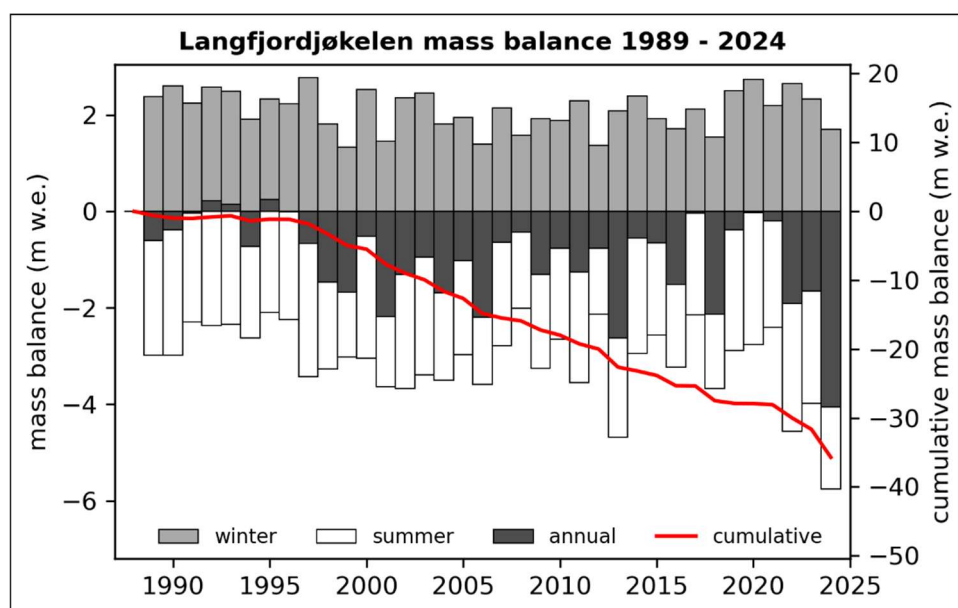


Figure 11-5
Mass balance on Langfjordjøkelen for the period 1989-2024. The total accumulated mass loss for 1989-2024 is 35.7 m w.e. (includes estimated values for 1994 and 1995).

11.3 Meteorological observations

A meteorological station 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, more continuous data exist for the periods 2009-2010 and 2012-2024.



Figure 11-6
The meteorological station, Langfjord Met.
Photo: Nils Larsen.

The mean summer temperature (1 June – 30 September) at Langfjord Met in 2024 was 8.4 °C. The mean summer temperature for 2012-23 was 5.0 °C. The melt season on the upper part of the glacier (above 900 m a.s.l.) started in the end of May and lasted until the end of September. Another period, from 19 to 27 October, were also relatively warm (1.5 °C) and hence, some melting probably occurred during these nine days. The monthly summer temperatures for 2024 were 7.2 °C (June), 10.7 °C (July), 10.9 °C (August) and 4.6 °C (September). The accordingly monthly mean summer temperatures for the period 2012-2023 are 3.1 °C (June), 7.8 °C (July), 6.2 °C (August) and 2.8 °C (September). Hence, all four “summer months” were about 2-4 °C warmer in 2024 than for the mean values during the 12-year period 2012-2023. The air temperature record for the summer season 2024 is shown in Figure 11-7.

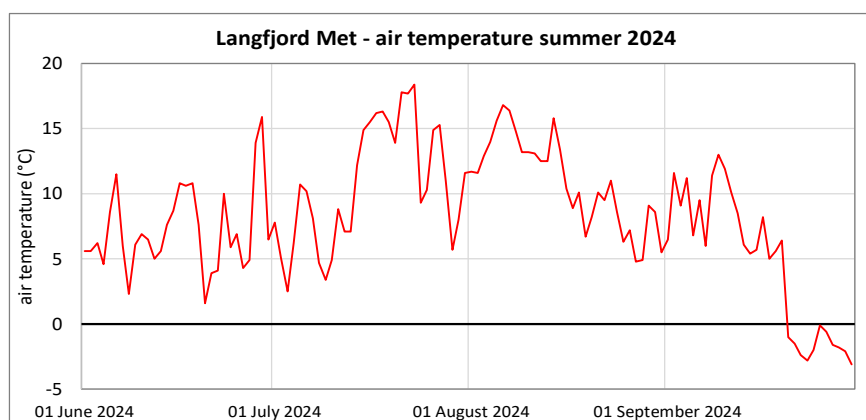


Figure 11-7
Air temperature at Langfjord Met (915 m a.s.l.) from 1 June to 30 September 2024.

12. Glacier front variations 2024

(Hallgeir Elvehøy)

Systematic observations of front variations of Norwegian glaciers started around Jostedalsgreen in 1899 (Rekstad, 1902). Measurements were then initiated in Jotunheimen (Øyen, 1906) and in Nordland (Hoel, 1910). Since then, front variations have been measured over several years for at least 74 glaciers in Norway. The longest and most complete record is for Fåbergstølsbreen, an eastern outlet from Jostedalsgreen. There, the observations started in 1899, and measurements have been conducted every year since 1907. Stigaholtbreen, Nigardsbreen and Austerdalsgreen, also outlets from Jostedalsgreen, and Styggedalsgreen in Jotunheimen have more than 100 observations. Sixteen glaciers have between 50 and 99 observations. The longest record in northern Norway is for Engabreen where measurements started in 1903. At present the monitoring programme of front variations includes 28 glaciers in southern Norway and 11 glaciers in northern Norway (Fig. 12-2 for location). The area of the monitored glaciers is 371 km², and they constitute about 16 % of the glacier area in Norway (Andreassen et al., 2022).



Figure 12-1

Skjelåtindbreen (Glacier ID 1272) in Beiarn, Nordland. The front variation measurements started in 2014 and shows a retreat of 94 meters in 10 years. The reference point SKJE2014 is located on the right-hand side of the lake close to the river outlet. Photo: Stein Simenstad/NVE.

Methods

The standard method is to measure the distance to the glacier terminus from one or several fixed points in defined direction(s), usually in September or October every year. The change in distance gives an estimate of the length change of the glacier. Alternatively, the front variation is measured between mapped terminus positions along a central flow line, or a combination of the methods are used. It is questionable how representative a front variation estimate for one year based on measurements from one reference point can be for the entire glacier terminus. However, when longer periods are considered, the measurements give valuable information about glacier fluctuations, and when several glaciers are observed regional tendencies are outlined (Andreassen et al., 2020).

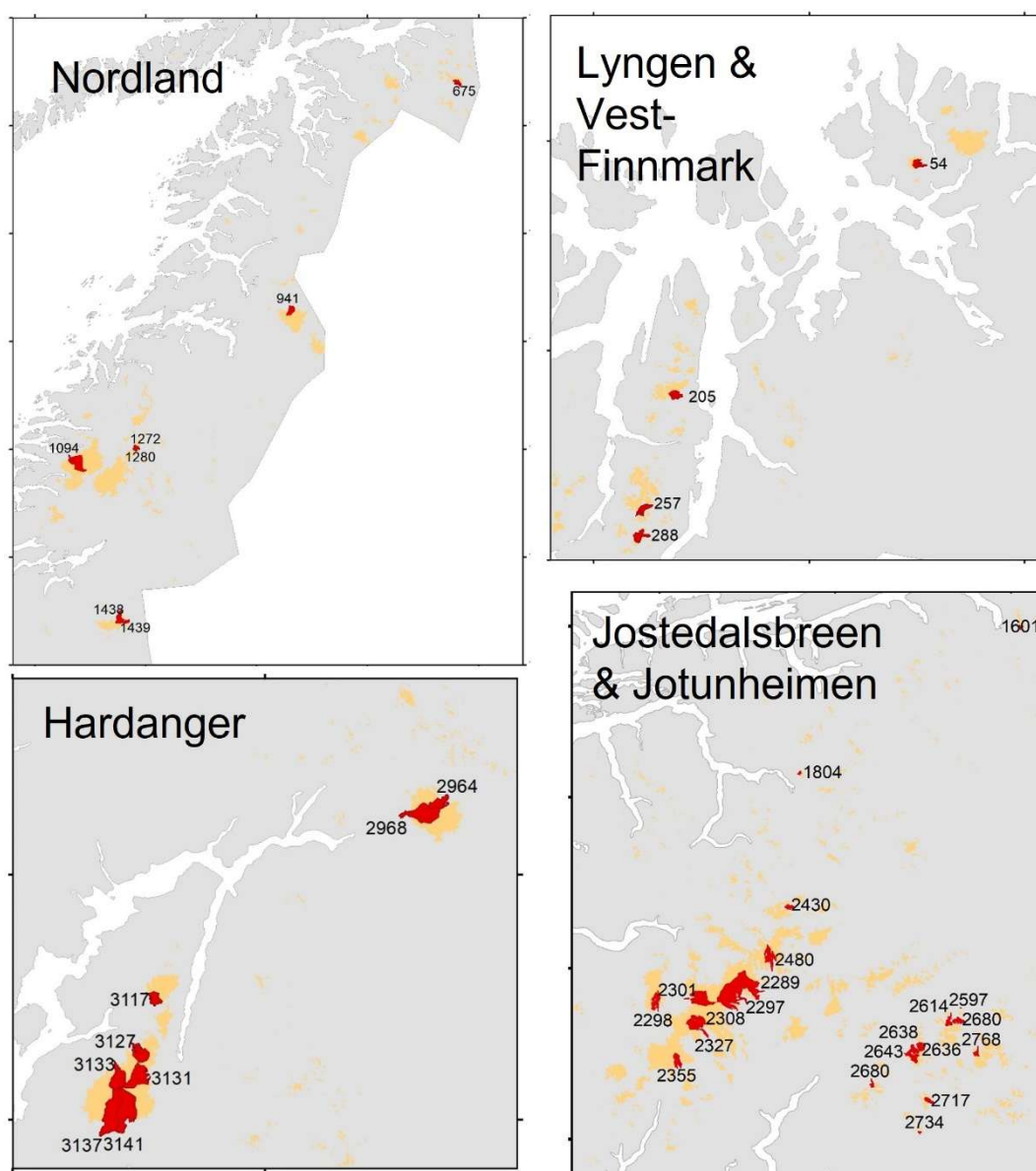


Figure 12-2

Map showing glaciers included in the front variation monitoring programme (in red) with glacier IDs (Tab. 12-2). Note that the different glacier areas are not to the same scale.

Results 2024

Thirty-five glaciers were measured, nine glaciers in northern Norway and twenty-five glaciers in southern Norway. The results for 2024, period(s) of measurements and number of observations (calculated front variations) are listed in Table 12-1. Thirty-three glaciers retreated and two glaciers showed no change (defined as within ± 2 meters). The annual front variation varied from ± 0 meters for Stigaholtbreen to -83 meters for Engabreen. The average annual retreat for the thirty-five glaciers was -26 meters. Four glaciers in the monitoring programme were not measured in 2024.

The mean cumulative front variation for the ten-year period 2014-2024 for 34 glaciers was -219 meters, ranging from -494 meters at Gråfjellsbrea to -52 meters at Svelgjabreen. Nine glaciers in northern Norway retreated on average 248 meters, and 25 glaciers in southern Norway retreated on average 208 meters. The data are available at <https://www.nve.no/hydrology/glaciers/>.

Table 12-1
Glacier front variations measured in 2024. See Figure 12-2 for glacier locations.

	Glacier	Glacier-ID	2024	Observer	Period(s)	Number obs.
Finnmark & Troms	Langfjordjøkelen	54	-33	NVE	1966-	28
	Koppangsbreen	205	-29	NVE	1952-	25
	Sydbreen	257	-17	NVE	1988-	20
	Steindalsbreen	288	-75	NVE	1953-	32
Nordland	Storsteinsfjellbreen	675	-28	NVE	1960-	19
	Rundvassbreen	941	NM	SISO	2011-	12
	Engabreen	1094	-83	S	1903-	92
	Skjelåtindbreen	1272	-46**	NVE	2014-	7
	Trollbergdalsbreen	1280	-78**	NVE	2010-	10
	Austre Okstindbreen	1438	-80	NVE	1908-44, 2006-	32
	Corneliussenbreen	1439	NM	NVE	2006-	10
Sunnmøre & Breheimen	Vinnufonna	1601	-25	NVE	2019-	4
	Trollkyrkjebreen	1804	-13	NVE	1944-74, 2008-	29
	Heimsta Mårådalsbreen	2430	-17	NVE	2002-	10
Jostedalsbreen	Fåbergstølsbreen	2289	-3	NVE	1899-	119
	Nigardsbreen	2297	-42	NVE	1899-	114
	Haugabreen	2298	-26	NBM	1933-41, 2013-	19
	Brenndalsbreen	2301	-38*	NVE	1900-62, 1964-65, 1996-	85
	Tuftebreen	2308	-11	NVE	2007-	17
	Austerdalsbreen	2327	-23	NVE	1905-19, 1933-	104
	Vetle Supphellebreen	2355	-12	NBM	1899-44, 2011-	48
	Stigaholtbreen	2480	0	NVE	1903-	118
Jotunheimen	Styggebreen	2608	-31	NFS	1951-63, 2011-	21
	Storjuvbreen	2614	-11	NVE	1901-07, 08-12, 33-61, 97-	64
	Storbreen	2636	-26	NVE	1902-	86
	Leirbreen	2638	-27	NVE	1907-77, 1979-	65
	Bøverbreen	2643	-32	NVE	1903-46, 1950-	51
	Styggedalsbreen	2680	-19	NVE	1901-	103
	Mjølkedalsbreen	2717	NM	NVE	1978-	28
	Kolledalsbreen	2734	NM	NVE	1978-	16
	Hellstugubreen	2768	-19	NVE	1901-	85
Hardanger	Midtdalsbreen	2964	-15	UiB	1982-	42
	Rembesdalskåka	2968	-18	S	1917-	49
	Botnabrea	3117	-1	GK	1996-	21
	Gråfjellsbrea	3127	-6	S	2002-	22
	Buerbreen	3131	-33	NVE	1900-	78
	Bondhusbrea	3133	-54	S	1902-	93
	Svelgjåbreen	3137	-6	SKL	1959-	23
	Blomstølskardsbreen	3141	-19	SKL	1994-	25

* – two years

** – three years

NM – not measured in 2024

Observers other than NVE:

SISO Siso Energi

S Statkraft AS

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

NFS Norsk Fjellsenter, Lom

UiB Prof. Jostein Bakke, University of Bergen

GK Geir Knudsen, Tyssedal

SKL Sunnhordland Kraftlag

Corrections of previously reported results

Hellstugubreen (ID 2768) 2005-2006 (GiN2006) is corrected from –15 to –14 metres based on the observations.

Storjuvbreen (ID 2614) 1954-55 and 1955-56 were reported as –31.5 and –33 meters, respectively. The observer's notes show the correct front variations are –41.5 and –23 meters.

At Leirbreen (ID 2638) there was a change in measuring line in 1976 as the old line hit the terminus' western side. At this time the pro-glacial lake had started to appear. The new reference point (LEIR1976) has later been mistakenly named LEIR75. The observations, references and comments are listed below (Tab. 12-2). The total frontal variation between 1976 and 1985 based on observations is –53 meters, in contrast to the reported variation of –64 meters.

Table 12-2
Glacier front variations 1976-1985 for Leirbreen (ID 2638). NP is Norsk Polarinstitutt. FoG 1980-85 is Fluctuations of Glaciers 1980-1985 (WGMS,1988).

	Source	Distance from LEIR1976	Reported front variation	Revised front variation	Comment
1976	Observer's note	36			New reference point established
1977	NP Årbok 1977 (published 1978)	42	-6	-6	Assumed distance
1979	Investigator's note	42		0	
1980	Investigator's note/ NP Årbok 1980	55.1	-13	-13	
1981	N50 map / NP Årbok 1981	67	-10	-12	Distance assessed from orthophoto, norgebilder.no
1983	NP Årbok 1983		-16 (3 y)		
1984	Investigator's note / FoG 1980-85	81.5	-11	-15	Interpolated across glacier river outlet
1985	Observer's note / FoG 1980-85	88.6	-8	-7	Interpolated across glacier river outlet

Table 12-3
Reference marks for Leirbreen (ID2368) surveyed with GNSS in 2022. See Figure 12-3 for locations.

Name	East	North	Elevation	Description
LEIR1909	450661	6827063	1477	Cairn on a large block with cross (cross not found), outside a prominent moraine
LEIR1937	450708	6827060	1477	Cairn on a medium size rock 45 m from Øyen's cairn.
LEIR1959	451087	6827074	1513	Cairn on a large block with red painted P's
LEIR1976S	451151	6827077	1519	Two red stones 64 meters in front of LEIR1959
LEIR1976	451190	6827310	1521	Red painted P on the northern side of the river.



Figure 12-3

Orthophoto from September 2024 showing the glacier foreland and pro-glacial lake of Leirbreen (ID 2368). The glacier outline from 1981 (red line) and surveyed reference points (red triangles) are shown. Other reference points are shown as black triangles. The horizontal extent is ca. 1500 meters.

Image source: www.norgebilder.no.

Addenda based on mapped glacier termini

Where front variation measurements have been abandoned for a period or measurements have been initiated recently, the records can be extended using maps, aerial photos, orthophotos or other georeferenced information. Front variations can either be calculated in the measuring direction from a surveyed reference point, or as change along a central flowline in a GIS, or from a combination of methods. When a mapped terminus position splits an existing period between ground measurements, the reported change here is from the earlier observation (Tab. 12-3).

At Lodalsbreen ground based observations stopped in 1970 because the observer found it too difficult to define the correct position of the sediment covered glacier terminus. The change between 1970 and 1984 was assessed from the change along the central flow line between the glacier outline on the N50-map based on aerial photos from 19 July 1966, and the glacier outline shown on the orthophoto from 8 June 1984, reduced with a part of the 1965/66 front variation (–100 of –145 m for 19 July to 3 October 1966) and annual front variations 1966-70. Front variations since 1984 was measured along the flow line. As the lower part of Lodalsbreen often has a large opening for the glacier river, the front variation between two consecutive front positions depends on where the flowline crosses the terminus. As the terminus is continuously receding the accumulated front variation is more representative than the single periods.

At Tuftebreen the front variation measurements started in 2007. The first known mapping of Tuftebreen was performed using terrestrial methods in 1937 (Pillewizer, 1950). This map was georeferenced using common objects (rivers, old bridges and buildings etc.). A central flow line was defined, and frontal variations were assessed (Tab. 12-3). Tuftebreen advanced at least 230 meters between the late 1970s/early 1980s and around 2000 (the culmination is not exactly dated).

At Mårådalsbreen the front variation measurements started in 2013. The record was extended using orthophotos and maps from 1966, 1993 and 2010. In addition, the terminus position was assessed from a photo taken by Tor Bruland in 2002 and an

observation made by Atle Nesje in 2006. The observations are referred to the original reference point MÅRÅ2013.

Table 12-4

Glacier front variations addenda from mapped glacier termini of Lodalsbreen, Tuftebreen, Mårådalsbreen and Leirbreen. Uncert. is the assumed uncertainty in the reported change. See Figure 12-2 for glacier locations.

Glacier	Bre-ID	Date	Source	Reference	Period	Change (m)	Uncert. (m)
Lodalsbreen	2266	08.06.1984	Orthophoto	Combined	1970-1984	-310	20
Lodalsbreen	2266	22.08.1993	N50-map	Flowline	1984-1993	-240	10
Lodalsbreen	2266	10.09.2005	Orthophoto	Flowline	1993-2005	-195	10
Lodalsbreen	2266	07.09.2010	Orthophoto	Flowline	2005-2010	-55	10
Lodalsbreen	2266	20.08.2015	Orthophoto	Flowline	2010-2015	-70	10
Lodalsbreen	2266	02.09.2019	Orthophoto	Flowline	2015-2019	-190	10
Lodalsbreen	2266	02.09.2024	Orthophoto	Flowline	2019-2024	-100	10
Tuftebreen	2308	1937	Map	Flowline	1937-1966	start	
Tuftebreen	2308	1966-07-19	Map	Flowline	1937-1966	-510	10
Tuftebreen	2308	1974-08-29	Aerial photo	Flowline	1966-1974	-70	20
Tuftebreen	2308	1984-06-08	Orthophoto	Flowline	1974-1984	+40	10
Tuftebreen	2308	1993-08-27	Map	Flowline	1984-1993	+30	10
Tuftebreen	2308	1997-08-14	Aerial photo	Flowline	1993-1997	+100	20
Tuftebreen	2308	2000	Trim line/moraine	Flowline	1997-2000	+60	20
Tuftebreen	2308	2004-08-12	Orthophoto	Flowline	2000-2004	-20	10
Tuftebreen	2308	2004-08-12	Orthophoto	TUFT07	2004-2007	-45	5
Mårådalsbreen	2430	1966-07-19	Orthophoto	MÅRÅ13	1966-1993	start	5
Mårådalsbreen	2430	1993-08-27	N50-map	MÅRÅ13	1966-1993	-210	10
Mårådalsbreen	2430	2002-08	Photo	MÅRÅ13	1993-2002	-120	10
Mårådalsbreen	2430	2006-08-11	Observation	MÅRÅ06	2002-2006	-43	5
Mårådalsbreen	2430	2010-09-05	Orthophoto	MÅRÅ13	2006-2010	-62	5
Mårådalsbreen	2430	2013-10-01	Observation	MÅRÅ13	2010-2013	-15	5
Leirbreen	2638	1966-08-15	Orthophoto	LEIR1959	1963-1966	-20	5
Leirbreen	2638	1981-08-29	N50-map	LEIR1976	1980-1981	-12	5



Figure 12-4
Slettmarkbreen (ID 2803) and the moraine formed by the advance in the 1990s as seen on 7 Sep 2024.
Photo: Hallgeir Elvehøy.

Addenda to previously reported results - Slettmarkbreen

Slettmarkbreen (ID 2803, Fig. 12-4) in Jotunheimen was observed for front variations between 1902 and 1958. Øyen (1903) had a cairn set up in 1902 just east of the medial surface moraine (SLETT1902), and frontal variations were reported until 1912 (Øyen, 1913a; 1913b). When Werenskiöld visited Slettmarkbreen in 1936 he located two cairns, one of them marked with a cross. He erected a new cairn (SLETT1936) on a high moraine 83.7 metres from the cairn marked with a cross. This moraine was probably the result of a glacier advance in the 1920s. Werenskiöld (1956) refers to the cairn with the cross as Øyen`s cairn from 1902.

Between 1947 and 1954 the observations of Slettmarkbreen was carried out by Olav Løken. His observation of the distance from SLETT1936 in 1947 (127 meters) and the reported frontal variations between 1936 and 1947 (–102.5 meters; Hoel and Werenskiöld, 1962) indicate that the distance from SLETT1936 to the glacier in 1936 was 24.5 meters. However, the reported distance from SLETT1902 in 1902 (15 meters; Øyen, 1903), the total frontal variation 1902-36 (–73.8 meters, Hoel and Werenskiöld, 1962) and the distance between the cairns (83.7 meters; Werenskiöld, 1956; Hoel and Werenskiöld, 1962) indicate that the distance from SLETT1936 to the glacier in 1936 was 5.1 meters. This discrepancy is not solved, but in a photo of the cairn and the glacier from 25 August 1936 by Werenskiöld the glacier seems to be more than 5 meters away from the cairn (Fig. 12-5). Consequently, the frontal retreat between 1912 and 1936 formerly reported as 32 meters is now increased to 51 meters.



Figure 12-5
The cairn built in 1936 by Werner Werenskiöld in front of Slettmarkbreen. Photo: Werner Werenskiöld.

Observations from 25 August 1913 and 26 August 1914 probably carried out by Kristian Vole, the former front observer, were found in notes to P.A. Øyen. They had not been published as the funding of Øyen's work on frontal variations had stopped. These observations are now included in the record.

Slettmarkbreen was visited on 7 September 2024. Two cairns were located ca. 85 meters apart. Neither the cross marking Øyen's cairn, the sighting cairn in front of Øyen's cairn nor the white paint marking Werenskiöld's cairn were found. However, the description of Øyen's cairn on top of a large rock, Werenskiöld's cairn on a high moraine, and the distance between the cairns (from handheld navigator GPS) justifies that the correct cairns were found. No more reference marks were found. A new reference mark (SLETT2024) was established on a large boulder inside the moraine (Tab. 12-3, Fig. 12-6).

Slettmarkbreen is one of a few glaciers in Jotunheimen which advanced in the 1990s. The distance from SLETT1936 to the moraine in the direction between the two cairns is 415 metres. The timing of the culmination of the advance is suggested as 2001 in line with the recorded culmination for Styggedalsbreen (2001), Bøverbreen (2001) and Storjuvbreen (2002). The advance was assessed from the distance between the mapped front position in 1981 and the moraine as 25 metres (Fig. 12-5). This is comparable to the amount of advance measured at Bøverbreen and Styggedalsbreen. The front variation series has been extended using aerial photos from 1981, 2007, 2017 and 2024

(Tab. 12-6, Fig. 12-7). The revised frontal variation record is available at www.nve.no/glacier.

Tab 12-5

Reference marks of Slettmarkbreen surveyed with a Navigator GPS in 2024. Elevations from www.norgeskart.no. See Figure 12-7 for locations.

Name	East	North	Elevation	Description
SLETT1902	470448	6809140	1433	Cairn on 2 m long and 1.5 m high boulder on the east side of the river. A cross was carved into the western side of the boulder (cross not found).
SLETT1936	470501	6809076	1438	Remnants of cairn on a moraine ridge 85 m closer to the glacier than SLETT1902.
SLETT2024	470855	6808675		Boulder in front of the terminus. Small cairn on top.

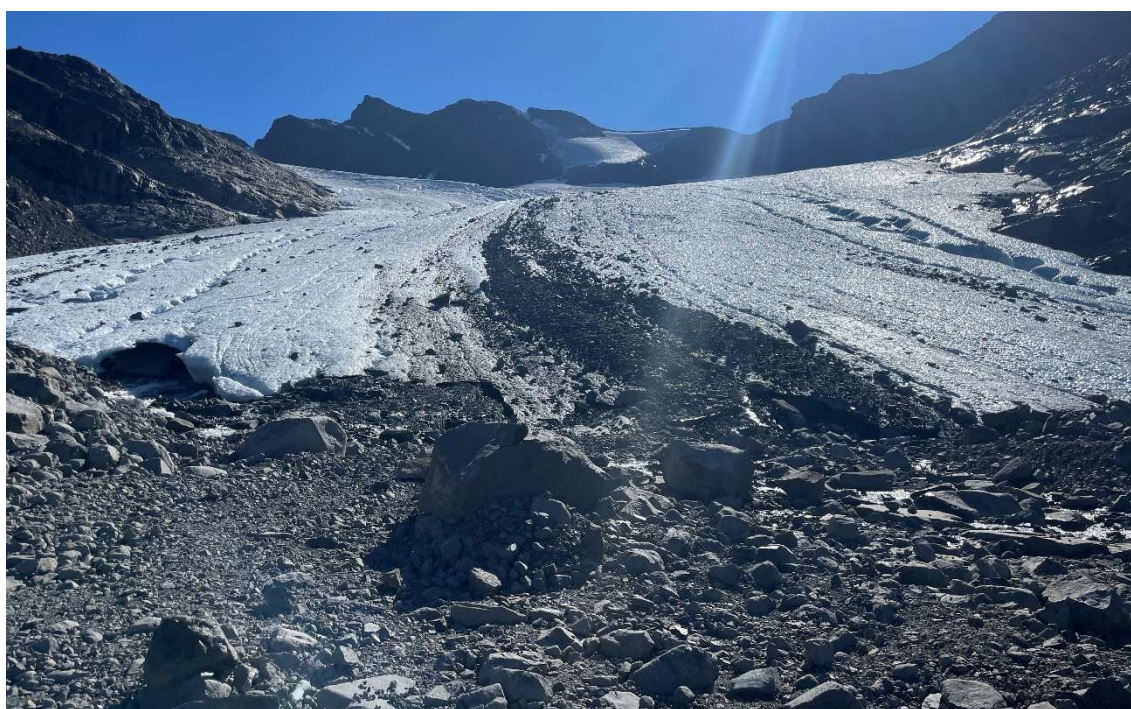


Figure 12-6

Slettmarkbreen on 7 September 2024. SLETT2024 is the cairn on top of the large boulder in the middle of the photo. The distance to the glacier was 41 meters. Photo: Hallgeir Elvehøy.



Figure 12-7
Orthophoto from 20 September 2024 showing the glacier foreland of Slettmarkbreen, the glacier outline from 1981 (red) and known reference points (red triangles). The horizontal extent is ca. 950 metres.
Image source: www.norgebilder.no.

Table 12-6
Glacier front variations addenda of Slettmarkbreen from mapped glacier termini in the direction defined by SLETT1902 and SLETT1936. Uncert. is the assumed uncertainty in the reported change.

Glacier	Date	Source	Reference	Period	Change (m)	Uncert. (m)
Slettmarkbreen	1981-08-29	N50-map	SLETT1936	1958-1981	-195	5
Slettmarkbreen	2001	Moraine ridge	SLETT1936	1981-2001	+25	10
Slettmarkbreen	2007-08-22	Orthophoto	SLETT1936	2001-2007	-20	5
Slettmarkbreen	2017-08-22	Orthophoto	SLETT1936	2007-2017	-50	5
Slettmarkbreen	2024-09-06	Orthophoto	SLETT1936	2017-2024	-100	10

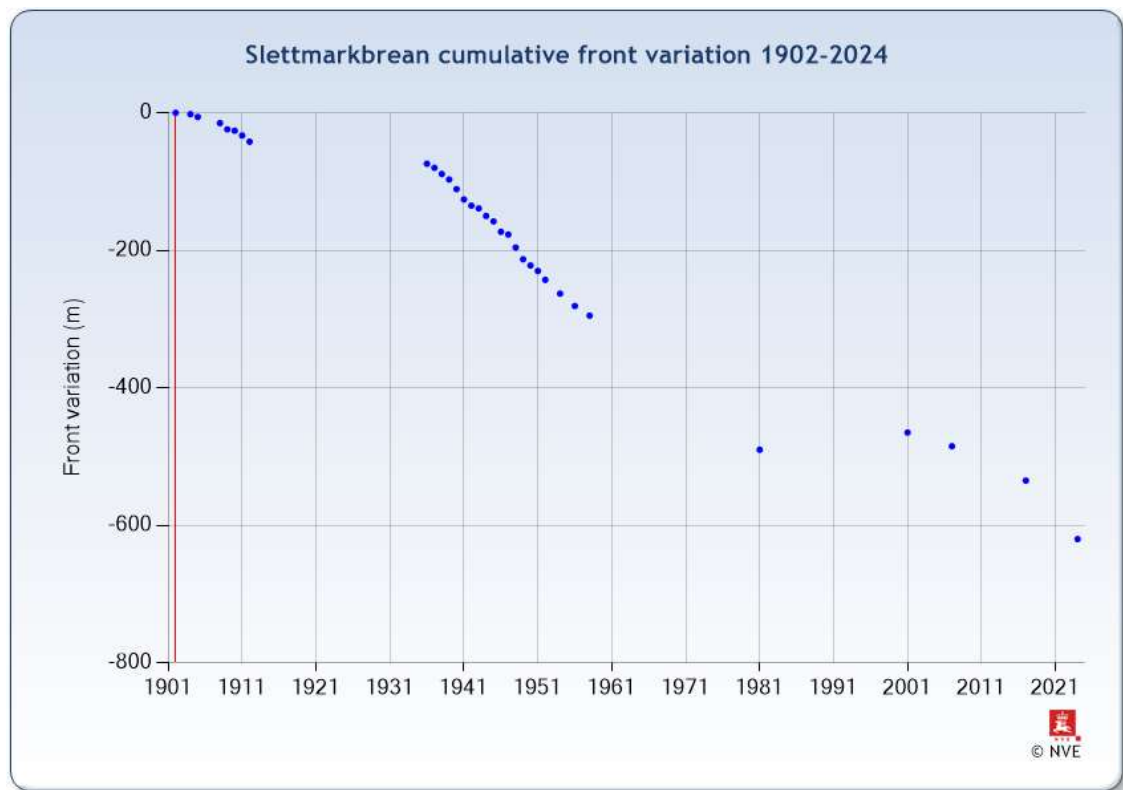


Figure 12-8
The front variation record for Slettmarkbreen in Jotunheimen.

13. Jøkulhlaup and runoff from glacier lakes

(Bjarne Kjøllmoen)

Jøkulhlaups, also known as Glacier Lake Outburst Floods (GLOFs), and drained glacier lakes, were registered at eight glaciers in Norway in 2024. Six of the events were observed on photographs and satellite images only.

Events were observed from glacier lakes at 1) Vivakulen (Jostedalsbreen) and 2) Rembesdalskåka (Hardangerjøkulen) (Fig. 13-1).

Inspection of glacier lakes on Sentinel-2 imagery showed drainage events at 3) Midtbreen (Lyngen), 4) Rundvassbreen (Blåmannsisen), 5) Oksfjellbreen (Okstindbreen), 6) Tystigbreen (Strynefjellet), and 7) Harbardsbreen and 8) Holåbreen (both Breheimen) (Fig. 13-1).

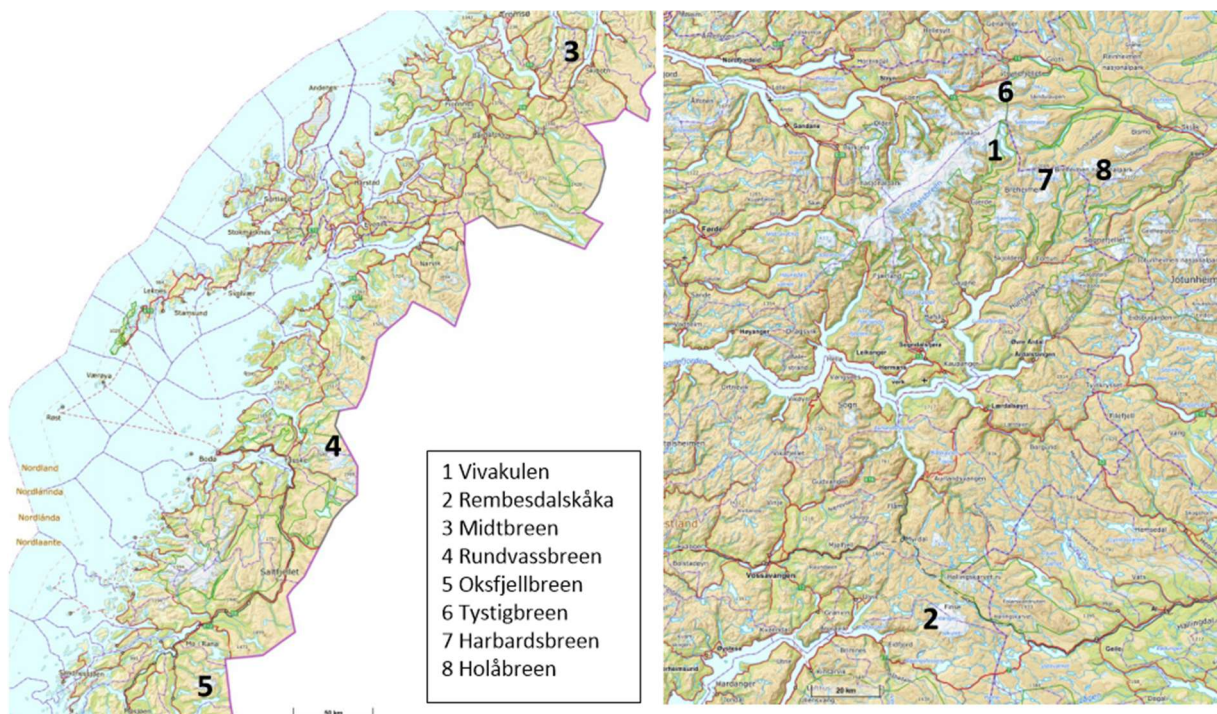


Figure 13-1
Jøkulhlaups and runoffs from glacier lakes were registered at eight glaciers in 2024, three in northern Norway (left) and five in southern Norway (right). Map source: norgeskart.no.

13.1 Events observed in the field

1 Vivakulen (Glacier ID 2490)

Vivakulen is a small glacier close to the northern part of Jostedalsbreen ice cap (Fig. 13-1) and was until summer 2024 connected to Jostedalsbreen just south of Austdalsbreen (Fig. 13-2). An ice-dammed lake is situated in the eastern part of the outlet (Fig. 13-2) and Sentinel image from 25 May also show a supraglacial lake at the northwestern side of the glacier (Fig. 13-4).



Figure 13-2
 Orthophoto from 1 September 2024 showing the glacier Vivakulen with the locations of the ice-dammed lake to the right and the supraglacial lake to the left. The glacier was separated from the Jostedalsgreen ice cap at the end of the summer in 2024. Source: norgebilder.no.

Jøkulhlaup 2024

On 28 May 2024, crew from NVE observed that water had drained from the ice-dammed lake in east (Fig. 13-3).



Figure 13-3
 The ice-dammed lake photographed towards south on 28 May 2024, after the run-off. Photo: Jostein Aasen.

Examination of Sentinel images confirm that both glacier lakes were filled with water three days before, on 25 May, and both lakes were empty on 11 June (Fig. 13-4). Consequently, both glacier lakes were emptied between 25 and 28 May. Whether the supraglacial lake in northwest drained through the ice-dammed lake in southeast was not confirmed, but it is likely that this is how it happened.

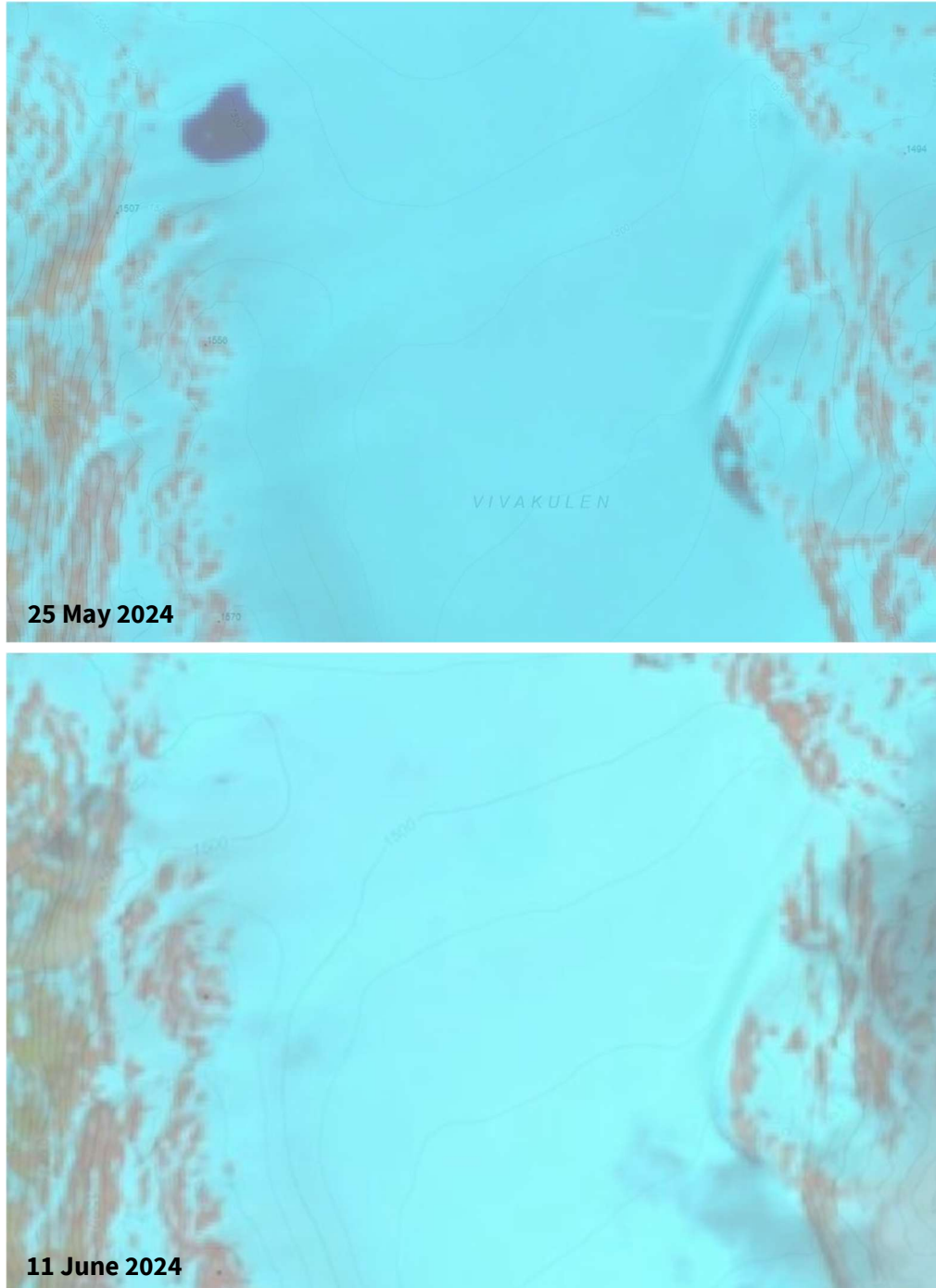


Figure 13-4
Satellite images (Sentinel-2) taken before (upper) and after (below) the runoff. The upper image, taken on 25 May, shows water in both the ice-dammed lake in southeast and the supraglacial lake in northwest. The lower image however, taken on 11 June, shows that both lakes were empty. Source: Varsom Xgeo.

Subsequent inspection of Sentinel satellite images from previous years suggest that there could also have been events in 2022 and 2023. Images from 26 June and 22 July 2022 suggest that the supraglacial was drained between these two dates. Again, images from 15 June and 24 June 2023 suggest a drainage from the supraglacial lake within this period.

2 Rembesdalskåka (Glacier ID 2968)

Rembesdalskåka, an outlet glacier of Hardangerjøkulen, dams a lake called Nedre Demmevatnet (0.14 km²) (Fig. 13-5). There have been many previous events recorded from Nedre Demmevatnet (Tab. 13-1), the earliest prior to 1813 (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 13-5
Orthophoto from 26 July 2019 showing the lower part of Rembesdalskåka and the glacier-dammed lake Nedre Demmevatnet. The hydropower reservoir Rembesdalsvatnet is seen to the left. Source: norgebilder.no.

Jøkulhlaup 2024

A new event occurred at the glacier-dammed lake on 3 June 2024. Over about seven hours, ca. 1 million m³ water drained under Rembesdalskåka and subsequently to the hydropower reservoir Rembesdalsvatnet (Fig. 13-5). Web camera photos from Gothecca show the inner part of the lake (close to the ice barrier) before, during and after the event (Fig. 13-6). A photograph of the inner part of the empty lake is also shown in figure 13-7.

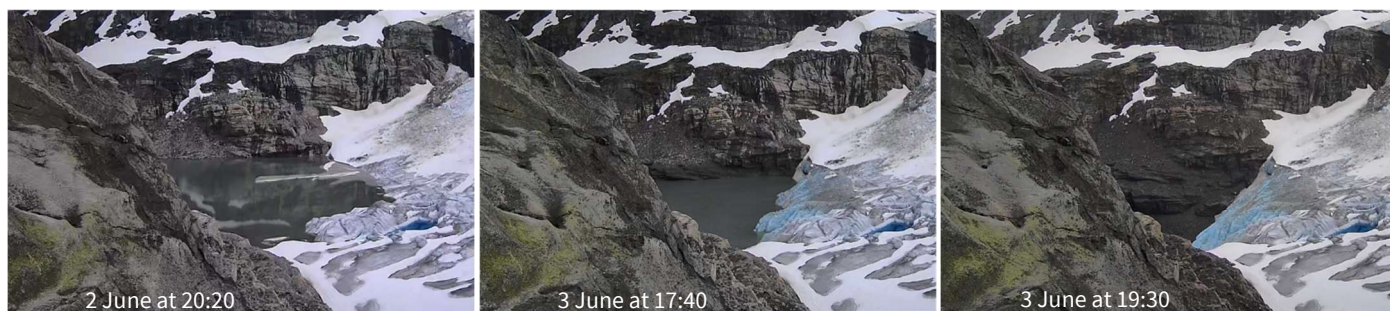


Figure 13-6
Web camera photos taken before (left), during (middle) and after (right) the event on 3 June. Source: Gothecca.



Figure 13-7
Part of the empty glacier lake Nedre Demmevatnet, and the ice barrier photographed on 11 June 2024, a week after the jökulhlaup. Photo: Hallgeir Elvehøy.

Table 13-1

Dates and approximate volumes of jökulhlaups from Nedre Demmevatnet. For events that occurred since 2014 the water volume is calculated by Statkraft as extra inflow to the hydro-power reservoir Rembesdalsvatnet.

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	17 September	Damage, including two bridges	unknown
1893	Late August	Catastrophic flood, lake drained in 24 hours	35
1897	17 August	Water flowed over glacier surface, lasted 24 hours	35
1937	10 August	Drained in 3.5 hours	12
1938	23 August	Flood before new drainage tunnel completed	10
2014	24 August	Event occurred over ~3 hours	1,9
2016	~25 January	Lake observed full 24 th January and empty 30 th January	1,44
2016	6 September	Event occurred over ~4 hours	1,87
2017	27 October	Event occurred over ~22 hours	1,85
2018	10 August		unknown
2019	24 August	Event occurred over ~3 hours	1,8
2020	6 September	Event occurred over 5-6 hours	2,3
2021	13 July	Event occurred over 3-4 hours	1,75
2022	29-30 August	Event occurred over ~11 hours	2,19
2023	22 June	Event occurred over ~6 hours	1,0
2024	3 June	Event occurred over ~7 hours	1

13.2 Events observed by photography and satellite images only

3 Midtbreen (Glacier ID 251)

Midtbreen is a small glacier with an area of just under 2 km² located on the Lyngen peninsula in Troms county in northern Norway (Fig. 13-1). A small glacier lake is located at the southern part of the glacier (Fig. 13-8). No earlier events have been observed from this glacier lake.



Figure 13-8
Midtbreen and the glacier-dammed located at the southern ice edge as seen on this orthophoto from 14 August 2024. Source: norgeibilder.no.

Jøkulhlaup 2024

Examination of Sentinel-2 images from the end of July and beginning of August 2024 suggest that the glacier lake was drained in the period between 22 July and 5 August (Fig. 13-9). The images show water in the lake on 22 July, less water on 30 July and empty lake on 5 August.



Figure 13-9
Sentinel-2 images of the glacier lake at Midtbreen from 22 July (left), 30 July (middle) and 5 August (right) 2024. The images show less water in the lake on 30 July than it was on 22 July and empty lake on 5 August, indicating that the lake was drained at the turn of the month between July and August. Source: Varsom Xgeo.

4 Rundvassbreen (Glacier ID 941)

Øvre Messingmalmvatnet (1043 m a.s.l.) is adjacent to and dammed by Rundvassbreen (Fig. 13-10), a northern outlet glacier of the Blåmannsisen ice cap in Nordland County (Fig. 13-1). There have been many previous events recorded from Øvre Messingmalmvatnet (Tab. 13-2), the first in 2001 (Engeset, 2002).



Figure 13-10
Orthophoto from 24 August 2022 showing the northern part of Rundvassbreen and the glacier-dammed lake Øvre Messingmalmvatnet. Source: norgebilder.no.

Jøkulhlaup 2024

A new event occurred from the glacier-dammed lake, Øvre Messingmalmvatnet on 12 August 2024. The drainage from the lake was detected by examination of Sentinel-1 images (radar) from 11 and 13 August and later confirmed by comparing Sentinel-2 images (optical) from 9 August and 6 September (Fig. 13-11).

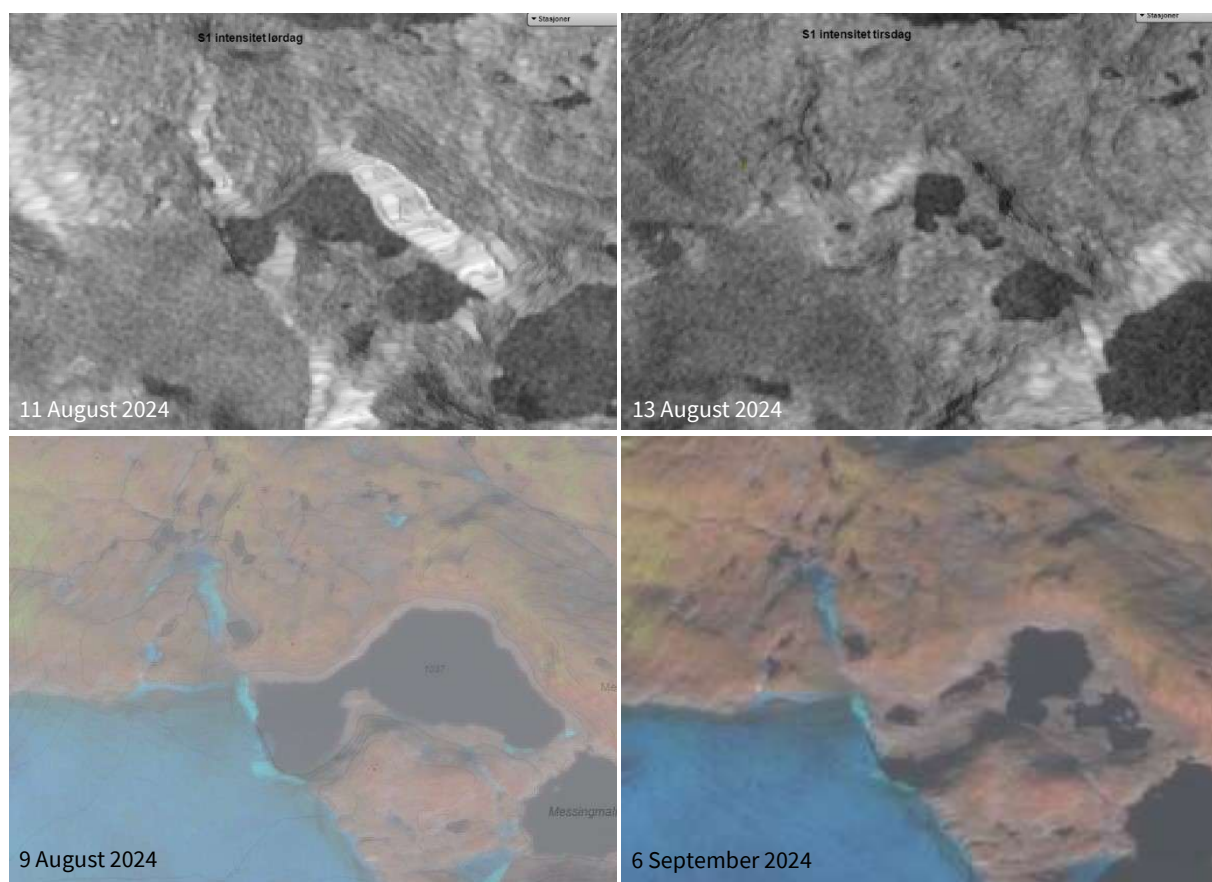


Figure 13-11

Above: Sentinel-1 radar images from 11 August (left) and 13 August (right) 2024. Below: Sentinel-2 optical images from 9 August (left) and 6 September (right) 2024. The images to the left are taken before the drainage, while the images to the right are taken after the drainage. Source: Varsom Xgeo.

The water level in Øvre Messingmalmvatnet was not measured before the jøkulhlaup and hence, the water volume from the jøkulhlaup could not be calculated. However, Sentinel-2 images suggest that the water level just before and after the jøkulhlaup in 2024 was approximately at same level as it was ahead of the jøkulhlaup in 2023 (Fig. 13-12). Consequently, it is reasonable to estimate that about 12 million cubic metres of water drained under the glacier and subsequently to the hydropower reservoir, Lake Sisovatnet also in August 2024. This is the fourteenth year that the glacier dammed lake has drained since the first known jøkulhlaup in 2001.

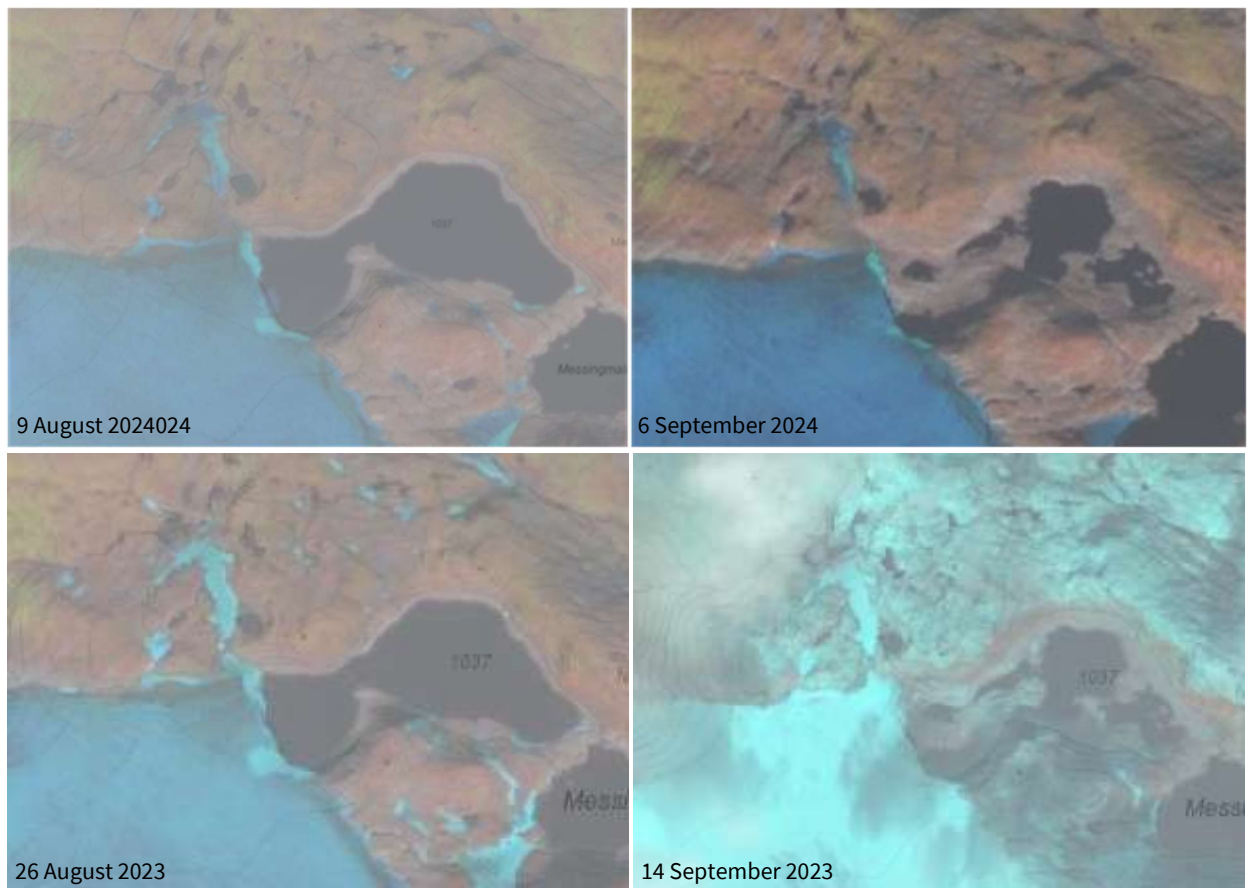


Figure 13-12

Above: Sentinel-2 images from 2024, before the drainage to the left and after the drainage to the right. Below: Sentinel-2 images 2023, before the drainage to the left and after the drainage to the right. The images suggest that the water level in Øvre Messingmalmvatnet was approximately the same in 2024 as it was in 2023, both before and after the jökulhlaups. Source: Varsom Xgeo.

Several previous events of different magnitudes have been recorded from Rundvassbreen (Jackson and Ragulina, 2014). The first was in September 2001, when 35 mill. m³ of water suddenly drained under the glacier and subsequently to the hydropower reservoir, Lake Sisovatnet. Previously the water had drained over a rock sill and flowed into a river towards Sweden (Engeset et al., 2005). The event in 2024 was the fourteenth, and the interval between events has varied from one year to four years. All recorded events from Rundvassbreen have been in late summer, i.e. August or September (Tab. 13-2).

Table 13-2

Dates, water level before and after the drainages and approximate water volumes of jøkulhlaups from Øvre Messingmalmvatnet 2001-2024.

Year	Date	Water level (m a.s.l.)		Comment	Water volume (mill. m ³)
		Before	After		
2001	5 - 7 September	~1051	~1007	WL estimated	35
2005	27 - 29 August	~1051	~1007	WL estimated	35
2007	29 August	~1040	~1007	WL estimated	20
2009	6 - 7 September	~1040	~1007	WL estimated	20
2010	8 - 17 September	~1028	~1007	WL estimated	11
2011	22 September	1029	1007.5	WL measured	13
2014	10 - 12 August	1050	1007.3	WL measured	36
2016	28 - 29 September	1040.7	~1007	WL measured/estimated	25
2018	25 - 26 August	1039.8	1007.3	WL measured	24
2019	9 - 10 September	1026.2	1007.2	WL measured	11
2020	3 - 4 September	1025.4	1007.0	WL measured	10
2022	6 September	1044.2	1007.1	WL measured/estimated	29
2023	27 - 28 August	1027.7	1007.0	WL estimated by SISO	12
2024	12 August		~1007	WV estimated	12

WL - Water Level

WV - Water Volume

5 Oksfjellbreen (Glacier ID 1450)

Oksfjellbreen is a southern outlet (3 km²) from the ice cap Okstindbreen in Nordland County (Fig. 13-1). A small ice-dammed lake (0.04 km²) is located in the northeastern part of the glacier (Fig. 13-13). Runoffs from Oksfjellbreen are registered every year since 2020.

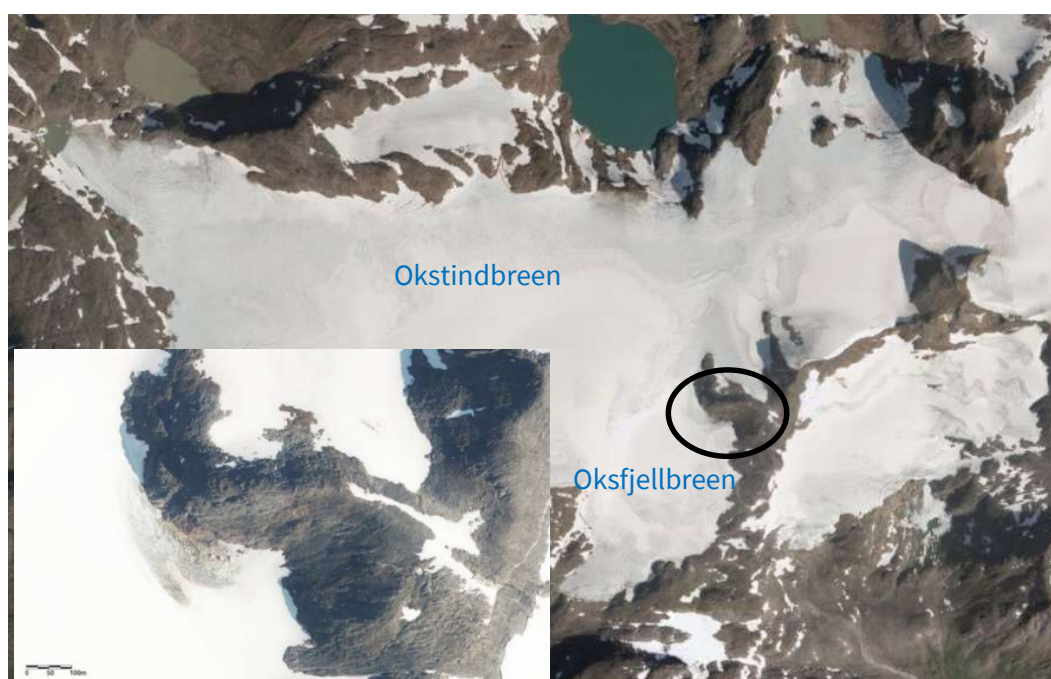


Figure 13-13

Oksfjellbreen is a southern outlet from the ice cap Okstindbreen. The glacier-dammed lake is located on the north-eastern side of the Oksfjellbreen outlet, indicated by the black ellipse in the orthophoto from 9 August 2014. The inset orthophoto shows an empty glacier lake on 28th July 2021. Source: norgebilder.no.

Jøkulhlaup 2024

Examination of Sentinel-2 images from 29 and 31 May 2024 suggest that the glacier-dammed lake emptied during this period (Fig. 13-14).

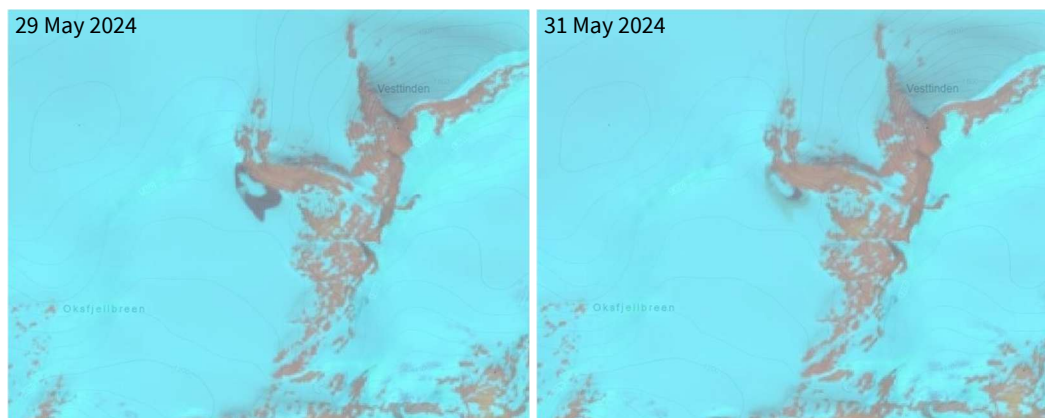


Figure 13-14
Sentinel-2 images from 29 May (left) showing water in the lake, and from 31 May (right) showing an empty lake.
Source: Varsom Xgeo.

6 Tystigbreen (Glacier ID 2429 and 2435)

Tystigbreen is a glacier complex (14 km²) in Stryn, just northeast of Jostedalbreen (Fig. 13-1). Two small ice-dammed lakes (ID 2429, 0.03 km² and ID 2435, 0.04 km²) are located in the northeastern part of the glacier complex (Fig. 13-15). Previous runoffs from the two lakes were registered in 2014 (ID2429) and in 2010 and 2018 (ID2435).



Figure 13-15
Tystigbreen is a glacier complex just northeast of Jostedalbreen. Two glacier-dammed lakes are located on the northeastern side of the glacier complex, indicated by the ellipse in the orthophoto from 1 September 2024. At the time of photograph both lakes were empty. Source: norgeibilder.no.

Jøkulhlaup 2024

Examination of Sentinel-2 images from 5 August and 2 September 2024 suggest that both glacier-dammed lakes emptied during this period (Fig. 13-16).

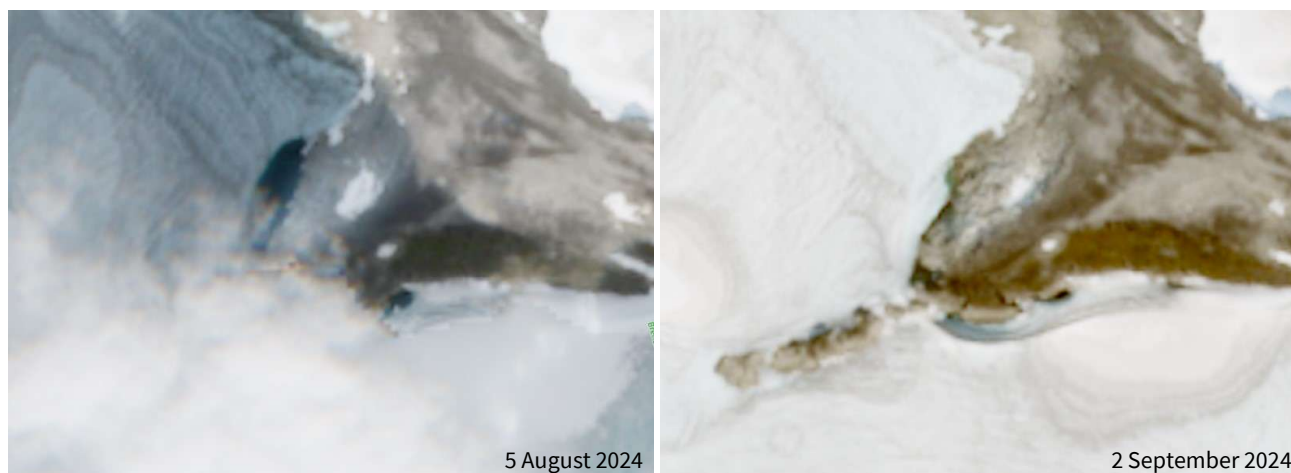


Figure 13-16
Sentinel-2 images from 5 August (left) showing water in the lakes, and from 2 September (right) showing two empty lakes. Source: Varsom Xgeo.

7 Harbardsbreen (Glacier ID 2514)

Harbardsbreen is a plateau glacier with an area of about 25 km² located in Breheimen, Vestland county (Fig. 13-1). In the central part the glacier dams two lakes (Fig. 13-17). Several previous jøkulhlaups have occurred at Harbardsbreen (Tab. 13-3), the last one in June 2023.



Figure 13-17
Orthophoto from 2 August 2024 showing the central part of Harbardsbreen and the two glacier-dammed lakes, empty at the time of photograph. Source: norgeibilder.no.

Jökulhlaup 2024

Examination of Sentinel-2 images suggest that the western glacier lake was drained between 22 and 25 May. The images below (Fig. 13-18) show a water-filled lake on 22 May, almost empty lake on 25 May and a completely empty lake on 24 June.

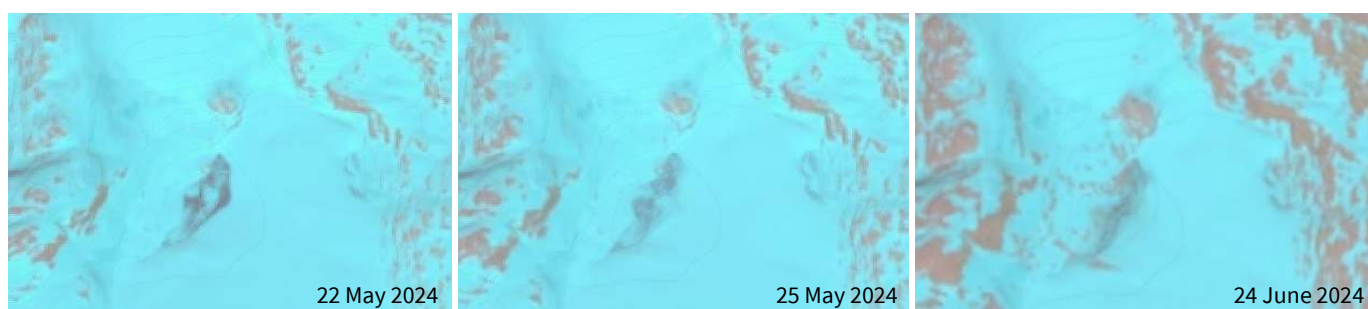


Figure 13-18
Sentinel-2 images from 22 May (left), 25 May (middle) and 24 June (right) 2024. The left lake was emptied during this period. Source: Varsom Xgeo.

Table 13-3
Dates and approximate volumes of jökulhlaups from the western glacier lake at Harbardsbreen.

Year	Date	Comment	Water volume (mill.m ³)
1996-97	14 September 96 - 19 May 97	Observations during field work	unknown
1997	19 May - 25 July	Observations during field work	0,6
1998-99	23 September - 8 May	Observations during field work	unknown
2000-01	13 September - 16 February	Observations during field work	unknown
2001	23 August - 19 September	Observations during field work	unknown
2010	4 - 6 August	Increased water level in Fivlemyrane	5,5
2012	Early summer	Observations during inspections	0,6
2015	21 - 24 August	Increased water level in Fivlemyrane	5,5
2020	19 - 24 June	Satellite images from Sentinel-2	unknown
2023	15 - 25 June	Satellite images from Sentinel-2	unknown
2024	22 - 25 May	Satellite images from Sentinel-2	unknown

8 Holåbreen (Glacier ID 2562)

Holåbreen is a glacier with an area of 7.6 km² (2019) located in the eastern part of Breheimen (Fig 13-1). A small, elongated ice-dammed lake (0.1 km²) is located at the southern edge of the glacier. No earlier events have been registered from this glacier lake.

Jøkulhlaup 2024

Satellite images suggest that the glacier lake was emptied between 13 and 19 July 2024 (Fig. 13-19).

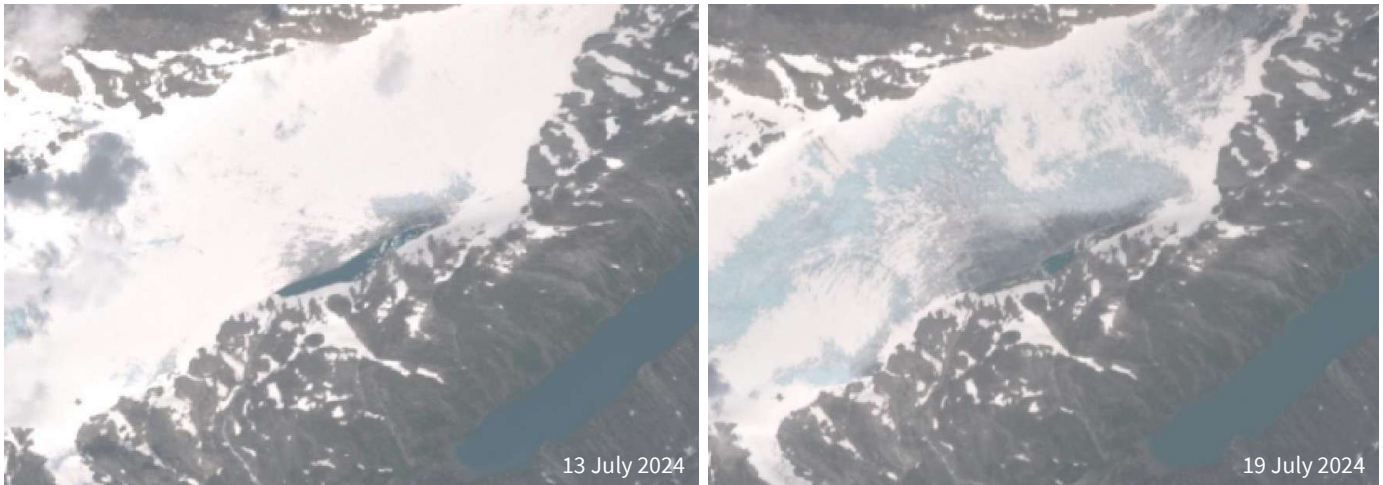


Figure 13-19
Holåbreen in the eastern part of Breheimen. The Sentinel-2 images are taken on 13 July (left) and 19 July (right) 2024. The ice-dammed lake at the southern edge of the glacier was emptied during this period.
Source: Varsom Xgeo.

13.3 Austerdalsisen - addenda to previously reported jøkulhlaups/events (Hallgeir Elvehøy)

Austerdalsisen (Glacier-ID 1361) is a southern outlet from Østisen/Eastern Svartisen in Nordland (Fig. 13-20). The glacier has Norway's largest glacier basin (50.49 km² in 2018). In front of the present glacier lies Lake Austerdalsvatnet (208 m a.s.l.). Early in the 20th century this lake was filled up with glacier ice, and the glacier drained both to Glomåga in the west and to Røssåga in the east. However, in line with the general glacier reduction in the 20th century a lake started to form at its western terminus, and the glacier tongue was thinning. In 1941 the first jøkulhlaup towards Røssåga from the newly formed Lake Austerdalsvatnet (285 m a.s.l.) occurred, and in the following years jøkulhlaups occurred annually. The jøkulhlaups caused damages to bridges, roads and property in the downstream Svartisdalen valley. As the glacier terminus retreated the lake volume and consequently the jøkulhlaup volumes and peak discharge increased (Fig. 13-22). The glacier evolution and jøkulhlaup up to and including 1954 are described and the volumes of the annual jøkulhlaups are calculated by Liestøl (1956).



Figure 13-20
Austerdalsisen after the jøkulhlaup that peaked on 2 September 1952. The emptied lake Austerdalsvatnet with ice bergs resting on the lake bottom is in the lower left corner. Lake Svartisvatnet in the right background.
Photo: Widerøe Flyveselskap AS.

After 1954 the glacier recession and annual jøkulhlaups continued. In the late 1950s it was decided to construct a diversion tunnel from the glacier dammed lake eastwards towards Svartisvatnet. This tunnel was opened in May 1959 and lowered the lake level in Austerdalsvatnet from ca. 274 m a.s.l. to 208 m a.s.l. Consequently, no more jøkulhlaups took place from Austerdalsvatnet. Here, the volumes of jøkulhlaups in 1955, 1956, 1957 and 1958 are assessed from discharge measurements.

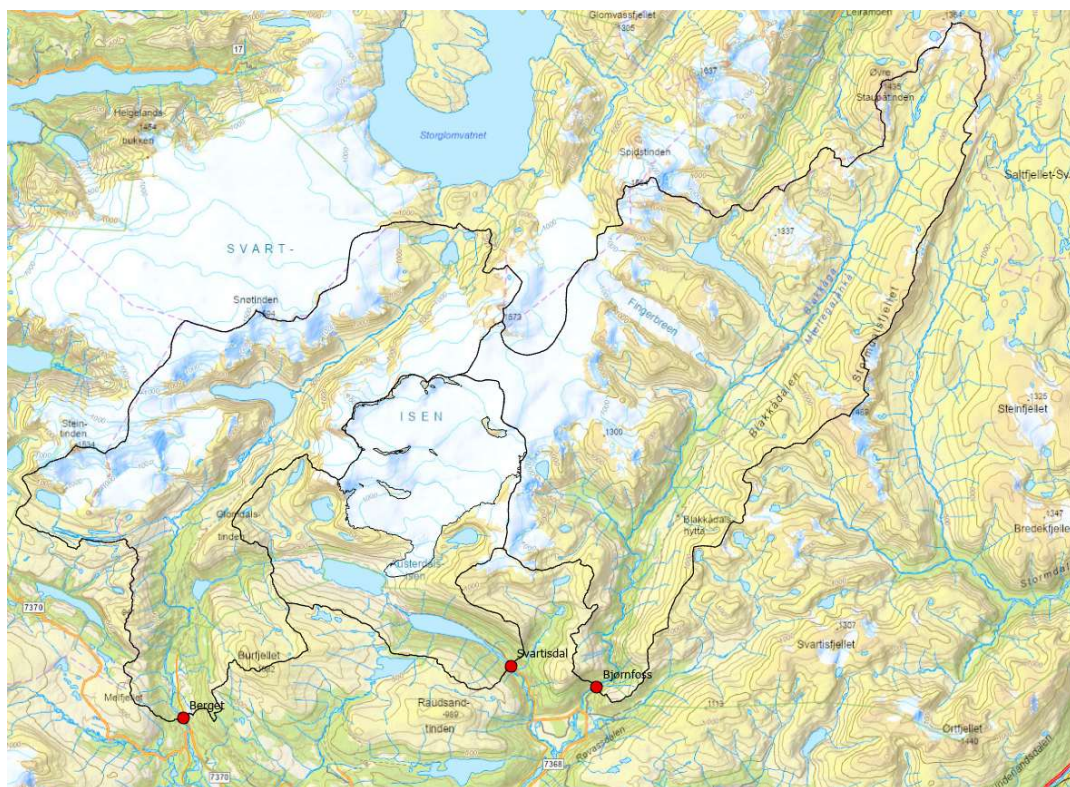


Figure 13-21
Map showing the drainage basins for three discharge stations south of Svartisen. Source: NVE Atlas.

The discharge station 156.8.0 Svartisdal is located in Svartisåga about 1.5 km from the outlet of lake Svartisvatnet (74 m a.s.l.) and 7 km from lake Austerdalsvatnet (209 m a.s.l.). The station has been in operation since 1929. When most of the runoff from Austerdalsisen drained towards Glomåga the drainage basin for 156.8.0 Svartisdal was ca. 24 km² (but varying depending on local drainage divide on Austerdalsisen). After completion of the diversion tunnel in 1959 the drainage basin has been 122 km². Additional discharge stations were established in 1950 in Glomåga west of Austerdalsisen (156.10.0 Berget, 211 km²) and in 1954 in Blakkåga to the east of Austerdalsisen (156.13.0 Bjørnfoss, 307 km²). All three stations are recording runoff from parts of Svartisen. Glaciers constitute around 30 % of the catchments. See Fig. 13-21 for locations and drainage basins.

Figure 13-22 show daily average discharge measured at 156.8.0 Svartisdal between 1940 and 1960. In 1940 a major part of the runoff from Austerdalsisen drained towards Glomåga in the west. The first jøkulhlaup occurred in 1941, and in 1959 there was an early peak related to the opening of the diversion tunnel in May. After 1959 the runoff drained towards Svartisdal.

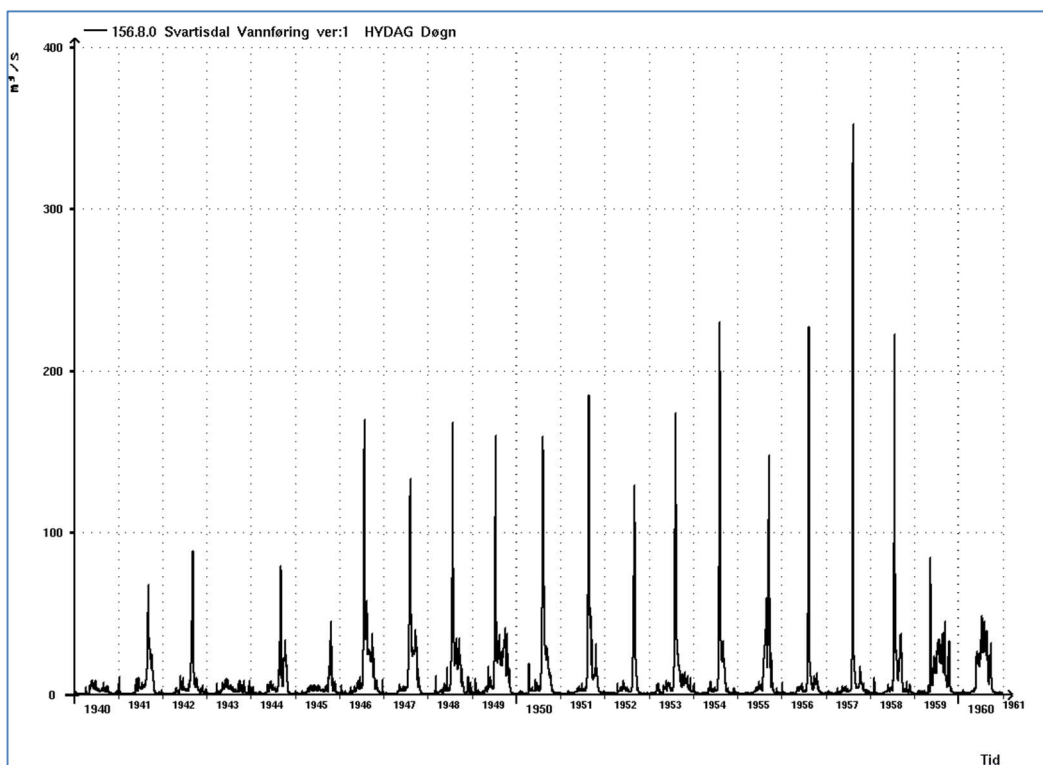


Figure 13-22
Daily average discharge at 156.8.0 Svartisdal 1948-1960. In 1941-58 the peak discharge occurs during the jøkulhlaups. In May 1959 there is a small peak related to the opening of the diversion tunnel. In 1940 and 1960 no jøkulhlaup occurred. Data source: NVE Hydrological data base.

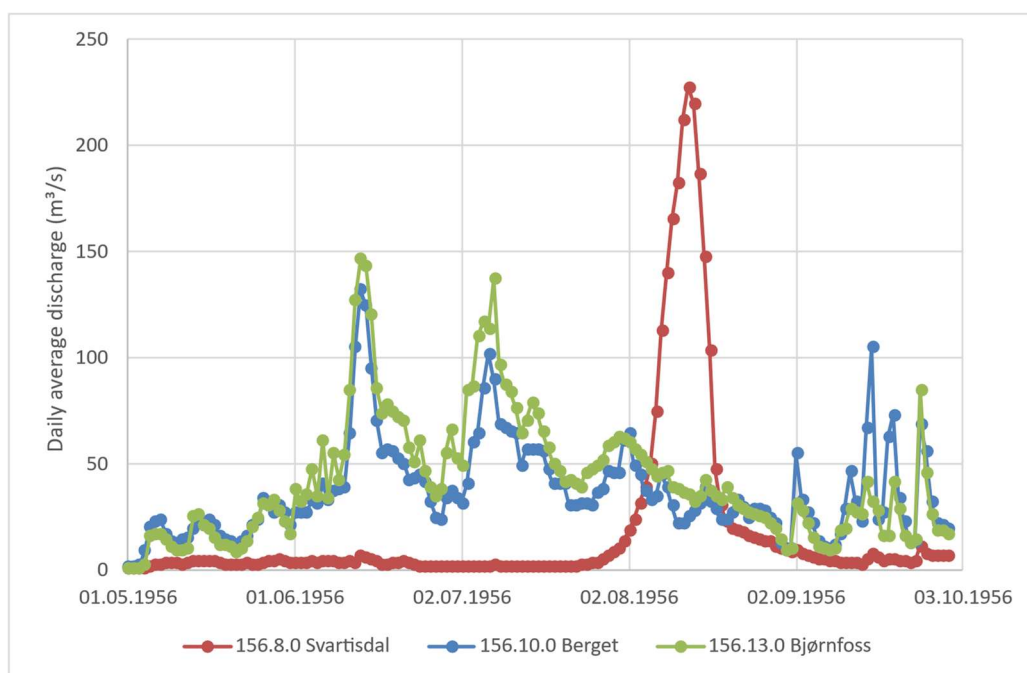


Figure 13-23
Daily average discharge in 1956 measured at 156.8.0 Svartisdal, 156.10.0 Berget and 156.13.0 Bjørnfoss. Source: NVE hydrological data base.

The hydrological conditions are illustrated with the discharge records from 1956. Early in the summer season the runoff to Berget and Bjørnfoss are quite similar. The runoff from Austerdalsisen was captured by the empty Austerdalsvatnet after the previous GLOF in September 1955. Then, around 28 July the discharge at Svartisdal started to increase, and peaked on 13 August. On 20 August the glacier dammed lake seems to have reached the defining outlet elevation, and the discharge at Svartisdal declines at a rate similar to Berget and Bjørnfoss.

From this, the GLOF volume is calculated as the accumulated discharge from and including the day the mean discharge exceeds 10 m³/s until and including the day the rate of change slows down considerably. To partly compensate for runoff not originating from the glacier lake, the calculated volume is reduced by 10 m³/s for the duration of the GLOF. The estimated GLOF volumes for 1948-1958 is listed in Tab. 13-4. Comparison of our results to results from Liestøl (1956) for 1948-1954 indicate our results are 25 % higher than Liestøl (1956). His analysis involved among others compensating for discharge into Austerdalsvatnet during the GLOF, and for stranded ice bergs in the emptied lake (Fig. 13-20). The estimated GLOF volumes in Liestøl (1956) for 1941-54 show an increasing magnitude reflecting the retreating glacier terminus and increasing lake area and volume. Our results are not reflecting this.

Table 13-4

Jøkulhlaup (GLOF) volumes 1948 – 1958 assessed from daily average discharge recorded at the discharge station 159.8.0 Svartisdal. Duration is the number of days from the discharge increased above 10 m³/s until the rate of reduction is slowing down (as in Fig. 13-22). Liestøl's (1956) estimates of reservoir capacity in Austerdalsvatnet (Reservoir) and GLOF volumes (GLOF) up to 1954 are listed for comparison.

Year	Date	Peak discharge daily average (m ³ /s)	Duration Days	GLOF volume (mill.m ³)	Reservoir Liestøl, 1956 (mill.m ³)	GLOF (mill.m ³)
1948	25 July	167	31	131		92
1949	13 July	159	21	113	93	85
1950	8 August	159	26	157		120
1951	23 August	184	25	176		132
1952	2 September	129	25	122	120	113
1953	7 August	173	20	147		136
1954	8 August	230	21	176	145	150
1955	19 September	147	21	118		
1956	13 August	227	20	160		
1957	13 August	352	18	182		
1958	22 July	222	18	126		

14. Results from JOSTICE (Liss M. Andreassen)

14.1 Background

JOSTICE - Natural and societal consequences of climate-forced changes of Jostedalsbreen Ice Cap - is a project funded by the Norwegian Research Council over the period 2020-2025. Jostedalsbreen is the largest ice cap in mainland Europe and currently (2019) covers 458 km², thereby comprising about 20 % of the total glacier area of mainland Norway (Andreassen et al., 2022). Jostedalsbreen has been divided into more than 80 glacier units, many of them with individual names (Andreassen et al., 2012; Fig. 14-1).

JOSTICE is led and administrated by Western Norway University of Applied Sciences. The Norwegian Water Resources and Energy Directorate (NVE) is partner together with the Universities of Oslo and Bergen, Western Research Institute, the Norwegian Glacier Museum and other regional and international partners. See jostice.no for more details. The objective of the JOSTICE project is to assess the present and future changes in mass balance, runoff, ice volume and local climate of Jostedalsbreen, and determine the societal impact of these changes on hydropower production, tourism and agriculture. In this chapter we summarize some of the results from the JOSTICE project.



Figure 14-1
Bergsetbreen and Baklibreen, part of Jostedalsbreen, on 6 September 2025. Photo: Jostein Aasen / NVE / Jostice.

14.2 Ice thickness and bed topography

A major effort in the JOSTICE project was to collect new ice thickness data. This was a joint effort by many partners including NVE, and the results are published in Earth System Science Data (Gillespie et al., 2024). The final dataset consists of more than 351,000 point values of ice thickness distributed along ~ 1100 km profile segments that cover most of the ice cap. About 90 % of the total ice cap area is now less than 300 m from a point of known ice thickness. Ice thickness was measured during field campaigns

in 2018, 2021, 2022 and 2023 using various ground-penetrating radar (GPR) systems with frequencies ranging between 2.5 and 500 MHz. The ice thickness data were used to calibrate an ice thickness model to produce ice thickness and bed topography maps. From these maps we calculated a mean ice thickness of c. 155 m and a total ice volume of $70.6 \pm 10.2 \text{ km}^3$ for Jostedalsbreen. A maximum ice thickness of $\sim 630 \text{ m}$ was measured on Tunsbergdalsbreen in the central part of the ice cap (Fig. 14-2). Locations of current and potential future lakes were calculated from the grid of subglacial bed topography at Jostedalsbreen, suggesting that a total of $\sim 14 \%$ of the present-day glacier area can be covered by lakes if the entire Jostedalsbreen melts away.

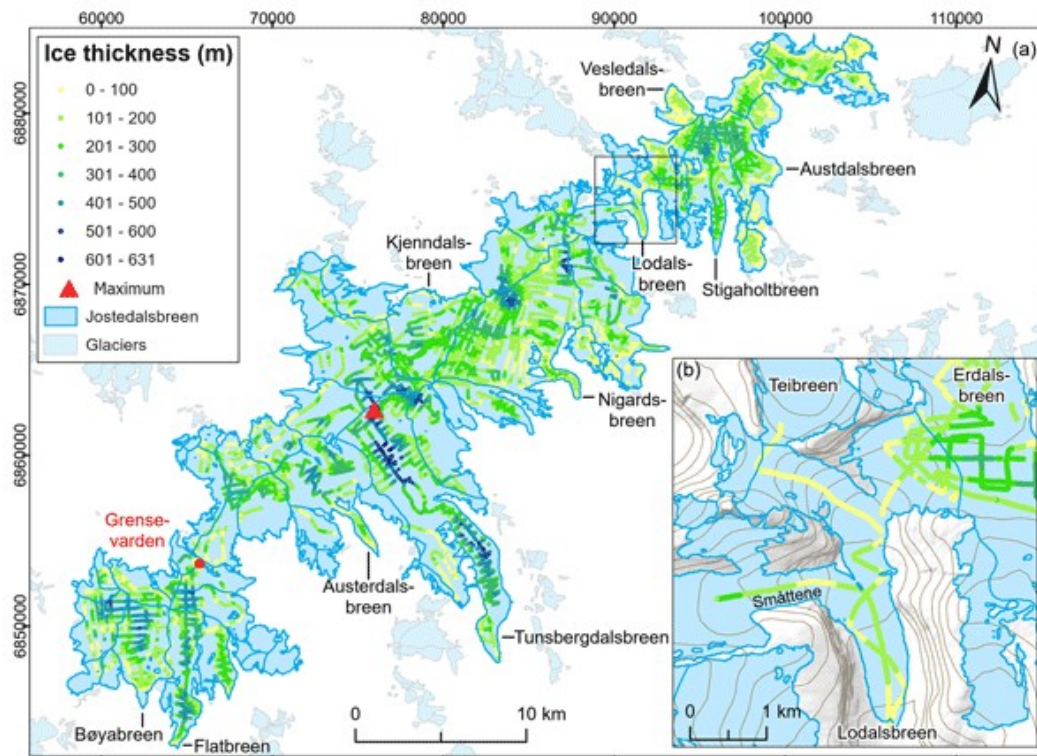


Figure 14-2

Ice thickness observations at Jostedalsbreen from field campaigns in 2018, 2021, 2022 and 2023. The point of maximum thickness was found at Tunsbergdalsbreen and is marked with a red triangle. (b) Section of Lodalsbreen with 100 m surface contours collected during the first test flight of the airborne radar system. The coordinate system is UTM 33N, datum ETRS89. Figure from Gillespie et al. (2024), Earth System Science Data.

14.3 Glacier changes of Jostedalsbreen

In JOSTICE we have provided a dataset for the Little Ice Age glacier extent of Jostedalsbreen (Fig. 14-3). First, Carrivick et al. (2022) mapped the former Little Ice Age glacier extent of Jostedalsbreen based on geomorphological evidence such as moraine ridges and trimlines, historical records, digital terrain models and high-resolution optical satellite images. The ice cap had its maximum LIA extent between 1740 and 1860 with a median date of 1755 (see references and details in Carrivick and others, 2022). However, this dataset did not have a mapped LIA maximum extent for Austdalsbreen and Syngneskarsbreen due to the hydropower lakes obscuring the geomorphological evidence. As new orthophotos from 1966 were available in Norgebilder.no we were able to identify and digitize LIA outlines for Austdalsbreen, Syngneskarsbreen and glacier

2485 with recourse to the 1966 datasets (See Fig 2. in Andreassen et al., 2023 and Fig. 14-3).

To assess the changes in surface elevation and geodetic mass balances of Jostedalsbreen we constructed a digital terrain model (DTM) of the ice cap from 1966 aerial photographs and compared it to an airborne LiDAR DTM from 2020 provided by the Norwegian mapping authority (Andreassen et al., 2023). The area mapped in both surveys covers about 3/4 of the ice cap area and 49 of 82 glacier units. The mean geodetic mass balance over the 49 glaciers was -0.15 ± 0.01 m w.e. a^{-1} , however, large variability is evident between glaciers, e.g. Nigardsbreen (-0.05 m w.e. a^{-1}), Austdalsbreen (-0.28 m w.e. a^{-1}) and Tunsbergdalsbreen (-0.36 m w.e. a^{-1}) confirming differences also found by the glaciological records for Nigardsbreen and Austdalsbreen.

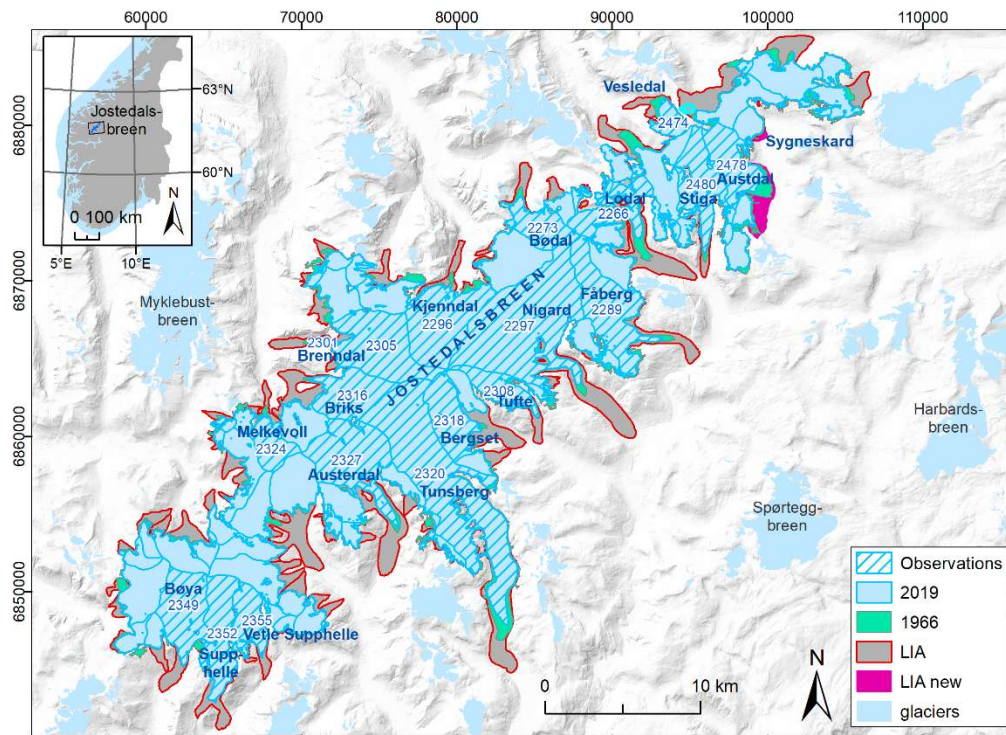


Figure 14-3

Location map of Jostedalsbreen. The inset map shows the location of the ice cap in southern Norway. The glacier extents in 2019, 1966 and Little Ice Age (LIA) are shown for Jostedalsbreen. For surrounding glaciers, only the 2019 extent is shown. 'LIA new' are new outlines in this study. Background mountain shadow is from the 100 m national DTM. Glacier ID from Andreassen and Winsvold (2012). Coordinate system geographical coordinates on inset and UTM 33N, datum ETRS_1989 on main map. Figure from Andreassen et al. (2023), *Annals of Glaciology*.

To understand how the mass of Jostedalsbreen has evolved in recent decades, the ice cap's surface mass balance (SMB) has been modelled from 1960 to 2020 using high-resolution temperature and precipitation from the seNorge dataset (Sjursen et al., 2025). During the 1990s Jostedalsbreen gained mass due to high winter accumulation, resulting in frontal advances that were recorded for several outlet glaciers. Since the early 2000s, the ice cap has experienced significant mass losses, mainly due to increased summer melting driven by increased air temperatures. Results reveal that while the mass balance of Jostedalsbreen was largely dominated by variations in winter

accumulation before the 2000s, increasingly negative summer mass balances have been the main control on mass balance in the 21st century.

Using several of the datasets collected in JOSTICE, Åkesson et al. (2025) have simulated the evolution of Jostedalsbreen since 1960 and the future of the ice cap in a changing climate up to 2300 (Fig. 14-4). The results suggest that Jostedalsbreen will likely be more resilient than many smaller glaciers and ice caps in Scandinavia. The fate of the glacier depends on emission scenario. However, substantial mass losses undergone until 2100 are irreversible. Under medium 21st century emissions (RCP4.5), the ice cap is bound to shrink by 90 % until 2300.

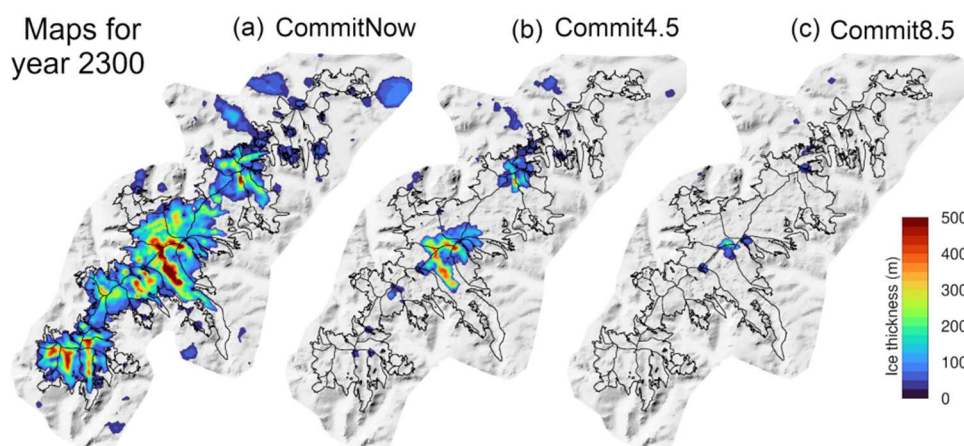


Figure 14-4

Maps of modelled ice thickness in 2300, after accounting for committed mass loss due to (a) SMB 2000–2020, (b) medium 21st century emissions; (c) high 21st century emissions. These ‘Commit’ simulations have temporally fixed SMB, and run over (a) 2021–2300; (b) 2101–2300; and (c) 2101–2300, see Table 2. The SMB in (b) and (c) is derived from ECEARTH/CCLM climate forcing. Present-day glacier outlines (2019) are shown with black lines. Figure and figure text from Åkesson et al. (2025). EGU sphere Preprint.

14.4 Other studies

A goal of JOSTICE has been to combine natural and societal consequences. JOSTICE has also had two exploratory workshops, at Tungestølen in September 2021 focusing on Austerdalsbreen and in Jostedal, Gjerde, September 2024 focusing on Nigardsbreen and Austdalsbreen. In addition, repeat drone surveys of many of the glacier tongues have been carried out. Studies range from overall studies of the ice cap to detailed studies of processes, see jostice.no for overview of all publications. Outreach is also important and JOSTICE cooperates with regional partners to disseminate results from the project. In April 2024 a poster displaying results on life of the ice of Jostedalsbreen was opened at the Norwegian Glacier Museum in Fjærland. (Fig. 14-5). Among the lifeforms found on the glacier are glacier mice (moss balls) that are only known found in Norway on Austerdalsbreen (Fig. 14-5). Other lifeforms are orange- or red-colored snow algae that covers large areas of snow during spring. On the ice we can find microscopic organisms such as tardigrades (water bears) and rotifers (wheel animals) that live in water-filled holes on the ice filled with granular dark debris called cryoconite.



Figure 14-5

Left: Krzysztof Zawierucha, University of Poznan, Pål Gran Kielland, Norwegian Glacier Museum, and JOSTICE project leader Jacob Clement Yde, Western Norway University of Applied Sciences at the poster exhibiting results from life on ice on 16 April 2024. **Photo:** Marianne Nilsen. **Right:** Glacier mice on Austerdalsbreen, September, 2021. **Photo:** Liss M. Andreassen.

14.5 Glacier photos of Jostedalsbreen

On 6 September 2024 many of the glacier outlets of Jostedalsbreen were photographed from helicopter (Fig. 14-6). A selection of the best photos has now been made available in NVE Fotostrøm, an online digital photo collection provided by NVE. The photos can be used free of charge under the licence <https://creativecommons.org/licenses/by-sa/4.0/> by crediting Jostein Aasen / NVE / Jostice. (Search for JOSTICE and see the images.) Other Images of Jostedalsbreen and the JOSTICE project are also available in the NVE Fotostrøm.

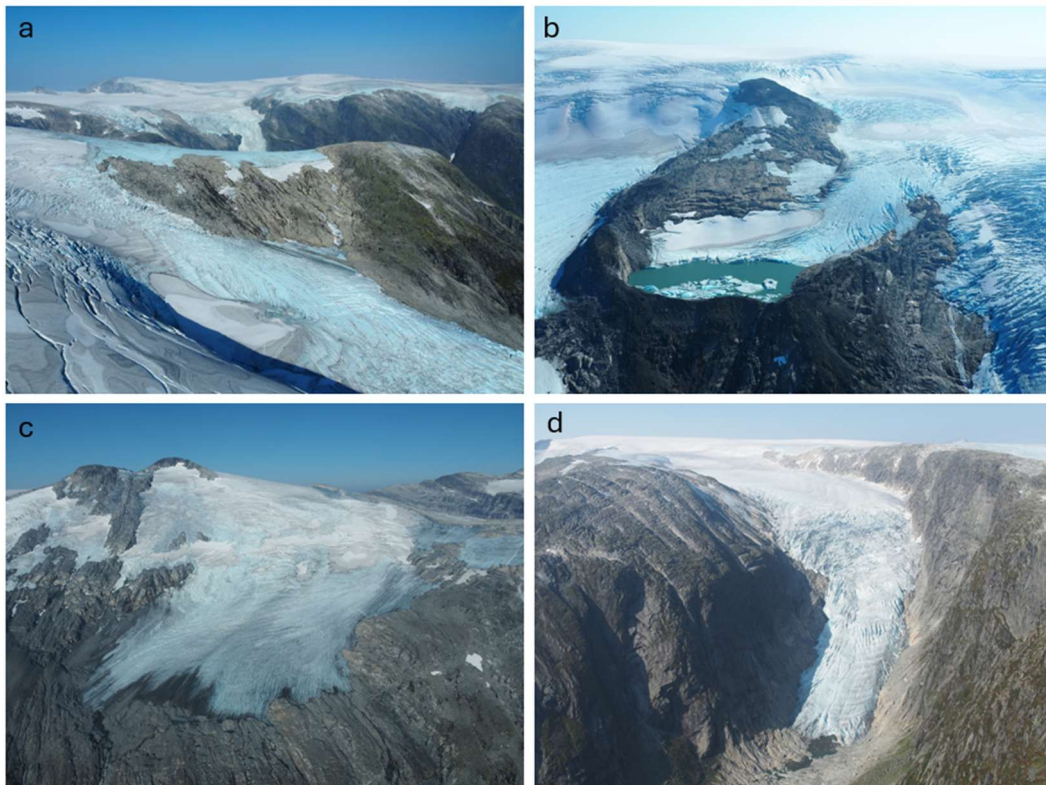


Figure 14-6

Selection of photos taken on 6 September 2024 available in NVE Fotostrøm. a) Glacier ID 2336 and other glaciers around Skytterpiggen, **b)** Melkevollbreen (ID 2324) and its glacier lake, **c)** Glacier ID 2271 east of Brenibba, and **d)** Tuftebreen (ID 2308). **Photos:** Jostein Aasen / NVE / Jostice.

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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 1949-2024. The table lists characteristic data for the investigated glaciers. The Glacier ID refers to ID in the glacier inventory of Norway (Andreassen et al., 2012).

Area/ No. Glacier	Glacier ID	Lat., Long.	Area (km ²)	Altitude (m a.s.l.)	Mapping year	Period	No. of years
Alfotbreen							
1 Alfotbreen	2078	61°45', 5°38'	3,5	1000-1360	2019	1963-	62
2 Hanseebreen	2085	61°44', 5°40'	2,5	927-1303	2019	1986-	39
Folgefonna							
3-4 Blomsterskardsbreen	¹⁾	59°58', 6°19'	45,7	850-1640	1959	1970-77	8
3 Svelgjåbreen	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-	63
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-	37
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-	62
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-	76
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-	15
29 Hellstugubreen	2768	61°34', 8°26'	2,7	1487-2213	2019	1962-	63
30 Gråsubreen	2743	61°39', 8°37'	1,7	1854-2277	2019	1962-	63
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 Svartiseibreen	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-	55
36 Storglombreen	⁵⁾	66°40', 13°59'	59,2	520-1580		1985-88	4
			62,4	520-1580	1968	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-	29

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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