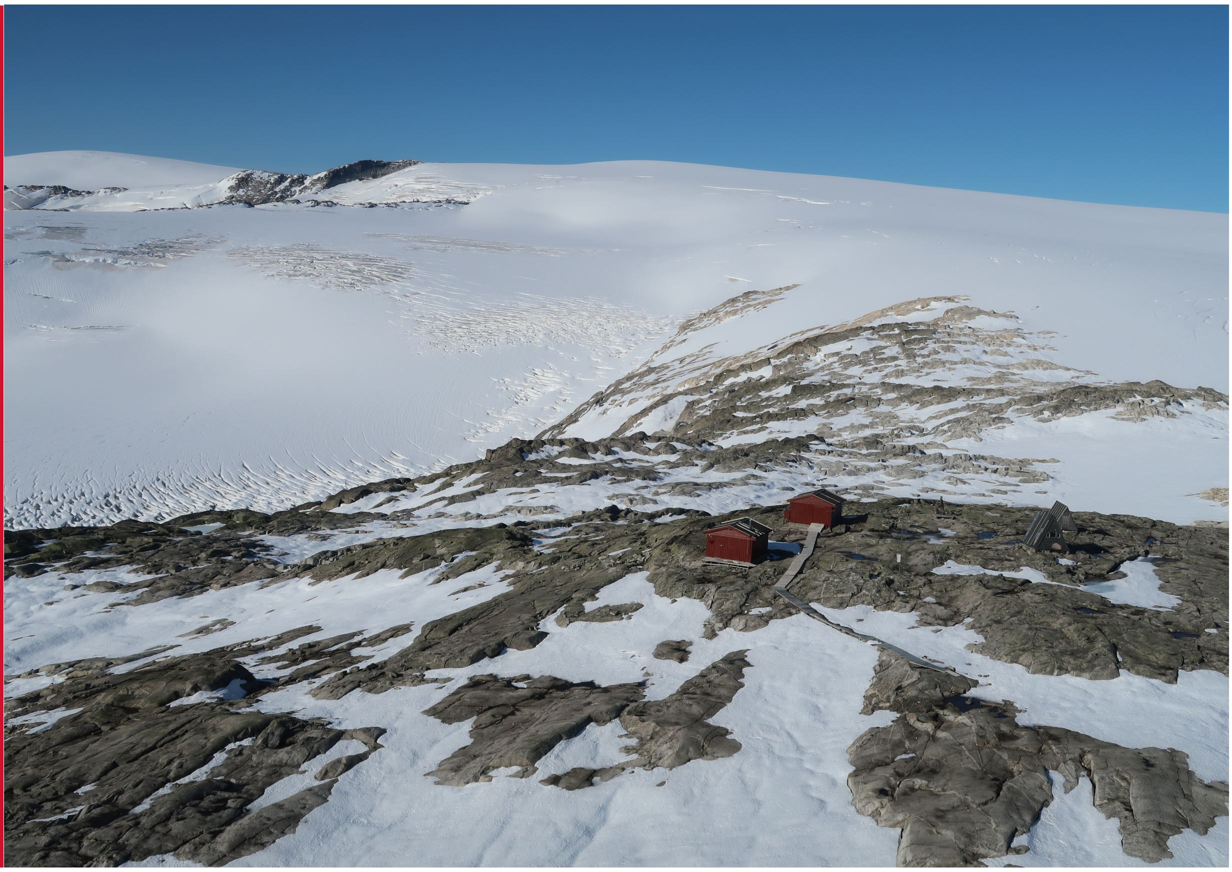
RAPPORT

Nr. 7/2022

Reanalysing a glacier mass balance measurement series – Nigardsbreen 2014-2020

Bjarne Kjøllmoen



NVE Rapport nr. 7/2022
Reanalysing a glacier mass balance measurement series – Nigardsbreen 2014-2020

Published by:	Norwegian Water Resources and Energy Directorate
Author:	Bjarne Kjøllmoen
Cover photo:	The field station Steinmannen in September 2019. Photo: Jostein Aasen.
ISBN:	978-82-410-2187-9
ISSN:	1501-2832
Case number:	200704565
Print:	Norwegian Water Resources and Energy Directorate
Number printed:	20

Abstract: Reanalysis of mass balance measurements at Nigardsbreen 2013-2020 including homogenization of both glaciological and geodetic observation series, uncertainty assessment, comparison of the glaciological and geodetic mass balance and calibration of the mass balance series.

Key words: Glaciological mass balance, Geodetic mass balance, Homogenization, Calibration

Norwegian Water Resources and Energy Directorate
Middelthuns gate 29
P.O. Box 5091 Majorstua
N-0301 Oslo
Norway

Telephone: +47 22 95 95 95
E-mail: nve@nve.no
Internet: www.nve.no

March, 2022

Contents

Preface 4
Summary 5
1 Introduction 6
1.1 Background 6
1.2 Nigardsbreen 6
1.3 Previous results 7
1.4 Outlook 8
2 Observations 9
2.1 Geodetic mass balance 9
2.1.1 Mapping 2013 9
2.1.2 Mapping 2020 10
2.1.3 Density 11
2.1.4 Adjustment for different dates 11
2.1.5 Glacier boundaries 12
2.2 Glaciological mass balance 12
2.2.1 Monitoring program and field measurements 12
2.2.2 Mass balance calculation 14
2.2.3 Glacier boundaries 15
2.2.4 Glaciological mass balance series 15
3 Homogenization 17
3.1 Geodetic mass balance 17
3.1.1 Mapping 2013 17
3.1.2 Mapping 2020 17
3.1.3 Mass change 2014-2020 19
3.2 Glaciological mass balance 20
3.2.1 Height-area distribution 20
3.2.2 Results 20
4 Comparison and calibration 22
4.1 Comparison of glaciological and geodetic mass balances 22
4.2 Calibration of glaciological mass balance 23
5 Conclusions 26
References 27

Preface

This report documents the results from reanalysis of mass balance measurements at Nigardsbreen over the period 2014-2020. The time series is based on traditional glaciological observations using stakes and probings, as well as geodetic observations using laser scanning and digital terrain models.

This report is prepared and written by Bjarne Kjøllmoen.

Oslo, March 2022

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

Bjarne Kjøllmoen
Senior engineer
Section for Glaciers, Ice and Snow

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

Summary

The glaciological and geodetic methods provide independent observations of glacier mass balance. The glaciological method is based on annual surface mass balance measurements, whereas the geodetic method includes surface elevation measurements, and estimates of internal and basal mass balance over a period of years.

The glaciological mass balance series for Nigardsbreen covers the period from 1962 to 2020. In this report, a re-analysed time series for the period 2014-2020 is presented. Within this period, Digital Terrain Models (DTMs) from 2013 and 2020 were generated. The re-analysis includes homogenization of both glaciological and geodetic observations, uncertainty assessment, comparison of the glaciological and geodetic mass balance and calibration of the mass balance series.

The two data sets for the period 2014-2020 were compared and the results show a significant discrepancy between the glaciological and geodetic mass balance series for the period 2014-2020. Calibration was applied over the years 2014-2020, as the deviation was larger than the uncertainty.

The calibrated glaciological cumulative mass balance over 2014-2020 was +0.54 m w.e., while the original mass balance over the same period was +2.98 m w.e.

1 Introduction

1.1 Background

The Norwegian Water Resources and Energy Directorate (NVE) operate the Norwegian mass balance observation programme. The observations are both traditional field measurements, referred to as the “glaciological method” (also called direct, conventional or traditional method) and geodetic surveys, referred to as the “geodetic method” (Cogley et al., 2011). This report describes reanalysis of the Nigardsbreen mass balance time series 2014-2020. The mass balance time series 1962-2013 was reanalysed in Kjøllmoen (2016).

The glaciological mass balance method measures surface mass balance at point locations, and data are extrapolated over the entire glacier surface to obtain glacier-wide averages. The cumulative mass balance is the sum of the annual balances over a period of several years. In the geodetic method, cumulative balance is calculated from glacier surface elevations measured in different years by differencing Digital Terrain Models (DTMs) and by converting the volume change to mass change using a density conversion. The geodetic method is often used as a check on the accuracy of annual measurements by the glaciological method (e.g. Andreassen, 1999 and Zemp, 2010). If a comparison between the glaciological and the geodetic method of a time series show great discrepancies, a calibration of the glaciological mass balance series is required.

1.2 Nigardsbreen

Nigardsbreen (61°42'N, 7°˚08'E) is one of the largest and best known outlet glaciers from the Jostedalsbreen (458 km^2 in 2019; Andreassen et al., 2022), which is the largest ice cap in Scandinavia (Fig. 1). It is located in a mountainous area about 100 km from the west coast of Norway with peaks up to 2000 m a.s.l.

Nigardsbreen has an area of 45 km^2 (2020) and flows southeast from the centre of the ice cap. It accounts for about 10 % of the total area of Jostedalsbreen. Nigardsbreen range from 1955 to 389 m a.s.l., with 88 % of its area located above 1400 m a.s.l. The large upper part of the glacier is a plateau, with an even gently sloping surface down to about 1400 m a.s.l. Between 1300 and 800 m a.s.l. the glacier flows through a heavily crevassed icefall. The distance along a central flow line is about 8 km, from the upper ice divide north-west of Kjenndalskruna, to the glacier terminus. The terminus has been land-based since 1973, but calved previously into the lake Nigardsbrevatnet.

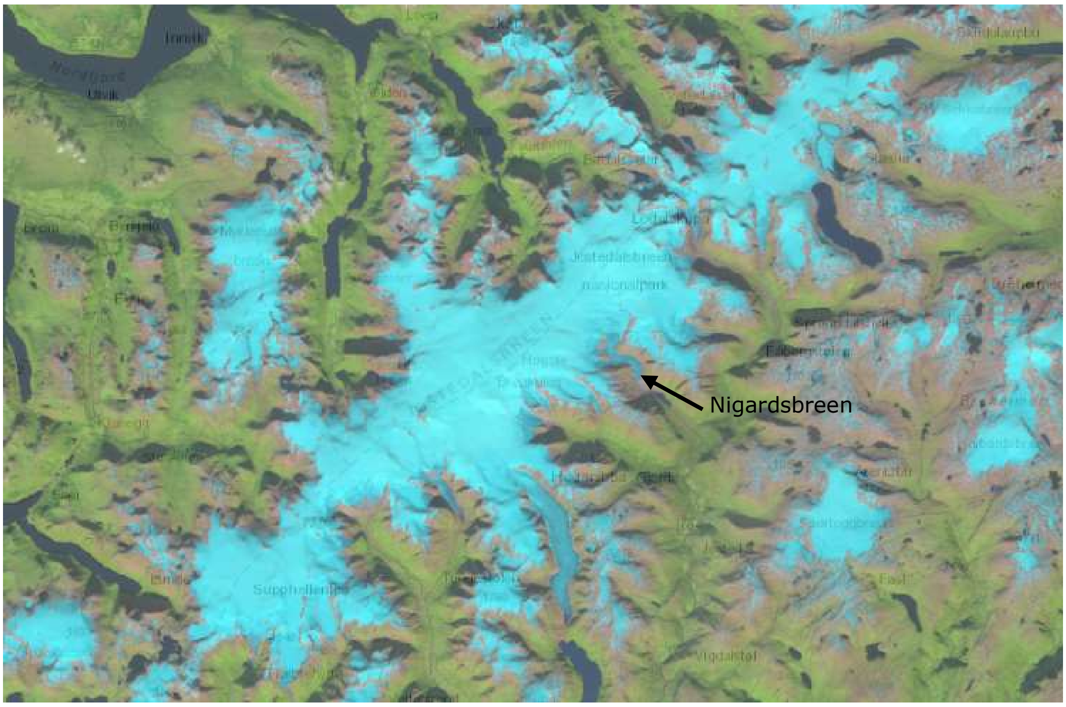


Figure 1
The ice cap Jostedalsbreen photographed on 31st August 2020. Source: Sentinel-2.

1.3 Previous results

NVE has carried out annual glaciological mass balance measurements on Nigardsbreen since 1962 (Østrem and Karlén, 1962). The measurements at Nigardsbreen are funded by Statkraft Energi AS. The results show a small surplus from 1962 to 1988, a large surplus from 1988 to 2000, a deficit from 2000 to 2014 and surplus again from 2014 to 2020.

Nigardsbreen has been surveyed by aerial photography about every decade since the 1930s. Detailed glacier maps have been constructed from the photographs taken in 1964, 1966/1974 (combined) and 1984, and by laser scanning (LIDAR) in 2009, 2013 and 2020. Detailed glacier maps have been constructed from all these mappings.

Glaciological and geodetic mass balance for the periods 1964-1984 and 1984-2013 was compared in Kjøllmoen (2016). The discrepancies found between glaciological and geodetic balance were significant for the period 1985-2013, but not significant for the period 1965-1984. Thus, only the period 1985-2013 was calibrated from (from 0.33 m w.e. a^{-1} to 0.00 m w.e. a^{-1}).

In this report the geodetic mass balance was calculated from LIDAR data in 2013 and 2020. Thus, the glaciological and geodetic mass balances were compared for the 7-year period 2014-2020.

Annual glacier length changes showed that the glacier retreated 2.5 km since measurements started in 1900. The recent measurements showed a 800 m rapid retreat 1962-1974, stable position 1974-1990, a 250 m rapid advance 1990-2000, stable 2000-2005 and 570 m rapid retreat 2005-2020.

1.4 Outlook

The mass balance measurements at Nigardsbreen is reanalysed following the reanalyses scheme proposed by Zemp et al. (2013). The major steps are:

1. Analysis and scrutiny of glaciological and geodetic measurements (ch. 2)
2. Homogenization of glaciological and geodetic measurements (ch. 3)
3. Uncertainty assessment (ch. 4)
4. Validation of glaciological measurements against geodetic measurements (ch. 4)

The output of the reanalysis is a *homogenized glaciological mass balance time series* with an uncertainty assessment, and if calibration is required, a *calibrated glaciological mass balance time series*.

2 Observations

2.1 Geodetic mass balance

Geodetic mass balance for the periods 1964-1984 and 1984-2013 was reported in Kjøllmoen (2016).

LIDAR from 10th September 2013 and 9th August 2020 were used to produce detailed DTMs of the glacier surface of Nigardsbreen.

The GIS-data processing of maps and DTMs by NVE was done using ArcGIS 9.3/10.2 software (©ESRI) and Surfer software version 15.

2.1.1 Mapping 2013

Vertical aerial photographs were taken and LIDAR data was recorded on 10th September 2013 by Terratec AS (Terratec AS, 2014).

The photographs were recorded by a Rollei metric AIC Pro P65 camera. The mean flying height was 1400 m above ground level and the picture resolution was 20 cm GSD (Ground Sampling Distance). The resulting resolution of the orthophoto is also 20 cm.

The LIDAR data was acquired using a Leica ALS70 lidar instrument. The mean flying height was 1400 m above ground level. The laser pulse rate was 115400 Hz and the scan angle ±17.5 degrees, resulting in a mean point density of 1.0 points per m^2. The theoretical absolute accuracy was assumed to be ±10 cm (height) and ±20-30 cm (horizontal), respectively.

The data delivery from Terratec was point clouds (las), regular grid data (10x10 m) and orthophoto (Fig. 2).

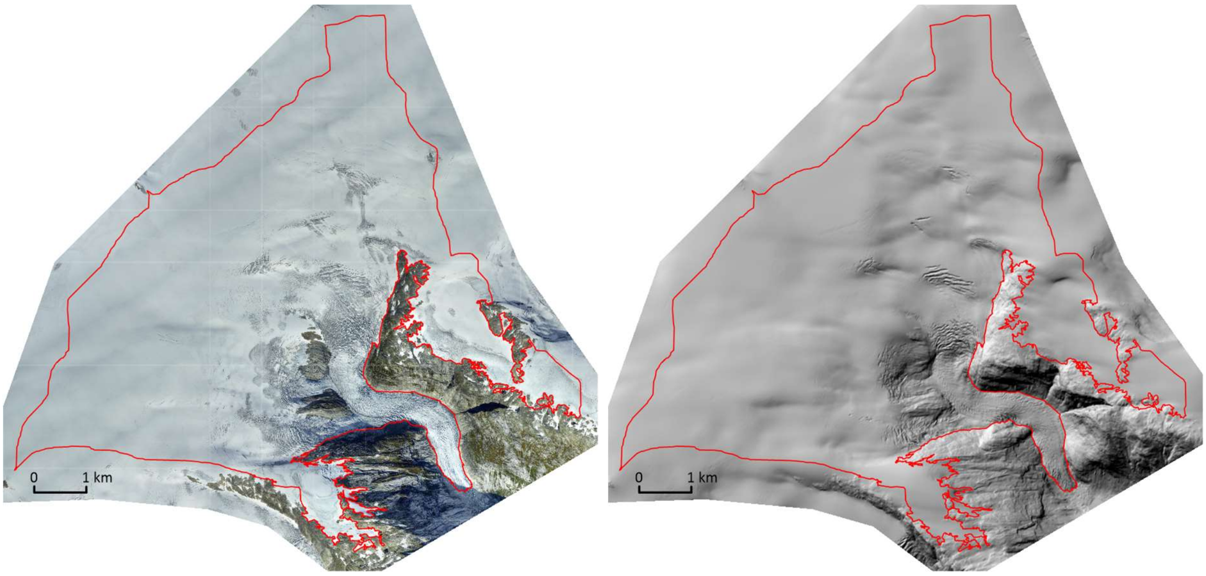


Figure 2
Orthophoto produced of aerial images from 10th September 2013 to the left and shaded relief based on the DTM 2013 to the right. The glacier boundary for 2013 in red.

The gridding method used for the regular grid data set is "Triangulated model Z". The 10x10 m regular grid data set was used in the following calculations.

The glacier border outlines were digitized by NVE from the orthophoto constructed from the aerial photographs. The ice divide determined from the laser DTM_{2009} was used in the following calculations.

All data was referred to the UTM co-ordinate system zone 32, Euref 89 datum and the Norwegian height system NN1954.

2.1.2 Mapping 2020

LIDAR data were recorded on 9th and 15th August 2020 by Terratec AS (Terratec AS, 2020) as a part of the national laser scanning program initiated by the Norwegian Mapping Authority. Most of the glacier was covered by the first flight on 9th August. The glacier tongue below 1000 m altitude and some small areas in south-east was covered by the flight on 15th August. The LIDAR data was acquired using a Riegl lidar instrument. The flying height was between 2800 and 3700 m above ground level. The laser pulse rate was 350000 Hz and the scan angle ±25 degrees, resulting in a mean point density of 2.0 points per m^2. The LIDAR data set was compared with measured control points in stable areas. The control revealed a systematic bias of 0.16 m. Thus the 2020 LIDAR data set was corrected. The control and calibration were done by Terratec AS. The homogeneity was described as good and the vertical accuracy of the corrected data set was estimated as <0.10 m. The data set produced by Terratec AS was point clouds (laz) (Fig. 3).

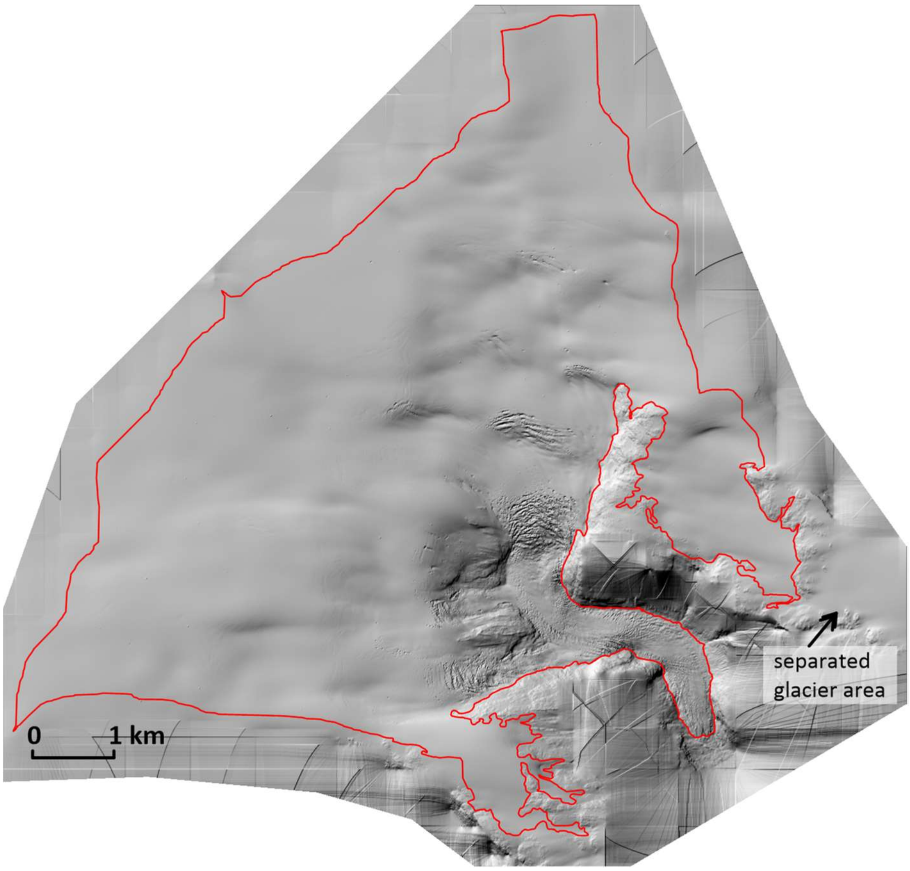


Figure 3
Shaded relief map based on the DTM 2020. The glacier boundary for 2020 in red. Note the separated glacier area in south-east.

The gridding method used for converting point cloud to regular grid data set (10x10 m) was “Kriging”. The 10x10 m regular grid data set was used in the following calculations.

Neither orthophoto nor optical satellite imagery covering Nigardsbreen in 2020 were available. Thus the glacier outlines were digitised using a shaded relief of the DTM_{2020} (Fig. 3) supported by orthophoto from 11th July 2019 and from satellite imagery from 27th August 2019. The ice divide determined from the laser DTM_{2009} was used in the following calculations.

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

2.1.3 Density

Determination of a density conversion factor was required in order to convert the volume change of snow, firn and ice to mass change. It is common to assume a constant density profile in the accumulation area, following Sorge’s law (Bader, 1954). Hence, density of glacier ice, 900-917 kg m^{-3} (Cuffey and Paterson, 2010), is often used for the conversion (e.g. Haug et al., 2009 and Andreassen, 1999). This assumption however, is valid only under steady-state conditions and was considered to be a maximum estimate in this study. Assuming a value of 850 ±60 kg m^{-3} to convert volume change to mass change is found to be appropriate for a wide range of conditions (Huss, 2013). Hence, this value was used for the conversion of the volumetric changes into water equivalent.

2.1.4 Adjustment for different dates

Comparison of glaciological and geodetic mass balance required an adjustment because the field measurements and aerial surveys were acquired at different dates. The related difference depends on the changes in surface elevation between the field and aerial surveys. Accordingly, increasing time span will result in increasing difference. The season (summer/ autumn) and the general mass turn over will also influence the difference. Dates for field measurements and aerial surveys and corresponding adjustments are shown in table 1.

Table 1
Survey dates and adjustments for 2013 and 2020.

year	date			correction	
	LIDAR	field $survey_{summer}$	field $survey_{autumn}$	category	ΔB_s (m w.e.)
2013	10th September	22nd August	25th September	melting	−0.08
2020	9th August	20th August	15th October	melting	−0.57

In 2013 the lidar data was acquired 10th September, and the ablation was measured on 25th September. In 2020, the lidar survey date was 9th August, and the ablation was measured on 13th and 15th October.

The melting for the intermediate periods in 2013 and 2020 could not be measured directly and was, hence estimated using a simple degree-day-model. Air temperature data from three weather stations (Sogndal, 497 m a.s.l., Fjærland, 3 m a.s.l. and Stryn, 208 m a.s.l.) was used in the model. Fresh snow at the time of ablation measurement in September 2013 and October 2020 was not included in the annual mass balances and was, hence not taken into account in these adjustments.

According to the estimated melting from the lidar survey dates to the field survey dates, the geodetic mass balances were adjusted as:

$-\Delta B_{s\,2013} + \Delta B_{s\,2020}$

2.1.5 Glacier boundaries

The hydrological basin was used for the glaciological mass balance calculations. This means that the entire glacier area within the hydrological catchment of the lake Nigardsbrevatnet was included. Due to a separated glacier area far to the east the hydrological drainage basins for the two years 2013 and 2020 are some different in area extent (Fig. 3). The ice divide from 2013 and 2020 are quite similar and thus the ice divide from 2013 was used for both DTMs. The hydrological basin area is 46.6 km^2 (2013) and 44.9 km^2 (2020), respectively. For the geodetic volume change calculations a combination of the glacier boundaries was used so that the analysis mask will surround both glacier areas. Areas within the glacier basin defined as rock in both years were not included.

2.2 Glaciological mass balance

Glacier surface mass balance at Nigardsbreen has been monitored annually since 1962 by NVE. The extent of measurements has varied considerably over time, but the method of calculation has been homogenized for the whole period. The measurements and calculations are in principle based on methods from Østrem and Brugman (1991) and as described in Andreassen et al. (2005) and Kjøllmoen et al. (2021).

The measurements are reported in "Glaciological investigations in Norway", which are annual reports published by NVE. A reanalysed mass balance series for Nigardsbreen 1962-2013 was reported in Kjøllmoen (2016).

2.2.1 Monitoring program and field measurements

The annual mass balance measurements started in May 1962 (Østrem and Karlén, 1962).

Normally, winter balance measurements were carried out between late April and late May, while the annual balance measurements were carried out between late September and late October. Winter balance was measured using a number of stakes, as well as doing a number of snow depth soundings to the late-summer surface from previous year. In addition to snow depth, snow density was measured in one vertical profile. The snow density measurements were done at the same time as the snow depth measurements. Annual balance was measured by stake readings.

A detailed description of the field measurements from 1962 to 2013 was given in Kjøllmoen (2016).

For the years 2014-2020 a network of 7-10 stakes on the plateau and 2 stakes on the tongue was maintained. The number of snow depth measurements, however, varied from 73 in 2020 to 140 in 2014 (Fig. 4 and Tab. 2). The snow density was determined in one location in this seven-year period.

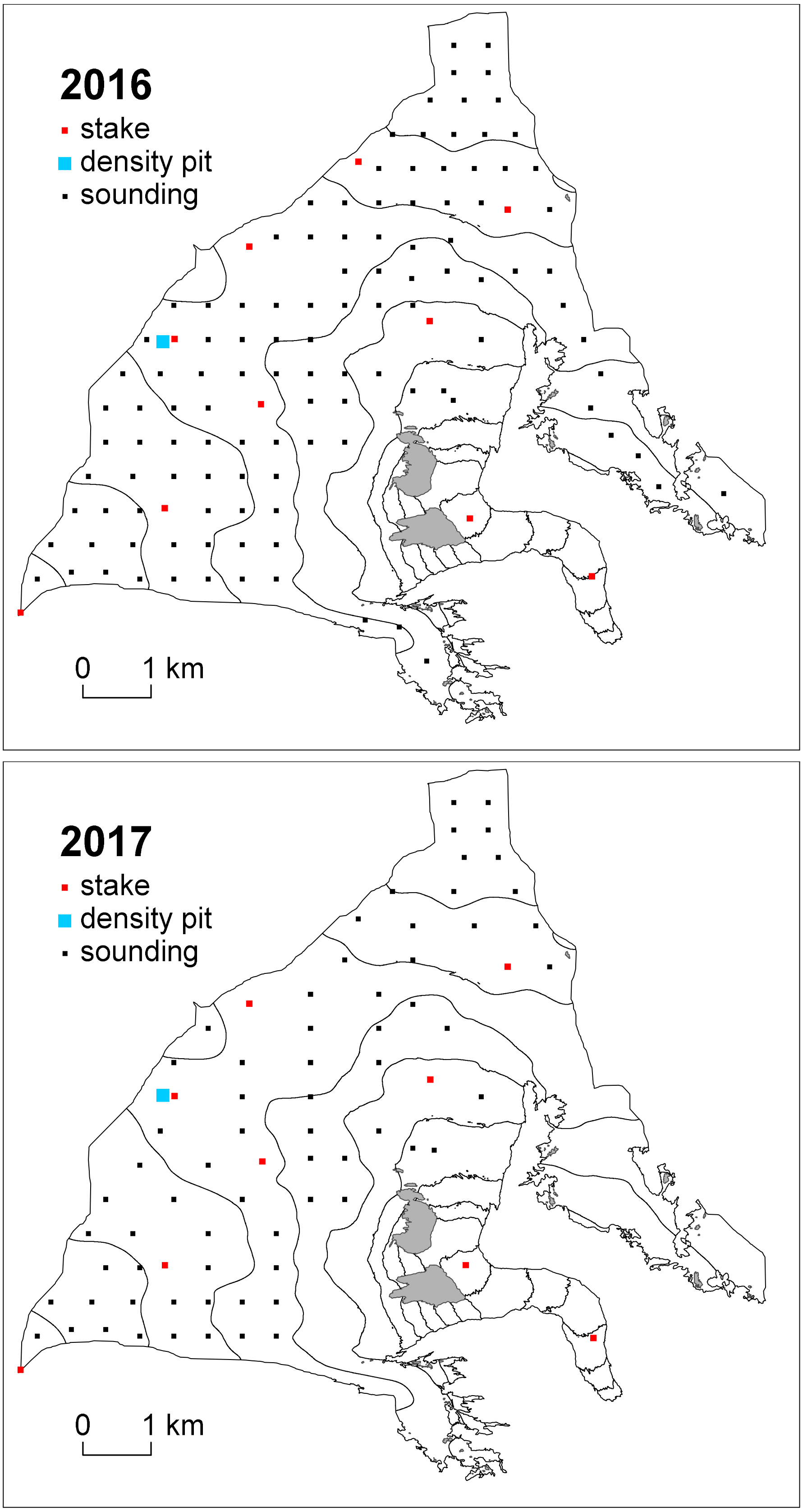


Figure 4
Typical stake network and snow depth soundings representing the period 2014-2020. Upper: example from 2016, representing the years 2014, 2016, 2018 and 2019. Lower: example from 2017, representing the years 2015, 2017 and 2020. Non-glaciated areas within the basin are shaded in grey.

Table 2
A summary of the annual mass balance measurements at Nigardsbreen over the years 2014-2020.

Year	Date		Stakes (number)			Density pit			Snow depth measurements				Data
	spring	autumn	b_w	b_s	b_a	position	depth (m)	ρ (kg m^{-3})	number	$\bar{x}$ (m)	min. (m)	max. (m)	quality
2014	19th May	17th Nov.	7	10	10	94	5.67	509	140	5.5	1.0	7.0	Medium
2015	8th June	14th Oct.	5	10	10	94	6.52	454	78	7.1	1.1	9.3	Good
2016	10th May	5th Oct.	6	10	10	94	5.28	474	126	5.9	1.5	8.2	Good
2017	21st June	18th Oct.	7	9	9	94	4.13	541	75	4.5	0.5	6.1	Good
2018	15th May	26th Oct.	8	9	9	94	4.60	547	123	4.6	0.9	5.7	Medium
2019	15th May	25th Sep.	9	11	11	94	4.93	479	106	4.7	0.6	6.4	Good
2020	19th May	13th Oct.	3	11	11	94	7.90	467	73	7.8	1.8	11.0	Medium

2.2.2 Mass balance calculation

The mass balance was in principle calculated using a stratigraphic system, i.e. between two successive summer surfaces, as described in Cogley et al. (2011). The spatial interpolation of point measurements was done by estimating accumulation and ablation in elevation intervals of 100 m vertical resolution. The altitudinal mass balance curves were made by plotting point measurements of winter, summer and annual balance versus altitude. Representative values for each 100-m elevation interval were then extracted from these scatter plots (Fig. 5). In the ice fall between the plateau and the upper tongue (1350-1000 m a.s.l.) and the ice-fall between the upper and lower tongue (1000-600 m a.s.l.) the balance curves were interpolated. Below 600 m altitude, the balance curves were extrapolated due to lack of measurements. The method is called the profile method.

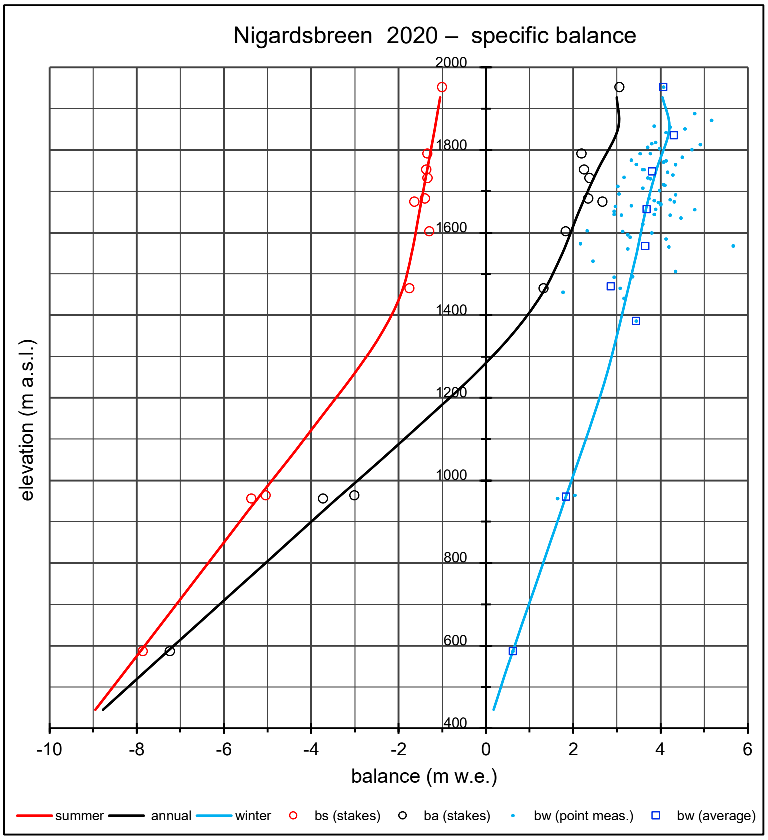


Figure 5
The altitudinal winter, summer and annual balance curves are plotted versus altitude. Point values for b_w (•), b_s (○) and b_a (○), together with average b_w (□) for each 100 m height interval are also plotted. This calculation method has been used for the whole period 1962-2020. The example diagram above is from 2020.

2.2.3 Glacier boundaries

The boundaries used for glaciological mass balance measurements and calculations can be defined by the hydrological basin or the glaciological basin. While the hydrological basin includes the entire glacier area within a certain hydrological catchment, the glacio-logical basin is limited to the glacier area providing ice to a defined glacier tongue. Independent of whether a hydrological or glaciological basin is used, the drainage basin is defined by the glacier outline and the drainage divide. The drainage divide can be defined in two different ways; either calculated from the glacier surface topography (ice drainage divide) or from a combination of subglacial topography and ice thickness (water drainage divide).

In Kjøllmoen (2016) the mass balance series for the period 1962-2013 was calculated using the hydrological basin draining to the lake Nigardsbrevatnet (Fig. 6). The drainage divide was calculated from the glacier surface topography using the 2009 DTM.

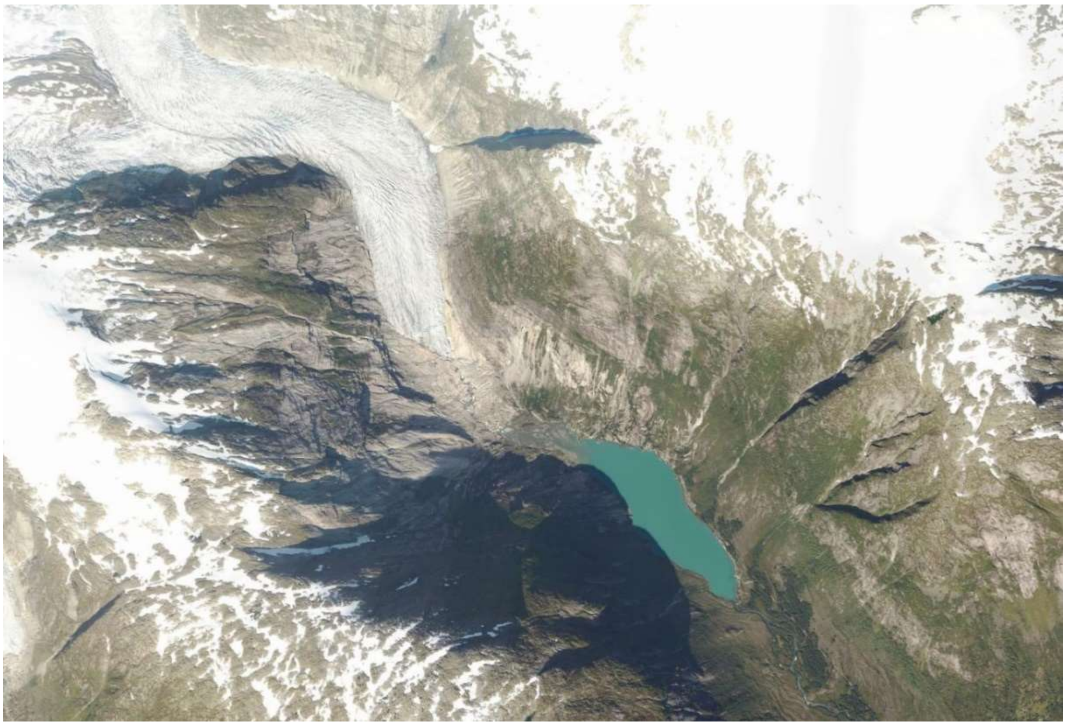


Figure 6
The hydrological basin of Nigardsbreen drains to the lake Nigardsbrevatnet. Source: norgeibilder.no.

In the reported datasets from 2012 to 2019 (e.g. Kjøllmoen et al., 2020), the mass balance calculations was based on the height-area distribution from the 2013 DTM.

2.2.4 Glaciological mass balance series

The reanalysed (1962-2013) and original (2014-2020) glaciological mass balance series gives a surplus of +6.8 m w.e. for the whole period 1962-2020. The results show a mass surplus from 1962 to 1976 (+4.8 m w.e.), a mass loss from 1977 to 1988 (−2.9 m w.e.), a mass surplus from 1989 to 2000 (+6.8 m w.e.), a mass loss from 2001 to 2014 (−5.2 m w.e.) and a mass surplus from 2015 to 2020 (+3.3 m w.e.).

The mean winter, summer and annual mass balances for 1962-2020 were 2.25, −2.13 and +0.11 m w.e., respectively. The reanalysed (1962-2013) and original (2014-2020) annual winter, summer and annual mass balance results from 1962 to 2020 are shown in figure 7.

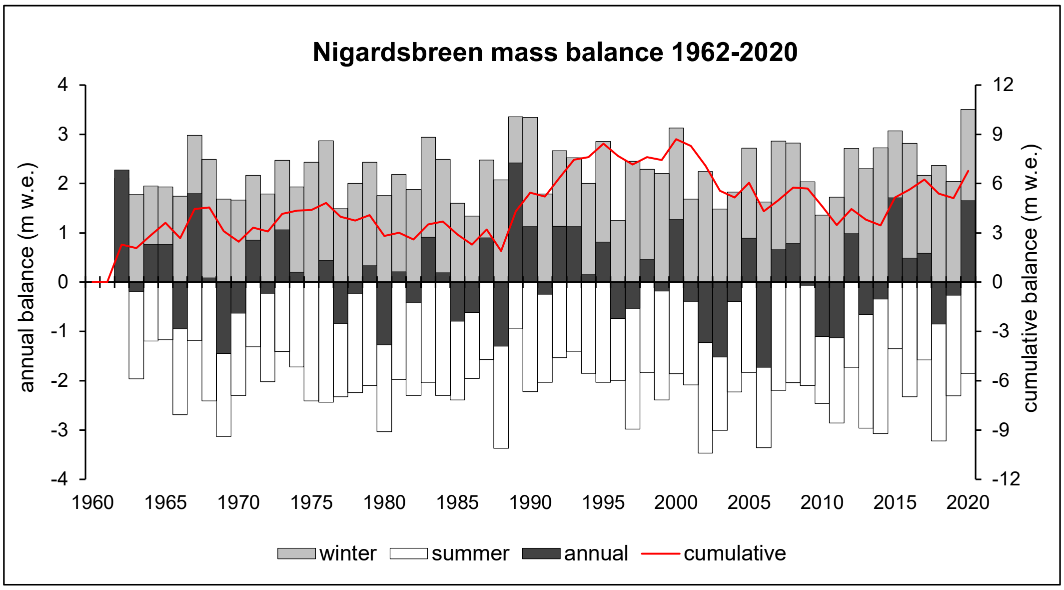


Figure 7
Reanalysed (1962-2013) and original (2014-2020) winter, summer and annual mass balance for Nigardsbreen over the period 1962-2020.

3 Homogenization

3.1 Geodetic mass balance

The accuracy of the final DTMs is principally influenced by the quality of the raw data and by the process from raw data to DTM. The raw data acquisition and the DTM processing were similar for 2013 and 2020.

The LIDAR data set from 2020 was referred to the Norwegian height system NN2000, while the data set from 2013 was referred to NN1954. The height difference between the two systems varies from −15 to + 35 cm, depending on where in Norway you are. Surveys from Nigardsbreen revealed height differences between the two systems less than 1 cm. Hence, the transition from NN1954 to NN2000 at Nigardsbreen is negligible.

3.1.1 Mapping 2013

The 2013 DTM was based on data acquired by LIDAR (see chap. 2.1.1). Generally, the accuracy of data sets acquired by LIDAR is of high quality. The accuracy of the LIDAR data was carefully evaluated and described in Kjøllmoen (2016). The evaluation concluded that the quality of the LIDAR data was good, and correction of the 2013 DTM was not necessary.

3.1.2 Mapping 2020

As the 2013 DTM, the 2020 DTM was also based on data acquired by LIDAR.

The LIDAR data 2020 was surveyed at two different dates, on 9th and 15th August (Fig. 8), but the data set was not split for each day. The glacier surface elevation changes from 9th to 15th August were not measured. A simple estimation based on stake measurements on 1st July and 20th August together with air temperature data from three weather stations close to Nigardsbreen, indicates a glacier surface lowering between 0.4 m (950 m a.s.l.) and 0.6 m (580 m a.s.l.) at the glacier tongue (Fig. 8).

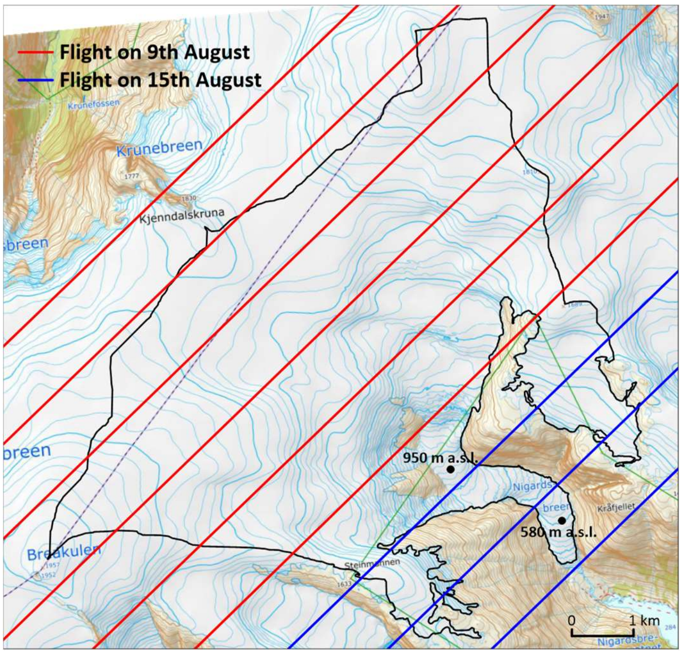


Figure 8
The LIDAR data set for 2020 was surveyed on 9th (red flight lines) and 15th August (blue flight lines).

The exact transition between data from 9th and 15th August could not be identified in the data set. Thus, the data set was considered homogeneous and 9th August was considered as the primary date.

At the time of aerial surveying (9th and 15th August 2020) two independent GNSS measurements were done. A selection of only two control points is not considered to be sufficient and hence, an evaluation based on GNSs measurements is not implemented.

The 2020 LIDAR data was compared with the 2013 LIDAR data in stable non-glacierized areas. Ideally the non-glacierized terrain from two DTMs should correspond exactly. However, due to inaccuracies, elevation differences will always occur when comparing two DTMs.

Comparing elevation values in steep terrain is considered to be very uncertain and should preferably be avoided. Thus, all areas steeper than 30° were removed. Accordingly, the results from 55200 grid points (5x5 m) showed differences from +3.7 to −5.8 m with an average of −0.16 m. The standard deviation was 0.65 m. Generally, the results indicated that the 2020 DTM and the 2013 DTM are quite similar in non-glacierized areas (Fig. 9).

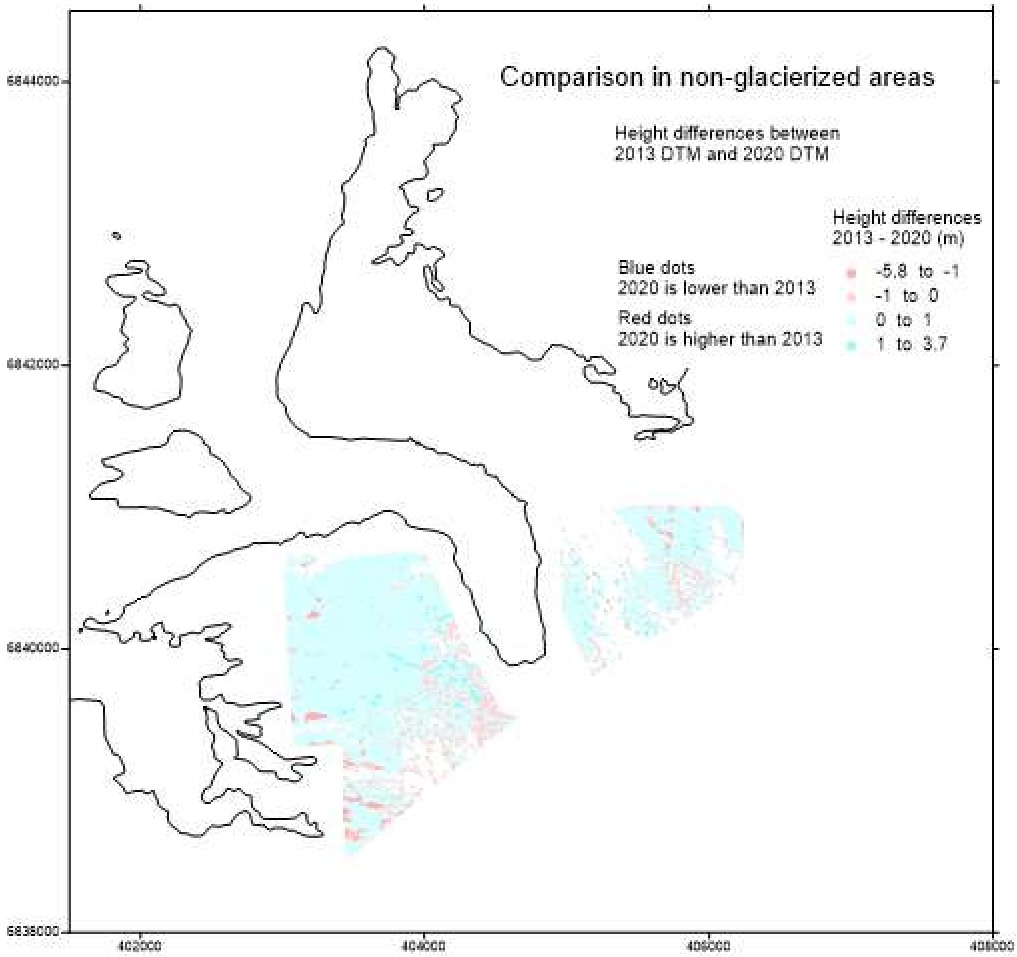


Figure 9
Aerial distribution of elevation differences in non-glacierized areas by comparing the 2020 DTM with the 2013 DTM. Thus, red dots indicate that the 2020 DTM is higher than the 2013 DTM and vice versa. Values in areas steeper than 30° were removed.

The maximum (+3.7 m) and minimum (−5.8 m) differences are rather great, but the average difference (−0.16 m) is low. The reasons for the highest differences can be that the terrain is not stable, and reflection errors from sloping areas. Factors like material (gravel) from landslides and remaining snow will influence the surface elevation. However, in accordance with the evaluation of the 2020 DTM, both DTMs are proved to be of high quality and no corrections were necessary.

3.1.3 Mass change 2014-2020

The spatial distribution of thickness changes at Nigardsbreen between 10th September 2013 and 9th August 2020 (here referred as 2014-2020) is shown in figure 10. The geodetic mass balance over the period 2014-2020 was calculated within the hydrological basin using grid size of 10 x 10 m. The volume change was multiplied with the density conversion factor (850 kg m^{-3}), divided with the mean area for 2013 and 2020, and adjusted for additional melting in 2013 and 2020. The results are given in table 3.

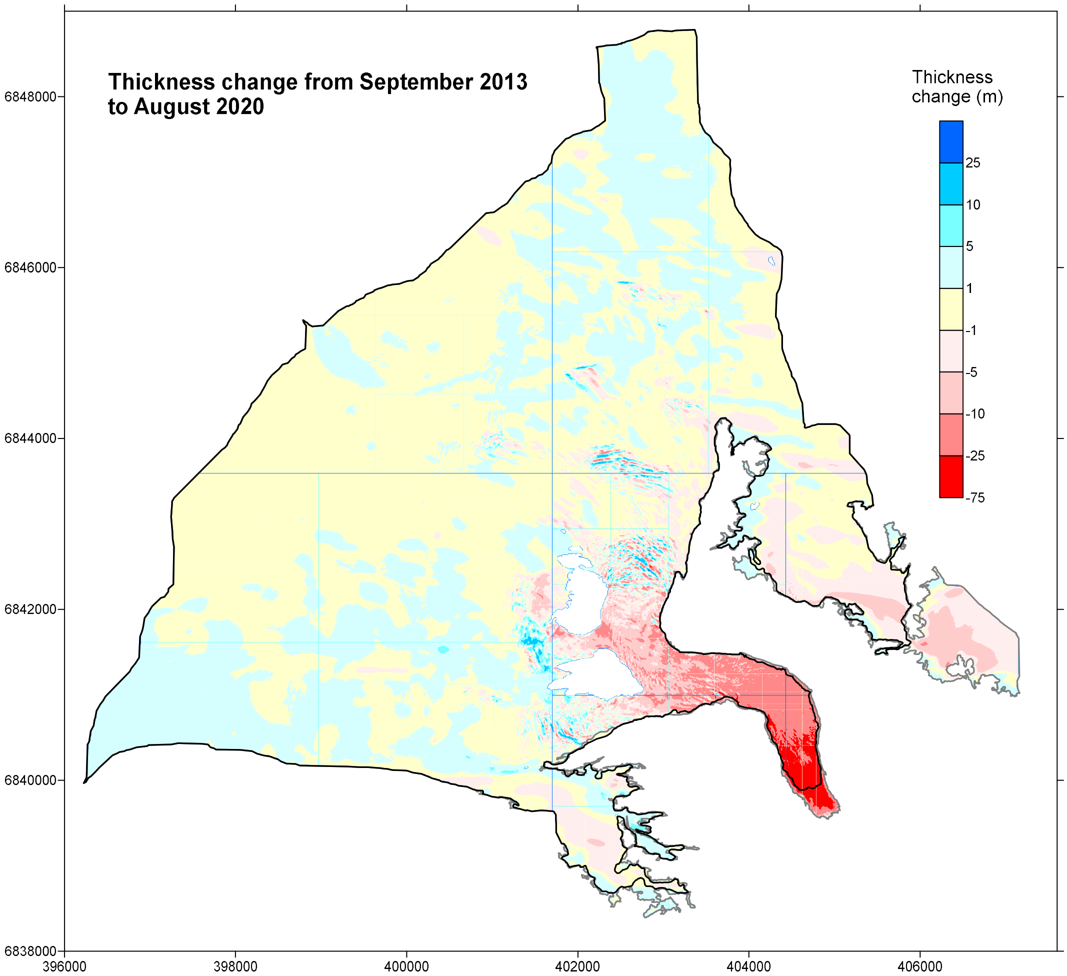


Figure 10
DTM differences within the hydrological basin of Nigardsbreen from 10th September 2013 to 9th August 2020. The glacier extents from 2013 (grey line) and 2020 (black line) are also shown.

Ice thickness change between September 2013 and August 2020 varied from +25 meters in the crevasse area to −75 meters at the glacier tongue (Fig. 10). Mean thickness change for the whole glacier surface was −0.43 meters. Thus, geodetic mass balance over 2014-2020 was −0.87 m w.e.

Table 3
Volume change and geodetic mass balance for Nigardsbreen from 2014 to 2020.

period	area$_{2013}$	area$_{2020}$	vol. ch.	dens. fac.	date adj. (m w.e.)		geod. mb. (m w.e.)	
glacier	(km^2)	(km^2)	(mill. m^3)	(kg m^{-3})	2013	2020	acc.	ann.
2014-2020								
Nigardsbreen	46,61	44,95	-20	850	-0,08	-0,57	-0,87	-0,124

area$_{2013}$ is the area of Nigardsbreen in September 2013
area$_{2020}$ is the area of Nigardsbreen in August 2020
vol. ch. is the volume change of ice, firn and snow over the given period
dens. fac. is the density used for converting from ice, firn and snow to water equivalent
date adj. is a correction for different dates for mapping and field survey for each year in the period
geod. mb. is accumulated (acc.) and annual (ann.) balance for the period

3.2 Glaciological mass balance

The methodology of the surface mass balance calculations was changed through the years from the beginning in 1962. Thus, a homogenization of the series 1962-2013 was implemented in Kjøllmoen (2016). Five major factors were considered and homogenized, 1) from contour-line method to profile method, 2) height-area distribution, 3) converting from snow depth to water equivalent, 4) ice-divide and 5) glacier boundaries.

For the mass balance series 2014-2020 four of the factors (1, 3, 4 and 5) were homogeneous with the period 1962-2013. As the new DTM from 2020 was available however, a homogenization of the series based on factor 2) height-area distribution, was required.

3.2.1 Height-area distribution

The original reported mass balance calculations 2014-2019 were based on height-area distribution from the DTM 2013, while the reported calculation for 2020 was based on the DTM from 2020 (Kjøllmoen et al., 2021). A period between two mappings is usually divided in two, where each map is applied to half of the period before the mapping year and half of the period after the mapping year (Fig. 11). Accordingly, the homogenization involved re-calculation of the reported years 2017, 2018 and 2019.

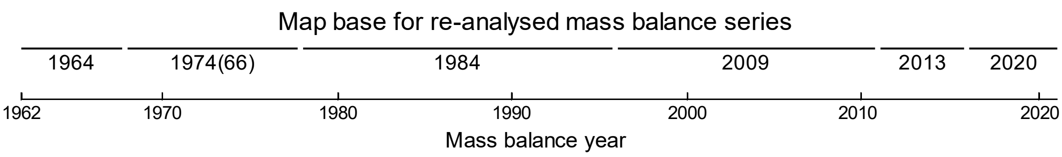


Figure 11
Upper line indicates map base for homogeneous mass balance series. Years denote year of validity period for each map.

3.2.2 Results

Homogenizing by re-calculation of the mass balance series 2017 to 2019 ensure a uniform methodology. Mass balance for 2020 was reported using the DTM 2020 and hence, was not necessary to re-calculate. The re-calculation was based on the DTM 2020.

Original and homogenized mass balance values for the three years 2017, 2018 and 2019 are shown in table 4.

Table 4
Original and homogenized mass balance values for Nigardsbreen for the years 2017, 2018 and 2019.

	Original mass balance series								Homogenized mass balance series							
Year	B_w	B_s	B_a	ΣB_a	ELA	AAR	DTM	Area	B_w	B_s	B_a	ΣB_a	ELA	AAR	DTM	Area
2017	2.17	-1.58	0.59	0.59	1440	84	2013	46.61	2.19	-1.55	0.63	0.63	1440	84	2020	44.95
2018	2.37	-3.22	-0.85	-0.27	1675	36	2013	46.61	2.38	-3.18	-0.80	-0.16	1675	38	2020	44.95
2019	2.04	-2.31	-0.27	-0.53	1580	62	2013	46.61	2.06	-2.27	-0.22	-0.38	1580	63	2020	44.95

The differences between original and homogenized mass balance values for the three years were rather small. The homogenized winter balance values were slightly more positive and the summer balance values were slightly less negative than the original series. The mean winter balance change was 0.016 m w.e. per year, and the mean summer balance change was 0.035 m w.e. per year. Accordingly, the cumulative annual balance for the three years 2017-2019 was changed from −0.531 to −0.377 m w.e. The Equilibrium-line altitude (ELA) was unchanged and the Accumulation-area ratio (AAR) was slightly higher.

The mass balance series over the period 1962-2020 shows a surplus of 6.93 m w.e., which gives a mean annual balance of +0.12 m w.e. a^{-1}. Over the 20 years period 2001-2020 however, the mean annual balance was −0.09 m w.e. a^{-1}.

4 Comparison and calibration

4.1 Comparison of glaciological and geodetic mass balances

Glaciological and geodetic mass balance for Nigardsbreen are compared for the period 2014-2020 (autumn 2013 to autumn 2020). Glaciological mass balance is based on annual measurements of snow depth and snow density at the end of the winter, and of ablation measurements at the end of the summer. Geodetic mass balance is based on changes in elevation and area between two mappings.

In order to compare glaciological and geodetic mass balance, the errors for the different methods and the internal balance were estimated. Internal balance was estimated using the methods described in Oerlemans (2013) and Alexander et al. (2011), and applied for ten glaciers in Norway in Andreassen et al. (2016). For this purpose internal balance is expressed as melting inside and underneath the glacier due to heat of dissipation. Melting due to rain was considered negligible, as most of this melting affects snow, firn and ice on the surface, rather than the subglacial system.

Internal balance (*B int*) was calculated for each elevation interval (100 meter) used in the surface mass balance by the formula

$$B\ int = \frac{\sum_h g * ph * ah * (h - bL)}{A * Lm}$$

where g is the acceleration of gravity, h is mean elevation of elevation interval used in surface mass balance calculations, ph is precipitation at h, ah is glacier area of elevation interval h, bL is bed elevation at glacier snout, A is total glacier area og Lm is latent heat of fusion.

Precipitation was defined as a linear function of elevation. Daily precipitation was extracted from www.senorge.no, and the gradient was selected to give an annual precipitation 1.5 times the measured winter balance.

The internal balance at Nigardsbreen was quantified as −0.16 m w.e. a^{-1} (Andreassen et al., 2016). The uncertainty, *σ.B. int*, was assumed to be one third of the estimated internal melting, which amounts to ±0.05 m w.e. a^{-1}.

In order to compare, the uncertainty of the measurements was estimated in accordance with Zemp et al. (2013) and Andreassen et al. (2016).

The results from glaciological, geodetic and internal mass balance, are shown in table 5.

The results show a difference between glaciological and geodetic mass balance (Δ) as 0.41 m w.e. a^{-1} for 2014-2020.

Table 5
Comparison of glaciological and geodetic mass balances and results of the uncertainty analysis for Nigardsbreen over the period 2014-2020. All mass balances and errors are in m w.e. a^{-1}.

glacier	years	B glac.	σ.glac. point	σ.glac. spatial	σ.glac. ref	B geod.	σ.geod. DTM	σ.dc	B int	σ.B. int	Δ
Nigardsbreen	7	0.45	0.26	0.21	0.06	-0.12	0.10	0.01	-0.16	0.05	0.41

B glac. is mean annual glaciological mass balance
σ.glac. point is random error for each point value in the glaciological mass balance
σ.glac. spatial is spatial random error in the glaciological mass balance
σ.glac.ref is random error as a consequence of glacier area changes over time
B geod. is mean annual geodetic mass balance
σ.geod. DTM is random error for the DTMs
σ.dc is random error for the density conversion
B int is internal melting
σ.B. int is random error for the internal melting
Δ is the difference between glaciological and geodetic balance, corrected for internal melting

In order to check whether the annual discrepancy between glaciological and geodetic mass balance is significant different or not, a hypothesis where the uncertainties are taken into account, is tested (Zemp et al., 2013). If the answer of this hypothesis is «no», it is recommended to calibrate the glaciological mass balance series. If the answer is «yes», it means that the glaciological balance is not significant different from the geodetic balance. By checking this hypothesis for Nigardsbreen, the answer was «no», which suggest the geodetic and glaciological series are significant different (Tab. 6). Hence, calibration of the series 2014-2020 was required.

Table 6
Comparison and check of glaciological and geodetic mass balance including the uncertainties.

glacier	Δ	σ	H0	β	ε
Nigardsbreen	0.41	2.40	no	33	0.61

Δ is the discrepancy (m w.e. a^{-1}) between glaciological and geodetic balance adjusted for internal melting
σ (dimensionless) is the reduced discrepancy, where uncertainties are accounted
H0 is the hypothesis whether the glaciological balance = the geodetic balance
β is the probability of accepting **H0** although the results of both methods are different at the 95 % confidence level
ε (m w.e. a^{-1}) is the limit for detection of bias

4.2 Calibration of glaciological mass balance

Based on the comparison and hypothesis in chapter 4.1 the mass balance period 2014-2020 was calibrated. A similar calibration was implemented for the period 1984-2013 in Kjøllmoen (2016).

The annual glaciological mass balance for Nigardsbreen 2014-2020 needed to be corrected with 0.41 m w.e. a^{-1}. Whether the discrepancy is a result of a bias in winter or summer balance was not proved. Thus, corrections of both winter and summer balances were applied. The percentual distribution (winter vs. summer) of the annual corrections can be done in several ways. In this calibration, the winter and summer corrections were assessed according to the size of the balance values; the greater balance value, the greater part of the correction. For instance, for the year 2014 the original B_w and B_s were 2.73 and −3.07 m w.e., respectively. The annual correction for the period 2014-2020 (−0.41 m w.e.) was then distributed as 47 % ((2.73/(2.73+3.07))*100) to B_w, and 53 % ((3.07/(3.07+2.73))*100) to B_s, resulting in calibrated B_w as 2.54 m w.e. (2.73+(0.41*47 %)), and B_s as −3.29 m w.e. (3.07+(0.41*53 %)). Winter, summer and annual balance curves for 2014 before and after the calibration are shown in figure 12.

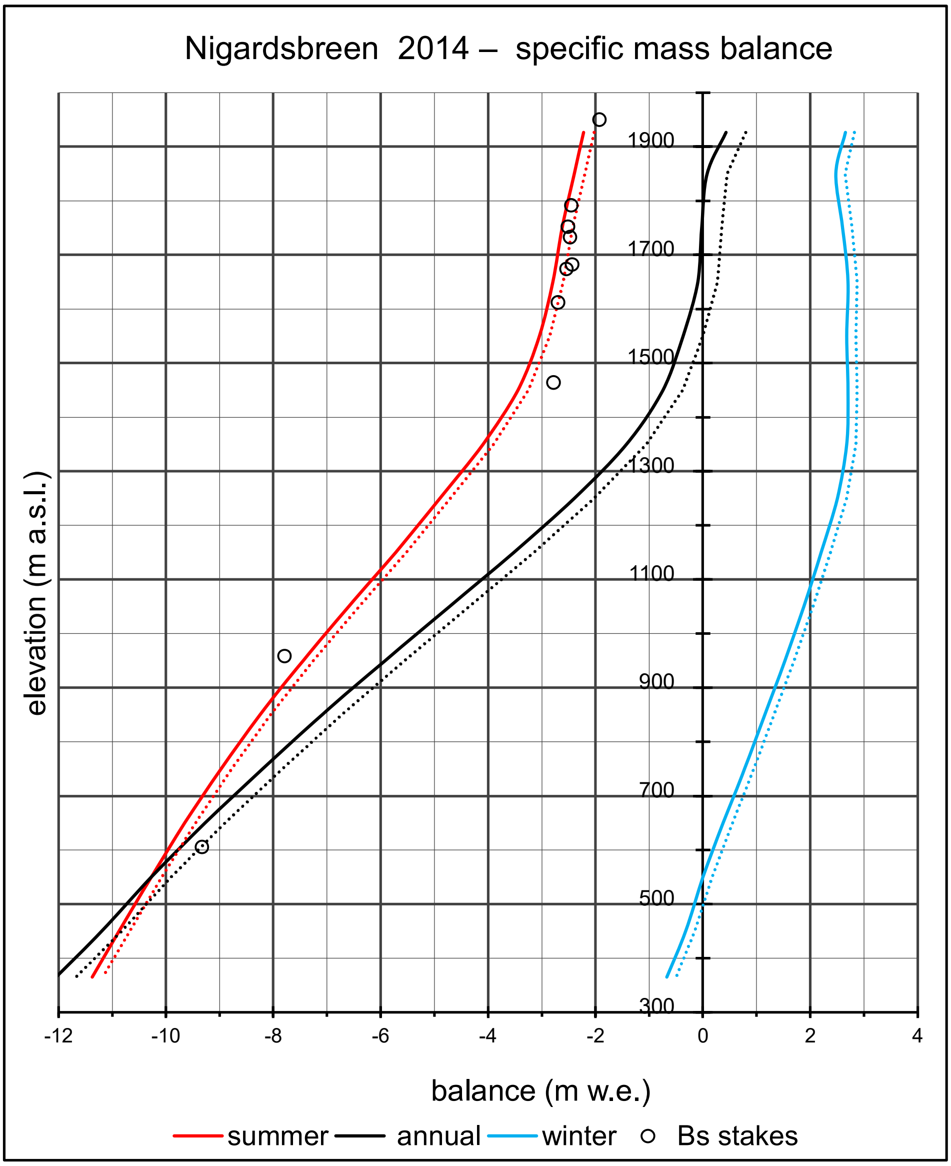


Figure 12
Winter, summer and annual balance curves in 2014 before (dotted) and after (solid) the calibration. Summer balance at each stake is also shown (○).

The calibrated mass balance series for the years 2014-2020 is shown in table 7 and the current mass balance series for the whole period 1962-2020 is shown in figure 13.

Table 7
Calibrated mass balance series for Nigardsbreen over 2014-2020.

	Original/homogenised mass balance series								Calibrated mass balance series					
Year	B_w	B_s	B_a	ΣB_a	ELA	AAR	DTM	Area	B_w	B_s	B_a	ΣB_a	ELA	AAR
2014	2.73	-3.07	-0.34	-0.34	1550	67	2013	46.61	2.54	-3.29	-0.75	-0.75	1820	8
2015	3.07	-1.35	1.71	1.37	1310	92	2013	46.61	2.78	-1.48	1.31	0.56	1355	90
2016	2.81	-2.33	0.49	1.85	1380	89	2013	46.61	2.59	-2.51	0.08	0.63	1470	80
2017	2.19	-1.55	0.63	2.49	1440	84	2020	44.95	1.95	-1.72	0.23	0.86	1510	75
2018	2.38	-3.18	-0.80	1.69	1675	38	2020	44.95	2.21	-3.41	-1.20	-0.34	1815	9
2019	2.06	-2.27	-0.22	1.48	1580	63	2020	44.95	1.86	-2.49	-0.62	-0.96	1645	47
2020	3.51	-1.85	1.65	3.13	1285	93	2020	44.95	3.24	-1.99	1.25	0.28	1330	91

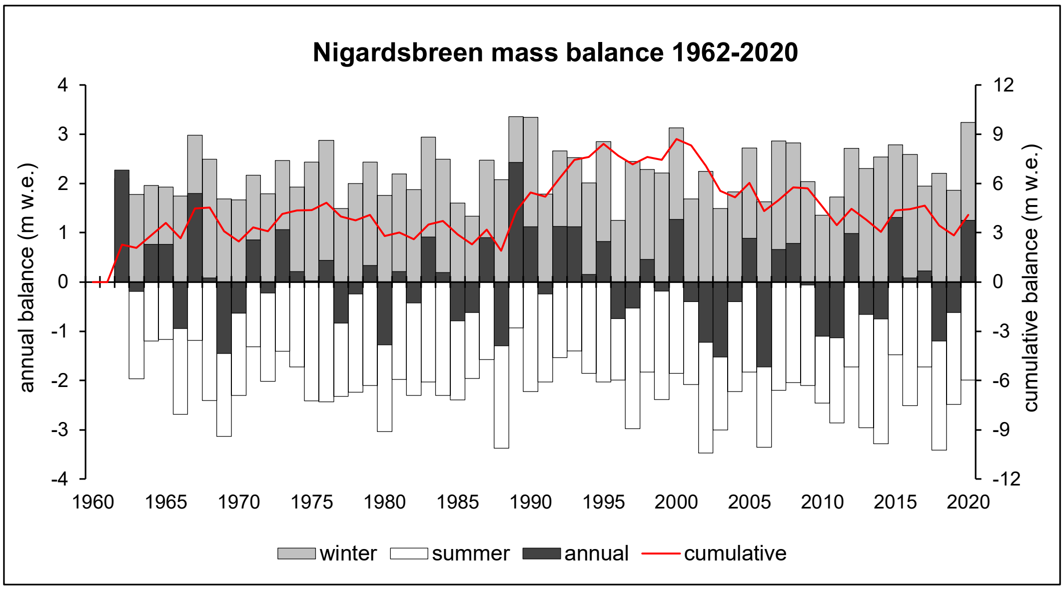


Figure 13
Calibrated mass balance series for Nigardsbreen over 1962-2020.

The calibrated cumulative mass balance for Nigardsbreen over 1962-2020 were +4.1 m w.e. and the mean annual balance values were 2.22 (B_w), −2.15 (B_s) and +0.07 m w.e. (B_a), respectively. The calibrated mass balance series was significant positive (>0.30 m w.e.) in 23 years, significant negative (<0.30 m w.e.) in 22 years and approximately in balance in 14 years.

The ELA and the AAR were also influenced by the calibration as they were calculated from the mass balance curves. From the original and homogenized to the calibrated mass balance series, the ELA over 2014-2020 was elevated between 45 and 270 meters. Accordingly, the mean AAR over the same years was decreased from 75 % to 57 %.

5 Conclusions

The aim of this report was to homogenize the glaciological mass balance series 2014-2020, compare the series with the corresponding geodetic mass balance, and hence, reveal a possibly significant discrepancy followed by a calibration of the glaciological series. Within this period, DTMs for 2013 and 2020 were produced.

In order to obtain comparable values the glaciological and the geodetic mass balances were first homogenized. The homogenized cumulative glaciological mass balance series over the years 2014-2020 was +3.13 m w.e. The corresponding geodetic mass balance was −0.87 m w.e. The internal mass balance was quantified as −1.15 m w.e. Accordingly, the mean annual difference ($\Delta_a = B_{a\ glac.} - B_{a\ geod.} + B_{a\ int.}$) over 2014-2020 was 0.41 m w.e. A hypothesis in Zemp et al. (2013) was tested and revealed that a calibration was required.

The periodic annual corrections were spread over both winter and summer balances. The percentual distribution between winter and summer balance corrections was assessed according to the size of the balance values.

The calibrated glaciological cumulative mass balance over 2014-2020 was +0.28 m w.e., while the original mass balance series over the same years was +2.97 m w.e.

The reanalysed mass balance values were updated in NVE's databases by flagging the series as homogenized and calibrated. The annual mass balance data are available for download from NVE's glacier application http://glacier.nve.no/glacier/viewer/ci/en/. The reanalysed data will be submitted to WGMS.

References

Alexander, D., J. Shulmeister and T. Davies
2011: High basal melting rates within high-precipitation temperate glaciers. *Journal of Glaciology, Vol. 57, No. 205,* p. 789–795.

Andreassen, L.M., H. Elvehøy, B. Kjøllmoen and R. Engeset
2016: Reanalysis of long-term series of glaciological and geodetic mass balance for 10 Norwegian glaciers. *The Cryosphere, 10*, p. 535-552.

Andreassen, L.M., H. Elvehøy, B. Kjøllmoen, R.V. Engeset, and N. Haakensen
2005: Glacier mass balance and length variation in Norway. *Annals of Glaciology, 42*, p. 317-325.

Andreassen, L.M.
1999: Comparing traditional mass balance measurements with long-term volume change extracted from topographic maps: A case study of Storbreen glacier in Jotunheimen, Norway, for the period 1940-1997. *Geografiska Annaler, 81 A (4)*, p. 467-476.

Bader, H.
1954: Sorge's Law of densification of snow on high polar glaciers. *Journal of Glaciology, 2(15),* p. 319–323.

Cogley, J. G., R. Hock, A.L. Rasmussen, A.A. Arendt, A. Bauder, R.J. Braithwaite, P. Jansson, G. Kaser, M. Möller, L. Nicholson and M. Zemp
2011: Glossary of Glacier Mass Balance and Related Terms, *IHP-VII Technical Documents in Hydrology No. 86, IACS Contribution No. 2, Paris, UNESCO-IHP,* 114 pp.

Cuffey, K.M. and W.S.B. Paterson
2010: The Physics of Glaciers, 4th edition. Butterworth-Heinemann, Oxford, 704 pp.

Haug, T., C. Rolstad, H. Elvehøy, M. Jackson and I. Maalen-Johansen
2009: Geodetic mass balance of the western Svartisen ice cap, Norway, in the periods 1968-1985 and 1985-2002. *Annals of Glaciology 50 2009*, p. 191-197.

Huss, M.
2013: Density assumptions for converting geodetic glacier volume change to mass change. *The Cryosphere, 7, 877–887*, doi:10.5194/tc-7-877-2013.

Kjøllmoen, B. (Ed.), L.M. Andreassen, H. Elvehøy and K. Melvold
2021: Glaciological investigations in Norway 2020. *NVE Rapport 31 2021*, 92 pp.

Kjøllmoen, B. (Ed.), L.M. Andreassen, H. Elvehøy and M. Jackson
2020: Glaciological investigations in Norway 2019. *NVE Rapport 34 2020*, 86 pp.

Kjøllmoen, B.
2016: Reanalysing a glacier mass balance measurement series – Nigardsbreen 1962-2013. *NVE Rapport 30 2016*, 59 pp.

Oerlemans, J.
2013: A note on the water budget of temperate glaciers. *The Cryosphere 7*, p. 1557-1564.

Terratec AS
2020: Laserskanning for nasjonal detaljert høydemodell. NDH Jostedalsbreen 2 pkt 2020, 20 pp.

Terratec AS
2014: Rapport for luftbåren laserskanning. Nigards- Tunsbergdalsbreen, 10 pp.

Zemp, M., E. Thibert, M. Huss, D. Stumm, C. Rolstad Denby, C. Nuth, S.U. Nussbaumer, G. Moholdt, A. Mercer, C. Mayer, P.C. Joerg, P. Jansson, B. Hynek, A. Fischer, H. Escher-Vetter, H. Elvehøy and L.M. Andreassen
2013: Reanalysing glacier mass balance measurement series. *The Cryosphere 7*, p. 1227-1245.

Zemp, M.
2010: Reanalysis of multi-temporal aerial images of Storglaciären, Sweden (1959-99) – Part 2: Comparison of glaciological and volumetric mass balances. *The Cryosphere 4*, p. 345-357.

Østrem, G. and M. Brugman
1991: Glacier mass-balance measurements. A manual for field and office work. National Hydrology Research Institute. *Scientific Report No 4*. Environment Canada, N.H.R.I, Sakatoon and Norwegian Water Resources and Energy Directorate, Oslo, 224 pp.

Østrem, G. and W. Karlén
1962: Nigardsbreens hydrologi 1962. *Norsk Geografisk Tidsskrift 18 (1962-62)*, p. 156-202.

NVE

Norwegian Water and Energy Directorate

MIDDELTHUNS GATE 29
P.O. BOX 5091 MAJORSTUEN
N-0301 OSLO
TELEPHONE: (+47) 22 95 95 95

www.nve.no