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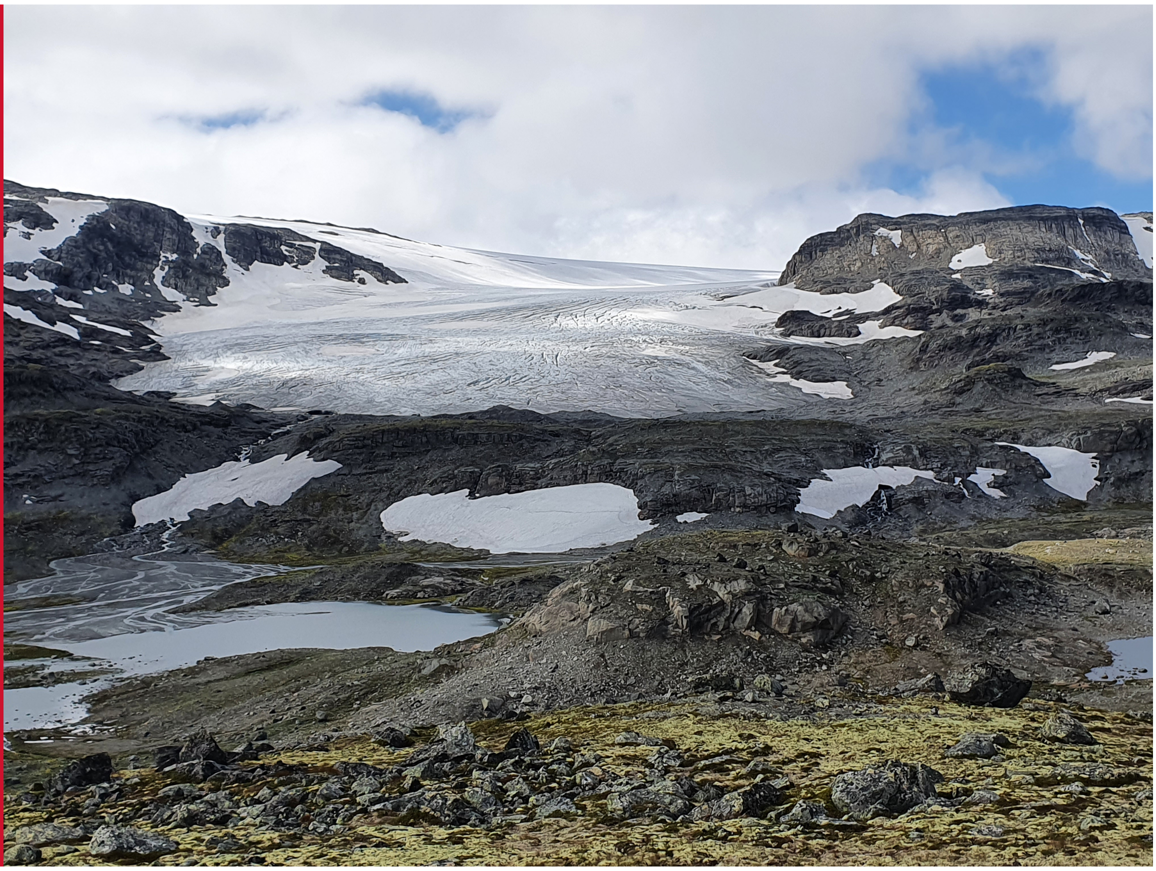
Norwegian Glacier Reference Dataset for Climate Change Studies

Liss M. Andreassen and Hallgeir Elvehøy



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Abstract: The NVE Hydrological Reference Dataset for studies of hydrological change was presented in Fleig et al (2013) and also included datasets of glacier mass balance and length change. This report in an update of the glacier datasets up to and including year 2021.

Keywords: Glacier, Mass balance, Length change, Homogenization, Calibration, Climate change

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Preface

Through its hydrological network, NVE is responsible for monitoring, registering and documenting the effects of climate change on hydrology. NVE has a central role in the management of Norwegian water resources, including national flood contingency planning. The directorate also has responsibility for reducing damage caused by avalanches and landslides and overall responsibility for maintaining national power supplies.

Improving knowledge about the impacts of climate change on our water resources is one of the main requirements to help facilitate adaptation to climate change. Therefore, monitoring and documentation of changes in hydrology is an important task, according to the strategy of NVE for the period 2022-2026. To achieve this, a high-quality dataset suitable for studying hydrological variability and change is required. These data should not be influenced by human activities, which may have caused non-climate related variability or change. NVE's Hydrological Reference Dataset for studies of the effect of climate change on hydrology in Norway comprises streamflow, groundwater, snow, glacier mass balance and length changes, lake and river ice and water temperature in rivers and lakes (Fleig et al., 2013).

In this report the glacier mass balance and glacier length reference datasets are revisited and updated up to and including year 2021.

Oslo, December 2021

Hege Hisdal Director	Rune V. Engeset Head of Section

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Summary

The NVE Hydrological Reference Dataset for studies of hydrological change presented in Fleig et al. (2013) included datasets of glacier mass balance and glacier length change. In this report we revisit and update the glacier reference datasets up to and including year 2021. Several glacier length-change records have been terminated in recent years due to glacier retreat hindering accurate or safe measurements.

Five criteria were used to select the reference glaciers:

- Absence of significant regulations, diversions or water use.
- Record length
- Active data collection
- Data accuracy
- Adequate metadata

We selected nine mass-balance glaciers and 26 length-change glaciers. The mass-balance glaciers were the same as in Fleig et al. (2013), whereas the selection of length- change glaciers included some new glaciers whereas other glaciers were left out. The reference glaciers are biased towards southern Norway, where seven out of nine mass-balance glaciers and 19 out of 26 length-change glaciers are located.

1 Introduction

The Norwegian Hydrological Reference Dataset for Climate Change Studies was published in 2013 and included streamflow, groundwater, snow, glacier mass balance and length change, lake ice and water temperature in rivers and lakes (Fleig et al., 2013). Here we focus on the glacier records only. The aim of this report is to revisit the Hydrological Reference Dataset for glaciers and present an updated glacier dataset suitable for the study of the effects of climate variability and change on the hydrology and cryosphere in Norway.

Glaciers in Norway have importance for hydropower, water management and tourism. The glaciers are sensitive climate indicators. Norway's present-day ice caps are highly vulnerable to surface mass balance changes due to their ice cap hypsometry (e.g. Åkeson et al., 2017). Changes in glaciers will affect future runoff (Hanssen-Bauer et al., 2015). Glacier length fluctuations are indicators of climate change (e.g. Leclercq et al., 2014).

Glaciers in Norway have changed markedly in recent years with pronounced retreat of glacier termini (Andreassen et al., 2020; Kjøllmoen et al., 2021). Some glacier length change measurements have been discontinued as the glacier terminus has changed so that accurate measurements are no longer possible (Fig. 1; Andreassen et al., 2020).

Figure 1. Bødalsbreen (ID 2273) is an example of a glacier that has retreated significantly in recent years. The glacier -measurements were terminated in 2015 after the terminus had retreated beyond the steep cliffs. It is now considered dangerous to approach the glacier due the danger of rockfalls. Photo: Liss M. Andreassen, 22 August 2020.

2 Selection criteria

The glaciological parameters considered for the Hydrological Reference Dataset for glaciers were surface mass-balance and length-change observations (also termed front-position change) (Fleig et al., 2013). The mass balance reflects annual weather directly, whereas records of length change are considered as proxies for glacier area change in response to climate change on a decadal-to-century time scale (Oerlemans, 2005).

The six following selection criteria were used for identification of suitable stream gauging reference stations (Whitfield et al., 2012), and were described in detail in Fleig et al. (2013):

1. Degree of basin development: Pristine or stable land-use conditions (<10% of the area is affected).
2. Absence of significant regulations, diversions, or water use. Only natural catchments.
3. Record length: Minimum 20 years and some stations with > 50 years.
4. Active data collection: Currently active and is expected to continue operation.
5. Data accuracy: High-quality data.
6. Adequate metadata: Adequate metadata should be available to support the previous five conditions.

Similar to the previous assessment of glacier series (Fleig et al., 2013), we used criteria 3 (record length) and 4 (active data collection) as a first criteria for selecting the possible reference series for glaciers. Thus, all annual glacier mass-balance and length-change series stored in NVE's Hydra II database that are longer than 20 years and classified as active were chosen as basis for the selection of reference stations. Overviews of all the monitored glaciers as well as a description of methods are found in Andreassen et al. (2005; 2020) with updates in Kjøllmoen et al. (2021).

3 Glacier datasets

3.1 Glacier surface

Glacier surface mass-balance measurements started in Norway in 1949 at Storbreen in Jotunheimen. NVE's mass-balance series contain winter, summer and annual (net) balances. The annual balance is the sum of winter balance and summer balance. Area-averaged values for winter and summer balances are calculated by inter- and extrapolating point measurements of snow density, snow depths and ablation. In 2021 mass balance was measured on 10 glaciers. Nine of the glaciers were selected as reference glaciers by Fleig et al. (2013; Table 1). Austdalsbreen (ID 2480) was excluded because it was calving into a hydro-power reservoir, and consequently the glacier is influenced by the lake level regulations.

Table 1. Long term mass-balance glaciers in Norway with series longer than 20 years up to and including 2021. ID refers to ID in the glacier inventory of Norway (Andreassen et al., 2012b).

ID	Name	Period(s)	Number of obs. years
54	Langfjordjøkelen	1989-93, 1996-	31
1094	Engabreen	1970-	52
2078	Ålfotbreen	1963-	59
2085	Hansebreen	1986-	36
2297	Nigardsbreen	1962-	60
2478	Austdalsbreen*	1988-	33
2636	Storbreen	1949-	73
2743	Gråsubreen	1962-	60
2768	Hellstugubreen	1962-	60
2968	Rembesdalskåka	1963-	59

*calving into a regulated lake

3.2 Glacier length change

Length-change measurements were initiated around 1900 at many glaciers in Norway. The glacier length-change record is derived from annual measurements of distance between one or several fixed reference points and the glacier terminus in defined directions. The extent of the monitoring programme has varied according to levels of funding and dedication. In 2021, 39 glaciers were part of the monitoring programme.

Eleven glaciers, one in Northern Norway and 10 in southern Norway, were selected as reference glaciers by Fleig et al. (2013). Unfortunately, the long record of annual measurements from Briksdalsbreen starting in 1899 was terminated in 2015. The location of the glacier terminus at the top of high cliffs hindered accurate measurements and were both risky and difficult (Fig. 2).

Figure 2. The terminus of Briksdalsbreen (ID 2320) is situated at the top of steep cliffs. Variations in ice discharge towards the glacier terminus will not result in variations in glacier length as the ice will calve off the terminus. Thereby, the glacier length will not reflect variations in climate. The conditions to perform accurate measurements were risky and difficult and measurements were terminated.
Photo: Erling Briksdal, 1 November 2015.

In 2021, a total of 22 glaciers have records longer than 20 years (initiated before 2001). Fifteen glaciers have records starting early in the 20th century, but several of the records were discontinued for various reasons. Seven glaciers have records starting in the 1970s, 1980s or 1990s (Table 2).

Unfortunately, only four of the 22 glaciers are situated in northern Norway. To increase the number of selectable glaciers in Northern Norway and Møre and Romsdal county we included six glaciers where the continuous record soon will reach 20 years as candidates for the reference data set. Several of those glaciers have a potential for extending the continuous record using mapped terminus positions, geo-referenced old reference points (cairns, marks etc.), moraines or similar (Table 3).

Table 2. Glaciers with long term observations of length change in Norway, with active measurements and with series spanning more than 20 years. ID refers to ID in the glacier inventory of Norway (Andreassen et al., 2012b). Number of obs. (observations) states the number of single observed periods (one or several years) included in the record. Length of continuous period states how many years back in time the record is continuous.

ID	Name	Period(s)	Number of obs.	Length of continuous period
54	Langfjordjøkelen	1998-	23	23
205	Koppangsbreen	1998-	21	23
288	Steindalsbreen	1978-	28	43
1094	Engabreen	1903-	88	118
2289	Fåbergstølsbreen	1899-	115	122
2297	Nigardsbreen	1899-	110	122
2305	Brenndalsbreen	1900-62, 1996-	82	25
2349	Austerdalsbreen	1905-20, 1933-	100	88
2480	Stigaholtbreen	1903-	107	118
2614	Storjuvbrean	1901-12, 1933-63, 1997-	60	24
2636	Storbreen	1902-	82	120
2638	Leirbrean	1909-77, 1979-	61	42
2643	Bøverbrean	1903-12, 1936-63, 1997-	47	24
2680	Styggedalsbreen	1901-	99	120
2717	Mjølkedalsbreen	1978-	25	43
2768	Hellstugubreen	1901-	81	120
2964	Midtdalsbreen	1982-	39	39
2968	Rembesdalskåka	1917-	46	104
3117	Botnabrea	1996-	17	25
3131	Buerbreen	1900-	74	121
3133	Bondhusbrea	1902-	89	119
3141	Blomstølskardsbreen	1994-	21	27

Table 3. Glaciers with length-change observations with continuous series spanning less than 20 years back in time. Mapped states years when aerial photographs were taken. Number of observation years (n) states the number single (annual or multi-annual) observed periods in the record. Length of continuous period states how many years back in time the record is continuous.

ID	Name	Period(s)	Mapped	n	Length of continous period
675	Storsteinsfjellbreen	2006-	1960, 1978, 1993	12	15
941	Rundvassbreen	2011-	1961, 1998	9	10
1280	Trollbergdalsbreen	2010-	1968, 1985, 2008	6	11
1438	Austre Okstindbreen	1908-44, 2006-	1962, 1999	29	15
1439	Corneliussenbreen	2006-	1965, 1999	9	15
1804	Trollkyrkjebreen	1944-74, 2008-	1965	26	13

3.3 Selection of glaciers

When selecting reference glaciers, the six general criteria in chapter 2 were considered. Criteria 3 (record length) and 4 (active data collection) are already used to select the available glaciers for the reference dataset. Below we briefly discuss the criteria for the mass-balance and length-change glaciers.

1. Degree of basin development

We do not consider this criterion as relevant for the glacier mass-balance and length-change records.

2. Absence of significant regulations, diversions, or water use

Mass balance: One of the glaciers with long record, Austdalsbreen, is calving into a regulated lake. Part of the ablation is caused by calving from the glacier (3-18% of the summer balance). Since the mass balance of this glacier is influenced to some extent by the regulation, this glacier was not included in the reference data set by Fleig et al. (2013).

Length change: None of the selected glaciers are directly influenced by regulations or water use.

3. Record length

Mass balance: All series are continuous for more than 20 years. The mass balance of Langfjordjøkelen was not measured for two years (1994, 1995). The mass balance for the missing years has been modelled using climate data as input (Kjøllmoen and Olsen, 2002; Andreassen et al., 2012a).

Length change: According to the record length criteria all the glaciers listed in Table 2 are to be included. Some of the series have minor gaps, but it should be noted that length change must not be measured every year to have a continuous series such as mass balance. If one year is missing one can obtain a length change of two years instead of one, thus losing the annual signal, but keeping the cumulative signal.

Length-change observations series can be extended, or discontinuous records can be tied together using maps, aerial photos, geo-referenced reference points or similar (Andreassen et al., 2020). At Trollkyrkjebreen the old and new parts of the record was tied together using an old relocated and geo-referenced reference point (a painted mark on bedrock).

However, one should critically consider if an apparent continuous retreat was interrupted by shorter periods of advance. This is the situation in the 1920s and 1990s at several glaciers. Of the six new candidates considered (Table 3), Storsteinsfjellbreen, Rundvassbreen and Trollbergdalsbreen in Nordland, and Trollkyrkjebreen in Møre & Romsdal do not show any signs of having an advance in the 1990s (Andreassen et al., 2020). The remaining two glaciers, Austre Okstindbreen (ID 1438) and Corneliussenbreen (ID 1439) probably advanced or were stationary in the 1990s.

4. Active data collection

All glaciers presented in Tables 1, 2 and 3 are active stations measured today (2021). We have no information on planned termination of any of the mass-balance or length-change series. However, it might occur that a glacier is no longer suited for length-change measurements, such as for Bødalsbreen (Fig. 1) and Briksdalsbreen (Fig. 2) after 2015 where the terminus became inaccessible or not suitable for glacier length observations.

5. Data accuracy

Mass balance: The accuracy of mass-balance measurements depends on both the accuracy of the point observations and the inter- and extrapolation of point values to spatially distributed values. Systematic errors may cause large cumulative errors in long term mass-balance series.

To validate the results of the annual glaciological mass-balance observations, cumulative balance can be calculated and compared to the geodetic mass balance (Zemp et al., 2013). This is calculated from glacier surface elevations mapped in different years by differencing digital terrain models (DTMs) and converting the volume change to mass using a density conversion factor (Huss, 2013). Geodetic and glaciological observations of the 9 glaciers was reanalysed by NVE (Andreassen et al., 2016). Three NVE reports give further details on four of the glaciers analysed: Engabreen (Elvehøy, 2016), Nigardsbreen (Kjøllmoen, 2016a), Ålfotbreen and Hansebreen (Kjøllmoen, 2016b). The reanalysis included (i) homogenisation of both glaciological and geodetic observation series, (ii) uncertainty assessment, (iii) estimates of generic differences including estimates of internal and basal melt, (iv) validation, and, for some glaciers, (v) calibration of the annual mass-balance series. In total, 21 periods of data were compared, and the results show discrepancies between the glaciological and geodetic methods for some glaciers, which are attributed in part to internal and basal ablation and in part to inhomogeneity in the data processing.

Homogenized glaciological and geodetic results were in overall agreement for Langfjordjøkelen, Austdalsbreen, Storbreen, Hellstugubreen and Gråsubreen for the periods considered, but they differed for Ålfotbreen (one of three periods), Hansebreen (both periods), Engabreen (both periods), Rembesdalskåka (one of two periods), and Nigardsbreen (one of two periods). These 7 periods were calibrated by applying an annual correction factor (the annual difference between the homogenised geodetic and glaciological mass balance) to the summer and winter balances according to their relative size.

The reanalysis process altered seasonal, annual, and cumulative balances as well as Equilibrium-line altitude (ELA) and Accumulation-area ratio (AAR) values for many of the years for the 9 glaciers selected here. For most glaciers the discrepancy between the "original" glaciological series as published in the series "Glaciological investigations in Norway" were small, but for others results differed significantly. The mass-balance series are now categorized as 'original' (as published in 'Glasiologiske undersøkelser i Norge/Glaciological investigations in Norway), 'homogenized' (for selected or all years) or 'calibrated' (periods are calibrated with geodetic observations) in the NVE database. The reanalysed and thus "official" values are available for download from NVE's website: http://glacier.nve.no/glacier/viewer/ci/en/. As new mappings are available, we will validate the glaciological mass-balance records using the same routines.

Glaciers are constantly adjusting to the present climate by reducing or increasing their area. All the mass-balance glaciers referred to here have been mapped multiple times producing maps/DTMs which have been used in the calculations. The mass-balance records are thus not based on one reference surface topography, so care must be taken when using long mass-balance series for extracting a climate signal. To isolate the effects of climate from the effects of changing glacier topography one must calculate reference-surface mass-balance series (Elsberg et al., 2001). It might be worthwhile to calculate reference-surface mass-balance series for climate studies, especially when changes in glacier geometry are large over the studied period (Andreassen et al., 2012a).

Length change: The accuracy of the electronic distance meter is within 1-2 m. However, where access is limited or dangerous or line of sight has been changed, the accuracy could be considerably poorer. The representativity of a single measurement line can vary from year to year. However, as long as the observation represents a central part of the terminus, multi-year averages will compensate for annual terminus shape variations. In general, glaciers have different response times because of different slope, length, and mass-balance gradients. Glacier retreat can also be enhanced significantly when calving into a lake. Monitoring several glaciers in an area is useful for filtering the influence of different glacier dynamics and geometries, and local meteorological conditions. Using just one glacier for extracting a climate change signal is not recommended.

Observations from topographical maps and orthophotoscan be used to control and homogenize or calibrate length-change series (e.g. Andreassen et al., 2020). The series of Briksdalsbreen (Kjøllmoen et al., 2007), Stigaholtbreen (Kjøllmoen et al., 2019) and Fåbergstølsbreen (Kjøllmoen et al., 2020) were homogenised due to differences between length changes measured on maps and the field observations.

6. Adequate metadata

All mass-balance and length-change data are stored in NVEs database Hydra II. The mass-balance data are published annually or biannually since 1963 in the report series 'Glaciological investigations in Norway' (e.g., Kjøllmoen et al., 2021). The length-change data have been published in different sources such as Bergens Museums Årbok (1904-1939), Norsk Polarinstitutts Årbok (1963-80), and in 'Glaciological investigations in Norway' since 1995. The data are also reported to the World Glacier Monitoring Service and published in their series Global Glacier Change Bulletin (e.g., WGMS, 2021). Although the reporting might be less detailed for some years/periods and some glaciers, the available metadata is found to be satisfactory for using the glaciers as reference glaciers.

Figure 3. Hellstugubreen in Jotunheimen has length-change data since 1902 and mass-balance data since 1962. Until the 1960s the glacier was connected to the cirque glacier to the right.
Photo: Liss M. Andreassen, 4 August 2020.

4 Glacier reference datasets

4.1 Mass balance

In total nine glaciers are selected to be included in the Norwegian Hydrological Reference Dataset (Table 4). The nine glaciers are the same as selected by Fleig et al. (2013). Five of the mass-balance series have been partly calibrated due to significant deviations between geodetic and glaciological observations (Andreassen et al., 2016). All mass-balance and length-change data are stored in NVEs database Hydra II. Length-change measurements are part of the monitoring programme at seven of the mass-balance glaciers (e.g. Hellstugubreen (Fig. 3) and Rembesdalskåka (Fig. 4)), but not at Ålfotbreen, Hansebreen and Gråsubreen.

Table 4. Mass-balance glaciers in Norway selected as reference glaciers. Code refers to abbreviation of name in Figure 5.

ID	Code	Name	Period	Remarks
54	L	Langfjordjøkelen	1989-	1994 and 1995 are modelled
1094	E	Engabreen	1970-	Partly calibrated
2085	Å	Ålfotbreen	1963-	Partly calibrated
2145	H	Hansebreen	1986-	Partly calibrated
2301	N	Nigardsbreen	1962-	Partly calibrated
2638	S	Storbreen	1949-	
2743	G	Gråsubreen	1962-	
2768	He	Hellstugubreen	1962-	
2968	R	Rembesdalskåka	1963-	Partly calibrated

Figure 4. Rembesdalskåka is an outlet glacier of Hardangerjøkulen. The glacier has length-change data since 1917 and mass-balance data since 1963. The mass-balance series have been homogenized and partly calibrated. Photo: Mark Reysoo, 26 August 2020.

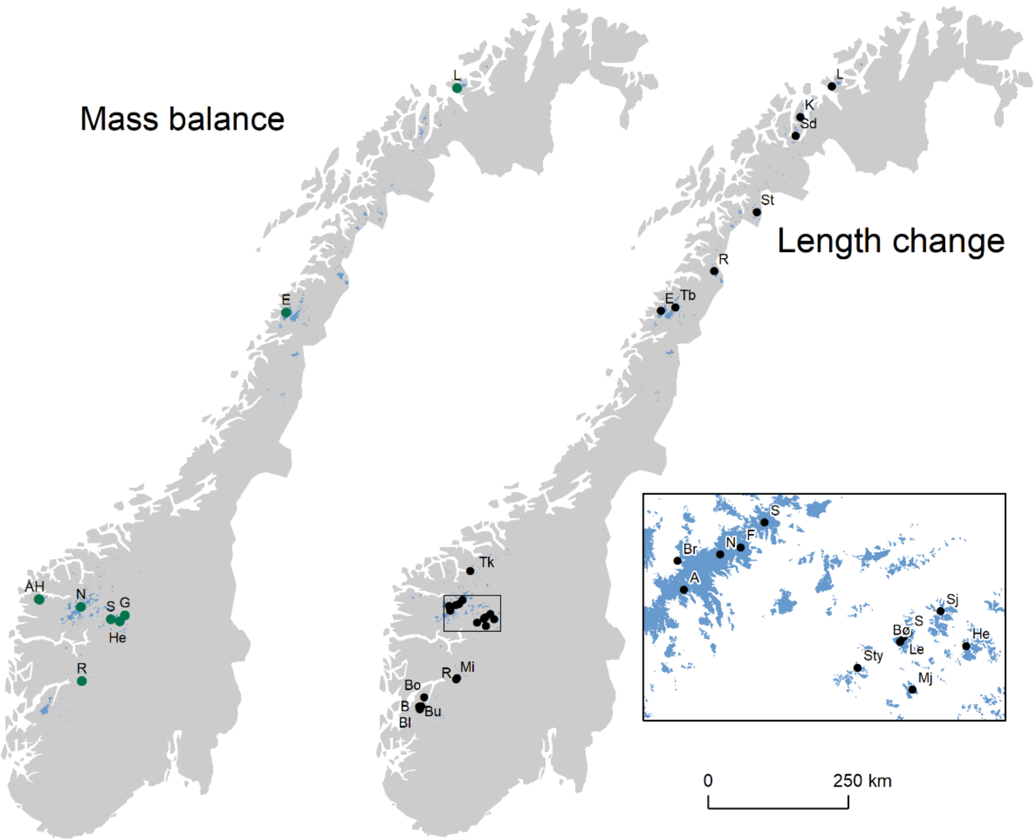

Figure 5. The mass-balance and length-change glaciers selected as reference glaciers. The glaciers are shaded in blue. The inset shows the length-change reference glaciers from Jostedalsbreen (to the left) and in Jotunheimen (to the right). See Table 4 and 5 for further information.

4.2 Length change

In total 26 glaciers are selected to be included in the Norwegian Hydrological Reference Dataset (Table 5). From the previous reference dataset (Fleig et al. 2013) Briksdalsbreen (ID 2320) is excluded as they are no longer active. We included all glaciers in Table 2 and four of the six glaciers in Table 3. The remaining two glaciers in Table 3, Austre Okstindbreen (ID 1438) and Corneliussenbreen (ID 1439), were not included in the reference data set. They can be included later if further investigations can tie together different parts of the records and sort out the extent of the 1990s advance.

Table 5. Length-change glaciers in Norway selected as reference glaciers. Code refers to abbreviation of name in Figure 4.

ID	Code	Name	Period	Remarks
54	L	Langfjordjøkelen	1998-	Extended from maps 1966 and 1994
205	K	Koppangsbreen	1998-	
288	Sd	Steindalsbreen	1978-	Proglacial lake
675	St	Storsteinsfjellbreen	1960-	Mass balance 1964-68 and 1991-95
941	R	Rundvassbreen	1961-	Mass balance 2002-04, 2011-17, GLOFs
1094	E	Engabreen	1903-	Proglacial lake 1931- ca.1942
1280	Tb	Trollbergdalsbreen	1968-	Extended from maps 1968, 1985 and 2008
1804	Tk	Trollkyrkjebreen	1944-	Tied together using old reference point
2289	F	Fåbergstølsbreen	1899-	Revised in 2019
2297	N	Nigardsbreen	1899-	Proglacial lake ca. 1931-1966
2305	Br	Brenndalsbreen	1996-	Re-generated glacier tongue
2327	A	Austerdalsbreen	1933-	Proglacial lake
2480	St	Stigaholtbreen	1903-	Revised in 2018
2614	Sj	Storjuvbrean	1997-	
2636	S	Storbreen	1902-	Two glacier tongues after 1984, GLOFs
2638	Le	Leirbreen	1979-	Proglacial lake
2643	Bø	Bøverbrean	1997-	
2680	Sy	Styggedalsbreen	1901-	Proglacial lake
2717	Mj	Mjølkedalsbreen	1978-	
2768	He	Hellstugubreen	1901-	
2964	Mi	Midtdalsbreen	1982-	
2968	R	Rembesdalskåka	1917-	GLOFs
3117	Bo	Botnabrea	1996-	
3131	Bu	Buerbreen	1900-	
3133	B	Bondhusbrea	1902-	
3141	Bl	Blomstølskardsbreen	1994-	Proglacial lake

4.3 Station characteristics

4.3.1 Mass balance

The selected glaciers include both small valley glaciers and small to large outlet glaciers from ice caps (e.g. Engabreen, Fig. 6). The most typical glacier types in Norway are thus well presented in the sample, except for cirque glaciers. The glaciers range in size from 1,7 km^2 (Gråsubreen) to 44.9 km^2 (Nigardsbreen) (Kjøllmoen et al., 2021). The nine selected glaciers cover in total an area of 116 km^2, which represents 4% of the present total glacier area in Norway of 2692 km^2 (Andreassen et al., 2012b). The mass-balance reference glaciers are biased towards southern Norway where seven out of nine are located, whereas only two are located in northern Norway.

Figure 6. Engabreen, an outlet of Vestre Svartisen in Nordland county. Annual length-change measurements began in 1903 and mass-balance measurements in 1970.
Photo: Hallgeir Elvehøy, 11 July 2021.

4.3.2 Length change

The selected glacier records include both small valley glaciers and small to large outlet glaciers from ice caps. The glaciers range in size from 1.0 (Trollkyrkjebreen, Fig. 7) to 44.9 km^2 (Nigardsbreen). In total, the 26 selected glaciers cover in total an area of 291 km^2, which represents about 11% of the present total glacier area 2692 km^2 (Andreassen et al., 2012b). Length-change glaciers are biased towards southern Norway, only seven of 26 glaciers are located in northern Norway.

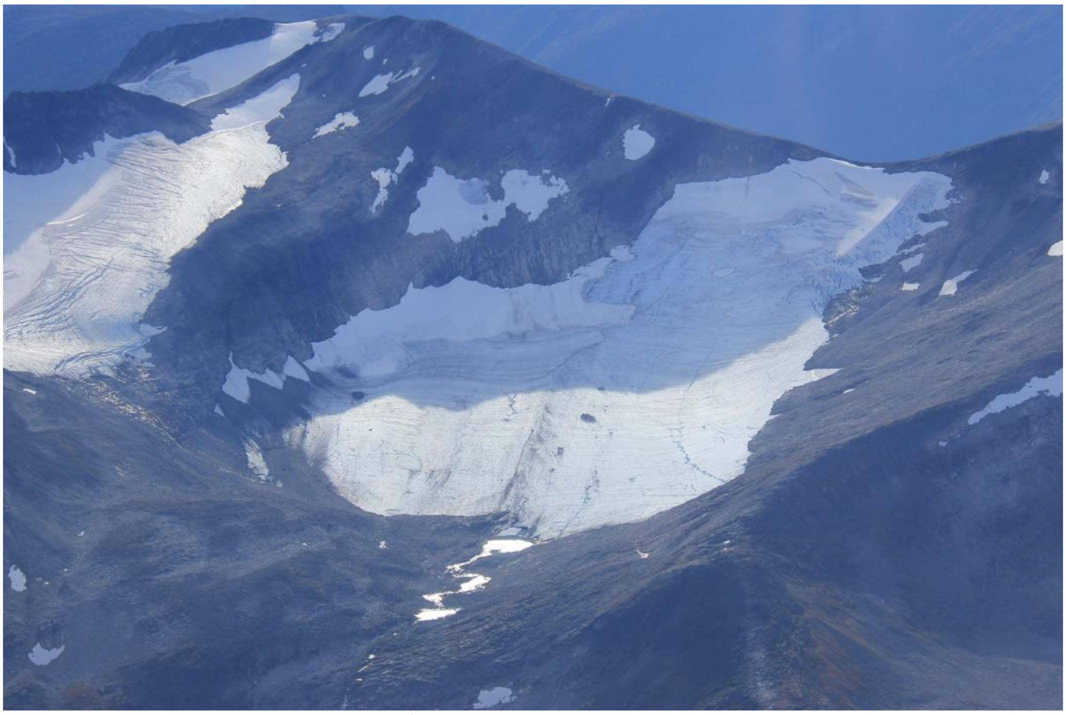

Figure 7. Trollkyrkjebreen, a small (1 km^2) glacier in Møre and Romsdal county. Annual length-change measurements began in 1944. Photo: Hallgeir Elvehøy, 20 September 2016.

5 Conclusions

Glaciers are sensitive climate indicators. In this report we have revisited and updated NVE's hydrological reference dataset for glacier mass balance and length change. We present a selection of nine mass-balance glaciers and 26 length-change glaciers. The mass-balance reference glaciers are the same as the previous dataset (Fleig et al., 2013), while the length-change reference glaciers have been extended from 11 to 26 glaciers. The selected reference glaciers span from small to large glacier sizes. The reference glaciers are biased towards southern Norway, where seven of nine mass-balance glaciers and 19 of 26 length-change glaciers are located.

All the mass-balance series and some of the length-change glaciers have been reanalysed and homogenized, and partly calibrated, in recent years based on updated surface elevation surveys and outlines from orthophotos.

When new datasets of glacier surface elevations and glacier outlines or new methodology will be available, the mass-balance and length-change reference glacier datasets can be reanalysed and homogenised.

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