Hydrology and Earth System Sciences

Open Access

Contribution of snow and glacier melt to discharge for highly glacierised catchments in Norway

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Abstract. Glacierised catchments show a discharge regime that is strongly influenced by snow and glacier meltwaters. In this study, we modelled the mass balance and discharge rates for three highly glacierised catchments ($> 50\%$ glacier cover) in western Norway over the period 1961–2012. The spatial pattern of the catchments follows a gradient in climate continentality from west to east. The model input were gridded temperature and precipitation values from *seNorge* (http://senorge.no) which are available at daily resolution. The model accounted for accumulation of snow, transformation of snow to firn and ice, evaporation and melt. Calibration and validation were performed for each catchment based on measurements of seasonal glacier mass balances and daily discharge rates, as additional validation data served daily melt rates from sonic rangers located in the ablation zones of two of the glaciers. The discharge sources snowmelt, glacier melt and rain were analysed with respect to spatial variations and temporal evolution. Model simulations reveal an increase in the relative contribution from glacier melt to total discharge for the three catchments from less than 10% in the early 1990s to 15–30% in the late 2000s. The decline in precipitation by 10–20% in the same period was therefore overcompensated, resulting in an increase in annual discharge by 5–20%. Annual discharge sums and annual glacier melt are most strongly correlated with annual and winter precipitation at the most maritime glacier and, with increased climate continentality, variations in both glacier melt contribution and annual discharge are becoming more strongly correlated with variations in summer temperatures. Therefore, glaciers in more continental climates are especially vulnerable to decrease in both annual and summer discharge with contin-
ued rise in summer temperatures and subsequent decrease in glacier extent. This may lead to significant changes to the discharge regime, with increase during spring but decline later in the year, especially for catchments in less maritime climate conditions.

1 Introduction

In highly glacierised catchments, meltwater constitutes a larger contribution to annual discharge than rain (Jost et al., 2012). Summer streamflow can be amplified or balanced by the presence of glaciers within the catchment (Dahlke et al., 2012), depending on the degree of glacier coverage and the interannual precipitation distribution. One sixth of the world's population is dependent on water originating from snow or glacier melt (Hock et al., 2006). In Norway, 98% of the electricity is generated by hydropower (Gebremedhin and De Oliveira Granheim, 2012) and catchments regulated for hydropower include 60% of the total glacier area (Andreassen et al., 2012). Thus, assessment of meltwater runoff is crucial for both water supply and hydropower applications. Changes in discharge are connected to variations in either air temperature or precipitation or a combination of both. Although future climatic and hydrological projections are subject to large uncertainties, ongoing climate change will result in major changes in both, timing and magnitude of the runoff regime. Glacier retreat and the release of freshwater are expected to be a key element in projections of discharge from glacierised catchments over the next decades (e.g. Huss et al., 2010; Finger et al., 2012).
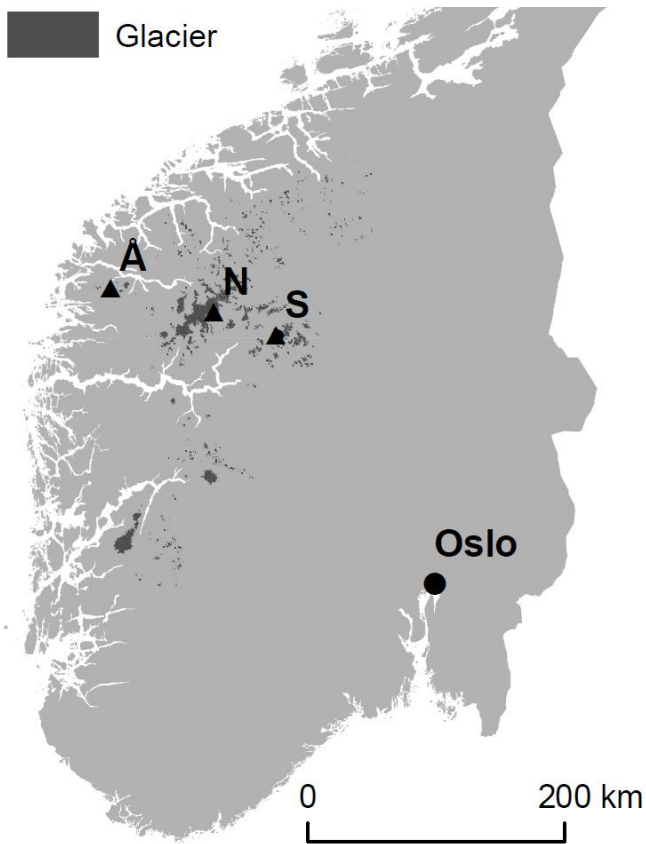
Fig. 1. Location of the study sites Ålfotbreen (Å), Nigardsbreen (N) and Storbreen (S) within the glacierised areas in southern Norway.

The future contribution of glaciers to discharge in a changing climate is therefore subject to research in many regions of the world (e.g. Farinotti et al., 2012; Immerzeel et al., 2012; Schaner et al., 2012). Using climate model data as forcing, different studies indicate an increase in discharge in spring due to earlier onset of snowmelt, but a decline later in the year due to reduced glacier extent (e.g. Stahl et al., 2008; Huss et al., 2008). Glacial meltwater can also have relevant impacts on the hydrological regime of larger watersheds further downstream. The study of Huss (2011) revealed that for catchments with a size of $100\,000\,\mathrm{km}^2$ and 1 % glacier cover in August the contribution of glaciers to discharge can be as high as 25 %.

Modelling melt from glaciers requires a melt model. Those models exist in a large range of different complexities (Hock et al., 2005). Since meteorological data needed for energy balance models are sparse for mountainous regions, temperature-index models have widely been used (e.g. Konz and Seibert, 2010; Jost et al., 2012; Engelhardt et al., 2013) which in the simplest form only employ air temperature and precipitation as meteorological input for snow accumulation and computing melt (see Hock, 2003, for a review). The use of a temperature-index model has been justified since surface

air temperature is the most influential parameter for determining melt. Furthermore, the heat sources shortwave radiation and sensible heat flux, which are especially important for glaciers at high latitudes (Sicart et al., 2008), are closely correlated with air temperature (Ohmura, 2001).

Uncertainties in quantifying precipitation at high altitudes due to the lack of measurements represent one of the biggest problems for modelling discharge (Verbunt et al., 2003). Satellite-derived precipitation data sets can be used as a data source for modelling discharge at larger scales in regions without ground-based measurement (Li et al., 2013). Hydrological models for glacierised catchments have often been applied as grid-based models (e.g. Hock and Noetzli, 1997; Klok et al., 2001). Model performance for discharge modelling improves significantly when seasonal mass balances are used as additional calibration criteria (e.g. Finger et al., 2011; Mayr et al., 2013).

This study aims to model the contributions to discharge for three highly glacierised catchments in southern Norway along a west–east profile. For calibration we used daily discharge data and seasonal mass balance data based on interpolated point measurements (Kjøllmoen et al., 2011). The calculations were performed on a daily resolution for the period 1957–2012, including a four-year spin-up period. The model structure follows an approach suggested by Hock (2005): (1) modelling seasonal glacier mass balances and daily runoff, and (2) discharge routing of rain and meltwater taking into account the different hydraulic properties of snow, firn and ice with respect to their flow rate velocities. For parameter calibration, $10\,000$ Monte Carlo runs were performed. We used two objective functions, the coefficient of variation for seasonal mass balances (until 2000) and the Nash–Sutcliffe coefficient for daily discharge (until 2010 for two of the catchments and 2011 for the third catchment). The parameter sets for melt and snow accumulation were validated for all catchments using seasonal mass balances for 2001–2012 and daily discharge for 2011–2012 for two of the catchments and 2012 for the third catchment. An additional validation was performed using point measurements in the ablation zones of two of the glaciers. The discharge was divided into the water sources snowmelt, glacier melt and rain. We evaluated differences in the runoff regimes between the three catchments as well as changes over time. Furthermore, we investigated correlations between discharge and the meteorological input.

2 Study sites and input data

The study was carried out for three catchments in southern Norway containing the glaciers Ålfotbreen, Nigardsbreen and Storbreen (Fig. 1) where both seasonal mass-balance and discharge measurements are available. The glacier coverage in each catchment is > 50 % (Table 1) and at each glacier, seasonal mass balance measurements have been carried out

Table 1. Overview of the three study catchments.

	Ålfotbreen	Nigardsbreen	Storbreen
Catchment size (km^2)	8.3	66	8.0
Glacier coverage (%)	51	72	65
Latitude (°N)	61.8	61.7	61.6
Longitude (°E)	5.6	7.1	8.1
Mean catchment elevation (m a.s.l.)	927	1401	1597
Start of mass-balance measurements	1963	1962	1949
Start of discharge measurements	1994	1962	2010

for more than 50 yr (Andreassen et al., 2005) following the traditional stratigraphic method (Østrem and Brugman, 1991). The catchments of Ålfotbreen and Storbreen are similar in size, covering about 8 km^2, whereas the catchment of Nigardsbreen is about eight times as large. At all sites, discharge data are available at daily resolution, with the longest series available for Nigardsbreen (50 yr) and the shortest at Storbreen where measurements started in September 2010.

The catchments are located at similar latitudes and therefore reflect a west–east profile from Ålfotbreen close to the Norwegian west coast to Storbreen, which is located east of the main mountain divide. The climate can be characterised as very maritime at Ålfotbreen to moderate continental at Storbreen. The variations in mean annual air temperature during the model period (1961–2012) are smallest for Ålfotbreen and largest for Storbreen (Fig. 2a). The summer temperatures (here: May–September) show a similar progression for all catchments (Fig. 2c), with increasing values from 1961 to 1970 and from 1995 to 2005 and constant to slightly decreasing values from 1970 to 1995 and from 2005 to 2012. The difference in summer temperature between the sites mainly reflects the mean catchment elevation which increases from west (Ålfotbreen) towards east (Storbreen). From the early 1990s to the 2000s all three sites experienced an increase in mean summer temperature of about 1–1.5 K.

Precipitation decreases considerably from west to east. The mean annual precipitation sum ranges from more than 5000 mm for Ålfotbreen to less than 2000 mm for Storbreen (Fig. 2b). In contrast to temperature, the annual precipitation sums show least variations at Storbreen where they remained almost constant between the 1960s and 1990s. Afterwards annual precipitation decreased slightly by about 10 % in the 2000s. Both Ålfotbreen and Nigardsbreen show similar variations in precipitation; however, they are more pronounced at Ålfotbreen: an increase in annual precipitation of 50 % (20 %) from the 1960s to the end of the 1980s at Ålfotbreen (Nigardsbreen) is followed by a decline of 20 % (10 %) towards the end of the 2000s (Fig. 2b). Winter precipitation (here: October–April), which predominantly falls as snow, follows a similar pattern for all catchments compared to the annual precipitation. On average, winter precipitation yields about two thirds of the annual sums (Fig. 2d).
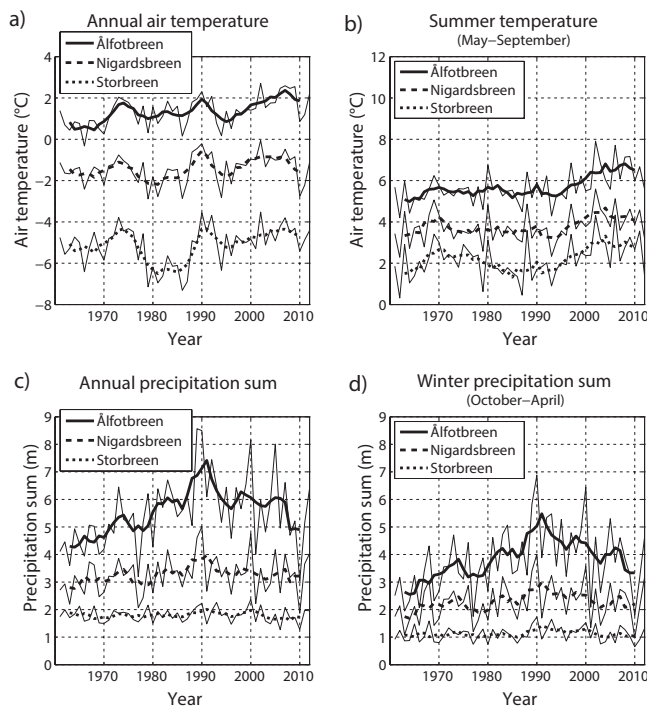
Fig. 2. Air temperature and precipitation data with 5 yr moving averages for the three catchments based on *seNorge* data.

For the study we used the gridded temperature and precipitation from *seNorge* (www.senorge.no). The data are based on station measurements which are interpolated on a 1 km horizontal grid for all of mainland Norway on a daily basis from 1957 to the present (Mohr, 2008). Despite some weaknesses with the inter- and extrapolation of precipitation in mountainous regions, different evaluation studies (Mohr, 2009; Dyrrdal, 2010; Engelhardt et al., 2012; Saloranta, 2012) found the gridded data of *seNorge* to be suitable for mass-balance modelling especially due to its high spatial resolution.

3 Methods

3.1 Precipitation correction

To account for uncertainties in the precipitation data from *seNorge* associated especially with the vertical adjustment, we applied a constant precipitation correction factor for each catchment to fulfil the (accumulated) water balance over the hydrological years (1 October–30 September) of available discharge data.

Neglecting in- or outflow of groundwater, the water balance equation reads (all terms in m a^{-1}):

$$P = Q + V + \Delta S, \tag{1}$$

where P denotes precipitation, Q discharge and V evaporation. ΔS is a storage term accounting for all water that remains in or additionally leaves the domain.

Snow- or glacier melt within the domain is therefore a negative contribution to the storage term. Considering highly glacierised catchments, we assumed the storage term to be the accumulated glacier mass balance over the period of measurements. Outside the glacierised areas, no storage was assumed. For evaporation we used the gridded data provided from *seNorge* which were only calculated for the non-glacierised areas and set to zero for the glacierised areas (Sælthun, 1996). This is justified since evaporation and condensation on glaciers may balance each other and their net effect is not likely to influence discharge in a significant way (e.g. Braun et al., 1994). Since the gridded precipitation data from *seNorge* for the glacier parts of all catchments (P_g) had already been evaluated in the study by Engelhardt et al. (2012), we now used the calculated precipitation correction factors (F_g) from that study for the glacierised areas and calculated the correction factors for the precipitation (P_{ng}) of the non-glacierised parts (F_{ng}) of the catchments. The water balance equation for the glacierised and non-glacierised areas was then modified to

$$Q = \underbrace{\frac{P_g}{F_g} - \Delta S}_{\text{glacier area}} + \underbrace{\frac{P_{ng}}{F_{ng}} - V}_{\text{non-glacier area}}. \tag{2}$$

Using the measurements of accumulated mass balance (e.g. Kjøllmoen et al., 2011) and discharge, the water balance was calculated over the period of available discharge data, which is 50 (hydrological) years for Nigardsbreen, 18 yr for Ålfotbreen and two years for Storbreen. The correction factors F_{ng} of the *seNorge* precipitation were calculated as an average over the respective periods (Table 2).

With the gained correction factors, the precipitation input for the model (P_{input}) is dependent on the grid point location (representing glacierised or non-glacierised areas) and was calculated to

$$P_{\text{input}} = \frac{P_{\text{seNorge}}}{F_{\text{n/ng}}}. \tag{3}$$

3.2 Model set-up

The study was performed with a conceptual model based on a temperature index approach including potential solar radiation. The glacier mass balances and meltwater runoff were calculated using air temperature and the corrected precipitation from *seNorge* (Sect. 3.1) as input. The model runs independently for each grid cell at a daily resolution. Despite the 1 km grid resolution, the model accounts for smaller areas along the glacier and catchment margins by weighting each grid cell with its contribution to the catchment and glacier ratio. The calculations covered the hydrological years 1961–2012 (1 October 1960–30 September 2012) and a preceding spin-up period (1957–1960) to accumulate snow and firn. The model accounts for mass gain due to accumulation of snow and mass loss due to evaporation and melting of snow and ice. The transition from snow to rain occurs within an interval of 2 K where the precipitation linearly shifts from snow to rain. The centre of this interval is denoted as the threshold temperature for snow (T_s).

To account for the transition of snow to firn and ice, snow that has not melted away during summer was defined as becoming firn at the beginning of each hydrological year (1 October). Additionally, 25 % of the existing firn was assumed to become ice, leading to an average transition time from firn to ice of 4 yr, which is in accordance with a simple time function introduced by Martinec (1977). The conceptual model calculates daily melt of snow, firn or ice $M_{\text{snow/ice}}$ by using a distributed temperature-index approach including potential solar radiation as used e.g. in Hock (1999) or Engelhardt et al. (2013). Melt is calculated if the *seNorge* temperature $T_{\text{sn}} > T_m$ (threshold temperature for melt):

$$M_{\text{snow/firn/ice}} = (\Theta + R_{\text{snow/firn/ice}} \cdot I) \cdot (T_{\text{sn}} - T_m), \tag{4}$$

with the melt factor Θ, the respective radiation coefficients for snow, firn and ice $R_{\text{snow/firn/ice}}$ and the potential direct solar radiation I. The potential solar radiation is dependent on latitude and day of year, and its usage effectuates a sinusoidal variation in the melt factor in the course of a year. Modifications due to exposition or shading effects of surrounding slopes were not accounted for as the model grid resolution would not appropriately resolve these phenomena. However, using potential radiation can significantly increase model performance (Huss et al., 2009). Since the melt efficiency of firn is higher than for snow but lower than for ice, the radiation factors for firn (R_{firn}) were assumed to be the mean of the ones for snow (R_{snow}) and ice (R_{ice}). At each grid point, firn starts to melt when the snow has melted and ice starts to melt once the firn has melted away.

The model calculates the reference surface mass balance (Elsberg et al., 2001). The area on which the calculations are based is the same area for which the available glacier mass-balance measurements have been performed (e.g. Kjøllmoen et al., 2011). This glacier area was e.g. 47.8 km^2 from 1984–2008 for Nigardsbreen and was updated to 47.2 km^2 in 2009.

Table 2. Water balance components (in m a^{-1}) and precipitation correction factors (F) for the glacierised (g) and non-glacierised (ng) parts of the three catchments. All water balance components are specific quantities for the respective catchment area (Table 1).

	Ålfotbreen	Nigardsbreen	Storbreen
Period (hydrological years)	1995–2012	1963–2012	2011–2012
Precipitation (g)	3.37	2.67	1.06
Precipitation (ng)	2.43	0.62	0.64
Discharge	5.66	3.01	2.60
Evaporation	0.06	0.05	0.02
Accumulated mass balance	−0.24	0.25	−0.65
F_g (from Engelhardt et al., 2012)	1.01	1.00	0.80
F_{ng}	1.13	0.99	1.00

All changes in glacier area during the model period are not larger than 6 % of the respective glacier area. To account even for such small area changes in the model, the glacier melt contribution of the grid point representing the lowest glacier altitude is changed by adjusting the glacier ratio of this grid point.

Besides melting, the model also accounts for a delay in runoff by using a linear reservoir for daily discharge for each catchment. The water from melt and rain is distributed over time using three storage constants for the linear reservoirs depending on the surface property snow, firn or ice.

At a daily time step (t) the reservoirs (W) for each grid point (i) were updated based on the previous values $W_i(t-1)$ and the calculated meltwater and rain for this location:

$$W_i(t) = W_i(t-1) + M_i(t) + R_i(t), \tag{5}$$

where M denotes the calculated melt rates and R the rain (precipitation at $T > T_s$).

The discharge for each grid q_i was calculated individually using a storage constant ($c_{\text{snow/firn/ice}}$) dependent on the surface property of this grid point:

$$q_i(t) = c_{\text{snow/firn/ice}} \cdot W_i(t). \tag{6}$$

The daily model resolution allowed the usage of a constant rather than a time-varying storage coefficient as used e.g. in Stahl et al. (2008). No water storage was applied for grid cells which are not covered by snow, firn or ice, since a fast runoff is assumed for these areas located in mountainous terrain and close to the discharge station. Thus, rain was treated like meltwater when falling on snow, firn, or ice, but was counted as discharge for the same day falling on areas free of snow or ice.

After the daily discharge rate was calculated, the water reservoir was updated and the daily simulated discharge for the whole catchment (Q_m) was calculated as the sum from all grid points:

$$W_i(t) = W_i(t) - q_i(t) \tag{7}$$

$$Q_m(t) = \sum_i q_i(t) \tag{8}$$

3.3 Calibration of model parameters and validation of model performance

For the calibration scheme we used for each catchment a Monte Carlo run of 10 000 random parameter sets consisting of eight parameters given in Table 3. For each parameter set, two optimization criteria were calculated: (1) the coefficient of variation (c_v) between measured (meas) and modelled (mod) glacier-wide seasonal mass balances (b) for the period 1961–2000, and (2) the Nash–Sutcliffe coefficient (E) for daily discharge for the period 1995–2010 at Ålfotbreen, 1963–2010 at Nigardsbreen, and for the year 2011 at Storbreen:

$$c_v = \frac{\sigma}{|b_{\text{meas}}|} \quad \text{with} \tag{9}$$

$$\sigma = \sqrt{\frac{(b_{\text{mod}} - b_{\text{meas}})^2}{n}} \quad \text{and} \tag{10}$$

$$E = 1 - \frac{\sum (Q_0 - Q_m)^2}{\sum (Q_0 - \overline{Q_0})^2}, \tag{11}$$

where n denotes the number of measured b and Q_0 measured daily discharge sums.

Following an approach by Konz and Seibert (2010), the combination of the two optimization criteria was performed by ranking the parameter sets separately according to their mass balance and runoff qualities. The ranks were summed and the 100 parameter sets with the lowest rank sums were selected. The ensemble average of the selected parameter values is given in Table 3.

For each catchment, the model was run for each of the 100 best parameter sets over the period of available *seNorge* data (1957–2012). The model runs were validated for all catchments with the seasonal mass balances for 2001–2012 and with daily discharge for 2011–2012 for Ålfotbreen and Nigardsbreen and 2012 for Storbreen.

As additional validation of the model performance, we used weekly melt rates measured with sonic rangers in the ablation zones of Storbreen (Andreassen et al., 2008) and

Table 3. Median of the 100 best parameter sets and model performance (coefficients of variation for seasonal mass balances and the Nash–Sutcliffe coefficient for daily discharge sums) of the 100 best ensemble runs for the calibration periods.

| Parameter	Description	Ålfotbreen	Nigardsbreen	Storbreen	Unit
T_0	melt threshold factor	0.2	−0.2	−0.3	°C
T_s	snow threshold factor	2.5	1.3	1.4	°C
R_{snow}	radiation coefficient for snow	4.3	3.8	3.6	mm K^{-1} d^{-1} kW^{-1} m^2
R_{ice}	radiation coefficient for ice	7.1	7.0	5.6	mm K^{-1} d^{-1} kW^{-1} m^2
Θ	melt factor	3.9	2.9	2.6	mm K^{-1} d^{-1}
c_{snow}	storage constant for snow	0.28	0.19	0.54	d^{-1}
c_{firn}	storage constant for firn	0.40	0.66	0.68	d^{-1}
c_{ice}	storage constant for ice	0.64	0.72	0.83	d^{-1}
c_v	coefficient of variation	0.18–0.20	0.16–0.17	0.15–0.16	–
E	Nash–Sutcliffe coefficient	0.76–0.78	0.85–0.88	0.88–0.91	–

Nigardsbreen. Data were available for 84 weeks with melt during the period 2002–2012 for Storbreen and for 43 weeks from the 2011 and 2012 melt seasons for Nigardsbreen. Weeks with data gaps or snow fall events were excluded. The melt rates at these two point locations were calculated by using the ensemble mean of the calibrated parameter set. The temperature and precipitation input for the sonic ranger locations were retrieved by interpolating the daily *seNorge* temperature and precipitation data to the horizontal sonic ranger positions and adjusting the data to the altitude, using the vertical gradients from the *seNorge* routines.

4   Results

The model performance for seasonal mass balance and daily discharge expressed by the coefficient of variation and the Nash–Sutcliffe coefficient was increasing from Ålfotbreen, the most maritime study site, towards Storbreen (Table 3). While there was little difference in modelling seasonal mass balances with coefficient of variation values between 0.15 and 0.20, daily discharge was modelled better for both Nigardsbreen and Storbreen, with a Nash–Sutcliffe coefficient E between 0.85 and 0.91 than at Ålfotbreen ($E = 0.76$–0.78).

The parameter uncertainty of the different individual model parameters in the 100 best model runs is given in Fig. 3. There was little difference in the uncertainty of the melt threshold temperature between the catchments. The snow threshold temperature showed largest uncertainty at Ålfotbreen, where this parameter showed the largest median value of 2.5 °C. For the melt parameters, the uncertainty in the two radiation coefficients was larger than for the melt factor. The storage coefficients increased from snow to ice, yielding faster runoff for meltwater from ice melt than from snowmelt.

The seasonal mass balances for the validation period 2001–2012 were better modelled for the Nigardsbreen and Storbreen glaciers, where absolute values of mass balances
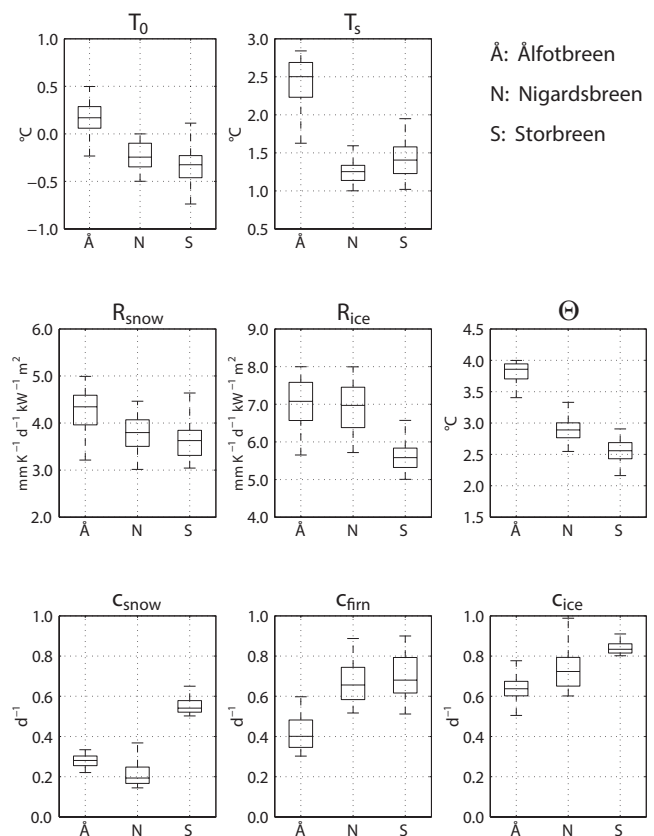
Fig. 3. Parameter uncertainty of the 100 best runs. In each box, the central mark is the median, the edges of the box are the 25th and 75th percentiles, and the whiskers extend to the most extreme data points. The ordinates indicate the parameter range in the calibration scheme. Parameter description and median values are given in Table 3.
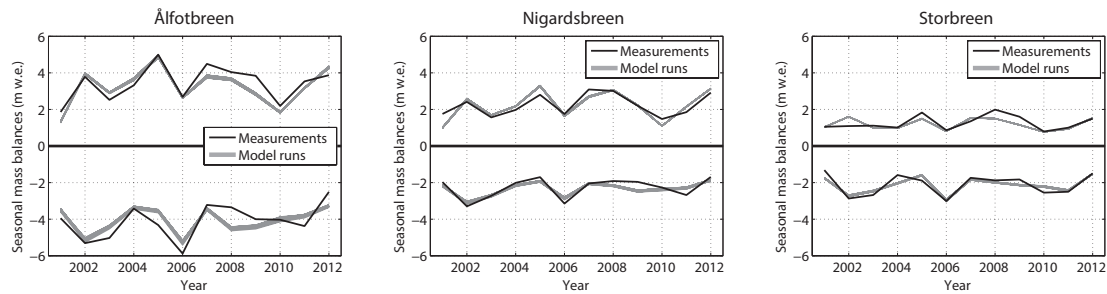
Fig. 4. Model performance for seasonal glacier mass balances for the three catchments for the validation period 2001–2012.
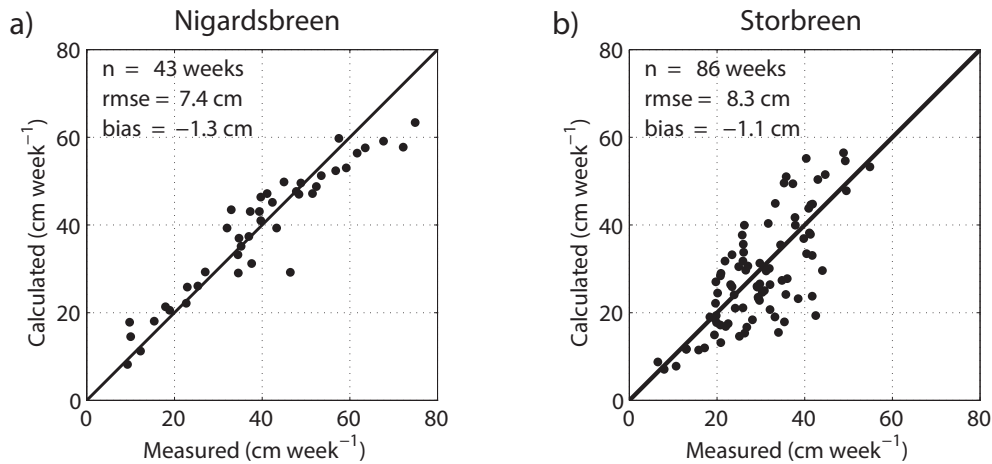
Fig. 5. Model performance for weekly melt at the sonic ranger position of Nigardsbreen (2011–2012) and Storbreen (2002–2012). Data for the modellings represent the mean of the 100 best model runs.

were smaller and year-to-year variations lower than at Ålfotbreen (Fig. 4).

The validation of the model parameter for calculating weekly melt at the sonic ranger positions showed a larger spread at Storbreen than at Nigardsbreen (Fig. 5). However, for Nigardsbreen the model had a tendency to underestimate high discharge values. At both locations the bias between modelled and measured melt rates was low, which means that the accumulated melt was modelled close to the measurements.

Daily discharge was simulated well at all catchments (Fig. 6). Although daily peak flows can be as high as $70 \, \mathrm{mm \, d^{-1}}$ at all catchments, variations in daily discharge were largest at Ålfotbreen and smallest at Nigardsbreen. Nigardsbreen and Storbreen showed a similar discharge pattern in the course of the year.

The annual sums of the modelled specific discharge over the period 1961–2012 revealed an overall increase for all three evaluated catchments for this period of about 20 % (Fig. 7), but also periods of declining discharge. At Ålfotbreen the discharge increased by about 40 % between the 1960s and the late 1980s followed by large variability within the following two decades, with annual discharge sums rang-

ing from 4 to $8 \, \mathrm{m \, a^{-1}}$. At Nigardsbreen and Storbreen, the annual discharge showed much smaller changes within the model period. Nevertheless, the 2000s were the decade when discharge was highest for these two catchments and about 20 % above average. The measured annual discharge sums corresponded quite well to the model simulations. However, the available data series for Storbreen were quite short, with only 2 yr of measurements.

Larger variations than for the discharge sums were visible in the proportion of the contributing discharge sources (Fig. 8). For all catchments the largest contribution denoted from snowmelt, which accounted for roughly 60 % of the annual discharge. Until the 1990s, Storbreen showed the highest relative contribution from snowmelt among the study sites, with values up to 70 % in the 5 yr moving averages in the 1960s and early 1990s. Most remarkable was the decrease from the 1990s to the 2000s, when the snowmelt contribution to discharge decreased at all sites from 65–70 % to 50–60 %. This decrease was larger for the small Ålfotbreen and Storbreen glaciers, whereas at Nigardsbreen the contribution of snowmelt to discharge during the model period was the most constant of all the catchments. Among our study sites, the relative contribution from glacier melt became larger with
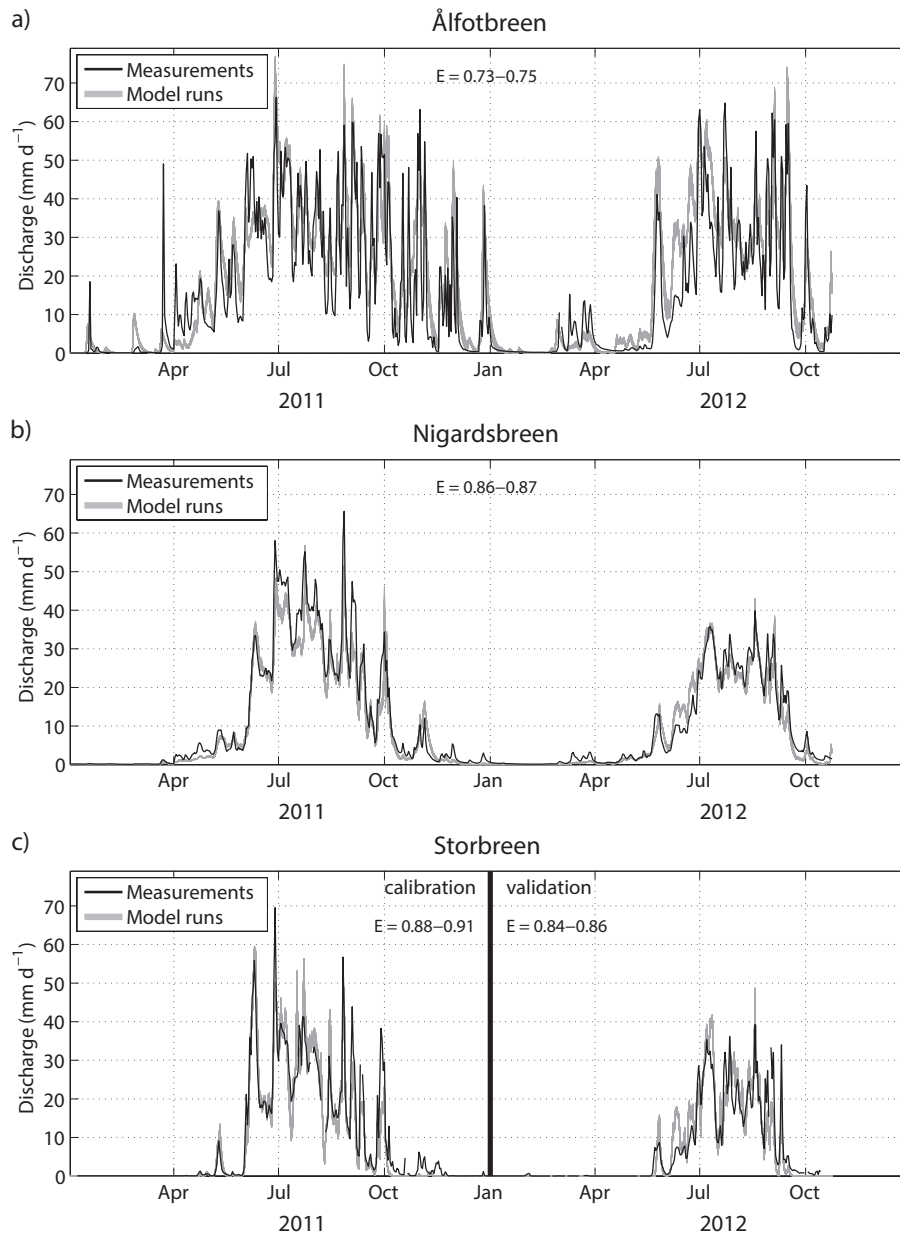
Fig. 6. Model performance for daily discharge sums at the three catchments for the validation years 2011 and 2012. Note: at Storbreen, daily discharge for 2011 is used for calibration, and 2012 for validation.

increasing climate continentality from west (Ålfotbreen) to east (Storbreen). A decrease from the 1970s to a minimum in the early 1990s, when at all sites less than 10 % of the annual discharge originated in glacier melt, was followed by an increase in the 2000s, surpassing the high values from the 1960s and 1970s. At Storbreen the relative contribution from glacier melt accounted for more than 25 % of the annual discharge in the first decade of the 21st century.

The remaining water source for discharge is rain. Its relative contribution was highest for Ålfotbreen ($\sim$ 37 %), moderate for Nigardsbreen ($\sim$ 27 %) and lowest for Storbreen

($\sim$ 19 %). While changes over time were smallest at Storbreen, for Ålfotbreen and to a lesser extent also for Nigardsbreen the relative component of rain to discharge had a maximum in the 1980s and a minimum in the 1960s and 1990s.

The uncertainty of the contributing discharge sources among the 100 best ranked parameter sets was highest for snowmelt, spreading in a band of 5 %, and lowest for glacier melt. For all discharge sources, the uncertainty was slightly higher for Ålfotbreen than for the other catchments.

The evaluation of the monthly discharge for the periods 1991–2000 and 2001–2010 revealed that for all three
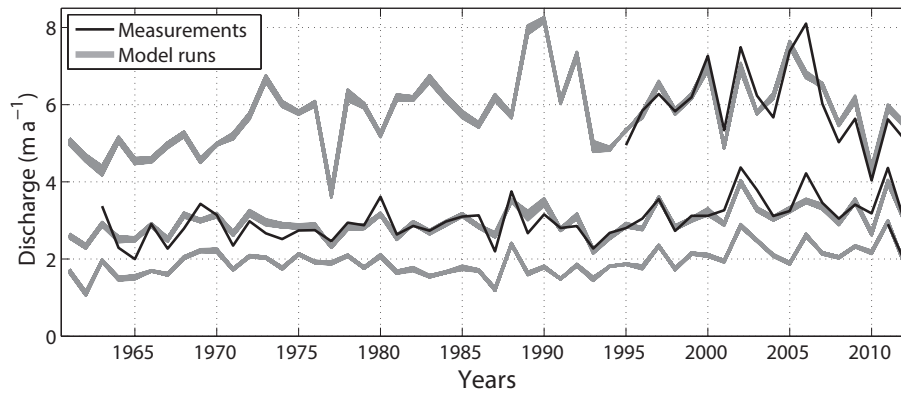
Fig. 7. Mean annual discharge sums for the catchments of Ålfotbreen (upper lines), Nigardsbreen (centre lines) and Storbreen (lower lines) for the period 1961–2012.
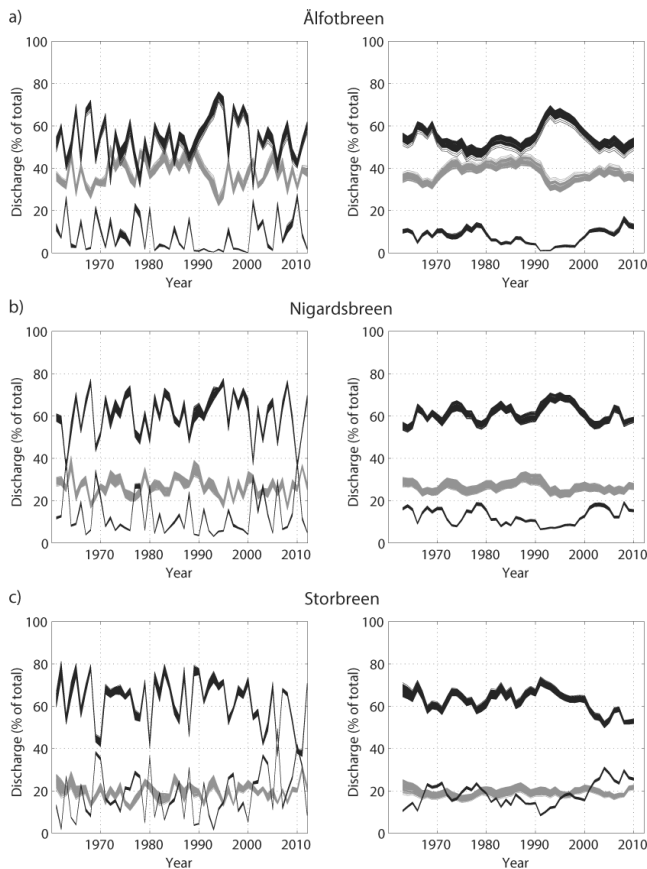

Fig. 8. Relative proportions of the contributing sources to the annual discharge (left column), and the respective 5 yr moving average (right column). Snowmelt is represented by the upper black lines, glacier melt by the lower black lines and rain by the grey lines.

catchments the majority of discharge occurred in the three months of June, July and August (Figs. 9, 10), accounting for about 60 % of the annual discharge for Ålfotbreen, 75 % for Nigardsbreen and 85 % for Storbreen. At all sites, the maximum of both, snowmelt and total discharge, is in July. However, from the 1990s to the 2000s snowmelt increased in May and June and decreased from July to September. While in the 2000s in June, about 80 % of the discharge derived from snowmelt for all three catchments, this proportion decreased within two months in August to less than half of the discharge for Nigardsbreen and to a third for Ålfotbreen and Storbreen. The maximum of glacier melt occurred at all catchments in August. In the 2000s glacier melt accounted for about a third of the discharge in August at Ålfotbreen and Nigardsbreen, and more than 50 % at Storbreen.

The most obvious difference between the two decades 1991–2000 and 2000–2010 is the increase in glacier melt at all sites. Due to increased snowmelt in May and June and increased glacier melt in August and September, the total discharge increased in almost all months from May through to October.

Correlation between meteorological input and annual discharge revealed a very high correlation of annual discharge with annual precipitation at Ålfotbreen (Table 4). The correlation was almost as high with winter precipitation (October–April). However, at Nigardsbreen and Storbreen, annual discharge was highest correlated with summer temperatures (May–September). While at Storbreen summer temperatures were also most strongly correlated with annual glacier melt (Table 5), both Nigardsbreen and Ålfotbreen show that glacier melt was strongly negatively correlated with the annual precipitation sum.
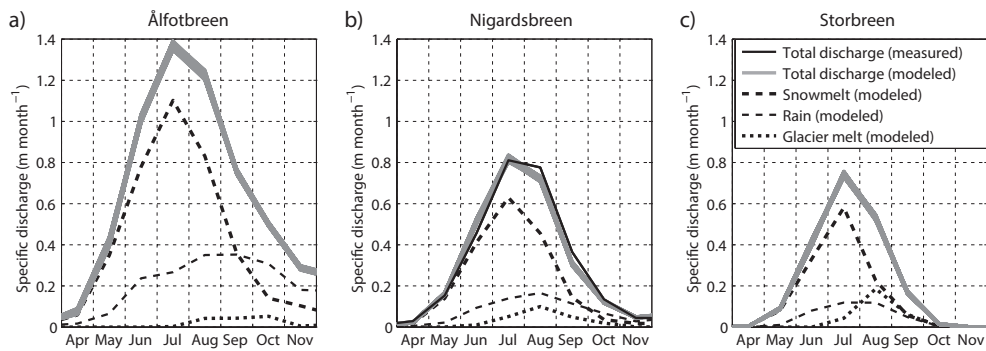
Fig. 9. Modelled monthly discharge rates and their contributing sources for Ålfotbreen, Nigardsbreen and Storbreen averaged for the period 1991–2000. Data for the contributing sources represent the mean of the 100 best model runs.
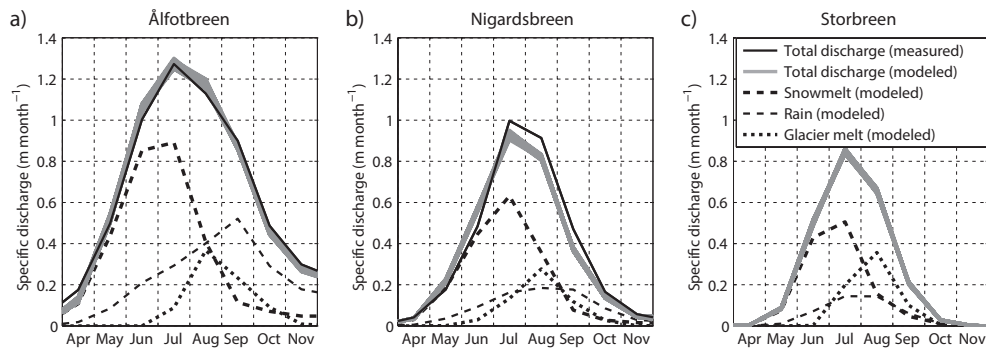
Fig. 10. Modelled monthly discharge rates and their contributing sources for Ålfotbreen, Nigardsbreen and Storbreen averaged for the period 2001–2010. Data for the contributing sources represent the mean of the 100 best model runs.

Table 4. Correlation coefficient of annual discharge sums (October–September) for the model period 2001–2010.

	Ålfotbreen	Nigardsbreen	Storbreen
Mean annual air temperature (October–September)	0.66	0.57	0.48
Mean summer temperature (May–September)	0.21	0.78	0.93
Annual precipitation sum (October–September)	0.87	0.17	0.05
Winter precipitation sum (October–April)	0.85	0.20	0.01

Table 5. Correlation coefficient of annual glacier melt for the model period 2001–2010.

	Ålfotbreen	Nigardsbreen	Storbreen
Mean annual air temperature (October–September)	−0.15	−0.51	−0.06
Mean summer temperature (May–September)	0.32	0.30	0.75
Annual precipitation sum (October–September)	−0.76	−0.88	−0.66
Winter precipitation sum (October–April)	−0.67	−0.85	−0.66

5 Discussion

The modelled increase in annual discharge at Ålfotbreen from the 1960s to 1980s corresponds to an increase in precipitation during this period. Although mean summer temperatures at this site remained unchanged until the 1990s, the relative contribution from glacier melt decreased. The increasing precipitation led to both, increased discharge and to a mass gain, since more of the winter snow did not melt away. Measurements show an average annual mass balance on Ålfotbreen of $+0.5\,\mathrm{m\,a^{-1}}$ from 1965 to 1995 (Kjøllmoen et al., 2011). The largest variations in annual discharge at Ålfotbreen can be attributed to larger variations in precipitation and to the higher mass-balance sensitivity of maritime glaciers to precipitation changes, which was also found in previous studies (e.g. Xu et al., 2012). On Nigardsbreen and Storbreen the increase in precipitation from the 1960s to 1990s was much smaller. In addition, the coinciding decrease in glacier melt led to almost unchanged mean discharge for these two catchments until the 1990s. In general, an increase in winter precipitation leads to increased snowfall, positive mass balances and reduced glacier melt during summer. At Nigardsbreen, increased winter precipitation was the reason for positive mass balances and the advance of the

glacier tongue in the 1990s (Winkler et al., 2009). While the annual precipitation slightly decreased at Nigardsbreen and Storbreen in the 2000s, the increase in discharge in the same period can be attributed to the increased summer temperature of 1–1.5 K. At all three sites, increasing temperatures after the mid 1990s and decreasing precipitation resulted in reduced snow depths and increased glacier melt.

Among the three study sites, annual discharge at Ålfotbreen is most sensitive to changes in precipitation (Table 4). The contribution of snow from areas outside the glacier at Ålfotbreen together with the large contribution from rain are the dominant factors in annual discharge at this site. At Nigardsbreen, where the glacier-free area is < 30 % and where precipitation is much smaller than at Ålfotbreen, the annual discharge, like for Storbreen, is most sensitive to summer temperature.

The correlation of glacier melt with temperature changes is largest on Storbreen (Table 5). Compared to Ålfotbreen, the annual precipitation at Storbreen is only about a third. The snow depth at the end of winter is accordingly lower, which leads to an earlier start of bare ice on Storbreen. Variations in glacier melt are therefore more strongly correlated with variations in summer temperature at Storbreen, whereas at both Nigardsbreen and Ålfotbreen glacier melt is most closely correlated with precipitation. A slightly higher correlation of glacier melt with annual rather than winter precipitation at these two sites is due to the fact that summer precipitation also indirectly affects glacier melt. Rainy days in summer coincide with more than average cloud cover and lower temperatures. In addition, snowfall events in summer even prevent glacier melt for several days (Oerlemans, 2004).

Previous studies (e.g. Chen and Ohmura, 1990) found that with increasing glacierization of a catchment, the occurrence of the maximum monthly runoff is delayed, and with decreasing glacier coverage the correlation of annual discharge with annual precipitation increases. We can partly sustain this finding for the lowest glaciated catchment of Ålfotbreen showing the highest correlation of annual discharge with annual precipitation sum, whereas for Nigardsbreen and Storbreen the annual discharge is most correlated with mean summer temperature. However, considering the relatively small range of glacier cover difference in our study sites (51–72 %), the correlation of annual discharge with annual precipitation reflects predominantly the climate continentality of the catchments rather than glacier coverage.

Long-term forecast for western Norway indicates a rise in the summer temperature of about 2 °C by the end of the 21st century (Nesje et al., 2008). For Storbreen, such an increase will double the period of potential glacier melt (Andreassen and Oerlemans, 2009). High glacier melt rates lead to a decrease in the glacier area and thus discharge would decrease especially in August when at Storbreen for 2001–2010 glacier melt accounted on average for more than 50 % of the discharge (Fig. 10c), which is in accordance with similar studies for the Alps (e.g. Finger et al., 2012).

6 Conclusions

In this study annual discharge series for the past five decades were modelled for three glacierised catchments in Norway. The model was calibrated through comparisons of modelled and observed seasonal mass balances and daily discharge sums. The time series of modelled annual discharge were split up into their contributing water sources snowmelt, glacier melt and rain. Changes in these contributing sources during the modelling period were much larger than variations in annual discharge sums.

Due to their location in different climate settings, the three studied catchments are representative of glaciers in Norway. Although for discharge, both year-to-year variability and variability throughout the year are largest at Ålfotbreen, the catchments closest to the western coast, glaciers with greater distance from the coast like Storbreen would experience larger changes in the discharge regime. Differences between the catchments in the seasonal discharge regimes and in year-to-year variability could be attributed to the large precipitation gradient and therefore to increasing climate continentality from west to east rather than differences in catchment size or degree of glacier coverage.

Discharge at the most maritime glacier Ålfotbreen is most strongly correlated with changes in precipitation, whereas discharge at the most continental catchment of Storbreen is most strongly correlated with changes in summer temperatures. Especially for Storbreen, glacier melt is a large contributor to discharge in late summer, which may lead to reduced discharge at this time of the year when its glacier area decreases.

In order to extrapolate the results into the future, a reduction in the glacierised area has to be accounted for when enhanced glacier melt has caused glacier volume to decrease significantly.

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