Hydrol. Earth Syst. Sci. Discuss., 10, 11485–11517, 2013
www.hydrol-earth-syst-sci-discuss.net/10/11485/2013/
doi:10.5194/hessd-10-11485-2013

Hydrology and Earth System Sciences Discussions
Open Access

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

M. Engelhardt[1], T. V. Schuler[1], and L. M. Andreassen[2]

[1]Department of Geosciences, University of Oslo, Oslo, Norway
[2]Norwegian Water Resources and Energy Directorate, Oslo, Norway

Received: 27 August 2013 – Accepted: 2 September 2013 – Published: 11 September 2013

Correspondence to: M. Engelhardt (markus.engelhardt@geo.uio.no)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Glacierised catchments significantly alter the streamflow regime due to snow and glacier meltwater contribution to discharge. 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 uses gridded temperature and precipitation values from *seNorge* (http://senorge.no) as input which are available at a daily resolution. It accounts for accumulation of snow, transformation of snow to firn and ice, evaporation and melt. The model was calibrated for each catchment based on measurements of seasonal glacier mass-balances and daily discharge rates. For validation, daily melt rates were compared with measurements from sonic rangers located in the ablation zones of two of the glaciers and an uncertainty analysis was performed for the third catchment. The discharge contributions from snowmelt, glacier melt and rain were analysed with respect to spatial variations and temporal evolution.

The model simulations reveal an increase of the relative contribution from glacier melt 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 of the annual discharge by 5–20 %. Annual discharge sums and annual glacier melt are strongest 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 stronger correlated with variations in summer temperatures.

1 Introduction

In highly glacierised catchments snow and glacier melt are the most important contributors to discharge (Jost et al., 2012). Year-to-year variations in streamflow can be amplified or balanced by the presence of glaciers within the catchment (Dahlke et al., 2012). 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 of which 15 % is based on discharge from glacierised basins. 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, precipitation or a combination of both. With ongoing climate change, major changes in both, timing and magnitude of the runoff regime are expected. The future contribution of glaciers to discharge in a changing climate is therefore subject to research in many regions of the world (e.g. Bolch et al., 2012; Farinotti et al., 2012; Immerzeel et al., 2012; Schaner et al., 2012). With continuing glacier shrinkage, the glacier contribution to runoff is expected to increase during spring and early summer, but to decrease later in the year (Stahl et al., 2008; Huss et al., 2008). Glacial meltwaters can also have relevant impacts to the hydrological regime of larger watersheds further downstream (Huss, 2011).

Modelling melt from glaciers requires glacier mass-balance models which exist in a large range of different complexities (Hock et al., 2005). Since meteorological data are sparse in mountainous regions, temperature-index models have been widely used (e.g. Konz and Seibert, 2010; Jost et al., 2012; Engelhardt et al., 2013) which employ air temperature and precipitation as meteorological input for snow accumulation and computing melt. The use of a temperature-index model has been justified since surface air temperature is the most influential variable 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 in high altitudes due to the lack of measurements represent one of the biggest problems for modelling discharge (Verbunt et al., 2003). Satellite-derived precipitation datasets can be used as a data source for modelling discharge at larger scales in regions without ground-based measurement (Li et al., 2013). Discharge models for glacierised catchments yield better results when applied as grid-based models (e.g. Hock and Noetzli, 1997; Klok et al., 2001). Mayr et al. (2013) showed that using seasonal mass balances as additional calibration criteria improves model performance for discharge modelling.

In the present study we used measured seasonal mass balances data together with daily discharge data from three catchments along a west-east profile in western Norway to calibrate a mass balance and discharge model. The model was applied on a daily resolution for the period 1957–2012, including a four-year spin-up period. The model was calibrated following 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. The parameter sets for melt and snow accumulation were validated against 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 and changes over time. Furthermore, we investigated correlations between discharge and the meteorological input.

2 Study sites

The study was carried out for three catchments in southern Norway containing the glaciers Ålfotbreen, Nigardsbreen and Storbreen (Fig. 1). The glacier coverage in each catchment is >50 % (Table 1) and at each glacier, seasonal mass balance measurements have been carried for more than 50 yr (Andreassen et al., 2005). 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 measurements are conducted 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 in similar latitude and reflect therefore an 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 1961–1970 and from 1995–2005 and constant to slightly decreasing values from 1970–1995 and from 2005–2012. The difference in summer temperature between the sites is mainly reflecting 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 by 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 for all catchment a similar pattern compared to the annual precipitation. On average, winter precipitation yields about two thirds of the annual sums (Fig. 2d).

HESSD
10, 11485–11517, 2013

3 Methods

3.1 Precipitation correction

As model input, 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 present. For a detailed review of the interpolation methods of temperature and precipitation, see the manual of 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 valuable especially due to its high spatial resolution. Too account for the uncertainties associated especially with the vertical adjustment, we applied a constant correction factor to the precipitation data from *seNorge* 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

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

where P denotes precipitation, Q discharge and V evaporation. S 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 is assumed. For evaporation we used the gridded data provided from *seNorge* which are only calculated for the non-glacierised areas and set to zero for the glacierised areas (Sælthun, 1996). Since the gridded precipitation data from *seNorge* for the glacier parts of all catchments (P_g) have already been evaluated in the study by Engelhardt et al. (2012), we now used the calculated precipitation correction factors (CF_g) from that study for the glacierised areas and calculated

HESSD
10, 11485–11517, 2013

the correction factors for the precipitation (P_{ng}) of the non-glacierised parts (CF_{ng}) of the catchments. The water balance equation for the glacierised and non-glacierised areas is then modified to

$$\underbrace{\frac{P_g}{CF_g} - S}_{\text{glacier area}} \quad + \quad \underbrace{\frac{P_{ng}}{CF_{ng}} - V}_{\text{non-glacier area}} \quad = \quad Q. \tag{2}$$

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 CF_{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 area) and is calculated to

$$P_{input} = \frac{P_{seNorge}}{CF_{g/ng}}. \tag{3}$$

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 on a daily resolution. The calculations cover 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 meltwater runoff and evaporation. A threshold temperature (T_s)

distinguishes between rain and snow. The transition occurs within a temperature interval of 2 K where the precipitation linearly shifts from rain to snow.

To account for the transition of snow to firn and ice, snow that has not melted away during summer was defined to become 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 to a simple time function introduced by Martinec (1977). The conceptual model calculates daily melt of snow, firn or ice $M_{\mathrm{snow/firn/ice}}$ by using a distributed temperature-index approach including potential solar radiation as used e.g. in Hock (1999) or Engelhardt et al. (2013). For $T_{\mathrm{sn}} > T_{\mathrm{m}}$ melt was calculated to

$$M_{\mathrm{snow/firn/ice}} = (\Theta + R_{\mathrm{snow/firn/ice}} \cdot I) \cdot (T_{\mathrm{sn}} - T_{\mathrm{m}}), \quad (4)$$

with the melt factor Θ, the respective radiation coefficients for snow, firn and ice $R_{\mathrm{snow/firn/ice}}$, the potential direct solar radiation I, the *seNorge* air temperature T_{sn} and the threshold temperature for melt T_{m}. The potential solar radiation is dependent on latitude and day of year, whereas modifications due to exposition or shading effects of surrounding slopes were not accounted for as the model grid resolution of 1 km 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}) are 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 (glacier) ice starts to melt, once the firn has melted away.

The model calculated the reference surface mass balance (Elsberg et al., 2001). The area on which the calculations were based on, was the same area for which the available glacier mass balance measurements were performed (e.g. Kjøllmoen et al., 2011). This glacier area was e.g. for Nigardsbreen 47.8 km^2 from 1984–2008 and has been updated to 47.2 km^2 in 2009. All changes in glacier area during the model period were not larger than 6 % of the respective glacier area. Thus, to account for such area changes in the model, we adjusted the contribution of the grid point in the model domain with the lowest altitude to melt and discharge of the whole glacier area.

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 daily resolution, the reservoirs for each grid were first filled with the calculated meltwater and rain for this grid point:

$$V_i(t) = V_i(t-1) + M(t) + R(t), \tag{5}$$

where V denotes the reservoir volume, M the calculated melt rates and R the rain (*seNorge* precipitation > T_s).

Then, discharge for each grid Q_i was calculated using a storage constant ($c_{\text{snow/firn/ice}}$) dependent on the surface property of the location:

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

No water storage is applied for grid cells outside the glacierised areas, when no snow is present. Thus, rain is treated like meltwater when it falls on snow, firn, or ice, but is counted as discharge for the same day when it falls on areas free of snow or ice.

After the daily discharge rate has been calculated, the volume of the reservoir is updated and the daily simulated discharge rate for the whole catchment (Q_m) is calculated as the sum from all grid points:

$$V_i(t) = V_i(t) - Q_i(t) \tag{7}$$

$$Q_m(t) = \sum Q_i(t) \tag{8}$$

3.3 Calibration and validation of model parameters

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) seasonal mass balances (SMB), and (2) the Nash–Sutcliffe coefficient (E) for daily discharge:

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

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

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

where n denotes the number of measured SMB 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 best 100 parameter sets over the period of available *seNorge* data (1957–2012) and the ensemble mean of the monthly and annual discharge sums were calculated.

For an independent validation of the model, we used weekly melt rates measured with sonic rangers in the ablations zones of Storbreen (Andreassen et al., 2008) and Nigardsbreen. Data are available for 84 weeks with melt during the period 2002–2012 for Storbreen and for 43 weeks from the melt seasons 2011 and 2012 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.

For Ålfotbreen, where no sonic ranger data are available, we evaluated the model performance for discharge during an average melt season.

4 Results

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 by about 20 % (Fig. 3a), but also periods of declining discharge. At Ålfotbreen the discharge increased by about 40 % between the 1960s and the late 1980s followed by a large variability within the following two decades with annual discharge sums ranging from 4.5–8.2 $\mathrm{m\,a^{-1}}$. 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 and about 20 % above average.

Larger variations than for the discharge sums were visible in the proportion of the contributing discharge sources (Fig. 3b–d). For all catchments the largest contribution denoted from snowmelt which accounted roughly for 60 % of the annual discharge (Fig. 3b). 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 glaciers Ålfotbreen and Storbreen, whereas at Nigardsbreen the contribution of snowmelt to discharge during the model period was most constant of all catchments.

Among our study sites, the relative contribution from glacier melt becomes larger with 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 was originating 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 (Fig. 3c).

The remaining water source for discharge is rain. Its relative contribution is highest for Ålfotbreen (∼ 37 %), moderate for Nigardsbreen (∼ 27 %) and lowest for Storbreen (∼ 19 %). Whereas changes over time were smallest at Storbreen, for Ålfotbreen and to a lesser extend also for Nigardsbreen the relative component of rain to discharge had a maximum in the 1980s and a minimum in the 1960s and 1990s (Fig. 3d).

The uncertainty of the contributing discharge sources among the 100 best ranked parameter sets is shown in Fig. 4. For all catchments the uncertainty is highest connected to snowmelt, spreading in a band of 5 % around the mean value, and lowest for glacier melt. For all discharge sources, the uncertainty is slightly higher for Ålfotbreen than for the other catchments.

The evaluation of the average discharge during the melt season at Ålfotbreen reveals an overestimation of discharge in May and June (Fig. 5). This might be induced by meltwater refreezing in the snow which is not covered by the model.

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. 6). However, 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.

The model performance for seasonal mass balance and daily discharge (Fig. 7) was poorest for Ålfotbreen, the most maritime study site where both the precipitation and absolute values of seasonal mass balances are highest, and best for Storbreen. Whereas there was little difference in modelling seasonal mass balances with coefficient of variation values between 0.15 and 0.18, daily discharge was modelled better for both Nigardsbreen and Storbreen with a Nash–Sutcliffe coefficient of 0.87 and 0.88. However, for Nigardsbreen, the catchment with the longest discharge time series, the model has a tendency to underestimate high discharge values (Fig. 7d). For Storbreen, the data series for this study were quite short with only 632 days of available measurements.

The evaluation of the monthly discharge for the periods 1991–2000 and 2001–2010 reveals that for all three catchments the majority in discharge occurs in the three months June, July and August (Fig. 8/9) 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. Whereas in the 2000s, in June for all three catchments about 80 % of the discharge derived from snowmelt, this proportion decreases 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 occured 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 throughout October.

5 Discussion

The modelled increase in annual discharge at Ålfotbreen from the 1960s to 1980s corresponds with 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 was leading 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 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 is 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 were the reason of positive mass balances and and 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 by 1–1.5 K. At all three sites, increased temperatures after the mid 1990s and decreased precipitation resulted in reduced snow depths and increased glacier melt.

Among the three study sites, the sensitivity of glacier melt to temperature changes is largest on Storbreen (Table 4). 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 stronger correlated to variations in summer temperature at Storbreen, whereas at both, Nigardsbreen and Ålfotbreen glacier melt is closest correlated to precipitation. A slightly higher correlation of glacier melt to annual rather than winter precipitation at these two sites is due to the fact that also summer precipitation 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.

Also annual discharge at Ålfotbreen is most sensitive to changes in precipitation (Table 5). The contribution of snow from areas outside the glacier at Ålfotbreen together with the large contribution from rain are the dominant factors for 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 is like for Storbreen most sensitive to summer temperature.

HESSD
10, 11485–11517, 2013

Previous studies (e.g. Chen and Ohmura, 1990) found that for with increasing glacier coverage of a catchment, the occurrence of the maximum monthly runoff is delayed, and with decreasing glacier cover 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 highest correlated with mean summer temperature. However, within the relatively small range of glaciation difference in our study sites (51–72 %), the correlation of annual discharge is predominantly controlled by the large differences in climate continentality between the catchments rather then by glacier coverage.

With continued temperature and precipitation values like in the 2000s, the discharge regime at Storbreen would experience the largest discharge change of the three catchments within the melt season. With further high glacier melt rates the surface area of Storbreen will decrease and annual discharge would decrease especially in August where between 2001–2010 glacier melt accounted on average for more than 50 % of the discharge (Fig. 9c).

6 Conclusions

In this study annual discharge series for the past five decades were modelled for three glacierised catchments in Norway. The discharge 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 in their contributing water sources snowmelt and glacier melt and rain. Changes in these contributing sources were much larger than the variations in annual discharge sums.

Differences between the catchments can be attributed to the increasing climate continentality from west to east rather than differences in catchment size or glacier coverage. Discharge at the most maritime glacier Ålfotbreen is most sensitive to changes in precipitation whereas discharge at the most continental catchment of Storbreen is most

HESSD
10, 11485–11517, 2013

sensitive to changes in summer temperatures. Especially for Storbreen, glacier melt is a large contributor to discharge in late summer which may lead to reduced discharge in this time of the year when its glacier area decreases.

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

Acknowledgements. This publication is contribution number 29 of the Nordic Center of Excellence SVALI, "Stability and Variations of Arctic Land Ice", funded by the Nordic Top-level Research Initiative (TRI).

The authors want to thank Statkraft and the glacier group of the Norwegian Water Resources and Energy Directorate (NVE) for supporting fieldwork, as well as collecting and providing data for this study. We also thank the Institute for Marine and Atmospheric Research, Utrecht (IMAU) for operating and providing data from the automatic weather station on Storbreen.

References

Andreassen, L. M., Elvehøy, H., Kjøllmoen, B., Engeset, R. V., and Haakensen, N.: Glacier mass-balance and length variations in Norway, Ann. Glaciol., 42, 317–325, 2005. 11488

Andreassen, L. M., van den Broeke, M. R., Giesen, R. G., and Oerlemans, J.: A 5 year record of surface energy and mass balance from the ablation zone of Storbreen, Norway, J. Glaciol., 54, 245–258, 2008. 11494

Bolch, T., Kulkarni, A., Kääb, A., Huggel, C., Paul, F., Cogley, J. G., Frey, H., Kargel, J. S., Fujita, K., Scheel, M., Bajracharya, S., and Stoffel, M.: The State and Fate of Himalayan Glaciers, Science, 336, 310–314, 2012. 11487

Chen, J. and Ohmura, A.: On the influence of Alpine glaciers on runoff, in: Hydrology in Mountainous Regions I – Hydrological Measurements; the Water Cycle (Proceedings of two Lausanne Symposia, August 1990: IAHS Publ. no. 193), 117–126, 1990. 11499

Dahlke, H. E., Lyon, S. W., Stedinger, J. R., Rosqvist, G., and Jansson, P.: Contrasting trends in floods for two sub-arctic catchments in northern Sweden – does glacier presence matter?, Hydrol. Earth Syst. Sci., 16, 2123–2141, doi:10.5194/hess-16-2123-2012, 2012. 11487

Dyrrdal, A. V.: An evaluation of Norwegian snow maps: simulation results versus observations, Hydrol. Res., 41, 27–37, doi:10.2166/nh.2010.019, 2010. 11490

Elsberg, D., Harrison, W., Echelmeyer, K., and Krimmel, R.: Quantifying the effects of climate and surface change on glacier mass balance, J. Glaciol., 47, 649–658, doi:10.3189/172756501781831783, 2001. 11492

Engelhardt, M., Schuler, T. V., and Andreassen, L. M.: Evaluation of gridded precipitation for Norway using glacier mass-balance measurements, Geogr. Ann. A, 94, 501–509, doi:10.1111/j.1468-0459.2012.00473.x, 2012. 11490

Engelhardt, M., Schuler, T. V., and Andreassen, L. M.: Glacier mass balance of Norway from 1961–2010 calculated by a temperature-index model, Ann. Glaciol., 54, 32–40, doi:10.3189/2013AoG63A245, 2013. 11487, 11492

Farinotti, D., Usselmann, S., Huss, M., Bauder, A., and Funk, F.: Runoff evolution in the Swiss Alps: projections for selected high-alpine catchments based on ENSEMBLES scenarios, Hydrol. Process., 26, 1909–1924, doi:10.1002/hyp.8276, 2012. 11487

Hock, R.: A distributed temperature-index ice- and snowmelt model including potential direct solar radiation, J. Galciol., 45, 101–111, 1999. 11492

Hock, R.: Glacier melt. A review on processes and their modelling, Prog. Phys. Geogr., 29, 362–291, 2005. 11488

Hock, R. and Noetzli, C.: Aerial melt and discharge modelling of Storglaciären, Sweden, Ann. Galciol., 24, 211–216, 1997. 11488

Hock, R., Jansson, P., and Braun, L.: Modelling the response of mountain glacier discharge to climate warming, in: Global Change and Mountain Regions – A State of Knowlegde Overview 243–252, edited by: Huber, U. M., Reasoner, M. A., and Bugmann, H., Springer, Dordrecht, the Netherlands, 2005. 11487

Hock, R., Rees, G., Williams, M. W., and Ramirez, E.: Preface: Contribution from glaciers and snow cover to runoff from mountains in different climates, Hydrol. Process., 20, 2089–2090, 2006. 11487

Huss, M.: Present and future contribution of glacier storage change to runoff from macroscale drainage basins in Europe, Water Resour. Res., 47, W07511, doi:10.1029/2010WR010299, 2011. 11487

Huss, M., Farinotti, D., Bauder, A., and Funk, M.: Modelling runoff from highly glacierized alpine drainage basins in a changing climate, Hydrol. Process., 22, 3888–3902, doi:10.1002/hyp.7055, 2008. 11487

HESSD
10, 11485–11517, 2013

Contribution of snow and glacier melt to discharge

M. Engelhardt et al.

Huss, M., Funk, M., and Ohmura, A.: Strong Alpine glacier melt in the 1940s due to enhanced solar radiation, Geophys. Res. Lett., 36, L23501, doi:10.1029/2009GL040789, 2009. 11492
Immerzeel, W. W., van Beck, L. P. H., Konz, M., Shrestha, A. B., and Bierkens, M. F. P.: Hydrological response to climate change in a glacierized catchment in the Himalayas, Climate Change, 110, 721–736, doi:10.1007/s10584-011-0143-4, 2012. 11487
Jost, G., Moore, R. D., Menounos, B., and Wheate, R.: Quantifying the contribution of glacier runoff to streamflow in the upper Columbia River Basin, Canada, Hydrol. Earth Syst. Sci., 16, 849–860, doi:10.5194/hess-16-849-2012, 2012. 11486, 11487
Kjøllmoen, B., Andreassen, L., Elvehøy, H., and Giesen, M. J. R. H.: Glaciological investigations in Norway in 2010, Report no. 3, Norwegian Water Resources and Energy Directorate (NVE), Oslo, Norway, 2011. 11491, 11492, 11497
Klok, E. J., Jasper, K., Roelofsma, K. P., Gurtz, J., and Badoux, A.: Distributed hydrological modelling of a heavily glaciated Alpine river basin, Hydrolog. Sci. J., 46, 553–570, doi:10.1080/02626660109492850, 2001. 11488
Konz, M. and Seibert, J.: On the value of glacier mass balances for hydrological model calibration, J. Hydrol., 385, 238–246, doi:10.1016/j.jhydrol.2010.02.025, 2010. 11487, 11494
Li, L., Engelhardt, M., Xu, C.-Y., Jain, S. K., and Singh, V. P.: Comparison of satellite-based and re-analysed precipitation as input to glacio-hydrological modelling for Beas River basin, northern India, Cold and Mountain Region Hydrological Systems Under Climate Change: Towards Improved Projections, Proceedings of H02, IAHS-IAPSO-IASPEI Assembly, Gothenburg, Sweden, July 2013 (IAHS Publ. 360, 2013), 2013. 11487
Martinec, J.: Expected snow loads on structures from incomplete hydrological data, J. Glaciol., 19, 185–195, 1977. 11492
Mayr, E., Hagg, W., Mayer, C., and Braun, L.: Calibrating a spatially distributed conceptual hydrological model using runoff, annual mass balance and winter mass balance, J. Hydrol., 478, 40–49, doi:10.1016/j.jhydrol.2012.11.035, 2013. 11488
Mohr, M.: New routines for Gridding of Temperature and Precipitation Observations for "senorge.no", Norwegian Meteorological Institute (met.no) note no. 08/2008, 40 pp., available at: http://met.no/Forskning/Publikasjoner/Publikasjoner2008/filestore/NewRoutinesforGriddingofTemperature.pdf (last access: 6 September 2013), 2008. 11490
Mohr, M.: Comparison of versions 1.1 and 1.0 of gridded temperature and precipitation data for Norway, Norwegian Meteorological Institute (met.no) note no. 19/2009, 44 pp., available

HESSD
10, 11485–11517, 2013

at: http://met.no/Forskning/Publikasjoner/Publikasjoner2009/filestore/note19-09.pdf (last access: 6 September 2013), 2009. 11490

Ohmura, A.: Physical Basis for the Temperature-Based Melt-Index Method, American Meteorological Society, 46, 753–761, 2001. 11487

Saloranta, T. M.: Simulating snow maps for Norway: description and statistical evaluation of the seNorge snow model, The Cryosphere, 6, 1323–1337, doi:10.5194/tc-6-1323-2012, 2012. 11490

Schaner, N., Voisin, N., Nijssen, B., and Lettenmeier, D. P.: The contribution of glacier melt to streamflow, Environ. Res. Lett., 7, 1–8, doi:10.1088/1748-9326/7/3/034029, 2012. 11487

Sicart, J. E., Hock, R., and Six, D.: Glacier melt, air temperature, and energy balance in different climates: The Bolivian Tropics, the French Alps, and northern Sweden, J. Geophys. Res., 113, D24113, doi:10.1029/2008JD010406, 2008. 11487

Sælthun, N. R.: The "Nordic" HBV Model. Description and documentation of the model version developed for the project Climate Change and Energy Production, Report no. 218, 7 pp., Norwegian Water Resources and Energy Directorate (NVE), Oslo, Norway, 1996. 11490

Stahl, K., Moore, R. D., Shea, J. M., Hutchinson, D., and Cannon, A. J.: Coupled modelling of glacier and streamflow response to future climate scenarios, Water Resour. Res., 44, W02422, doi:10.1029/2007WR005956, 2008. 11487

Verbunt, M., Gurtz, J., Jasper, K., Lang, H., Warmerdam, P., and Zappa, M.: The hydrological role of snow and glaciers in alpine river basins and their distributed modeling, J. Hydrol., 282, 36–55, doi:10.1016/S0022-1694(03)00251-8, 2003. 11487

Winkler, S., Elvehøy, H., and Nesje, A.: Glacier fluctuations of Jostedalsbreen, western Norway, during the past 20 years: the sensitive response of maritime mountain glaciers, Holocene, 19, 395–414, doi:10.1177/0959683608101390, 2009. 11498

Xu, M., Yan, M., Kang, J., and Ren, J.: Comparative studies of glacier mass balance and their climatic implications in Svalbard, Northern Scandinavia, and Southern Norway, Environ. Earth Sci., 67, 1407–1414, doi:10.1007/s12665-012-1585-3, 2012. 11497

HESSD

10, 11485–11517, 2013

Contribution of snow and glacier melt to discharge

M. Engelhardt et al.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀◀ | ▶▶
◀ | ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

Table 1. Overview of the three catchments.

Glacier name	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

HESSD
10, 11485–11517, 2013

Table 2. Components of the water balance (in m a^{-1}) and precipitation correction factors for the three catchments.

Period (hydrological years)	Ålfotbreen 1995–2012	Nigardsbreen 1963–2012	Storbreen 2011–2012
Precipitation (*seNorge*)	5.79	3.29	1.70
Discharge	5.66	3.01	2.60
Evaporation (*seNorge*)	0.06	0.05	0.02
Accumulated mass balance	−0.24	0.25	−0.65
CF_g (from Engelhardt et al., 2012)	1.01	1.00	0.80
CF_{ng}	1.13	0.99	1.00

HESSD
10, 11485–11517, 2013

Contribution of snow and glacier melt to discharge

M. Engelhardt et al.

HESSD
10, 11485–11517, 2013

Contribution of snow and glacier melt to discharge

M. Engelhardt et al.

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

Parameter	Description	Ålfotbreen	Nigardsbreen	Storbreen	Unit
T_0	melt threshold factor	0.3	−0.2	−0.3	°C
T_s	snow threshold factor	2.4	1.3	1.4	°C
R_{snow}	radiation coefficient for snow	4.2	3.8	3.7	$\text{mm K}^{-1}\ \text{d}^{-1}\ \text{kW}^{-1}\ \text{m}^2$
R_{ice}	radiation coefficient for ice	6.8	6.9	5.6	$\text{mm K}^{-1}\ \text{d}^{-1}\ \text{kW}^{-1}\ \text{m}^2$
Θ	melt factor	3.9	2.9	2.6	$\text{mm K}^{-1}\ \text{d}^{-1}$
c_{snow}	storage constant for snow	0.28	0.21	0.55	d^{-1}
c_{firn}	storage constant for firn	0.45	0.67	0.70	d^{-1}
c_{ice}	storage constant for ice	0.64	0.74	0.84	d^{-1}
c_v	coefficient of variation	0.18	0.16	0.15	–
E	Nash–Sutcliffe coefficient	0.76	0.88	0.82	–

Table 4. 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	0.76
Annual precipitation sum (October–September)	−0.76	−0.88	−0.66
Winter precipitation sum (October–April)	−0.67	−0.85	−0.66

HESSD
10, 11485–11517, 2013

Table 5. 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

HESSD
10, 11485–11517, 2013

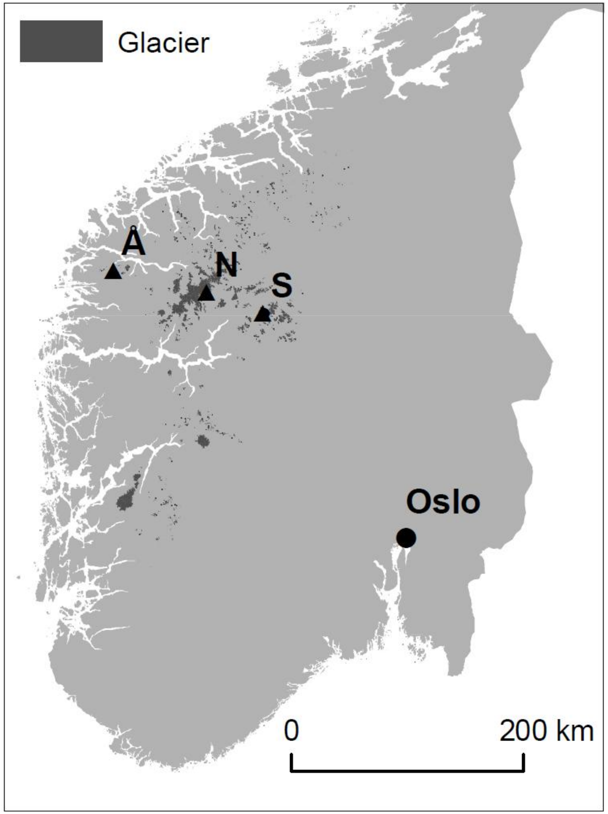

Fig. 1. Location of the study sites Ålfotbreen (Å), Nigardsbreen (N) and Storbreen (S) within the glacierised areas in southern Norway.

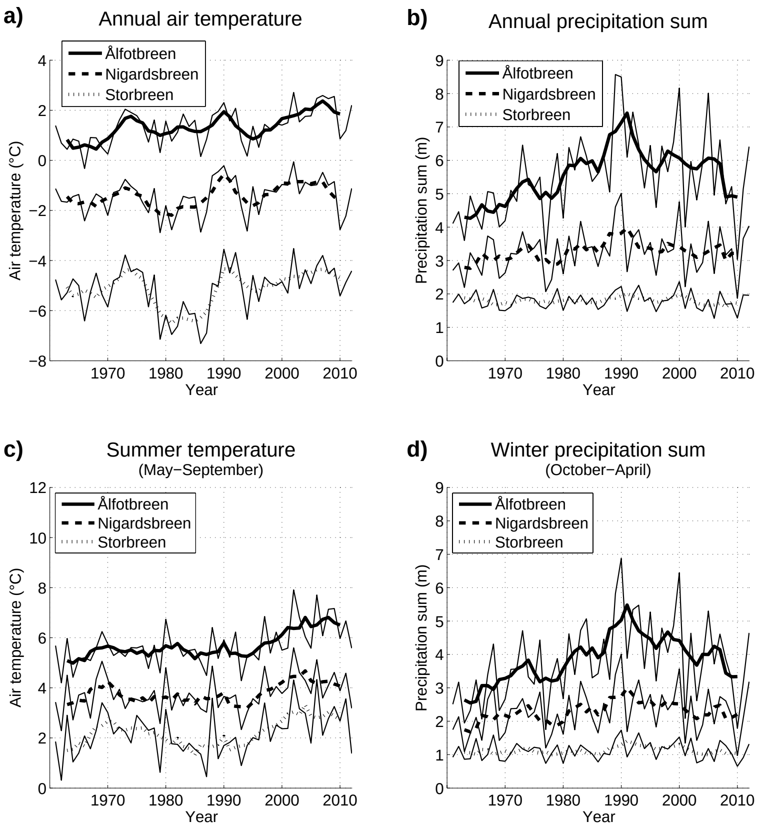

Fig. 2. Air temperature and precipitation data with 5-yr moving averages for the three catchments based on *seNorge* data.

HESSD
10, 11485–11517, 2013

Contribution of snow and glacier melt to discharge

M. Engelhardt et al.

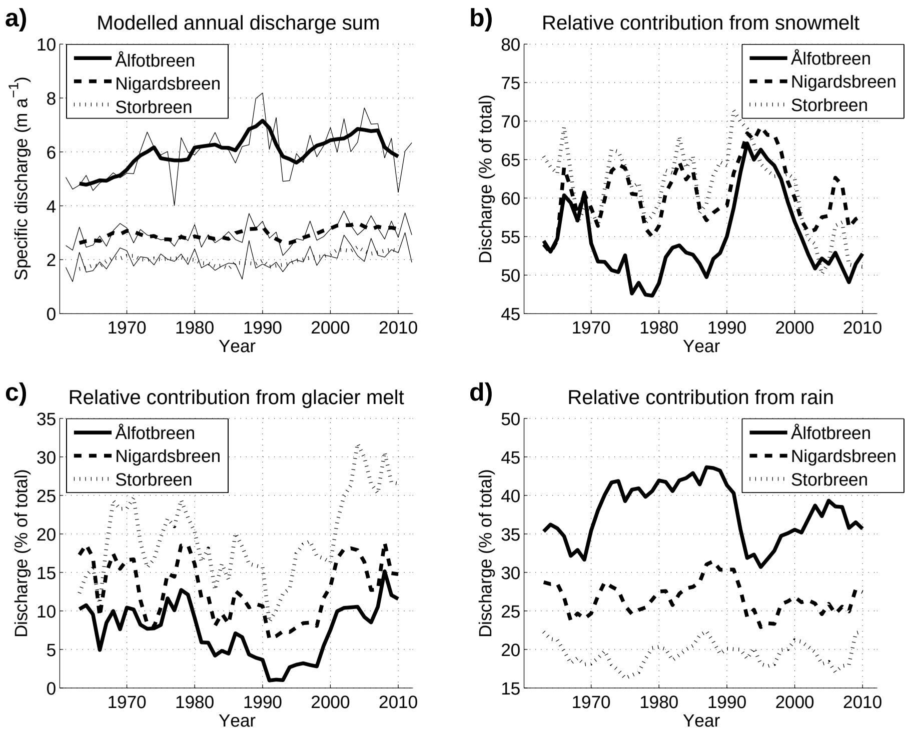

Fig. 3. Modelled annual discharge sum with 5-yr moving average **(a)** and 5-yr moving average of the relative proportion of the contributing sources **(b–d)**.

HESSD
10, 11485–11517, 2013

Contribution of snow and glacier melt to discharge

M. Engelhardt et al.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◂ ▸
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

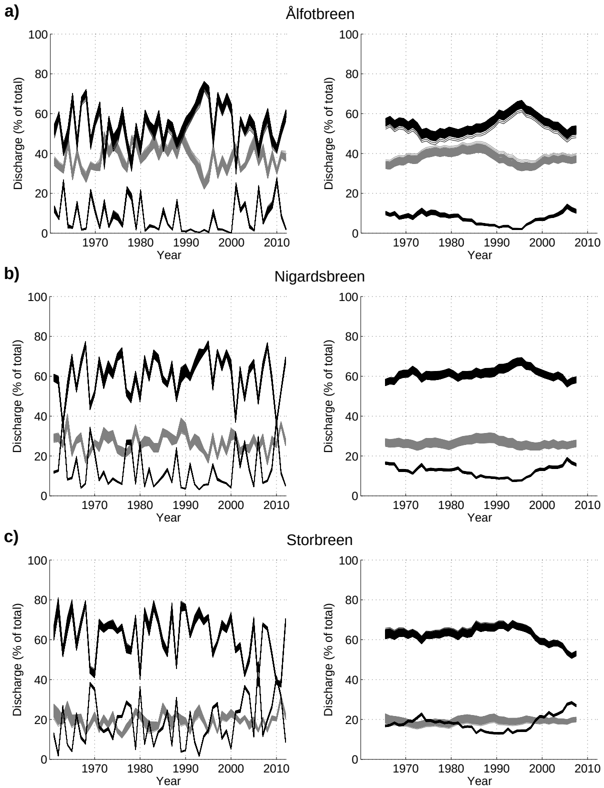

Fig. 4. Ensemble runs for the relative proportions of the contributing sources to the annual discharge (left colon), and the respective 10-yr moving average (right colon). Snowmelt is represented by the upper black lines, glacier melt by the lower black lines and rain by the grey lines.

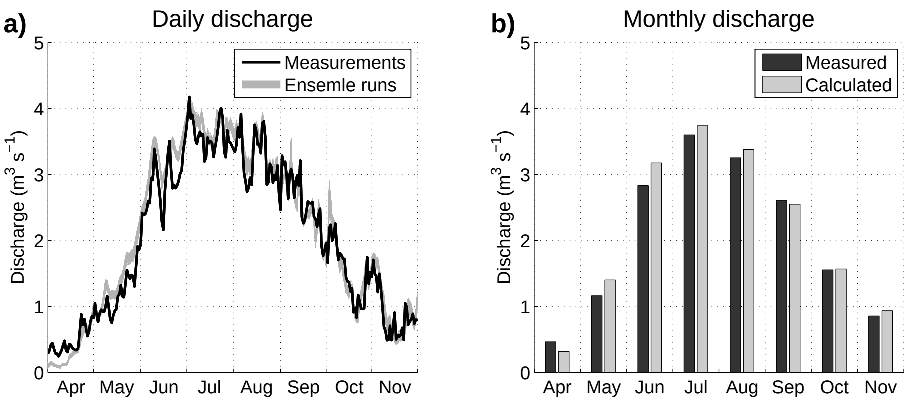

Fig. 5. Model performance for mean daily and monthly discharge for the catchments of Ålfotbreen for the period 1996–2012.

HESSD
10, 11485–11517, 2013

Contribution of snow and glacier melt to discharge

M. Engelhardt et al.

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀◀ ▶▶
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

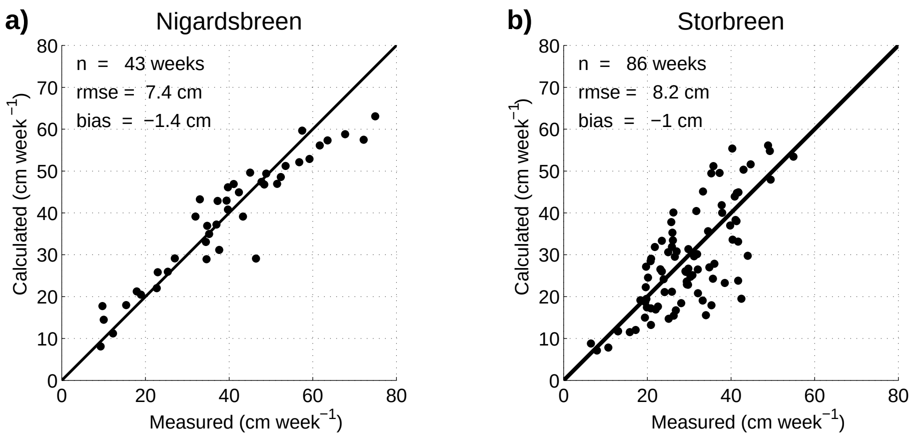

Fig. 6. Model performance for weekly melt at the sonic ranger position of Nigardsbreen (2011–2012) and Storbreen (2002–2012).

HESSD
10, 11485–11517, 2013

Contribution of snow and glacier melt to discharge

M. Engelhardt et al.

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

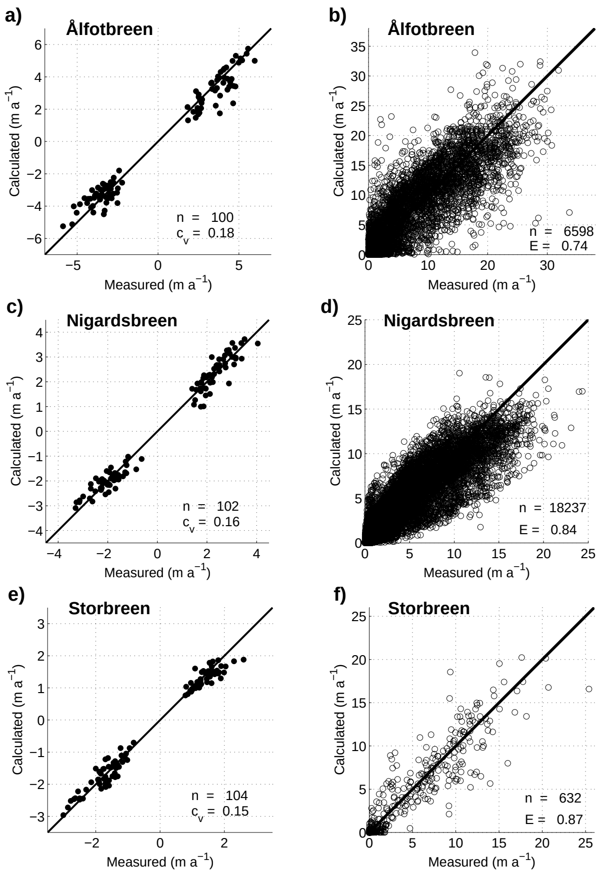

Fig. 7. Model performance for measured against calculated seasonal mass balances and specific daily discharges at Ålfotbreen **(a,b)**, Nigardsbreen **(c,d)** and Storbreen **(e,f)** using the parameter set of Table 3 (ensemble mean).

HESSD
10, 11485–11517, 2013

HESSD

10, 11485–11517, 2013

Contribution of snow and glacier melt to discharge

M. Engelhardt et al.

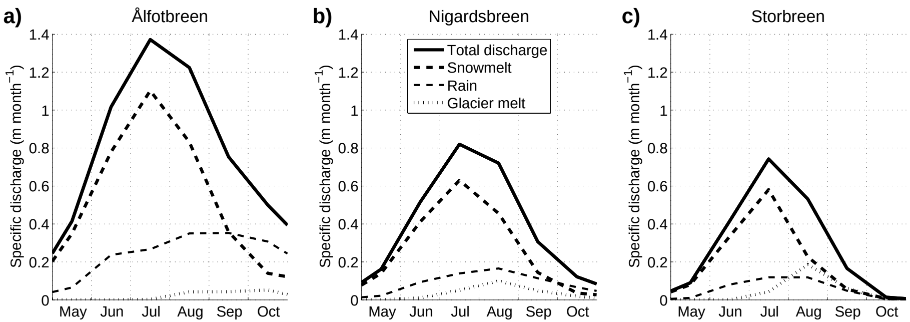

Fig. 8. Modeled monthly discharge rates and their contributing sources for Ålfotbreen, Nigardsbreen and Storbreen averaged for the period 1991–2000.

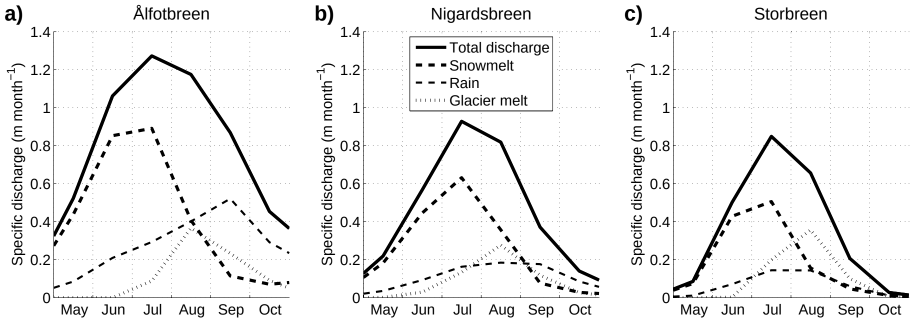

Fig. 9. Modeled monthly discharge rates and their contributing sources for Ålfotbreen, Nigardsbreen and Storbreen averaged for the period 2000–2010.

HESSD
10, 11485–11517, 2013

Contribution of snow and glacier melt to discharge

M. Engelhardt et al.