Oslo, 05.12.2013

Dear Editor and Reviewers,

thank you very much for your considerate and helpful reviews of our submitted discussion paper. We have modified our manuscript according to your suggestions and would like to address these changes in the following.
We hope that we have responded to all answer all referee comments in a satisfying way and would like to thank you again for your helpful comments and suggestions.

Since we are referring to new / modified figures in the responses, we attached all mentioned figures at the end of this document.

Best wishes,
Markus Engelhardt, Thomas V. Schuler and Liss M. Andreassen

[Comments of the referees in normal text.]

[Our answers are given in bold.]

Referee # 1

General comments

This contribution describes the application of a conceptual hydrological model to three different glaciated catchments in Norway. For model validation, runoff, mass balance data and melt measurements are used. The model output is used to examine changes in the runoff regimes. The discharge is divided into the water sources snow melt, glacier melt and precipitation and the differences in between the different catchments and over time are analyzed. The model does not contain new findings, but the use of corrected seNorge temperature and precipitation data and the analysis of discharge changes over time in areas with different climate characteristics show interesting insight into the local runoff characteristics of the different catchments. The contribution is well written and most working steps are well documented.

Specific comments

The model structure should be described in a more detailed way. Also, the available data allow more detailed validation of the results which should be made up, as explained in the comments below. I recommend changing the order of the paragraphs in the result section. Start with model performance (page 11496, line 21-29) and then show the modeling results.

As suggested, the order of the paragraphs in the *Results* section has been changed.

The validation of the model performance has been improved significantly:
In addition to the melt rates at two of the glaciers (new fig. 5), the seasonal mass balances have been validated for the period 2001-2012 (new fig. 4), and the daily discharge rates have been validated for the years 2011 and 2012 (for Storbreen due to data shortage only 2012) (new fig. 6).
The model structure has been explained in more detail. The model description (section 3.2) includes all processes relevant for reproducing the model results. It is not the scope of the article to explain all these processes in more detail. However, if one of the descriptions is not sufficient or gives room for misunderstandings or confusion, we are happy to elucidate it in even more detail.

Introduction:

P. 11487

Line 3-4. Please specify data source: "In Norway, 98% of the electricity is generated by hydropower of which 15% is based on discharge from glacierised basins"

A reference has been added to the first part of this information: Gebremedhin and Granheim (2012).
The second part of the sentence has been reworded to provide a different and to our opinion more important information:
"glaciers which represent 60% of the total glacier area drain to catchments regulated for hydropower (Andreassen and Winsvold, 2012)."

Line 16-19. Hock 2005 uses the phrase "melt models"

The phrase has been changed to "melt models" to be in accordance to the reference.

Line 17-21. Please rewrite phrase. As precipitation and temperature are also meteorological data, point out that temperature-index models need significantly less data than energy-balance models.

The phrase has been rewritten to:

"Since meteorological data needed for energy balance models are sparse for mountainous regions, temperature-index models have been widely used (e.g. ...) which in the simplest form only employ air temperature and precipitation as meteorological input for snow accumulation and computing melt."

Line 22. I recommend to use "parameter" instead of "variable"

The expression has been changed to "parameter".

Page 11488

Line 1. In my opinion "discharge models" should be replaced by "hydrological models", as this is the commonly used term

The expression has been changed to "hydrological models".

Line 1f. Better results compared to what? As far as I see, the model used in this study is grid based, but on a grid resolution of 1km. I am wondering if this scale really gives better results than lumped models which divide a catchment into different elevation and exposition classes.

We think, the improvement in our model compared to a lumped model is the gridded input dataset from *seNorge*. However, since a lumped model could also provide good results in this case, the sentence has been reworded to:
"Hydrological models for glacierised catchments have often been applied as grid-based models (e.g. ...)."

Line 5. how are the seasonal mass balance data derived?

The seasonal mass balance data are derived from point measurements performed by the Norwegian Water Resources and Energy Directorate (NVE).

The sentence has been rewritten and a reference has been added:

"For model calibration we used seasonal mass balance data which are based on point measurements (Kjøllmoen et al., 2011) together with daily discharge data."

Line 7. Maybe "hydrological model" is possible here?

Due to rewriting this sentence (following the previous comment), this comment is not longer relevant.

Line 9f. Points (1) and (2) do not belong to the calibration approach but to the model structure. For calibration, you should mention your Monte Carlo runs and the used objective functions, Nash-Sutcliffe coefficients and the coefficient of variation. There are plenty of years with runoff and mass balance data available, why don't you validate using runoff and mass balance additionally to the point measurements of ablation?

Comment, part 1:

We agree to this comment. The sentence reads now:

"The model structure is following an approach suggested by Hock (2005): ... "

In addition, as suggested, we mention already here the Monte Carlo runs together with the two objective functions:

"For parameter calibration, 10 000 Monte Carlo runs were performed. We used two objective functions, the coefficient of variation for seasonal mass balances and the Nash-Sutcliffe coefficient for daily discharge. 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."

Comment, part 2:

As mentioned above, the validation part of the study has been extended, using both seasonal mass balances and daily discharge as additional validation data.

Study sites

Line 20. Why did you choose just these catchments?

The choice of the catchments is restricted to these three, for which discharge only includes glaciers for which mass balance measurements are available.
In addition, these three catchments are on a west-east profile in western Norway.
For clarification, the following sub-clause has been added:
"...where both seasonal mass balance and discharge measurements are available."

Line 22. Missing word: “carried out”

The missing word has been added.

Line 21. Please add some more information about the measurement method of the seasonal mass balances

More information has been added her:

“ ... following the traditional stratigraphic method (Østrem and Brugman, 1991).”

Line: 24f. “Discharge data are available at daily resolution”

The sentence has been reworded as suggested.

Page 11489
Line 23: “catchments”

corrected

Methods:

Page 11490

Line 10f: “to account”

corrected

Line 22ff. Please give more information why evaporation is not relevant in glacierised areas

In the *seNorge* dataset, which we used as input, evaporation or condensation data are not calculated for the glacierized parts of the catchments.

However, this is not of relevance which we explained in more detail:

“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). This is justified since evaporation and condensation on glaciers may balance each other and their net effect is not likely to influence discharge in significant way (e.g. Braun et al., 1994).”

Page 11491

Table 2: Should it be possible to recalculate runoff based on the CFg and CFng values in this table? I tried but got different results using the glacier coverage presented in Table 1. Is this caused by updated glacier areas? Please clarify.

It was not possible to calculate the runoff alone with the provided information, since the precipitation sum is averaged for the catchment. Since precipitation is significantly higher in the (higher elevated) glacierized parts, the correction factor for the glacierized parts is somewhat "higher weighted".

However, the catchment-average correction factor has been included in the table. Now, the runoff can be calculated with the given numbers:

From the water balance equation (P = Q + E+ ΔS) (all numbers in m/a):

Q (Ålfotbreen) = P(seNorge)/CF_c - E - ΔS = 5.79/1.01 - 0.06 + 0.24 = 5.64.

Q (Nigardsbreen)= P(seNorge)/CF_c - E - ΔS = 3.29/1.00 - 0.05 + 0.25 = 2.99.

Q (Storbreen) = P(seNorge)/CF_c - E - ΔS = 5.79/1.01 - 0.02 + 0.65 = 2.58.

Discrepancies to the numbers in the table are due to rounding errors. With more exact numbers, for example:

Q (Nigardsbreen)= P(seNorge)/CF_c - E - ΔS = 3.294/0.998 - 0.045 + 0.248= 3.008= 3.01.

Splitting up the correction factor for the glacierized and non-glacierized parts yields the two factors provided ad CF_g= 1.01 and CF_ng = 1.13.

To calculate these two numbers, one would also need the individual precipitation sums for these two parts in the catchments.

Model Setup

Line 18. You should talk about the models grid size at this point (see comments on Line 16 below)

As described to the comment on line 16 below, additional information is provided in the text:

"Despite of 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."

Line 22. Mass loss is caused by melting of snow and ice, runoff is just a consequence

The sentence has be reworded accordingly:

"... and mass loss due to evaporation and melting of snow and ice."

Page 11492

Line 2. Not completely clear: Is the percental share of rain, and snow respectively, linearly increased within the temperature interval?

Yes, the percentile share of snow increases linearly within the temperature interval.

For clarification, the statement has been reworded:

"A threshold temperature (T_s) distinguishes between rain and snow. This temperature is centered within an interval of 2 K where the precipitation linearly shifts from snow to rain."

Line 16. Is the model calculating in grid resolution of 1km because of the resolution of the meteorological input data? Is each pixel either glacier or not glacier? Two of your glaciers only have an area of about 8km2. Why don't you calculate more detailed using temperature lapse rates and a topographic input? Then, the potential clear sky solar radiation would be more efficient than only giving a radiation difference over the course of the year.

First question: Yes, the model is running at the resolution of the input data.

Second question: No, a "pixel" can also represent a partly glacier covered area. Glacier discharge is then multiplied with the glacier ratio of this grid point.

As mentioned above, for clarification, the following sentence has been included here:

"Despite of 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."

Third question: Introducing additional model uncertainty by using lapse rates for temperature (and precipitation) is what we wanted to avoid by using the gridded input from *seNorge*. A higher model resolution of e.g. 100m would increase computational power by 100 but yielding little improvement for the results. Modeling test for the glacier tongue of Nigardsbreen, which has the narrowest tongue among the three glaciers, shows little shading effects during summer. However, the radiation difference over the course of the year is much larger and yields model improvement for daily melt at the ablation zone of Nigardsbreen.

Line 21. Braces at (glacier) are not necessary, particularly as you don't allow ice development outside of glacier areas

Theoretically, ice development outside the glacier area is possible. It is stated that

"...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 years..."

This applies for the whole catchment area. The area outside the glacier area was assumed to be free of snow and ice in the beginning of the 4-year spin-up period. Afterwards, both snow and ice can form in the non-glacierized parts of the catchment until they melt. However, no significant developments of firn or ice occurred outside the glacier areas during the model period.

Line 28ff. I don't understand what you did here. Please explain more detailed how area changes are considered.

More information has been provided here:

"To account for 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."

Page 11493

Line 11. (seNorge precipitation > Ts): precipitation is bigger than the threshold temperature?

This has been changed to "precipitation at T > Ts"

Calibration and validation of model parameters

Line 26. You write on page 11492 that Rfirn is assumed to be the mean of Rsnow and Rice. Here it looks like you calibrated this parameter. Please clarify.

It is true that R_firn is assumed to be the mean of Rsnow and R_ice.

Here, the eight mentioned parameters, given in Table 3, do not include R_firn. So, we do not see a contradiction.

Table 3. Please check the units of the storage constants.

The units of the storage constants (c) are correctly given in 1/d. They provide information of how much water (Q) is released from the reservoir (V) per day. See

eq. (6): Q = c*V; with Q in mm/d, c in 1/d, and V in mm; (all terms as specific values)

Page 11494

Line 14. Did you consider all years with runoff and mass balance data during calibration?

In the first submitted version, all years were used for the calibration.

In the revised version, the years from 2001-2012 are not included in the calibration, but used for validation. For the discharge, the years 2011-2012 are used for validation (only 2012 for Storbreen) and therefore not included in the calibration scheme.

(see also: answer to the specific comment in the beginning)

Line 22 and Table 3. To show how representative the ensemble mean for the 100 values of each parameter is, the range of each should be presented. Also, the possible ranges of the different model parameters would be interesting. Instead of calculating Nash-Sutcliffe coefficient and coefficient of variation of the ensemble mean, the maximum and minimum values of these objective functions within the 100 best sets would have more information content.

This is a valuable comment! We addressed this comment in a new boxplot figure (new fig. 3) which is showing the range of uncertainty for each glacier and for each parameter using the 100 best parameter sets.

The possible parameter range is also included in the boxplot figure (new fig. 3) by setting the limits of the y-axis to the parameter range.

The range of the objective functions is provided in table 3.

Page 11494

Line 21f. I'm not sure if using the mean parameter values really gives you good simulation results. Why don't you calculate the melt rates at the points for all sets of your ensemble as done for monthly and annual discharge as described in the results section? As already mentioned in the introduction section, I would recommend using some years of runoff and mass balance data to perform a split sample for validation of the model. The melt rates can be used as additional verification.

We agree. All of the 100 best model runs are now used in order to show the model performance (new fig. 4, 6, 7, 8, 9 and 10).

The median parameter values are now only used for validating the melt rates (new fig. 5), since the range of all model runs is small in this case and of minor importance.

Page 11495

Results

Line 6. Are these values the ensemble means of all ensemble parameter sets, as described in the last section? That should be mentioned (in text and figure 3).

It is true that these values represented the ensemble means of all ensemble parameter sets.

In the revised version this figure is not included anymore. It has been replaced by the new figures (new fig. 7 and 8) showing the range of all 'best 100' model runs.

Line 6-13. At Nigardsbreen, runoff data for nearly the whole period exists. These should to be used here to validate your results.

As mentioned above, additional validation of the daily discharge has been performed for the years 2011 and 2012. Only for these years, discharge data is available for all three catchments. Test have shown that for Nigardsbreen, model performance is similar for other years. Since daily discharge is difficult to illustrate for longer time series, we

restricted the validation to the year with data for all catchments, since it is easier to encounter differences in model performance between the catchments.

However, for the model performance of annual discharge from 1961-2012 (new fig. 7), all available measurements have been included.

Page 11496

Line 14. Why did you choose the period 1996-2012 at Alfotbreen for model validation? At Nigardsbreen, this data is also available. Why don't you show these results? Maybe this can be presented at monthly scale together in figure 8? It seems that some results are presented twice.

The period for Ålfotbreen was showing the model performance for discharge, since no melt rates are available for validation at this glacier.

However, as mentioned above, we included validation for both seasonal mass balances and daily discharge in the revised version.

Figure 7. Scale figure axes equal for easier understanding

This figure is not included in the revised version anymore, since model performance has been validated against seasonal mass balances (new fig. 4) and daily discharge (fig. 6). In addition, model performance of annual discharge is provided (new fig. 7).

Therefore, these scatter plot do not additional information anymore.

Page 11497

Line 1. Explain the choice of the time periods. Which parameter set is used for the calculations? Here, also the measured runoff data from Nigardsbreen should be used for comparison as they are available for both periods (Alfotsbreen in the second period).

The chosen time periods represent the two most recent decades. Between these two decades, the largest changes in discharge contribution components are visible during the last 50 years (see new fig. 8). For this reason, we want to evaluate the monthly changes in discharge and the contributing sources for these two decades.

As suggested here, in the new fig. 9 and 10 (old fig. 8/9) the measured discharge has been included.

Discussion

Page 11498

Line 13 and 24. Table 4 and 5 should be mentioned in the results section.

We agree. Both tables are now mentioned in the *Results* section.

Page 11499

Line 1. "that with"

corrected

Referee # 2

General comments:

1) The validation of the model performance could be improved. In my opinion it would be a lot more useful to compare simulated and measured discharge rates directly rather than monthly averages or scatter plots. A direct comparison in form of hydrographs and time series of sonic ranger measurements would reveal how the model actually performs during low flow and high flow. As an illustration of up to 40 years may not be very easy to illustrate in one figure, I would also suggest to discuss model validation for specific time periods (e.g. the 70's, the 80's, 90's ect.)?

The validation of the model performance has been improved:
In addition to the melt rates at two of the glaciers (new fig. 5), the seasonal mass balances have been validated for the period 2001-2012 (new fig. 4), and the daily discharge rates have been validated for the years 2011 and 2012 (for Storbreen only 2012) as hydrographs to illustrate how the model performs during high and low flow (new fig. 6).

2) In the introduction it is briefly mentioned that discharge from glaciated catchments provide water resources to hydropower dams in Norway. This statement is certainly true, but was not discussed in more detail and the results of the study could be put into the context of potentially declining water resources for hydropower production. What can be learned from the simulations? And is the model accuracy high enough to assess impacts on water availability for the downstream areas?

To this comment, which is mentioned several times in different ways below, we addressed in the following way:

We improved the manuscript by mentioning the importance for hydropower production in the future, both in the Introduction and the Conclusions. However, the focus of this study is about variations in past 50 years together with differences between three catchments in a west-east profile. Detailed projections of future developments of discharge and its contributing components are outside the scope of this study.

3) Structure of the manuscript: In my opinion the validation of model performance should be discussed before presenting the results. Accordingly I would first present all validation figures, then present the estimates of snow, glacier and rain contribution and finally put these results in context of potential effects on downstream water availability.

As suggested, the order of the paragraphs has been changed.

4) The model uncertainty in regard to the conclusion could be assessed and discussed. For instance, Finger et al. (2012) used the variance within the ensemble of 'good' simulations in order to assess the uncertainty and subsequently performed an analysis of variance to discuss the origin of uncertainty in the conclusions. A similar assessment could be performed here; subsequently the consequences of the results for stakeholders

in downstream areas could be discussed.

We illustrated the parameter uncertainty using a boxplot. The new boxplot figure (new fig. 3) is showing the range of uncertainty for each glacier and for each parameter using the 100 best parameter sets.

The possible parameter range is also included in the boxplot figure (new fig. 3) by setting the limits of the y-axis to the parameter range.

I believe that if the four points mentioned above are addressed adequately, the study would improve significantly, making it a substantial contribution to the ongoing discussion about snow glacier and rain contribution to downstream water resources. Accordingly, I would also suggest a more focused title, e.g: Assessing changes in the contribution of snow, glacier and rain to downstream water resources in three glaciated Norwegian catchments.

The suggested title would be focusing on the contribution changes. In the study, our aim is not restricted to assess the temporal changes, but also providing an overview of the contribution of the discharge components in different catchments. Changes over time are still smaller than changes between the catchments. Thus, in order to avoid confusion, we would like to keep the presented title.

Specific recommendations:

Abstract:

Ln2: it is rather the rate of glacier melt that influences stream flow, not the catchment itself

The sentence was reformulated to:

"Glacierised catchments show a discharge regime that is strongly influenced by snow and glacier meltwater."

Ln 6: does the model have a name?

The model does not have a name. It was developed by the main author based on algorithms available in the literature (e.g. temperature-index modeling by Hock, 2003).

Ln 16: to what does the % refer to? What is the reference for 100%?

For clarification, the expression "to total discharge" has been added here.

Ln 23: a general statement how these results contribute to hydrology would be helpful here.

An additional statement has been added here (in the abstract):

"Therefore, especially glaciers in more continental climate settings are vulnerable for decrease in both annual and summer discharge with continued rise of summer temperatures and subsequent decrease in glacier extent."

Introduction:

Ln26: This is a contradictory statement, as your own results show that rain contributes more than glaciers (fig 3)

It is true that contribution from rain is (mostly) larger than glacier melt, however the sum of the two components snowmelt and glacier melt is larger than rain.
For clarification, the sentence has been reworded to:
"In highly glacierised catchments meltwater constitutes a larger contribution to discharge than rain"

Pg11487

Ln 1: amplified or balanced? If it is both then it should be explained why, otherwise this statement is redundant

Both can be true, however not at the same time. If a glacier acts amplifying or balancing depends on the glacier cover and the season when the precipitations peaks.

For clarification, the sentence was reworded:

"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."

Ln4: 15% comes from glaciers? What is the reference? And if this has been assessed, did they also estimate contribution for the sites presented in this study?

It is not stated that 15% of the discharge comes from glaciers, but that "15% [of the hydropower production] is based on discharge from glacierised basins", which also includes rain and snowmelt outside the glacier area. There has not been performed an assessment on the discharge sources rain, snowmelt and glacier melt so far.

To avoid confusion, the sentence has been reworded and the information has been replaced by a more valuable information. It reads now:

"In Norway, 98% of the electricity is generated by hydropower (Gebremedhin and Granheim, 2012) and all catchments regulated for hydropower include 60% of the total glacier area" (Andreassen and Winsvold, 2012)."

Ln12: many studies demonstrated that in Europe glaciers only melt in late summer, in spring it is primarily snow melt

It is true that during spring it is mostly snowmelt contributing to discharge. To avoid confusion, the sentence was reformulated:

"Using climate model data as forcing, different studies indicate an increase of discharge in spring due to earlier onset of snowmelt, but a decline later in the year, due to reduced glacier extent (e.g. ...)."

Ln13: Here you may give a number on how much the glacier contribution is in large downstream watershed, as estimated by Huss

The following sentence has been added to provide more detailed information here:

"The study of Huss (2011) revealed, that for catchments with a size of 100 000 km^2 and 1% glacier cover in August the contribution of glaciers to discharge can be as high as 25 %.

Ln19: cite original references, the listed references surly did not apply a temperature-index model for the first time

The provided references intent to provide examples where temperature-index model have been employed.

We cannot cite the an original reference, since a relationship between air temperatures and melt rates was already used for an Alpine glacier by Finsterwalder and Schunk (1887).

However, a detailed analysis of temperature-index modeling in mountainous areas war carried out by Hock (2003). This reference was added after the following sentence:

"... (see Hock, 2003 for a review)."

Pg:11488

Ln1: 'better results' in regard to what?

The meaning was that a grid-based model yields better results than lumped models. However, since this is not generally true, the sentence has been reworded:

"Hydrological models for glacierised catchments have often been applied as grid-based models (e.g. ...)"

Ln7: What is the name of the model? Has it been newly developed? Has it been applied before? References?

As mentioned already above, the model does not have a name. It has been developed by the main author based on components well established in the provided literature. The mass balance part of the model has been applied for the glacierized parts of Norway in a previous study: (Engelhardt et al., 2013, Annals of Glaciology 54(63): 32-40).

Study sites

Ln18: As you present also data I suggest the following title: "study site and data"

As suggested the section title has been changes to "Study sites and input data".

Since the first sentence in the following section (Methods) suits better to "data", this sentence was moved to this new section 'Study sites and input data'.

Pg.11489

ln7: Fig2b should come before Fig2c

The figures 2b and 2c have been switched names.

Ln12: is this increase significant?

The sentence reads: "From the early 1990s to the 2000s all three sites experienced an increase in mean summer temperature by about 1-1.5 K."

This increase is not significant, however, we find it worth mentioning, since it coincides with an increase in glacier melt as discussed later.

Methods

Pg 11490

Ln3: Model name?

As mentioned above, the model does not have a name.

Furthermore, this sentence has been reworded to:

"For the study we used..."

Ln 6: a reference is needed at the end of the sentence, the following sentence is redundant

As suggested, the reference after the second sentence has been moved to the first sentence and the second sentence has been removed.

Ln10: valuable in regard to what?

The expression "valuable" has been replace with:

"suitable for mass-balance modeling"

Ln16: Units for equation is missing

The units for the variables has been added.

Ln17: S should be rather called deltaS

changed as suggested to ΔS

Pg11491
Ln 4: Q should be on the left side

changed as suggested

Pg11492
entire page: In accordance with reviewer 1, I also think that
the model description is poor. Who developed the model, was it used before, on what previous versions/models does it rely on: : : etc: : : if the model was newly developed. The authors might also consider submitting a complete description of the model as

non-print auxiliar material.

As stated above, the model has been developed by the main author. The mass balance part of the model has been applied for the glacierized parts of Norway in a previous study: (Engelhardt et al., 2013).

The model description (section 3.2) includes all processes relevant for reproducing the model results.

It is not the scope of the article to explain all these processes in more detail.

However, if one of the descriptions is not sufficient or gives room for misunderstandings or confusion, we are happy to elucidate it in even more detail.

Pg11493
Ln1-2: More detail is needed to describe how the model accounts for changes in glacier volume.

More information has been provided here:

"To account for 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."

Pg11494
Ln1: SMB needs to be described in more detail: : : is it every 100 m altitude band? How long are the seasons? Ect.

More information about the seasonal mass balance is provided in the beginning of the section 'Study sites and input data':

"... at each glacier, seasonal mass balance measurements have been carried out for more than 50 years (Andreassen et al., 2005) following the traditional stratigraphic method (Østrem and Brugman, 1991)."

In the mentioned passage, we added the expression:

"glacier-wide seasonal mass balances".

Calibration and validation

Ln24: the model is calibrated the model performance is validated; not the parameters

We agree. The name of the subsection has been changed to:

"Calibration of model parameters and validation of model performance"

Ln26: Calibration and validation periods are not defined

The calibration and validation periods have been added in the text.

Ln 17 to end: the validation of discharge needs to be explained here as well.

Information about validation has been improved:

"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."

Results

General comment on results: the numbers of increase may not be significant: a climatic change can only be observed between periods of about 30 years, otherwise it might just be due to inter-annual meteorological variability. I strongly recommend revising this entire section. This could be done along with the major comment. Finger et al. 2012 have done something similar. Also, long term trends in discharge may be discussed with measured discharge and compared to modeling results. However, the contribution of snow and glacier is highly interesting and can only be estimated with modeling.

The *Results* section has been revised. The order of the results has been changed and the results illustrated in the new figures are presented. For example, the long-term modeled annual discharge has been compared with available measured discharge (new fig. 7).

Discussion

The discussion is valuable and interesting, but the results from other studies should be put in context to the presented modeling results. Also, as stated in the major concerns above, the discussion section would improve if an assessment of the uncertainty regarding the estimations of snow, glacier and rain contribution was included. Furthermore, the relevance of the results for downstream water availability could be discussed. Why is this work necessary, what is novel?

More references have been added to put the results in context with other studies.

The uncertainty of the model parameters has been assessed (new fig. 3). The uncertainty of the estimated contributing sources (new fig. 8) provides the range among the best 100 model runs.

As mentioned in the response to the general comment, we improved the manuscript by mentioning the importance for hydropower production in the future, both in the Introduction and the Conclusions. However, the focus of this study is about variations in past 50 years together with differences between three catchments in a west-east profile. Detailed projections of future developments of discharge and its contributing components are outside the scope of this study.

Pg11498

Ln13: Just because the correlation coefficient for T is biggest for Storbreen does not necessary proof that glacier melt is most sensitive to temperature.

The expression 'sensitivity' has been changed to 'correlation':

"Among the three study sites, the correlation of glacier melt to temperature changes is largest on Storbreen (Table 4)."

Conclusions

Pg11499

Ln24: why are differences due to increasing climate continentality? What differences are meant?

We mean the differences in seasonal discharge and interannual variations between the catchments.

The sentence has been reworded. It now reads:

"Differences between the catchments in the seasonal discharge regimes and in year-to-year variability can 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."

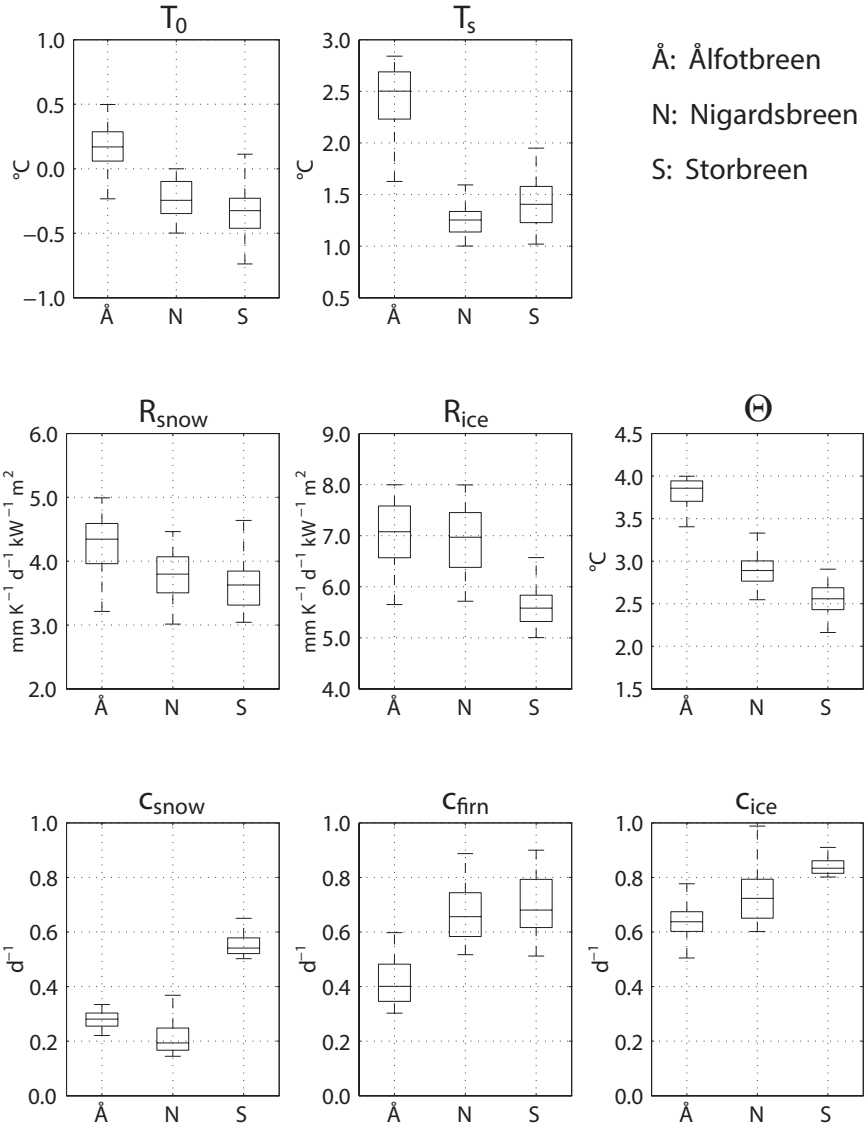

Fig. 3. Parameter uncertainty of the 100 best runs. In each box, the central mark is the median, the edges of the box are the 25^{th} and 75^{th} percentiles, the whiskers extend to the most extreme data points. The ordinate indicate the parameter range in the calibration scheme. Parameter description and median values are given in Tab. 3.

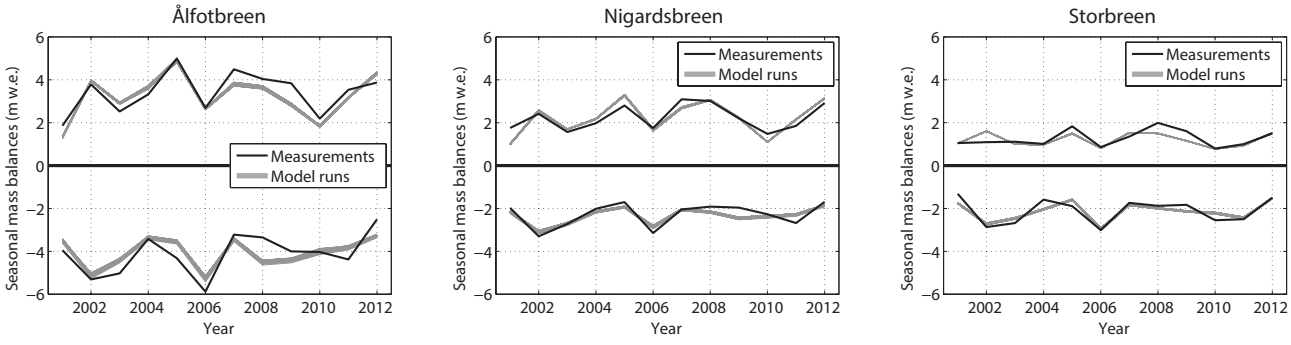

Fig. 4. Model performance for seasonal glacier mass balances for the three catchments for the validation period 2001-2012.

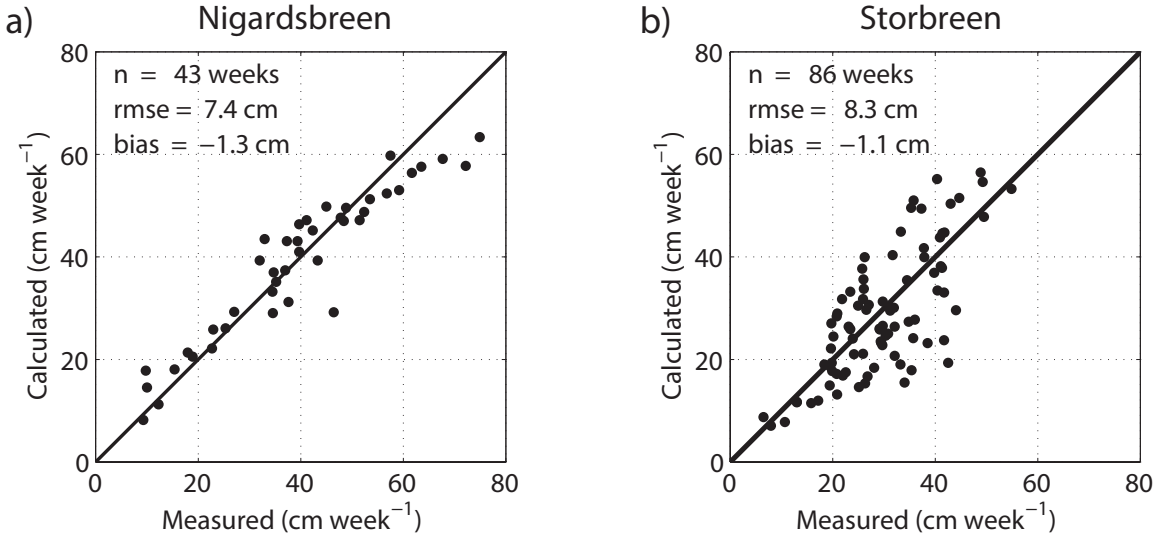

Fig. 5. Model performance for weekly melt at the sonic ranger position of Nigardsbreen (2011-2012) and Storbreen (2002-2012). Data for the modelings represent the mean of the best 100 model runs.

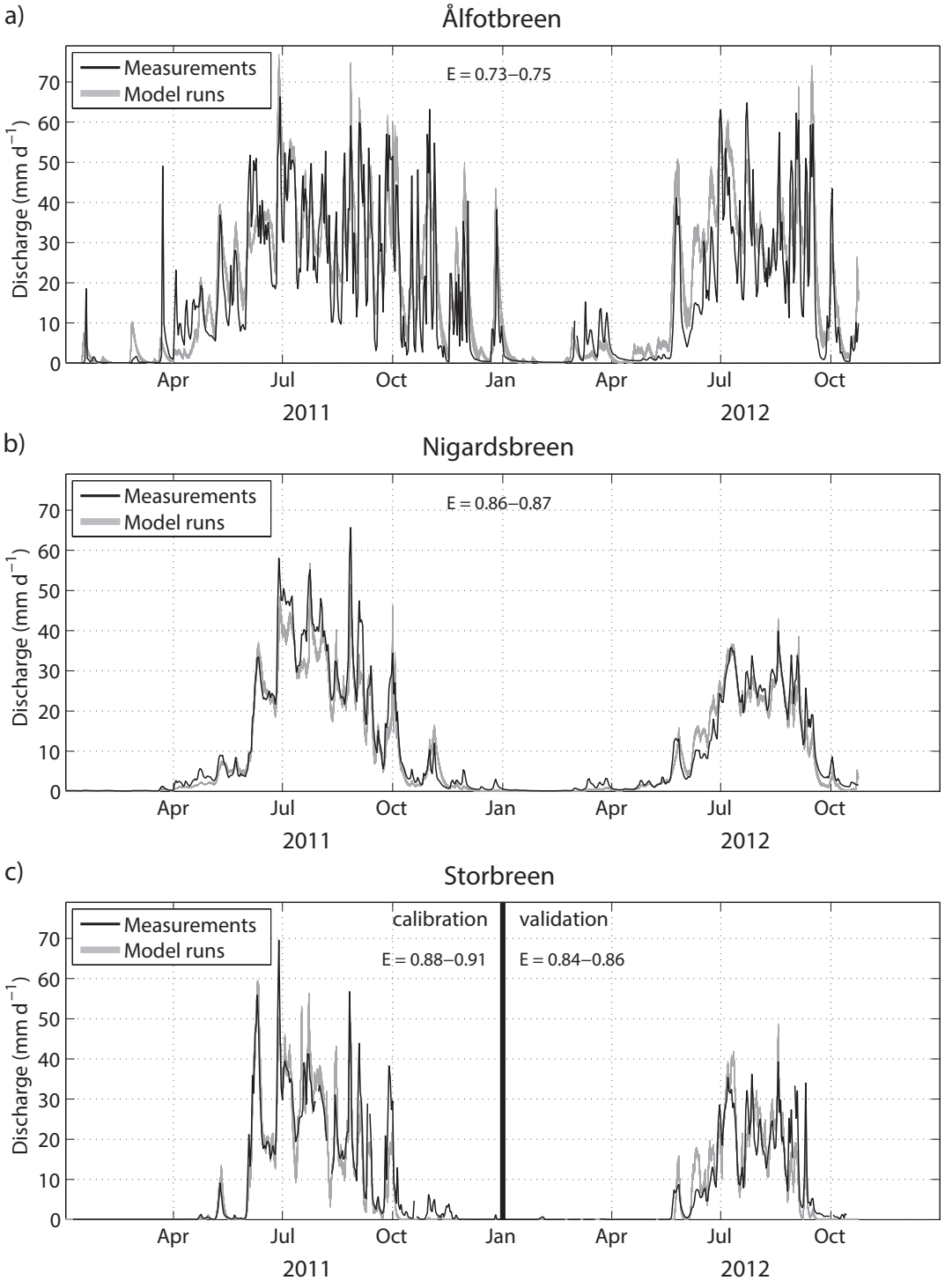

Fig. 6. Model performance for daily discharge sums at the three catchments for the validation years 2011 and 2012. Note: At Storbreen, daily discharge for 2011 is used for calibration, and 2012 for validation.

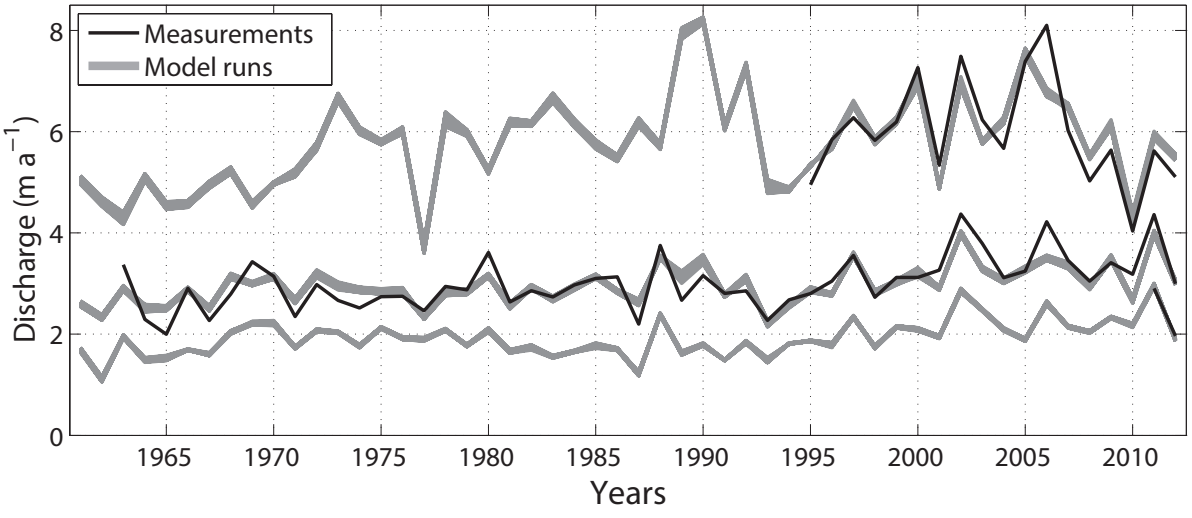

Fig. 7. Mean annual discharge sums for the catchments of Ålfotbreen (upper lines), Nigardsbreen (center lines) and Storbreen (lower lines) for the period 1961-2012.

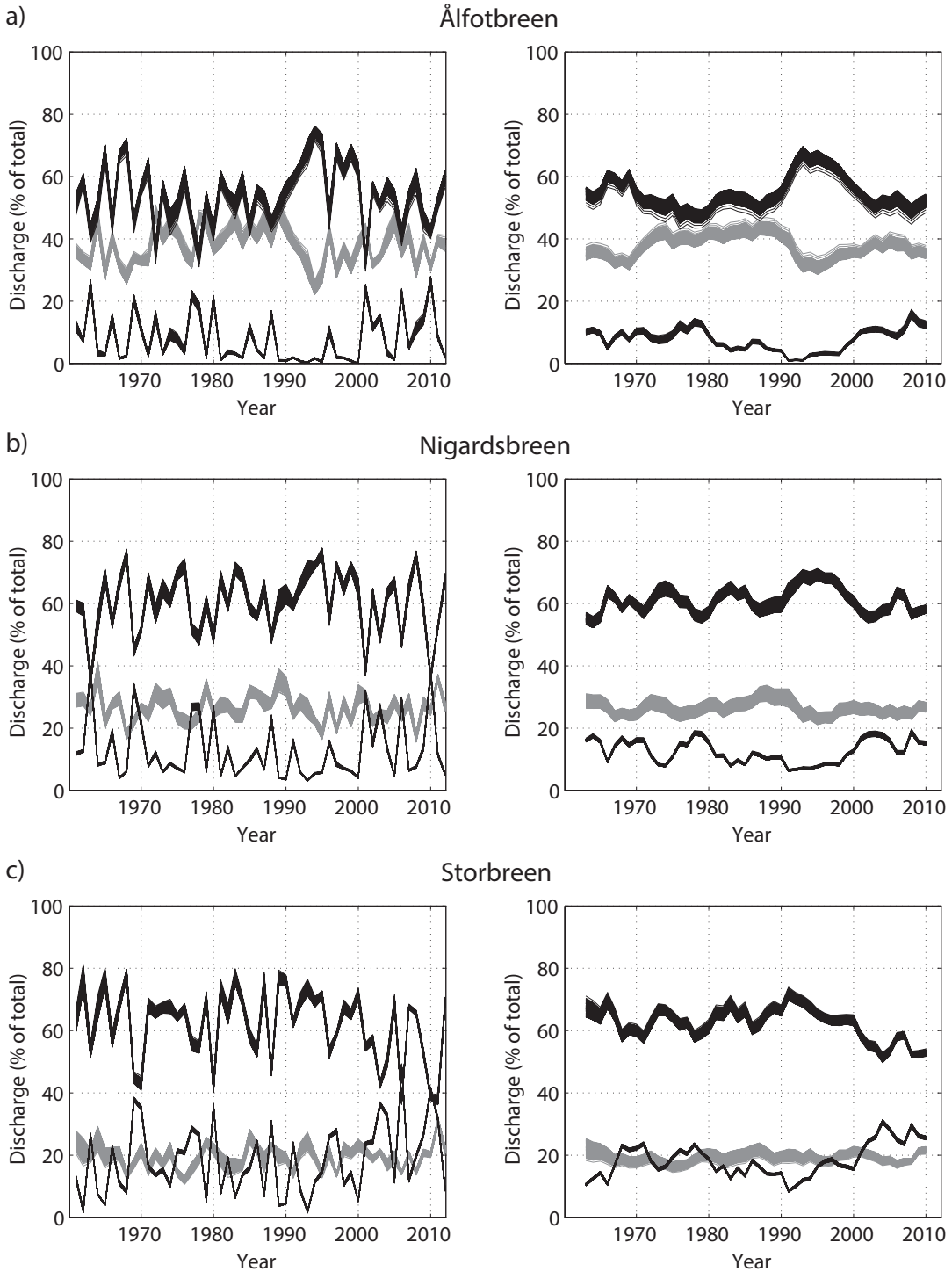

Fig. 8. Relative proportions of the contributing sources to the annual discharge (left column), and the respective 5-year moving average (right column). Snowmelt is represented by the upper black lines, glacier melt by the lower black lines and rain by the grey lines.

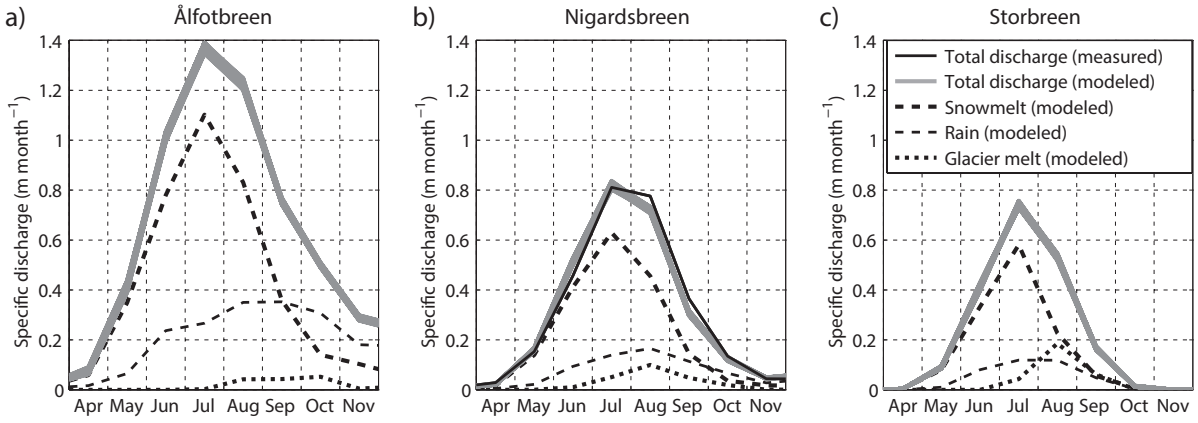

Fig. 9. Modeled monthly discharge rates and their contributing sources for Ålfotbreen, Nigardsbreen and Storbreen averaged for the period 1991-2000. Data for the contributing sources represent the mean of the best 100 model runs.

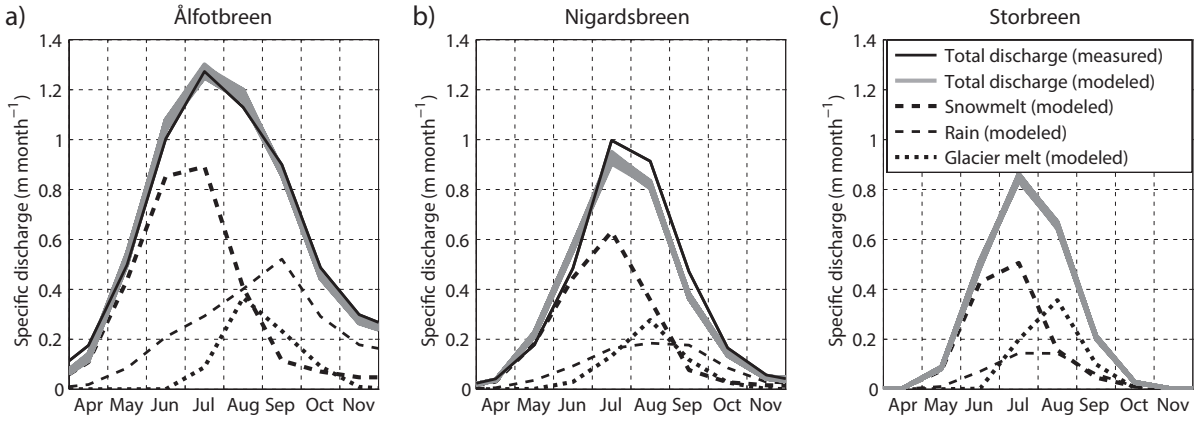

Fig. 10. Modeled monthly discharge rates and their contributing sources for Ålfotbreen, Nigardsbreen and Storbreen averaged for the period 2001-2010. Data for the contributing sources represent the mean of the best 100 model runs.

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

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

	Ålfotbreen	Nigardsbreen	Storbreen
Period (hydrological years)	1995-2012	1963-2012	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_{c}	1.06	1.00	0.87
CF_{g} (from *Engelhardt et al., 2012)*	1.01	1.00	0.80
CF_{ng}	1.13	0.99	1.00

Table 3. Median of the 100 best parameter sets and model performance (coefficients of variation for seasonal mass balances and 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	-

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	0.75
Annual precipitation sum (October-September)	-0.76	-0.88	-0.66
Winter precipitation sum (October-April)	-0.67	-0.85	-0.66

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