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Modelling annual mass balances of eight Scandinavian glaciers using statistical models

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Abstract

Glacier mass balances are mainly influenced by accumulation-season precipitation and ablation-season temperature. We use a suite of statistical models to determine the influence of accumulation-season precipitation and ablation-season temperature on annual mass balances of eight Scandinavian glaciers, ranging from near coastal, maritime glaciers to inland, continental glaciers. Accumulation-season precipitation is more important for maritime glaciers, whereas ablation-season temperature is more important for annual balances of continental glaciers. However, the importances are not stable in time. For instance, accumulation-season precipitation is more important than ablation-season temperature for all glaciers in the 30 year period 1968–1997. In this time period the Atlantic Multidecadal Oscillation (AMO) index was consistently negative and the North Atlantic Oscillation (NAO) Index was consistently positive between 1987 and 1995, both being favourable for glacier growth. Hence, the relative importance of precipitation and temperature for mass balances is possibly influenced by the AMO and the NAO.

Climate sensitivities estimated by statistical models are similar to climate sensitivities based on degree-day models, but are lower than climate sensitivities of energy balance models. Hence, future projections of mass balances found with our models seem rather optimistic. Still, all average mass balances found for the years 2050 and 2100 are negative.

1 Introduction

Glaciers respond to climate change because their mass balance and extent are mainly a result of variations in winter accumulation and ablation-season temperature. Over time, glacier changes exhibit some of the clearest evidence of variations in the Earth's climate system. As a result, glaciers are a key indicator of global, regional and local climate change (IPCC, 2007, 2013).

The winter accumulation on Norwegian glaciers is mainly a result of precipitation (as snow) and wind redistribution of snow during the winter season. Glacier ablation is more complex and depends on the total energy available for melt. These processes have been extensively studied by means of physically based mass balance models (Andreassen et al., 2006; Andreassen and Oerlemans, 2009; Giesen and Oerlemans, 2010; Laumann and Nesje, 2009a, b, 2014; Oerlemans, 1992, 1997). Physically based mass balance models take into account the different accumulation and ablation processes, model the ice flow and take into consideration the hypsometry of a glacier. They therefore need reasonable parameterisation requiring extensive calibration and they are therefore time-consuming to set up and run. This is avoided by using statistical models (Steiner et al., 2005; Vincent et al., 2004; De Woul and Hock, 2005) that are not modelling processes, but are looking for least-squares or maximum likelihood parameter estimates to model dependent variables as function of independent variables. Statistical models can again be divided into two different groups: (i) temperature-index models (De Woul and Hock, 2005), that use positive degree-day sums and “sums of daily precipitation with air temperatures below the threshold temperature which discriminates rain from snowfall” (Hock et al., 2007), and (ii) models that use seasonal or monthly mean temperatures and precipitation that implicitly assume a fixed length of accumulation and ablation season (Steiner et al., 2005; Vincent et al., 2004). All statistical models require little calibration and are therefore rapid to run.

When modelling the joint influence of ablation-season temperature and accumulation-season precipitation on annual mass balance, statistical models allow for assessing the individual influence of ablation-season temperature and accumulation-season precipitation on annual mass balance. In this study, we focus on assessing the influence of accumulation-season precipitation and ablation-season temperature on annual mass balances. The aims of this study are therefore threefold:

i. Modelling the annual mass balances of eight Scandinavian glaciers with long annual mass balance series using a suite of statistical models using seasonally averaged climate data as input variables. These models enable us to compare the relative importances of accumulation-season precipitation and ablation-season temperature on annual mass balances of glaciers.

ii. Assessing temporal changes of relative importances of accumulation-season precipitation and ablation-season temperature. These temporal changes are then compared to large-scale oceanic and atmospheric modes, such as the Atlantic Multidecadal Oscillation (AMO) and the North Atlantic Oscillation (NAO).

iii. In a last step we compare the climate sensitivities of ablation-season temperature and accumulation-season precipitation of statistical models to results from other modelling approaches, namely temperature index models and physically based models. We then used the mass balance models and climate projections for the years 2050 and 2100 to predict average annual mass balances for these years.

2 Data and methods

2.1 Data

We modelled the mass balances of eight glaciers in Scandinavia, Ålfotbreen (ALF), Rembedalskåka (REM), Nigardsbreen (NIG), Storbreen (STO), Hellstugubreen (HEL), Gråsubreen (GR) in southern Norway and Engabreen (ENG) and Storglaciären (STORGL) in northern Norway and northern Sweden, respectively (Fig. 1). Storglaciären has the longest annual mass balance time series, beginning in 1946 and Engabreen has the shortest time series, initiated in 1970. For all glaciers, data until 2010 was considered. Glacier mass balance data are available at www.nve.no/bre, (Andreassen and Winsvold, 2012) and bolin.su.se/data/tarfala. For all glaciers, winter balances, summer balances and annual balances are available.

For modelling mass balances in southern Norway, we used meteorological data from the meteorological station Bergen-Florida that is available for the entire period of mass balance measurements. We decided to exclusively use precipitation data from Bergen-

Florida for all glaciers in southern Norway since Bergen-Florida records the large synoptic weather systems and is not affected by local topographic effects that are affecting meteorological stations in the deep and narrow valleys closer to the glaciers studied (e.g. Nesje, 2005). For glaciers in northern Scandinavia, we used meteorological data from the coastal station Glomfjord available from the beginning of the mass balance series. The temperature measurements are continuous, but the precipitation series ends in 2003. We extended the precipitation series with data from the nearby Bodø meteorological station. The precipitation data from Bodø was scaled to the data from Glomfjord in the period of overlap (1953–2003) of the two data series.

2.2 Methods

Our main objective was to model annual glacier mass balances and to quantify importances of accumulation-season precipitation and ablation-season temperature on annual mass balances.

A first qualitative measure for assessing the importance of accumulation-season mass balance and ablation-season mass balance on the annual mass balance is to correlate the seasonal balances with the annual mass balance (Nesje et al., 2000). The exact assessment of relative importance of accumulation-season precipitation and ablation-season temperature on annual mass balances is not possible with this method.

For modelling annual mass balances, we compared three statistical models with increasing complexity and number of parameters that need to be estimated:

i. linear models using a climate index as independent variable;

ii. linear models using temperature and precipitation as independent variables;

iii. additive models using temperature and precipitation as independent variables.

If the variance explained by two models was not significantly different, we favoured the simpler model, as it was more parsimonious.

Since glaciers are mainly sensitive to ablation-season temperatures and accumulation-season precipitation, models were calculated using one ablation-season temperature and one accumulation-season precipitation as independent variables. We tested the influences of two ablation-season temperatures, namely temperatures from May to September (T MJJAS) and temperatures from June to August (T JJA), and two accumulation-season precipitation variables, precipitation October to April (P OND-JFMA) and precipitation from November to March (P NDJFM) on annual glacier mass balances. This resulted in a total of four possible combinations of input variables. We chose the combination that resulted in lowest Akaike information criterion (AIC).

2.2.1 Climate indices

The simplest way of modelling the joint influence of precipitation and temperature on glacier mass balances is to generate a climate index, where accumulation-season precipitation and ablation-season temperature are equally weighted (Imhof et al., 2012; Nesje, 2005). This was achieved by standardising the two environmental variables and subtracting standardised temperature from standardised precipitation, as the two variables have opposed influences.

$$z = \left(\frac{\boldsymbol{P} - \overline{P}}{s_P}\right) - \left(\frac{\boldsymbol{T} - \overline{T}}{s_T}\right) \quad (1)$$

$$\boldsymbol{y} = a + b \cdot z \quad (2)$$

where z is the climate index, $\boldsymbol{P}$ accumulation-season precipitation, $\boldsymbol{T}$ ablation-season temperature, s are SDs, bars denote means, $\boldsymbol{y}$ is the annual mass balance and a and b are regression coefficients.

2.2.2 Linear models

Annual mass balances were modelled by linear models with one temperature and one precipitation variable as independent variables. In a first step, we tested interactions between temperature and precipitation and quadratic terms for significance. F tests indicated that neither interaction terms, nor quadratic terms were significant ($p < 0.05$).

The linear regression equation

$$\boldsymbol{y} = a + b_1 \cdot \boldsymbol{x}_1 + b_2 \cdot \boldsymbol{x}_2 \tag{3}$$

is interpreted as follows: if $\boldsymbol{x}_2$ is kept constant and $\boldsymbol{x}_1$ is changed by one unit, $\boldsymbol{y}$ changes by b_1 units (e.g. Legendre and Legendre, 2012). Hence the regression coefficients of unscaled variables are as well the climate sensitivity of this variable. Usually, $\boldsymbol{x}_1$ and $\boldsymbol{x}_2$ are measured in different units, which hampers the comparison of the influence of the two variables on $\boldsymbol{y}$. This problem is, however, solved by standardising all the variables. The effect of standardisation is two-fold:

i. the intercept of the regression model is zero, and more importantly,

ii. the partial regression coefficients are now comparable and are a "means of assessing the relative importance of each explanatory variable x_j included in the regression model: the variables with the highest standard regression coefficient (in absolute values) are those that contribute the most to the estimated $\dot{y}$ values" (Legendre and Legendre, 2012).

Hence the ratio b_1/b_2 is a measure of relative importance of the two independent variables.

For standardized variables, calculus with

$$\mathbf{B} = (\mathbf{X}' \cdot \mathbf{X})^{-1} \cdot (\mathbf{X}' \cdot \mathbf{Y}) \tag{4}$$

as starting point (Legendre and Legendre, 2012) proofs that the partial regression coefficients are estimated as:

$$b_1 = \frac{r_{x_1y} - r_{x_1x_2} \cdot r_{x_2y}}{1 - r^2_{x_1x_2}} \tag{5}$$

$$b_2 = \frac{r_{x_2y} - r_{x_1x_2} \cdot r_{x_1y}}{1 - r^2_{x_1x_2}} \tag{6}$$

and hence the ratio of the two relative importance is calculated as

$$\frac{b_1}{b_2} = \frac{r_{x_1y} - r_{x_1x_2} \cdot r_{x_2y}}{r_{x_2y} - r_{x_1x_2} \cdot r_{x_1y}}. \tag{7}$$

The significance of the partial regression coefficients and differences between partial regression coefficients was assessed using *t* tests and linear models were compared to models based on climate indices using *F* tests.

The difference between the linear models and the climate index is that accumulation-season precipitation and ablation-season temperature are individually weighted when using linear models, whereas the two independent variables are equally weighted when employing the climate index.

2.2.3 Additive models

In contrast to linear models, where coefficients link independent and dependent variables, this linking is achieved by a smoothing term in additive models

$$\boldsymbol{y} = a + f_1(\boldsymbol{x}_1) + f_2(\boldsymbol{x}_2) \tag{8}$$

(Zuur et al., 2009) (see as well Fig. 4). We used cubic regressions splines with three knots as smoothing terms. The number of knots was kept low to ensure monotony of the smoothing terms. The additive models were compared to linear models and climate index models by *F* tests.

2.2.4 Cross-validation and analysis in running windows

All the models were tested by calculating leave-one-out cross-validation (jack-knifing) and *h*-block cross-validation (Burman et al., 1994) where *h*-samples are left out on either side of the sample to be predicted. In this study we set *h* to 2. *h*-block cross-validation is a powerful method to test effects of temporal autocorrelation in time-series. However, preliminary autocorrelation calculations revealed no significant ($p < 0.05$) AR1 autocorrelation coefficients. We calculated cross-validated mean absolute deviations and coefficients of determination.

After calculating models for the entire observation period, we also calculated models for 30 year moving windows. The significance of changes in variance explained was again tested with *F* tests. According to these tests, additive models were never superior to linear models.

Analysis in running windows usually needs many statistical tests, resulting in a multiple testing problem. This problem is avoided by using Bayesian inference. We used the simplest possible Bayesian model, namely setting a uniform prior for the two partial regression coefficients for accumulation-season precipitation and ablation-season temperature. This results in posterior distributions for the parameter estimates that are proportional to the maximum likelihood estimates of the parameter values. In contrast to confidence bounds of maximum likelihood estimation, Bayesian credible intervals are simple to interpret and indicate the parameter space within which a parameter is found with a certain probability.

2.2.5 Comparison to climate modes

Two main modes of variability influence the climate in the North Atlantic realm. The North Atlantic Oscillation (NAO), an atmospheric pattern with an approximately decadal cyclicity (Hurrell et al., 2001; Wanner et al., 2001) and the Atlantic Multidecadal Oscillation (AMO), a pattern in sea-surface temperature that is linked to changes in thermohaline ocean circulation with a cyclicity of 65–70 years (Schlesinger and Ramankutty, 1994; Trenberth and Shea, 2006) The NAO mainly influences the strength and tracks of the westerlies and thereby the amount of winter precipitation in north-western Europe. As most of the glacier mass balance series investigated are not longer than 50 years, we investigated the effects of changes in NAO by dividing the time series into two sections with NAO-indices above and below the median of the NAO-index for the period, in which mass balance measurements were available. We calculated mass balance models for these periods and correlated the NAO-index with accumulation-season mass balances and annual mass balances. Considering the period 1946–2010, the average monthly November through April precipitation for the phase with above median NAO-index was 230 mm and significantly ($p < 0.05$) lower in the phase with below median NAO-index precipitation of 170 mm.

The longest mass balance series started in 1946. The AMO is generally positive from ca. 1930 to 1962 and from 1997 to the present, whereas it was negative between 1963 and 1996. In the negative phase of the AMO, the correlation between the NAO-index and extended winter precipitation in Bergen is $r = 0.82$, whereas it is $r = 0.56$ for the years with predominantly positive AMO-index. The average November through April precipitation is not differing between the two phases ($200\,\mathrm{mm\,month^{-1}}$). The average May through September temperature from Bergen-Florida for the positive AMO phase was 14.4 °C, whereas it was 12.6 °C in the negative AMO phase. Average T MJJAS for the period 1949–1962 was 13.8 °C, which is as well significantly ($p < 0.05$) higher than the average temperature in the negative AMO phase.

Since we have two long data series starting in 1946 and 1949, respectively, we wanted to assess possible changes in the influence of accumulation-season precipitation and ablation-season temperature on the annual mass balances change in the phases of predominantly positive and negative AMO.

2.2.6 Future projections

Projections for future climate for Norway were taken from the governmental report “Klima i Norge 2100” (Climate in Norway in 2100, Hanssen-Bauer et al., 2009).

For southern and northern Norway, climate model-based scenarios indicate a mean summer temperature change of +1.3 °C (low estimate: +0.7 °C; high estimate: +1.9 °C) and +2.3 °C (+1.2; +3.5 °C) in 2050 and 2100, respectively, relative to the 1961–1990 mean (http://www.miljodirektoratet.no). Winter precipitation scenarios for southern Norway indicate an increase of 12 % (+4; +22 %) and +22 % (+7; +40 %) in 2050 and 2100, respectively (relative to the 1961–1990 mean). For northern Norway, an increase of 6.5 % (−6; +21 %) and +12 % (−12; +39 %) in 2050 and 2100, respectively (relative to the 1961–1990 mean) are estimated (http://www.miljodirektoratet.no).

For each glacier, the most parsimonious model (input variables and model type, Table 1) was used to predict future mass balances. Uncertainties were calculated as confidence bounds of the mean and not as uncertainties of individual predictions, since the projections are climatologies, i.e. 30 year normals. For all the temperature variables, projected changes of summer (JJA) temperatures were used as independent variables and for all precipitation variables projected changes of winter (DJF) precipitation were used as independent variables. Future average annual mass balances were calculated for all nine possible combinations of projected temperatures and precipitation.

All calculations were done in R (R Core Team, 2014) and its add-on packages lmodel2 (Legendre, 2014) and mgcv (Wood, 2014).

3 Results

Cumulative mass balance changes are shown in Fig. 2. The three maritime glaciers Ålfotbreen (ALF), Rembesdalsskåka (REM), and Nigardsbreen (NIG) in southern Norway and the maritime glacier Engabreen (ENG) in northern Norway show positive cumulative net balances between the initiation of the measurements and 2010 (Fig. 2). Mass balances are especially positive during the first half of the 1990s. The continental glaciers Storbreen (STO), Hellstugubreen (HEL), and Gråsubreen (GR) in southern Norway and the continental glacier Storglaciären (STORGL) in northern Sweden experienced negative cumulative mass balances between the start of the measurements and 2010. For these glaciers the mass balance loss was reduced in the first half of the 1990s.

The influence of the winter mass balance on the annual mass balance is stronger than the influence of the summer mass balance for the four maritime glaciers Ålfotbreen, Rembesdalsskåka, Nigardsbreen and Engabreen, whereas the summer balance is more important for the continental glaciers Storbreen, Hellstugubreen, Gråsubreen and Storglaciären (Fig. 3).

The employed statistical models explained large proportions of the variance of annual balances (Table 1). For the maritime glaciers, the models explained more than 70 % of the variance. The variance explained for continental glacier varied between 50 and 70 %. Table 1 shows input variables, model types, variance explained by the most parsimonious models and partial regression coefficients of linear models and their standard errors. For Storbreen, Engabreen and Storglaciären, the statistical models using climate indices as input variables were most parsimonious. These are the only glaciers where partial regression coefficients of linear models were not significantly different. Hence, linear models were as well assigning about similar weights to ablation-season temperature and accumulation-season precipitation for these three glaciers. For the maritime glaciers Rembesdalsskåka and Nigardsbreen, linear models indicated a higher relative importance of accumulation-season precipitation than of ablation-season temperature, whereas for the continental glaciers Hellstugubreen and Gråsubreen, the relative importance of ablation-season temperature was higher than the relative importance of accumulation-season precipitation. For the maritime Ålfotbreen, an additive model was explaining significantly ($p < 0.05$) more of the total variance than a linear model. The smooth terms of ablation-season temperature and accumulation-season precipitation are shown in Fig. 4. The slope of the smooth for temperature was flatter than the slope of a linear model for below average temperatures and steeper than the slope of a linear model for above average temperatures. Hence the expected sensitivity of the annual mass balance for a change of 1 °C increased with increasing temperatures. In contrast, the slope of the smooth for precipitation was steeper than the slope of a linear model for below average precipitation values and was flatter than the slope of a linear model for above average precipitation levels. The expected sensitivity of the annual mass balance for a change in precipitation decreased with increasing precipitation.

Cross-validated r^2 using leave-one-out cross-validation and h-block cross-validation were comparable to apparent r^2. The only exception was Ålfotbreen, where F tests indicate that an additive model was most parsimonious. Cross-validated r^2 was reduced by 0.1, i.e. the variance explained was reduced by 10 % and linear models had higher r^2 under cross-validation. Cross-validated mean absolute deviations were as well lowest for the models chosen, except for Ålfotbreen, where again linear models yielded lowest mean absolute deviations.

Considerable changes in the relative importance of summer temperature and winter precipitation were found through time. For 30 year windows ending between 1993 and 1997, the relative importance of accumulation-season precipitation was increased compared to ablation-season temperature for glaciers in southern Norway (Figs. 5b and 6). The Bayesian credible intervals of the partial regression coefficients of accumulation-season precipitation and ablation-season temperature for the maritime glaciers Ålfotbreen, Nigardsbreen and Rembesdalsskåka were not overlapping up to the early 2000s. For the continental Storbreen, Gråsubreen and Hellstugubreen, the relative importance of ablation-season temperature increased in the late 1990s and got higher than the relative importance of accumulation-season precipitation in the 2000s.

The relative importance of accumulation-season precipitation was lowest at the end of the observation period. Variance explained remained fairly constant for all the time windows, but the importance of ablation-season temperature increased through time, while the correlation between ablation season temperature and accumulation season precipitation remained low (see Eqs. 5 and 6 for effects of correlations). The two glaciers with the longest mass balance series Storbreen and Storglaciären indicated about equal importance of accumulation-season precipitation and ablation-season temperature for 30 year windows prior to 1975.

For phases with above median NAO, models for Ålfotbreen, Rembesdalsskåka, Nigardsbreen and Storbreen explained as much of the variance of the mass balance as models for the entire data series, whereas for Hellstugubreen and Gråsubreen, the variance explained was reduced compared to the models for the entire period. Interestingly, for Ålfotbreen partial regression coefficients for accumulation-season precipitation and ablation-season temperature were not significantly ($p < 0.05$) different. For the phase with below median NAO-index, models for Ålfotbreen, Rembesdalsskåka and Nigardsbreen explained less of the variance than in the entire period and partial regression coefficients for precipitation and temperature were not significantly ($p < 0.05$) different, whereas models for Gråsubreen and Hellstugubreen explained more of the variance than in the entire period, and together with Storbreen displayed a higher importance of ablation-season temperature than accumulation-season precipitation. The two glaciers with long data series had an average mass loss of 0.54 m water equivalents per year ($\mathrm{m\,w.e.\,yr^{-1}}$) when the NAO was low, but an average gain of 0.03 $\mathrm{m\,w.e.\,yr^{-1}}$ for Storglaciären and an average loss of 0.08 $\mathrm{m\,w.e.\,yr^{-1}}$ for Storbreen with high NAO.

Correlations between NAO-index and accumulation season balance and annual balance respectively were as well different for phases with above median NAO-index and below median NAO-index (Fig. 7), with higher correlations for the phase with above median NAO-index.

The mass balance models for positive and negative AMO were differing for Storbreen in southern Norway (Table 1), whereas they remained unchanged for Storglaciären in northern Sweden. For Storbreen, the influence of accumulation-season precipitation was significantly higher than the influence of ablation-season temperature with negative AMO-index, whereas the situation was opposite with positive AMO-index (Table 1). For both glaciers, the average annual mass balance was different in the two phases defined by positive and negative AMO indices: Storbreen lost an average of 0.5 $\mathrm{m\,w.e.\,yr^{-1}}$ and Storglaciären 0.48 $\mathrm{m\,w.e.\,yr^{-1}}$ when the AMO-index was positive, whereas the loss was reduced to averages of 0.15 and 0.02 $\mathrm{m\,w.e.\,yr^{-1}}$ for Storbreen and Storglaciären, respectively, when the AMO-index was negative.

Climate sensitivities of models and mass balance projections

Climate sensitivities of the linear models are given in Table 2 and the smooth terms of Ålfotbreen that are in fact the curves of climate sensitivity are shown in Fig. 4. Additionally, we display the smooth terms of an additive model for Storbreen in Fig. 4b, as Storbreen is the only glacier where additive models show non-linearities when using the optimal input variables. Mass balance projections for (average) climate projections in 2050 and 2100 are shown in Fig. 8. All the average mass balances are negative in 2050 as well as in 2100.

4 Discussion

Our results showed, as also demonstrated in other studies (Andreassen and Oerlemans, 2009; Giesen and Oerlemans, 2010; Laumann and Nesje, 2009a, b, 2014; Oerlemans, 1992), that the annual glacier mass balance on near coastal, maritime glaciers was mainly controlled by the accumulation-season precipitation and the annual mass balance on the inland, continental glaciers were mainly controlled by ablation-season temperature (Andreassen et al., 2005; Nesje et al., 1995). But, most importantly, as shown in this study, the importance of accumulation-season precipitation and ablation-season temperatures for annual mass balance was changing through time (Fig. 5).

For instance, maritime glaciers had a consistently positive mass balance between 1988 and 1996 and continental glaciers were no longer loosing mass (Nesje et al., 2000; Nesje and Matthews, 2012). Looking at the 30 year window from 1967 to 1996, we found that the absolute value of the partial regression coefficient of accumulation-season precipitation was higher than the absolute value of the partial regression coefficients of ablation-season temperature for all glaciers, including the continental glaciers. This means that accumulation-season precipitation was more important than ablation-season temperature for all the glaciers in this particular time period, although the differences were not significant for the continental Gråsubreen. In this phase, the AMO-index was consistently negative and the NAO-indexes were consistently positive between 1988 and 1996 (Fig. 5). In tendency, negative AMO indices were associated with reduced summer temperatures over Europe and positive NAO-indexes were associated with increased zonal flow in winter, entailing more winter precipitation in Northern Europe. Hence, the large-scale oceanic and atmospheric patterns were favourable for glacier growth.

As another example, in the 2000s all glaciers except Engabreen and Nigardsbreen generally experienced negative mass balances and mass balances of Engabreen and Nigardsbreen were at equilibrium. In this period, the importance of ablation- season temperature for the annual mass balance was increased (Fig. 5). The AMO-index changed sign in the late 1990s and summer temperatures where in general higher than between 1985 and 1995.

For glaciers in the European Alps, Huss et al. (2010) found pronounced mass loss during phases of positive AMO-index and mass gain in phases of negative AMO-index, which is similar to finds in this study. The phases of increased glacier melt are, however, not simultaneous in the Swiss Alps and in Scandinavia. In the Swiss Alps, a pronounced mass loss lasting to the present started in the late 1980s, whereas glacier melt in Scandinavia started in the early 2000s. This is most probably caused by the fact that changes in melt rates are most influential for mass balances in the Alps (Huss et al., 2010), whereas a decade with predominantly positive NAO-indexes began in the late 1980s (1988/1989 winter) associated with increased relative importance of accumulation-season precipitation for Scandinavian glaciers (Fig. 5).

Clear differences are found between the phases with above median and below median NAO-index. In winters with high NAO-index, stronger westerly flow and increased precipitation is expected. For all glaciers, the correlation between NAO-index and accumulation-season and annual mass balance was higher during above median NAO-index. The mass balance models of the maritime glaciers explained more of the total variance with high NAO-index and the relative importance of accumulation-season precipitation for the total mass balance was increased. This was according to expectations, as increased winter precipitation is expected to increase the importance of the accumulation-season precipitation for mass balance models.

For the two glaciers with long mass balance time-series, the influence of NAO seemed equal to the influence of the AMO, since the difference between the average mass balances in the two NAO levels considered was about equal to the difference in the two AMO states. The AMO states only include consecutive years, whereas individual years were assigned to the NAO-index. The phase between ca. 1987 and 1995 with major mass gain for maritime glaciers and neutral mass balances for continental glaciers was characterised by negative AMO-index and predominantly positive NAO-index, that were both favourable for glaciers.

The relation between AMO and NAO seems rather complex and depends on the time scale considered (Li et al., 2013; Peings and Magnusdottir, 2014). On short time scales, the atmospheric NAO pattern influences the sea surface temperature, whereas on longer time scales, the sea-surface temperature AMO pattern drives the atmospheric NAO. Hence Li et al. (2013) find the NAO to lead the AMO by 16 years and state that the NAO is an excellent predictor for AMO and thereby Northern Hemisphere temperature, whereas Peings and Magnusdottir (2014) find "that the multidecadal fluctuations of the wintertime North Atlantic Oscillation (NAO) are tied to the AMO, with an opposite signed relationship between the polarities of the AMO and the NAO. Our statistical analyses suggest that the AMO signal precedes the NAO by 10–15 years [. . .]"

The association of negative AMO and positive NAO seems to be typical (Peings and Magnusdottir, 2014), whereas positive AMO favours negative NAO and blocking situations. For the time period 1965–1998, with negative AMO only 10 years had a negative NAO-index, whereas for the considerably shorter phase 1999–2010 already 6 years had a negative NAO-index. Hence, the two modes favouring glacier mass gain and mass loss, respectively, tended to occur simultaneously. However, the influence of AMO and NAO should not be overestimated, as similar weather patterns still result in different amounts of precipitation and in different levels of temperature (Jacobeit et al., 2003; Kuettel et al., 2011). Kuettel et al. (2011), for instance, attribute 60 % of the changes of winter precipitation over southern Norway between the periods 1900–1949 and 1950–1999 to changes within weather patterns and only 40 % to changes in frequencies of weather patterns.

Climate sensitivities of models and mass balance projections

The comparison of climate sensitivities between degree day models and physically based models and statistical models used in this study is complicated for three reasons: (i) we were exclusively accounting for temperature changes in the ablation season and precipitation changes in accumulation season, whereas especially temperature changes in the accumulation season might affect the amount of precipitation falling as snow. Additionally, temperature increase will extend the melting season, (ii) by the fact that we modeled the joint influence of accumulation-season precipitation and ablation-season temperature on annual glacier mass balance and not their influences on accumulation-season and ablation-season mass balance, respectively as in studies using the degree day approach, (iii) the time periods for which climate sensitivities were estimated differed slightly.

Nevertheless, temperature and precipitation sensitivities modelled in this study were fairly close to temperature sensitivities obtained from the studies using degree-day approaches (Hock et al., 2007; Rasmussen and Conway, 2005; De Woul and Hock, 2005). The climate sensitivities of physically based models (Andreassen and Oerlemans, 2009; Giesen and Oerlemans, 2010; Oerlemans, 1992; Schuler et al., 2005) were higher than estimates of climate sensitivity found in this study. However, climate sensitivities estimated by an energy balance model for Storbreen (Andreassen and Oerlemans, 2009) were comparable to climate sensitvities of an additive model.

For future scenarios, the average projected increase in winter precipitation was not able to compensate for the effects of the average projected increase in temperature (Giesen and Oerlemans, 2010; Nesje et al., 2008; Oerlemans, 1997). For maritime glaciers predictions using the lower bound of temperature increase and the upper bound of precipitation increase still resulted in significantly positive average mass balances for 2050 and 2100, but this scenario is highly unlikely, and we did not assess if this scenario is physically possible.

For projections, our statistical models have the main shortcoming that they assume that all the winter precipitation falls as snow (Huss et al., 2010) and that they do not account for changes in hypsometry (Rasmussen et al., 2007). For lower elevations, precipitation falling in form of rain instead of snow might be a serious problem in autumn and spring.

5 Conclusions

We modelled annual glacier mass balances of eight Scandinavian glaciers as function of accumulation-season precipitation and ablation-season temperature. The relative importances of accumulation-season precipitation and ablation-season temperature were in agreement with expectations with accumulation-season precipitation dominating mass balances of maritime glaciers and increased importance of ablation-season temperature for continental glaciers. This pattern was, however, variable in time. These changes seemed influenced by both, the North Atlantic Oscillation (NAO) and the Atlantic Multidecadal Oscillation (AMO). Phases with negative AMO index and positive NAO index tended to occur together and favoured glacier growth, whereas positive AMO index and negative NAO index, that tended to co-occur simultaneously, were associated with negative net balances.

Climate sensitivities of mass balance models used in this study compared well with climate sensitivities found by degree day models, but were somewhat lower than climate sensitivities of energy balance models. Still, all average mass balances found for the years 2050 and 2100 were negative, which is in accordance with all glacier projections for Scandinavian glaciers.

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Table 1. Table of most parsimonious models. Input variables used and model types are indicated along with variance explained by these models. Variance explained in brackets are variances explained in phases with above median and below median NAO-index, respectively. For STO, values in square brackets indicated variance explained by linear models during phases of AMO+ and AMO−, respectively, and partial regression coefficients for the same models. ALF (Ålfotbreen), REM (Rembesdalsskåka), NIG (Nigardsbreen), STO (Storbreen), HEL (Hellstugubreen), GR (Gråsubreen), ENG (Engabreen), STORGL (Storglaciären).

Glacier	Observation period	Input variables	Model type	Variance explained	Cross-validated var exp	MAD [m.w.e.]	LM coeffs pp	LM coeffs tt	Std err
ALF	1963–2010	MJJAS NDJFM	AM	75.5 (73/53)	66.1	0.66	0.773	−0.51	0.078
REM	1963–2010	MJJAS NDJFM	LM	81.2 (82/67)	77.9	0.37	0.83	−0.52	0.065
NIG	1962–2010	MJJAS NDJFM	LM	76.5 (76/69)	72.6	0.45	0.769	−0.57	0.072
STO	1949–2010	MJJAS NDJFM	CI	68.1 (67/63) [64/75]	65.5	0.32	0.603 [0.453 [0.772	−0.66 −0.77] −0.47]	0.073
HEL	1962–2010	JJA ONDJFMA	LM	69 (59/74)	64.3	0.30	0.452	−0.77	0.082
GR	1962–2010	JJA ONDJFMA	LM	54.1 (46/60)	47.7	0.35	0.296	−0.72	0.1
ENG	1970–2010	MJJAS ONDJFMA	CI	74.3 (73/72)	70.8	0.37	0.713	−0.59	0.082
STORGL	1946–2010	MJJAS NDJFM	CI	62.3 (54/65)	59.9	0.32	0.449	−0.56	0.086

Table 2. Comparison of climate sensitivities. Comparison of climate sensitivities found in this study to climate sensitivities found by means of degree day and energy balance models.

	This Study				De Woul and Hock (2005)			Rasmussen and Conway (2005)			Oerlemans (1992)		Hock et al. (2007)	
	Bn +1 °C	SE	Bn +10 %	SE	Bn +1 °C	Bn +10 %	Bs +1 °C	Bn +1 °C	Bn +10 %	Bs +1 °C	Bn +1 °C	Bn +10 %	Bn +1 °C	Bn +10 %
Storgl	−0.46	0.06	0.11	0.02	−0.46	0.15	−0.37	−0.38	0.13	−0.34			−0.49[b]	0.19[b]
ENG	−0.77	0.11	0.30	0.03	−0.99	0.32	−0.66	−0.91	0.35	−0.57	−1.1[c]	0.35[c]	−0.53[b]	0.19[b]
ALF	−0.88	0.13	0.29	0.03	−1.25	0.36	−0.84	−1.01	0.41	−0.56	−1.11		−0.58[b]	0.22[b]
NIG	−0.68	0.09	0.21	0.02	−0.66	0.22	−0.52	−0.59	0.24	−0.48	−0.88		−0.41[b]	0.20[b]
REM	−0.65	0.08	0.28	0.02	−0.66	0.28	−0.55	−0.64	0.22	−0.42	−0.92[a]	0.31[a]	−0.61[b]	0.22[b]
STO	−0.55	0.06	0.11	0.014	−0.65	0.12	−0.54	−0.42	0.15	−0.35				
HEL	−0.45	0.05	0.11	0.02	−0.58	0.07	−0.50	−0.48	0.13	−0.42				
GR	−0.41	0.06	0.07	0.024	−0.47	0.08	−0.41	−0.73	0.12	−0.70	−0.72			
		Change wrt 1961–1990	Estimate	SE	Sensitivity	Oerlemans (1992)		Change wrt 1969–2006	Estimate	SE	Sensitivity	Andreassen and Oerlemans (2009)		
Ålfotbreen	Additive model	Reference period	0.31	0.15			**Storbreen**	Reference period	−0.09	0.067		bw	bs	bn
		−1 °C	0.98	0.284	**0.672**	**1**		−1 °C	0.39	0.11	**0.48**	0.09	0.38	**0.47**
		1 °C	−0.57	0.16	**−0.88**	**−1.1**		1 °C	−0.66	0.077	**−0.57**	−0.14	−0.49	**−0.63**
		2 °C	−1.64	0.26	**−1.95**	**−2.3**		2 °C	−1.32	0.1409	**−1.23**	−0.34	−1.06	**−1.40**
		3 °C	−2.8	0.47	**−3.11**	**−3.6**		3 °C	−2.00	0.25	**−1.91**	−0.60	−1.66	**−2.26**
		−10 %	−0.04	0.143	**−0.35**	**−0.5**		−10 %	−0.22	0.064	**−0.13**	−0.16	−0.05	**−0.21**
		10 %	0.63	0.157	**0.32**	**0.45**		10 %	0.04	0.069	**0.13**	0.15	0.05	**0.19**
		20 %	0.93	0.159	**0.62**	**0.85**		20 %	0.16	0.0717	**0.25**	0.31	0.07	**0.38**
		30 %	1.19	0.158	**0.88**	**NA**		30 %	0.27	0.07	**0.36**	0.47	0.09	**0.56**
		+2 °C and +10 %	−1.32	0.26	**−1.63**	**−1.85**		+2 °C and +10 %	−1.19	0.139	**−1.10**	−0.19	−0.98	**−1.18**

[a] Data from Giessen and Oerlemans (2010).

[b] All models for Storglaciären.

[c] Data from Schuler et al. (2005).

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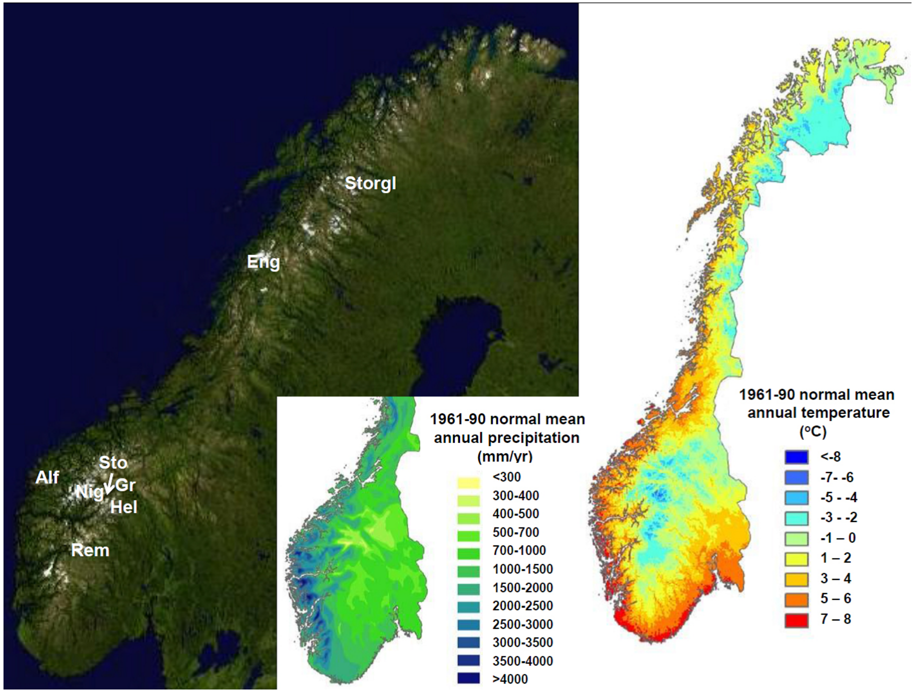

Figure 1. Location map glaciers: Ålfotbreen (ALF), Rembesdalsskåka (REM), Nigardsbreen (NIG), Storbreen (STO), Hellstugubreen (HEL), Gråsubreen (GR), Engabreen (ENG) and Storglaciären (STORGL). The insert maps show 1961–1990 normal annual precipitation and temperature.

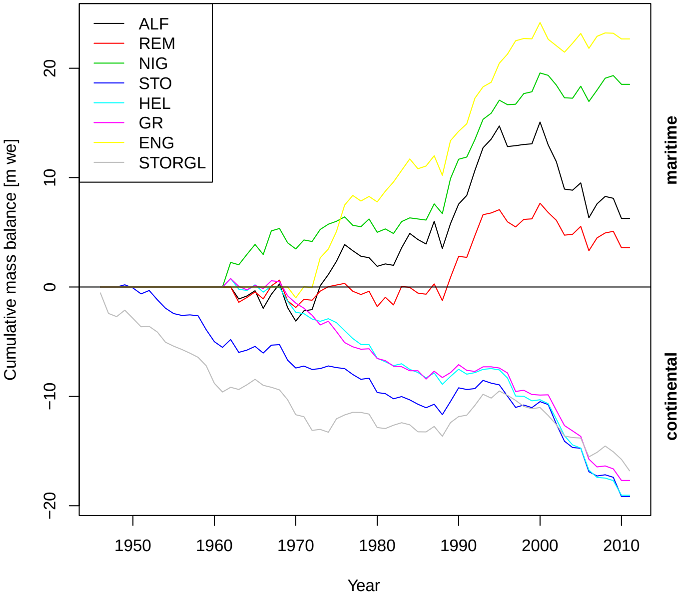

Figure 2. Cumulative mass balances for Ålfotbreen (ALF), Rembesdalsskåka (REM), Nigardsbreen (NIG), Storbreen (STO), Hellstugubreen (HEL), Gråsubreen (GR), Engabreen (ENG) and Storglaciären (STORGL). Data: nve.no/bre (Norwegian glaciers) and bolin.su.se/data/tarfala (Storglaciären, northern Sweden).

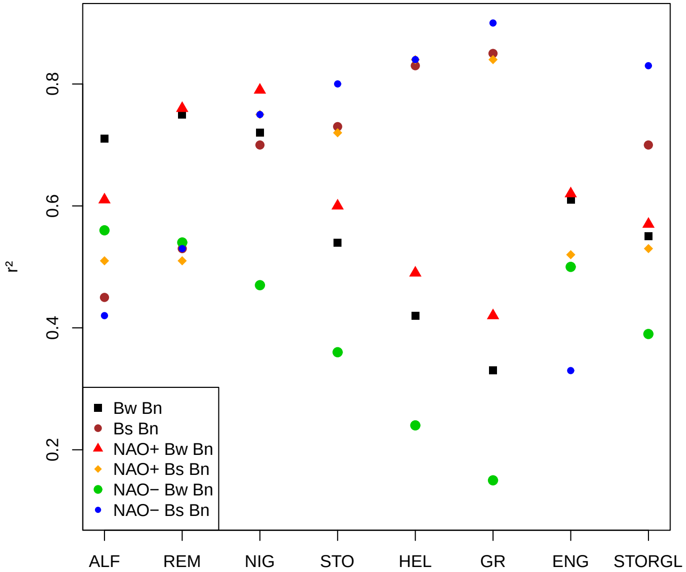

Figure 3. Coefficients of determination (r^2) accumulation-season, ablation-season and annual mass balances. Coefficients of determination between accumulation-season mass balances and annual mass balances and ablation-season mass balances and annual mass balances. Coefficients of determinations are shown for the entire measurement period and for periods of above and below median NAO-index, respectively. Bw: accumulation-season mass balance, Bn: annual mass balance, Bs: ablation-season mass balance. NAO+: above median NAO-index, NAO−: below median NAO-index.

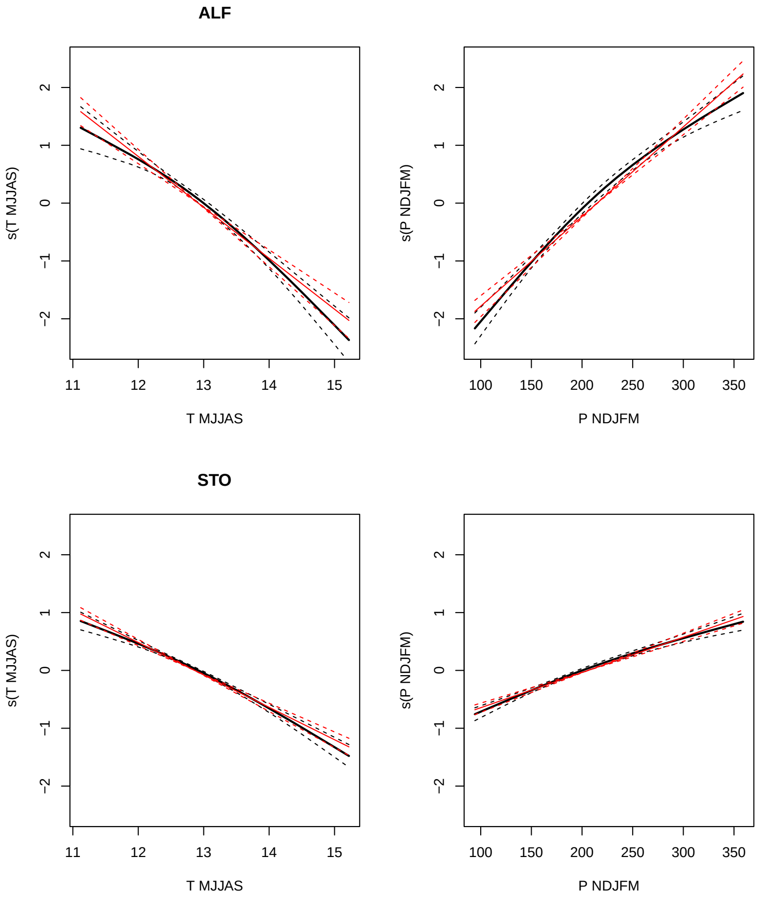

Figure 4. Additive model for Ålfotbreen (upper row panels) and Storbreen (lower row panels). Black: smooth terms for precipitation (NDJFM, right) and temperature (MJJAS, left). Red: linear model. Dotted lines indicate confidence bounds.

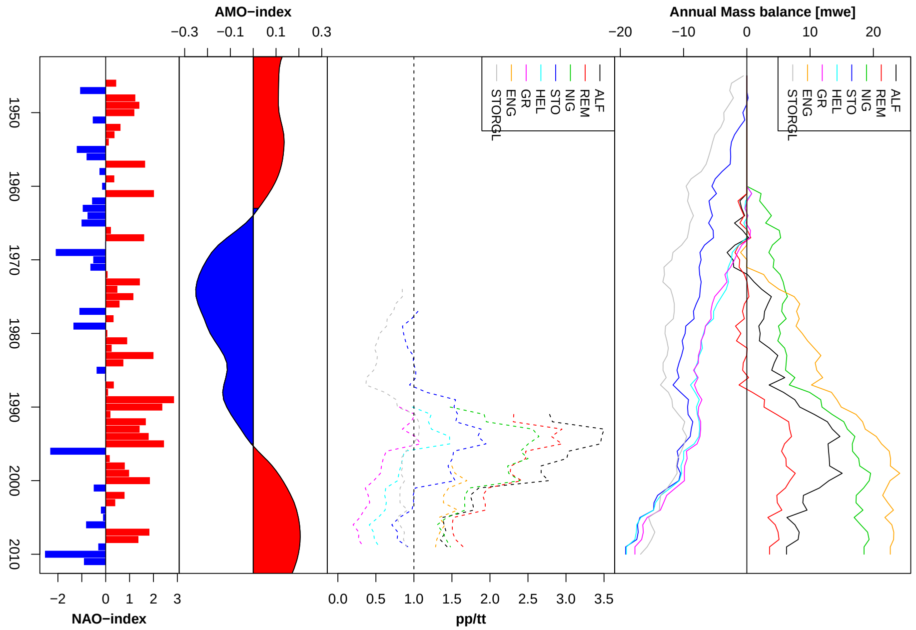

Figure 5. **(a)** Cumulative mass balances together with the **(b)** relative influence of accumulation-season precipitation and ablation-season temperature (bp/bt) on glacier net mass balances, displayed as 30 year trailing windows, **(c)** Atlantic Multidecadal Oscillation Index (http://www.esrl.noaa.gov/psd/data/timeseries/AMO/, 30 year loess-smoothed) **(d)** North Atlantic Oscillation Index (Jones et al., 1997). Ålfotbreen (ALF), Rembesdalsskåka (REM), Nigardsbreen (NIG), Storbreen (STO), Hellstugubreen (HEL), Gråsubreen (GR), Engabreen (ENG) and Storglaciären (STORGL).

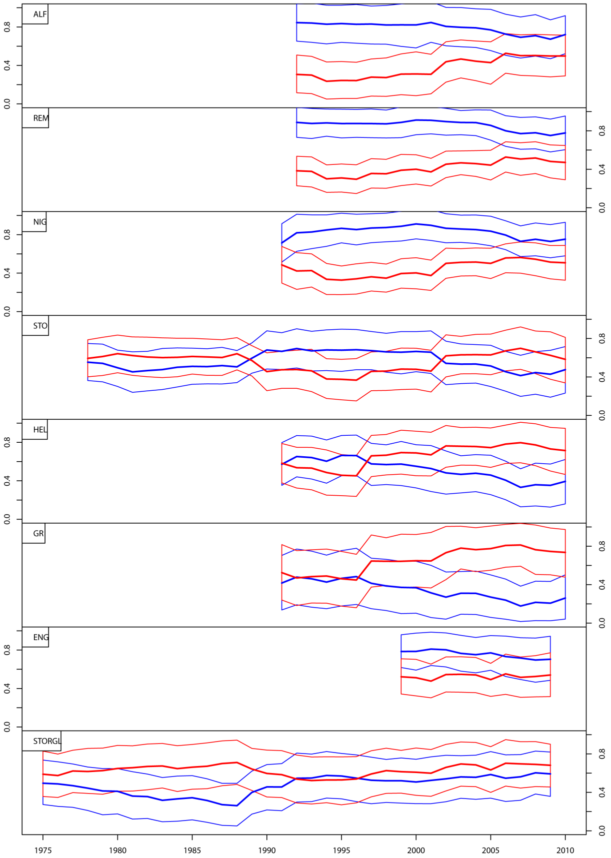

Figure 6. Trajectories of partial regression coefficients with Bayesian credible intervals. Absolute values of partial regression coefficients of accumulation-season precipitation (blue) and ablation-season temperature (red) of 30 year trailing windows. Blue and red areas indicate 2.5 and 97.5 % quantiles of Bayesian credible intervals.

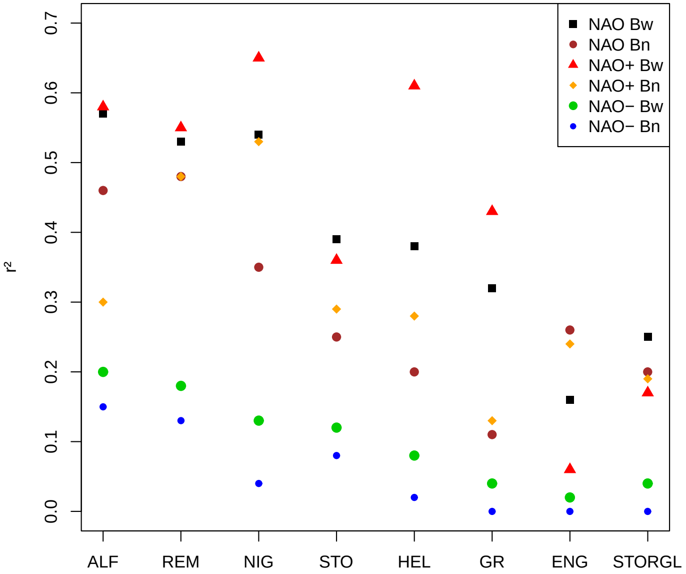

Figure 7. Coefficients of determination (r^2) among mass balances and North Atlantic Oscillation (NAO) Index (Jones et al., 1997). Coefficients of determination between accumulation-season mass balances and annual mass balances and winter NAO-index. Coefficients of determinations are shown for the entire measurement period and for periods of above and below median NAO-index, respectively. Bw: accumulation-season mass balance, Bn: annual mass balance; NAO+: above median NAO-index, NAO−: below median NAO-index.

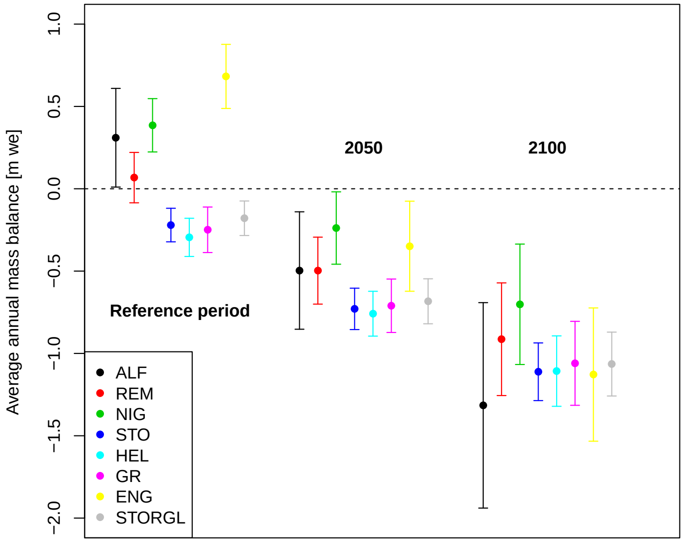

Figure 8. Modelled average annual mass balances. Modelled average annual mass balances for the 1961–1990 reference period (left), 2050 (middle) and 2100 (right). Means of projections were used. Dots indicate means of the modelled average annual mass balance, horizontal lines indicate upper and lower confidence bounds, respectively. Ålfotbreen (ALF), Rembesdalsskåka (REM), Nigardsbreen (NIG), Storbreen (STO), Hellstugubreen (HEL), Gråsubreen (GR), Engabreen (ENG) and Storglaciären (STORGL).