Modelling the climate sensitivity of Storbreen and Engabreen, Norway.

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Norwegian Water Resources and Energy Directorate

2006

Report No. 3
Modelling the climate sensitivity of Storbreen and Engabreen, Norway.

Published by: Norwegian Water Resources and Energy Directorate (NVE)

Editor: Liss M. Andreassen

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ISBN: 82-410-0597-0
Printed by: NVE
Number printed: 20

Front page photo: Storbreen in Jotunheimen in August 2004.
Photo: Liss M. Andreassen

Photo page 1: Engabreen and Engabrevatn in October 2004.
Photo: Hallgeir Elvehøy.

Abstract: In this report we model the mass balance of two Norwegian glaciers and study their sensitivity to climate change and the impact the changes have on runoff from the glaciers.

Keywords: mass balance model, automatic weather station (AWS), energy balance, climate sensitivity, climate change, run-off

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October 2006

Content

Preface

This report is a delivery to the *Climate and Energy* (CE) project financed by Nordic Energy Research. The work described in this report has also been financed by NVE as part of the project "Modellere massebalansen på Storbreen og dens respons på klimaendringer" (Model the mass balance of Storbreen and its response to climate change). The Institute of Atmospheric Research (IMAU), Utrecht University, have financed and operated the automatic weather station at Storbreen since 2001.

The overall aim of this report is to model the sensitivity of the glaciers to climate change and the estimate the impact on runoff. Two different mass balance modelling approaches were used. The energy-balance model work for Storbreen was carried out by Liss M. Andreassen together with Johannes Oerlemans. The degree-day model approach at Engabreen was carried out by Hallgeir Elvehøy together with Tómas Jóhannesson. Michiel van den Broeke performed energy-balance calculations from the AWS-data on Storbreen. Stein Beldring contributed to the chapter on climate scenarios. Liss M. Andreassen was the editor of the report. Øyvind Nordli and Ketil Isaksen at the Norwegian Meteorological Institute provided meteorologic data. Tore Tonning made two of the location maps. Al Rasmussen provided many helpful comments to the report.

Oslo, October 2006

Morten Johnsrud
Department director

Rune Engeset
Section manager

Summary

In this report we have modelled the mass balance of two Norwegian glaciers using two different approaches. At Storbreen, a continental glacier in southern Norway, a simplified energy balance model was used. At Engabreen, a maritime glacier in northern Norway, a degree day model was used. Both glaciers have long term mass balance series, detailed topographic maps, micro-meteorological data and nearby meteorological stations outside the glacier. The models have been calibrated with micro-meteorological data from the glacier (Storbreen only), and by traditional mass balance measurements.

Downscaled climate scenarios were used to predict the future climate for the two glaciers. Results from the atmosphere-ocean general circulation models ECHAM4/OPYC3 developed at the Max Planck Institute and the HadAm3H developed at the Hadley Centre were used. Assumptions about future greenhouse gas emissions were based on the IPCC SRES B2 scenario. The period 1961-1990 was used as control climate and for the future climate the time slice 2071-2100 was used. The downscaled climate scenarios show a mean temperature increase between the two periods of between 2.2 and 3.3 K for Storbreen and between 2.3 and 2.7 K for Engabreen. The precipitation is predicted to increase by 3-23 % for Storbreen and between 7 and 48 % for Engabreen.

The climate sensitivity was calculated by combining calculated Seasonal Sensitivity Characteristics and normalised and smoothed seasonal scenario values. This resulted in a mean temperature sensitivity of Storbreen and Engabreen of -0.50 and -0.90 m w.e. respectively for a 1K warming. A 10 % increase in precipitation represents a climate sensitivity of +0.17 m w.e. for Storbreen. For Engabreen the sensitivity varies between +0.51 and +0.38 m w.e. using the Max Planck and the Hadley scenario respectively.

Based on the climate change scenarios and the calculated static climate sensitivities, we estimate that Storbreen will have lost about 30 % of its volume by around 2050. The volume estimates of Engabreen range from a 4 % increase by 2100 (using the MaxPlanck scenario) to a 30 % decrease within 2056 (using the Hadley scenario). The extra annual run-off will be larger from Engabreen than Storbreen due to its much bigger size, by 2050 it will be in the order of 4 mill. m^3 water from Storbreen and 50 mill. m^3 water from Engabreen.

1 Introduction

1.1 Background

Glaciers are considered as a primary indicator on climate change (IPCC, 2001). The predicted global warming during the next decades is expected to have pronounced effects on glaciers and ice caps and lead to major changes in runoff magnitude and seasonality from glaciated areas.

Many glaciers and ice caps in the Nordic countries are projected to almost disappear during the next 100–200 years (Jóhannesson et al., 2004). These changes may have both local and global implications, such as changes in the discharge of glacial rivers (Hock et al., 2005) and a rise in global sea level (Church et al., 2001).

1.2 Mass balance models

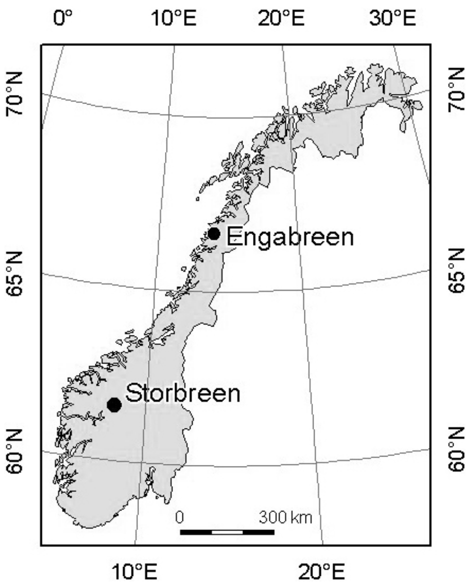
In order to understand the spatial and temporal variations in mass balance and to study the climate sensitivity of the glaciers, mass balance models are needed. A whole range of models exists, from simple regression models to complex energy balance models. Traditionally, the so-called degree-day model has been a popular choice since the ablation is related to temperature only (e.g. Hock, 1999; Schuler et al., 2005). The degree-day mass balance models have the advantages of being computationally cheap and only need temperature and precipitation as input data. However, a physically based energy balance model is considered to be a more physically correct description of the processes (Greuell and Genthon, 2004). The input data required for an energy balance model can be comprehensive and will often make it difficult to obtain long time-series of the needed meteorological data. Thus, to model a long time-series several simplifications compared with a full energy-balance approach may be necessary.

1.3 Objectives

The goal of the Climate and Energy project is to assess the effect of future climate changes on the mass balance and runoff from glaciers in the Nordic countries. In this report we model the mass balance of two Norwegian glaciers and study their sensitivity to climate change. We have used two different approaches. At Storbreen, a continental glacier in southern Norway, a simplified energy balance model was set up. At Engabreen, a maritime glacier in northern Norway, a degree-day model developed by Tómas Jóhannesson was used. The glaciers are described in chapter 2. For both glaciers the main purpose was

- to establish a mass balance model that captured annual variations in mass balance
- to study the climate sensitivity of the glaciers
- to estimate future changes in runoff from the glaciers

2 Study glaciers



Two study glaciers were selected, Storbreen in southern Norway and Engabreen in northern Norway (Fig. 2-1). Both glaciers have long term mass balance series, detailed topographic maps, micro-meteorological data and nearby meteorological stations outside the glacier. The basic characteristics of the glaciers are given in Table 2-1.

Figure 2-1. Map of Norway with the location of Storbreen and Engabreen.

Table 2-1. Basic characteristics of Storbreen and Engabreen.

	Storbreen *(mapped 1997)*	**Engabreen** *(mapped 2001)*
Area (km^2)	5.4	39.6
Length (km)	3.0	11.0
Altitudinal interval (m asl.)	1390-2090	10-1575
Mass balance measurements	1949-present	1970-present
Mean ice thickness (m)	115	205

2.1 Storbreen

2.2 Setting

Storbreen (61°36' N, 8°8' E) is located in the western part of Jotunheimen, a mountain area in southern Norway. The glacier has a total area of 5.4 km^2 and ranges in altitude from 1390 to 2090 m a.s.l. (Fig. 2-2). The length of this north-east-facing glacier is 3 km, and it has an average slope of 14°. Storbreen has fairly well defined borders, and may be characterised as a short valley glacier or a composite cirque glacier (Liestøl, 1967). A subglacial ridge divides the glacier in two rather well defined parts. From its little ice age (LIA) maximum extent the glacier has reduced its area by 25% and the length by almost 40% (Andreassen, 1999).

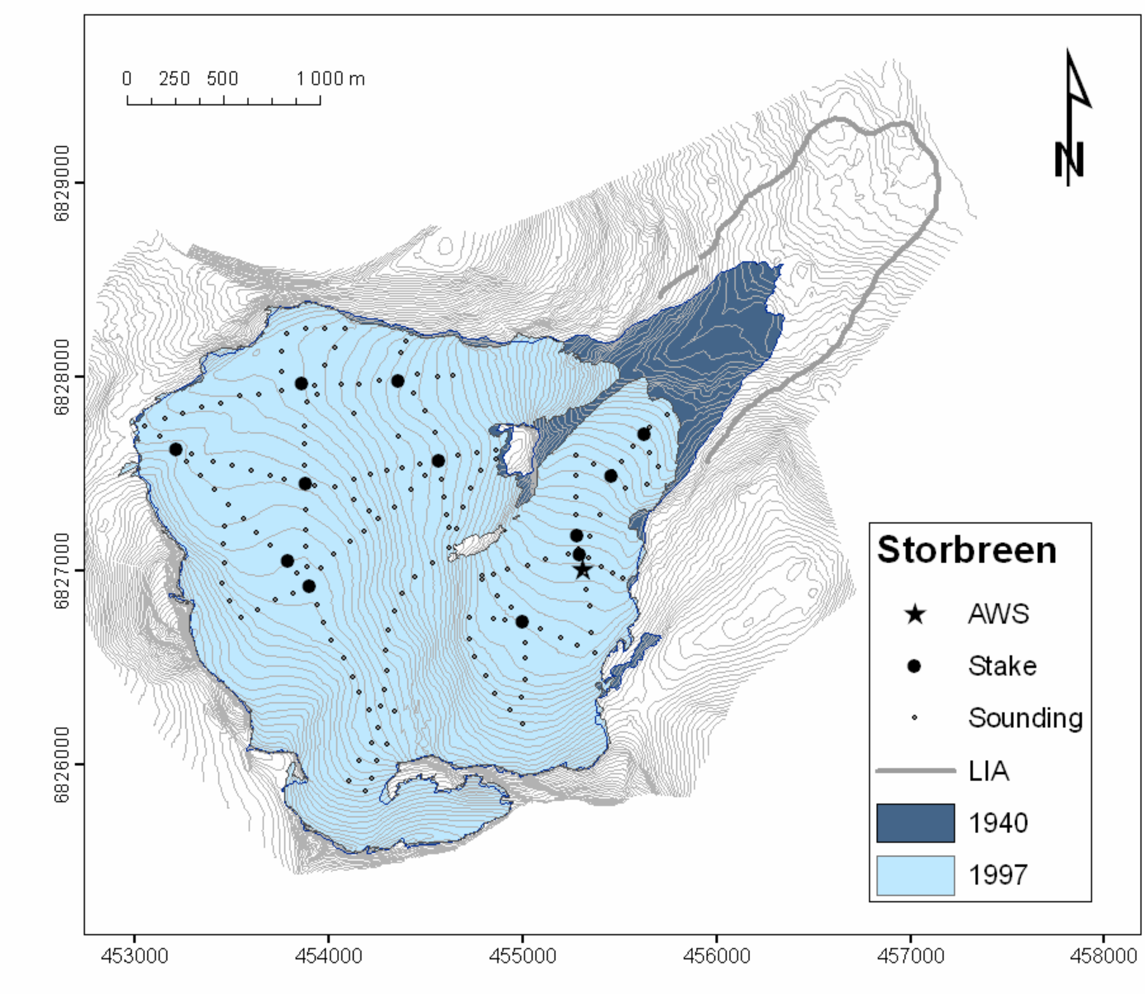


Figure 2-2. Map of Storbreen showing the present mass balance stake network and soundings (2005) and the position of the automatic weather station (AWS). The little ice age (LIA) limit is also shown, as well as the glacier extent in 1940 and 1997.

2.2.1 Mass balance data

Methods

The mass balance measurements on Storbreen started in spring 1949 by the Norwegian polar Institute (Liestøl, 1967). NVE took over the measurements in 1994. Although the principal methods have not changed much over the years, the amount of field work has varied. In the first 15 years the monitor program at Storbreen was very comprehensive, often three or more snow density pits were dug, snow depth was measured in about 600 points and ablation was measured on 30 stakes evenly distributed on the glacier (Liestøl, 1967). Based on experience of the snow pattern, the observations were gradually reduced in the 1960s (Østrem and Liestøl, 1964). For a period in the 1970s and 1980s measurements were quite sparse and reduced to a minimum, for some years snow accumulation was only measured at 10-20 points. Then from the mid 1990s; the mass balance program was extended. Presently, mass balance is measured at about 10 stakes and snow depth is measured at 150 points, and snow density is measured at one or two points (Fig. 2-2). The mass balance is usually calculated using the stratigraphic method, i.e. between two successive “summer surfaces” (surface minima). Consequently,the measurements describe the state of the glacier *after* the end of melting and *before* fresh snow starts to fall (Andreassen et al., 2005). Published figures from Storbreen for the period 1949-1984 does in general not include the date of measurements. From 1985 these dates are available.

The mass balance profiles are made by plotting point measurements of winter and summer balance versus altitude, and their mean values for each 50-m elevation interval are determined. The curves are extrapolated to the lower and upper parts. Another approach, however, was used until the 1980s when hand-contoured maps of accumulation and ablation were made from the observations. The areas within each height interval (50 m) were planimetered and the total amount of accumulation and ablation was calculated for each height interval, and profiles bw(z), bs(z) and bn(z) were created. Further information about the methods can be found in Andreassen et al. (2005) and Kjøllmoen et al. (2006).

Results

Except for a transient mass surplus in the period 1989-1995, the main mass balance trend of Storbreen has been mass deficit and the glacier had a total mass loss of -15 m w.e. for the period 1949-2005 or -0.26 m w.e. per year (Fig. 2-3). The mean specific winter balance is 1.44 m w.e, the summer balance -1.69 m w.e. Generally, the summer balance values have a larger variability than the winter balance values.

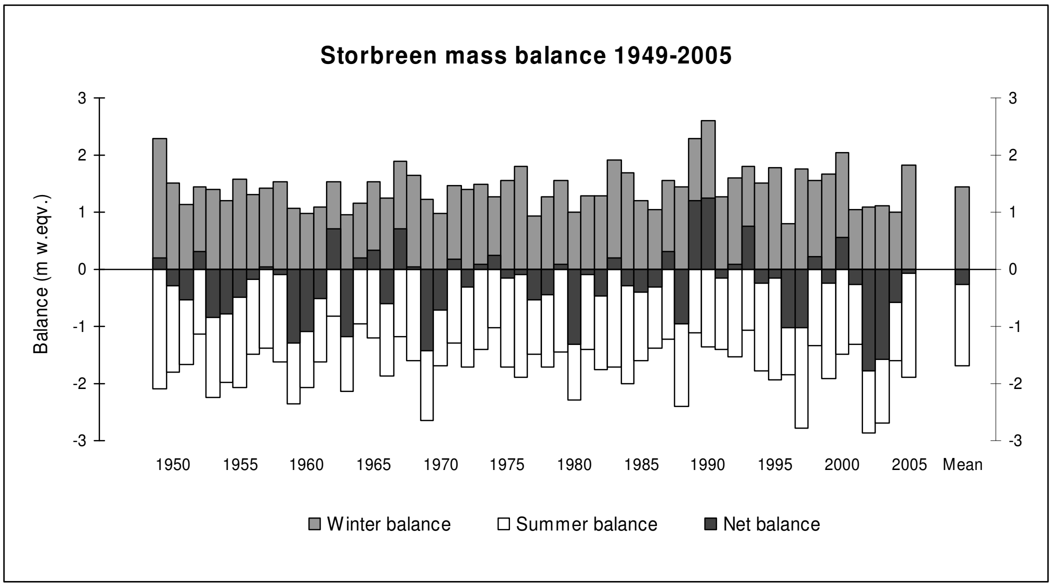


Figure 2-3
Winter, summer and net balance at Storbreen for the period 1949-2005.

2.2.2 Micro-meteorology

An automatic weather station (AWS) has been operating in the ablation zone of Storbreen, at about 1580 m a.s.l. (Fig. 2-4) since September 2001. The station was erected and is operated by the Institute of Marine and Atmospheric Research (IMAU), Utrecht University, the Netherlands. The AWS stands freely on the ice and sinks with the melting surface. Data is sampled every few minutes and then converted into 30-min mean values and stored on a data logger. The AWS measures short-wave and long-wave radiation, temperature, relative humidity, pressure, wind speed and direction and surface height. Measurements of temperature, relative humidity and wind are done in two levels, at about 2 m and 6 m, above the ice surface. In this study, the measurements from the AWS have been used to calculate the energy balance fluxes at the surface and to calibrate the energy-balance model (chapter 3.1).

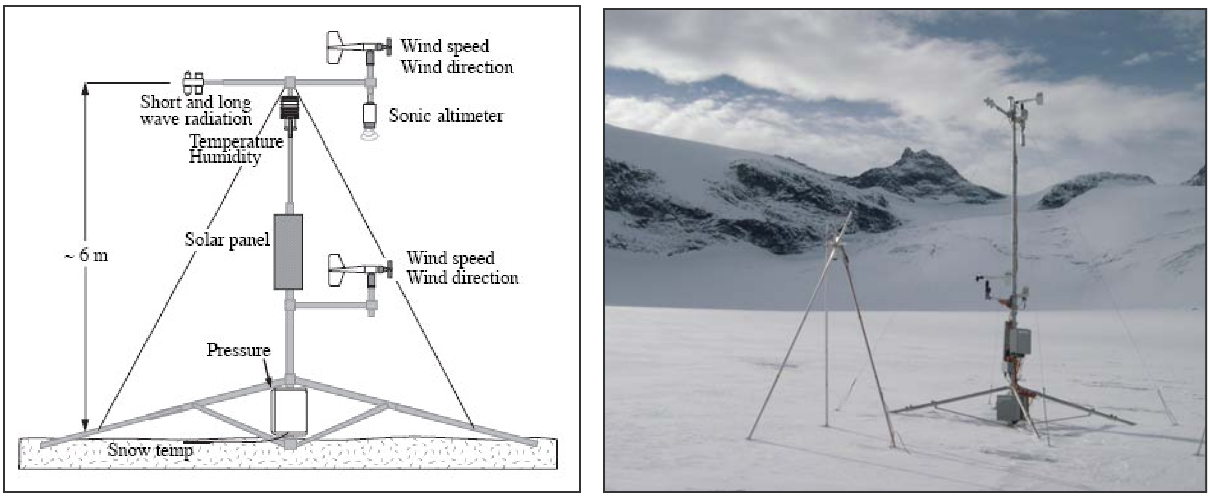


Figure 2-4. Left: Sketch of the automatic weather station (AWS). Cortesy: Institute for Marine and Atmospheric research (IMAU), University of Utrecht. Right: The AWS and the sonic ranger (left in the photo) in September 2005. Photo: Liss M. Andreassen.

Storbreen is a continental glacier and the winter months are cold with hardly any melting even at the lower parts. The ablation season usually starts in Mid May and lasts until Mid September, although the length of the ablation season naturally varies from year to year. The measurements from the AWS have been used to calculate the energy balance fluxes at the surface (Figure 2-5). The results reveal that the net shortwave radiation is the dominant contributor to the energy budget. However, the net longwave and the sensible and the latent heat fluxes also contribute to the budget. The averaged daily temperature, wind speed and relative humidity for one summer season reveal marked daily cycles (Fig. 2-6, left). The daily wind maximum is found in the afternoon, a few hours after the maximum temperature, indicating that katabatic wind is present at the glacier tongue of Storbreen. The averaged fluxes for one summer season (Fig. 2-6, right) illustrate the pronounced daily cycle in shortwave radiation, while the other variables reveal little daily variation.

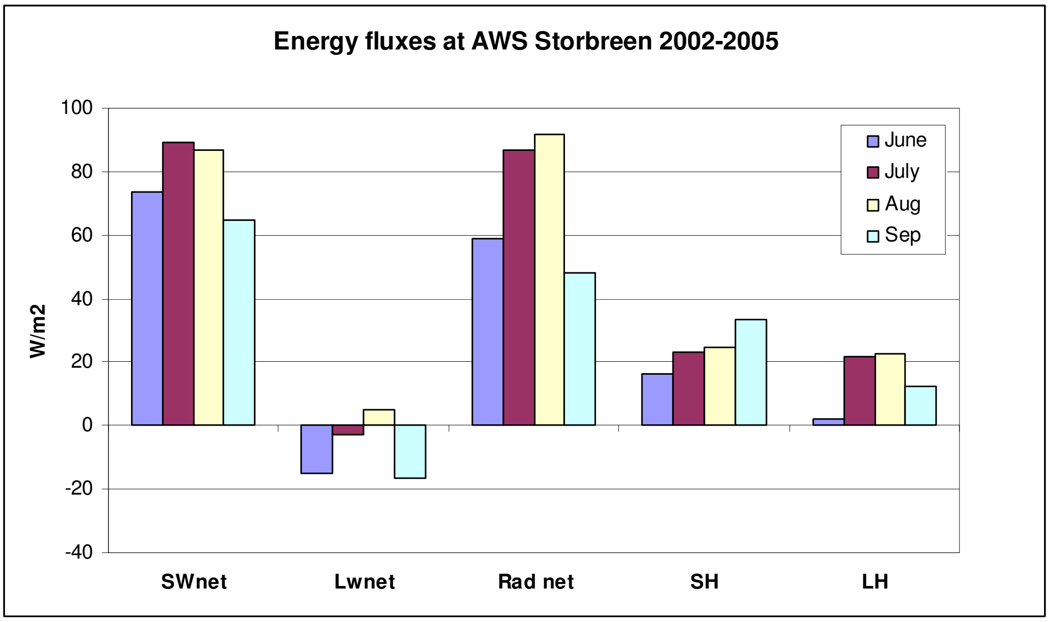
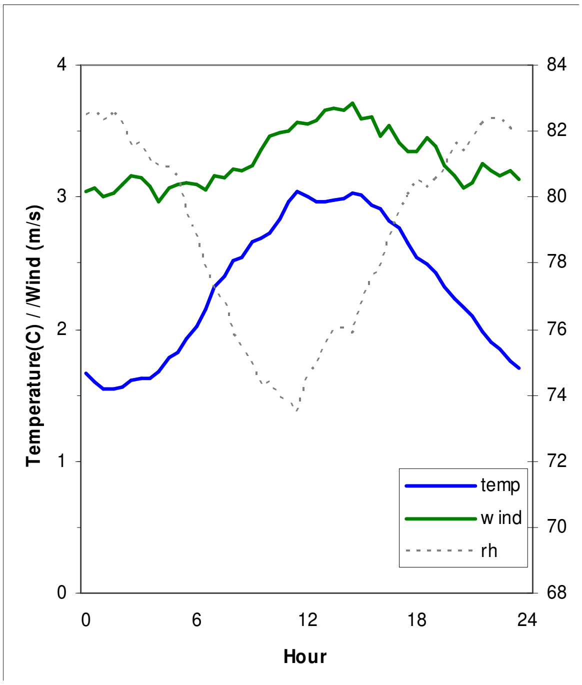


Figure 2-5. Mean monthly energy balance fluxes measured and calculated at the AWS for the period 2002-2005. SWnet-Shortwave net radiation, LWnet-Longwave net radiation, Rad net-Net radiation, SH-Sensible heat flux, LH-Latent heat flux.



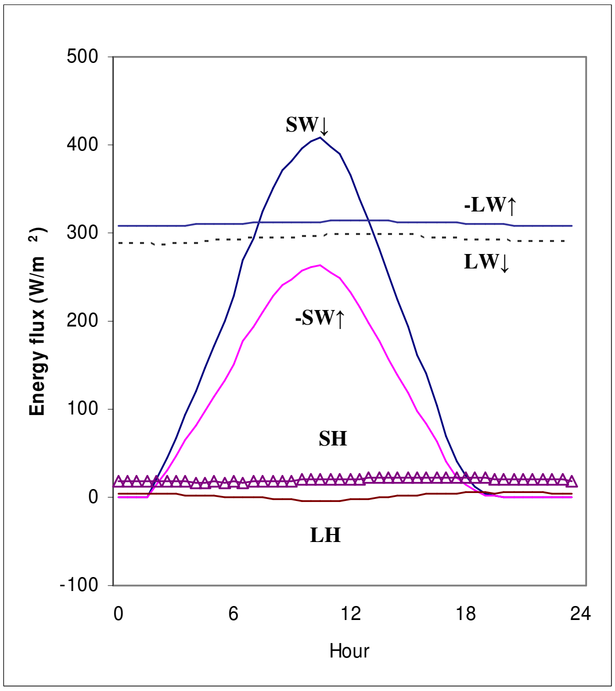


Figure 2-6. Left: Avaraged dailly temperature, wind speed and relative humidity. Right: Averaged energy fluxes measured and calculated at the AWS. Both Figures are for the period 1st May to 1st October 2004. SW↓ and SW↑- Shortwave insoming and outgoing radiation.LW↓ and LW↑-Longwave incoming and outgoing radiation, SH-Sensible heat flux, LH-Latent heat flux.

2.2.3 Meteorology outside the glacier

Storbreen is surrounded by several meteorological stations (Fig. 2-7, Table 2-2). The closest one is Sognefjellhytta (1413 m asl.), 8 km west of Storbreen. Data was recorded in a 10 year period from 1979 to 1988. Then measurements were resumed in 1994, and an automatic weather station has been running there since then. The data from Sognefjellhytta show good correlation with the data from the AWS on Storbreen. However, the monitoring period does not cover the whole observation period, and there are also many gaps in the data. Thus, stations farther away were needed to provide continuous and longer time-series in order to model the period 1961-1990 which was requested for the CE project. In this report, we have used data from Fokstua II (972 m asl), 60 km northeast of the glacier as main input for temperature, relative humidity, air pressure and wind. Precipitation data have been taken from Bråtå, Bøverdalen and Skåbu. Unfortunately, long term observation series of radiation are rare in Norway. The closest long-term radiation series is from Bergen, which is considered to be too far away to be used as input data to model the energy-balance at Storbreen. However, since 1999 an automatic weather station which also measures radiation has been running at Juvasshø, 15 km northeast of Storbreen (Isaksen et al., 2003).

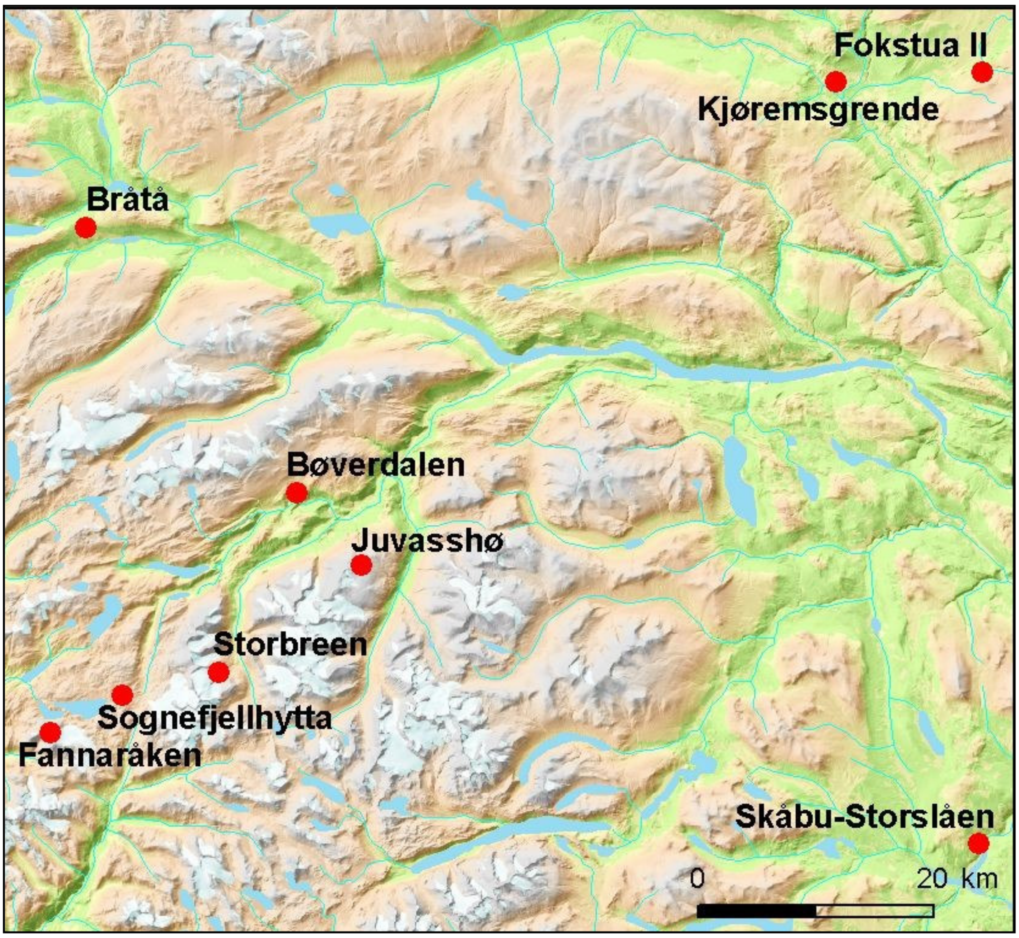


Figure 2-7. Meteorological stations used as input data or for calibration for the mass balance model of Storbreen.

Table 2-2. Overview of weather stations used for calibration or input in the model. P-precipitation, u-wind, rh-relative humidity, t-temperature, p-pressure, R-radiation

Name	m asl	From	To	Parameter
Bråtå	712	1957	1998	P
Bråtå-Sletom	664	1998	-	P
Bøverdalen	701	1957	2000	P
Fanaråken	2062	1957	1978	u, rh, t, p, P
Foksta NSB		1923	1968	u, rh, t, p, P
Fokstua	952	1957	1968	u, rh, t, p, P
Fokstua II	972	1968	-	u, rh, t, p, P
Juvasshø	1894	1999	-	u, rh, t, p, R
Kjøremsgrendi	626	1949	1976	u, rh, t, P
Kjøremsgrendi	626	1976	2002	u, rh, t, P
Skåbu-Storslåen	865	1968	2003	u, rh, t, p, P
Sognefjellshytta	1413	1978-89, 1994-		u, rh, t, p, P

2.3 Engabreen

2.3.1 Setting

Engabreen (66˚40'N, 13˚50'E) is a northern outlet glacier from Vestisen (221 km^2), the western part of Svartisen ice cap in Nordland, northern Norway. It is located in a mountainous area close to the ocean with peaks at 1400-1600 m a.s.l. Engabreen covers 39 km^2 and ranges in altitude from 10 to 1575 m a.s.l. (Fig. 2-8). Below 900 m a.s.l there is a heavily crevassed icefall. The icefall covers 7 % of the glacier area. The glacier tongue is exposed to periodical melting throughout the winter due to frequent occurrence of positive temperatures at sea level in a maritime climate. Consequently, the glacier tongue is often snow-free early in spring. From the ice divide west of Snøtind to the glacier terminus the distance along a flow line is 11 km. The average slope on the plateau above 900 m a.s.l. is 4˚, while the slope of the ice fall is 15˚.

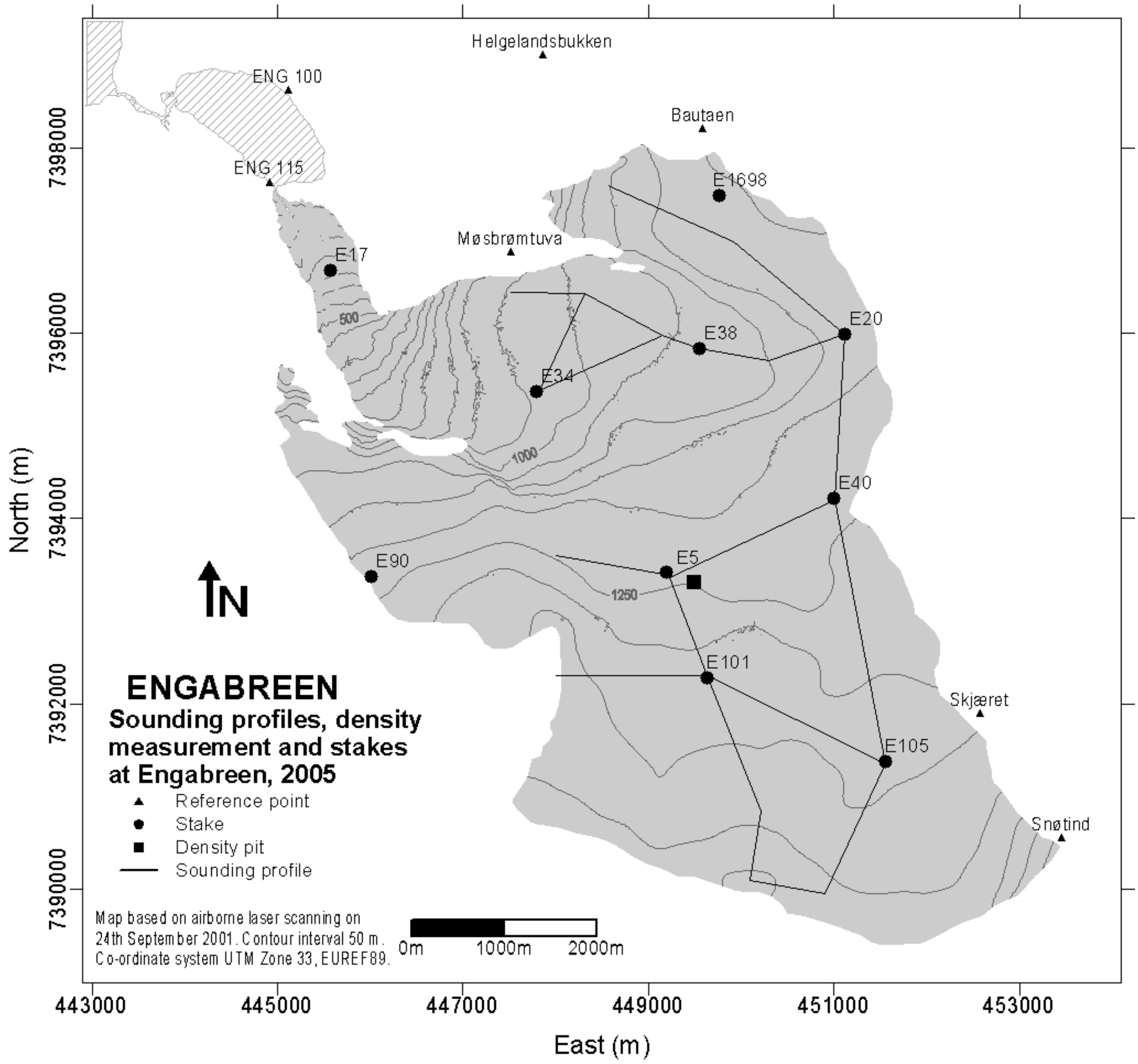


Figure 2-8. Map of Engabreen showing stakes, density pit and sounding profiles in 2005.

2.3.2 Mass balance data

At Engabreen glacier mass balance has been monitored since 1970. The extent of the measurements has varied considerably, and different methods of calculation have been used. Between 1970 and 1982, 20 to 30 stake locations were maintained, and the snow depth was sounded in 300-500 points on the glacier plateau. However, the glacier tongue close to sea level was not monitored for winter balance calculations. The reported values represent estimates of remaining snow at the date of measurement. Since the balance values in the icefall are interpolated, this procedure influences the elevation bands below 900 m a.s.l. Between 1983 and 1998, 4 to 10 stake locations were maintained, and the snow depth was sounded in 40 to 100 points on the plateau. Since 1990, one stake location has been maintained on the tongue both for winter and summer balance calculations. After 1998 the number of stakes and sounding points has been increased. Presently, mass balance is measured at about 10 stake locations, snow depth is measured in approximately 150 points, and the snow density is measured in one point (Fig. 2-8).

The mass balance is calculated using a stratigraphic method, i.e. between two successive “summer surfaces” (surface minima). From 1970 until 1988 maps of winter and summer balances were drawn from the measurements. The areas with different specific values within each height interval (100 m) were planimetered and the total amount of accumulation and ablation was calculated for each height interval. Then altitudinal balance values bw(z), bs(z) and bn(z) were calculated. Above 900 m a.s.l., accumulation corresponds to stratigrafic winter balance. On the tongue (lower than 500 m a.s.l.) the remaining snow at time of spring measurement was reported as winter balance. Consequently, reported winter balance values for altitudinal bands below 900 m a.s.l. are not comparable to measured or modelled winter balance values. However, stakes were maintained from year to year for net balance calculations.

Since 1989, the altitudinal mass balance profiles have been made by plotting point measurements of winter and summer balance versus altitude, and extracting representative values for each 100-m elevation interval from the scattered points. In the ice fall between the lower tongue and the plateau (400-900 m a.s.l.) the balance values are interpolated.

The mass balance measurements show that the glacier volume increased substantially from 1971 to 1977 (+9.4 m w.e.) and again from 1989 to 1997 (+12.3 m w.e.). From 1978 to 1988 and after 1997 there were only small changes (+1.8 and +0.1 m w.e., respectively). Mean winter and summer balance is 2.96 and -2.36 m w.e., respectively (Fig. 2-9).

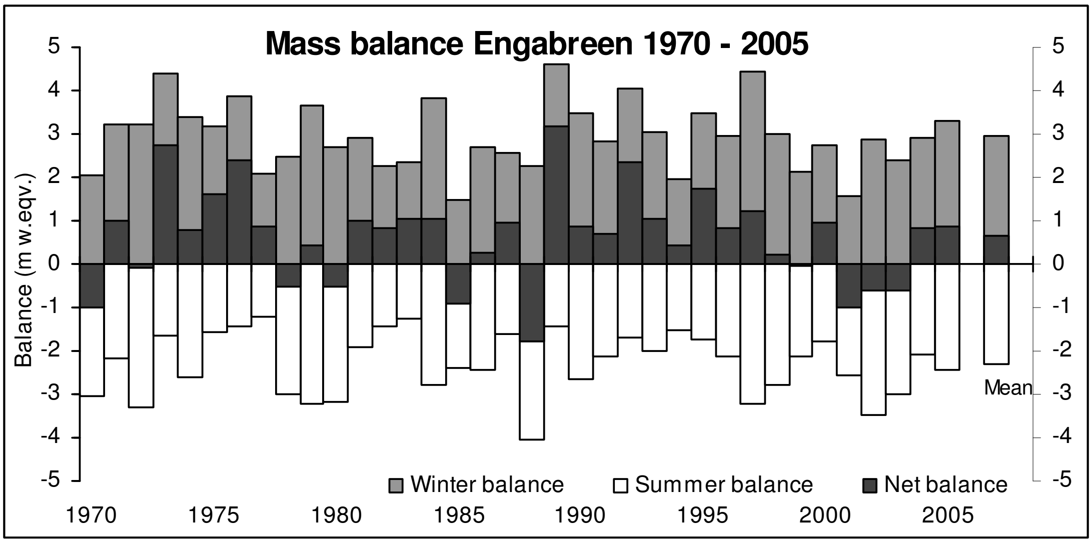


Figure 2-9 **Winter, summer and net balance at Engabreen for the period 1970-2005.**

2.3.3 Meteorological data

Data from the meteorological station in Glomfjord 10 km north-east of Engabreen is used as input to the mass balance model. The station (No. 87600, 39 m a.s.l., location 66°48.6' N, 13°58.9' E) has been operated since 1916. Annual precipitation is approximately 2000 mm, and annual mean temperature is 5.3 ˚C. Mean monthly temperature in winter is close to 0 ˚C. Annual temperature from 1916 is shown in Figure 5-4.

3 Mass balance modelling

3.1 Energy balance model (Storbreen)

Introduction

The model setup is a simplified version of a model developed by Klok and Oerlemans (2002). Data from the AWS has been used to calibrate the model and to evaluate the model performance. The model is 2-dimensional and calculates accumulation and melting for 25 m grid cells. The model accounts for topographic shading, slope and aspect. Basically, the mass balance, B, is calculated as the sum of ablation and solid precipitation. A finite time interval of one hour is used as time step.

$$B = \sum \left\{ \min(0; \frac{Q}{L_m}) + P_{solid} \right\}$$

where Q is the energy available for melt, L_m is the latent heat of melting and P_{solid} is precipitation as snow. Melting (and runoff) occurs when the surface energy flux is positive (Oerlemans, 2001). In order to compare with observed values, accumulation is modelled from the day of the ablation measurements in the fall to the day of accumulation measurements in spring when these dates are known. Ablation is thus modelled from the day of accumulation measurements to the day of ablation measurements. For the years from 1957 up to 1985 the mass balance is modelled using the dates 15th September to 15th May as start or stop dates for the routines. The accumulation and ablation routines are further described in the next sub-chapters.

Accumulation

Precipitation is considered as snow if temperature is below 2 °C. To adjust the precipitation measured at the station to the precipitation at the glacier, the amount of precipitation was multiplied by a tuning factor and an altitudinal gradient was applied. Data from the nearest precipitation stations Bøverdalen, Bråtå and Skåbu as well as data from the European Center for Medium range Weather Forecasting (ECMWF) were tested.

Ablation

The energy available for melting is the total energy flux from the atmosphere toward the glacier surface. Melting occurs when the surface energy flux (Q) is positive. We calculated the surface energy balance as:

$$Q = S\downarrow(1-\alpha) + L\downarrow - L\uparrow + Q_H + Q_L + Q_R$$

S↓- short-wave incoming radiative flux, α - surface albedo, L↓- long-wave incoming radiative flux, L↑ - long-wave outgoing radiative flux, Q_H *- sensible heat flux,* Q_L*- latent heat flux*

The contributions from rain and refreezing were neglected.

Shortwave radiation

Shortwave incoming is internally calculated in the model. Long term observation series of radiation are rare in Norway and the closest long-term radiation data is Bergen, which is considered to far away to be used as input data to the model.

The model calculates the solar elevation and azimuth as function of time of day and day of year for each time-step, and it calculates the effective solar radiation as function of slope and aspect. The solar radiation is divided into diffuse and direct according to Oerlemans (1992).

Albedo is calculated as a function of snow depth and accumulated temperature according to Brock et al. (2000). Also a simpler parameterisation using only snow depth was tested. The modelled albedo was tested against the albedo measured at the AWS.

The shortwave incoming flux is multiplied by the transmissivity, τ. The transmissivity is calculated from the AWS as the ratio between the mean shortwave incoming radiation and the top of the atmosphere radiation which was calculated using standard formulas. The transmissivity varies beween 0.46 (2002) and 0.43 (2003, 2004) for the three years measured. The value of 2003 and 2004 was chosen since it was considered more representative than the record-warm and sunny 2002-season.

The modelled incoming radiation will not reflect any annual variations in the incoming radiation since the cloudiness and the transmissivity are kept constant. Measurements from Bergen indicate that there was a decrease in incoming radiation in the 1960s and a small increase in the 1990s (Olseth, 2005), such an reduction and increase in radiation is also observed at many other stations in the world, and is referred to as a global dimming and brightening (Wild et al, 2005).

Longwave radiation

The longwave incoming radiation is calculated as a function of the air temperature and the emissivity (calibrated from the AWS-data):

$$L_{\downarrow} = \varepsilon \sigma T_{air}^{\ 4}$$

where ε-emissivity, σ – Stefan-Bolzmann`s constant, T_{air}*- air temperature*

The longwave outgoing is calculated as:

$$L_{\uparrow} = \sigma T_s^{\ 4}$$

where T_s *is the surface temperature.*

The surface temperature is assumed to be 0°C, which is a reasonable assumption during the melt season, however, the modelled fluxes will not be correct during spring and fall.

Turbulent fluxes

The sensible heat flux, Q_H, and the latent heat flux, Q_L, were calculated as:

$$Q_L = 0.622\rho_{air} L_v C_{tu} u \frac{e_a - e_{sat}}{p}$$

$$Q_H = \rho_{air} c_p C_{tu} u T_{air}$$

ρ_{air} – density of air, c_p – heat capacity, C_{tu}- turbulent exchange coefficient, u – wind, L_v – latent heat of vaporisation, e_a e_{sat}, p -pressure

The turbulent fluxes are calculated using a turbulent exchange coefficient as a tuning parameter. This parameter was derived from the AWS.

3.2 Degree-day model (Engabreen)

Glacier accumulation and ablation are computed from daily, monthly or annual temperature and precipitation records at nearby meteorological stations. Daily melting, *m*, is computed according to the equation

$$m = dd \max(T(z),0)$$

where $T(z)$ is daily mean temperature at altitude *z* on the glacier, and *dd* is the degree-day factor, which has separate values *dds* and *ddi* for snow and ice, respectively. When the snow thickness becomes less than a specified threshold, the degree-day factor is found as a weighted average of the degree-day factors for snow and ice.

Temperature on the glacier is found using a constant vertical temperature lapse rate *grt* (grt<0)

$$T(z) = T_{stn} + grt(z - elt)$$

where T_{stn} denotes temperature at the meteorological station and *elt* is station elevation.

Precipitation, *P*, is computed using horizontal precipitation gradients, *pgx* and *pgy*, in addition to a vertical gradient, *grp*,

$$P(x,y,z) = (1+grp(z-e1p))(1+pgx(x-xc0)+pgy(y-yc0))P_c$$

where *x* and *y* are horizontal coordinates, and P_c is corrected and scaled precipitation at precipitation station. The station precipitation is corrected for gauge losses using separate correction factors for snow and rain and scaled with a constant correction factor in order to transfer it to a reference altitude z_0 at location *xc0*, *yc0*.

Accumulation, *c*, is found by assuming a constant snow/rain threshold $T_{s/r}$

$$c = P \text{ if } T(z) \leq tsn, \; c = 0 \text{ if } T(z) > tsn \,.$$

The mass balance, *b*, is then given as the sum of the accumulation and the ablation

$$b = c + a = c - m + r$$

where *r* is refreezing.

Seasonal and annual mass balance is calculated for periods between reported dates of measurements in spring and autumn.

3.2.1 Calibration of the MBT-model

Daily temperature and precipitation from the meteorological station in Glomfjord is used as input to the MBT model. The model set up includes a number of pre-defined parameters listed in Table 3-1. The model is calibrated against the calculated winter and summer balance at stakes from 2000-2004. The calibration was performed using non-linear least squares parameter fitting, minimising the root-mean-squared error (RMSE) of the difference between measured and modelled winter and summer balances at individual stakes for individual years (Jóhannesson et al. 2006). The resulting, calibrated parameters are listed in Table 3-2. The measured and modelled winter and summer balance at individual stakes in individual years are compared in Figure 3.1. The RMSEs for the winter and summer balance calibrations are 0.61 m w.e. and 0.63 m w.e., respectively. The modelled winter balance was higher than measured in 2000, and lower than measured in 2004. The modelled summer balance was smaller (less negative) than measured in 2003. The RMSEs reported here are higher than reported by Jóhannesson et al. (2006) for Hofsjökull (0.40 and 0.42 m w.e. a^{-1}, respectively). However, their calibration was carried out using interpreted values for elevation bands. This reduces the effect of local (topographic) conditions at the individual stake locations.

Table 3-1. Pre-defined model parameters of the MBT-model.

Parameter	Name	Value	Unit
Temperature standard deviation	sgm	3.4	˚C
Snow/rain threshold	tsn	1.0	˚C
Snow thickness for mixed snow/ice	sis	0.3	m w.e.
Refreezing ratio	rfr	0.07	
Elevation of temperature station	elt	39	m a.s.l.
Elevation of precipitation station	elp	39	m a.s.l.
Reference x-location for horizontal precipitation gradient	xc0	450000	m
Reference y-location for horizontal precipitation gradient	yc0	7395000	m
Starting elevation for vertical precipitation gradient	elq	39	m a.s.l.

Table 3-2. MBT-model parameters that were optimised in the calibration.

Parameter	Name	Value	Unit
Temperature lapse rate	grt	-0.62	˚C per 100 m
Rain correction factor at station	rko	1.28	
Snow correction factor at station	sko	1.80	
Degree-day factor for ice	ddi	0.0059	m w.e. $˚C^{-1}d^{-1}$
Degree-day factor for snow	dds	0.0038	m w.e. $˚C^{-1}d^{-1}$
Precipitation-correction factor	pko	1.29	1
Precipitation /elevation gradient	grp	0.023	m per 100 m
Horizontal precipitation gradient (east)	pgx	-0.0195	m per km
Horizontal precipitation gradient (north)	pgy	0.0076	m per km

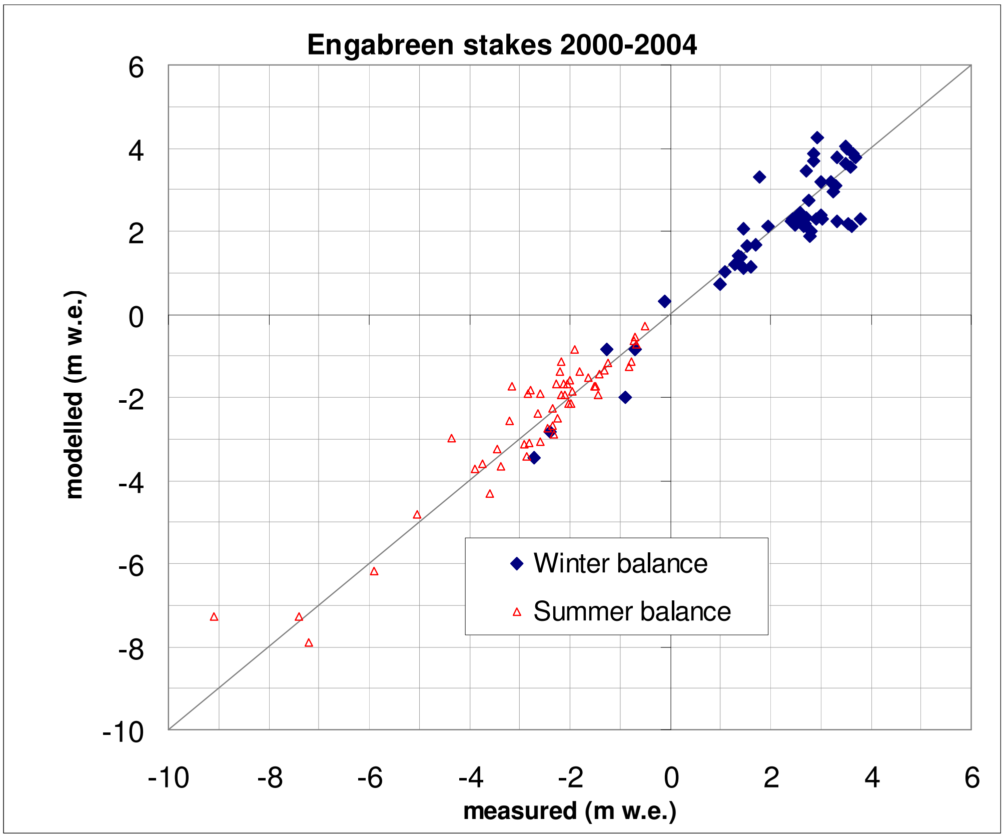


Figure 3-1. Scatter plot of measured and modelled winter and summer mass balance at stakes on Engabreen in 2000-2004.

4 Modelled mass balance

4.1 Storbreen

4.1.1 Winter balance

Winter accumulation was calculated from different stations. Modelled bw based on precipitation data from Bråtå showed best agreement with measured balance at the glacier (RMSE = 0.29 m w.e.) (Fig. 4-1). The model explains about 63 % of the variance in the winter balance. In general, the modelled values capture the interannual variations in winter balance. However, major discrepancies between modelled and observed balance occurred in several years, probably due to changes in prevailing wind conditions. The RMSE for the reference period 1961-1990 only, was 0.27 m w.e. and the model explains 72 & of the variance for this period.

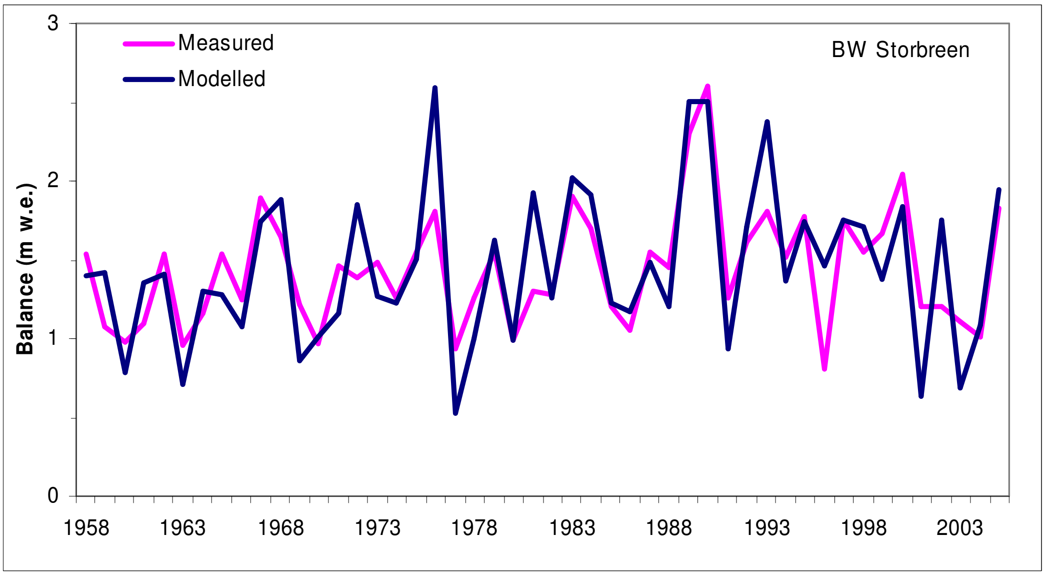


Figure 4-1. Modelled (using precipitation data from Bråtå) and measured winter balance for Storbreen for the period 1958-2005.

4.1.2 Summer balance

Summer balance was modelled using Fokstua as input data. In the calibration period 1997-2005 the RMSE is 0.27 m w.e. (Fig. 4-2). When running the model for the period 1961-1990 the RMSE increased to 0.38 m w.e.(Fig. 4-3). The largest discrepancies between modelled and observed balance was in the mid 1980s. These were years with very sparse mass balance measurements on Storbreen. The RMSE for the whole modelled period 1957-2005 was 0.36 m w.e.

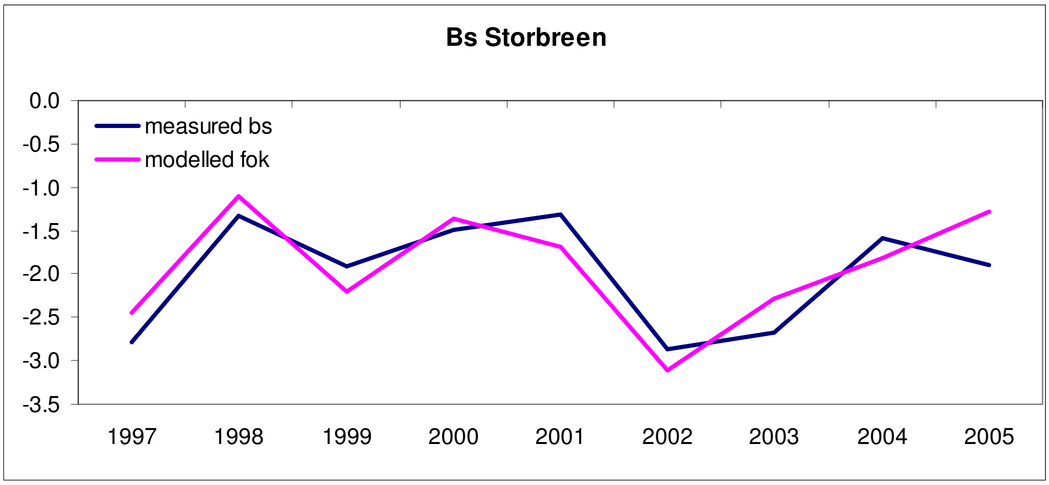


Figure 4-2. Modelled (using input data from Fokstua) and measured summer balance for Storbreen for the calibration period 1997-2005.

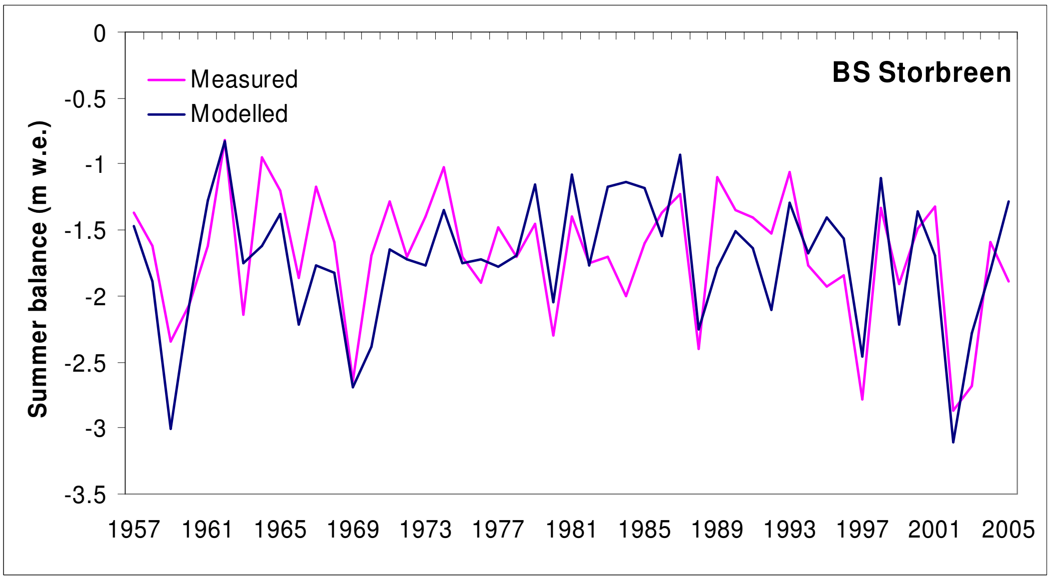


Figure 4-3. Modelled (using input data from Fokstua) and measured summer balance for Storbreen for the validation period 1957-2005.

4.1.3 Model evaluation

The results of the mass balance modelling are affected by errors in both the simulated accumulation and by errors in modelling the ablation. Although discrepancies occurred in some years, the mass balance model was able to reproduce the main characteristics of the annual and seasonal mass balance of the glaciers. Furthermore, deviations between the measured and modelled mass balance can also be partly caused by wrong start and stopdays before 1985 and by comparing the measured stratigraphic mass balance data with the floating data calculation that the model provides. Thus, the model was considered to be able to give realistic estimates of the response of the glaciers to climate change and was used to calculate the climate sensitivity of Storbreen (see chapter 6).

4.2 Engabreen

4.2.1 Validation

The model calibration was validated by comparing modelled winter and summer balances to stake measurements from 1994 to 1999 (Fig. 4-4). The resulting RMS errors are smaller than those obtained in the calibration, implying that the calibration is valid (Tab. 4-1). A large portion of the total errors is caused by the stake on the glacier tongue, both indicating the effect of the larger turn-over, larger variability at the tongue, and the focus of the calibration on the glacier plateau where most of the stakes are located.

Table 4-1. Comparison of MBT-modelled mass balance to calculated mass balance at stakes.

	no	b_w RMSE (m w.e. a^{-1})	b_s RMSE (m w.e. a^{-1})
2000-2004	53,	0.61	0.63
1994-1999	31	0.60	0.57

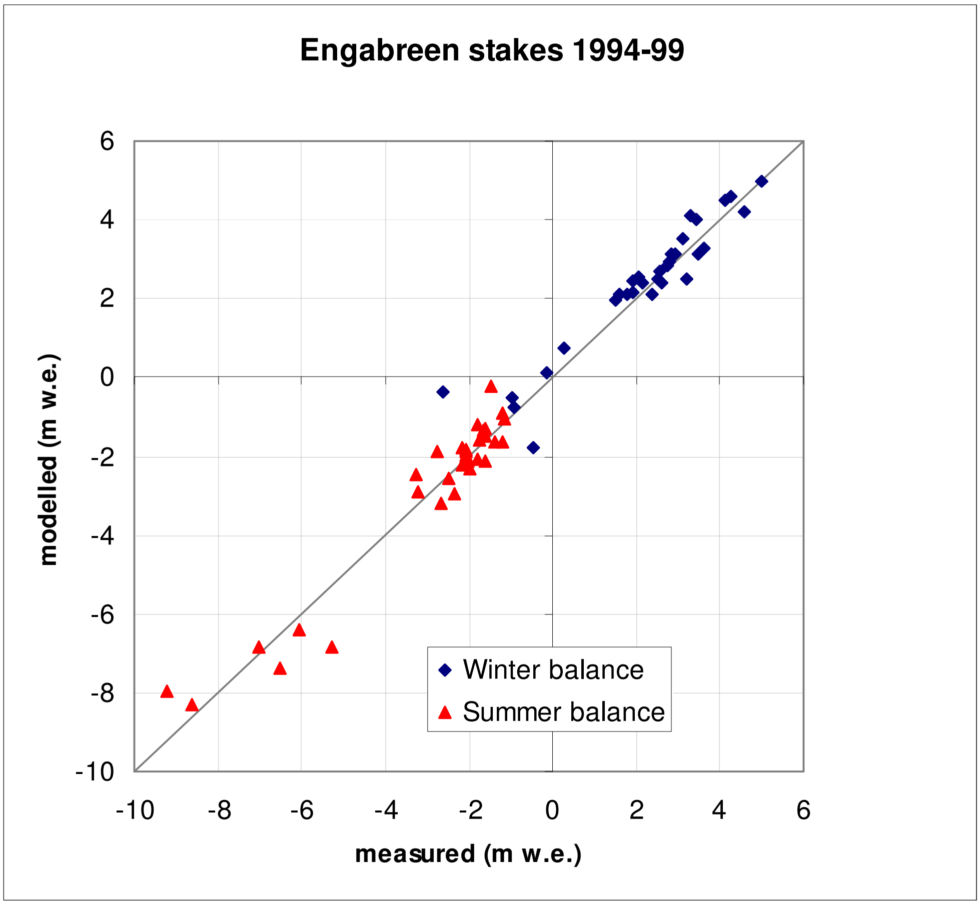


Figure 4-4. Comparison of measured and modelled (MBT) mass balance at individual stakes in 1994-99.

4.2.2 Mass balance calculation

The winter and summer balance was modelled for one point on a central flow line in each of the 15 elevation bands between 100 and 1537 m a.s.l. as a proxy to the mean balance values in the elevation bands. Then the glacier averaged balances were computed using the elevation-area distribution from 2001. The winter and summer balances from 1970-89 and 1991 is not directly comparable to modelled balances due to the way the winter balance was calculated on the glacier tongue in these years (see chap. 2.3.2). Therefore, only the balance terms from 1990 and 1992-2004 are compared (tab. 4-2). Both the modelled winter and summer balances are more positive than the measured terms, while the modelled winter balance varies more than the measured winter balance.

Table 4-2. Comparison of measured and modelled total winter and summer mass balance at Engabreen in 1990 and 1992-2004.

	mean	standard deviation
Measured winter balance	2.91	0.87
Modelled winter balance	3.00	1.04
Measured summer balance	-2.31	0.66
Modelled summer balance	-2.15	0.64

The measured and modelled glacier averaged net mass balance values for 1970-2004 are compared in Figure 4-6. Obviously, the modelled net balance is more positive than the measured net balance. The mean measured net balance in 1970-2004 is 0.71 m w.e.a^{-1}, compared to the modelled mean net balance of 1.10 m w.e.a^{-1}. The standard deviation is 1.23 m w.e. and 1.25 m w.e., indicating that the model captures the variability in the measured net balance.

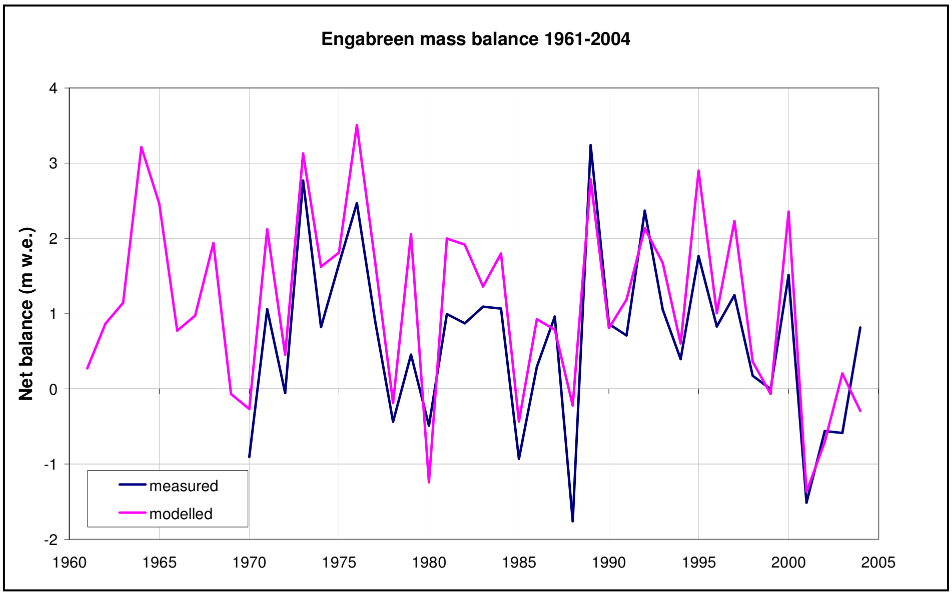


Figure 4-6. Specific net balance at Engabreen in the period 1961-2004.

5 Climate scenarios

Results from the general circulation models (GCMs) ECHAM4/OPYC3 developed at the Max Planck Institute (Roeckner *et al.*, 1999), and HadAM3H developed at the Hadley Centre (Gordon *et al.*, 2000) have been used for assessment of climate change impacts on glacier mass balance in Norway. Assumptions about future greenhouse gas emissions were based on the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emission Scenarios (SRES) B2 scenario (Nakićenović *et al.*, 2000). The general circulation model simulations were used as boundary conditions for dynamical downscaling with the Rossby Centre Regional Atmosphere-Ocean (RCAO) model (Döscher *et al.*, 2002). The glacier mass balance simulations used the time slice approach whereby model simulations representing a slice of time in present climate (control) and in a future climate (scenarios) were performed. The time slice for the control climate was 1961-1990 and for the future climate 2071-2100. The glacier impact studies were done with off-line simulations with the mass balance models. Observed meteorological data were used as a control climate. Changes in meteorological variables between the control and the scenario simulations from the regional climate models were transferred to a database of meteorological data. This can be referred to as the delta change approach, e.g. Hay *et al.* (2000) and is a common method of transferring the signal of climate change from climate models to hydrological models. Monthly relative precipitation changes and absolute temperature changes predicted by the regional climate models were used to modify the daily meteorological data driving the glacier mass balance models for the baseline period 1961-1990. The same monthly precipitation changes were used for all years of the impact simulations and for extreme values as well as for average conditions. The number of precipitation days was not changed in the scenario climate. Constant monthly temperature changes for all temperature intervals were applied for the impact simulations.

5.1 Downscaled climate scenarios Storbreen

The mean temperature change from 1961/90 to 2071/2100 for two climate scenarios downscaled for the area covering Storbreen is +2.7 ˚C. The Hadley Scenario is lower than the MaxPlanck-scenario (+2.1 vs. +3.3 ˚K) (Fig. 5-1).

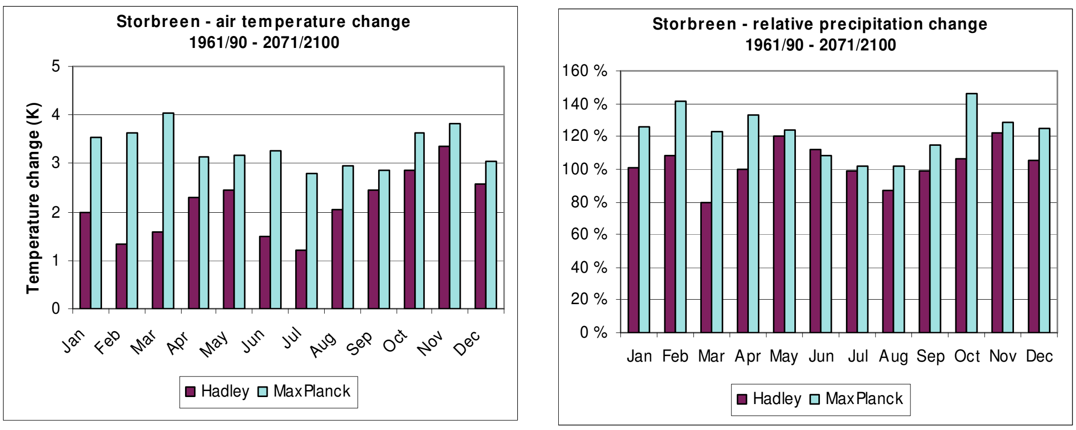
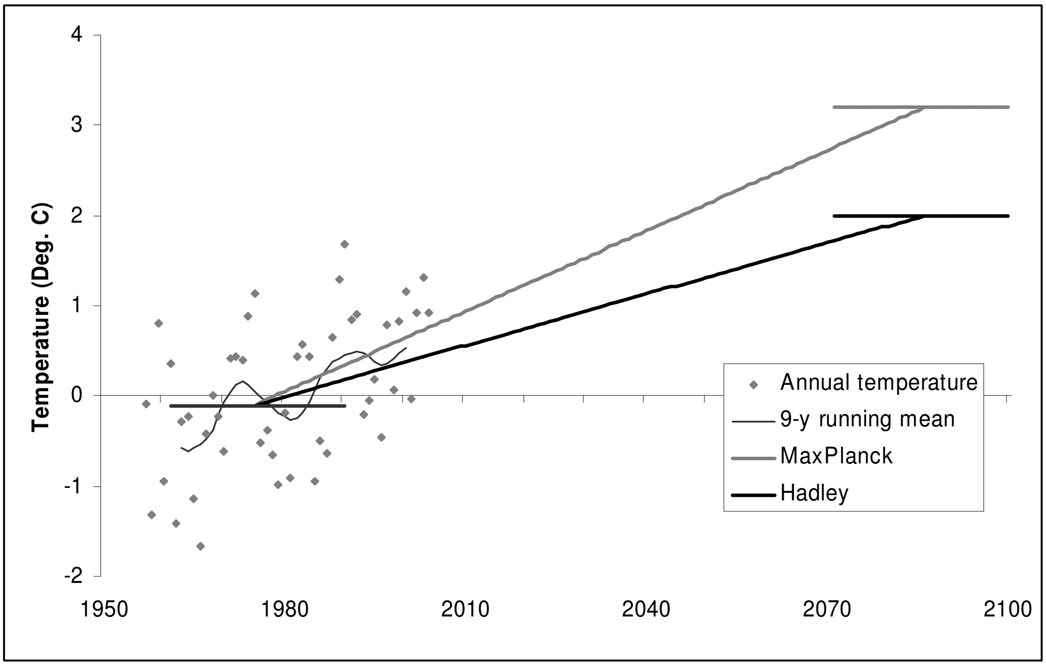


Figure 5-1. The monthly air temperature (left) and precipitation (right, relative to 100%) changes downscaled for Storbreen for two B2-scenarios using the delta-change method.

The predicted temperature increase is higher in winter than in summer. The mean precipitation increase between 1961/90 and 2071/2100 from the two B2- scenarios is 13 %. The Hadley-scenario shows a small 3 % increase, while the MaxPlanck-scenario shows a 23 % increase.

The annual mean temperature in Fokstua and precipitation sum in Bråtå since 1957 is shown in Figure 5-2 with the delta change from 1961-90 to 2071-2100 for the two B2-scenarios.



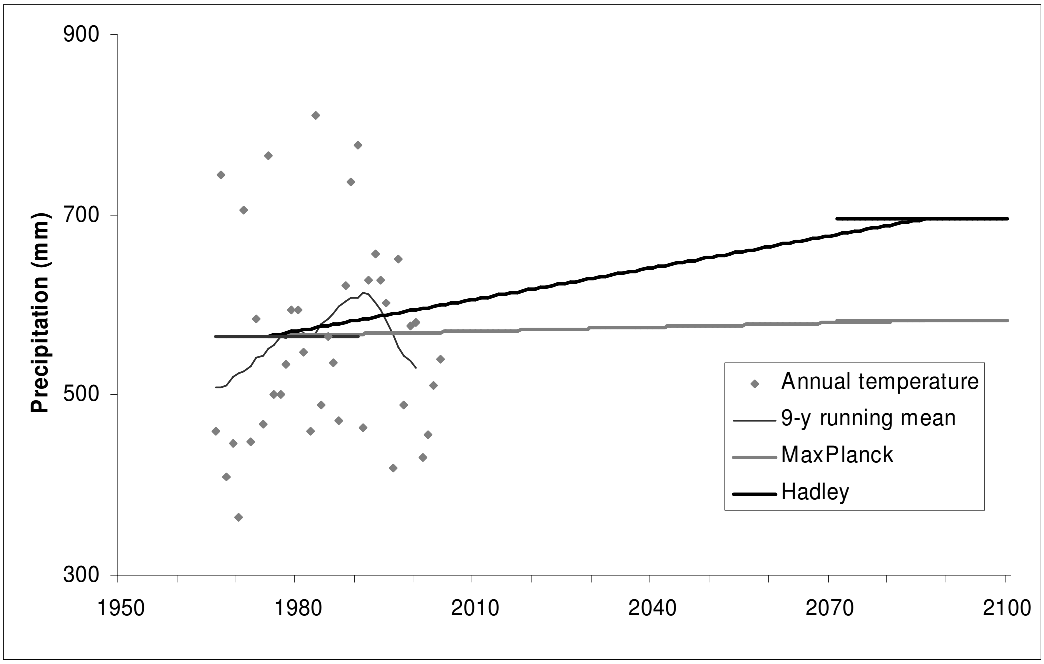


Fig 5-2
Annual temperature (upper) in Fokstua and precipitation (lower) in Bråtå and predicted climate 2071-2100 (mean of runs using two GCMs (Hadley and MaxPlanck) with emission scenario B2) using the delta change method where 1961-1990 is the control period.

5.2 Downscaled climate scenarios Engabreen

The annual temperature change for Engabreen/Glomfjord from the two climate scenarios is +2.3 and +2.7˚C (Fig. 5-3). As for Storbreen, the Hadley Scenario predicts smaller temperature change than the MaxPlanck-scenario, however, the difference between the two scenarios is smaller for Engabreen. The temperature increase is higher in winter (+3.1˚C in October to April) than in summer (+1.7˚C in May to September).

The predicted annual precipitation increase between 1961/90 and 2071/2100 from the two climate scenarios differs greatly. The predicted increase is 7 % from the Hadley-run and 48 % from the MaxPlanck-run. The precipitation increase is highest in spring and lowest in mid-winter. The MaxPlanck-run have a secondary maximum increase in precipitation in October.

The annual mean temperature and precipitation sum in Glomfjord since 1917 is shown in Figure 5-4 with the delta change from 1961-90 to 2071-2100 for the two B2-scenarios. The predicted warning will exceed +1K about 2020. The temperature development after 1975 (mean 1961-90) is comparable with the predicted temperature increase. The precipitation development, however, is not comparable with the predicted precipitation increase.

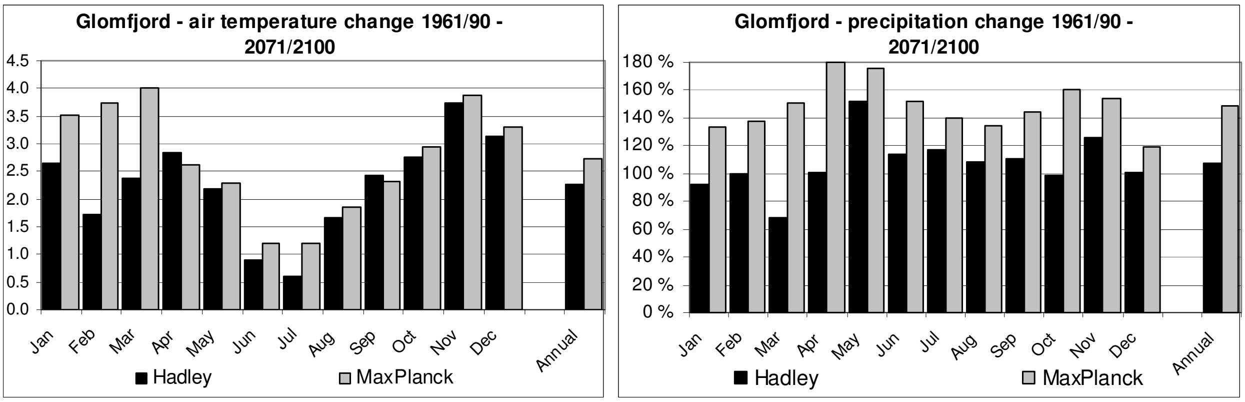


Figure 5-3. The monthly air temperature (left) and precipitation (right - relative to 100%) changes downscaled for Engabreen/Glomfjord for two GCM runs with emission scenario B2 down-scaled to the meteorological station.

5.3 Uncertainty of climate scenarios

Projected precipitation and temperature changes from the control to the scenario climate based on the RCAO regional climate model using ECHAM4/OPYC3-B2 and HadAM3H-B2 GCM results are consistent regarding whether an increase or a decrease will occur, but the magnitudes of the changes differ. These results were confirmed by Rummukainen (2006) in a comparison of the regional climate scenarios applied in the CE project. Calculated annual temperature and precipitation changes for Northern Europe from 1961-1990 to 2071-2100 were approx. 3.7 ˚C and 23 % respectively for the ECHAM4/OPYC3-B2 scenario and approx. 2.7 ˚C and 8 % for the HadAM3H-B2-scenario. The projected changes in precipitation increase as areas situated further north are considered. Although the changes applied in this study are larger, they are realistic in the sense that they are results from observed data that have been adjusted using the regional climate model results of the CE project.

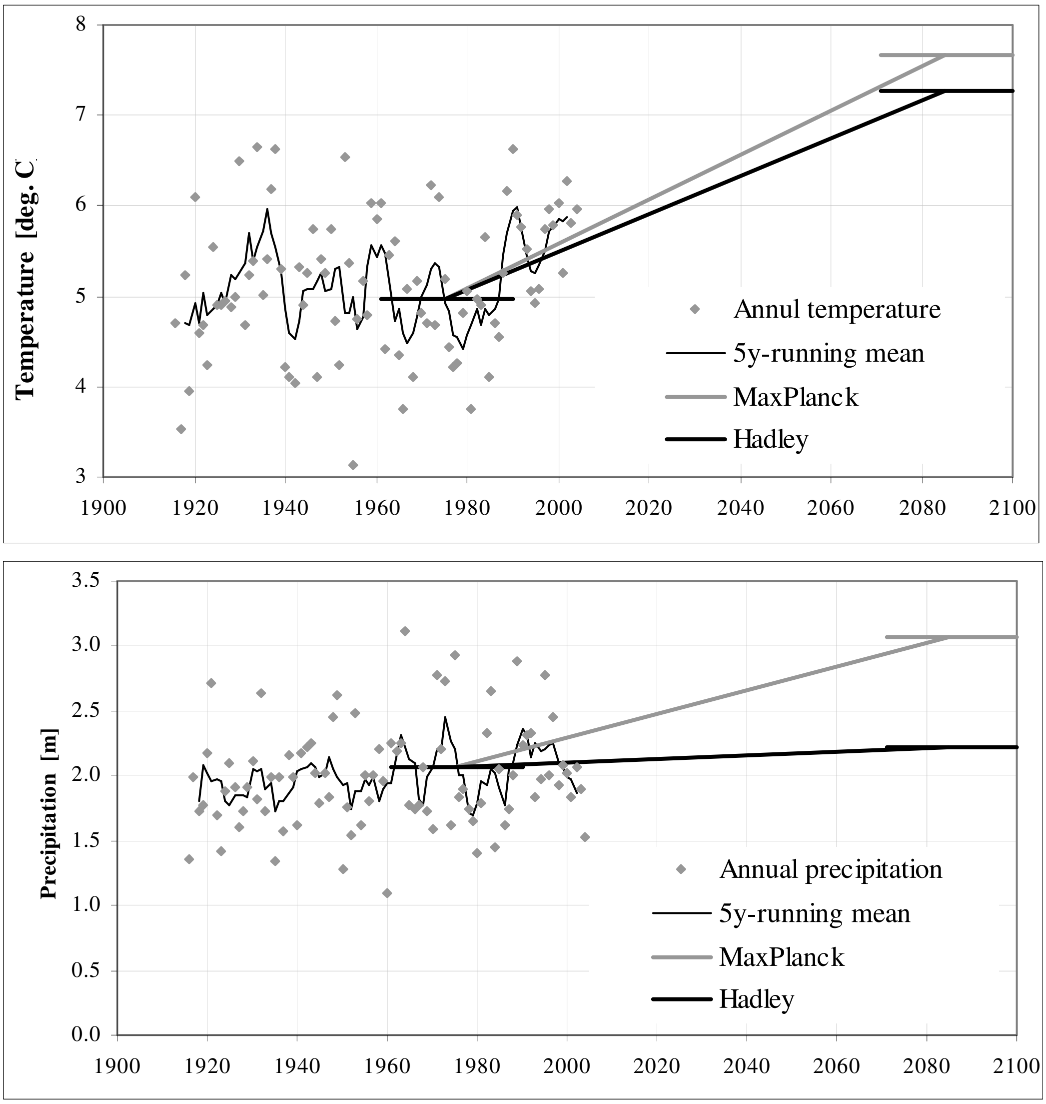


Fig 5-4 Annual temperature (upper) and precipitation (lower) in Glomfjord 1917-2004, and predicted climate 2071-2100 down-scaled from runs using two GCMs (Hadley and MaxPlanck) with emission scenario B2.

The total span of uncertainty in the glacier mass balance scenarios is generated by all components along the production chain from emission scenarios, via global and regional climate models, through the mass balance models. Each one of these steps includes assumptions and model formulations which affect the end result. In addition there are assumptions in the interfaces between the models, for example the delta change approach between the climate models and the hydrological model, which can be critical. The delta change approach has several shortcomings. One is that the timing and frequency of extreme weather events from the GCMs are difficult to represent. Another is that the delta change approach is unable to represent that temperature increases in the Nordic countries are more prominent at extreme low temperatures, and less at temperatures around the freezing point. However, the delta change method can probably be trusted for the average weather conditions which are important for glacier mass balance, but extreme hydrological events such as floods have to be analysed more carefully (Bergström et al., 2003).

6 Climate sensitivity

6.1 Static sensitivity using uniform perturbations

A common way of studying the climate sensitivity of a glacier is to induce perturbations of temperature and precipitation on a calibrated model. One can look at the change in equilibrium altitude (ΔELA) or the change in the mean specific balance (ΔB_n). The climate sensitivity, C_T, of the mean specific balance to a uniform temperature change can be defined as:

$$C_T \cong \frac{B_n(+1K) - B_n(-1K)}{2}$$

Similarly, the climate sensitivity, C_P, of a uniform change in precipitation can be defined as:

$$C_P \cong \frac{B_n(+10\%P) - B_n(-10\%P)}{2}$$

(Oerlemans, 2001). It is also common to only report climate sensitivity as the change for a 1 K warming and/or 10 % precipitation increase (e.g. de Woul and Hock, 2005).

The ratio of a change in the specific mass balance of a glacier (the mass balance averaged over the surface area of the glacier) to a small change in a climatic parameter is termed the *static sensitivity* (Church et al. 2001). The static sensitivity ignores retreat of the terminus, changes in geometry of the glacier, non-linear effects due to the finite size of the climate change and other dynamic or non-linear effects (Jóhannesson et al., 2004). In order to include these effects and calculate the *dynamic sensitivity* dynamical modelling is needed.

For Storbreen, the simplified energy balance model was run with uniform perturbations added to average daily values of temperature, relative humidity, wind, air pressure and precipitation for 1961-90 in Fokstua. The area distribution from 1997 was used; any changes in area were neglected. For Engabreen, the MBT-model was run with uniform perturbations added to average monthly values of temperature and precipitation 1961-90 in Glomfjord. From the model results, the mass balance was calculated based on the area distribution from 2001. The results are summarized in Table 6-1 showing a sensitivity for a 1K warming as -0.62 m w.e for Storbreen and -0.94 m w.e. for Engabreen. The sensitivity for a 10 % increase in precipitation is 0.14 m w.e. for Storbreen and 0.40 m w.e. for Engabreen. The results reveal, as expected and in accordance with previous studies, that the maritime Engabreen is more sensitive than the continental Storbreen both to temperature and precipitation changes. The sensitivity numbers will vary according to the way they are computed (model formulation, input data, etc). Thus, the second decimal means little (Regine Hock, pers.comm.).

Studies using simple regression models have yielded similar results for both Storbreen (-0.65 m w.e. $a^{-1}K^{-1}$ and +0.12 m w.e. a^{-1} $(10\%)^{-1}$, de Woul and Hock, 2005, and -0.42 m w.e. $a^{-1}K^{-1}$ and +0.15 m w.e. a^{-1} $(10\%)^{-1}$; Rasmussen and Conway, 2005), and Engabreen (-0.99 m $a^{-1}K^{-1}$ and +0.32 m a^{-1} $(10\%)^{-1}$ (de Woul and Hock, 2005) and -0.91 m $a^{-1}K^{-1}$

and +0.35 m a^{-1} (10%)$^{-1}$ (Rasmussen and Conway, 2005)). Schuler et al. (2005) calculated static sensitivities for Engabreen using a degree-day model including potential radiation based on daily temperature and precipitation 1974-2002 in Glomfjord. The sensitivity to a 1K warming was -1.06 m w.e. and for a 10% precipitation increase it was +0.35 m w.e.

Table 6-1. Mass balance change from uniform perturbations in temperature and precipitation and climate sensitivity, calculated for Storbreen and Engabreen. Units: m w.e.a^{-1}.

	-1 K	+1 K	-10%P	+10%P	C_T(1k)	C_P(10%P)
Storbreen	+0.51	-0.62	-0.14	+0.14	0.56	0.14
Engabreen	+0.79	-0.94	-0.41	+0.40	0.86	0.40

6.2 Climate sensitivity using seasonal perturbations

6.2.1 The seasonal sensitivity characteristic

The actual climate sensitivity of a glacier depends not only on the total amount of precipitation or the total change in temperature, but also how the changes are distributed over the year. One way of characterising the glaciers sensitivity is to use monthly perturbations in temperature and precipitation. Oerlemans and Reichert (2000) introduced the Seasonal Sensitivity Characteristics, SSC, where the input data are perturbed for one month while the other months are kept fixed.

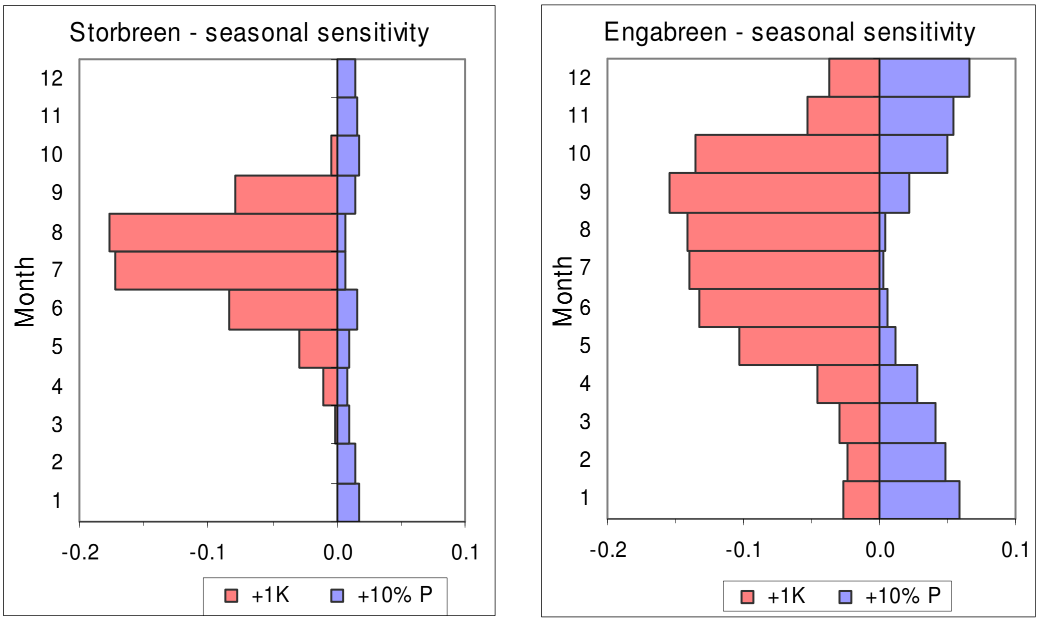


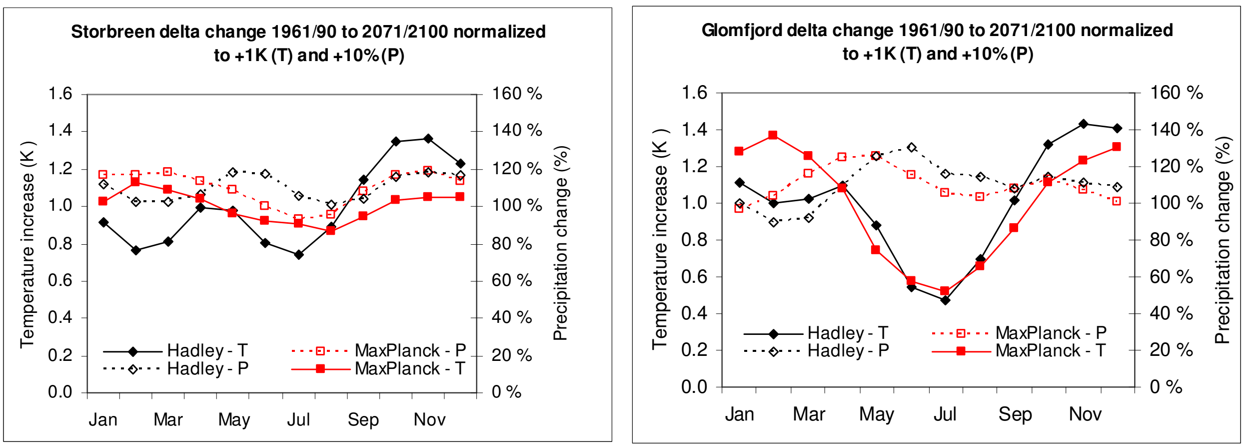
Figure 6-1. Seasonal sensitivity characteristics (SSC) calculated for Storbreen and Engabreen. Unit on the x-axis is m w.e.

The SSC for Storbreen and Engabreen are shown in Figure 6-1 for a +1K and a +10% change in temperature and precipitation respectively. Storbreen is most sensitive for temperature changes from June to September, and is not influenced by a +1K change in the winter months. Engabreen is affected by a +1K temperature change in all the twelve months of the year, but mainly in May to October. The effect of temperature increase in winter is due to strengthening of existing periods of surface melting on the glacier. A 10% increase in precipitation affects both glaciers positively in all the months. Schuler et. al. (2005) calculated SSC for Engabreen using a degree-day model including potential radiation. Their approach yielded higher temperature sensitivities in summer (June-September), and lower precipitation sensitivities in all months, but revealed the same annual pattern as showed in this report.

6.2.2 The climate sensitivity calculated using predicted monthly changes in temperature and precipitation

The predicted monthly changes in temperature and precipitation downscaled from the two GCMs were normalised to a +1K temperature change and a +10% precipitation change. The normalised monthly values were then smoothed using a 3-month running filter (Fig. 6-2). The climate sensitivity was calculated by combining the SSC calculated for Storbreen and Engabreen and the normalised and smoothed seasonal scenario values (Tab. 6-2). This resulted in a lower sensitivity in temperature and a slightly higher sensitivity in precipitation for Storbreen. For a 1K warming Storbreen and Engabreen have a mean sensitivity of -0.5 and -0.9 m w.e., respectively. A 10 % increase in precipitation represents a climate sensitivity of +0.17 m w.e. for Storbreen. For Engabreen the sensitivity varies between +0.51 (Max Planck) and +0.38m w.e. (Hadley).

Figure 6-2. Normalised (to +1 K) monthly mean air temperature change and normalised (to 110%) monthly precipitation relative change for emission scenario B2 at Storbreen (left) and Engabreen (right). The monthly values are smoothed using a 3-month averaging window.



	GCM	+1 K	+10% P
Storbreen	Max Planck	-0.50	+0.17
	Hadley	-0.49	+0.17
Engabreen	Max Planck	-0.87	+0.51
	Hadley	-0.92	+0.38

Table 6-2. Calculated climate sensitivity for Storbreen and Engabreen using normalised seasonal perturbations in temperature and precipitation downscaled from climate scenarios from two GCMs. Units: m w.e. a^{-1}.

7 Changes in glacier runoff

The predicted climate changes will have a substantial effect on the runoff from the glaciated area in the Nordic countries, both by changes in the total precipitation and its annual distribution, and by increased glacier melt. Many glaciers and ice caps are expected to disappear over the next 100-200 years. Runoff from glaciated watersheds in Iceland is projected to increase by 25-50% of the current runoff during this century (Jóhannesson et al., 2004; Aðalgeirsdóttir et al., 2006). The effect of climate warming on glacial runoff includes an initial increase in total glacier runoff and peak flows and a considerable amplification in the diurnal runoff oscillation, followed by significantly reduced runoff totals and diurnal amplitudes as the glaciers retreat (e.g. Hock et al., 2005).

In this chapter we use the calculated static climate sensitivities (chapter 6) combined with the predicted temperature and precipitation scenarios (chapter 5) to estimate the future volume and runoff changes from Storbreen and Engabreen. The approach is simple and crude, but gives estimates of the range of changes using the two B2-scenarios.

7.1 Projected changes in glacier volume

The mass balance change was calculated by assuming a linear increase in temperature and precipitation from the reference level 1961-1990 to the period 2071-2100 (Fig. 5-2 and 5-4). The calculated climate sensitivities for temperature and precipitation increase are used to estimate the volume change (Tab. 6-2). The contributions from temperature and precipitation are calculated separately. The annual change in volume is calculated for both scenarios. The ice thickness and area of Storbreen and Engabreen have been used to give an estimate of the total water volume of the glaciers (Table 7-1). The future volume changes have been projected from a relative volume of 1 starting in 1975, representing the reference period of 1961-90 (Fig. 7-1). The glacier area will be reduced gradually as the glacier is exposed to negative mass balances, thereby making the glacier mass balance less negative. At the same time the thinning of the glacier will counteract this effect because of the mass balance/elevation feedback. In this report we have cut-off the volume change predictions when the ice volume has been reduced by 30 % (Fig. 7-1).

The two GCMs represent quite different projections for temperature at Storbreen and precipitation at Engabreen. Consequently, the mass balance and volume changes differ between the scenarios. According to the MaxPlanck scenario the volume of Engabreen will increase by 4 % in 2100. According to the Hadley scenario, the volume of Engabreen will decrease by 30 % within 2056. Both B2 scenarios show that the volume of Storbreen will be reduced during the next century, sooner for the MaxPlanck scenario than for the Hadley scenario.

Table 7-1. The ice thickness and water volume of Storbreen and Engabreen.

	Area	**Ice thickness**	**Water layer**	**Water volume**
	km^2	m	m w.e.	10^6 m^3 w.e.
Storbreen	5.3	115[1]	100	530
Engabreen	39.0	205	185	7200

[1] *Based on interpolation of 44 point measurements in 2005.*

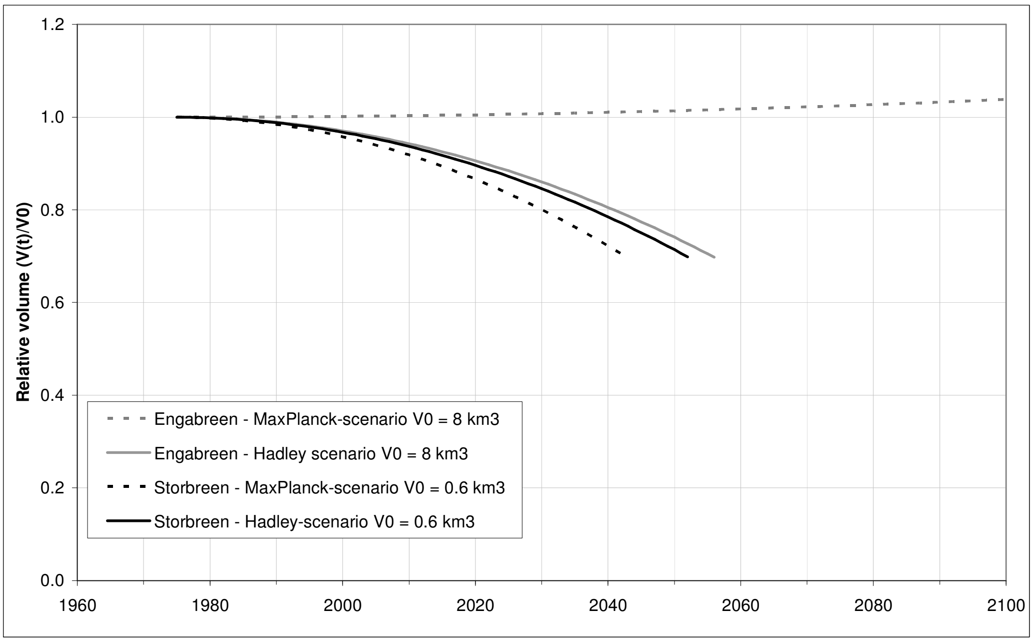


Figure 7-1. Projected volume change of Storbreen and Engabreen using a simple static sensitivity approach and assuming a linear increase in temperature and precipitation. Changes in glacier geometry and non-linear effects are neglected.

7.2 Projected changes in runoff

The estimated run-off changes from the glaciers are both due to changes in precipitation and changes in glacier mass balance. The contribution from mass balance is the inverse of the volume change described in Chapter 7.1, using volumes given in Table 7.1 as a basis. The contribution from precipitation change is calculated from the linear increase expressed in the scenarios between 1961-90 and 2071-2100. The basis for calculating the contribution from the precipitation change is the normal precipitation over the glacier area as defined by the normal (1961-90) run-off from the basin. This is 1633 and 3870 mm/a at Storbreen and Engabreen, respectively. The starting point is chosen to be 1975, the mid-point of the reference period. The differences in volume between 1975 and the time of mapping, 1997 for Storbreen and 2001 for Engabreen, are small compared with the uncertainty in the volume estimates.

The extra runoff contribution from the glaciers is shown in Figure 7-2. As for the volume change calculation, we stop the calculations when the glaciers have lost 30 % of their present volume. In 2050, the extra annual run-off will be in the order of 4 mill. m^3 water from Storbreen, and in the order of 50 mill. m^3 water from Engabreen.

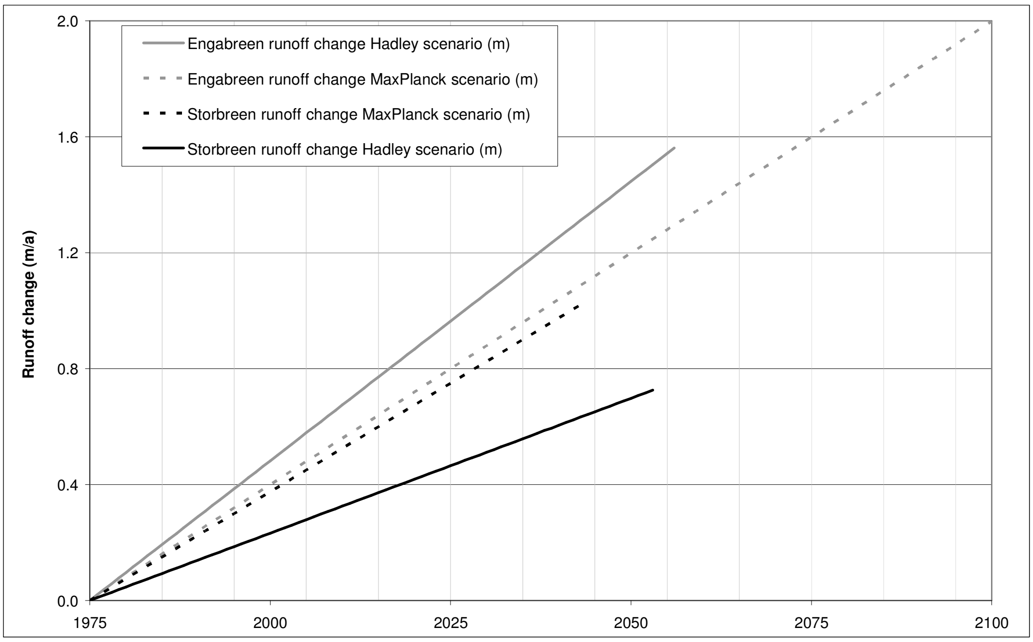


Figure 7-2. Increased runoff from Storbreen and Engabreen according to climate change scenarios for 1961/90 – 2075/2100. The projected changes are cut-off when the glacier has lost 30% of its initial volume.

7.3 Projected changes in streamflow from the catchments

In a study recently published by NVE and the Norwegian Meteorological Institute streamflow scenarios of five heavy glaciated basins were compared with three glacier free catchments (Lappegard et al., 2006). The study involved the catchments that include Storbreen (Elveseter) and Engabreen (Engabrevatn). The projected future streamflows were simulated by the Gridded Water Balance Model (GWB). Their study used the same climate change scenarios with the same time periods for control and future climate. The main findings of their study were that the glaciated catchments will have increased streamflow for the future climate (2071-2100) during summers. In case of a complete melt down of glaciers, the streamflow will decrease for Elveseter and Engabrevatn in the future climate. The study also showed that summers will be drier, and summer droughts may become more severe in the case of a glacier-free environment. Further details on this study and the results are found in Lappegard et al. (2006).

8 Concluding remarks

In this report we have modelled the mass balance of two different Norwegian glaciers and studied their sensitivity to climate change. The mass balance models were enable to reproduce the main characteristics of the annual and seasonal mass balance of the glaciers and were expected to give realistic estimates of the response of the glaciers to climate change. The static climate sensitivity was calculated using perturbations in temperature and precipitation. The results reveal, as expected and in accordance with previous studies, that the maritime Engabreen is more sensitive than the continental Storbreen both to temperature and precipitation changes. The climate sensitivity calculated by combining calculated Seasonal Sensitivity Characteristics and normalised and smoothed seasonal scenario values resulted in a mean temperature sensitivity of Storbreen and Engabreen of -0.50 and -0.90 m w.e. respectively for a 1K warming. A 10 % increase in precipitation represents a climate sensitivity of +0.17 m w.e. for Storbreen, while for Engabreen the sensitivity varies between +0.51 and +0.38 m w.e. using the Max Planck and the Hadley precipitation scenarios respectively.

Based on the climate change scenarios and the calculated static climate sensitivities, we estimate that Storbreen will loose about 30 % of its volume by around 2050. The volume estimates of Engabreen range from a 4 % increase by 2100 (using the MaxPlanck scenario) to a 30 % decrease within 2056 (using the Hadley scenario). The estimated extra annual run-off is larger from Engabreen than Storbreen due to its much bigger size, by 2050 it will be in the order of 4 mill. m3 water from Storbreen and 50 mill. m3 water from Engabreen. We have neglected changes in glacier geometry and non-linear effects. A dynamic model is needed in order to take into account these geometric effects and to calculate the dynamic sensitivities. However, the main source of uncertainty in the volume and runoff estimates is the future climate development. Both the temperature and precipitation scenarios spans over a large range. The precipitation predictions have a large degree of uncertainty in both the total amount as well as the in the seasonal and spatial distribution. The projected precipitation differences between the two B2 scenarios are large, especially for Engabren, and influence greatly on the predicted changes of the volume and runoff from the glaciers.

9 References

Aðalgeirsdóttir, G., T. Jóhannesson, H. Björnsson, F. Pálsson and O. Sigurðsson. 2006. The response of Hofsjökull and southern Vatnajökull, Iceland, to climate change. *Journal of Geophysical Research, 111, F03001,* doi:10.1029/2005JF000388.

Andreassen, L.M. 1999. Comparing traditional mass balance measurements with long-term volume change extracted from topographical maps: a case study of Storbreen glacier in Jotunheimen, Norway, in the period 1940 - 1997. *Geografiska Annaler, 81 A,* 467-476.

Andreassen, L.M., H. Elvehøy, B. Kjøllmoen, R.V. Engeset and N. Haakensen. 2005. Glacier mass balance and length variations in Norway. *Annals of Glaciology, 42,* 317-325.

Bergström, S., J. Andréasson, S. Beldring, B. Carlsson, L. P. Graham, J. F. Jónsdóttir, K. Engeland, M. A. Turunen, B. Vehviläinen and E. J. Førland. 2003. Climate Change Impacts on Hydropower in the Nordic Countries. State of the art and discussion of principles. *CWE Report No. 1, CWE, Reykjavík,* 40 pp.

Brock, B.W., I.C. Willis and M.J. Sharp. 2000. Measurement and parameterisation of albedo variations at Haut Glacier d'Arolla, Switzerland. *Journal of Glaciology*, 46 (155), 675-688.

Church, J. A., J. M. Gregory, P. Huybrechts, M. Kuhn, K. Lambeck, M. T. Nhuan, D. Qin and P. L. Woodworth. 2001. Changes in sea level. *In* Houghton, J. T., Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell and C.and C. A. Johnson, *eds. Climate Change 2001:The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK, and New York, NY, USA, Cambridge University Press,* 881 pp.

Döscher, R., Willén, U., Jones, C., Rutgersson, A., Meier, H.E.M., Hansson, U. and Graham, L.P. 2002. The development of the regional coupled ocean-atmosphere model RCAO. Boreal Environ. Res. 7, 183-192.

Gordon, C., Cooper, C., Senior, C.A., Banks, H., Gregory, J.M., Johns,T.C., Mitchell, J.B.F. and Wood, R.A. 2000. The simulation of SST, sea ice extents and ocean heat transport in a version of the Hadley Centre coupled model without flux adjustments, Clim.Dyn., 16,147-168.

Greuell, W. and Genthon, C. 2004. Modelling land-ice surface mass balance. In: Bamber J.L. and A.J.Payne: Mass balance of the chryosphere: observations and modeling of contemporary and future changes. *Cambridge University Press,* 644 pp.

Greuell, W. and C.J.J.P. Smeets. 2001. Variations with elevation in the surface energy balance on the Pasterze (Austria). *Journal of Geophysical Research, 106 (D23), 31*, 717-727.

Hay, L.E., Wilby, R.L. and Leavesley, G.H., 2000. A comparison of delta change and downscaled GCM scenarios for three mountainous basins in the United States. *Journal of the American Water Resources Association, 36,* 387-397.

Hock, R. 1999. A distributed temperature-index ice- and snowmelt model including potential direct solar radiation. *Journal of Glaciology, 45 (149),* 101–111.

Hock, R., P. Jansson, P. and L. Braun. 2005. Modelling the response of mountain glacier discharge to climate warming. In Huber, U. M., H. K. M. Bugmann and M. A. Reasoner, eds. Global Change and Mountain Regions—A State of Knowledge Overview. *Advances in Global Change Series. Dordecht, Springer,* 243–52.

IPCC. 2001. Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Houghton, J. T., Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell and C. A. Johnson, eds. Cambridge University Press, Cambridge, UK, and New York, NY, USA, 881 pp.

Isaksen K, E.S.F Heggem, S. Bakkehøi, R.S. Ødegård, T. Eiken, B. Etzelmüller and J.L. Sollid. 2003. Mountain permafrost and energy balance on Juvvasshøe, southern Norway. In Proceedings Volume 1, Eight International Conference on Permafrost, Zurich, Switzerland, 21-25 July, Phillips M, Springmann SM,Arenson LU (eds.). Swets & Zeitlinger, Lisse, 467-472.

Jóhannesson, T., G. Aðalgeirsdóttir, H. Björnsson, C. E., Bøggild, H. Elvehøy, S. Guðmundsson, R. Hock, P. Holmlund, P. Jansson, F. Pálsson, O. Sigurðsson and Þ. Þorsteinsson. 2004. The impact of climate change on glaciers in the Nordic countries. *The CWE Project, Report No. 3.*

Jóhannesson, T., O. Sigurðsson, B. Einarsson and T. Thorsteinsson. 2006. Mass balance modeling of the Hofsjökull ice cap based on data from 1988–2004*. Orkustofnun, Hydrological Service Division. OS-2006/004.*

Kjøllmoen, B., L.M. Andreassen, R. Engeset, H. Elvehøy, M. Jackson and R.H. Giesen, 2006. Glasiological investigations in Norway 2005. *NVE Report No. 2 2005*, 91 pp + app.

Klok, E.J. and J. Oerlemans. 2002. Model study of the spatial distribution of the energy and mass balance of Morteratschgletscher, Switzerland. Journal of Glaciology, Vol. 48, No. 163, 505-518.

Lappegard, G., S.Beldring, L.Roald, T. Engen-Skaugen and E.J.Førland. 2006. Projection off uture streamflow in glaciated and non-glaciated catchments in Norway. *NVE Oppdragsrapport A, No. 9,* 61 pp + app.

Liestøl, O. 1967. Storbreen glacier in Jotunheimen, Norway. *Norsk Polarinstitutt Skrifter 141*, 63 pp.

Nakićenović, N., J. Alcamo, G. Davis, B. de Vries, J. Fenhann, S. Gaffin, K. Gregory, A. Grübler, T.Y. Jung, T. Kram, E.L. La Rovere,, L. Michaelis, S. Mori, T. Morita, W. Pepper, H. Pitcher, L. Price, K. Riahi, A. Roehrl, H.-H. Rogner, A. Sankovski, M. Schlesinger, P. Shukla, S. Smith, R. Swart, S. van Rooijen, N. Victor, Z. Dadi. 2000. *IPCC Special Report on Emission Scenarios. Cambridge Univ. Press,* 599 pp.

Oerlemans, J. 1992. Climate sensitivity of glaciers in southern-Norway: application of an energy-balance model to Nigardsbreen, Hellstugubreen and Alfotbreen. *Journal of Glaciology, 38 (129),* 223-232.

Oerlemans, J. 2001. Glaciers and climate change, AA Balkema Publishers, 148 pp.

Oerlemans, J. and B.K. Reichert. 2000. Relating glacier mass balance to meteorological data using a Seasonal Sensitivity Characteristic (SSC). *Journal of Glaciology,* 46 (152), 1-6.

Olseth, J. A. 2005. Global dimming. *Cicerone 4/2005*, 24-25.

Rasmussen, L. A., and H. Conway. 2005. Influence of upper-air conditions on glaciers in Scandinavia. *Annals of Glaciology,* 42, 402-408.

Roeckner E, L. Bengtsson, J. Feichter, J. Lelieveld and H. Rodhe. 1999. Transient climate change simulations with a coupled atmosphere-ocean GCM including the tropospheric sulphur cycle. *Journal of Climate, 12,* 3004-3032.

Rummukainen, M. 2006. The CE regional climate scenarios. *European Conference on Impacts of Climate Change on Renewable Energy Sources, Reykjavik, Iceland, June 5-9,* 9-12.

Schuler, T., R. Hock, M. Jackson, H.Elvehøy, M. Braun, I. Brown, J.-O. Hagen. 2005. Distributed mass balance and climate sensitivity modelling of Engabreen, Norway. *Annals of Glaciology, 42,* 395-401.

de Woul, M. and R. Hock. 2005. Static mass balance sensitivity of Arctic glaciers and ice caps using a degree-day approach. *Annals of Glaciology, 42,* 217-224.

Wild, M., H. Gilgen, A. Roesch, A. Ohmura, C.N. Long, E.G. Dutton, B. Forgan, A. Kallis, V. Russak, and A. Tsvetkov. 2005. From Dimming to Brightening: Decadal Changes in Solar Radiation at Earth's Surface. *Science, 308*, 847.

Østrem, G. and O. Liestøl. 1964. Glasiologiske undersøkelser i Norge i 1963. Norsk Geografisk Tidsskrift, Bd. 18, h7-8, 281-340.

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