Modeling future glacier mass balance and volume changes using ERA-40 reanalysis and climate models: A sensitivity study at Storglaciären, Sweden

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Modeling the response of glaciers to future climate change is important for predicting changes in global sea level rise and local water resources. We compute until the year 2100 the mass balance and volume evolution of Storglaciären, a small valley glacier in Sweden, using a temperature index mass balance model. We focus on the sensitivity of results to the choice of climate model and variants of adjusting ERA-40 temperatures to local conditions. ERA-40 temperature and precipitation series from 1961 to 2001 are validated and used both as input to the mass balance model and for statistical downscaling of one regional and six global climate models (GCMs). Future volume projections are computed using area-volume scaling and constant glacier area. ERA-40 data correlate well with observations and capture observed interannual variability of temperature and precipitation. The mass balance model driven by several variants of ERA-40 input performs similarly well regardless of temporal resolution of the input series (daily or monthly). The model explains ~70% of variance of measured mass balance when the input temperatures are reduced by the lapse rate that maximizes model performance. Fitting ERA-40 temperatures to observations close to the glacier does not improve the performance of the model, leading us to conclude that ERA-40 can be used for mass balance modeling independent of meteorological observations. Projected future volume series show a loss of 50–90% of the initial volume by 2100. The differences in volume projections vary by 40% of the initial volume for six different GCMs input to mass balance model, while each volume projection varies by 20% depending on whether volume-area scaling or constant area is used and by 10% depending on details in the mass balance model used. The correction of biases in the seasonal temperature cycle of the GCMs with respect to the ERA-40 data is crucial for deriving realistic volume evolution. Static mass balance sensitivities to temperature and precipitation change in the 21st century are \(-0.48 \text{ m yr}^{-1} \text{ K}^{-1}\) and \(0.025 \text{ m yr}^{-1}\) per % increase, respectively.


1. Introduction

Glaciers have generally retreated during the last century with notably accelerated mass losses in recent years [Dyurgerov and Meier, 2000; Meier et al., 2003]. Further glacier wastage will have major implications on all spatial scales, ranging from local effects on river runoff [Hock et al., 2005] to global effects through meltwater contribution to sea level rise [e.g., Church et al., 2001; Arendt et al., 2002]. Modeling the response of glaciers to future climate change therefore has major societal implications. Traditionally, glacier models have been forced by meteorological observations in the vicinity of the glaciers [e.g., Schneeberger et al., 2001; Abdalghisdoitter et al., 2006], but scarcity of meteorological data in remote glacierized areas poses serious constraints to such an approach and hampers larger-scale glacier modeling.

Climate reanalysis products can be very useful for investigating climatic patterns of largely inaccessible regions, thus circumventing the need for direct meteorological measurements. Reanalyses are derived by processing multidecadal sequences of past meteorological observations using modern data assimilation techniques developed for numerical weather prediction. The result is a dynamically consistent three-dimensional gridded data set that represents the best estimate of the state of the atmosphere at a certain time. Therefore it should be superior to the gridded climatology of the Climate Research Unit (CRU) which is derived from interpolation of observations [New et al., 1999], and has been used in mass balance modeling [Raper and Braithwaite, 2006]. Reanalyses products are as yet little exploited in glacier monitoring. Hanna et al. [2001], Reichert et al. [2001], and Rasmussen and Conway [2004]
have used NCEP/NCAR reanalysis or the 15-year reanalysis (ERA-15, 1979–1993) by the European Centre for Medium-Range Weather Forecast (ECMWF) to estimate present glacier mass balance, or have used them to downscale the output from global climate models (GCMs) in order to model future mass balance changes. Recently, ECMWF completed the ERA-40 project, which produced a global reanalysis of the state of the atmosphere, land and surface over the period of mid-1957 to mid-2002 [Simmons and Gibson, 2000; Källberg et al., 2004]. This “second-generation” ECMWF reanalysis, ERA-40, opens a new potential in glacier-climate modeling [e.g., Velicogna et al., 2005].

In this study we estimate the mass balance and volume changes of Storglaciären, a small valley glacier in northern Sweden, for the 21st century using climate scenarios derived from one regional climate model (RCM) and six GCMs downscaled by means of ERA-40 data. Storglaciären is chosen as the best case since it is a well investigated glacier with a wealth of available data. Specifically, it has the longest detailed mass balance record in the world [Holmlund et al., 2005]. We use a simple mass balance model based on air temperature and precipitation data and apply volume-area scaling [Bahr et al., 1997] for the volume change computations.

The specific goals are (1) to validate the ERA-40 data in the study area and to explore the potential to use ERA-40 data in mass balance modeling, (2) to investigate the sensitivity of the results to variations in the input of the mass balance model, such as variations caused by using monthly or daily input data, using different calibration periods, and applying different downscaling methods for the ERA-40 data, (3) to investigate the sensitivity of mass balance and volume predictions to the choice of the GCM, and (4) to derive the mass balance sensitivities for the 21st century. Hence this study focuses on sensitivity analyses, addressing uncertainties in the modeling of the response of glaciers to climate change. We present a methodology to use daily or monthly ERA-40 data and statistically downscaled monthly GCM output for glacier predictions which, due to its modest data requirements, may be suitable to predict future glacier wastage on large spatial scales.

2. Study Site

Storglaciären (67.90°N, 18.57°E) has a length of 3 km and an area of approximately 3.1 km², ranging from 1130 m to 1720 m asl in altitude. The average and maximum ice thicknesses are 95 m and 250 m, respectively. The glacier is temperate with a perennial cold (~0°C) surface layer in the ablation area reaching up to 60 m in depth [Pettersson et al., 2004]. Storglaciären is located along a strong climate gradient with a maritime climate in the west and a more continental climate toward the east, due to a dominant wind direction from the west and the effect of topography. The glacier has been intensively studied for several decades. Glaciometeorological studies have revealed that the turbulent fluxes contribute on average 40–60% of the energy available for melt [Hock and Holmgren, 1996, 2005]. The mean annual air temperature (1965–2003) at Tarfala Research Station (67.92°N, 18.60°E, 1130 m asl) located ~1 km from the glacier is ~3.7°C, and summer temperature (June–August) is 5.7°C, while annual precipitation is estimated to amount roughly to 1000 mm. The glacier has retreated considerably since the beginning of 20th century when its front reached the maximum in response to cooling during the 19th century [Holmlund, 1987]. The retreat was interrupted by periods of higher winter precipitation in the mid–1970s which translated into a complete halt in the retreat during the 1980s. A period of significantly enhanced winter precipitation between the late 1980s and mid-1990s caused positive mass balances and mass gain but no change in terminus position. Studies of glacier-climate coupling show that the net balance of Storglaciären is well correlated with the summer temperature at the Tarfala Research Station [Holmlund, 1987].

3. Data

Our study is based on various data sets including the mass balance record of Storglaciären, daily temperature data from Tarfala Research Station, daily temperature and precipitation data from four additional meteorological stations up to 80 km away from the glacier, daily temperature and precipitation analyses from ERA-40 and a RCM from several grid points close to the glacier for the period 1958–2001 and 1961–2100, respectively, and monthly temperature and precipitation data from the grid point closest to Storglaciären from six GCMs for the period 1961 to 2100. These data sets are briefly described below.

3.1. Mass Balance of Storglaciären

A detailed mass balance program was initiated in 1945 and revised with time. Since 1966 winter mass balance has been computed from snow probing programs on a regular 100 × 100 m grid and several density pits. Ablation stakes at a density of about 20 per km² are used for the summer balance. Winter and summer data have been extrapolated to five topography maps generated at 10 year intervals to yield area-averaged mass balances [Holmlund et al., 2005]. Since 1969, according to available maps, the glacier area change is less than 1%. Mean winter, summer and net balances (in water equivalent) for the period 1945/1946–2003/2004 are +1.43, −1.66, and −0.23 m yr⁻¹, respectively.

3.2. Meteorological Observations

Daily temperature and precipitation data were available from Tarfala Research Station (67.92°N, 18.58°E, 1135 m asl) for the period 1965 to date and from four additional weather stations run by the Swedish Meteorological and Hydrological Institute (SMHI) but for shorter time periods (Figure 1): Ritsen (67.73°N, 17.47°E, 524 m asl, 1981–2002), Riksgränsen (68.43°N, 18.13°E, 508 m asl, 1961–2002), Abisko (68.36°N, 18.82°E, 388 m asl, 1966–2001) and Nikkaluokta (67.85°N, 19.02°E, 468 m asl, 1966–1975).

3.3. Reanalysis Data: ERA-40

The 40-year reanalysis project of the ECMWF, ERA-40, uses the ECMWF numerical weather forecast model to produce gridded analyses of the state of the atmosphere with a 6-hour time interval. Through data assimilation, meteorological observations along with data from satellites and information from a previous model forecast are input into a short-range weather forecast model. This is integrated
forward and combined with observational data for the corresponding period. ERA-40 is derived for the period of mid-1957 to mid-2002 and it covers the whole globe with spectral resolution $T_1159$, corresponding to a grid spacing close to 125 km (1.125°) in the horizontal and with sixty levels in the vertical [Källberg et al., 2004]. Until 1967 almost no observations from Scandinavia were included in the ERA-40 assimilation, which resulted in an underestimation of the observed warming trend over that region for the period 1958–2001. The overall observing system improved at the end of 1978 when more satellite temperature and humidity observations became available to include in the analysis. As a result, the accuracy of medium-range forecasts initiated from the ERA-40 analysis improved from 1979 onward [Simmons et al., 2004]. In comparison with the NCEP/NCAR reanalysis, ERA-40 monthly temperatures show better agreement in trends and variability to the CRU climatology based on observations [Simmons et al., 2004].

We retrieved 6-hourly 2 m air temperature and precipitation ERA-40 data from a bilinearly interpolated grid ($0.5° \times 0.5°$) for the area containing Storglaciären, forming 3 $\times$ 3 grid cells with the grid cell containing Storglaciären in the center (Figure 1). The data represent averages over a grid cell. Daily temperature of each grid cell is calculated as the average of the 6-hourly temperature. Daily precipitation is based on the forecasted fields. Since the forecast is affected by spin-up effects, the most reliable technique to derive daily precipitation is to use the 24 h forecasts that are started every 12 hours [Martin, 2004]. We subtract the precipitation accumulated in 12 hours for each run from the precipitation accumulated in 24 hours for the same run. Precipitation derived for 00–12 h and 12–24 h time intervals is then summed to provide daily precipitation.

### 3.4. Regional Climate Model: RCA3

[12] Predictions of temperature and precipitation are derived from the regional climate model RCA3 of the Rossby Centre of the Swedish Meteorological and Hydrological Institute [Kjellström et al., 2005]. It runs with a resolution of about 50 km grid spacing on an area of roughly $5000 \times 5000$ km$^2$ with Scandinavia in focus for the time period of 1961–2100. The lateral boundaries are given by output of the General Circulation Model ECHAM4/OPYC3, and runs are forced by A2 and B2 emission scenarios from Intergovernmental Panel on Climate Change (IPCC) [2001].

[13] We retrieved 3-hour temperature and precipitation data for 1961 to 2100 from the runs with B2 emission scenarios for the grid points covering the study area (66°–70°N, 16°–20°E). The B2 emission scenario represents a modest scenario among the large suite of available emission scenarios. We chose the B2 run since it has widely been used in climate impact studies [e.g., Oerlemans et al., 2005]. Daily data were calculated as the arithmetical averages of 3-hour temperatures and as the sum of 3-hour precipitation values.

### 3.5. General Circulation Models

[14] Time series of monthly temperature and precipitation as predicted by six GCMs (ECHAM/OPYC3, HADCM3, CSIRO-Mk2, GFDL-R30, CGCM2, CCSR/NIES) were downloaded from the IPCC Data Distribution Centre (http://ipcc-ddc.cru.uea.ac.uk/). As for the RCA data, we use the predictions based on the B2 emission scenario [IPCC, 2001]. Downloaded data series span from 1961 to 2100. For each model only the data from the output grid point nearest to Storglaciären was considered in further analysis. More details about the gridded climate data sets are given in Table 1.

### 4. Methods

[15] We adopt the following overall methodology: First we evaluate the ERA-40 data using meteorological observations, and we derive transfer functions to convert the grid point ERA-40 data to observations. Second, the ERA-40 data are used to calibrate a temperature-index mass balance model where air temperature is related to summer mass balance and precipitation is related to winter mass balance. We compare the performance of nine approaches differing in the temporal resolution of the input data and manipulation of the ERA-40 temperature data. We also investigate the stability of regression coefficients when using different time periods. Third, time series of temperature and precipitation until 2100 are downscaled from RCA3 and the GCMs using ERA-40 data, and then used as input to the mass balance model for projections of mass balance and volume changes of Storglaciären in the coming century. We run eight variants of the calibrated mass balance model with the RCA3-derived climate scenario to study the sensitivity of the mass balance model. The variant with highest performance is then run with climate forcing derived from

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**Figure 1.** Study area including the meteorological stations used for validation of ERA-40 data. Storglaciären is located ~1 km southwest of Tarfala. Nine grid cells with the resolution of $0.5° \times 0.5°$ (~50 km) correspond to ERA-40 gridded data, while the large grid cell for comparison shows the grid cell used from the GCM with highest resolution (ECHAM/OPYC3, $2.8° \times 2.8°$).
six GCMs in order to investigate the sensitivity of results to the choice of the climate model. We also compare the impact of using predictions based upon volume-area scaling versus predictions assuming constant glacier area. Finally, static sensitivities for 21st century are computed from the RCA3 run.

4.1. Validation of Temperature and Precipitation From ERA-40

[16] Linear regression analysis is applied in order to investigate the correlation between the ERA-40 data and the observational data on daily, monthly and seasonal timescales. We use temperature data from Tarfala Research Station (1965–2002) since it is located in the immediate vicinity of Storglaciären. Ritsem’s data (1981–2002) are used for validation of precipitation, since year-round precipitation data are not available from Tarfala, and Ritsem’s data has been shown to correlate best with Storglaciären’s winter balance compared to data from other surrounding stations [de Woul and Hock, 2005].

[17] In order to analyze interannual variability of temperature and precipitation without being affected by systematic bias, time series of the temperature and precipitation ratio, $R$, between two consecutive years are estimated as follows:

$$ R = \frac{X(t)}{X(t+1)} $$  \hspace{1cm} (1)

where $t$ is the time index of the year, $R$ equals $R_{OBS}$ ($R_{ERA}$) when $X$ corresponds to 3-month averaged observational (ERA-40) data. Correlations between $R_{OBS}$ and $R_{ERA}$ are then used as indicators of correlation of interannual variability between ERA-40 and observational data. The function $F(t)$ expressed as:

$$ F(t) = \frac{R_{ERA}(t)}{R_{OBS}(t)} $$  \hspace{1cm} (2)

indicates high interannual similarity if $F(t)$ values are near unity.

[18] Since the gridded and the measured data refer to different elevations, temperature differences between ERA-40 and the observations from Tarfala station and three additional meteorological stations (Riksgränsen, Abisko and Nikkaluokta; Figure 1) were analyzed in order to adjust ERA-40 temperature to local conditions.

4.2. Mass Balance Model

[19] Melt has been found to correlate well with air temperature [e.g., Krenke and Khodakov, 1966; Braithwaite, 1984; Vallon et al., 1998] forming the basis for most mass balance models [Hock, 2003]. We use a simple degree-day approach following de Woul and Hock [2005]:

$$ b_w = \alpha_i \sum_{i=1}^{n} a_i T_i + \beta_i, \hspace{1cm} \begin{cases} \alpha_i = 1, T_i > 0 \\ \alpha_i = 0, T_i \leq 0 \end{cases} $$  \hspace{1cm} (3)

$$ b_w = \alpha_i \sum_{i=1}^{n} a_i P_i + \beta_i, \hspace{1cm} \begin{cases} \alpha_i = 1, T_i < 0 \\ \alpha_i = 0, T_i \geq 0 \end{cases} $$  \hspace{1cm} (4)

where $\alpha$ and $\beta$ are the coefficients derived from linear regression between measured summer mass balances ($b_w$) and positive degree-day sums ($\sum a_i T_i$) over the entire mass balance year and between measured winter mass balances ($b_w$) and annual sums of daily/monthly precipitation ($\sum a_i P_i$) with negative air temperatures. The mass balance year is defined from 1 October ($t_1$) to 31 September ($t_2$). The model needs calibration based on seasonal mass balance data, thus hampering direct transferability to other glaciers.

[20] We aim to show if and how much ERA-40 needs to be adjusted (downscaled) before being used in the model. Therefore the model performance, i.e., the percentage of the explained variance of measured mass balance by the modeled one, is tested according to nine variants of the model input. Variants differ in the temporal resolution of the input data (seasonal, daily or monthly averages) and in the method by which ERA-40 temperatures are adjusted prior to model input. In methods 1–3 $T_i$ is taken from ERA-40 without any adjustments, while in methods 4–9 temperatures are adjusted by different types of lapse rates to represent local conditions. The following input variants are used.

[21] 1. $\sum a_i T_i$ is equal to the sum of mean June, July and August temperatures ($T_{Jun} + T_{Jul} + T_{Aug}$), while $\sum a_i P_i$ is the sum of precipitation from all months except June, July and August.

[22] 2. $T_i$ is monthly temperature and $P_i$ is monthly precipitation sum.

[23] 3. $T_i$ is daily temperature and $P_i$ is daily precipitation sum.

[24] 4. $T_i$ is daily temperature which is adjusted in two steps: first by adjusting ERA-40 temperatures using the monthly variable lapse rate derived from validation of ERA-40 with Tarfala temperature data. By this ERA-40 temperatures are fit to the observations. The second step is further reduction of the temperature by the lapse rate (between
Tarfala elevation and Storglaciären’s equilibrium line altitude = 1468 m) that maximizes correlation between degree-day sums (\(\Sigma a_iT_i\)) and \(b_c\). \(P_i\) is daily precipitation sum.

[25] 5. Method is as in 4, but \(T_i\) and \(P_i\) are monthly data.

[26] 6. \(T_i\) is daily temperature lowered by the lapse rate that maximizes correlation between degree-day sums (\(\Sigma a_iT_i\)) and \(b_c\). Hence observational data are not needed. \(P_i\) is daily precipitation sum.

[27] 7. Method is as in 6, but \(T_i\) and \(P_i\) are monthly data.

[28] 8. \(T_i\) is monthly temperature lowered by the average lapse rate derived from the temperature and altitude difference between ERA-40 and four meteorological stations. \(P_i\) is monthly precipitation sum.

[29] 9. \(T_i\) is synthetic temperature data derived from the monthly data from 5 applying a normal distribution of daily temperatures from 4. The normal distribution is derived for each month of each year and the method is used only for calibration of summer mass balance. Winter mass balance is not modeled for this case.


4.3. Future Runs of Mass Balance Model

4.3.1. Climate Forcing

[31] Direct use of meteorological output from climate models is currently not applicable for impact studies, as climate models are unable to represent local subgrid-scale features and dynamics [Giorgi et al., 2001] which leads to biases in both temperature and precipitation. Since the degree-day model is particularly sensitive to the seasonal distribution of temperature, such differences will strongly affect the mass balance simulations. Also, the direct use of coarse GCM grid points naturally results in a poor representation of the local climate, especially for precipitation, which is highly dependent on the local orographic conditions. Therefore downscaling techniques need to be applied to the climate model output [Wilby et al., 1998; Giorgi et al., 2001]. Downscaling methods generally use observations as a reference climate [Salathé, 2005]. We use ERA-40 because these data are the input to the mass balance model. We apply a simple statistical downscaling method, referred to as ‘local scaling’ [Widmann et al., 2003; Salathé, 2005], which for temperature can be thought as a lapse rate correction due to elevation difference of the local grid point relative to the climate model grid. Downscaled series were produced for RCA3 and each GCM for the period 2001 to 2100 by correcting the monthly climate model output series by the averaged difference over a baseline period prior to 2001 between climate model and ERA-40 for each month. Hence the average seasonal cycle from ERA-40 is used as a reference by which the seasonal cycle from the climate model is ‘corrected’. Future temperature time series (\(T_i\)) were calculated by

\[
T_i(t) = T_{i,c}(t) + \left(\frac{T_i\text{ERA} - T_{i,c}}{C_0}\right), \quad i = 1, \ldots, 12
\]

where \(T_{i,c}\) is monthly temperature for the \(i\)th month from the climate model output from \(t = 2001\) to \(2100\), \(T_i\text{ERA}\) and \(T_{i,c}\) are mean temperature from climate model and ERA-40, respectively, for the \(i\)th month averaged over a chosen baseline period. Five different baseline periods are chosen for comparison: 1961–2001, 1971–2001, 1981–2001, 1991–2001 and 2000–2001.

[32] As an example, Figure 2 shows the seasonal cycles for ERA-40 temperatures averaged over the 1961–2001 period compared with those modeled by the six GCMs. Although overall patterns are reproduced well, some models have strong seasonal biases. CSIRO and CCSR/NIES have the temperature maximum shifted by one month combined with subdued seasonality, probably since the grid cell used contains large ocean percentage due to coarse horizontal resolution.

[33] For precipitation, the local scaling method simply multiplies the large-scale simulated precipitation at each local grid point by a seasonal scale factor [Widmann et al., 2003]. Since changes in precipitation over the year show no obvious seasonal cycle but a more random distribution, we scale precipitation equally throughout the year. Thus the future series \(P_i(t)\) is generated by

\[
P_i(t) = P_{i,c}(t) \frac{P_{i,\text{ERA}}}{P_{i,c}}, \quad i = 1, \ldots, 12
\]

where \(P_{i,c}\) is monthly precipitation sum from the climate model from \(t = 2001\) to \(2100\), \(P_{i,c}\) and \(P_{i,\text{ERA}}\) are mean precipitation from the climate model and ERA-40, respectively, averaged over the baseline period. Climate models tend to underestimate large amounts of precipitation and overestimate small amounts [Xiu, 1999]. This is also a characteristic of ERA-40 precipitation when compared to observations from Ritsem station (Figure 3). However, ERA-40 captures well the temporal variability, which is more crucial than absolute amounts for the type of mass balance model chosen (equation (4)). Figure 4 illustrates the annual time series of temperature and precipitation derived.
from downscaling the RCA3 model with different baseline periods. Since the differences in the series resulting from the baseline periods 1961–2001, 1971–2001, 1981–2001 and 1991–2001 are too small to be distinguished in Figure 4, only one of these series is presented while the series derived from 2-year baseline period 2000–2001 shows notable differences.

4.3.2. Volume Changes

[34] In response to prolonged mass balance changes, glacier area and volume will change. These changes may be approximated by volume-area scaling [Bahr et al., 1997; Van de Wal and Wild, 2001]. Glacier volume change, $\Delta V$, is estimated by

$$\Delta V(t) = b_n(t)A(t),$$

where $b_n$ is the modeled future annual net mass balance and $A$ is the area of the glacier. Volume $V$ is related to area $A$ by the empirical relation:

$$V(t) = k[A(t)]^y,$$

where $y = 1.375$ was obtained by Bahr et al. [1997] using theoretical considerations and the constant $k = 0.0633$ km$^{-3}$–1 $S$ is derived from Storglaciären’s initial volume $V(t = 2001) = 0.3$ km$^3$ and the initial area $A(t = 2001) = 3.1$ km$^2$. After each mass balance year a new volume is computed from which a new glacier area is derived. For comparison, we also perform runs with glacier area kept constant.

4.3.3. Static Mass Balance Sensitivity

[35] Modeled future mass balances are used to estimate static mass balance sensitivities due to temperature ($db/dT$) and precipitation ($db/dP$) changes. The concept of mass balance sensitivity [e.g., Braithwaite et al., 2002] has been widely used in predicting glacier changes [Gregory and Oerlemans, 1998; Oerlemans et al., 1998, 2005]. We derive static mass balance sensitivities in the 21st century by calculating time series of $db/dT$ and $db/dP$ based on the difference between 20-year running averages of mass balances, temperature and precipitation, and corresponding averages over a fixed 20-year reference period (2001–2020):

$$\frac{db}{dT} = \frac{\sum_{t=0}^{b_{n,20}} b_n(t) - \sum_{t=2001}^{2020} b_n(t)}{\sum_{t=0}^{T(t)} - \sum_{t=2001}^{2020} T(t)},$$

$$\frac{db}{dP} = \frac{\frac{1}{20} \sum_{t=0}^{b_{n,20}} b_n(t) - \frac{1}{20} \sum_{t=2001}^{2020} b_n(t)}{\left(\sum_{t=0}^{P(t)} - 1\right) 100},$$

Figure 4. Annual time series of (a) temperature and (b) precipitation, derived from downscaling RCA3 output using two different baseline periods: (1) 41-year period, 1961–2001, and (2) 2-year period, 2000–2001.
are static rather than dynamic. In addition, the mass balance model was calibrated for a period of roughly constant glacier area. Therefore the mass balance record and the derived regression coefficients in the mass balance model reflect climate forcing but neglect the effect of area changes [Elsberg et al., 2001; Harrison et al., 2005].

5. Results and Discussion

5.1. Validation of ERA-40 Temperature

Regression daily, monthly and annual precipitation from ERA-40 (all nine grid points) against corresponding data from Ritsem yields the highest correlation for the grid point west from the central grid point with $r_w^2 = 0.381$, $r_m^2 = 0.670$ and $r_s^2 = 0.563$, respectively. Analysis of seasonal averages revealed that correlation was better in autumn (September, October, November (SON)) and winter (December, January and February (DJF)) than in the remaining seasons ($r_{DJF}^2 = 0.807$, $r_{MAM}^2 = 0.748$, $r_{JJA}^2 = 0.601$, $r_{SON}^2 = 0.882$). As expected, these correlations are lower than those for temperature. When analyzing interannual variability, the highest correlation between $R_{OBS}$ and $R_{ERA}$ was obtained for the winter season ($r_{DJF}^2 = 0.830$, $0.8 < F(t) < 1.3$) and the lowest for the summer season ($r_{JJA}^2 = 0.484, 0.6 < F(t) < 1.6$). On the basis of high correlation for interannual variability we conclude that ERA-40 can be used as a reference for downscaling precipitation (equation (6)).

5.2. Validation of ERA-40 Precipitation

Table 2 presents the results of the regression analysis between measured and modeled mass balances, as produced by the nine (1–9) variants of the input to the mass balance model. In most cases correlation is higher for the summer than the winter balance, with $r^2$ ranging from 0.49 to 0.80 for $b_2$ and 0.28 to 0.73 for $b_w$. The highest correlations are comparable and even slightly higher than those derived for Storglaciären from model 6 using measured data from Ritsem ($r_{DJF}^2 = 0.87$, $r_{MAM}^2 = 0.65$ [de Woul and Hock, 2005]).

The most sophisticated method 4, which fits the ERA-40 temperatures to the observed Tarfala temperatures before adjusting it further to the glacier site, does not yield the highest correlation. In fact, all methods except 2 and 3 tend to produce very similar correlations regardless of the average lapse rate derived from ERA-40 data and annual data from four weather stations amounts $-0.0037 \text{K m}^{-1}$ ($r^2 = 0.76$) and is applied in the mass balance model with method 9.

5.3. Calibration of the Mass Balance Model

The highest correlations are comparable and even slightly higher than those derived for Storglaciären from model 6 using measured data from Ritsem ($r_{DJF}^2 = 0.87$, $r_{MAM}^2 = 0.65$ [de Woul and Hock, 2005]).

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Table 2. Explained Variance ($r^2$) Between the Measured Summer Mass Balances, $b_s$, and Positive Degree-Day Sums, $\Sigma a_i T_i$, and Between Measured Winter Mass Balances, $b_w$, and Annual Snow Precipitation, $\Sigma a_i P_i$, as Produced by the Nine Variants of the Input to the Mass Balance Model and for Three Different Calibration Periods

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<tr>
<td>5 (m)</td>
<td>0.605</td>
<td>0.611</td>
<td>0.776</td>
<td>0.705</td>
<td>0.650</td>
<td>0.646</td>
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<tr>
<td>6 (d)</td>
<td>0.678</td>
<td>0.634</td>
<td>0.777</td>
<td>0.654</td>
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<td>0.647</td>
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<tr>
<td>7 (m)</td>
<td>0.621</td>
<td>0.732</td>
<td>0.794</td>
<td>0.640</td>
<td>0.650</td>
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</tr>
<tr>
<td>8 (d)</td>
<td>0.579</td>
<td>0.400</td>
<td>0.790</td>
<td>0.652</td>
<td>0.631</td>
<td>0.546</td>
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<tr>
<td>9 (m)</td>
<td>0.648</td>
<td>0.751</td>
<td>0.625</td>
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</tr>
</tbody>
</table>

$^a$See text for explanation. Letters in parentheses correspond to daily (d) or monthly (m) meteorological input of temperature and precipitation. Highest $r^2$ for each calibration period are bold.

5.4. Mass Balance and Volume Projections Until 2100

5.4.1. Sensitivity to Mass Balance Model Input

Our projection of 30% loss of volume by the middle of the 21st century closely coincides with the loss projected for Storglaciären by a distributed melt model combined with a three-dimensional ice flow model driven by ECHAM4 [Schneebberger et al., 2001]. A one-dimensional ice flow model allows for more realistic simulations of the mass balance changes over the calibration period 1980/1981–2000/2001. The differences of modeled volume change by 2100 derived from all methods, excluding methods 1 and 3, are within a range of 10% of initial volume.

Figure 7. Measured and modeled (a) summer mass balance, $b_s$, (b) winter mass balance, $b_w$, and (c) net mass balance, $b_n$. Modeled mass balance is based on method 7 of the mass balance model and forced by ERA-40 data using the calibration period 1980/1981–2000/2001.
model driven by hypothetical warming of 0.02 K per year without change in precipitation projected 20% volume loss by 2050 and 80% loss by 2100 [Oerlemans et al., 1998].

5.4.2. Sensitivity to Choice of Reference Climate

The effect of the choice of the baseline period in generating the future climate time series on the volume evolution is illustrated in Figure 8b which shows the volume evolution estimated by the model with method 7 when the five baseline periods are applied to downscale the RCA3. All volume curves, except for the one forced by the climate series derived from the 2000–2001 baseline, are within a range of 3% of initial volume. This is smaller than the difference caused by the choice of the method for the mass balance model. The outlier is explained by lower future sums of precipitation compared to the sums from other baselines (Figure 4b), which is immediately reflected in reduced winter mass balance and therefore in enhanced loss of mass. It is obvious that the baseline needs to be properly chosen and include a sufficient number of years to subdue the effect of interannual variability. In our case the model is insensitive to the choice of any of the >10 years long baseline periods used.

5.4.3. Sensitivity to the Glacier Area Assumptions

Figure 8c presents the volume change derived from the mass balance model (method 7) with volume-area scaling and with constant area in the equation (7). Until the middle of the 21st century there is no substantial difference between the two curves. Thereafter the volume decrease becomes considerably overestimated (by 20% at the end of 2100) if the area reduction is not considered. Results must be considered as rough estimates since feedback between mass balance and area-elevation distribution is neglected (i.e., mass balance becomes less negative as area is removed from low-lying high-ablation altitudes). The larger volume loss when the glacier area is kept constant is a mathematical consequence of the use of equation (8) when \( b_n \) becomes consistently negative.

5.4.4. Sensitivity to Choice of Climate Model

In order to investigate the sensitivity of mass balance and volume predictions to the choice of the GCM, the mass balance model (method 7) is forced by downscaled temperature and precipitation from six GCMs (Figure 8d). Table 3 contains the trends in temperature and precipitation for annual, winter (DJF) and summer (JJA) means.

All models predict volume losses between 50% (ECHAM) to 90% (CCSR) of the initial value. This is a direct consequence of warming trends in the range of 2.3 to 4.9 K per century, which is more evident in the winter than in the summer season for most of the models. Positive trends in precipitation contain relative errors of more than 100% in the estimates (Table 3) which make the trends insignificant. Even if the trend was real, the increase in the range of 57 to 212 mm \( {\text{yr}}^{-1} \) per century cannot compensate the increased ablation due to the warming.

The CCSR model predicts the largest mass loss due to its extreme warming trend. CGCM2, although showing

Figure 8. Volume projections for Storglaciären in the 21st century derived from (a) eight methods (1–8) of the mass balance model and RCA3 output downscaled with ERA-40 reference climate for the baseline period 1961–2001, (b) method 7 applied on the RCA3 output downscaled by use of five different baseline periods, (c) method 7 applied on the RCA3, downscaled using the 1961–2001 baseline period and with volume-area scaling and constant area, and (d) method 7 applied on the six GCMs which are downscaled using 1961–2001 baseline period. In all projections, unless noted differently, the volume is derived from volume-area scaling.
trends comparable with other models, predicts smaller loss of volume than CCSR but larger loss in comparison with the other models. This is due to a sudden shift to higher annual temperatures in the period 2001–2010 and higher maximum temperatures in the interannual variations after 2060 while lacking any trend in precipitation. HADCM3, due to its higher-precipitation and low-temperature trend from 2001 to 2020, predicts a small growth of volume in that period. Afterward the volume decreases due to an increase in temperature. GFDL-R30 follows the volume evolution as in CGCM and CCSR until 2020 when it starts to predict lower mass loss (by 50% at the end of 2100) probably caused by lower slope in temperature trend and, in general, lower minimum temperatures in the interannual variability. ECHAM maintains almost the same volume evolution as CSIRO until 2070 when it shifts to the smaller loss of volume because it projects higher sums of precipitation.

An analysis of the differences in temperature and precipitation trends and interannual variations predicted by the GCMs shows how the differences are highly reflected in the modeled future mass balance. The range of volume change by the end of 2100 is within 40% of the initial volume. This is the largest range in total sensitivity in this study.

5.4.5. Static Mass Balance Sensitivity

Running 20-year relative changes of net mass balance ($db$), temperature ($dT$) and precipitation ($dP$) with respect to the reference period 2001–2020 are presented in Figure 10. Mass balance is obtained from method 7 of the mass balance model with the climate input from RCA3 downscaled with the baseline period 1961–2001. Temperature change shows constant increase due to a linear warming trend, while % precipitation change shows increase with a secondary minimum at the end of the 2020s. Mass balance changes gradually decrease toward more negative values.

Figure 9. Volume projections for Storglaciären in the 21st century, derived from method 7 of the mass balance model and forced by output from six GCMs. The temperature bias between GCM and ERA-40 is corrected for by the averaged difference over the baseline period 1961–2001 instead of using seasonally variable values.

Figure 10. Running 20-year relative changes of (a) net mass balance, $db$, (b) air temperature, $dT$, and (c) precipitation, $dP$, with respect to the reference period 2001–2020.

Table 3. Annual, Winter (DJF), and Summer (JJA) Trends in the Climate Models for the Grid Point Nearest to Storglaciären

<table>
<thead>
<tr>
<th>Model</th>
<th>Trend</th>
<th>T</th>
<th>P</th>
<th>Trend</th>
<th>T</th>
<th>P</th>
<th>Trend</th>
<th>T</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Annual</td>
<td>Winter</td>
<td>Summer</td>
<td>Annual</td>
<td>Winter</td>
<td>Summer</td>
<td>Annual</td>
<td>Winter</td>
<td>Summer</td>
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<tr>
<td>HADCM3</td>
<td>3.24 ± 0.34</td>
<td>57 ± 41</td>
<td>2.77 ± 0.85</td>
<td>34 ± 21</td>
<td>2.72 ± 0.38</td>
<td>49 ± 20</td>
<td></td>
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<tr>
<td>CSIRO-Mk2</td>
<td>3.11 ± 0.18</td>
<td>136 ± 36</td>
<td>2.90 ± 0.32</td>
<td>44 ± 19</td>
<td>3.02 ± 0.17</td>
<td>10 ± 18</td>
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<td></td>
</tr>
<tr>
<td>GFDL-R30</td>
<td>2.31 ± 0.37</td>
<td>76 ± 43</td>
<td>2.97 ± 0.87</td>
<td>14 ± 17</td>
<td>1.45 ± 0.40</td>
<td>8 ± 29</td>
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<td></td>
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</tr>
<tr>
<td>CGCM2</td>
<td>2.67 ± 0.35</td>
<td>44 ± 45</td>
<td>2.48 ± 0.87</td>
<td>23 ± 20</td>
<td>1.95 ± 0.28</td>
<td>64 ± 26</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>CCSR/NIES</td>
<td>4.87 ± 0.20</td>
<td>199 ± 59</td>
<td>5.04 ± 0.36</td>
<td>17 ± 21</td>
<td>4.56 ± 0.25</td>
<td>53 ± 35</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ECHAM/OPYC3</td>
<td>3.25 ± 0.31</td>
<td>212 ± 52</td>
<td>4.62 ± 0.62</td>
<td>92 ± 23</td>
<td>1.97 ± 0.50</td>
<td>7 ± 24</td>
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</tr>
<tr>
<td>RCA3</td>
<td>2.94 ± 0.26</td>
<td>143 ± 38</td>
<td>4.37 ± 0.61</td>
<td>64 ± 17</td>
<td>2.28 ± 0.31</td>
<td>2 ± 22</td>
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</tr>
</tbody>
</table>

*Temperature trends (T) are in K per century, and precipitation trends (P) are in mm yr$^{-1}$ per century, while the uncertainties are based on the error from the least squares method by which the slope of the trend is determined.
Figure 11. Static mass balance sensitivity due to (a) temperature change, \( \frac{db}{dT} \), and (b) precipitation change, \( \frac{db}{dP} \), calculated from the equations (9) and (10).

[58] The static mass balance sensitivity due to temperature \( \frac{db}{dT} \) and precipitation \( \frac{db}{dP} \) change is presented in Figure 11. Sensitivity to temperature, excluding any precipitation trend, varies around the mean value of \(-0.48\) m yr\(^{-1}\) K\(^{-1}\) with a standard deviation of 0.002 m yr\(^{-1}\) K\(^{-1}\). The mean value agrees well with \(-0.46\) m yr\(^{-1}\) K\(^{-1}\) derived from a model forced by observational data [de Woul and Hock, 2005] where a hypothetical increase of 1 K was applied. Also, the result agrees well with \(-0.48\) m yr\(^{-1}\) K\(^{-1}\) calculated by the degree-day method and local data for Storglaciären [Braithwaite and Zhang, 1999]. Sensitivity to precipitation excluding any temperature trend, gives almost a constant value in time: 0.025 m yr\(^{-1}\) per 1% increase in precipitation. The negative peak occurring around 2030 is due to the drop in \( dP \) (Figure 10). Derived \( \frac{db}{dP} \) is slightly higher than the 0.015 m yr\(^{-1}\) per 1% increase in precipitation obtained by de Woul and Hock [2005].

[59] The results show no substantial variation in static mass balance sensitivity. However, the sensitivity to climate forcing is partly incorporated in the correlation coefficients of the mass balance model, which are kept temporally constant in future projections. Therefore the static sensitivities reflect the linearity of the model and no substantial changes in time are effected given the model assumptions.

6. Conclusions

[56] We have used ERA-40 in the calibration of a simple mass balance model and for downscaling climate models in order to estimate future volume changes of Storglaciären. Our main findings are as follows.

[57] 1. Validation of ERA-40 in the Storglaciären’s region showed that ERA-40 temperature explains more than 80% of the variance of observed daily, monthly and annual temperatures at Tarfala Station and that interannual variability is captured well. Precipitation from ERA-40 explains, on average, 50% of the variance of observed precipitation sums at Ritsem station and interannual variability is captured sufficiently well for use in the mass balance modeling.

[58] 2. A mass balance model driven by nine variants of ERA-40 input performs similarly well regardless of temporal resolution of the input data (daily or monthly averages). The model explains 70% of the variance of measured mass balance when the ERA-40 temperatures are reduced by the optimized (tuned) lapse rate between grid point elevation and glacier’s ELA. Fitting ERA-40 temperatures to observations does not improve the performance of the model. Hence, in this case ERA-40 can be used for mass balance modeling independently of meteorological observations.

[59] 3. Projections of volume change in the 21st century driven by the B2 emission scenario from statistically downscaled RCA3 and six GCMs outputs result in a volume loss of 50–90% of the glacier’s initial volume by end of 2100. Differences in these projections vary within 40% of the initial volume. Each volume projection varies within a range of 20% due to applied volume-area scaling or constant area. The choice of the method in the mass balance modeling, after excluding obvious outliers, corresponds to an uncertainty range of 10% for the volume projection, while the choice of the baseline period for the downscaling method results in 3% uncertainty range. In the range of uncertainties we need to add the uncertainty in the performance of the degree-day model itself: for the period of calibration 30% of the variance of the measured mass balance remains unexplained by the model. Modeled projections are not only highly sensitive to the choice of GCMs but can completely offset the results if seasonal biases in future series are not corrected by the reference climate, i.e., if a proper downscaling method is not applied.

[60] 4. The static mass balance sensitivities to future temperature and precipitation change, calculated as running difference between 20-year averages of \( b_n \) and averaged \( b_n \) over the reference period 2001–2020, show very small variations in time with the mean values of \( \frac{db}{dT} = -0.48 \) m yr\(^{-1}\) K\(^{-1}\) and \( \frac{db}{dP} = 0.025 \) m yr\(^{-1}\) per 1% precipitation increase.

[61] This sensitivity study showed that the model is capable of predicting future volume changes that are comparable with those derived from more sophisticated models [Oerlemans et al., 1998; Schneeberger et al., 2001] and that the estimated static mass balance sensitivity corresponds well to previous estimates on Storglaciären [Braithwaite et al., 2002; de Woul and Hock, 2005]. A possible way of using our results for global assessment of glacier volume change in the 21st century is direct application of the model to other glaciated regions taking advantage of the model’s simple data requirements available from ERA-40 reanalysis. However, further study is needed to evaluate how far the calibrated mass balance model for one glacier is transferable to other glaciers, and whether representative sets of model parameters can be found for glaciers in similar environmental settings. Alternatively, a more sophisticated mass balance model based on energy balance calculations [e.g., Greuell and Konzelmann, 1994] may be used, but it requires more inventory and climate data. In the end, one needs to find the balance between model requirements and data availability. At present, air temperature and precipitation variables that are most readily available and have received most scrutiny in terms of validation and downscaling techniques, and are therefore the best suited for mass balance projections.
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