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# Response of Hofsjökull and southern Vatnajökull, Iceland, to climate change

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[1] (Possible changes in glacier mass balance are among the most important consequences of future climate change with both local and global implications, such as changes in the discharge of glacial rivers, changes in the vertical stratification in the upper layers of the Arctic Ocean, and a rise in global sea level. The response of the Hofsjökull and southern Vatnajökull ice caps in Iceland to climate change is analyzed with a vertically integrated, finite difference ice flow model coupled with a degree day mass balance model. Transient climate change simulations are forced with a climate change scenario for the Nordic countries, which for Iceland, specifies a warming rate of 0.15°C per decade in midsummer and 0.3°C per decade in midwinter, with a sinusoidal variation through the year starting from the baseline period 1981–2000. Precipitation is either held steady or is increased at 5% per °C of warming. Modeled ice volume is reduced by half within 100–150 years. About 2030, annual average runoff from the area that is presently covered by ice is projected to have increased by approximately 0.7 m $\mathrm{yr}^{-1}$ for Hofsjökull and by 1.4 m $\mathrm{yr}^{-1}$ for southern Vatnajökull. The sensitivity of the mass balance of the ice caps to climate change was found to be in the range 0.4–0.8 $\mathrm{m_{w.e.}\ yr^{-1}\ {}^{\circ}C^{-1}}$ for Hofsjökull and 0.8–1.3 $\mathrm{m_{w.e.}\ yr^{-1}\ {}^{\circ}C^{-1}}$ for southern Vatnajökull. The sensitivity remained within these ranges more than 150 years into the future.)

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## 1. Introduction

[2] Melting of all glaciers and ice caps on Earth, excluding the large ice sheets of Greenland and Antarctica, has been estimated to raise sea level by about 0.5 m [*Church et al.*, 2001]. However, there is still considerable uncertainty in the sea level rise equivalent of the ice stored in these glaciers (for contrasting estimates, see *Raper and Braithwaite* [2005] and *Dyurgerov and Meier* [2005]). The rate of retreat of glaciers, and their contribution to sea level rise has been monitored and modeled, and found to have increased in the latter part of the 20th century [*Meier*, 1984; *Oerlemans and Fortuin*, 1992; *Gregory and Oerlemans*, 1998; *Oerlemans et al.*, 1998; *Arendt et al.*, 2002]. Increased meltwater flux from glaciers into the world oceans may also have other far-reaching effects including changes in salinity and vertical stratification of the upper layers of the Arctic Ocean and nearby oceanic areas with possible consequences for thermohaline circulation in the Atlantic Ocean [*Intergovernmental Panel on Climate Change* (*IPCC*), 2001].

[3] An increase in the magnitude and changes in the seasonality of glacial runoff are among the most important hydrological consequences of future climate change in Iceland and many other glacierized areas in the world. The aim of this paper is to assess the present state and the response of Hofsjökull and the southern part of Vatnajökull (Figure 1) to possible changes in climate and to estimate the hydrological consequences of changes in the mass balance and geometry of the glaciers. These ice caps were chosen for this study because they have the longest running mass balance monitoring programs in Iceland and because of their significance for the hydropower industry. A change in the discharge of glacial rivers caused by a reduction in ice volume has practical implications for the design and operation of hydroelectric power plants, which utilize runoff from the Icelandic highlands. This study forms a part of the Nordic research project Climate, Water and Energy (CWE) initiated by the directors of the Nordic Hydrological Institutes (CHIN) [*Kuusisto*, 2003] and its Icelandic counterpart Veðurfar, vatn og orka (VVO). Glaciers and ice caps in Iceland constitute only on the order of one or a few percent of the total volume of ice stored in glaciers and small ice caps globally. Nevertheless, a study of their sensitivity to climate change is valuable because these glaciers are well monitored, in contrast to glaciers in many other more remote glacierized regions, and because they should be

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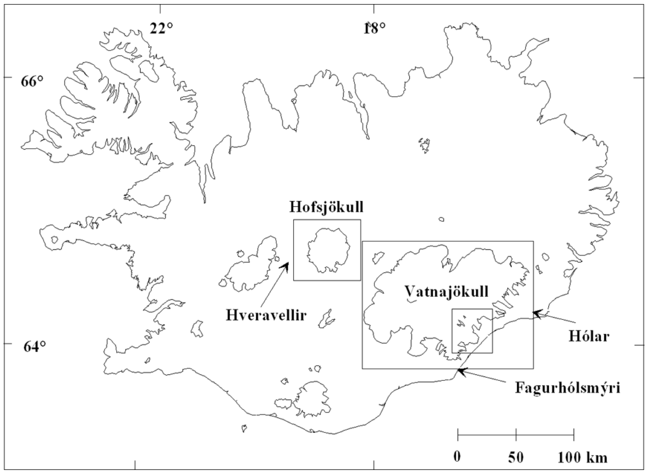

**Figure 1.** Outline of Iceland and the largest ice caps in the country. The location of the meteorological stations used in the mass balance computations is shown with arrows. Boxes indicate the boundaries of the maps of Hofsjökull and Vatnajökull in Figure 2, and the map of Breiðamerkurjökull in Figure 6.

representative for glaciers in maritime climates elsewhere in the world.

[4] In previous studies, the response of the Hofsjökull ice cap to climate change has been modeled with an equilibrium line altitude (ELA) parameterization of the mass balance [*Jóhannesson*, 1991] and a degree day mass balance model [*Jóhannesson et al.*, 1995b] together with a dynamic flow line glacier model [*Jóhannesson*, 1997]. In this study, the response of the whole ice cap is analyzed with a 2-D vertically integrated, finite difference, shallow ice approximation (SIA) flow model coupled with a degree day mass balance model. The response of the Vatnajökull ice cap is also modeled. However, the northern and western parts of Vatnajökull are excluded from the computations due to irregular flow behavior caused by surges of the outlet glaciers there, which the flow model does not adequately account for. The main outlet glaciers to the south from Vatnajökull that are included in the study, Skeiðarárjökull and Breiðamerkurjökull, are also affected by surges, but to a lesser degree than the northern and western parts of the ice cap. The western part of Skeiðarárjökull surged by about 1 km in 1991, and the almost continuous retreat of Breiðamerkurjökull since early in the 20th century has been interrupted by short advances along parts of the margin several times, the last time in 1987 [*Björnsson et al.*, 2003]. These surges of Skeiðarárjökull and Breiðamerkurjökull are, however, much smaller than the surges of Dyngjujökull and Brúarjökull in the north, which affect the whole outlet glaciers and can be up to 10 km long for Brúarjökull [*Björnsson et al.*, 2003]. The south flowing outlet glaciers also lie on a steeper terrain compared with the outlet glaciers in northern and western parts of the ice cap, which makes it easier to obtain a reasonable initial geometry for the ice cap for simulations with our traditional ice flow model.

[5] A recent modeling study with the same model as applied here, for the whole of Vatnajökull [*Aðalgeirsdóttir et al.*, 2005] emphasizes the necessity of including the effect of surges in order to obtain a realistic model for the whole ice cap. In the absence of surges, the modeled ice cap initially thickens in the central accumulation area and the glacier termini retreat. Subsequently, the model ice cap either retreats and thins to considerably smaller size than at present, or it advances and is simulated to reach far beyond current outline. Which of these two possibilities is realized, depends on the assumed mass balance distribution, which for both cases may be chosen within the range spanned by the available mass balance observations on the ice cap.

[6] Another model study of Vatnajökull, where a dynamic ice model is coupled to a model of the basal hydrology, and basal sliding is specified based on subglacial water pressure [*Flowers et al.*, 2003, 2005; *Marshall et al.*, 2005], improves the modeled geometry of the present ice cap. They conclude that equilibrium solutions are not appropriate for modeling the present ice cap and that a spin-up with a historical climate forcing is required for achieving a realistic geometry. Many of the modeled outlet glaciers in their reference model, which was generated by a simulation with climate forcing corresponding the period 1600–2000, are thicker and steeper, or shorter and thinner than the present outlet glaciers, indicating that a part of the dynamics is not well accounted for in the models. This can partly be explained by the fact that the different outlet glaciers are at present in different phases of their surge cycles. Since the surges are not captured by the models, discrepancy of this type is to be expected, but the magnitude of the discrepancy is probably too large to be explained by this effect alone. *Flowers et al.* [2005] conclude that the most pronounced discrepancies between their reference model and the observed present day ice cap can only be improved by selective alteration of the climate fields or heterogeneous tuning of the model parameters.

[7] An additional source of difficulty is related to the precipitation-elevation feedback. The model used in the transient simulations of *Flowers et al.* [2005] and *Marshall et al.* [2005] does not include the precipitation-elevation feedback, although the equilibrium simulations presented in *Marshall et al.* [2005] include this feedback. In our mass balance simulations for Hofsjökull and Vatnajökull, this feedback is a considerable part of total mass balance-elevation feedback (about 40% for Hofsjökull and about 20% for the southern part of Vatnajökull). The lack of this feedback may be expected to reduce the problems described by *Aðalgeirsdóttir et al.* [2005], but at the cost of eliminating an aspect of the real mass balance distribution on the ice cap.

[8] We bypass the problems related to the surges of the broad, flat outlet glaciers in the northern and western parts of Vatnajökull by considering only the steeper south and east flowing parts of the ice cap. Modeling only the steeper parts of the ice cap reduces the importance of the mass balance elevation feedback in the dynamics compared with a model of the whole ice cap, which makes it easier to avoid problems related to the instability of the modeled ice cap [*Aðalgeirsdóttir et al.*, 2005]. We also use a heterogeneous specification of the sliding parameter in the ice flow model to improve the agreement between the initial or baseline model geometry with the observed present geometry of the

ice cap. This somewhat arbitrary specification of the model domain and model dynamics compared to *Flowers et al.* [2005] and *Marshall et al.* [2005] makes it possible to adjust the reference ice volume and glacierized area to the present geometry of the southern part of the ice cap.

[9] The present study applies coupled two-dimensional glacier mass balance and ice flow models to assess the response of the Hofsjökull and the southern part of Vatnajökull ice caps to climate change. The climate change scenario is based on GCM results downscaled with regional climate models. This type of scenario has not previously been used in a model study of glaciers in Iceland. The model of Hofsjökull is the first two-dimensional coupled mass balance/ice flow model of that ice cap. The model of southern Vatnajökull is the first model of this type, which is calibrated with available mass balance measurements from the ice cap, that is used for a climate change study. The modeling of the two ice caps using the same models and scenarios makes it possible to compare the sensitivity of the mass balance to climate change under the different conditions encountered on the ice caps.

## 2. Data

[10] Vatnajökull (8100 km$^2$, the southeastern part considered here is 3600 km$^2$) and Hofsjökull (900 km$^2$) are two of the four largest ice caps that cover approximately 10% of the surface area of Iceland (Figure 1). Hofsjökull, with an elevation range of 600–1800 m asl, covers a caldera in the central highland of Iceland, and Vatnajökull is located at the southeast coast, reaching down to sea level from a maximum elevation of more than 2000 m asl. The basis for the modeling work presented here are measurements of the surface and bed topography, annual mass balance and surface velocity that have been collected during the last two decades. The measured surface and bedrock topography of the ice caps are the results of radio echo sounding surveys which were undertaken in the years 1980–1996 [*Björnsson*, 1986, 1988; *Björnsson and Pálsson*, 1991; *Björnsson et al.*, 1992]. Surface velocity and annual mass balance have been measured at about 35 locations on Hofsjökull since 1988 [*Sigurðsson*, 1989–2004] and at about 45 locations on Vatnajökull since 1992 [*Björnsson et al.*, 1998, 2002]. The locations of the mass balance stakes on each ice cap are shown in Figures 2c and 2d. Most of the mass balance stakes on Vatnajökull are on the northern and western parts of the ice cap and are not shown in Figure 2. Measurements at some stakes are missing in some years and the mass balance values measured at the individual stakes may contain fluctuations due to local conditions that are not considered representative for the elevation range where the stake is located. The winter and summer measurements of each mass balance year from each of the three monitored outlet glaciers on Hofsjökull have been interpreted in terms of mass balance as a unique function of elevation over the entire elevation range of the respective outlet glacier. The interpreted values are used to estimate the specific winter, summer and annual mass balance for the monitored ice flow basins on the ice cap. They are the main data for the mass balance modeling described here, although the raw measurements at the stakes have also been used for comparison. The mass balance model for Vatnajökull, on the other hand, is based directly on the observed mass balance at the stakes as the data processing of the mass balance measurements on Vatnajökull does not involve this step.

## 3. Mass Balance Model

[11] The mass balance model is a degree day (temperature index) model that has been developed for temperate glaciers in Iceland and the Nordic countries [*Jóhannesson et al.*, 1995b; *Jóhannesson*, 1997]. In this model, glacier accumulation and ablation are computed from daily temperature and precipitation observations at nearby meteorological stations. Daily melting, $f$, is computed according to the equation

$$f(z) = DDF\,\max(T(z), 0), \tag{1}$$

where $T(z)$ is daily mean temperature at altitude $z$ on the glacier, and $DDF$ is the degree day factor, which has separate values $DDF_s$ and $DDF_i$ for snow and ice, respectively.

[12] The mass balance model may also be based on monthly mean temperatures, $T_m$, in which case fluctuations of the daily mean temperatures about the monthly average are assumed to be normally distributed with a standard deviation $\sigma$ so that the sum of positive degree days within the month, $PDD$, is given by

$$PDD = \frac{365/12}{\sigma\sqrt{2\pi}} \int_0^\infty T e^{(T-T_m)^2/(2\sigma^2)} dT, \tag{2}$$

and the amount of melting is given by equation (1) with $\max(T(z), 0)$ replaced by $PDD$ [*Braithwaite*, 1985; *Reeh*, 1991; *Jóhannesson et al.*, 1995b].

[13] 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. It is assumed that a part of the melting, $r$, is refrozen or stored as liquid water in the snowpack. The refrozen or retained water can be up to a given fraction of the snow remaining since the start of the current mass balance year. This leads to a delay in the onset of runoff from the annual snowpack with respect to the start of melting on the glacier. The ablation, $a$, is defined as the negative of the melting plus the refrozen or retained liquid water.

[14] Temperature on the glacier is found using a constant vertical lapse rate, $\Gamma$,

$$T(z) = T_{stn} + \Gamma(z - z_{stn}), \tag{3}$$

where the subscript $stn$ denotes values at the meteorological station.

[15] Precipitation, $p$, is computed using horizontal precipitation gradients, $g_x$ and $g_y$, in addition to a vertical gradient, $g_z$,

$$p(x,y,z) = (1 + g_z(z - z_0))\big(1 + g_x(x - x_0) + g_y(x - x_0)\big)p_c, \tag{4}$$

where $x$ and $y$ are horizontal coordinates, and $p_c$ is corrected and scaled precipitation. The precipitation at the meteorological station 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 $x_0$, $y_0$.

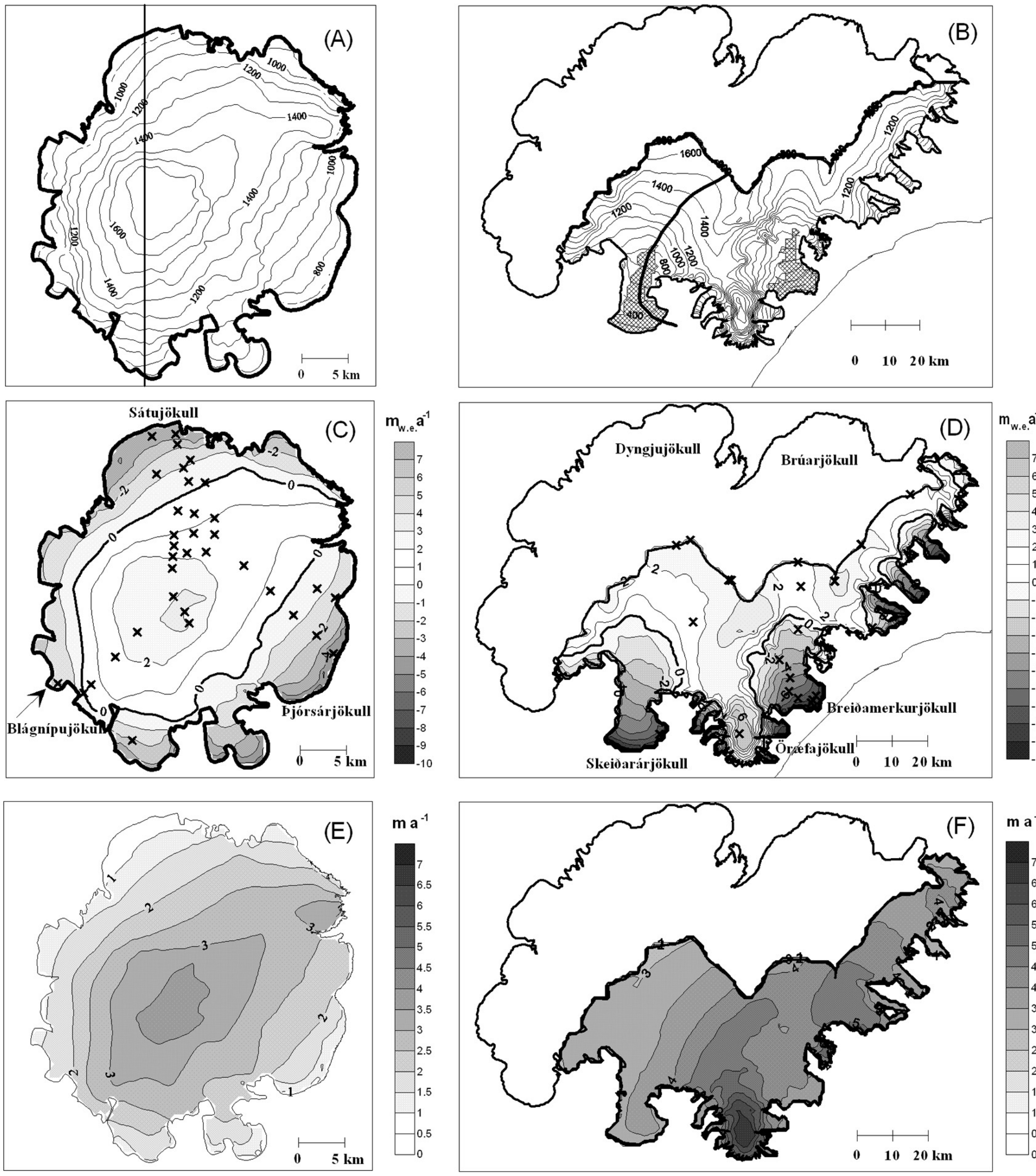

**Figure 2.** (a and b) Initial ice surface topography, contour interval = 100 m, (c and d) simulated mass balance distribution, and (e and f) simulated annual precipitation distribution, for (left) Hofsjökull and (right) southern Vatnajökull for the period 1981–2000. The model for Hofsjökull is based on temperature and precipitation observation from Hveravellir. The model for southern Vatnajökull is based on temperature observations from Hólar and precipitation observations from Fagurhólsmýri. The location of the transects shown in Figure 5 is indicated with thick lines on the maps, and the map of Vatnajökull shows the main east-west ice divide, which forms the boundary of the computation domain for the dynamic model. The areas in Skeiðarárjökull and Breiðamerkurjökull, where basal sliding is specified ($C \neq 0$), is indicated with hatched polygons. The location of the mass balance stakes used in the model calibration is shown with crosses on the mass balance map.

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

$$c = p \text{ if } T(z) \leq T_{s/r}, \quad c = 0 \text{ if } T(z) > T_{s/r}. \tag{5}$$

[17] The mass balance, $b$, is then given as the sum of the accumulation and the ablation

$$b = c + a = c - f + r. \tag{6}$$

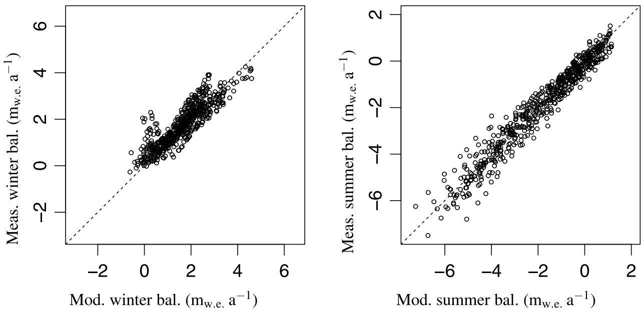

**Figure 3.** Measured and modeled (left) winter and (right) summer mass balance at stakes on Hofsjökull 1988–2003 (interpreted stake values from each year). The location of measurements is shown with crosses in Figure 2c. The largest deviations in the winter balance are at low elevations on Sátujökull where snow drift leads to a local increase in snow accumulation in a small area near the terminus.

[18] The above expressions may be used to compute the cumulative mass balance over the winter and summer seasons by summing over the appropriate time periods.

[19] Usually, stakes on the same outlet glacier are visited on the same day in the spring and autumn of each year or within a few day period. Occasionally, the stakes on the same outlet glacier have, however, been visited with a time difference of up to a month or more. In order to take this into account, separate measurement days are used for all stakes and all years in the calibration of the mass balance model, without fixed assumptions about the beginning or end of the winter and summer seasons. In dynamic glacier model calculations, annual mass balance values are computed by summing daily or monthly values over a whole mass balance year, which is assumed to start on 1 October.

[20] The period 1981–2000 is chosen as a reference period for this modeling study. Most of the nonsurging glaciers in Iceland were roughly in equilibrium during this period, advancing a little during the early part of the period and starting to retreat near the end of it [*Sigurðsson*, 1998; *Sigurðsson*, 2005; *Dowdeswell et al.*, 1997]. One would therefore expect the average mass balance of the nonsurging glaciers in this period to have been near zero.

[21] The model for the Hofsjökull ice cap was calibrated against winter and summer mass balance observations from about 35 stakes on the outlet glaciers Sátujökull, Þjórsárjökull and Blágnípujökull [*Sigurðsson*, 1989–2004] in the period 1988–2003 using daily meteorological data from the meteorological station at Hveravellir (station 892, located at 64°52′N, 19°34′W, 641 m asl) to the west of the ice cap. Figure 3 shows a comparison between the modeled and observed winter and summer mass balance. The model explains more than 80% of the variance in the winter balance and over 95% of the variance in the summer balance data. The larger proportion of the explained variance of the summer balance by the model is due to much larger year to year variations in the summer balance compared with the winter balance. Some of the largest deviations are related to snow accumulation by snow drift into the lowest elevations near the terminus of the Sátujökull outlet glacier, which affect a comparatively small area, and an unusually high melting of snow due to tephra from the 1991 Hekla eruption that was deposited over large areas on Hofsjökull.

**Table 1.** Model Parameters Common to Both Glaciers

| Parameter | Value | Unit |
|---|---|---|
| Snow/rain threshold ($T_{s/r}$) | 1.0 | °C |
| Temperature standard deviation ($\sigma$) | 3.0 | °C |
| Threshold snow thickness used in degree day computations | 0.3 | $m_{w.e.}$ |
| Refreezing ratio | 0.07 | – |

[22] The simulated mass balance of Hofsjökull based on monthly averages of meteorological observations at Hveravellir during the period 1981–2000 with superimposed temperature fluctuations within each month according to equation (2) [*Jóhannesson et al.*, 2004] is shown in Figure 2c. The corresponding precipitation distribution is shown in Figure 2e. The simulated mass balance distribution agrees well with the overall spatial distribution of the mass balance data, with an ELA near 1200 m asl on the southeastern flanks of the ice cap rising to about 1300 m asl in the northwestern and western parts. The simulated mean specific net balance for 1981–2000 averaged over the area of the ice cap is close to zero within 0.1 $m_{w.e}$ $yr^{-1}$, which agrees well with the observation that the ice cap does not seem to have been far out of equilibrium during these decades. The average yearly precipitation over the whole ice cap for the period 1981–2000 is about 2.4 $m_{w.e.}$ $yr^{-1}$ according to the model. This simulated mass balance for the period 1981–2000 is used as a datum or reference mass balance field in the transient dynamic modeling in order to define a baseline steady state configuration for the glacier.

[23] The model parameters (Tables 1 and 2) derived from observations over the whole Hofsjökull ice cap in the period 1988–2003 are in good agreement with the parameters that were found previously for Sátujökull only (the northern part of the ice cap) based on data from the much shorter period

**Table 2.** Mass Balance Model Parameters Determined From the Measured Summer and Winter Balance of Hofsjökull

| Parameter | Value | Unit |
|---|---|---|
| Degree day factor for ice ($DDF_i$) | 0.00731 | $m_{w.e.}$ $d^{-1}$ °$C^{-1}$ |
| Degree day factor for snow ($DDF_s$) | 0.00529 | $m_{w.e.}$ $d^{-1}$ °$C^{-1}$ |
| Temperature lapse rate ($-\Gamma$) | 0.6 | °C per 100 m |
| Precipitation/elevation gradient ($g_z$) | 0.212 | per 100 m |
| Rain correction factor | 1.32 | – |
| Snow correction factor | 2.0 | – |
| Precipitation correction factor | 1.102 | – |
| Elevation of temperature station | 641 | m asl |
| Elevation of precipitation station | 641 | m asl |
| Starting elevation for precipitation gradient ($z_0$) | 880 | m asl |
| Reference $x$ location for horizontal precipitation gradient ($x_0$) | 510 | km |
| Reference $y$ location for horizontal precipitation gradient ($y_0$) | 480 | km |
| Horizontal precipitation gradient in east direction ($g_x$) | 0.0196 | per km |
| Horizontal precipitation gradient in north direction ($g_y$) | −0.0170 | per km |

**Table 3.** Mass Balance Model Parameters Determined From the Measured Summer and Winter Balance of Southern Vatnajökull

| Parameter | Value | Unit |
|---|---|---|
| Degree day factor for ice ($DDF_i$) | 0.0053 | $m_{w.e.}$ $d^{-1}$ °$C^{-1}$ |
| Degree day factor for snow ($DDF_s$) | 0.00445 | $m_{w.e.}$ $d^{-1}$ °$C^{-1}$ |
| Temperature lapse rate ($-\Gamma$) | 0.56 | °C per 100 m |
| Precipitation/elevation gradient ($g_z$) | 0.0497 | per 100 m |
| Rain correction factor | 1.28 | – |
| Snow correction factor | 1.8 | – |
| Precipitation correction factor | 1.633 | – |
| Elevation of temperature station | 16 | m asl |
| Elevation of precipitation station | 46 | m asl |
| Starting elevation for precipitation gradient ($z_0$) | 46 | m asl |
| Reference $x$ location for horizontal precipitation gradient ($x_0$) | 626 | km |
| Reference $y$ location for horizontal precipitation gradient ($y_0$) | 389 | km |
| Horizontal precipitation gradient in east direction ($g_x$) | 0.046 | per km |
| Horizontal precipitation gradient in north direction ($g_y$) | −0.0818 | per km |

1988–1992 [*Jóhannesson et al.*, 1995b]. Model parameters derived for each of the outlet glaciers independently for the period 1988–2003 are also consistent with the parameters that are found for the whole ice cap. The degree day factors for ice and snow are for example all in comparatively narrow ranges 5.0–7.8 $mm_{w.e.}$ °$C^{-1}$ $d^{-1}$ and 4.5–6.0 $mm_{w.e.}$ °$C^{-1}$ $d^{-1}$, respectively, in all these cases.

[24] The mass balance model for the southern part of Vatnajökull ice cap was derived by calibration against mass balance observation from about 23 stake locations on the outlet glaciers Breiðamerkurjökull and Skeiðarárjökull, from the central part of the accumulation area of the ice cap and from the summit of the ice covered Öræfajökull volcano [*Björnsson et al.*, 1998, 2002; *Gudmundsson*, 2000] during the period 1993–2002 (Tables 1 and 3). The temperature measurements are from Hólar in Hornafjörður (station 710, located at 64°18′N, 15°11′W, 16 m asl) and the precipitation measurements from Fagurhólsmýri (station 745, located at 63°53′N, 16°39′W, 46 m asl). This choice of stations was made after experimenting with different combinations from available stations near the ice cap. The chosen stations resulted in a slightly better agreement between the mass balance model and the stake observations than other possible choices. Figure 4 shows a comparison between the modeled and observed winter and summer mass balance. The model explains 84% of the variance in the winter balance at stakes where the winter balance is positive, i.e., when low altitude points where all winter snow is ablated during the winter season are not considered, but 92% of the variance if all stakes are included. It explains 92% of the variance in the summer balance and 95% of the variance in the yearly balance. This is a better result than for Hofsjökull.

[25] It turns out to be impossible to derive a realistic datum mass balance model for southern Vatnajökull based on monthly average temperature and monthly precipitation for 1981–2000 with superimposed statistical temperature fluctuations according to equation (2) as was done for Hofsjökull. This is caused by a high correlation between daily temperature and precipitation, because precipitation is more likely to fall on warm days in SE Iceland, particularly during the winter season. Instead of basing the datum mass balance model on monthly temperature and precipitation as for Hofsjökull, it is based on a random sample of 365 days from the temperature and precipitation time series from October 1980 to September 2000, intended to provide a "representative" or an "average" mass balance year from this reference period. Each of these values is chosen randomly from the sample of 20 measurements from the same Julian day within the mass balance year, which starts on 1 October as mentioned above. These data have similar statistical properties as the real temperature and precipitation series, including the monthly and yearly averages and the correlation between the daily temperature and precipitation values. Average mass balance for the whole southern Vatnajökull area and for individual ice drainage areas computed in this manner are similar as found with daily data for the whole period. An improved agreement with results obtained from daily values from the whole period may be obtained by retaining only data sets, which lead to specific mass balance over the entire ice cap within 0.1 $m_{w.e.}$ $yr^{-1}$ of the mean value obtained with daily data from all years in the period. Synthetic climate data generated in this way were used to define a datum mass balance field which served as a baseline for the transient dynamic simulations. Several synthetic data sets of this kind were generated and turned out to yield very similar annual mass balance values, which were typically within 0.1 m $yr^{-1}$ of each other when averaged over ice drainage basins.

[26] Figure 2d shows the simulated mass balance of the southern part of the Vatnajökull ice cap. As for Hofsjökull, the simulated mass balance distribution agrees well with the overall spatial distribution of the mass balance data. The simulated ELA of the southern part of Vatnajökull is between 1000 and 1100 m asl in agreement with observa-

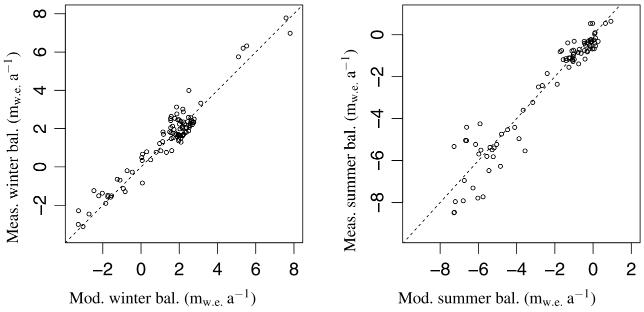

**Figure 4.** Measured and modeled (left) winter and (right) summer mass balance at stakes on S-Vatnajökull 1993–2002. The location of measurements is shown with crosses in Figure 2d. The model successfully predicts the interannual variation in the winter balance at Öræfajökull, the highest point on the ice cap near its southern margin (the five highest points). The residuals are larger for the summer balance than for the winter balance, especially a the lower altitudes (most negative summer balance values). This indicates the inability of the degree day mass balance model to fully capture the interannual mass balance variability which is partly caused by variability in wind and radiation conditions which are not represented in the degree day model.

tions. The simulated specific net balance averaged over this part of the ice cap is, as for Hofsjökull, close to zero within 0.1 $m_{w.e.}$ $yr^{-1}$. The corresponding average yearly precipitation shown on Figure 2f is mainly characterized by the vertical precipitation gradient, but the horizontal reduction in the precipitation toward NW also has influence, in particular on Skeiðarárjökull. The average yearly precipitation over the whole area for the period 1981–2000 is about 4.1 $m_{w.e.}$ $yr^{-1}$ according to the model.

## 4. Dynamic Glacier Model

### 4.1. Ice Flow Model

[27] The dynamic model is a traditional ice flow model that solves the continuity equation for the ice mass

$$\frac{\partial h}{\partial t} + \vec{\nabla} \cdot \vec{q} = b, \tag{7}$$

where $h$ is the ice thickness, $\vec{q}$ is the ice flux, which is assumed to consist of two components $\vec{q}_d$ arising from the internal deformation and $\vec{q}_s$ due to bottom sliding, and $b$ is the mass balance. This equation is solved on a 1 km grid with an alternating direction, semi-implicit, finite difference scheme [*Huybrechts*, 1986].

[28] The ice mechanics is formulated according to the shallow ice approximation (SIA) [*Hutter*, 1983], which implies that it does not include a representation for longitudinal or transverse stress gradients. Furthermore, the model contains no description of glacier surges. The constitutive equation for ice is *Glen's* [1955] flow law, which describes a relation between strain rate and deviatoric stress [*Paterson*, 1994]. This leads to the following depth integrated expression for the ice flux component due to internal deformation, $\vec{q}_d$, in terms of the local ice thickness, $h$, and surface slope, $(-\vec{\nabla} z_s)$,

$$\vec{q}_d = K_1 h^{n+2} |-\vec{\nabla} z_s|^{n-1} \left(-\vec{\nabla} z_s\right), \tag{8}$$

where $z_s$ denotes the ice surface elevation, $K_1 = 2A(\rho g)^n/(n+2)$, $n = 3$, $\rho = 917$ kg $m^{-3}$ is the density of ice, $g = 9.82$ m $s^{-2}$ is the acceleration due to gravity, and $A$ is the ice viscosity, which we determine as described below.

[29] A model-model comparison by *Leysinger-Vieli and Gudmundsson* [2004] showed that a SIA model and a full system model, which solves all the terms in the momentum balance equation, give approximately the same advance and retreat rates for a given mass balance distribution. In a model study, as presented here, where the integrated response to changes in the mass balance is assessed, it is therefore sufficient to use a SIA model.

[30] For the computations on the southern and eastern part of Vatnajökull a boundary condition, which prevents the flow of ice across the main northeast/southwest ice divide was implemented in the numerical code. The ice divide is thus kept fixed in space during the computations while the ice thickness there is free to change. An upstream version of the space discretization of *Mahaffy* [1976] (method 2 of *Hindmarsh and Payne* [1996]) is used. It should be noted that the implementation of an ice divide as a boundary condition along the northern margin of the model domain imposes a condition of zero surface gradient perpendicular to the margin. This is likely to be realistic in the initial decades of the simulations, but imposes an unphysical constraint on changes in the geometry of the ice cap after significant changes in the modeled ice volume have taken place.

### 4.2. Calibration of Ice Viscosity and Specification of Basal Sliding

[31] For Hofsjökull, basal sliding was implicitly taken into account by adjusting the flow parameter $A$ in Glen's flow law [*Paterson*, 1994] until an optimal, least squares, steady state fit to the measured surface geometry was attained, corresponding to the average mass balance distribution for the period 1981–2000. It is believed that the average mass balance of the ice caps was comparatively close to zero during this period as mentioned above. The best fit was found for the flow law parameter value $A = 6.0 \times 10^{-24}$ $Pa^{-3}$ $s^{-1}$. This is close to the recommended value for temperate ice, $A = 6.8 \times 10^{-24}$ $Pa^{-3}$ $s^{-1}$ [*Paterson*, 1994]. The resulting steady state ice caps computed with the two values for $A$ are not significantly different in shape. Therefore it was decided to use the value recommended by Paterson. A transect across the ice cap, north-south is shown in Figure 5, where the measured topography is compared with the modeled steady state corresponding to the selected value for A. The modeled steady state geometry was used as the initial geometry for the dynamical simulations in order to prevent rapid initial adjustment of the dynamical model when it is initialized with the observed ice cap geometry.

[32] The value of $A$ found for Hofsjökull, which is about 3 times higher than the value previously found to give the best fit to measured surface velocity on Vatnajökull [*Aðalgeirsdóttir et al.*, 2000], did not lead to a realistic surface geometry for the southern part of Vatnajökull. In order to obtain similar volume to the present ice cap, the rate factor had to be chosen $A = 10.0 \times 10^{-24}$ $Pa^{-3}$ $s^{-1}$, which is considerably higher than the value recommended for temperate ice. The ice cap modeled with this rate factor is thinner in the accumulation area and thicker in the ablation area than the measured ice cap. Furthermore, the extent of some of the outlet glaciers is too large. This difference indicates that the modeled ice cap is too soft in the central area, but seems, at the same time, to be too restrictive to the ice movement in the ablation area. The steady state volume of the ice cap corresponding to a higher viscosity (lower rate factor) is, however, too large. This indicates that a model with internal deformation only cannot describe the flow regime of southern and eastern Vatnajökull. This is in agreement with the conclusions of *Flowers et al.* [2003], who emphasize the importance of basal sliding to obtain a realistic shape of the ice cap. In the lower areas of the large outlet glaciers Skeiðarárjökull and Breiðamerkurjökull, the bedrock is not as steep as farther upstream and the underlying bed is believed to consist mainly of soft sediments, or sandur, which are highly deformable. This is in contrast to the situation for Hofsjökull where the model simulates the measured ice cap reasonably well (Figure 5) without additional sliding. It is therefore likely that sliding is a higher proportion of the total flux on the outlet glaciers of Vatnajökull than on Hofsjökull. It was thus decided to prescribe sliding at the bed in these lower areas

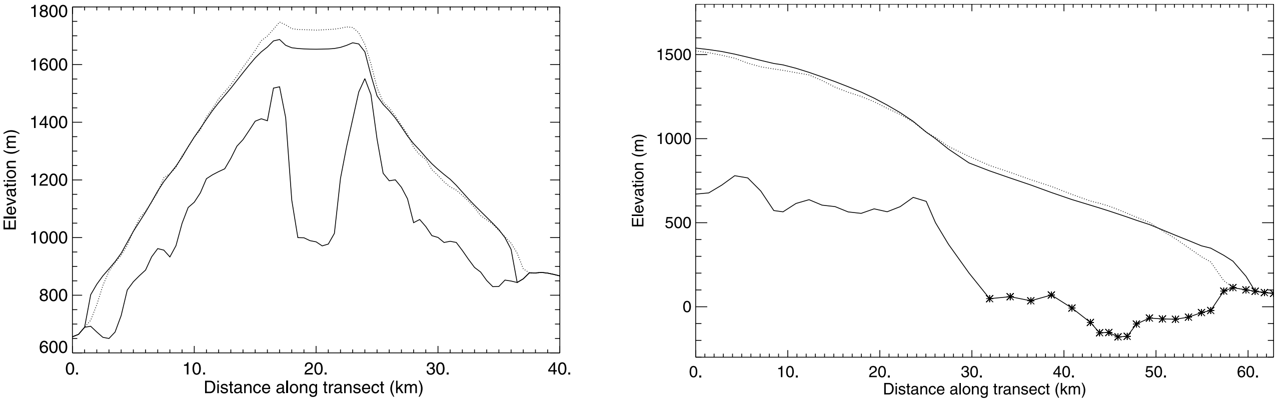

**Figure 5.** A comparison of the measured (dotted line) and modeled (solid line) surface elevation (left) across Hofsjökull and (right) along Skeiðarárjökull. The grid points where sliding is allowed ($C \neq 0$) are shown with asterisks at the bed elevation. The location of the transects is shown in Figures 2a and 2b for Hofsjökull and Skeiðarárjökull, respectively.

in order to obtain a more realistic reference geometry for the ice cap.

[33] Sliding at the bed is specified by a sliding law similar to Weertman sliding [*Paterson*, 1994]. The flux due to basal sliding, $\vec{q}_s$, is assumed to depend on the basal shear stress, $\tau_b$, according to

$$\vec{q}_s = C h \tau_b^m \frac{\left(-\vec{\nabla} z_s\right)}{|-\vec{\nabla} z_s|} = K_2 h^{m+1} |-\vec{\nabla} z_s|^{m-1} \left(-\vec{\nabla} z_s\right), \qquad (9)$$

where $C$ is a constant, $K_2 = C(\rho g)^m$ and the exponent $m$ is assumed to be $m = 3$. The amount of sliding is thus controlled by the thickness of the ice and the local slope of the ice surface, similar as the internal deformation according to equation (8), along with a parameter, $C$, which has to be chosen. Several configurations for sliding at the bed were tested. The best result was obtained when sliding was prescribed at predefined grid points where the surface slope is low, water pressure at the bed is likely to be comparatively high, and deformable sediments are probable at the bed. The areas where sliding was prescribed are shown in Figure 2b. They correspond roughly to areas with bedrock elevation below 200 m asl for Skeiðarárjökull and below 100 m asl for Breiðamerkurjökull. In order to prevent a discontinuity in the model parameters, the $C$ value was tapered linearly from a full value to zero over a 50 m elevation interval. This is admittedly not a physically based sliding model, but an *ad hoc* way to prescribe sliding in areas where it is most likely to be important.

[34] Several model runs were carried out to select the value for the sliding parameter, $C$. The rate factor $A$, that controls the internal deformation, was in all cases chosen $A = 6.8 \times 10^{-24}$ Pa$^{-3}$ s$^{-1}$ as for Hofsjökull. The desired result is an ice cap, not too far from a steady state, that has similar ice thickness, length of the outlet glaciers, and shape of the boundary as the measured ice cap. In all the model runs Breiðamerkurjökull outlet glacier retreats and it is not possible to maintain its present size with plausible model parameters. This is not unexpected. The bedrock of Breiðamerkurjökull is partially below sea level and the glacier flows along an approximately 200 m deep trough [*Björnsson*, 1988]. It has retreated during most of the 20th century, causing a pro-glacial lake, Jökulsárlón, to emerge in 1934 and continuously expand since then at a rate of 0.5 km$^2$ a$^{-1}$ with calving activity at the terminus [*Björnsson et al.*, 2001]. This outlet glacier is therefore clearly not near a steady state corresponding to the average climate of 1981–2000. In addition, calving into the lake is not included in the model and therefore we ignored this outlet glacier in the model calibration. The best surface geometry in a least squares sense was achieved with the sliding parameter, $C = 200 \times 10^{-15}$ m a$^{-1}$ Pa$^{-3}$. The current geometry of Skeiðarárjökull is well approximated by the modeled steady state corresponding to this value of the sliding parameter. A comparison of the measured and modeled surface elevation along Skeiðarárjökull is shown in Figure 5 (right). There is some discrepancy between the modeled steady state for the eastern outlet glaciers and for Öræfajökull. The modeled small outlet glaciers on the eastern side of the ice cap and the outlet glaciers flowing out from Öræfajökull are thicker than observed, but the top of Öræfajökull is thinner. The bedrock in these areas has not been measured with radio echo sounding and is thus not well known, and the grid size of the model, 1 km, is too large to represent the small outlet glaciers adequately. For the purpose of the simulations presented here, this model resolution is, however, sufficient. The larger outlet glaciers, Skeiðarárjökull and Breiðamerkurjökull, their current configuration and response to climate change are our main interest in this study. The modeled steady state geometry for the ice cap was used as the initial geometry for the dynamic simulations, except for the Breiðamerkurjökull ice drainage area where the observed geometry was used.

## 5. Climate Change Scenario

[35] The climate change scenario of the CWE project, "The Climate, Water and Energy–Nordic climate scenario" (abbreviated CWE-NCS), is described by *Rummukainen et al.* [2003], and further GCM downscaling results for the Nordic countries are discussed by *Räisänen et al.* [2004]. The scenario provides a projection of climate change in the Nordic countries for the period from 1990 to 2050

corresponding to the IPCC SRES B2 emission scenario [*IPCC*, 2000, 2001]. The scenario is the average of scaled grids of mean monthly projections of four regional climate models over the North Atlantic and the neighboring continental areas (the Swedish RCA-H and RCA-E models, and the Danish and Norwegian HIRHAM regional climate models (RCM), see *Rummukainen et al.* [2003] for references describing these models). The RCM simulations use boundary conditions from global, transient climate change simulations by the ECHAM4/OPYC3 [*Roeckner et al.*, 1999] and HadCM2 [*Johns et al.*, 1997] coupled OAGCM models.

[36] The four RCM simulations correspond to different time horizons and different scenarios of future anthropogenic forcing. Before averaging, the RCM results were harmonized with respect to time horizon and emission scenario to correspond to the SRES B1 emission scenario by a scaling procedure described by *Rummukainen et al.* [2003] and *Christensen et al.* [2001]. The domain of one of the RCMs (the Danish HIRHAM model) does not include Iceland. Therefore the CWE-NCS scenario for Iceland used here is the average of the remaining three RCM simulations, rather than all four as for the Scandinavian continental area.

[37] The projected temperature change varies strongly over the North Atlantic Ocean. Iceland is situated in a steep horizontal gradient in the warming, between a local minimum south and east of Greenland and a maximum between northern Norway and Greenland. This relative minimum is a common feature of many, but not all, coupled global and regional climate model simulations in this area [*IPCC*, 2001; *Räisänen et al.*, 2004]. It is related to a projected weakening in the thermohaline circulation, which is associated with a reduced rate of deep water formation in the northern North Atlantic Ocean [*IPCC*, 2001]. Figure 6 shows the projected seasonality of the CWE-NCS temperature and precipitation change averaged over the area near Iceland. There are some fluctuations in the temperature signal, and especially in the precipitation signal, that appear to be caused by natural variability rather than being a climate change signal caused by the assumed buildup of greenhouse gases in the atmosphere. This indicates that the monthly values averaged over the area near Iceland shown in Figure 6 are too much influenced by natural variability to be used directly in impact analyses and need to be smoothed to extract a climate change signal suitable for use in the glacier modeling [*Rummukainen et al.*, 2003].

[38] In order to provide for more smoothing in the temperature change signal, the monthly values shown in Figure 6 where replaced by a sinusoidal variation through the year, varying from a winter maximum of +0.3°C per decade in late January to a summer minimum of +0.15°C per decade in late July with a sinusoidal variation between these values (dashed curve in Figure 6). The monthly fluctuations in the relative precipitation change appear without a clear climate change signal and they are quite inconsistent between the different RCMs [see *Rummukainen et al.*, 2003, Figures 2 and 4]. The precipitation change was therefore simplified to a constant relative change of 5% per degree of warming independent of season. Because of the uncertainty of the precipitation change, a scenario with the same rate of warming but without any change in precipitation was also defined in order to analyze the relative importance of the assumed changes in temperature and precipitation.

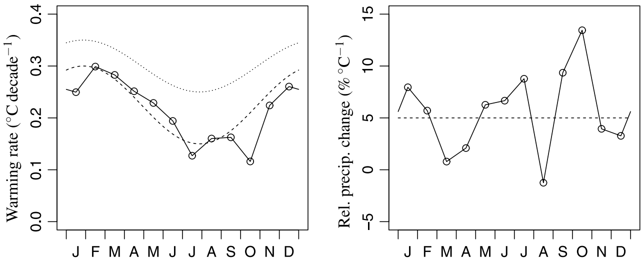

**Figure 6.** Monthly CWE-NCS (left) temperature (°C per decade) and (right) precipitation (% per °C) change scenarios near Iceland. Dashed curves show the simplified temperature and precipitation scenarios used in the glacier model simulations (see the text for explanations). The dotted curve to the left shows the CCEP temperature scenario, which is also used in the glacier simulations.

[39] The CWE-NCS climate change scenario is intended to show change with respect to the year 1990. In our study this is taken to mean change with respect to the average climate of the period 1981–2000. The original CWE-NCS scenario given by *Rummukainen et al.* [2003] represents temperature change from 1990 to 2050. The corresponding rate of warming per decade is used in the glacier model computations until 2200.

[40] The CWE-NCS climate scenario projects rather low temperature increase for Iceland, compared with neighboring areas, especially during the summer. This is due to a local minimum in the warming in the North Atlantic Ocean that is simulated by some coupled ocean-atmospheric general circulation models (OAGCM). The observed warming in Iceland in the last two to three decades has not been characterized by lower warming during the summer compared with the winter, in fact the summer warming is quite similar to the mean annual warming for the meteorological station at Hveravellir and the autumn warming at many stations is larger than the warming in other seasons [*Jóhannesson et al.*, 2004]. It is the magnitude of the summer warming that is most important for changes in glacier mass balance due to a warmer climate, and to a lesser degree the spring and autumn warming. The possible future reduction in the strength of the thermohaline circulation in the North Atlantic Ocean projected by some coupled OAGCMs must be considered highly uncertain and this presents a major problem for hydrological and glaciological modeling of the consequences of the climate warming in Iceland.

[41] In view of these circumstances, the climate change scenario from a previous Nordic project; Climate Change and Energy Production (CCEP) [*Sælthun et al.*, 1998; *Jóhannesson et al.*, 1995a] was also used in the mass balance and dynamic modeling of Hofsjökull and Vatnajökull. This scenario, which is shown with a dotted curve in Figure 6, prescribes a yearly mean warming of 0.3°C per decade, varying from a summer minimum of 0.25°C per decade to winter maximum of 0.35°C per decade, and a relative precipitation change of 5% per degree of warming, independent of the season. This warming is closer to the projected warming in other ocean areas on a similar latitude as Iceland, although not as high as in

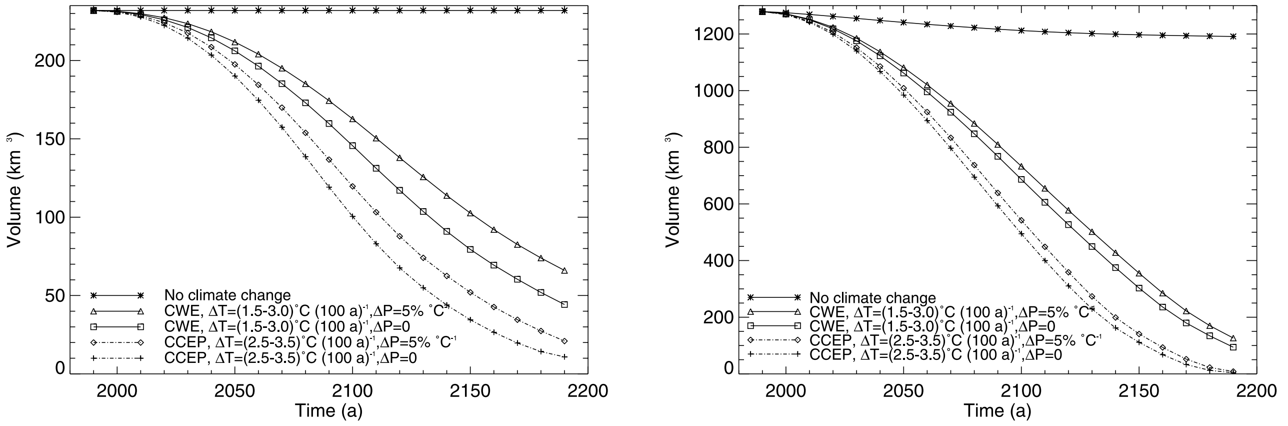

**Figure 7.** Projected volume reduction as a function of time for (left) Hofsjökull and (right) southern Vatnajökull, according to four scenarios for future changes in temperature and precipitation.

Scandinavia or other continental areas in the same latitude range. The use of the climate change scenario from the previous CCEP study serves the purpose to investigate the consequences of climate changes in case the strength of the thermohaline circulation in the North Atlantic Ocean is not reduced as much as projected by some coupled OAGCM. It also provides a direct comparison with the results of the previous study.

## 6. Results

[42] Two main model experiments were carried out. First, a control run with a constant climate corresponding to the baseline period 1981–2000, and, second, a transient run starting in 1990 in which the CWE-NCS climate change scenario was applied. In addition, the models were run with the previously determined climate change scenario for the Nordic countries [*Jóhannesson et al.*, 1995a] (denoted by CCEP in Figures 7 and 8).

### 6.1. Retreat of Breiðamerkurjökull Under Current Climate

[43] As discussed above, Breiðamerkurjökull retreats in the control simulation. The modeled retreat is shown in Figure 9 and the corresponding evolution of ice volume is shown as the topmost curve in Figure 7. In our computations, no account is taken of the effect of the proglacial lake or of calving into it and the growing lake is not shown in Figure 9. Another study, with a flow line model that takes calving into account, but does not include warmer climate [*Björnsson et al.*, 2001], shows that calving contributes to the retreat rate of the terminus of Breiðamerkurjökull, that the observed retreat will continue to increase under current climate conditions, and that the glacier may retreat from the lake depression after ≈200 years and almost vanish in ≈400 years. Imposing warmer climate would speed up this retreat. Although calving is not represented in our model, our results are in overall agreement with the study of *Björnsson et al.* [2001], which indicates that including calving in our model would not alter our results fundamentally.

### 6.2. Response to Climate Change

[44] The change in the volume of the ice caps corresponding to the different climate change scenarios is shown in Figure 7, and the change in annual average runoff from the area that is initially covered with ice is shown in Figure 8. Only changes in annual average runoff are

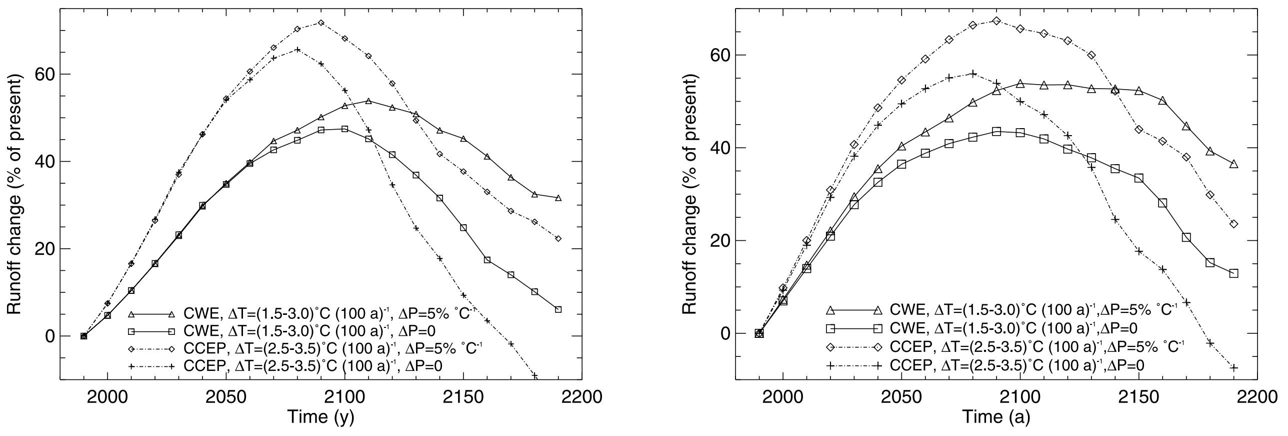

**Figure 8.** Projected runoff change as a function of time from the area initially covered by (left) Hofsjökull and (right) southern Vatnajökull, according to four scenarios for future changes in temperature and precipitation.

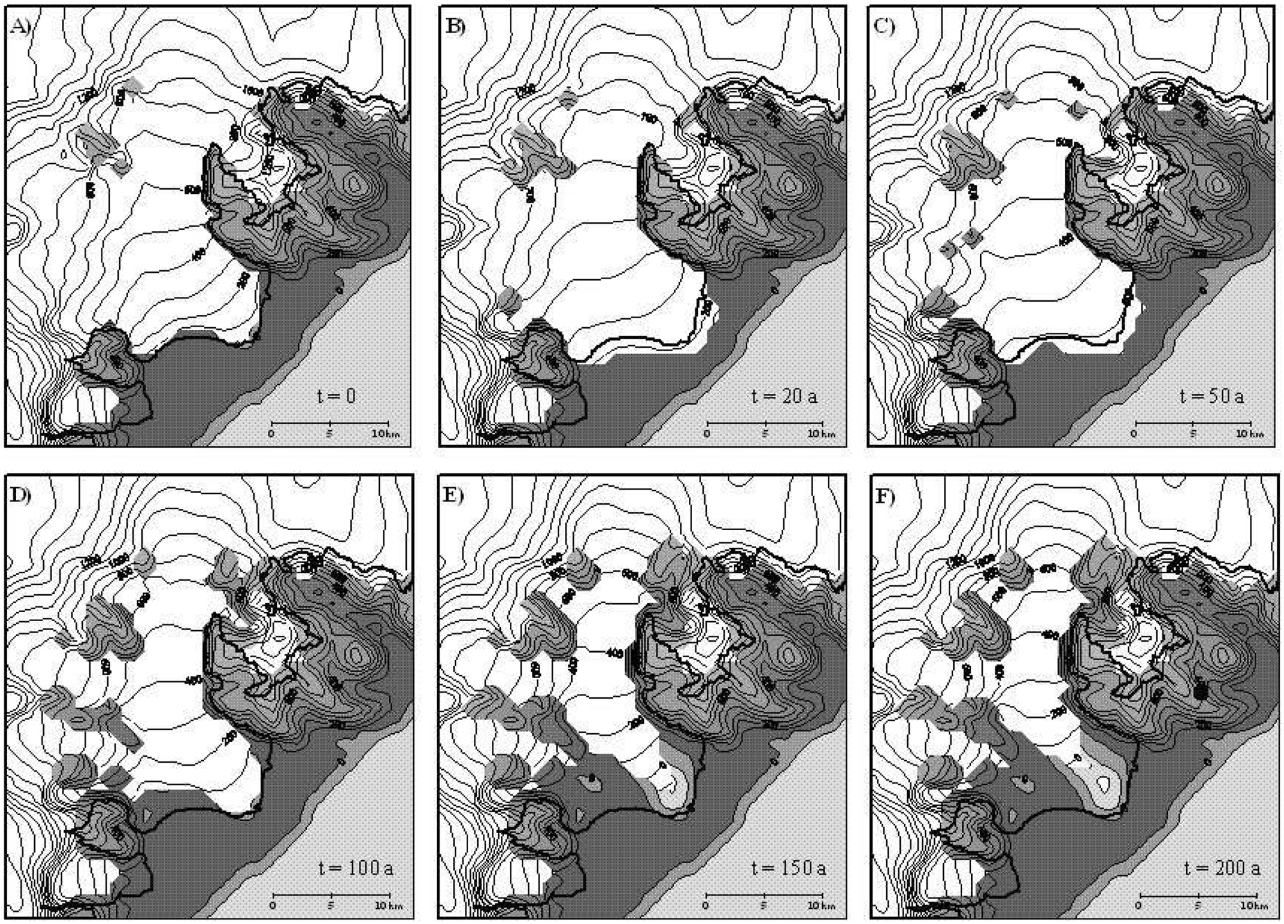

**Figure 9.** Projected retreat of Breiðamerkurjökull under present climate condition. Area covered with glacier is indicated with white contoured area. (a) Initial size of the glacier. Note that the proglacial lake is not shown as it is not included in the computation and neither is the calving of the front. The size of the outlet glacier is shown after (b) 20 years of computations with a steady climate, (c) after 50 years, (d) after 100 years, (e) after 150 years, and (f) after 200 years.

considered here and not changes in seasonal or diurnal runoff characteristics, which may also be important. Changes in runoff generation due to the shrinking glacierized area, which exposes the underlying bedrock with different storage and routing properties compared with an ice covered area, are not considered either. Precipitation falling on the growing ice-free area within the initial glacier margin is included in the modeled annual average runoff changes shown in Figure 8, so runoff changes are caused by reduction in the ice volume, changes in precipitation over the original glacierized area as specified by the climate scenario, and changes in precipitation caused by the dynamic lowering of the ice surface.

[45] The ice volume of Hofsjökull and the southern part of Vatnajökull is projected to be reduced by approximately half within the next 100 years and the ice caps essentially disappear 200 years after the start of the simulations, given that the rate of warming remains the same. The volume reduction is qualitatively similar for Hofsjökull and southern Vatnajökull. The response to the warming is slow at first, but speeds up with the progressively larger temperature increase. The modelled mass balance for year 2005, 15 years into the simulations, is about $-0.2$ m yr$^{-1}$ for Hofsjökull and $-0.4$ m yr$^{-1}$ for southern Vatnajökull. These values can of course not be directly compared with measurements from any single year, but they are not as low as the negative mass balances that have been observed in recent years on the glaciers, which have since 2000 been in the range $-(0.4-1.5)$ m yr$^{-1}$ for Hofsjökull and $-(0.4-1.3)$ m yr$^{-1}$ for Vatnajökull as a consequence of substantially larger warming since 1990 than specified by the CWE-NCS scenario. According to the simulations, Hofsjökull will be depleted of its about 200 km$^3$ of ice in 200 years, while southern Vatnajökull loses about 1200 km$^3$ during the same time.

[46] It must be kept in mind that for southern Vatnajökull, these results are for the isolated southern part of the ice cap, keeping the main ice divide at a fixed location. The outlet glaciers of southern Vatnajökull are more sensitive to climate warming than the outlet glaciers to the north and west because the southern ice margin reaches down to lower elevations. Therefore one may expect the southern part of the ice cap to thin and retreat more rapidly than the northern part. This will tend to move the ice divide toward north and more ice volume will be available to the south flowing glaciers compared with the idealized situation considered here where the location of the ice divide is fixed. The

**Table 4.** Static Sensitivity, $S_s$, of the Mass Balance of Hofsjökull and Southern Vatnajökull for Temperature Seasonality as Specified by the CWE-NCS and CCEP Climate Change Scenarios With and Without a 5% Precipitation Increase per Degree of Warming Computed for a Warming of 1 °C[a]

| | CWE-NCS $\Delta P = 0$ | CWE-NCS $\Delta P = 5\%$ | CCEP $\Delta P = 0$ | CCEP $\Delta P = 5\%$ |
|---|---|---|---|---|
| Hofsjökull | −0.58 | −0.46 | −0.69 | −0.57 |
| Southern Vatnajökull | −1.13 | −1.01 | −1.19 | −1.07 |

[a] See equation (10) for $S_s$; see text for climate change scenarios. Values are in $m_{w.e.}\ yr^{-1}\ °C^{-1}$.

response during the first 50–100 years will, however, not be much affected by ice divide migration as the mass balance changes are largest near the margins and smaller in the accumulation area where the ice divides are located. The migration of the ice divides may be expected to take place mainly through the dynamical response of the ice flow to changes in the geometry of the ice cap, which take time to accumulate. The inclusion of the northern and western parts will delay the total disappearance of the south flowing glaciers somewhat compared with our results, but the initial thinning and retreat rate will be similar as shown here.

[47] The runoff from the area, that is initially covered by ice, is predicted to increase by 25–35% and 30–40% until the year 2030 for Hofsjökull and the southern part of Vatnajökull, respectively. This amounts to about 0.6–0.9 m $yr^{-1}$ and 1.1–1.7 m $yr^{-1}$ over the area that is currently covered by Hofsjökull and the southern part of Vatnajökull, respectively. The projected runoff change continues to increase approximately linearly to a maximum of 1.1–1.7 m $yr^{-1}$ for Hofsjökull and 1.7–2.8 m $yr^{-1}$ for the southern part of Vatnajökull after about 100 years, after which it levels off and decreases due to the decreasing area of the ice caps. This corresponds to about 50–70% increase in runoff from the area presently covered with ice.

## 7. Mass Balance Sensitivity

[48] The sensitivity of the mass balance of glaciers and ice caps to climate change is important for future global sea level rise that may occur as a consequence of climate warming. It is also of interest as a general measure of the hydrological effect of changes in the mass balance of glacierized areas due to climate changes. It is important to ascertain whether model parameters determined from the current climate can be used to predict changes associated with a different climate. The meteorological conditions on typical glaciers span a large range of temperature and precipitation due to the large altitude range, which is often on the order of 1000 m. Climate conditions in the near future are likely to remain within the already observed range on the glaciers to some approximation, unless the climate changes are so large or rapid that the climate of the region changes in a fundamental way. Thus parameter values, determined from mass balance observations for the current climate, may be expected to be meaningful for climate change studies to some approximation.

[49] The static mass balance sensitivity is defined as the ratio of the change of the specific mass balance of the glacier to the magnitude of a small temperature change

$$S_s = \frac{\Delta B}{\Delta T}, \tag{10}$$

where $\Delta B$ is change in mean specific mass balance resulting from a change in temperature $\Delta T$. It does not take time-dependent changes in the geometry of the glacier into account. Although the static sensitivity is defined with respect to a small uniform change in temperature it is useful to compute the change in specific mass balance as a consequence of a finite temperature change which may vary through the year with and without an accompanying precipitation increase. The results of such computations for Hofsjökull and Vatnajökull for a warming of $\Delta T = 1$°C with a seasonality and relative precipitation increase as specified in the climate scenarios described above are given in Table 4. The static sensitivity of Vatnajökull is about two times that of Hofsjökull, due to a longer ablation season for the lower-lying Vatnajökull. This is a similar result as found by *de Woul and Hock* [2005] and indicates that the maritime nature of Vatnajökull makes it one of the most sensitive glaciers in the world.

[50] The static sensitivity ignores the effect of the time-dependent retreat of the glacier terminus, changes in the geometry of the glacier, nonlinear effects due to the finite size of the climate change and other dynamic and nonlinear effects. Including these effects leads to the concept of dynamic sensitivity of glaciers to climate change [*Jóhannesson*, 1997; *Oerlemans et al.*, 1998]

$$S_d(t) = \frac{V(t) - V(t_0)}{A(t_0)(t - t_0)\Delta\bar{T}}, \tag{11}$$

where $V(t)$ and $A(t)$ are the volume and area of the glacier as a function of time, $t$, and $\Delta\bar{T}$ is the average temperature change over the time interval from $t_0$ to $t$. This equation assumes that the glacier is near a steady state at time $t_0$. If this is not the case, the dynamic sensitivity must be computed from the volume difference at time $t$ between a control run, without a climate change, and a transient run, corresponding to a change in climate, rather than the simple difference $V(t) - V(t_0)$, which is used in equation (11).

[51] The dynamic sensitivity is computed directly from the simulated volume reduction of a glacier as it responds to a time-dependent climate change. It takes into account the warming associated with the lowering of the ice surface, and the reduction in the glacierized area due to the retreat of the glacier. In addition, it of course takes into account the seasonal variation in the warming, a precipitation change if present, and the finite size of the warming. The total contribution of a glacier to sea level rise during some time period may be found by multiplying the dynamic sensitivity with the average warming during the period, the current or initial area of the glacier, $A(t_0)$, and the length of the time window. In this way the dynamic and static sensitivities defined in equations (10) and (11) are used in the same way to compute ice volume changes. Using the initial area of the

**Table 5.** Dynamic Sensitivity, $S_d$, of the Mass Balance of Hofsjökull as a Function of the Length of the Time Window From the Start of the Integration in 1990/1991 for the CWE-NCS and CCEP Climate Change Scenarios With and Without a 5% Precipitation Increase per Degree of Warming[a]

| Time Period | CWE-NCS $\Delta P = 0$ | CWE-NCS $\Delta P = 5\%$ | CCEP $\Delta P = 0$ | CCEP $\Delta P = 5\%$ |
|---|---|---|---|---|
| 1990–2010 | −0.60 | −0.46 | −0.71 | −0.58 |
| 1990–2030 | −0.62 | −0.48 | −0.76 | −0.62 |
| 1990–2090 | −0.66 | −0.53 | −0.78 | −0.66 |
| 1990–2140 | −0.58 | −0.48 | −0.58 | −0.52 |

[a] See equation (11) for $S_d$; see text for climate change scenarios. Values are in $m_{w.e.}$ $yr^{-1}$ $°C^{-1}$.

glacier in equation (11) does, however, mean that changes in the dynamic sensitivity are not a direct measure of changes in the specific mass balance of the glacierized area over the time period in question.

[52] The dynamic sensitivities of Hofsjökull and the southern part of Vatnajökull for several different time windows are shown in Tables 5 and 6. In computing the dynamic sensitivity for Vatnajökull, the change in volume is relative to the reference run shown with the top line in Figure 7, so the retreat of Breiðamerkurjökull is not included in the computation of the dynamic sensitivity in this case. Both the static and dynamic sensitivities are in the range 0.4–0.8 $m_{w.e.}$ $yr^{-1}$ $°C^{-1}$ for Hofsjökull and 0.8–1.3 $m_{w.e.}$ $yr^{-1}$ $°C^{-1}$ for the southern part of Vatnajökull. These values are in both cases comparatively independent of the character of the climate change and the dynamic sensitivities remain within these ranges quite far into the future. The dynamic sensitivity increases in magnitude during the initial decades of the simulations because of the positive feedback between ablation and the lowering of the ice surface. As a consequence, the dynamic sensitivity is initially higher than the static sensitivity. This feedback becomes weaker as the ice-covered area is reduced and the dynamic sensitivity becomes similar to the static sensitivity again after about 150 years for Hofsjökull and about 100 years for southern Vatnajökull.

## 8. Discussion

[53] The static and dynamic sensitivities computed for the CCEP scenario is compared with the CWE sensitivities in Tables 4–6. In all cases, the sensitivities for the CCEP scenario are higher, as expected, because of the larger temperature increase and smaller seasonal variation. The volume and runoff changes resulting from the CCEP scenario are shown with dashed lines in Figures 7 and 8. The volume reduction is similar for all scenarios in the first decades, but then the CCEP scenario leads to faster melting for both Hofsjökull and southern Vatnajökull, and results in an almost complete disappearance of the glaciers in about 200 years. The increase in precipitation with warmer temperatures slows the ice wastage slightly, but the effect of the warming dominates the counteracting effect of the increase in precipitation.

[54] The runoff changes computed with the CCEP scenario are more rapid, both the increase and the decrease, than the changes computed with the CWE-NCS scenario, and they have a higher peak value. Negative values indicate that the runoff is less than at present. A more rapid warming, as specified by the CCEP scenario, will therefore have a greater impact on river runoff, and consequently on the water supply to hydroelectric power stations, than the more moderate CWE-NCS scenario.

[55] These results of the mass balance and dynamic modeling of the Hofsjökull ice cap are in good agreement with previous results of *Jóhannesson et al.* [1995b] and *Jóhannesson* [1997]. Two outlet glaciers of Hofsjökull were modeled with a flow line model [*Jóhannesson*, 1997] and it was found that a climate warming of this magnitude would decrease their volume by about 40% over a period of 100 years and the runoff was projected to increase by about 0.5 m $yr^{-1}$ after 30 years, which corresponds to about 25% of the present glacier runoff. The static and dynamic sensitivities of the mass balance for Hofsjökull were found to be in the approximate range 0.5–1 $m_{w.e.}$ $yr^{-1}$ $°C^{-1}$, similar as found above. This indicates that the results are robust against various details in the formulation and calibration of the mass balance model, and the level of sophistication of the ice flow model.

[56] The modeled change in runoff from southern Vatnajökull (Figure 8) is compatible with results of model simulations for the whole ice cap by *Flowers et al.* [2005]. In that study, the increase in the discharge from the whole ice cap (their Figure 11C) peaks after 100 years, 110 years, 130 years and 180 years by about 50%, 40%, 25% and 5% for warming rates of 0.4°C, 0.3°C, 0.2°C and

**Table 6.** Dynamic Sensitivity, $S_d$, of the Mass Balance of Southern Vatnajökull as a Function of the Length of the Time Window From the Start of the Integration in 1990/1991 for the CWE-NCS and CCEP Climate Change Scenarios With and Without a 5% Precipitation Increase per Degree of Warming[a]

| Time Period | CWE-NCS $\Delta P = 0$ | CWE-NCS $\Delta P = 5\%$ | CCEP $\Delta P = 0$ | CCEP $\Delta P = 5\%$ |
|---|---|---|---|---|
| 1990–2010 | −1.15 | −1.01 | −1.24 | −1.10 |
| 1990–2030 | −1.19 | −1.05 | −1.29 | −1.16 |
| 1990–2090 | −1.07 | −0.97 | −1.12 | −1.04 |
| 1990–2140 | −0.88 | −0.82 | −0.83 | −0.80 |

[a] See equation (11) for $S_d$; see text for climate change scenarios. Values are in $m_{w.e.}$ $yr^{-1}$ $°C^{-1}$.

0.1°C per decade, respectively, and no precipitation change. Our study projects somewhat larger proportional changes in runoff from the southern part of Vatnajökull only for a comparable rate of warming (54% increase after 110 years for the CWE-NCS scenario with no precipitation change where the mean annual warming rate is 0.225°C per decade). This is to be expected because of the longer ablation season on the outlet glaciers from the southern part of Vatnajökull, which reach to lower elevations than the outlet glaciers from the northern and western parts, and these are omitted in our simulations.

## 9. Conclusions

[57] The response of two ice caps in Iceland to changes in climate specified by the Nordic CWE-NCS climate scenario was computed with a coupled degree day mass balance model and a traditional SIA ice flow model. Both Hofsjökull and the southern part of Vatnajökull will retreat if the climate changes as projected by this scenario. The retreat is relatively slow during the initial decades but speeds up with time as the climate warms. The modeled glaciers are projected to almost disappear within the next 200 years. The simulated response to different climate change scenarios shows that the temperature increase dominates the effect of a possible increase in precipitation that may accompany a warmer climate.

[58] The runoff of rivers from the area that is presently covered with ice will have increased by approximately 30% of the 1981–2000 baseline value by about 2030 and by about 50% by the end of this century, but after that the runoff decreases due to diminishing area of the ice caps. The projected increase in glacial runoff is one of the most important hydrological consequences of future climate change in Iceland. The static and dynamic sensitivities of the mass balance were computed for the ice caps and both are about two times higher on the southern part of Vatnajökull than on Hofsjökull. Vatnajökull is one of the most sensitive glaciers in the world.

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