Nordic Hydrology, 22, 1991, 81-94

Modelling the Effect of Climatic Warming on the Hofsjökull Ice Cap, Central Iceland

Paper presented at the Nordic Hydrological Conference
(Kalmar, Sweden, August – 1990)

Tómas Jóhannesson

Orkustofnun (National Energy Authority)
Reykjavik, Iceland

A time-dependent cylindrically symmetric computer model of the Hofsjökull ice cap, Central Iceland, has been defined in order to investigate the time-scale of possible glacier variations. The model is forced with a set of hypothetical mass balance scenarios, chosen to span the range of plausible mass balance variations of Hofsjökull caused by greenhouse warming. For each mass balance scenario the model computes the change in the volume of the ice cap and the associated time-dependent runoff variations. The response time of the ice cap is found to be of the order of 50-100 years, when mass balance – elevation feedback is taken into account. The response time increases with the size of the climatic perturbation. The model indicates that increased runoff from the area now covered by Hofsjökull, caused by a possible greenhouse warming, will be significant for 100-200 years after the climate starts to change. A mass balance scenario produced by raising the equilibrium line by 200 m (corresponding roughly to a warming of 1-1.5°C) over a 50-year period leads to a maximum runoff increase of about 40 m^3s^{-1} occurring 50 years after the equilibrium line starts to rise. This amounts to approximately 50 % of the total precipitation that falls on Hofsjökull at present and approximately 25 % of the present discharge of rivers that issue from Hofsjökull and the neighbouring area.

Introduction

Glaciers and ice caps in Iceland have shown dramatic variations in historical time as a result of climatic changes, for example during the Little Ice Age. The climatic changes that are proposed during the next century, as a consequence of increased concentration of CO_2 and other greenhouse gases in the atmosphere, are by far greater than the changes that have occurred in Iceland during historical time. Very significant glacier variations are therefore to be expected.

The runoff from the Hofsjökull ice cap, Central Iceland, is a substantial component in the discharge of a number of rivers that are important for hydro-power generation. Climatic changes that affect the mass balance of Hofsjökull may lead to significant changes in the discharge of these rivers. The dynamical response of the ice cap to mass balance variations will be an important factor determining runoff changes in the future.

It is estimated that increasing concentration of CO_2 and other greenhouse gases in the atmosphere will lead to a large increase in the globally averaged surface air temperature during next century. There are some indications that this warming has already started (Jones *et al.* 1986). A doubling of the effective CO_2 concentration is believed to lead to global warming of 2-5°C (*c.f.* Hansen *et al.* 1988). In general, the warming will be more pronounced near the poles. From the global average, one might therefore expect a large warming in Iceland (*c.f.* Bergthórsson *et al.* 1987). Recently, coupled ocean-atmosphere general circulation models have begun to throw some light on the regional distribution of the time-dependent warming (Washington and Meehl 1989). These models indicate that the increasing concentration of greenhouse gases may lead to an initial cooling in the North Atlantic and northern European regions. Predictions of the effect of the increasing concentration of greenhouse gases on the climate of Iceland are therefore highly uncertain at the moment. In light of this uncertainty, it is of interest to compute the response of an idealized model of Hofsjökull to a range of plausible climate scenarios. The purpose is to outline the response of Hofsjökull to climatic variations in general, and to estimate how long it takes the ice cap to complete its adjustment to a climatic change in particular.

Hofsjökull

Hofsjökull is the third largest ice cap in Iceland with an area of 923 km^2 and a volume of 208 km^3 (Fig. 1). The surface and bed topography are well known from radio echo sounding and precision barometric altimetry (Björnsson 1988). The mass balance of the ice cap is, however, relatively poorly known since regular monitoring of accumulation and ablation was not started until 1987.

Geometry of Hofsjökull

Hofsjökull covers a subglacial volcano, which reaches a maximum altitude of 1,500-1,600 m a.s.l. close to the center of the nearly circular ice cap. The maximum altitude of the ice surface is 1,800 m a.s.l. The ice flow is close to being radial from the center (see Björnsson 1988, Map 19). The area and volume distribution with

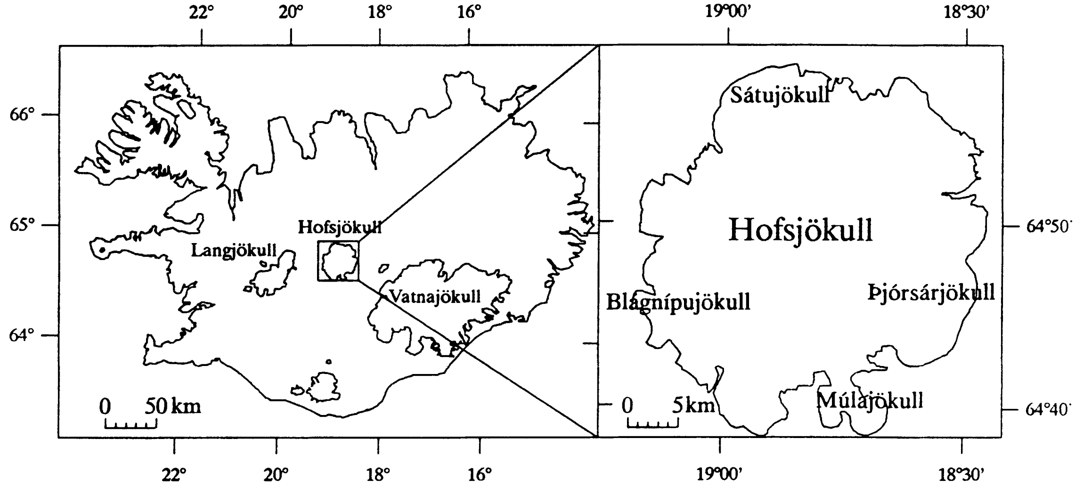

Fig. 1. Map showing the location of Hofsjökull in Iceland (left) and the location of the outlet glaciers of Hofsjökull mentioned in the text (right).

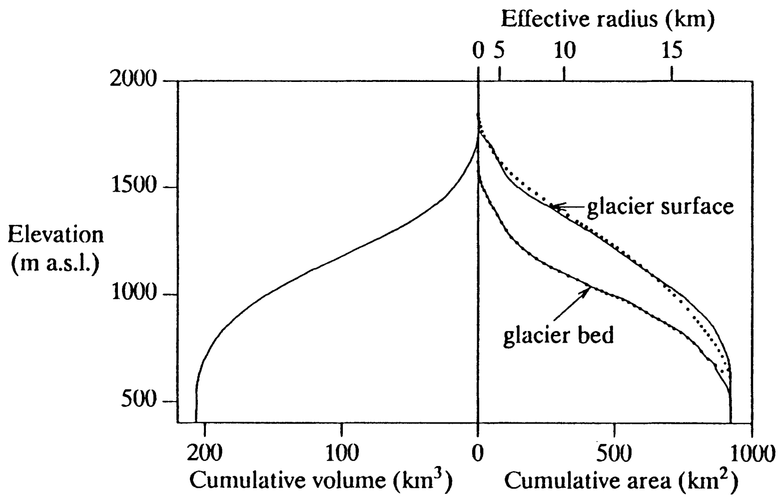

Fig. 2. The area and volume distribution with elevation for Hofsjökull (solid curves, from Björnsson 1988, Fig. 3.12). The curves show the cumulative area and volume above the elevation on the y axis. The intersections of the curves with the x axis indicate the total volume and area of the ice cap. The surface and the bed profiles (dotted curves) of the datum ice cap ($z_s(r)$ and $z_b(r)$, (see text) are also shown.

elevation of Hofsjökull is shown in Fig. 2. The lowest altitude of the glacier edge is approximately 620 m a.s.l. at the terminus of Múlajökull, but the area distribution of the glacier bed reaches to lower elevations because of overdeepening behind the terminus.

Mass Balance of Hofsjökull

Measurements of termini of the outlet glaciers of Hofsjökull indicate that the ice cap has been relatively near an equilibrium (steady state) for the last decades (Sigurðsson 1989a). Long term averages of accumulation and ablation are not available. The mass balance of the outlet glacier Sátujökull (Fig. 1) in 1987-1988 was measured by Sigurðsson (1989b) who found an equilibrium line altitude of approximately 1,330 m a.s.l. The mass balance was fairly close to a linear function of altitude with a mass balance gradient with respect to altitude of 0.008-0.010 $m_{H_2O}a^{-1}m^{-1}$. The mass balance of the outlet glaciers Sátujökull, Þjórsárjökull and Blágnípujökull (Fig. 1) in 1988-1989 was measured by Sigurðsson (personal communication). The equilibrium line altitude was between 1,000 and 1,200 m a.s.l. and the mass balance gradient (approximating the mass balance as a function of altitude by a linear function) was 0.0062-0.0069 $m_{H_2O}a^{-1}m^{-1}$.

Response Time

One of the most important physical variables that characterizes the response of a glacier to climatic variations is the *response time* of the glacier. The response time can be defined as the time constant in an exponential asymptotic approach to a final steady state after a sudden change in climate to a new constant climate. The response time is a measure of the time lag between climate change and glacier response. It determines how long a climatic event affects the size of the glacier and therefore how long the climatic event affects runoff from the glacier.

A simple method has recently been introduced for determining the response time of glaciers (Jóhannesson *et al.* 1989a,b). According to this method the response time of a glacier τ_M, may be estimated by the equation

$$\tau_M = \frac{H}{-b_t} \quad (1)$$

where H is a thickness scale of the glacier and $(-b_t)$ is a scale of the ablation along its terminus.

This estimate of the response time is based on the idea that the response time is equal to the so-called *volume time scale* of the glacier. The volume time scale is defined as the time needed for a changed mass balance to produce the volume change between the corresponding initial and final steady states.

For Hofsjökull, reasonable values for H and $(-b_t)$ are 200-300 m and 4-6 $m_{ice}a^{-1}$ respectively. Eq. (1) therefore leads to the estimate, $\tau_M \approx$ 35-75 years, for the response time of Hofsjökull.

Eq. (1) does not take mass balance – elevation feedback into account. As discussed in Jóhannesson *et al.* (1989b) this feedback leads to somewhat longer response times than is expected from Eq. (1). We may therefore expect the response time of Hofsjökull to be somewhat longer than 35-70 years. This result will be compared to model predicitions in the sections to follow.

Model Calculations

An idealized numerical model of Hofsjökull has been developed in order to obtain quantitative estimates of the time-dependent variations in the volume of the ice cap and the associated runoff changes. The model takes mass balance – elevation feedback into account so that its effect on the response time of the ice cap can be determined.

The model assumes the ice cap will reach a steady state if the climate does not vary with time for a sufficiently long period of time. This excludes the possibility of glacier surges and the possible effect of glacier surges on the response of Hofsjökull to climatic variations is therefore not addressed by the modelling.

Formulation

Because of the circular shape of Hofsjökull and the near radial flow pattern, the model will be based on an assumption of cylindrical symmetry, *i.e.* bedrock elevation z_b, ice surface elevation z_s, ice thickness h, mass balance b, ice flux q, *etc.* are functions of the distance r, from the center of the ice cap. This simplification makes it possible to model Hofsjökull as a one-dimensional flow system analogous to traditional models of valley glaciers flowing in valleys with variable width w (*c.f.* Waddington 1981). The width in the case of cylindrical symmetry is $w(r) = 2\pi r$. A cylindrically symmetric model is highly idealized because of subglacial valleys and other irregularities in the geometry of Hofsjökull. The great uncertainty in the climatic forcing and lack of data on the mass balance and flow characteristics of Hofsjökull does, however, not justify more detailed modelling.

The model is based on the equation of continuity for ice assuming a unique density of ice and a flux-geometry relationship which incorporates the flow law or the rheology of ice. The ice flow is described by the ice volume-flux distribution $Q(r,t)$, which is related to ice thickness $h(r, t)$, channel width $w(r)$, and mass balance $b(r, t)$, through the one-dimensional continuity equation (Paterson 1981)

$$\frac{1}{w}\frac{\partial Q}{\partial r} + \frac{\partial h}{\partial t} = b \qquad (2)$$

The flux-geometry relationship is taken to be

$$q \equiv \frac{Q}{w} \equiv K\left(-\frac{\partial z_s}{\partial r}\right)^n h^{n+2} \qquad (3)$$

with $K = 2A(\varrho g)^n/(n+2)$, $n = 3$, $\varrho = 900$ kg m^{-3}, $g = 9.82$ m s^{-2} and A is a constant in the flow law of ice (Glen 1955). This often-used equation describes flow of ice in a parallel-sided slab without regard to sliding (Paterson 1981). A term, which is also proportional to powers of the surface slope $(-\partial z_s/\partial r)$ and the ice thickness h, should be added to the flux when sliding is introduced (Paterson 1981). For the purpose of the idealized model presented here, it is assumed that sliding can be adequately taken care of by varying the constant K in Eq. (3). In view of the uncertain values of the constants K and n in Eq. (3) (Paterson 1981) this is not a drastic simplification.

Eq. (3) does not take longitudinal stress gradients (Kamb and Echelmeyer 1986) into account. This is a common simplification in time-dependent glacier modelling and should not make a significant difference in the results with regard to response time and runoff changes.

The numerical formulation of Eqs. (2) and (3) is based on the control-volume concept (Patankar 1980). A time step $\Delta t = 1$ year and a grid spacing $\Delta r \equiv 0.25$-0.5 km were used in the model calculations.

Datum Ice Cap

The model is started with a datum steady state ice cap which is designed to match the present geometry and mass balance of Hofsjökull.

The geometry of the datum ice cap is based on the area distributions of the subglacial bedrock and the ice surface of Hofsjökull (Fig. 2 in this paper which is based on Björnsson 1988). The cumulative area A, may be used to define an effective radius $r \equiv \sqrt{A/\pi}$. Then the profiles of the ice surface and glacier bed in Fig. 2 can be viewed as profiles of $z_s(r)$ and $z_b(r)$ of a cylindrically symmetric ice cap with the same area distributions of subglacial bedrock and ice surface as Hofsjökull. A minor modification must be made in $z_b(r)$ because of overdeepening near the terminus. $z_b(r)$ of the datum ice cap (lower dotted curve in Fig. 2) is raised slightly near the terminus so that the bedrock profile of the datum ice cap meets the ice surface profile at the altitude of the terminus.

Sigurðsson's mass balance measurements in 1987-1988 and 1988-1989 indicate that the mass balance as a function of altitude, z, may be expressed as

$$b(z) = b_g(z - z_e) \tag{4}$$

where b_g is the mass balance gradient and z_e is the equilibrium line altitude. I will use the estimate $b_g = 0.0075\ \mathrm{m_{ice}a^{-1}m^{-1}}$ on the basis of Sigurðsson's measurements, independent of z_e. More detailed expressions of the mass balance are not justified in view of the limited measurements.

Assuming Hofsjökull has been close to a steady state for the last decades, the long-term average of the equilibrium line altitude $\langle z_e \rangle$, can be determined from Eq. (4) and the area distributions in Fig. 2 as

$$\langle z_e \rangle = \frac{\int_0^R z_s(r)\, 2\pi r\, dr}{A(R)} \tag{5}$$

where R is the distance from the center to the terminus of the datum ice cap. Eq. (5) leads to the estimate $<z_e>$ = 1,240 m a.s.l. which is in relatively good agreement with the equilibrium line altitudes found by Sigurðsson in 1987-1988 and 1988-1989.

The only parameter in the model defined by Eqs. (2), (3) and (4) which has not yet been determined is the constant K in the flux relationship (Eq. (3)). I choose the value of K such that the steady state ice surface profile computed by the model is as close to the measured ice surface (Fig. 2) as possible. This leads to $K \approx 4.2 \times 10^{-5}a^{-1}m^{-3}$. The upper dotted curve in Fig. 2 shows the steady state ice surface profile predicted by the model for this value of K.

The value of the constant A of the flow law of ice that corresponds to $K = 4.2 \times 10^{-5}a^{-1}m^{-3}$ is $A \approx 4.8 \times 10^{-24}s^{-1}Pa^{-3}$ which is slightly lower than $5.3 \times 10^{-24}s^{-1}Pa^{-3}$ which is the value recommended by Paterson (1981). Paterson's value does not include a contribution from sliding. Since Hofsjökull is a temperate ice cap, and therefore likely to slide along its base, one would have expected a higher value of K. This discrepancy could be removed by increasing the mass balance gradient to b_g = 0.0085 $m_{ice}a^{-1}m^{-1}$ or greater. The uncertainty in the value of constant in the flow law of ice (Paterson 1981), the scarce data on the mass balance and sliding of Hofsjökull and the idealized geometry of the cylindrically symmetric model do not justify such an arbitrary tuning of the model. The value $K = 4.2 \times 10^{-5}a^{-1}m^{-3}$ will be used in the subsequent computations, but it has been checked that varying K does not significantly alter the results.

Mass Balance and Runoff Variations

Climatic variations in the following numerical experiments are represented by changes in the equilibrium line altitude z_e. Changes in z_e can be caused by changes in precipitation, temperature, radiation and a number of other variables. Greenhouse warming will primarily affect glacier ablation through higher temperature, but it is also expected to increase precipitation, which may either fall as snow or as rain. As a rough estimate a 1-1.5°C warming may be expected to lead to of the order of 200 m rise in z_e.

Greenhouse warming may lead to an increase in precipitation falling as rain, or to cancelling changes in glacier accumulation and ablation, which do not affect the mass balance. Such climatic changes will lead to glacier runoff variations in addition to the runoff variations caused by mass balance changes. Only mass balance changes, represented by changes in z_e, will be considered here.

As Hofsjökull retreats the precipitation that falls on the area which is covered by the ice cap at present, will increasingly fall on ice free land. This will tend to reduce the glacier component of the rivers that flow from the ice cap. In the absence of changes in the total precipitation this effect will, however, not lead to changes in the total runoff from the area presently covered by the ice cap.

The runoff variations computed in the following are derived solely from changes in the volume of the ice cap. In the absence of changes in the total precipitation these runoff variations will reflect changes in the total runoff (whether glacial or not) from the area presently covered by the ice cap. In reality, total runoff changes from this area will be the superposition of many components, one of which will be the runoff variations caused by the decreasing volume of the ice cap.

Final Steady States

The first numerical experiment was the computation of final steady state profiles by running the model until a new steady state was reached for higher values of z_e. A warming of 1-1.5°C corresponds roughly to raising the equilibrium line by 200 m. Fig. 3 (left) shows steady state profiles for a range of z_e from 1,240 to 1,650 m a.s.l. The curve on the right of Fig. 3 shows the steady state volume as a function of z_e. It shows that raising z_e by 100 m reduces the volume of Hofsjökull by about 70 km^3 and raising z_e by 200 m reduces the volume by about 150 km^3.. Raising z_e by more than 350 m, that is above 1,600 m a.s.l., essentially removes the ice cap. this corresponds roughly to a warming of 2-3°C.

Response to a Step Change

The distribution of the volume reduction with time is of great interest with regard to glacier river discharge. This distribution is to a large extent determined by the response time τ_M, of the ice cap. In order to estimate the response time of Hofsjökull in the absence of mass balance – elevation feedback, the volume reduction was computed as a function of time for a uniform step change in the mass balance of $-0.075\ m_{ice}a^{-1}$. This change in the mass balance is equivalent to raising z_e by 10 m. The model was started with the datum ice cap (Fig. 2) and the changed mass balance which was held fixed until the ice cap reached a new steady state. Fig. 4 shows that the volume reduction as a function of time is well approximated by an exponential function of the form $\delta V(t) = \delta V(t = \infty)(1\text{-}e^{(-t/\tau_M)})$, with $\tau_M \approx 40$ years. This response time is in good agreement with the prediction of Eq. (1) that $\tau_M \approxeq$ 35-75 years.

Mass Balance – Elevation Feedback

In order to estimate the response time when mass balance – elevation feedback is included, the volume reduction was computed as a function of time for a 10 m step change in z_e. The model was started with the datum ice cap (Fig. 2) and a raised z_e

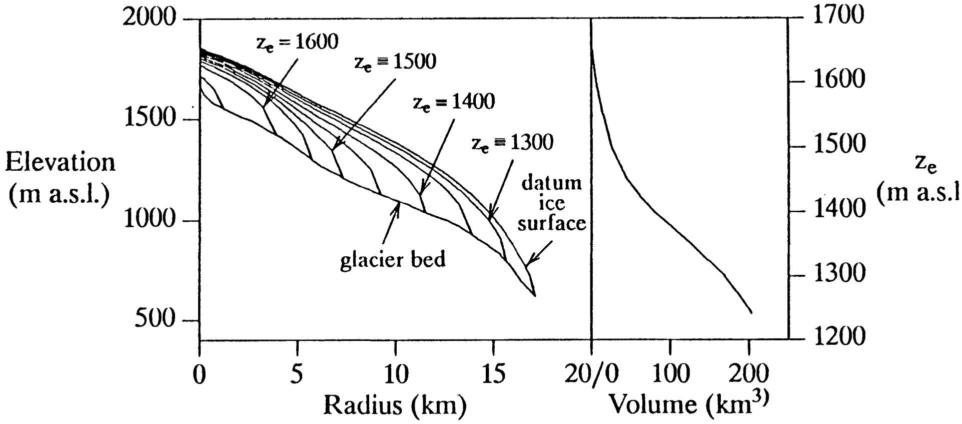

Fig. 3. Final steady state profiles for different equilibrium line altitudes z_e (left). The outermost profile is the datum ice surface profile corresponding to $z_e \equiv 1{,}240$ m a.s.l. The inner profiles span the z_e range from 1,300 to 1,650 m a.s.l. with an increment of 50 m. The curve on the right shows the volume of the steady state profiles as a function of z_e.

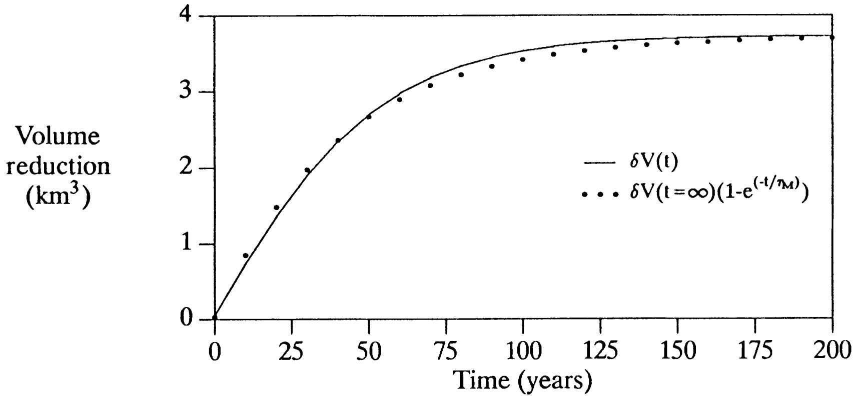

Fig. 4. Volume reduction as a function of time for a uniform step change in the mass balance of -0.075 $m_{ice}a^{-1}$ which is equivalent to raising z_e by 10 m (solid curve). Mass balance – elevation feedback is not taken into account. The dotted curve shows an exponential fit to the volume reduction with a response time $\tau_M \equiv 40$ years.

which was held fixed until the ice cap reached a new steady state. The mass balance was computed from Eq. (4) as the ice cap retreated and the ice surface was lowered. Fig. 5 shows that the volume reduction as a function of time is well approximated by an exponential function with $\tau_M \approx 50$ years. The mass balance – elevation feedback increases the volume change by 40% and the response time by 20% (compare Figs. 4 and 5).

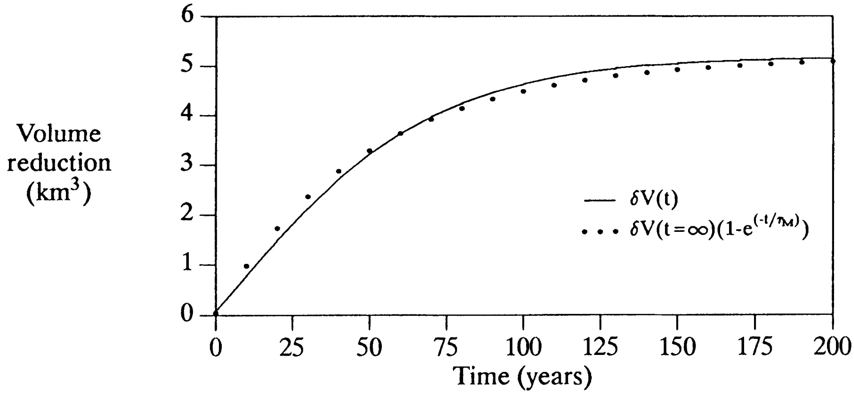

Fig. 5. Volume reduction as a function of time for a 10 m step change in z_e (solid curve). Mass balance – elevation feedback is taken into account. The dotted curve shows an exponential fit to the volume reduction with a response time $\tau_M \equiv 50$ years.

More model runs with higher values of z_e (not shown) indicate that the response time increases as z_e is raised reaching a maximum value of $\tau_M \approx 100$ years when z_e is raised by about 200 m to 1,440 m a.s.l. The model therefore predicts that the response time of Hofsjökull is between 50 and 100 years, depending on the size of the climatic perturbation. This response time is in good agreement with Eq. (1).

Response to a Warming Trend

The purpose of the above computations for step changes in the climate was to estimate the response time of Hofsjökull. A more realistic variation of the climate with time must be used in order to obtain a realistic estimate of the distribution with time of increased runoff as a consequence of greenhouse warming. For this purpose the computer model was run with a time-dependent equilibrium line altitude starting with the datum ice cap (Fig. 2). z_e was increased linearly from 1,240 to 1,440 m a.s.l. during the initial 50 years of the model run and held fixed at 1,440 m a.s.l. after that. This corresponds roughly to a warming of 1-1.5°C taking place over a 50-year period.

A warming of 1-1.5°C or a 200 m rise of the equilibrium line altitude is by no means the most likely climatic change for Hofsjökull during the next 50 years. It is not possible at present to estimate »the most likely climatic change« in the North Atlantic area caused by increased concentration of CO_2 and other greenhouse gases. A 200 m rise of the equilibrium line is, however, well within the range of possible changes caused by greenhouse warming predicted by general circulation models.

Fig. 6 shows the surface profiles of the ice cap at times t = 0, 50, 100, 150 and 200

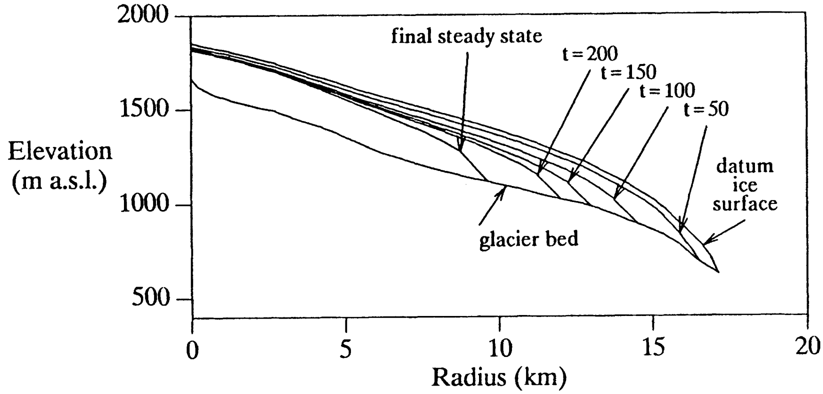

Fig. 6. Glacier profiles as a function of time with a time-dependent equilibrium line altitude z_e increasing linearly from 1,240 to 1,440 m a.s.l. during the initial 50 years of the model run and held fixed at 1,440 m a.s.l. after that. The outermost profile is the datum ice surface profile corresponding to $z_e \equiv 1{,}240$ m a.s.l. The innermost profile is the final steady state profile corresponding to $z_e \equiv 1{,}440$ m a.s.l. The intermediate profiles show the ice surface at $t \equiv 50$, 100, 150 and 200 years.

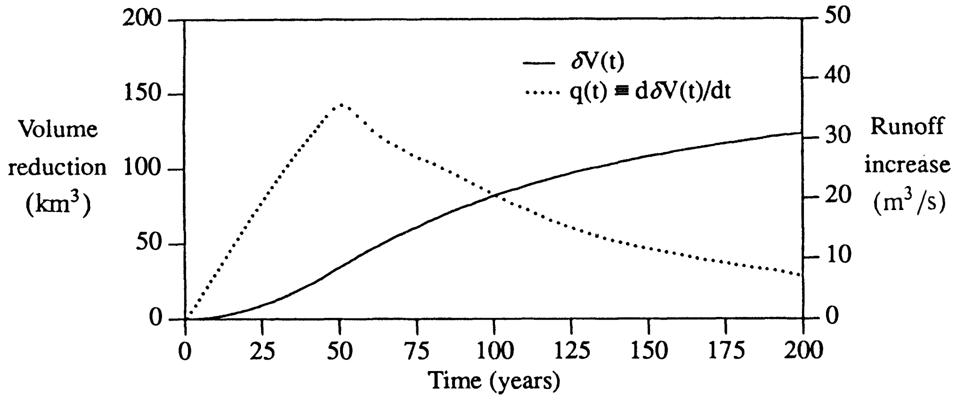

Fig. 7. Volume reduction as a function of time (solid curve) with a time-dependent equilibrium line altitude z_e, increasing linearly from 1,240 to 1,440 m a.s.l. during the initial 50 years of the model run and held fixed at 1,440 m a.s.l. after that. The doted curve shows the corresponding increase in the runoff from the area covered by the Hofsjökull ice cap at present.

years and the final steady state profile. The ice cap eventually retreats by 7.5 km and its volume is reduced from 200 km^3 to 50 km^3. The retreat takes longer than for a step change in climate because the climate is still changing 50 years after the start of the computation.

Fig. 7 shows the reduction in ice volume as a function of time. The figure shows that reduction in ice volume is most rapid around $t = 50$ years. The figure also shows the increased river discharge from the area presently covered by the ice cap as a function of time (assuming no changes in the total precipitation over this area as discussed above). It reaches a maximum of about 40 m^3s^{-1} around $t = 50$ years. The average precipitation over the Hofsjökull ice cap is approximately 2.5-3.0 $m_{H_2O}a^{-1}$ at present (Sigurðsson, personal communication). The maximum runoff change thus amounts to approximately 50 % of the present total precipitation that falls on Hofsjökull. A perhaps more meaningful comparison from an economic or hydro-power point of view, is provided by the present total discharge, of the order of 150 m^3s^{-1}, of rivers issuing from the ice cap and neighbouring highland areas (Snorrason, personal communication). The maximum runoff change amounts to approximately 25 % of this discharge.

Further modelling indicates that the results of the model for a 200 m time-dependent rise of the equilibrium line (Figs. 6 and 7) are very similar to the results for smaller or greater changes in the equilibrium line altitude (not shown).

Assessment of Results

The model computations indicate that the response time of Hofsjökull is between 50 and 100 years. This is in good agreement with theoretical predictions (Eq. (1)). The response time depends on mass balance – elevation feedback and the size of the climatic change. The shortest response times are predicted for small mass balance changes and no mass balance – elevation feedback. The reason that the response time is longer for a large warming is that the ablation at the terminus is reduced as the ice cap retreats to higher elevations. According to Eq. (1) the response time is inversely proportional to ablation along the terminus. This dependence on the ablation turns out to be more important than the shortening of the response time caused by the thinning of the ice cap as it retreats, which is also predicted by Eq. (1).

The modelling predicts that for a 100 m rise of the equilibrium line the steady state volume of Hofsjökull is reduced by approximately 70 km^3. This amounts to approximately 1/3 of the present volume of the ice cap. A rise of 100 m in the equilibrium line altitude corresponds to only 0.5-1°C warming which is quite small in comparison with predicted greenhouse warming. Therefore we may expect large changes in the size of Hofsjökull (and other Icelandic glaciers and ice caps) even for a relatively small greenhouse warming.

Modelling of a time-dependent rising of the equilibrium line predicts that the runoff from the area presently covered by the ice cap continues to increase as long as the climate is warming (50 years in the case considered). After the warming stops the runoff is reduced while the ice cap is approaching a new steady state.

When the new steady state is reached the runoff from this area returns to its former level (assuming that the precipitation has not changed). Although both the model and the climate history are highly idealized, the model indicates that runoff changes of the order of 40 m^3s^{-1} within the next 50 years are possible for moderate greenhouse warming. Increased precipitation caused by greenhouse warming may add to the predicted runoff changes.

Acknowledgements

Data on the geometry of Hofsjökull were made available by Helgi Björnsson at the Science Institute, University of Iceland. Data on the mass balance of Hofsjökull were made available by Oddur Sigurðsson at the National Energy Authority (Orkustofnun).

References

Bergthórsson, P., Björnsson, H., Dýrmundsson, Ó., Guðmundsson, B., Helgadóttir, Á., and Jónmundsson, J. V. (1987) The effect of climatic variations on agriculture in Iceland. In M. L. Parry, T. R. Carter and N. T. Konijn, eds. *The Impact of Climatic Variations on Agriculture, Volume 1. Assessments in Cool Temperate and Cold Regions,* Reidel, Dordrecht, The Netherlands.

Björnsson, H. (1988) *Hydrology of Ice Caps in Volcanic Regions,* Societas Scientarium Islandica, Rit 45.

Glen, J. (1955) The creep of polycrystalline ice, Proceedings of the Royal Society of London, A 228, pp. 519-538.

Hansen, J., Fung, I., Lacis, A., Rind, D., Lebedeff, S., Ruedy, R., and Russel, G. (1988) Global climate changes as forecast by Goddard Institute for Space Studies three-dimensional model, *Journal of Geophysical Research, Vol.* 93, pp. 9341-9364.

Jóhannesson, T., Raymond, C. F., and Waddington, E. D. (1989a) A simple method for determining the response time of glaciers. In J. Oerlemans, ed. *Glacier Fluctuations and Climatic Change,* pp. 343-352, Kluwer Academic Publishers, Dordrecht.

Jóhannesson, T., Raymond, C. F., and Waddington, E. D. (1989b) Time-scale for adjustment of glaciers to changes in mass balance, *Journal of Glaciology, Vol.* 35 (121), pp. 355-369.

Jones, P. D., Wigley, T. M. L., and Wright, P. B. (1986) Global temperature variations between 1861 and 1984, *Nature, Vol.* 322, pp. 430-434.

Kamb, B., and Echelmeyer, K. A. (1986) Stress-gradient coupling in glacier flow: I. Longitudinal averaging of the influence of ice thickness and surface slope, *Journal of Glaciology, Vol.* 32 (111), pp. 267-284.

Patankar, S. V. (1980) *Numerical Heat Transfer and Fluid Flow,* Hemisphere Publishing Corporation, Washington.

Paterson, W. S. B. (1981) *The Physics of Glaciers, Second edition,* Pergamon Press, Oxford.

Sigurðsson, O. (1989a) Afkoma Hofsjökuls 1987-1988 (in Icelandic). Report OS-89005/VOD-02 B, National Energy Authority, Reykjavík.

Sigurðsson, O. (1989b) Jöklabreytingar 1930-1960, 1960-1980, 1980-1987 og 1987-1988. *Jökull, Vol.* 39, pp. 108-113.

Waddington, E. D. (1981) Accurate modelling of glacier flow (Ph.D. thesis, University of British Colombia, unpublished).

Washington, W. M., and Meehl, G. A. (1989) Climate sensitivity due to increased CO_2: experiments with a coupled atmosphere and ocean general circulation model, *Climate Dynamics, Vol.* 4, pp. 1-38.

First received: 10 January, 1991
Revised version received: 27 March, 1991
Accepted: 4 April, 1991

Address:
Orkustofnun,
(National Energy Authority)
Grensásvegi 9,
IS-108 Reykjavik,
Iceland.