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Modelling the response of glaciers to climate change by applying volume-area scaling in combination with a high resolution GCM

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Abstract A seasonally and regionally differentiated glacier model is used to estimate the contribution that glaciers are likely to make to global sea level rise over a period of 70 years. A high resolution general circulation model (ECHAM4 T106) is used to estimate temperature and precipitation changes for a doubled CO_2 climate and serves as input for the glacier model. Volume-area relations are used to take into account the reduction of glacier area resulting from greenhouse warming. Each glacieriated region has a specified glacier size distribution, defined by the number of glaciers in a size class and a mean area. Changes in glacier volume are calculated by a precipitation dependent mass balance sensitivity. The model predicts a global sea level rise of 57 mm over a period of 70 years. This corresponds to a sensitivity of 0.86 mm $yr^{-1}K^{-1}$. Assuming a constant glacier area as done in earlier work leads to an overestimation of 19% for the contribution to sea level rise.

1 Introduction

Simulation of global volume changes of small glaciers (defined as: all land ice except the Greenland ice sheet and Antarctica) has so far been hampered by the difficulty in estimating the changing geometry of glaciers over time. In the past, volume changes were estimated without taking changes in the geometry into account (Gregory and Oerlemans 1998) or by calculating the volume change of a limited number of glaciers by means of numerical ice flow models (Oerlemans et al. 1998). Here we show that previous estimates can be improved if volume-area scaling (Bahr et al. 1997) is included. The proposed glacier model calculates the rate of change dV/dt of world glacier volume for 100 glacieriated regions. The most important new element that we introduce in the model is the reduction of glacier area over time. Another new element in our model is that we included not only the change in volume resulting from changes in temperature but also changes in volume resulting from changes in precipitation and the change in sensitivity of the glacieriated regions due to the change in precipitation. Previously precipitation changes were neglected or schematically prescribed. High resolution experiments improve the precipitation fields, particularly of the orographically induced precipitation, due to improved orographic forcing (e.g. Wild and Ohmura 2000). Here changes in temperature and precipitation are derived from the ECHAM4 T106 model at the time when CO_2 concentration is expected to have doubled.

The high resolution atmospheric model is run at the time where the CO_2 concentration is expected to double, using prescribed boundary conditions of sea surface temperature and sea-ice distribution for this period, which are derived from a lower resolution, transient coupled atmosphere-ocean scenario run. More specifically, T106 (1.1°) experiments with ECHAM4 were carried out for both present day and $2 \times CO_2$ conditions with associated sea surface temperature and sea-ice distributions derived from a transient scenario run with ECHAM4 at T42 (2.8°) resolution coupled to the OPYC ocean model (Roeckner et al. 1998). This scenario run takes into account a gradual increase in CO_2 and other greenhouse gases according to the IPCC Scenario IS92 an (Kattenberg et al. 1996) in which CO_2 doubles in 70 years. The T106 experiment for present day conditions uses the AMIP sea surface temperature (SST) climatology (Gates 1992), on which are superimposed detrended SST variabilities from the coupled T42 experiment

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representative for the decade 1971–1980. The experiment under $2 \times CO_2$ conditions is representative for the decade 2041–2050 and uses the SST obtained through a superposition of the AMIP SST climatology with the mean SST changes between the periods 1971–1980 and 2041–2050 and the SST variabilities for 2041–2050, both taken from the coupled T42 experiment. The high resolution experiment is thus of transient nature and not comparable to an $2 \times CO_2$ equilibrium type experiment where the warming would be significantly higher. Results of these runs are also used to calculate the contribution to sea level from Greenland Van de Wal et al. (in press).

A plea will be presented justifying the use of modelled precipitation results from the GCM in the next section. This study will mainly focus on how the reduction of glacieriated area can be accounted for in future predictions of glacier volume. It will be explained how volume-area scaling can be applied for this purpose (Sect. 3). Results will be presented in terms of sea level rise (Sect. 4) and discussed in terms of sensitivity to climate change (Sect. 5). Results in Sect. 4 exclude small glaciers and ice caps around Greenland and Antarctica. They will be discussed separately in Sect. 5.

2 On the use of global circulation model results to estimate volume changes of glaciers

The global performance of the GCM model is in line with the results of other GCM models as presented in the second IPCC report by Gates et al. (1996). Table 1 presents the results of ECHAM4 T106 in terms of global mean summer and winter precipitation in comparison with a set of 11 coupled ocean-atmosphere models and observations (Gates et al. 1996). It should be noted that the resolution of the 11 models is considerably lower, probably explaining the wide scatter for the precipitation. Zonal averages, not shown here, are also in line with the observations. The fact that global values are reasonable does not necessarily mean that the GCM can be used for the glaciated regions or any other specific region. For this purpose the control run was compared directly with the observed precipitation from climatological maps over the 100 glaciated regions (Oerlemans 1993; Zuo and Oerlemans 1997).

Precipitation from the gridded GCM has somehow to be interpolated to the glacier regions used in this study. Various approaches can be used. Figure 1 shows the results of this intercomparison for different methods of interpolation. Figure 1a shows the results of a weighted average approach. In this case the precipitation on the four grid points around a glacier area are used

Table 1 Global average values of temperature and precipitation of coupled GCM calculations for the current climate and observations for the months December, January, February (DJF) and June, July, August (JJA) Data from 11 GCMs with standard deviation from Gates et al. (1996)

	T (°C) DJF	*T* (°C) JJA	*P* (mm/d) DJF	*P* (mm/d) JJA
Observed	12.4	15.9	2.74	2.90
11 GCMs	12.3 ± 1.5	15.9 ± 1.5	2.87 ± 0.38	2.95 ± 0.34
ECHAM4 T106	12.75	16.63	2.73	2.85

to estimate the precipitation at the glacier. The four values are averaged with a weight equal to the inverse of the distance to the glacier area. A significant correlation exists between observations and ECHAM4 T106. Figure 1b shows the results by using the GCM model point which is nearest to the glacier area. Apparently, this does not improve the correlation. Figure 1c shows the results of an optimalization procedure. Grid points are selected from the four surrounding quadrants of a glacier area such that the difference between GCM and observations is minimized. This approach, of course improves the correlation between observations and model. This is probably a statistical artefact but also partly due to strong local variations in precipitation for instance due to orographically forced precipitation and therefore be a more realistic approach.

There is of course a wide scatter in the size of the glacier areas represented in the data set of 100 glaciated regions. One can question whether a GCM with a resolution of 1.125° can ever predict reasonable values for areas of only several square kilometres for a single glacier. These small areas are, on the other hand, unimportant for global sea level. Most important are the larger glacier areas. For this reason we selected those glacier areas which are comparable in magnitude to a grid box in the GCM or over 5000 km^2. Results of this selection using the weighted average approach presented in Fig. 1a, are shown in Fig. 1d. It seems that the precipitation values in the larger glacier areas are reasonably well represented by the GCM, except for Iceland.

For this reason we believe that it is useful to apply GCM results to estimate the effect of precipitation changes. It might be noted here that the same analyzing technique does not yield better results in terms of regression coefficients for a global data set (New et al. 1999) with a grid spacing of $0.5 \times 0.5°$. This suggests that the unexplained part of the variance is either due to very local effects smaller than $0.5 \times 0.5°$ or to inaccuracies in the glacier precipitation data set or to inadequacies in the model. From now on we will use the weighted average approach presented in Fig. 1a, d. It might be noted that the application of other interpolation approaches (presented in Fig. 1b, c) in terms of sea level rise are small.

3 Calculation of volume changes of small glaciers

The glacier model is an extended version of the model used by Gregory and Oerlemans (1998) and calculates the rate of change of the volume, $\mathrm{d}V/\mathrm{d}t$, of land ice (except for the Greenland ice sheet and Antarctica) during a year (t) as:

$$\frac{\mathrm{d}V}{\mathrm{d}t} = \sum_{j=1}^{n}\sum_{k=1}^{m} A(j,k,t) \times \left\{ \Delta T_s(j,t)\frac{\mathrm{d}B_{P(j,t)}}{\mathrm{d}T_s} + \Delta T_{ns}(j,t)\frac{\mathrm{d}B_{P(j,t)}}{\mathrm{d}T_{ns}} + \Delta P(j,t) \right\} \quad (1)$$

which is the sum over $n = 100$ glaciated regions (Oerlemans 1993; Zuo and Oerlemans 1997) and $m = 15$ size classes. Each glaciated region (j) has a glacier area with a size distribution (k). Note that the climatological variables temperature and precipitation are independent of size class. The change of volume in Eq. (1) is determined by the change in temperature and precipitation. The mass balance sensitivity ($\mathrm{d}B/\mathrm{d}T$) has a part resulting from changes in summer temperature (ΔT_s) and non-summer months (ΔT_{ns}). Summer months are June–July–August for the Northern Hemisphere and December–January–February for the Southern Hemisphere. The mass balance sensitivity depends strongly on precipitation (P) (Oerlemans and Fortuin 1992) which changes in time. Values for the mass balance sensitivity as a function of the precipitation are taken from (Zuo and Oerlemans 1997). Precipitation change (ΔP) is calculated as:

$$\Delta P_{j,t} = P_{j,obs}\left(\frac{P_{j,t_e}}{P_{j,t_0}} - 1\right)\frac{t}{t_e} \qquad 0 \le t \le t_e \quad (2)$$

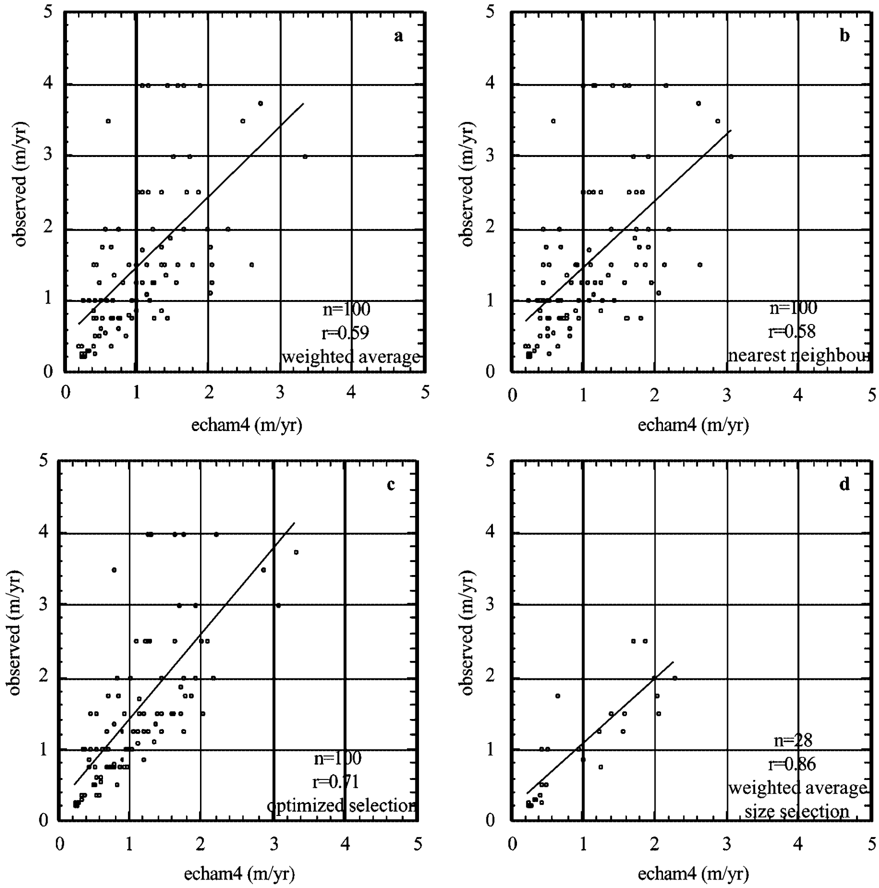

Fig. 1 Relation between ECHAM4 T106 precipitation and observed precipitation in the glacieriated regions **a** for a weighted average approach, **b** for a nearest neighbour approach **c** for an optimalization procedure, **d** for a selection of large glaciers

In this equation $P_{j,obs}$ is the observed precipitation in a region, so the precipitation change is taken as the relative change in modelled precipitation ($P_{j,t}$) multiplied by the observations and linearly interpolated in time. Experiments have shown that with respect to global sea level this approach yields comparable results to an approach in which the absolute change in modelled precipitation was used instead of the relative change. It is assumed that all precipitation is snow. This means that the model overestimates the changes caused by snowfall as well as the sensitivity, because some precipitation will fall as rain and might runoff directly. Unfortunately this effect cannot be addressed without detailed height dependent modelling which is impossible for all glaciers.

Volume (V) and area (A) are related, for each individual glacier, via a power law (Bahr et al. 1997):

$$V_{j,k,t} = cA^{\gamma}_{j,k,t} \tag{3}$$

Gamma is the dimensionless scaling coefficient of 1.375 which is based on theoretical considerations by Bahr et al (1996). This value is in agreement with observations presented by Meier and Bahr (1996), Macheret (1988) and Chen and Ohmura (1990). The constant c in Eq. 3 equals 0.12 $m^{3-2\gamma}$ and is tuned such that the integrated volume over all glacieriated regions is close to 0.5 m global sea level (Warrick et al. 1996). Each glacieriated region has a specified size distribution, defined by the number of glaciers (N) in a size class and a mean area (a):

$$A_{j,t} = \sum_{k=1}^{m} N_{j,k^*}\overline{a}_{j,k,t} \tag{4}$$

The size of the classes is: k_1: 2^{-6}–2^{-5} km^2, k_2: 2^{-5}–2^{-4} km$^2, \ldots, k_{15}$: $\geq 2^9$ km^2, which is determined by the availability of glacier data (Haeberli et al. 1989). After the volume change has been calculated at $t = 0$ (with Eq. 1) the glacieriated area at the next time step, $t = 1$ for each class is calculated by inverting Eq. (3). The new area at $t = 1$ is used to calculate the volume change at $t = 1$ by using again Eq. (1). As a result the number of glaciers in a region is constant, but the mean area changes for each class in each region over time. Data for the present-day climate size distribution are derived from (Haeberli et al. 1989). A selection of five glacieriated areas is shown in Fig. 2.

Unfortunately an accurate size distribution as presented in Fig. 2 is not known for all regions. Only for 41 glacieriated regions covering 38% of the total glacieriated area is the size distribution known. The size distribution for those regions with no known size distribution is obtained by determining the average fraction of each size class, and mean area of a certain size class over the 41 known regions. This procedure results in the explicit treatment of 10^5 glaciers which seems to be somewhat smaller than what is generally believed to be the total number of glaciers in the world.

In order to take the present-day imbalance into account, calculations are started in 1865. Historical temperatures over the period 1865–1975 are based on a compilation by Zuo and Oerlemans (1997). Volume and area in 1865 are calculated iteratively such that the present-day size distribution is matched after integrating over the period 1865–1975.

One might argue that the theory behind the power law relation (Bahr et al. 1997) assumes a glacier to be in steady state. Observations do however show that this relation is valid for glaciers with observed volume and area (Meier and Bahr 1996; Macheret et al. 1988). Schwitter and Raymond (1993) also argue that changes in volume can be estimated from steady state considerations. Of course, these glaciers are not necessarily in steady state. Another possibility to test the validity of a power law relation for non-steady state conditions is to use numerical ice flow models to establish volume area relations under non-steady state conditions. Experiments with these kinds of models show that a retreating glacier is at any arbitrary time not more than 20% smaller in

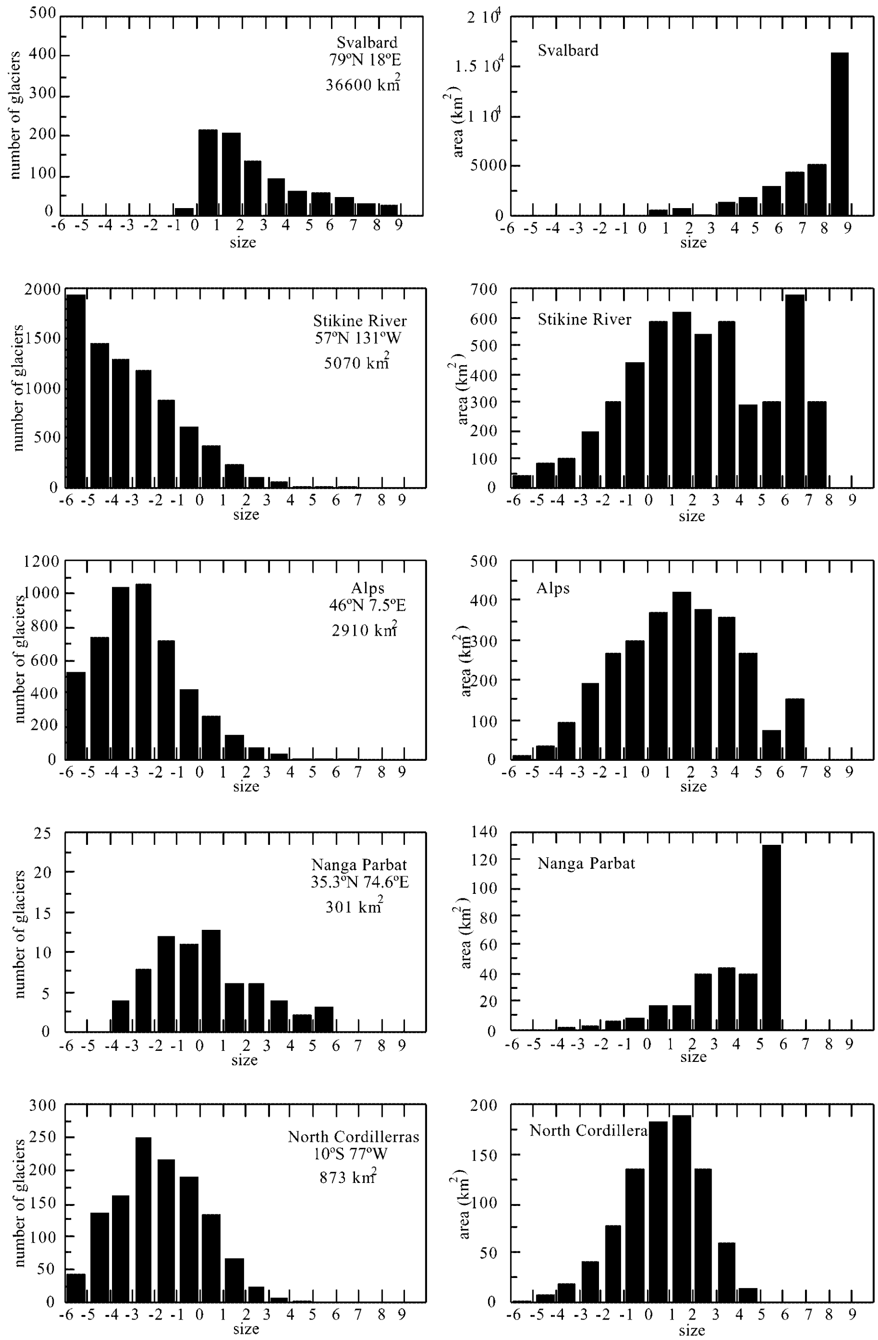

Fig. 2 Size distribution for five selected areas. Note that the scale of the vertical axes is different for each region. The size is presented such that 1–2 means 2^1–2^2 km^2, which equals size class 8

volume than expected from the scaling relation given by Eq. (3). This implies that the instantaneous reduction of area resulting from change in volume (Eq. 3) is a reasonable approach. A second uncertainty in the power law scaling arises from difficulties in the scaling of glacier width and the role of sliding. These factors lead to a range in γ of $\pm 1/8$. Sensitivity experiments with γ based on this range and c $\pm$ 25% show only a variations of few percent in the results. This means that splitting up the data set in glaciers and ice caps with different values for c and γ for glaciers and ice caps reveals nearly identical results.

Results of numerical flow models can also be used to evaluate the dynamical properties of the power law scaling with respect to volume changes. Table 2 shows that the fractional loss derived from the power law concept is in reasonable agreement with the loss derived by numerical ice flow models. However Table 2 is far from representative for all glaciers on the world. More numerical experiments with drier ice sheets (which are not available) can change this preliminary insight in the dynamical properties of the volume-area scaling approach. The results presented by Oerlemans et al. (1998) indicate that the response times of the three largest glaciers in their study, which are most important for sea level, are approximately 25% shorter than those derived from the power law scaling approach used here. The power law concept is therefore a useful tool with adequate dynamical properties, but improvements could be obtained by subdividing the glacier data base into glacier types (e.g. ice sheet/glacier, continental/maritime, sliding dominated/deformation dominated, including a shape factor) each type having its own power law variables c and γ.

The dynamical properties of our method are shown in Fig. 3. The figure shows contour lines of the fractional volume for a per-

Table 2 Fractional volume from Blöndjökull, Illviðrajökull, King George Ice Cap based on a power law concept (such that power law volume equals initial flow model volume) and by numerical flow models. Precipitation is 1.3 m for King George Ice Cap and 2.5 m for the Icelandic glaciers. These precipitation rates are used to calculate the mass balance sensitivity. The temperature increase is 2 K/100 years. Results are presented after 70 years of integration and show good agreement

	Numerical ice flow model (%)	Power law concept (%)
King George Ice Cap	86	83
Blöndjökull	84	87
Illviðrajökull	83	84

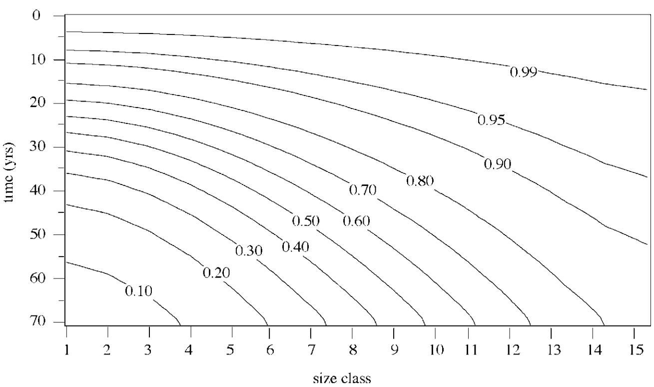

Fig. 3 Fractional volume per size class as a function of time for a temperature increase of 2 K/100 years. The figure shows that after 70 years the small glaciers have almost disappeared but the large glaciers are almost unchanged

turbation of 0.02 K/year and constant sensitivity. The figure shows that the general idea of faster response for smaller systems is satisfied. This follows directly from Eq. (1), where volume loss is related to surface area and not to the volume itself. If γ would be equal to one there would be no size dependence. Note that this is only true if the sensitivity is constant. In reality larger glaciers are often more sensitive and might respond faster. This is implicitly taken into account because the sensitivity depends on precipitation.

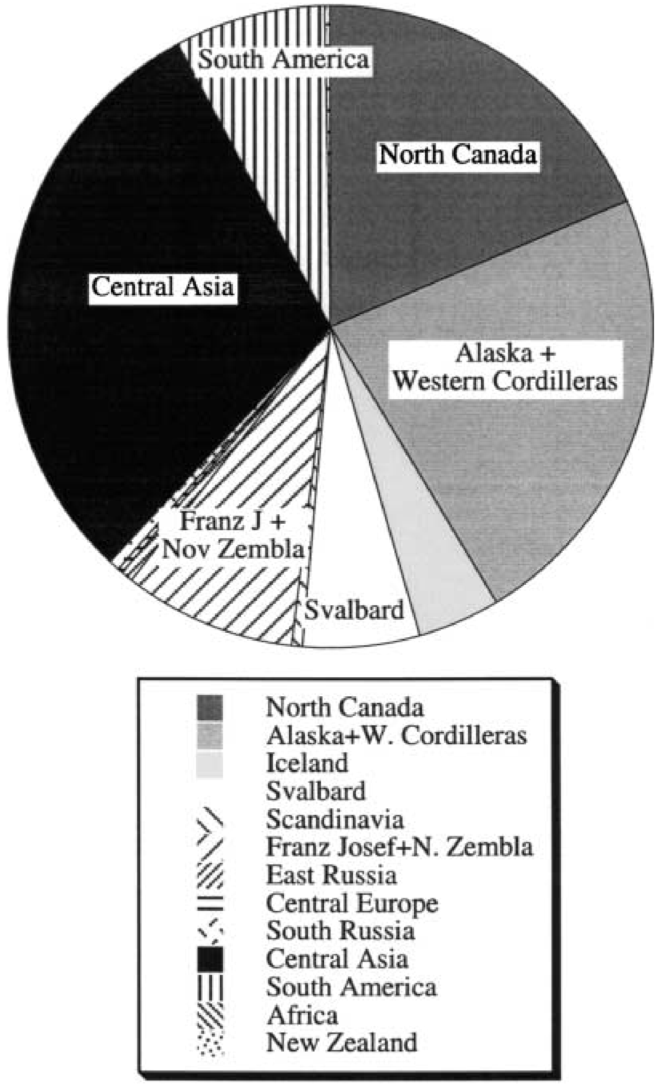

Fig. 4 Contribution of the different regions to global sea level change. The three largest regions, Central Asia, Alaska, Western Cordilleras and North Canada together produce 73% of the total volume change

4 Sea level rise

In order to summarize the contribution of the different regions to sea level rise over the next 70 years we scaled the contribution from each region with the total sea level rise resulting from only the temperature change. The subdivision into regions is in line with that of Zuo and Oerlemans (1997). Figure 4 shows the results. Some regions, such as Scandinavia, East Russia, Africa and New Zealand make an almost negligible contribution (< 1%). The three largest glaciated regions, Central Asia, Alaska, Western Cordilleras and North Canada together produce 72% of the total volume change. The relative contribution by central Asia is comparable to results presented by Gregory and Oerlemans (1998), for their greenhouse gases experiment (GHG). The largest contribution namely 31%, derives from Central Asia. The ECHAM4 T106 results used here do not include the aerosol effect. The above-average temperature increase is therefore most likely the reason for the fact that Central Asia shows the largest contribution. Whether this is realistic can probably be addressed more reliably if more GCMs are compared. Figure 5 shows for each region separately the contribution to sea level rise due to precipitation and temperature changes. A negative contribution from precipitation changes corresponds to an increase in precipitation in a region. Apparently in all regions the precipitation changes can be neglected compared to the effect of the changes in temperature. It is therefore not surprising that the total contribution from small glaciers due to precipitation changes is small.

The most important experiment with the proposed model shows that if the glacieriated regions are considered to have a constant area (infinite source of ice), sea level rise is overestimated by approximately 19%. More sensitivity

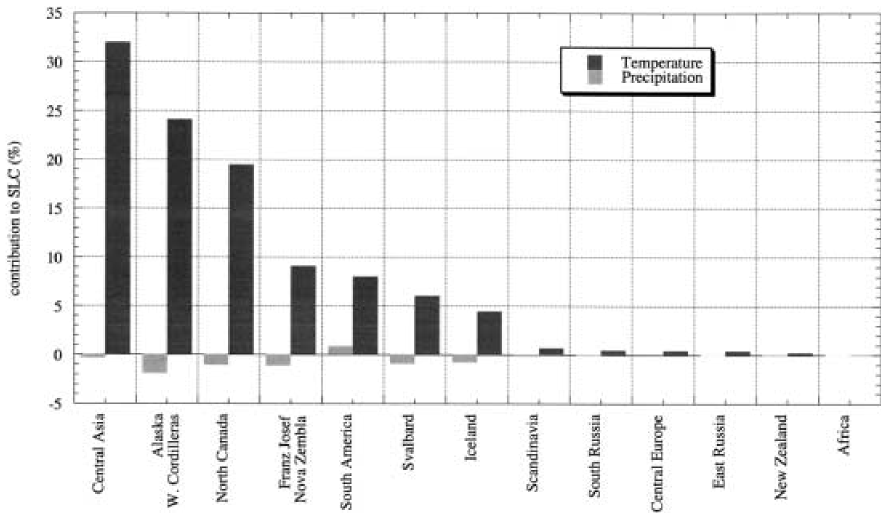

Fig. 5 This shows for each region separately the contribution to sea level rise due to precipitation and temperature changes

Table 3 Summary of the different effects for the predicted sea level change (SLC) as described in the text. All tests concern the change of only one effect relative to the reference experiment. All effects are almost additive. The reference experiment includes seasonality, size distribution for each region, sensitivity dependent on precipitation, local temperature and precipitation forcing

	mm SLC	Scaled (%)
Reference experiment	55	100
Annual global mean *T* and *P*	43	79
Annual local mean *T* and *P*	63	115
Precipitation constant	55	100
Sensitivity constant for a region in time	52	95
Constant area	65	119

experiments are shown in Table 3. The table shows that precipitation effects are not so important. Neglecting precipitation changes is expected to result in virtually no change of sea level. In fact the increased precipitation is expected to be more important indirectly because the temperature sensitivity increases for increased precipitation, assuming the sensitivity to be constant for a region, in time would lead to an underestimation of 5% for the sea level rise (Table 3). Using annual global mean temperatures reduces the total sea level rise by 21%. Using annual mean values, but now regional values increases the sea level rise by 15%. The importance of the climatological forcing was also suggested by earlier work and our results are therefore compared to the results presented by Gregory and Oerlemans (1998).

To be able to compare the results with previous work (Gregory and Oerlemans 1998) we have to make a couple of corrections. First of all, we have to exclude the change in temperature sensitivity resulting from precipitation changes. This effect is approximately 5% (Table 3). Secondly, we have to correct for differences in the length of the climate simulation. Here we consider only 70 years, whereas Gregory and Oerlemans (1998) considered 110 years. Thirdly, we have to assume precipitation to be constant and fourthly, we have to assume

Table 4 Comparison with (Gregory and Oerlemans 1998) (GR-98). All results are considered over a 70 years period. This means that the results from Gregory and Oerlemans (1998) are scaled with a factor $(7/11)^2$, being the fraction of the integrated temperature perturbation over 110 years. For our calculation the sensitivity is constant, precipitation changes are neglected and the glacieriated regions are considered to be an infinite source of ice. GHG is the greenhouse experiment, SUL is the aerosol experiment

	mm SLC This study (%)	GR-98 GHG (%)	GR-98 SUL (%)
Reference setting GR-98	65 (100)	74 (100)	53 (100)
Annual global mean *T* and *P*	49 (74)	60 (81)	44 (83)
Annual local mean *T* and *P*	76 (116)	89 (120)	66 (125)

a linear trend for the temperature perturbation. And last but not least, the glacieriated area has to be kept constant. The results of Gregory and Oerlemans (1998) are recalculated in Table 4, in order to facilitate direct comparison. One might argue that discrepancies are due to differences in the temperature perturbation itself. The global temperature rise for their greenhouse experiment (GHG) is 3.3 K which is equivalent to an increase of 0.03 K/year and 0.025 K/year for their aerosol experiment (SUL). The ECHAM4 results show an increase of 0.027 K/year. Table 4 shows that the effect of seasonality is slightly larger for ECHAM4 compared to HADCM2 used by Gregory and Oerlemans (1998). Using annual local mean temperature and precipitation yields a slightly smaller overestimation compared to the results obtained by HADCM2.

5 Discussion and conclusions

Besides uncertainties in the volume-area scaling concept, there is also considerable uncertainty about the contribution made by small glaciers and ice caps around the Greenland ice sheet and Antarctica. Each of the two areas adds roughly 15% to the total glacieriated area of small glaciers and ice sheets. In order to apply the glacier model to Greenland we used data derived from (Weidick and Morris 1998) for location of the ice bodies (only size class 15), and from Ohmura and Reeh (1991) for accumulation rate. Application of the same glacier model described here to the small ice sheets around the Greenland ice sheet adds 6% to the global sea level rise as a result of small glaciers and ice sheets. This relatively small addition is mainly a result of the low precipitation rate in these glacieriated regions. The glacier model is not applied to small ice caps and glaciers around the Antarctic ice sheet because the small temperature increase will not necessarily lead to melting owing to the low average temperatures.

In order to take the differences due to the magnitude of temperature perturbation into account we express the sea level rise in a sensitivity value (S) defined as:

$$S = \frac{SLC}{\Delta t \Delta \bar{T}} \quad , \tag{5}$$

in which SLC is the integrated sea level rise, t time and ΔT global temperature. Note that we use the mean temperature increase. $S = 1.0$ mm $\mathrm{y^{-1}K^{-1}}$ for the results presented by Gregory and Oerlemans (1998) as well as for the results presented by De Wolde et al. (1997) based on a zonal averaged energy balance model. Note that both have different definitions of S, but their results are recalculated according to Eq. (5). Note that differences between SUL and GHG scenarios in Gregory and Oerlemans (1998) are eliminated by correcting for the average temperature change. In this study we obtain $S = 1.0$ mm $\mathrm{y^{-1}K^{-1}}$ for the case in which the setting is comparable to Gregory and Oerlemans (1998). This implies that use of the spatial and temporal distribution of the temperature change leads to a similar sensitivity. If we use the preferred setting including the reduction of the surface area we obtain a value of $S = 0.86$ mm $\mathrm{y^{-1}K^{-1}}$, a value which is 14% lower than previous estimates. Note that if the time period considered increases differences between this approach and the constant area approach will also increase. The results imply a considerable reduction in predictions of global sea level rise since the relative contribution of small glaciers is thought to be significantly more important e.g. Warrick et al. (1996), De Wolde et al. (1997) than the contribution of Greenland and Antarctica. The results presented here, in combination with reduced SLC for Greenland (Wild and Ohmura 2000), mean that SLC predictions as reported by the IPCC (Warrick et al. 1996) have to be lowered. The proposed procedure eliminates a systematic error in previous analysis.

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