The Cryosphere Discuss., 5, 1655–1695, 2011
www.the-cryosphere-discuss.net/5/1655/2011/
doi:10.5194/tcd-5-1655-2011

The Cryosphere Discussions

An assessment of uncertainties in using volume-area modelling for computing the twenty-first century glacier contribution to sea-level change

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Received: 23 May 2011 – Accepted: 26 May 2011 – Published: 1 June 2011

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

A large part of present-day sea-level change is formed by the melt of glaciers and ice caps (GIC). This study focuses on the uncertainties in the calculation of the GIC contribution on a century timescale. The model used is based on volume-area scaling, combined with the mass balance sensitivity of the GIC. We assess different aspects that contribute to the uncertainty in the prediction of the contribution of GIC to future sea-level rise, such as (1) the volume-area scaling method (scaling constant), (2) the choice of glacier inventory, (3) the imbalance of glaciers with climate, (4) the mass balance sensitivity, and (5) the climate models. Additionally, a comparison of the model results to the 20th century GIC contribution is presented.

We find that small variations in the scaling constant cause significant variations in the initial volume of the glaciers, but only limited variations in the glacier volume change. If two existing glacier inventories are tuned such that the initial volume is the same, the GIC sea-level contribution over 100 yr differs by 0.027 m. It appears that the mass balance sensitivity is also important: variations of 20 % in the mass balance sensitivity have an impact of 17 % on the resulting sea-level projections. Another important factor is the choice of the climate model, as the GIC contribution to sea-level change largely depends on the temperature and precipitation taken from climate models. Combining all the uncertainties examined in this study leads to a total uncertainty of 4.5 cm or 30 % in the GIC contribution to global mean sea level. Reducing the variance in the climate models and improving the glacier inventories will significantly reduce the uncertainty in calculating the GIC contributions, and are therefore crucial actions to improve future sea-level projections.

1 Introduction

Sea-level change is an important issue in the field of climate change. Currently, the largest contributions to sea-level change are the addition of mass through land ice melt and the thermal expansion of the ocean water (Bindoff et al., 2007). The land ice contribution consists of mass loss from the two large ice sheets (Greenland and Antarctica) and the glaciers and ice caps (GIC) outside the ice sheets. Both are important contributions and need further consideration for future sea-level predictions. Here we focus on the contribution of the GIC.

There are several methods to calculate the evolution of glaciers in time and their response to climatic changes. A physically based approach would be to use flow line models forced by appropriate mass balance schemes. However, these require detailed input, such as glacier bed topography, ice thickness and knowledge of the micro climate, which is available for only a few glaciers around the world. It is therefore not possible to use this approach on a global scale yet. As an alternative, scaling methods are used, which are based on relatively simple geometric features of glaciers, such as the length or the area, and their relation to the volume of the glacier. Examples are volume-length scaling (Oerlemans et al., 2007; Leclercq et al., 2011), volume-area scaling (e.g. Bahr et al., 1997; Van de Wal and Wild, 2001), or volume-area-length scaling (Radić and Hock, 2011). All methods use empirical relations derived for a small set of glaciers, which are extended to a global scale. Additionally, the required mass balance changes may be obtained by using seasonal sensitivity characteristics (Oerlemans and Reichert, 2000), modelling the changes in mass balance profiles (Raper and Braithwaite, 2006), or by using a relation between mass balance sensitivity and precipitation (e.g. Gregory and Oerlemans, 1998; Van de Wal and Wild, 2001). An even more direct way to obtain a global estimate of glacier changes is to use a scaling relation between global temperature change and total ice volume without area size classes or latitudinal dependence, as applied in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) (see Appendix 10.A.3 in Meehl et al., 2007b).

Over the past few years, several studies have presented estimates for the twenty-first century GIC sea-level contribution using different methods. IPCC AR4 projected a contribution of 0.08–0.15 m for the A1B scenario (Meehl et al., 2007b), based on a range of climate models and three different values for the initial volume of all glaciers.

As a follow-up on IPCC AR4, Meier et al. (2007) estimated a GIC contribution of 0.1–0.25 m by 2100, where the spread originates from the assumption for the acceleration of ice loss. Another estimate was presented by Pfeffer et al. (2008), who found a GIC contribution of 0.17–0.55 m by 2100, based on kinematically constrained scenarios. However, none of these studies provide regional estimates of GIC volume changes. The latter is done in a recent study by Radić and Hock (2011), who find a global mean contribution of 0.124 ± 0.037 m. They use volume-area-length scaling to calculate regional glacier mass volume changes in response to climate model projections. Another study that provides regional estimates is Slangen et al. (2011), who use volume-area scaling and arrive at a glacier contribution of 0.17 ± 0.04 m.

The current study does not aim at improving the estimate of the GIC sea-level contribution as most of the above studies do, but at providing insight in the uncertainties of the GIC contribution. Therefore, this study should be considered as an assessment of different aspects which contribute to the uncertainty in the prediction of the contribution of GIC to future sea-level rise, rather than an attempt to improve the best estimate of the contribution itself.

The model used here is based on the volume-area scaling method, which builds on concepts developed by Bahr et al. (1997) and was applied for sea-level projections by Van de Wal and Wild (2001) and Slangen et al. (2011). The model uses the volume-area relation in combination with a relation for the mass balance sensitivity of the glaciers and the amount of precipitation. The present study uses the same approach and data as the Slangen et al. (2011)-study, with the only difference that Antarctic glaciers are excluded here to enable a comparison to the older Van de Wal and Wild (2001)-data. This leads to a lower value for the total GIC contribution to sea-level change.

Details of the model set-up and the data used in this study are presented in Sect. 2. A comparison of the model results for the past GIC contribution and a description of the reference experiment is presented in Sect. 3. In Sect. 4 the sensitivity studies are described, which forms the core of this paper. We distinguish uncertainties related to the the mass balance sensitivity (Sect. 4.1), the GIC volume-area scaling method (Sect. 4.2), the imbalance of GIC with climate (Sect. 4.3), the choice of glacier inventory (Sect. 4.4), and the climate change models (Sect. 4.5). Finally, in Sect. 5, a summary of the findings in the previous sections is presented.

2 Data and methods

2.1 The volume-area model

The model we use to calculate the GIC contribution to sea-level change is based on volume-area scaling considerations (e.g., Bahr et al., 1997; Van de Wal and Wild, 2001). The method assumes that the area of a glacier is proportional to its volume using a power law:

$$V = cA^{\gamma}, \tag{1}$$

where c and γ are scaling parameters. For glaciers, γ is set to 1.375 (Bahr et al., 1997; Chen and Ohmura, 1990). For c, Van de Wal and Wild (2001) used a value of $0.12\,\mathrm{m}^{3-2\gamma}$ to obtain a total glacier volume of 0.50 m sea-level equivalent (SLE) including GIC surrounding Antarctica and Greenland. Radić and Hock (2010) use a value of $0.2055\,\mathrm{m}^{3-2\gamma}$ and arrive at 0.60 m SLE for their glacier inventory. Here we vary c from 0.05 to $0.30\,\mathrm{m}^{3-2\gamma}$ in the sensitivity analysis (Sect. 4.2). For ice caps, γ is set to 1.25 and c to $1.7026\,\mathrm{m}^{3-2\gamma}$, as described in Radić and Hock (2010). These values are kept constant throughout the study.

The specific glacier model used in this study is developed by Van de Wal and Wild (2001), and it calculates the evolution of GIC in time given a certain initial glacier inventory. The volume change of all GIC is calculated while accounting for the change of glacier area in time (t), temperature changes (ΔT) and precipitation changes (ΔP), by applying the following expression:

$$\frac{dV}{dt} = \sum_{j=1}^{n}\sum_{k=1}^{m} A(j,k,t)\cdot \left\{ \Delta T_{\mathrm{s}}(j,t)\frac{dB_{P(j,t)}}{dT_{\mathrm{s}}} + \Delta T_{\mathrm{ns}}(j,t)\frac{dB_{P(j,t)}}{dT_{\mathrm{ns}}} + \Delta P(j,t) \right\}. \tag{2}$$

In Eq. (2), glacier area A is summed over n regions and m size bins. The mass balance sensitivity $dB_{P(j,t)}$ is a function of the local precipitation P using the relation from Zuo and Oerlemans (1997) (Z97), and changes due to local summer temperature variations (dT_{s}) (summer is JJA in Northern Hemisphere, DJF in Southern Hemisphere), as well as non-summer temperature variations (dT_{ns}) according to:

$$\frac{dB}{dT_{\mathrm{s}}} = -0.259P^{0.427} \tag{3}$$

$$\frac{dB}{dT_{\mathrm{ns}}} = -0.387P^{0.683} + 0.259P^{0.427}. \tag{4}$$

Temperature (T) and precipitation (P) are taken from Atmosphere-Ocean coupled General Circulation Models (AOGCM's) (Meehl et al., 2007a) using the nearest neighbour approach. Both T and P are time dependent, which implies that the sensitivity itself changes over time as well.

All values for initial volume (V_{i}) and volume change of the glaciers (δV) shown in the next sections are, unless explicitly mentioned, ensemble mean values of calculations with 12 different temperature and precipitation scenarios, obtained from 12 different AOGCM's (Meehl et al., 2007a). The used AOGCM's will be more thoroughly described in Sect. 2.3.

The imbalance of the GIC with climate is accounted for by starting the calculations in 1865, and applying a global temperature increase of $0.7\,^{\circ}\mathrm{C}\,100\,\mathrm{yr}^{-1}$ over the period

1865–1990 (Trenberth et al., 2007). The importance of the imbalance of the GIC with climate is tested in Sect. 4.3, by applying data of Z97, which cover the period 1865–1990. For this reason we adopt 1990 as the starting year for the future contribution. The starting volume and area in 1865 are calculated iteratively, such that the modelled volume and area in 1990 agree with the glacier inventory. The model calculations are continued for another 100 yr after 1990, which results in a total of 225 modelled years. Future volume changes are therefore defined as the difference between 1990 and 2090.

2.2 Two glacier inventories

In this study, two glacier inventories are used. The first and default glacier inventory is an upscaled version of the WGI-XF (Cogley, 2009a), which has a World Glacier Inventory core (WGI, National Snow and Ice Data Center, 1999, updated 2009), and is combined with Icelandic and Alaskan data (Radić and Hock, 2010). The GIC are divided into 19 large regions, of which two are located around Antarctica. As the second data set (described below) does not contain any Antarctic data, the two Antarctic regions of this data set will be excluded from this comparison. We sort the remaining 17 regions into 14 regions as shown in Table 1. Using these 14 regions of Z97 facilitates a comparison of Radić and Hock (2010)-data with the second glacier data set. The total area in the Radić and Hock (2010)-data set is 568 709 km^2, and is shown in Fig. 1a. Each region has a size distribution in 18 size classes, ranging from $< 2^{-3}$ km^{-2} to 2^{13}–2^{14} km^{-2}. We will from now on refer to this data set as R10.

The second data set used in this study also has a WGI core, but uses an older version than the R10 data set. Furthermore, the treatment of data-sparse regions differs from R10. This data set consists of 135 regions, of which 100 regions are the main glaciated regions outside the two major ice sheets (Oerlemans, 1993, Z97), and 35 regions are located around the Greenland ice sheet (Van de Wal and Wild, 2001). The 135 regions are also divided into 14 large regions, as shown in Table 1. The total glaciated area in this data set is 597 613 km^2, presented in Fig. 1b. For 41 of the 135

glaciated regions a size distribution is available in 15 size classes (from 2^{-6}–2^{-5} km^{-2} to $\geq 2^9$ km^{-2}). For the 35 regions on Greenland it is assumed that all glaciers are in the largest possible size class. The remaining 59 regions are assigned the average size distribution of the first 41 regions. From now on we will refer to this data set as W01.

As the GIC contribution to sea level is dominated by the large size classes a detailed description of those is desirable. For that reason we prefer the R10 data set as the reference as this data set has a better subdivision of the large classes than the W01 data set. Nevertheless, we will also use the W01 data to show how differences in the version, upscaling and area binning of the inventory contribute to the uncertainty in the calculation of the future contribution, and to allow for a comparison of the recent data to earlier results (Sect. 4.4).

In Fig. 1 it can be seen that the division of glacier area over the regions is almost similar for both data sets. However, as the volume-area relation is non-linear, the volume also depends on the size of the glaciers in each region and thus the volume will not necessarily be equal for both data sets. These differences in the initial volume in 1990 (V_i) are a potential source of uncertainty and will be addressed in Sect. 4.

2.3 Twelve climate models

The glacier model requires information on atmospheric temperature and precipitation to calculate the glacier contribution to sea-level change. These data are taken from the results of simulations with AOGCM's, of which the names and references are presented in Table 2. These models are a subset of the World Climate Research Programme's CMIP3 multi-model data set (Meehl et al., 2007a) used for IPCC AR4. This subset contains 12 models and was also used in Slangen et al. (2011). In this study we only consider the emission scenario A1B, as defined in the IPCC Special Report on Emission Scenarios (Nakicenovic and Swart, 2000). The ensemble mean global average temperature increase in 2090–2099 w.r.t. 1980–1999 is +2.8 °C (1.7 to 4.4 °C) for this scenario (Meehl et al., 2007b).

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As the resolution of the different climate models is highly variable, the data are linearly interpolated to one grid to be able to construct an ensemble mean. We choose a grid with 512 longitude points and 256 latitude points, as this is the grid used in the sea-level model that calculates the sea-level patterns resulting from land ice mass changes.

In order to apply the ensemble mean climate forcing to the two data sets R10 and W01 we use temperature and precipitation differences between 1980–2000 and 2090–2099. The values at each of the 135 locations of the W01 data set are averaged over the 14 regions as defined in Table 1. These mean values are used as forcing for the volume-area model. This procedure is necessary as locations of the GIC are not specified for the R10 data set.

3 Reference experiment and past sea-level contribution

3.1 Reference experiment

A reference experiment is defined for the remainder of this study, using the R10 glacier inventory. The reference V_i in 1990 is calculated using Eq. (1), with $c = 0.2055\,\text{m}^{3-2\gamma}$ and $\gamma = 1.375$, which are the values proposed by R10. This results in a V_i of $1.8122 \times 10^{14}\,\text{m}^3$, or 0.50 m sea-level equivalent (SLE). Note that ice caps are included using $c = 1.7026\,\text{m}^{3-2\gamma}$ and $\gamma = 1.25$. These values are kept constant throughout this study, and variations on model parameters will only be performed on the glacier part, which is by far the largest contribution (90 %). The value of 0.50 m SLE is lower than the original value by R10 (0.60 m SLE), because glaciers around Antarctica are excluded as they are not explicitly located in R10 and only taken into account by a scaling consideration in W01. Using the settings as described in Sect. 2.1, we compute a sea-level contribution for 1990–2090 (δV) of 0.149 ± 0.022 m SLE for the reference experiment.

To compare the results for the two glacier inventories, the total V_i of the W01 data set is tuned such that it equals the total V_i of the reference experiment R10, by varying

the parameter c in Eq. (1). The value found for W01 is $c = 0.144\,\text{m}^{3-2\gamma}$. This value for c is slightly larger than the original value adopted by W01 of $0.12\,\text{m}^{3-2\gamma}$, which would yield a V_i of 0.42 m SLE for all glaciers except the Antarctic region, and 0.5 m SLE including glaciers around Antarctica and Greenland. With a c of $0.144\,\text{m}^{3-2\gamma}$ and all other settings as in the reference experiment, we find for the W01 glacier inventory a δV of 0.176 ± 0.025 m SLE.

Using the two glacier inventories thus leads to a difference of 0.027 m SLE, which is quite large: 18 % difference with respect to the R10 reference inventory. The reason for this difference will be analysed in Sect. 4.4.

3.2 Past sea-level contribution

The model is set up such that a steady state with the prevailing climate is assumed before 1865, after which a temperature perturbation of $0.7\,^{\circ}\text{C}\,100\,\text{yr}^{-1}$ is applied for the period 1865–1990. By imposing this temperature perturbation it is ensured that GIC are not in a steady state in 1990, which is very important for future projections (Z97, Van de Wal and Wild, 2001). The influence of the choice of temperature perturbation will be shown in Sect. 4.3.

For the reference experiment, the 1865–1990 GIC sea-level contribution is 5.7 cm for the R10 data and 6.4 cm for the W01 data. In Fig. 2 the modelled sea-level contributions of R10 and W01 (blue and red line, respectively) are compared to the pentadal mass balance series of Cogley (2009b) (green line) and the estimated GIC contribution of Leclercq et al. (2011) (black line). The latter is a global reconstruction of glacier length records back to 1800 using volume-length scaling (Bahr et al., 1997; Oerlemans et al., 2007). Note that the total area differs between the data sets: Cogley (2009b) and Leclercq et al. (2011) use 785 000 km^2 (including Antarctic glaciers), W01 has a surface area of 597 613 km^2 and R10 is the smallest with 568 709 km^2, as both R10 and W01 exclude Antarctic glaciers.

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The data of Cogley (2009b) are available from 1950 onwards. In Fig. 2 the Cogley data shows pentadal variability, which is not present in W01 and R10 because a uniform temperature increase was applied. The higher variability might also explain the larger increase in mass loss in the Cogley (2009b)-data after 2000, which is not captured by the model. Around 1990, the slopes of R10 and W01 are quite similar to Cogley (2009b), which implies that the imbalance applied in the model in 1990 is similar to the observed imbalance of Cogley.

The model results are also compared to the values of Leclercq et al. (2011), who find a contribution of 7.8 ± 2.2 cm for the period 1865–1990. Our model results fall in their range, but at the lower end. R10 and W01 show a smaller increase for the 1865–1925 period, which is caused by a difference in history, i.e. the imbalance before 1865. The model assumes all glaciers to be in balance with climate before 1865, whereas the Leclercq et al.-data are already in imbalance in 1865 (Leclercq et al., 2011, their Figure 6). Nevertheless, the period after 1925 shows a increase in sea-level contribution similar to our experiments, which indicates that applying the imbalance of $0.7\,^{\circ}\mathrm{C}\,100\,\mathrm{yr}^{-1}$ is appropriate for future calculations starting in 1990.

4 Sensitivity experiments

Five sensitivity experiments are described in this section. First, the model set-up is investigated, by varying some of the model parameters. The two parameters that will be discussed are the mass balance sensitivity (Sect. 4.1) and the scaling constant c in Eq. (1) (Sect. 4.2). Second, the influence of varying the input data is tested, by using several imbalance histories (Sect. 4.3), two glacier data sets (Sect. 4.4), and twelve climate models (Sect. 4.5).

4.1 Mass balance sensitivity

The mass balance sensitivity of a glacier indicates how the mass balance responds to changes in temperature and precipitation. Oerlemans and Fortuin (1992) found that it strongly depends on the amount of precipitation the glacier receives in a year. We therefore use Eqs. (3) and (4) to relate precipitation to mass balance sensitivity, as proposed by Z97. This mass balance sensitivity relation is a parameterisation based on mass balance observations on 12 glaciers described in Oerlemans and Fortuin (1992) and Oerlemans (1994), and has been confirmed by Braithwaite and Raper (2002). However, the mass balance sensitivity may vary between different climate zones, and those 12 glaciers possibly are not representative for the entire distribution of GIC on Earth. Hence, we study the effect of the uncertainty in the mass balance sensitivity.

To test the consequences of variations in the mass balance sensitivity for the future scenarios, we apply a variation of 20 %, which is considered a fair estimate of the uncertainty due to the limited data set used to derive the sensitivity. Additionally, the precipitation used to calculate the mass balance sensitivity is varied with 20 %.

Varying the total mass balance sensitivity with 20 % leads to a deviation of 17 % in the future sea-level contribution. Varying the precipitation rate with 20 % leads to smaller changes, of 12 % in the future δV. Thus, differences in precipitation rate appear to be less important than variations in the mass balance sensitivity itself given a range of variation of 20 %. With respect to the reference experiment, varying the mass balance sensitivity with 20 % leads to an average deviation of 0.026 m SLE.

4.2 Model parameter c

In this second sensitivity experiment, the model parameter c in Eq. (1) is varied within a range of 0.05 to $0.30\,\mathrm{m}^{3-2\gamma}$. This influences not only the 1990–2090 contribution of GIC to sea-level change (δV), but also the initial volume in 1990 (V_{i}), because both are calculated by applying the volume-area relation (Eq. 1) to the glacier data.

The results in terms of V_i and δV for variations in the parameter c are shown in Fig. 3. In this figure, the values obtained for V_i and δV with $c = 0.20\,\mathrm{m}^{3-2\gamma}$ are taken as reference values, and the quantities shown are V_i and δV relative to these reference values for a range of values of c: $\frac{V_i}{V_{i,c=0.20}}$ and $\frac{\delta V}{\delta V_{c=0.20}}$. Figure 3 shows that V_i increases linearly with c, for both the R01 and the W01 data set. However, δV shows a different, less sensitive, response than V_i to an increase in c. If values for c are varied $\pm 0.05\,\mathrm{m}^{3-2\gamma}$ (25 %), V_i changes by 25 %, while δV varies with only 9 % (0.014 m SLE). This means that small deviations in the parameter c will not have a large influence on the modelled contribution of GIC to sea-level change. This is encouraging since c is poorly constrained and may therefore vary between glaciers and regions, which is reflected by the different values that can be found in literature (e.g., Bahr, 1997; Chen and Ohmura, 1990).

The cause of the different response of V_i and δV to variations in c can be explained by the fact that GIC in a changing climate generally do not reach a new equilibrium state in 100 yr time. The time scale for a transition between an initial and final equilibrium state is estimated to be several hundreds of years. Smaller glaciers adjust quicker than larger glaciers, which is illustrated in Fig. 4, where the volume evolution in time for a few size classes is shown. While the smaller size classes reach a new equilibrium before 2100, the larger size classes are still in a transition phase. The same holds for the entire GIC data set: if the initial total volume is larger, it will take longer to reach an equilibrium state.

Figure 4 suggests that the volume evolution in time can be described by an *arccotan* function. This is the case for all glacier size classes separately, but also for the total GIC volume. Hence, the evolution of volume (V) with time (t) can be written as:

$$V_t = \operatorname{arccotan} \frac{t\text{-}D}{E} + \frac{\pi}{2}, \tag{5}$$

where D and E are mathematical constants describing the fit without any specific physical interpretation. Figure 4 implies that E increases for larger V_i. As an example, fits

have been made for the R10 data set of the total modelled volume loss pattern over time for different values of c. The parameters resulting from the fits are shown in Table 3. From the Table it appears that D/E is more or less constant. The derivative of Eq. (5) reads:

$$\frac{\delta V}{\delta t} = \frac{1}{1 + t_*^2} \tag{6}$$

with t_* being $(t\text{-}D)/E$. As E ranges from 200 to 270, this implies that for the first 200 yr differences in the volume loss over time are small. So if c is varied with ±25 %, the δV between 125 and 225 yr varies with only 10 %. This implies that within the time frame considered in this study the precise value of c is not that important.

Radić et al. (2007) performed a sensitivity study on the other parameter in Eq. (1), γ. They concluded that V_i is also very sensitive to the choice of the scaling exponent γ, and that δV is fairly insensitive.

4.3 Imbalance in 1990

Throughout this study, the 1990 imbalance of the GIC is simulated by imposing a temperature change of 0.7 °C 100 yr^{-1} for the period 1865–1990, which is in line with the IPCC AR4 estimate (see Table 3.2 in Trenberth et al., 2007). However, in this section we will impose a range of different options for the imbalance on the R10 data to quantify their influence on the future sea-level change.

The first option we explore is the GIC contribution without an imbalance effect. This means that the glacier model starts its calculations in 1990, which clearly influences the resulting contribution (Fig. 5, light blue line) with a difference as large as 30 % from the reference experiment (0.7 °C 100 yr^{-1}, green dashed line). However, it is not very realistic to assume that GIC are currently in balance with climate, and this option shows how important it is to include an imbalance, as it has a large influence on the future sea-level contribution.

As a second test, the rate of temperature change for 1865–1990 is varied: 0.6 °C 100 yr^{-1} (Fig. 5, magenta line) and 0.8 °C 100 yr^{-1} (black line). For the sea-level contribution before 1990 this results in a deviation of about 1 cm from the reference in 1865. However, looking at the future sea-level contribution, the differences are in the order of 0.5 cm, which is about 4 %. This indicates that the exact value of the rate of temperature change is not a large source of uncertainty, as long as the value chosen is close to the observations.

Another factor that influences the volume change is the precipitation. Increasing the initial precipitation amount in 1990 leads to a larger contribution from the GIC to sea-level change, because the mass-balance sensitivity highly depends on the precipitation and will consequently increase. This makes GIC more sensitive to temperature changes. An increase of 10 % in the precipitation in 1990 combined with a temperature change of 0.6 °C 100 yr^{-1} for the imbalance leads to a similar sea-level contribution in 2100 as a temperature increase of 0.7 °C 100 yr^{-1}. The same holds for a temperature change of 0.8 °C 100 yr^{-1} combined with a precipitation decrease of 10 %.

To test the influence of regional variations, we now prescribe a temperature change for each region separately, similar to the way the future climate changes are used for the 1990–2090 period (see Sect. 2.3). We test two options: for the first we use a compilation of historical temperatures from Z97 (Fig. 5, dark blue line); for the second we take the regional temperatures from the 20th century climate model runs 20C3M (Fig. 5, red line). Figure 5 shows that for the 1990–2090 contribution the Z97-data are very close to the 0.7 °C 100 yr^{-1} option and the 20C3M-data result in a slightly smaller contribution. For the 1865–1990 contribution, the difference is larger, 1 cm for Z97 and 2 cm for the climate models. This indicates that taking regional values for the temperature change over the past, despite having influence on the past contribution, does not have a large impact on the future contribution.

As can be seen in Fig. 5, the different options for the imbalance show larger deviations in the past volume change than in the future contribution. The past contribution is a spin-up period, which starts with all glaciers in balance with climate. Depending

on the prescribed climate, the glaciers are brought in imbalance with climate, leading to relatively large deviations from the reference run. For the future contribution however, the climate is the same, the only difference is the initial imbalance in 1990. It appears that this leads to differences in the past being more pronounced than in the future contribution.

We find that if an imbalance is included (all options except "no imbalance"), the average deviation in the future contribution is 0.009 m SLE, provided that the temperature increase between 1865 and 1990 is around 0.7 °C 100 yr^{-1}.

4.4 Choice of inventory

In this section we consider the importance of the geometrical input to the model and its influence on the resulting sea-level contribution (δV). We compare the two glacier data sets using the reference experiment settings as defined in Sect. 3.1. As mentioned before, the initial area per region (Fig. 1) is quite similar for both glacier inventories. Furthermore, since the experiment considered here is the reference experiment, also V_i is similar. However, V_i is not divided equally over the different regions. In Fig. 6 it can be seen that there are substantial differences between the two data sets. In Central Asia, South America and Greenland the regional V_i in R10 is smaller than the V_i in W01, while the opposite is true for Canada, Alaska and Franz Jozef.

To establish the cause of these differences, we focus on Arctic Canada and Central Asia. Arctic Canada occupies 25 % of the initial area in both data sets, but the V_i differs substantially (10 % more in R10). Figure 7a shows how the total area is divided over the size bins: the largest W01 size bin ($> 2^9$ km^2) contains most of the W01 area, where the R10 size bins (until $> 2^{14}$ km^2) allow for a more precise classification of these larger GIC. To calculate the volume according to the volume-area relation, the average area in the size bins is used. As the volume-area relation gives an exponential increase in volume for an increasing area, this means that the larger size bins of R10 result in a larger volume, explaining the different V_i for this region. As a second example, the size bins for Central Asia are shown in Fig. 7b. In this case, W01 classifies more GIC into the largest size bin than R10, which leads to a higher V_i for the W01 data. Hence, differences in V_i per region are often caused by differences in the classification of GIC in size bins. These classification differences are not only the result of the increased amount of glaciers in the R10 data set, but also due to the division of large ice bodies into smaller glaciers.

The R10 reference experiment yields a δV for 1990–2090 of 0.149 ± 0.022 m SLE, and W01 0.176 ± 0.025 m SLE, which is a difference of 0.027 m SLE. The uncertainty represents one σ uncertainty among the 12 climate model ensemble members, and will be further discussed in the next section (Sect. 4.5). Figure 8 shows the ensemble mean relative δV per region for both data sets, including the ensemble standard deviation. The larger differences (>1 %) between the two data sets are in regions with significant contributions; Arctic Canada, Alaska, Svalbard, Franz Jozef, Central Asia, South America and Greenland. So, although the V_i is the same, the regional contributions of V_i and δV differ significantly. This is important when local sea-level change is the key interest rather than the global average sea-level change.

The relative values (Figs. 6 and 8) show how the mass change is divided over the regions, but not how this relates to the V_i per region. Therefore, in Fig. 9 V_i and δV (1990–2090) are presented in m SLE per region. This immediately shows the largest glaciated regions and the regions with the highest mass loss. The V_i of R10 is clearly larger in Arctic Canada, Alaska, Iceland, Svalbard and Franz Jozef, while W01 shows larger values in Central Asia, South America and Greenland. The total δV is larger for the W01 data, which is mainly caused by a difference in the amount of melt in Central Asia, South America and Greenland. This can again be explained by the way GIC are classified into size classes in the two inventories.

For each of the two data sets, the sea-level change pattern resulting from the ice mass changes is computed with a sea-level model (Schotman, 2008). This model calculates a gravitationally consistent field of sea-level change while accounting for rotational processes. For more information on the model, the reader is referred to

Slangen et al. (2011). In Fig. 10a the sea-level change is shown relative to the global mean sea-level change for R10. Thus, the percentage presented is $\frac{\delta V_{\text{local}}}{\delta V_{\text{global mean}}} \cdot 100\,\%$.

In the figure, values below zero imply a sea-level drop, values between 0 and 100 % imply a sea-level rise below the R10 global average, and values above 100 % indicate a sea-level rise larger than the global average. The figure shows that the Southern Hemisphere will experience a sea-level rise, while the Arctic region will experience a sea-level drop from the contribution of GIC. This is because most glaciers are situated around the Arctic, and where the largest decrease in ice mass will be. Melt in the Arctic leads to a sea-level drop in the Northern Hemisphere and sea-level rise above the global average in the Southern Hemisphere. Differences further inland, such as in Central Asia, only have a minor effect.

In Fig. 10b the differences in the sea-level change pattern between R10 and W01 are shown in percentages. A positive value indicates that R10 has a larger relative contribution, while a negative value implies a larger relative contribution for W01. Locations with large differences are for instance India, South America, Greenland, Alaska and Franz Jozef. Thus, the largest differences in sea-level pattern can be found close to the large melt sources, such as in the Arctic Ocean or the tip of South America. This is a consequence of the non-linear pattern of the gravitational adjustment with a strong response close to the source of mass change and a gradual transition in the far field. Consequently, further away from the melting ice the patterns of R10 and W01 are very similar.

4.5 Choice of climate model

The ensemble mean sea-level change (1990–2090) calculated for the reference experiment is 0.149 ± 0.022 m SLE for R10 and 0.176 ± 0.025 m SLE for W01. These uncertainties are based on the spread in the climate models used for the calculations (Sect. 2.3). In this section we consider the δV for the twelve climate models individually. In Fig. 11, δV is shown for each climate model and both glacier inventories separately.

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The dashed line indicates the ensemble mean value of each data set. The figure shows that there are large differences among the climate models, yielding values in the range of 12 to 22 cm SLE volume loss. These differences are caused by variations in temperature and precipitation patterns of the climate models. All models consistently present larger contributions for the W01 data set than for R10, due to differences in the classification of the GIC in size bins. The difference between the highest and the lowest climate model is 0.065 m (R10) and 0.079 m (W01), the maximum deviation from the ensemble mean is 0.034 m (R10) and 0.042 m (W01). The average deviation from the ensemble mean for both data sets combined is 0.018 m. Clearly, the choice of climate model has a significant impact on the resulting GIC contribution. It is therefore important to use a large ensemble and not to rely on a single climate model as long as we cannot prove one to be superior to the others.

5 Conclusions

This study examined sources of uncertainty in the computation of the future sea-level contribution of melting GIC with a volume-area model. Five sources of uncertainty were examined, being the volume-area parameter c, the mass balance sensitivity, the initial imbalance of glaciers with climate, the glacier inventory and the climate model. Of these five, two are model parameters and the other three are model input. The results of the sensitivity studies are summarised in Table 4, which shows the applied variations and the resulting ensemble mean deviations from the reference experiment for global δV.

In Sect. 4.1, the mass balance sensitivity was varied with 20 %, which led to a variation of 17 % or 0.026 m SLE in the contribution to sea-level change. This means that variations in mass balance sensitivity have a notable effect on the contribution. Thus, if the applied sensitivity is not representative for a global approach, it will introduce a significant error in the calculated sea-level contribution.

The influence of changes in parameter c was examined in Sect. 4.2. It appeared that small variations in c cause significant variations in the V_i in 1990 (25 %), but only limited changes in the future contribution to sea-level change. For a range of $\pm 0.05\,\mathrm{m}^{3-2\gamma}$, δV varied with only 9 % or 0.014 m. The remarkable difference in sensitivity between V_i and δV can be explained by considering the time scale of interest (100 yr) and the response time of a glacier to a changing climate.

As glaciers are currently not in balance with climate, a temperature history has to be prescribed, for which several options were explored in Sect. 4.3. It appeared that it is important to include an imbalance, as excluding it leads to a systematic underestimation of the future sea-level contribution. The various options for a temperature history for the period 1865–1990 did not result in large deviations; the average difference is only 0.009 m SLE for the future contribution.

If the two glacier inventories sets are tuned such that the V_i is the same, the δV over 100 yr differs by 0.027 m. An important difference between the two data sets is the way the area is divided into size bins, which leads to differences in the contribution of some regions. As R10 has a more complete inventory in for instance Central Asia and Greenland, where differences between W01 and R10 are the largest, R10 probably gives a better indication of the GIC contribution than the older W01 data. The differences between these data sets indicate that it is very important to obtain information on the missing glaciers in the glacier inventories, especially in underrepresented but largely glaciated areas, such as Alaska, Arctic Canada and Antarctica.

Despite the differences in global mean values and among the different regions, we found that for the majority of the ocean surface there are only minor differences in the sea-level change patterns between the two glacier inventories (Fig. 10b). The largest differences in the pattern occur close to the melt areas, such as in the Arctic region. Further away from the GIC, the sea-level change is above the global average due to the self-gravitation effect, and differences between results obtained with the two inventories are small.

Section 4.5 and Table 4 show that the choice of global climate model can lead to large differences. It is best to use an ensemble where possible, as this will reduce the influence of outliers in the climate models. Another way to reduce the uncertainty due to climate models would be to use a smaller grid, such that smaller glacierised areas will be better represented in the climate model, because currently the grid size of the climate model is often larger than the size of the glacierised area (Randall et al., 2007). Additionally, glaciers are found in mountainous areas, which are poorly resolved by climate models. Therefore, the climate model yields a temperature and precipitation change that is possibly not representative for the glacierised area. Improving the climate models will significantly reduce the uncertainty in calculating the GIC contributions and is therefore a crucial action for the future.

It should be noted that this uncertainty assessment holds only for the assumption of climate change following the A1B scenario. Depending on socio-economic developments in the next century, the actual climate might be warmer of cooler, which of course also influences the amount of GIC melt and thus their sea-level contribution. Using the same glacier model and data, Slangen et al. (2011) found that the sea-level contribution for the A1B scenario differed 0.03 m and 0.02 m from respectively the B1 and A2 scenario.

An example of an uncertainty that could not be accounted for is the response of calving glaciers and tide-water glaciers to a warming climate. As indicated by Radić and Hock (2011) and references therein, the scarcity of estimates and complexity of the mechanisms do not allow for a good estimate of the contribution of these glaciers on a global scale. Therefore, the uncertainties presented here only concern the contribution to sea-level change as a response to surface mass balance changes.

Combining the uncertainties obtained with the sensitivity experiments in this study, we arrive at a total uncertainty of 4.5 cm on a contribution of 14.9 cm when using the volume-area approach, which is 30 %. The sea-level rise estimates of Meehl et al. (2007b); Meier et al. (2007); Pfeffer et al. (2008); Radić and Hock (2011), mentioned in the introduction, all fall at least partly within this range. The Meehl

et al. (2007b) estimate is slightly lower than our contribution, which might be caused by our initial GIC volume estimate being higher than their highest volume estimate: 0.50 m SLE vs. 0.37 m SLE. Radić and Hock (2011) use the same data set as in this study (R10), but find a lower contribution while they include Antarctica. They perform a different evaluation of the volume changes, because instead of grouping the glaciers into 14 regions, each glacier is modelled separately. Also, they use a volume-area-length approach instead of volume-area scaling. The difference between their result and this study is therefore also an illustration of the uncertainty for using different methods. However, the main uncertainties in their method are the same as those described in this study: a mass balance sensitivity based on few glaciers, an incomplete glacier database and the use of global climate models. These points should therefore be the focal points when aiming at improving the estimate of GIC contribution to sea-level change.

Acknowledgements. We would like to thank P. Leclercq for helpful discussions and R. Giesen for commenting on an earlier version of the manuscript. We also thank NSIDC and WGMS, V. Radic and J. Cogley for collecting, archiving and providing the glacier inventories. We acknowledge the international modeling groups for providing their data for analysis, the Program for Climate Model Diagnosis and Intercomparison (PCMDI) for collecting and archiving the model data, the JSC/CLIVAR Working Group on Coupled Modelling (WGCM) and their Coupled Model Intercomparison Project (CMIP) and Climate Simulation Panel for organizing the model data analysis activity, and the IPCC WG1 TSU for technical support. A. S. is supported by the Netherlands Institute for Space Research (SRON) (ALW-GO-AO/07-14).

References

Bahr, D. B.: Global distributions of glacier properties: A stochastic scaling paradigm, Water Resour. Res., 33, 1669–1679, doi:10.1029/97WR00824, 1997. 1667

Bahr, D. B., Meier, M. F., and Peckham, S. D.: The physical basis of glacier volume-area scaling, J. Geophys. Res., 102, 20355–20362, 1997. 1657, 1658, 1659, 1664

Bindoff, N. L., Willebrand, J., Artale, V., Cazenave, A., Gregory, J., Gulev, S., Hanawa, K., Quéré, C. L., Levitus, S., Nojiri, Y., Shum, C. K., Talley, L. D., and Unnikrishnan, A. (Eds.): Observations: oceanic climate change and sea level, in: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., and Miller, H. L., Cambridge University Press, Cambridge, UK and New York, NY, USA, 2007. 1657

Braithwaite, R. J. and Raper, S. C. B.: Glaciers and their contribution to sea level change, Phys. Chem. Earth, 27, 1445–1454, 2002. 1666

Chen, J. and Ohmura, A.: Estimation of Alpine glacier water resources and their change since the 1870's, IAHS, 193, 127–135, 1990. 1659, 1667

Cogley, J. G.: A more complete version of the World Glacier Inventory, Ann. Glaciol., 50, 32–38, 2009a. 1661

Cogley, J. G.: Geodetic and direct mass-balance measurements: comparison and joint analysis, Ann Glaciol, 50, 96–100, 2009b. 1664, 1665

Delworth, T. L., Broccoli, A. J., Rosati, A., Stouffer, R. J., Balaji, V., Beesley, J. A., Cooke, W. F., Dixon, K. W., Dunne, J., Dunne, K. A., Durachta, J. W., Findell, K. L., Ginoux, P., Gnanadesikan, A., Gordon, C. T., Griffies, S. M., Gudgel, R., Harrison, M. J., Held, I. M., Hemler, R. S., Horowitz, L. W., Klein, S. A., Knutson, T. R., Kushner, P. J., Langenhorst, A. R., Lee, H.-C., Lin, S.-J., Lu, J., Malyshev, S. L., Milly, P. C. D., Ramaswamy, V., Russell, J., Schwarzkopf, M. D., Shevliakova, E., Sirutis, J. J., Spelman, M. J., Stern, W. F., Winton, M., Wittenberg, A. T., Wyman, B., Zeng, F., and Zhang, R.: GFDL's CM2 Global Coupled Climate Models. Part I: formulation and simulation characteristics, J. Climate, 19, 643–674, 2006. 1682

Flato, G. M.: The third generation coupled global climate model (CGCM3), available at: http://www.cccma.ec.gc.ca/models/cgcm3.shtml, 2005. 1682

Furevik, T., Bentsen, M., Drange, H., Kvamsto, N., and Sorteberg, A.: Description and evaluation of the Bergen climate model: ARPEGE coupled with MICOM, Clim. Dynam., 21, 27–51, 2003. 1682

Gordon, C., Cooper, C., Senior, C. A., Banks, H. T., Gregory, J. M., Johns, T. C., Mitchell, J. F. B., and Wood, R. A.: The simulation of SST, sea ice extents and ocean heat transports in a version of the Hadley Centre coupled model without flux adjustments, Clim. Dynam., 16, 147–168, 2000. 1682

Gregory, J. M. and Oerlemans, J.: Simulated future sea-level rise due to glacier melt based on regionally and seasonally resolved temperature changes, Nature, 391, 474–476, 1998. 1657

Jungclaus, J. H., Keenlyside, N., Botzet, M., Haak, H., Luo, J. J., Latif, M., Marotzke, J., Mikolajewicz, U., and Roeckner, E.: Ocean circulation and tropical variability in the coupled model ECHAM5/MPI-OM, J. Climate, 19, 3952–3972, 2006. 1682

K-1 model developers: K-1 coupled model (MIROC) description, Tech. rep. 1, Center for Climate System Research, University of Tokyo, 2004. 1682

Leclercq, P. W., Oerlemans, J., and Cogley, J. G.: Estimating the glacier contribution to sea-level rise over the past 200 years, Surveys in Geophysics, doi:10.1007/s10712-011-9121-7, in press, 2011. 1657, 1664, 1665

Lucarini, L. and Russell, G. L.: Comparison of mean climate trends in the northern hemisphere between National Centers for Environmental Prediction and two atmosphere-ocean model forced runs, J. Geophys. Res., 107(D15), 4269, doi:10.1029/2001JD001247, 2002. 1682

Meehl, G. A., Covey, C., Delworth, T., Latif, M., McAvaney, B., Mitchell, J. F. B., Stouffer, R. J., and Taylor, K. E.: The WCRP CMIP3 multi-model dataset: A new era in climate change research, B. Am. Meteorol. Soc., 88, 1383–1394, 2007a. 1660, 1662

Meehl, G. A., Stocker, T. F., Collins, W. D., Friedlingstein, P., Gaye, A., Gregory, J., Kitoh, A., Knutti, R., Murphy, J., Noda, A., Raper, S., Watterson, I., Weaver, A., and Zhao, Z.-C.: Global climate projections, in: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., and Miller, H. L., Cambridge University Press, Cambridge, UK and New York, NY, USA, 2007b. 1657, 1662, 1675

Meier, M. F., Dyurgerov, M. B., Rick, U. K., O'Neel, S., Pfeffer, W. T., Anderson, R. S., Anderson, S. P., and Glazovsky, A. F.: Glaciers dominate eustatic sea-level rise in the 21st century, Science, 317, 1064–1067, 2007. 1658, 1675

Nakicenovic, N. and Swart, R. (Eds.): Emission scenarios, Cambridge University Press, Cambridge, UK, 2000. 1662

National Snow and Ice Data Center: World glacier inventory, World Glacier Monitoring Service and National Snow and Ice Data Center/World Data Center for Glaciology, Boulder, CO, 1999, updated 2009. 1661

Oerlemans, J.: Modelling of glacier mass balance, in: Ice in the climate system, Nato ASI Ser. I 12, 1993. 1661

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Oerlemans, J.: Quantifying global warming from the retreat of glaciers, Science, 264, 243–245, 1994. 1666
Oerlemans, J. and Fortuin, J. P. F.: Sensitivity of glaciers and small ice caps to greenhouse warming, Science, 258, 115–117, 1992. 1666
Oerlemans, J. and Reichert, B. K.: Relating glacier mass balance to meteorological data by using a seasonal sensitivity characteristic, J. Glaciol., 46, 1–6, doi:10.3189/172756500781833269, 2000. 1657
Oerlemans, J., Dyurgerov, M., and van de Wal, R. S. W.: Reconstructing the glacier contribution to sea-level rise back to 1850, The Cryosphere, 1, 59–65, doi:10.5194/tc-1-59-2007, 2007. 1657, 1664
Pfeffer, W. T., Harper, J. T., and O'Neel, S.: Kinematic constraints on glacier contributions to 21st-century sea-level rise, Science, 321, 1340–1343, doi:10.1126/science.1159099, 2008. 1658, 1675
Radić, V. and Hock, R.: Regional and global volumes of glaciers derived from statistical upscaling of glacier inventory data, J. Geophys. Res., 115, F01010, doi:10.1029/2009JF001373, 2010. 1659, 1661
Radić, V. and Hock, R.: Regionally differentiated contribution of mountain glaciers and ice caps to future sea-level rise, Nat. Geosci., 4, 91–94, doi:10.1038/NGEO1052, 2011. 1657, 1658, 1675, 1676
Radić, V., Hock, R., and Oerlemans, J.: Volume-area scaling vs flowline modelling in glacier volume projections, Ann. Glaciol., 46, 234–240, 2007. 1668
Randall, D. A., Wood, R. A., Bony, S., Colman, R., Fichefet, T., Fyfe, J., Kattsov, V., Pitman, A., Shukla, J., Srinivasan, J., Stouffer, R. J., Sumi, A., and Taylor, K. E.: Climate models and their evaluation, in: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., and Miller, H. L., Cambridge University Press, Cambridge, UK and New York, NY, USA, 2007. 1675
Raper, S. C. B. and Braithwaite, R. J.: Low sea level rise projections from mountain glaciers and icecaps under global warming, Nature, 439, 311–313, 2006. 1657
Schmidt, G. A., Ruedy, R., Hansen, J. E., Aleinov, I., Bell, N., Bauer, M., Bauer, S., Cairns, B., Canuto, V., Cheng, Y., Del Genio, A., Faluvegi, G., Friend, A. D., Hall, T. M., Hu, Y., Kelley, M., Kiang, N. Y., Koch, D., Lacis, A. A., Lerner, J., Lo, K. K., Miller, R. L., Nazarenko, L., Oinas, V.,

Perlwitz, J., Rind, D., Romanou, A., Russell, G. L., Sato, M., Shindell, D. T., Stone, P. H., Sun, S., Tausnev, N., Thresher, D., and Yao, M. S.: Present day atmospheric simulations using GISS ModelE: Comparison to in-situ, satellite and reanalysis data, J. Climate, 19, 153–192, 2006. 1682
Schotman, H. H. A.: Shallow-Earth rheology from glacial isostasy and satellite gravity, Ph.D. thesis, TU Delft, 2008. 1671
Slangen, A. B. A., Katsman, C. A., van de Wal, R. S. W., Vermeersen, L. L. A., and Riva, R. E. M.: Towards regional projections of twenty-first century sea-level change based on IPCC SRES scenarios, Clim. Dynam., doi:10.1007/s00382-011-1057-6, in press, 2011. 1658, 1662, 1672, 1675
Trenberth, K. E., Jones, P., Ambenje, P., Bojariu, R., Easterling, D., Tank, A. K., Parker, D., Rahimzadeh, F., Renwick, J., Rusticucci, M., Soden, B., and Zhai, P.: Observations: surface and atmospheric climate change, in: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., and Miller, H. L., Cambridge University Press, Cambridge, UK and New York, NY, USA, 2007. 1661, 1668
Van de Wal, R. S. W. and Wild, M.: Modelling the response of glaciers to climate change by applying volume-area scaling in combination with a high resolution GCM, Clim. Dynam., 18, 359–366, 2001. 1657, 1658, 1659, 1661, 1664
Washington, W. M., Weatherly, J. W., Meehl, G. A., Semtner Jr., A. J., Bettge, T., Craig, A., Strand Jr., W., Arblaster, J., Wayland, V., James, R., and Zhang, Y.: Parallel climate model (PCM) control and transient simulations, Clim. Dynam., 16, 755–774, 2000. 1682
Yukimoto, S. and Noda, A.: Improvements of the Meteorological Research Institute Global Ocean-atmosphere Coupled GCM (MRI-CGCM2) and its climate sensitivity, Tech. rep. 10, NIES, Japan, 2002. 1682
Zuo, Z. and Oerlemans, J.: Contribution of glacier melt to sea-level rise since AD 1865: a regionally differentiated calculation, Clim. Dynam., 13, 835–845, 1997. 1660

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Table 1. Regions and initial volume in 1990 (km^3) used in this study.

This study	Region name (R10)	Volume (km^3)	Region name, number (W01)	Volume (km^3)
1 Arctic Canada	Arctic Canada	81 943	North Canada, 1–6	63 149
2 Alaska	Alaska/W. Canada/W. US	30 519	Alaska/Rocky Mountains, 7–30	21 802
3 Iceland	Iceland	4558	Iceland, 53–57	2191
4 Svalbard	Svalbard	10 199	Svalbard, 58	6995
5 Scandinavia	Scandinavia	222	Scandinavia, 62–63	155
6 Franz Jozef	Franz Joz./N. Zemlya/S. Zemlya	17 658	Franz Jozef, 59–61	11 134
7 East Russia	North and East Asia	168	East Russia, 88–93	351
8 Central Europe	Central Europe	192	Central Europe, 64–65	130
9 South Russia	Caucasus	88	South Russia, 66–69	374
10 Central Asia	High Mountain Asia	12 536	Central Asia, 70–87	24 514
11 South America	South America I/II	7570	South America, 31–52	14 873
12 Africa	–	0	South Africa, 94–96	0.2
13 New Zealand	New Zealand	82	New Zealand, 98–100	219
14 Greenland	Greenland	16 099	Greenland, 101–135	36 398

Table 2. CMIP3-Models used in this study.

Model name	Reference
BCCR-BCM2.0	Furevik et al. (2003)
CGCM3.1(T47)	Flato (2005)
ECHAM5/MPI-OM	Jungclaus et al. (2006)
GFDL-CM2.0	Delworth et al. (2006)
GFDL-CM2.1	Delworth et al. (2006)
GISS-EH	Schmidt et al. (2006)
GISS-ER	Schmidt et al. (2006)
GISS-AOM	Lucarini and Russell (2002)
MRI-CGCM2.3.2	Yukimoto and Noda (2002)
MIROC3.2(hires)	K-1 model developers (2004)
NCAR-PCM	Washington et al. (2000)
UKMO-HadCM3	Gordon et al. (2000)

Table 3. Results of fits on the evolution of V (Eq. 5) for 3 values of c (Eq. 1), using the R10 data. $V_{t=0\,\mathrm{yr}}$ represents the 1865 volume, $V_{t=125\,\mathrm{yr}}$ the 1990 volume, $V_{t=225\,\mathrm{yr}}$ the 2090 volume. Sea-level equivalent (SLE) is calculated assuming an ocean area of $3.62 \times 10^8\,\mathrm{km}^2$.

	Small V_i $c = 0.1$	Medium V_i $c = 0.15$	Large V_i $c = 0.2$
$V_{t=0\,\mathrm{yr}}$ (SLE m)	0.33	0.44	0.54
$V_{t=0\,\mathrm{yr}}$ ($10^5\,\mathrm{km}^3$)	1.22	1.58	1.97
$V_{t=125\,\mathrm{yr}}$ ($10^5\,\mathrm{km}^3$)	0.99	1.39	1.78
$V_{t=225\,\mathrm{yr}}$ ($10^5\,\mathrm{km}^3$)	0.61	0.95	1.30
D (yr)	338	402	454
E (yr)	204	240	270
D/E	1.66	1.68	1.68
Volume loss ($10^5\,\mathrm{km}^3$)	0.38	0.44	0.48

Table 4. Summary of the differences in δV found with the sensitivity studies.

Sensitivity test	Section	Variation	Difference
Mass balance sensitivity	4.1	±20 %	0.026
Model parameter c	4.2	±25 %	0.014
Imbalance 1865–1990	4.3	5 options	0.009
Choice of inventory	4.4	2 datasets	0.027
Choice of climate model	4.5	12 models	0.018
Total uncertainty			0.045

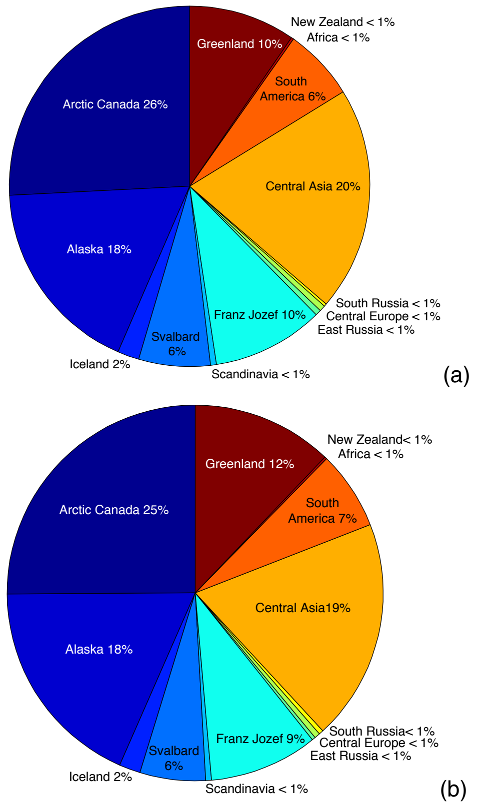

Fig. 1. Initial GIC area divided over 14 regions **(a)** R10 **(b)** W01.

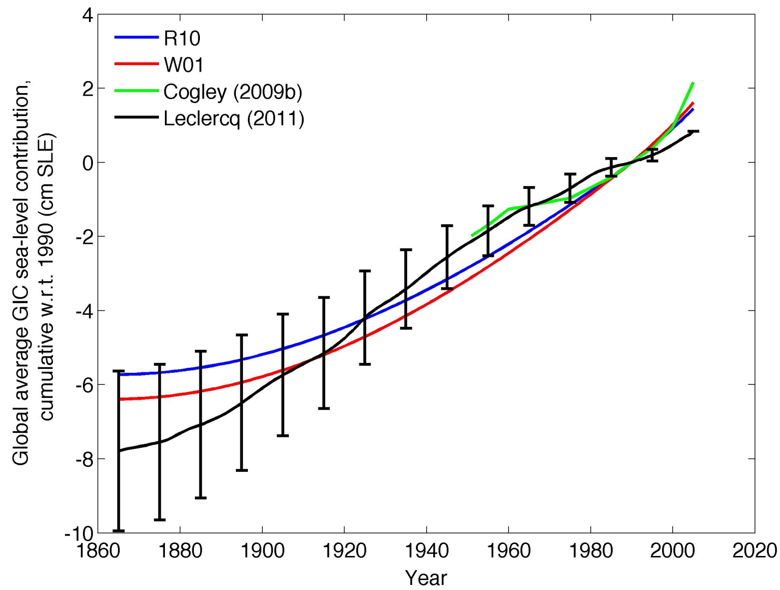

Fig. 2. Glacier sea-level contribution 1865–2005 (cm SLE) relative to 1990.

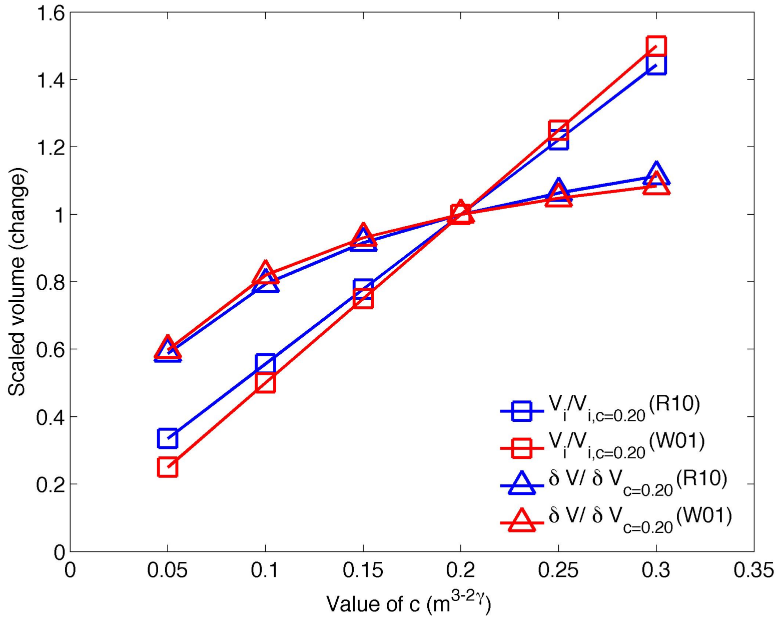

Fig. 3. Initial glacier volume (V_i) relative to $V_{i,c=0.20}$, and 1990–2090 volume change (δV) relative to $\delta V_{c=0.20}$.

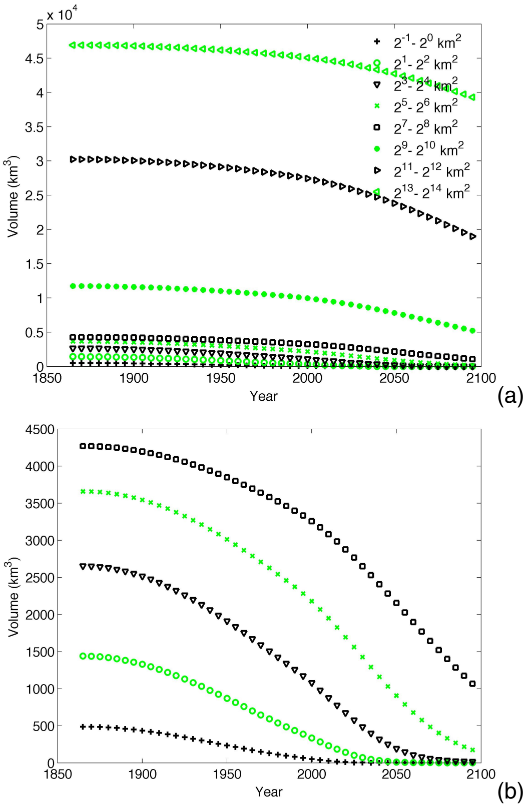

Fig. 4. Volume evolution (km^3) over time for **(a)** every second size class for reference experiment R10 and **(b)** close-up of the smallest 5 size classes in **(a)**.

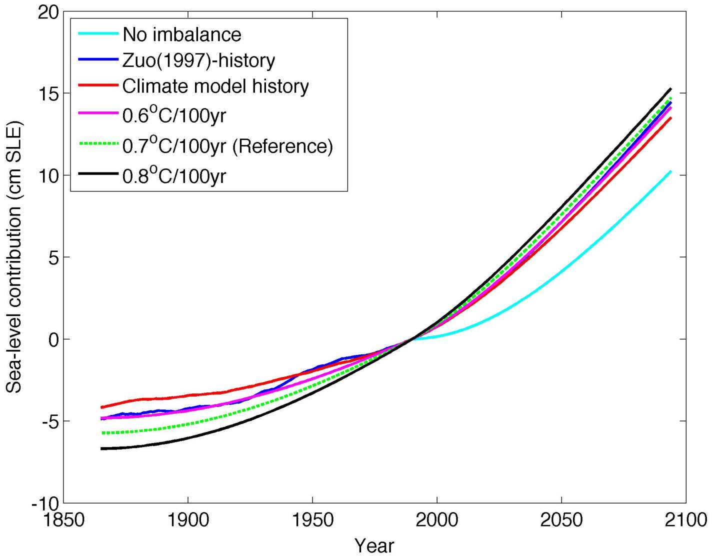

Fig. 5. Glacier sea-level contribution 1865–2090 (cm SLE) for different imbalance options, R10 glacier inventory.

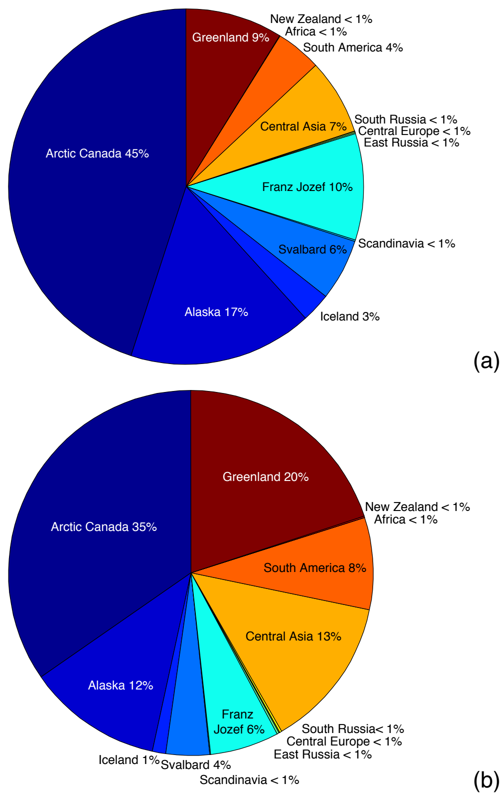

Fig. 6. Initial volume per region relative to $V_{i,t=1990}$ ($V_{i,R10} = V_{i,W01}$) **(a)** R10 **(b)** W01.

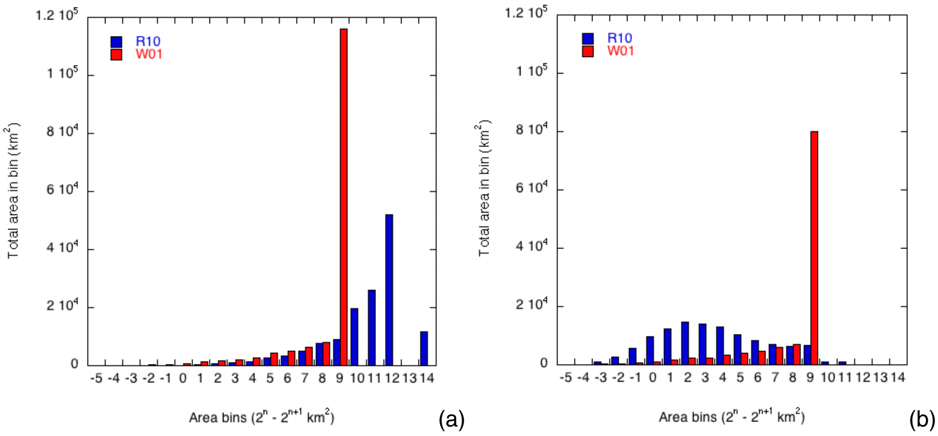

Fig. 7. Initial (1990) area (km^2) per size bin for **(a)** Arctic Canada and **(b)** Central Asia. R10 uses size bins −3 (all GIC with area $< 2^{-2}$ km^2) to 14 ($> 2^{14}$ km^2), W01 uses size bins −5 ($< 2^{-4}$ km^2) to 9 ($> 2^9$ km^2).

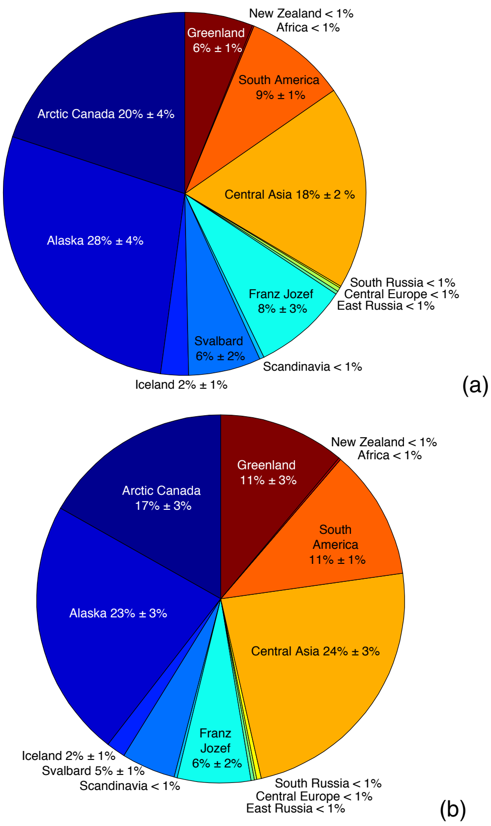

Fig. 8. Volume change $\pm 1\sigma$ per region relative to δV **(a)** R10 **(b)** W01.

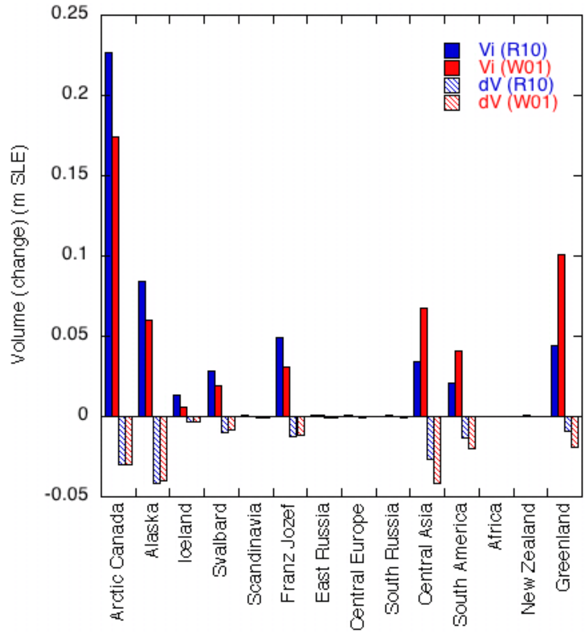

Fig. 9. Glacier initial volume (V_i) and volume change (δV) per region (m SLE).

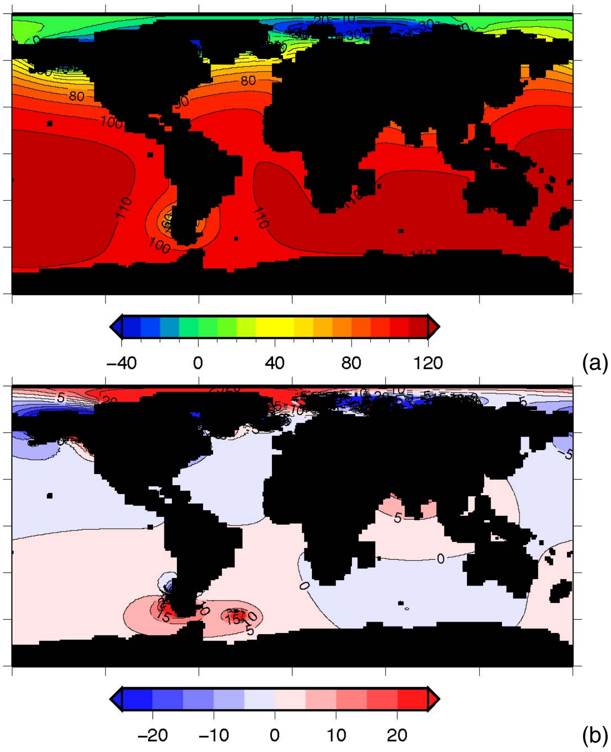

Fig. 10. **(a)** Local sea-level change (1990–2090) relative to the ensemble global mean sea-level change (%) (R10, global average 0.149 m). **(b)** Difference in relative sea-level change (%) (R10–W01).

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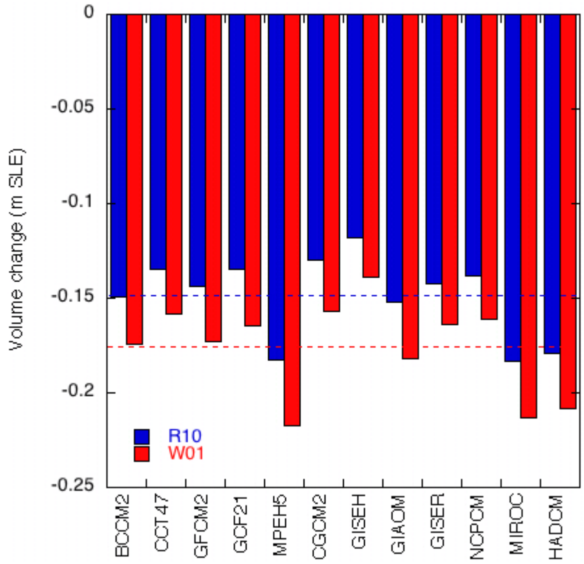

Fig. 11. Glacier volume change (1990–2090) per climate model (m SLE). Dashed lines represent ensemble mean volume change per data set.