Modeling of Future Sea Level Rise Through Melting Glaciers

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ABSTRACT

The aim of this paper is to project 21st century volume changes of all mountain glacier and ice caps and to provide systematic analysis of uncertainties originating from different sources in the and their contribution to sea level rise and the assessment of uncertainties. Trends in global climate warming and sea level rise are observed during the last 100-years which both, according to global climate models, will continue in the future Intergovernmental Panel on Climate Change (IPCC) State-of-threat knowledge on climate, ocean and land processes identifies melting mountain glaciers and ice caps, after ocean thermal expansion, as the currently second major contributor to sea level rise. However, both the observations and models on sea level changes carry a variety of uncertainties. In this section, by following the question-answer concept, I will briefly present the importance of global sea level change for society, the current state of knowledge of sea level changes in response to climate change and the attempts to project future sea level changes until 2100 including discussion on related uncertainties.

Melting mountain glaciers and ice caps (MG&IC) are the second largest contributor to rising sea level after thermal expansion of the oceans and are likely to remain the dominant glaciological contributor to rising sea level in the 21st century. The aim of this work is to project 21st century volume changes of all MG&IC and to provide systematic analysis of uncertainties originating from different sources in the calculation. I provide an ensemble of 21st century volume rojections for all MG&IC from the World Glacier Inventory by modeling the surface mass balance coupled with volume-area-length scaling and forced with temperature and precipitation scenarios from four Global Climate Models (GCMs). By upscaling the volume projections through a regionally differentiated approach to all MG&IC outside Greenland and Antarctica (514,380 km2) I stimated total volume loss for the time period 2001-2100 to range from 0.039 to 0.150 m sea level equivalent. While three GCMs agree that Alaskan glaciers are the main contributors to the projected sea level rise, one GCM projected the largest total volume loss mainly due to Arctic MG&IC.

Keywords : *Global Climate Model, Melting mountain glaciers and ice caps (MG&IC) etc.*

1. INTRODUCTION

Modeling future glacier volume changes on a global scale contains a cascade of uncertainties starting from assumptions on initial glacier area and volume, simulation of glacier mass balance and ice dynamics, and projecting local climatic scenarios. To date about 37% of the estimated total glacier area is inventoried and made available through the World Glacier Monitoring Service (WGMS) and National Snow and Ice Data Center (NSIDC). The estimates on total volume of 30 glaciers and mountain ice caps (MG&IC) are derived from assumed regional glacier size distributions based on percolation theory [1] and a scaling relationship between individual glacier volume and area [2]. Volume-area scaling implies that the volume of a mountain glacier in a steady state is proportional to its area. Although the relationship has

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strong physical basis [3] the constant of proportionality in the volume-area power law has originally been derived from approximately 100 glaciers [4] and then applied globally. This constant contributes to a large uncertainty in projected volume changes for each individual glacier and in assessments of global volume changes [5]. The lack of complete glacier inventory and disagreements on estimates of total MG&IC areas make the estimates on total volumes to differ considerably. *IPCC* [2007] reported that the potential sea level equivalent of all MG&IC, excluding those surrounding Greenland and Antarctic ice sheets, is in the range from 0.15 m and 0.37 m. Including the MG&IC that surround the ice sheets the potential SLE ranges from 0.50 m to 0.72 m.In the light of these uncertainties future global volume changes have been projected either by an 'indirect' approach via mass balance sensitivities to temperature and precipitation changes [6] or a 'direct' approach via modeling mass balance in time [7]. The 'indirect' approach relates mass balance sensitivities, derived for the glaciers with available mass balance observations, to temperature and precipitation changes. The established relationships are then used to extrapolate the mass balance sensitivities to all the glacierized regions with no mass balance observations. Future volume projections are derived for hypothetical changes in temperature and precipitation or for changes derived from output of General Circulation Models (GCMs) [8].

The 'direct' approach models the changes in glacier mass balance by forcing mass balance models with an output from a GCM. In both approaches, if the glacier area is kept constant in time, volume loss of an individual glacier is overestimated when compared to volume projections derived from the ice flow models [9]. The most common way to account for glacier area changes in volume projections on a global scale is through the scaling relationships between glacier volume, area and length [10] applied the scaling relationship to develop a 'geometric' model which, coupled with a mass balance 31 model, enables the glacier to reach a new equilibrium in a perturbed climate. Applying this model and forcing it with temperature scenarios from two GCMs [11]

Projected the sea level rise from all MG&IC outside Greenland and Antarctica for 21st century to be 0.046 m and 0.051 m. Another source of uncertainty in modeling future volume changes are the mass balance models which range from full energy balance models to linear regression temperature-index models, making the projections highly sensitive to the choice of the mass balance model [12]. However, since positive degree days are good indicators of surface melt [13] the degree-day models are most commonly applied for deriving regional and global estimates of recent and future mass balance [14]. Nevertheless, two major criticisms of the application of surface mass balance models for global volume projections are that (1) the sample of glaciers with available mass balance observations to which the models are calibrated is biased toward small glaciers, area < 10 km2 [15] and (2) the models do not consider dynamical processes, such as calving, of maritime-terminating glaciers which account for two-thirds of total ablation of glaciers and ice sheets around the world [16]. Taking into account sparse information on tidewater glaciers with changes in ice dynamics [17] estimated that the worldwide glacier melt has experienced acceleration due to thinning and dynamic instability of tidewater glaciers. Assuming this acceleration to remain constant over the 21st century they projected total volume change from MG&IC, including those surrounding Antarctica and Greenland ice sheets, to be 0.240 m ± 0.128 m in SLE by the end of 2100. Assuming no acceleration of present rate of mass balance loss the volume change in SLE would be 0.140 m ± 0.025m. Their former result appears to be much larger than the one suggested by the *IPCC* [2007], where SLE from MG&IC

projected by GCMs with several emission scenarios varies between 0.070 m and 0.170 m, but in close agreement with the recent work by [18] recognize the lack of sufficient glaciological data and models as a large uncertainty in the estimates of future glacier melt.

Considering all the social and economical importance of future sea level rise only a few studies have been devoted to lower the ranges of uncertainties in the projection of MG&IC contribution to sea level rise. Although the problem of incomplete World Glacier Inventory (WGI) is 32 recognized and addressed through Global Land Ice Measurements from Space (GLIMS), methods for global assessments of glacier changes are not adequately tested for MG&IC which are presently available in WGI. Projections of volume changes have been derived for samples of glaciers worldwide where each sample consists of assumed number of glaciers and their sizes any information on their exact location, geometry, and local climate regime. In the light of these assumptions the total error in the global estimates can only be assumed and it is a common way to assume cancellation or decrease of errors in the global assessments due to large scatter of independent errors for each glacier [19].

2. SEA LEVEL RISE – A REVIEW

2.1 Why do we care about sea level change?

In 1990, the near-coastal population (area with 100 km horizontally and 100 m vertically of the shoreline) was 1.2 billion people, meaning that 23% of the world's population lives in the area with three times the global-mean density . Human settlements are also preferentially located close to the world's shoreline, including most of the largest cities, which means that the world's economy is also concentrated in the coastal zone . Thus, sea level rise has a major impact on coastal cities, deltaic lowlands, small islands, and coastal ecosystems. The potential threat has triggered studies on impacts and responses to sea-level rise which are focused on a range of direct and indirect socio-economic impacts such as loss of land and buildings, loss of tourist amenity, increasing flood risk, impact on variety of commercial infrastructure, coastal process plants and offshore oil and gas production. In practice, existing studies have focused on a sub-set of natural system effects (inundation, flood and storm damage, wetland loss, erosion, saltwater intrusion etc.) while the treatment of adaptation to climate change has been limited or even ignored. Also, protection costs against sea-level rise may have been underestimated, especially for deltas and small islands . Globally averaged sea level is an integrator of changes in the Earth's heat budget. Thus, precise estimates of the global mean sea level change provide strong constraints on climate model simulations. From a scientific point of view this is very important because climate models at present provide the only insight we have concerning how the Earth system might evolve in coming decades in response to increasing greenhouse gases

2.2What do we know from the paleo/historical record about global sea level changes?

The geological indicators of past sea level are usually not sufficiently precise to enable fluctuations of sub-meter amplitude to be observed. It is important that the areas, which provide proxy data on sea level rise, are tectonically stable and that no barriers or other shoreline features caused changes in the local conditions. Such areas are: Mediterranean (include archeological data and biological indicators of sea level change, the Baltic Sea (fresh-to-marine transitions, and stable tropical islands and continental margins . The results from these areas indicate that for the past 3,000 to 6,000 years oscillations in global sea level on time-scales of 100 to 1,000 years are unlikely to have exceeded 0.3 to 0.5 m. However,global sea level rose by about 120 m after the end of the last ice age

(approximately 21,000 years ago), as a result of loss of mass from the ice sheets, and stabilized between 3,000 and 2,000 years ago. Sea level indicators suggest that global sea level did not change significantly from then until the late 19th century [*IPCC*, 2007]

2.3 What do recent global sea level observations show and can we trust them?

Tide gauges, which measure the radial position of the surface of the ocean with respect to the crust, particularly highlight the impact of the solid Earth on sea-level estimation. On the time scale of a century, motion of the Earth's surface can be the same order of magnitude as motion of the sea surface (~0.1 m) and locally can exceed this by a significant amount. Thus, the problem of the impact of sea-level variations requires consideration of the land motion. Land motion corrections from the tide gauge records have relied primarily on models of glacial isostatic adjustment (GIA), however no corrections due to other land motions are considered. *IPCC* [2007] summarized the global sea level trends for the 20th century obtained from tide gauge with GIA correction studies as 1.7 ± 0.5 mm yr-1, while the assessment for 1961-2003 is 1.8 ± 0.5 mm yr-1. derived new estimates for the period 1961- 2003 with a trend of 1.6 ± 0.2 mm yr-1. However, the global coverage in tide gauges still suffers from scarcity of data, especially for the Southern Hemisphere, while the models for GIA correction still need improvement.Since 1992, global mean sea level can be computed at 10-day intervals by averaging the altimetric measurements from the satellites over the area of coverage (66°S to 66°N). The emergence of global altimeter datasets and reconstructions of upper ocean heat content based on historic hydrographic data provided insight into spatial patterns associated with interannual and lower frequency sea level variations . The dominant sea level signal at these time scales is associated with ocean volume redistribution, and not the ocean's volume change meaning that the redistribution signal needs to be removed from the trends at each tide gauge station. suggested that the under-sampling problem of tide gauges could lead to overestimation of the global sea level trend, although the magnitude of this effect has been questioned . The current best estimate of average rate of global sea level rise from satellite altimetry over 1993-2003 is 3.1 ± 0.7 mm yr- [*IPCC*, 2007]. However, the error in the instrumental calibration dominates the error budget noted that sea level estimated from satellite altimeter observations follows the tide gauge estimate closely up to 1999 and then begins to diverge, implying a higher rate of rise. It is still unclear why the tide gauge and satellite estimates diverge.

2.4 How do we explain the observed global sea level change?

The observation of sea level change contains information on land movements, mass redistribution or geoid changes and changes in ocean volume or distribution of water within the ocean basins.The changes in the ocean volume are affected by the changes in ocean density (steric sea level change, where thermosteric is due to temperature changes while halosteric is due to salinity changes) and the influx of water from the continents (eustatic sea level rise). This influx is more likely due to melting of the mountain glaciers and polar ice than due to changes in terrestrial water storage. The studies on steric sea level rise and those on contribution from terrestrial water storage are briefly presented here while the cryospheric contribution will be presented separately and with more details later. estimated a linear trend of 0.36 ± 0.06 mm yr-1 rise in thermosteric sea level considering heat content in the 0-700 m layer in the period 1955-2003. Consideration of a deeper ocean layer, 0-3000 m, increased this estimate to 0.40 mm/yr for the period 1957-1997. An additional small halosteric component (salinity change) was estimated as 0.04 ± 0.01 mm yr-1, consistent with the earlier

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estimate. Halosteric expansion is nearly compensated by a decrease in volume of the added freshwater when its salinity is raised (by mixing) to the mean ocean value. However, for regional changes in sea level, thermosteric and halosteric contributions can be equally important reported improved estimates for thermosteric sea level rise of 0.52 ± 0.08 mm yr-1 for 1961-2003 (0-700 m layer) which are about 50% larger than earlier estimates. For the 1993-2003 decade, the estimated 1.6 ± 0.5 mm/yr of thermosteric (0-750 m) sea level rise accounted for more than half of the rise in total sea level. However, pointed out the bias in this estimate due to errors in the fall rate of expendable bathy-thermographs (XBTs) and reported lower trend for 1993-2003 of 0.79 mm yr-1. All the results indicate that there is a substantial interannual-to-decadal variability and regional variability, not only in the rate of ocean warming, but also in the ratio of thermosteric to total sea level change. Part of the recently observed rise (~0.5 mm/yr) may be due to the recovery of sea level after the cooling effects of the eruption of Mt. Pinatubo in 1991.

Since the Earth's gravitational field is not sensitive to the thermal expansion of sea water, observations of the gravitational field can be used in concert with sea level change observations to separate the steric from eustatic sea level rise . However, geodetic observations of the gravitational field have significant errors due to uncertainty in the terrestrial reference frame, meaning that a 2 mm yr-1 error in relative velocity between the mean surface of the Earth and the Earth system's center of mass can result in an error as large as 0.4 mm yr-1 in mean global sea level variation . Changes in terrestrial water storage result from climate variations, from direct human interventions in the water cycle, and from human modification of the physical characteristics of the land surface. For contribution to sea level one should consider (i) climate-driven changes of terrestrial water storage (deep ground water, lakes, lake-affected ground water, permafrost) and (ii) anthropogenic changes (artificial reservoirs, dam-affected ground water, groundwater mining, irrigation, wetland drainage, urbanization and deforestation). Order-of-magnitude estimates suggest that the permafrost thawing resulting in decrease of stored water in the soil column and enhancing subsurface hydraulic connectivity (thus leading to more free drainage of the landscape) has potential to be an important contributor to sea-level rise in recent years . On the other hand, impoundment of water behind dams removes water from the ocean and lowers sea level . However, it is very difficult to provide estimates of the net anthropogenic contribution, given the lack of worldwide information on each factor. Thus, *IPCC* [2007] summarized that the land contribution either is small (< 0.5 mm yr-1) or is compensated for by unaccounted or underestimated contributions.

The estimated contributions to the budget of global mean sea level change and the observed rates of sea level rise are presented in Table 1.1. To summarize, the observed global mean sea level rise over 1961-2003 is 1.8 ± 0.5 mm yr-1, the estimate of steric contribution is 0.42 ± 0.12 mm yr-1, the contributions from terrestrial water storage are probably very small, the contribution from mountain glacier and ice caps is 0.50 ± 0.18 mm yr-1, from Greenland ice sheet is 0.05 ± 0.12 mm yr-1 and from Antarctic ice sheet 0.14 ± 0.41 mm yr-1 [*IPCC*, 2007]. Thus, the sum of thermal expansion and contribution from land ice is smaller by 0.7 ± 0.7 mm yr-1 than the observed global average sea level rise. Even with the new estimates with observed sea level rise of 1.6 ± 0.2 mm yr-1 and steric contribution of 0.7 ± 0.1 mm yr-1, the gap between observed and explained sea level rise is not closed. However, during 1993-2003 period the observed sea level rise of 3.1 ± 0.7 mm yr-1 and the sum of steric and eustatic components of 2.8 ±

0.7 mm yr-1 show that the discrepancy between observed and explained sea level rise is smaller.Nevertheless, the increased thermal expansion in this period (1.6 ± 0.5 mm yr-1) may partly reflect decadal variability rather than an acceleration.

2.5 How successful are the attempts to predict future global sea level changes?

High-resolution Atmosphere Ocean General Circulation Models (AOGCMs) which can reproduce detailed ocean features have been used to understand and project future sea level changes under global warming. Since climate is a profoundly nonlinear system in which variability on different time and spatial scales interact, accuracy in projected future changes depends on how well the AOGCMs incorporate processes on as many different space and time scales as possible. If greenhouse gas concentrations are on one end of the chain while climate impact on sea level rise is on the other, these ends are linked through processes such as radiative forcing, atmospheric regimes and teleconnections, ocean-atmosphere-land interactions,cryospheric interactions and biogeochemical interactions. Thus, the model accuracy with which the climate impact can be determined from the underlying climate forcing is determined by the chain's weakest link. Additionally, good AOGCM performance evaluated from the present climate does not necessarily guarantee reliable predictions of future climate . The 'chain analogy' is especially applicable for sea level projection due to thermal expansion since this process can be calculated directly in AOGCM by simulating the changes in ocean temperature. However, the contributions to sea level rise from the ice sheets and mountain glaciers are projected by ice sheet-climate or glacier-climate coupled models. This means that processes on glacier-climate interface are currently not fully coupled in AOGCMs, but the AOGCMs output scenarios are used to force ice sheet and glacier dynamical models in order to project the volume changes. This adds additional uncertainty in future sea level projections from cryospheric component which will be discussed later. Furthermore, the models for glacial isostatic rebound, which are used in extracting the land motion signals from tide gauge sea level observations, depend on glaciological and climate input. For terrestrial water storage land surface models are used, although their priority is to calculate fluxes from land to atmosphere for the purpose of atmospheric modeling. Thus, modeling future global sea level is a complex task which needs an interdisciplinary approach. Except modeling sea level changes due to climate forcing there have been efforts to combine numerical models of solid Earth deformation with large catalogues of seismic events to estimate the cumulative impacts of this seismicity on global sea level estimated a mean sea level signal at tide gauge stations of as much as 0.25 mm yr-1. The signal mainly originates from the very large thrust events . Thus, the history of seismicity, and future events, may contribute non-negligibly to observed sea-level trends. *IPCC* [2007] projected global sea level rise between the present (1980-1990) and the end of this century (2090-2099) to range between 0.18 m to 0.59 m under various emission scenarios, spread of AOGCMs and not including uncertainty in carbon cycle feedbacks. Sea level rise during 21st century is projected to have substantial geographical variability.

3. MODELING GLOBAL MEAN SPECIFIC MASS BALANCE 161-1990.

Large-scale numerical models used to predict the evolution of the Greenland and Antarctic ice sheets require time-dependent boundary conditions (surface mass balance, surface temperature, and sea level, the latter needed to model grounding-line changes). Current ice sheet models employ grids of 20 to 40 km horizontal spacing with 10 to 30 vertical layers and include ice shelves, basal sliding and bedrock

adjustment . However, ice sheet models run for recent climate do not capture the rapid coastal flow (outlet glaciers) accelerations observed since the mid-nineties [*IPCC*, 2007]. Most of the glacier accelerations in Antarctica closely followed reduction or loss of ice shelves, which is caused by changes in basal melting or iceberg calving. Ice-shelf basal melting depends on temperature and ocean circulation within the cavity beneath. Isolation from direct wind forcing means that the main drivers of sub-ice-shelf circulation are tidal and density (thermohaline) forces, but lack of knowledge of sub-ice bathymetry does not allow the models to simulate circulation beneath the thinning ice shelves. If outlet glaciers' accelerations were to be sustained in the future these models under-predict future contributions to sea level. For computational efficiency, most long simulations with comprehensive ice flow models use a simplified stress distribution, but recent changes in ice sheet margins and ice streams cannot be simulated accurately with these models, demonstrating a need for resolving the full stress configuration. Additionally, current models are not capable of simulating the increases in ice flow of slow-moving ice due to greater drainage of surface melt water into the ice sheet as observed for sites on Greenland. It should be noted that there is also a large uncertainty in current model predictions of the atmosphere and ocean temperature changes which drive the ice sheet changes, and this uncertainty is probably at least as large as that of the dynamic ice sheet response.

Global mean specific mass balance is derived as an area-weighted average over all the glacierized grid cells. The glacierized area for each grid cell is derived from the data and the total area of MG&IC from WGI. If the latter is ±20% of the former, the WGI value is assumed. Otherwise, the estimate is assumed to represent the total glacierized area of the grid cell. In the case where an individual ice mass from WGI has surface area which exceeds the total area of the grid cell we adopt the WGI value. With described methodology we obtain a grid-based global mean specific mass balance for 1961- 1990 of 0.326 myr-1, which differs from the value of -0.219± 0.092 m yr-1 reported in *IPCC* [2007]. Since we are interested in future volume projections it is important that our modeled global mass balance for the recent climate does not have an initial offset from the previous estimates. Therefore we initialize the mass balance model, following *Raper and Braithwaite* [2006], by uniformly adjusting the model parameter *lrERA* to make the grid-based global mean specific mass balance approximately agree with the *IPCC* [2007] estimate. Adjustment of *lrERA* is chosen since the parameter, i.e. the correction of biases in ERA-40 air temperatures, is not well constrained by the calibration of the mass balance model on 36 glaciers. Results are shown in Table 1. The uniform adjustment of *lrERA* from -0.69 K(100)-1 to -0.52 K(100m)-1 is needed to arrive at the global mean specific mass balance of -0.214 m yr-1 or, expressed in SLE, -0.305 mm yr-1.

Area-averaged specific mass balance for grid cells containing one or more MG&IC from WGI is -0.200 m yr-1, while the remaining grid cells yielded -0.232 m yr-1. Size distribution of MG&IC from WGI with corresponding area-size distribution and volume changes is illustrated in Figure 1. The majority of MG&IC from WGI occur in the first few size bins (A < 3 km2) for which the model derived negative specific mass balance. The largest size bin, containing the ice cap from Novaya Zemlya (A=11 130 km2) has positive specific mass balance and therefore compensates partially for the loss of volume from the small mountain glaciers. This shows the importance of modeling accurately the mass balance from very large MG&IC since they carry most of the weight in global estimates of SLE.

Table-1. Total glacierized area, modeled mean specific mass balance for 1961-1990 and corresponding sea level equivalent (SLE), and modeled area-weighted global mean mass balance sensitivity to temperature increase of 1K and precipitation increase of 10%

Glacierized grid cells	Area (km^2)	Mean specific mass balance (m yr^{-1})	SLE (mm yr^{-1})	$\frac{\Delta \overline{b_n}}{\Delta T}\left[\frac{m}{yr\,K}\right]$	$\frac{\Delta \overline{b_n}}{\Delta P}\left[\frac{m}{yr\,10\%}\right]$
With MG&IC from WGI	288,710	-0.200	-0.18	-0.73	0.16
Without MG&IC from WGI	225,710	-0.232	-0.13	-0.66	0.15
All	514,420	-0.214	-0.31	-0.70	0.15
IPCC (2007)	546,000	-0.219 ± 0.092	-0.33 ± 0.14		

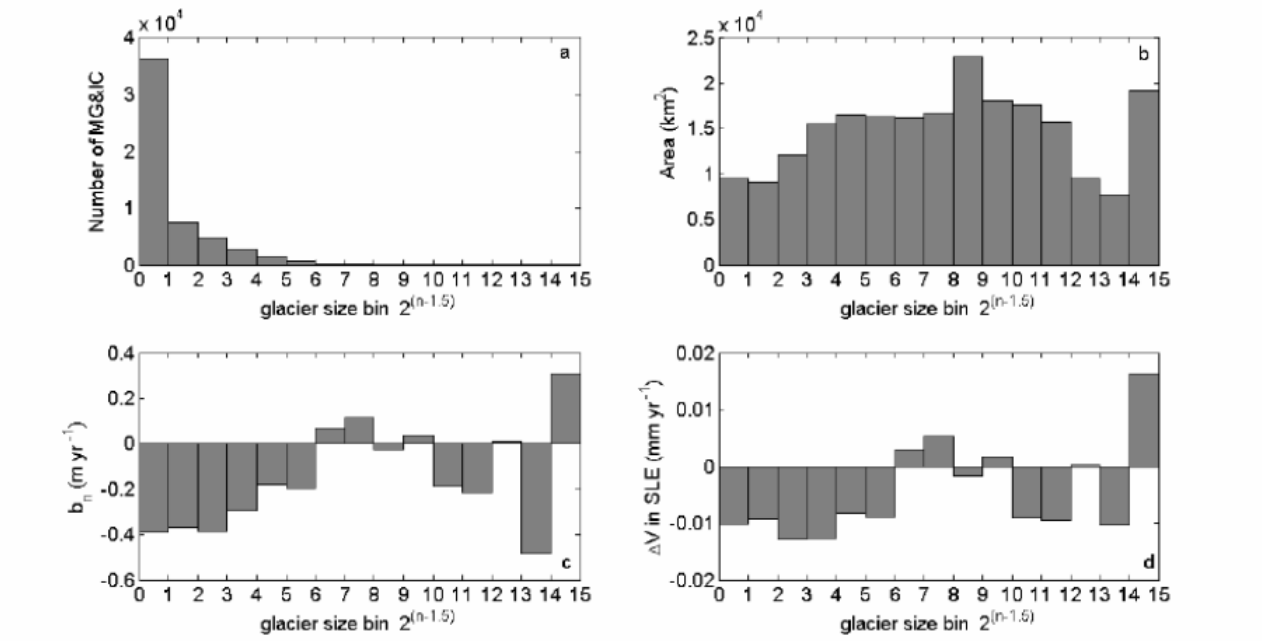

Fig. 1. (a) Size distribution of MG&IC from WGI, (b) total area for each size bin, (c) areaweighted mean specific mass balance for each size bin and (d) volume change in SLE for each size bin for 1961-1990.

4. CONCLUSION

We provided an ensemble of 21st century volume projections for all mountain glaciers and ice caps (MG&IC) from the World Glacier Inventory (WGI) by modeling the surface mass balance coupled with volume-area-length scaling and forced with temperature and precipitation scenarios with A1B emission scenario from four GCMs. Results showed that total volume change in SLE of 53,413 MG and 602 IC, with initial total area of 222,642 km2 and volume 52,780 km3, is in the range of -0.018 m to -0.089 m, depending on which GCM is applied. By upscaling the volume projections through a regionally differentiated approach to all MG&IC outside Greenland and Antarctica (514,380 km2) we estimated total volume change to be in the range of -0.039 m to - 0.150 m for the time period 2001-2100. The lower estimate agrees with the previous estimates which applied only temperature scenarios from two GCMs with A1B emission scenarios. However, CCSM3 model opens possibility for more dramatic glacier melt. While three GCMs agreed that Alaskan glaciers are the main contributors to the projected sea level rise (followed by MG&IC from Iceland, Svalbard, Himalaya and Patagonia), CCSM3 model projected the largest total volume loss mainly due to Arctic MG&IC (Canadian Arctic, Svalbard,

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Severnaya Zemlya, Novaya Zemlya and Franz Joseph Land). This is probably due to increased projected polar amplification in CCSM3 than in the other three GCMs.

The mass balance model was calibrated on 36 glaciers with available mass balance observations and the functions between climate variables and model parameters were derived. By this we achieved a certain amount of confidence in the model parameters that are applied to all MG&IC from WGI. However, a major source of uncertainty in the methodology is the temperature forcing in the mass balance model which depends on bias correction of ERA-40 temperatures in order to simulate the local temperatures on a mountain glacier or ice cap. By perturbing the 'statistical lapse rate', *lrERA*, by ±0.02 K/(100m)-1 the global specific mass balance for the period 1961-1990 changes by ±0.1 mm yr-1 of SLE. Correction of ERA-40 temperatures should be applied regionally instead of globally, however the lack of available data on mass balance hampers adjustment of *lrERA* region by region. Other major sources of uncertainties are the volume-area scaling in deriving initial glacier volume and upscaling the volume changes with assumptions on glacier-size distributions in each glacierized region. Our projected 21st volume loss is probably a lower bound since no calving is modeled. Nevertheless, the large range of our projections depends on the choice of GCM emphasizing the importance of ensemble projections. This is especially the case for the Arctic regions whose mountain glaciers and ice caps are major potential contributors to global sea level rise while climate projections from GCM contain large uncertainties due to the complex feedback mechanism. We emphasize that our estimates are for only those MG&IC that lie outside of Greenland and Antarctica. Therefore, the question on how to account for the huge number of MG&IC that are peripheral to the large ice sheets still remains open. Our projection of total volume change is possibly a very low bound, not accounting for ~50% or more of the total area of MG&IC that may now be, or will be, contributing to sea level rise.

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