Greenland Ice Sheet Contribution to Future Global Sea Level Rise based on CMIP5 Models

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ABSTRACT

Sea level rise (SLR) is one of the major socioeconomic risks associated with global warming. Mass losses from the Greenland ice sheet (GrIS) will be partially responsible for future SLR, although there are large uncertainties in modeled climate and ice sheet behavior. We used the ice sheet model SICOPOLIS (SImulation COde for POLythermal Ice Sheets) driven by climate projections from 20 models in the fifth phase of the Coupled Model Intercomparison Project (CMIP5) to estimate the GrIS contribution to global SLR. Based on the outputs of the 20 models, it is estimated that the GrIS will contribute 0–16 (0–27) cm to global SLR by 2100 under the Representative Concentration Pathways (RCP) 4.5 (RCP 8.5) scenarios. The projected SLR increases further to 7–22 (7–33) cm with 2×basal sliding included. In response to the results of the multimodel ensemble mean, the ice sheet model projects a global SLR of 3 cm and 7 cm (10 cm and 13 cm with 2×basal sliding) under the RCP 4.5 and RCP 8.5 scenarios, respectively. In addition, our results suggest that the uncertainty in future sea level projection caused by the large spread in climate projections could be reduced with model-evaluation and the selective use of model outputs.

Key words: sea level rise, Greenland ice sheet, ice sheet modeling, model evaluation

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1. Introduction

Global sea level rise (SLR) is one of the major societal and economic risks in response to global warming, as much of the global population and infrastructure resides in low-lying coastal areas. For the period 2003–08, the mass loss of the Greenland ice sheet (GrIS) contributed 0.60–0.67 mm yr^{-1} to global SLR (Sørensen et al., 2011; van den Broeke et al., 2011), which was approximately three times larger than the period 1993–2003 (Bindoff et al., 2007). Other estimates (e.g., Zwally et al., 2011) also confirm the recently accelerated mass loss of the GrIS. Additionally, an enhanced freshwater input into the North Atlantic from the GrIS melting could perturb the thermohaline circulation and consequently influence the global climate. Thus, it is important to project global sea level change due to GrIS mass loss through out the 21st century.

According to the IPCC Fourth Assessment Report (AR4), global sea level will rise by 1–12 cm by 2100 due to the decrease of the GrIS surface mass balance (SMB) (Meehl et al., 2007b). However, the contribution from rapid ice flow was specifically excluded in the IPCC AR4 projections. Offline ice sheet modeling has proved a useful method for projecting future sea level (Huybrechts et al., 2004; Graversen et al., 2011; Greve et al., 2011), as it considers both the influence of SMB and ice flow changes over the ice sheet. However, the reliability of future sea level projections using ice sheet modeling depends on the input climate conditions provided by global climate models. If a model lacks skill in reproducing present-day climate, the corresponding projections may lack reliability (Franco et al., 2011). Previous studies have shown that climate models in the third phase of the Coupled Model Intercomparison Project (CMIP3) (Meehl et al., 2007a) vary considerably in their ability to reproduce the modern climate over Greenland (Walsh et al., 2008; Franco et al., 2011), and a

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major part of the uncertainty in projecting future SLR is thus attributed to the spread among climate models (Graversen et al., 2011).

The latest model outputs (phase five of the project; CMIP5) (Taylor et al., 2012) have recently become available to the research community. However, no study has assessed the skill of CMIP5 models in reproducing surface climate conditions over Greenland, and global SLR due to GrIS mass loss has not yet been simulated using these state-of-the-art models. In the present paper, using offline ice sheet modeling and a critical evaluation of modeled Greenland climate, we produce new estimates of global sea level projections for the 21st century under the new emissions scenarios of the Representative Concentration Pathways (RCPs) 4.5 and 8.5 (Moss et al., 2010; Meinshausen et al., 2011).

2. Methodology

2.1. *Data*

The monthly surface air temperature (SAT) and precipitation from the 20th century and future projection simulations of 20 CMIP5 models (Table 1) are used in this study. The data used to validate the models were derived from the ERA-interim reanalysis for the period 1979–2005 (Dee et al., 2011). It has been proven that the ERA-interim precipitation over Greenland is better than the European Centre for Medium-Range Weather Forecasts (namely ERA-40) and the National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) reanalysis (Chen et al., 2011). To facilitate the model–model intercomparison and model–observation validation, all the CMIP5 model outputs were interpolated onto a resolution of $1.5^\circ \times 1.5^\circ$ (ERA-interim grid).

2.2. *Evaluation and validation methods*

Since the monthly SAT and annual mean precipitation are the main climatic forcings required by the ice sheet model for future projections, we evaluate the simulated summer (June–July–August) SAT, winter (December–January–February) SAT and annual mean precipitation over Greenland against the ERA-interim reanalysis in terms of climatological mean and temporal evolution. Here, the temporal evolution includes two aspects: (1) the interannual variability, which is defined as the interannual standard deviation of the simulated field for the period 1979–2005 at each grid point and (2) the linear trend, which is defined as the linear trends of the simulated field for the period 1979–2005 at each grid point.

A Taylor diagram (Taylor, 2001) is employed to evaluate how well CMIP5 models simulate an observed climate field. In a Taylor diagram, the observed field is represented by a point (identified as "REF") at unit distance from the origin on the *x*-axis. The standard deviation of the modeled field is the radial distance from the origin. The centered RMSE is the distance to the observed point. The azimuthal position gives the correlation coefficient. The centered RMSE and the modeled standard deviation are normalized by the observed standard deviation.

We define a weighted skill score S_{w} to rank the model

Table 1. CMIP5 models used in this study. More information about the CMIP5 models can be found at http://cmip-pcmdi.llnl.gov/cmip5/.

Model	Model name	Modeling center (or group)
1	BCC-CSM1.1	Beijing Climate Center, China Meteorological Administration
2	CanESM2	Canadian Centre for Climate Modelling and Analysis
3	CCSM4	National Center for Atmospheric Research
4	CNRM-CM5	Centre National de Recherches Meteorologiques/Centre Europeen de Recherche et Formation Avancees en Calcul Scientifique
5	CSIRO-Mk3.6.0	Commonwealth Scientific and Industrial Research Organization in collaboration with the Queensland Climate Change Centre of Excellence
6	GFDL-CM3	NOAA Geophysical Fluid Dynamics Laboratory
7	GFDL-ESM2G	NOAA Geophysical Fluid Dynamics Laboratory
8	GFDL-ESM2M	NOAA Geophysical Fluid Dynamics Laboratory
9	GISS-E2-R	NASA Goddard Institute for Space Studies
10	HadGEM2-CC	Met Office Hadley Centre
11	HadGEM2-ES	Met Office Hadley Centre
12	INMCM4	Institute for Numerical Mathematics
13	IPSL-CM5A-LR	L'Institut Pierre-Simon Laplace
14	IPSL-CM5A-MR	L'Institut Pierre-Simon Laplace
15	MIROC5	Atmosphere and Ocean Research Institute (University of Tokyo), National Institute for Environmental Studies, and the Japan Agency for Marine-Earth Science and Technology
16	MIROC-ESM	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (University of Tokyo), and the National Institute for Environmental Studies
17	MIROC-ESM-CHEM	
18	MPI-ESM-LR	Max Planck Institute for Meteorology
19	MRI-CGCM3	Meteorological Research Institute
20	NorESM1-M	Norwegian Climate Centre

performance over Greenland following Taylor (2001):

$$S = \frac{4(1+R)^4}{(\delta + 1/\delta)^2(1+R_0)^4} \; ; \qquad (1)$$

$$S_\mathrm{w} = \sum_{i=1}^{3} \alpha_i \sum_{j=1}^{3} \beta_j S_{i,j} \; . \qquad (2)$$

In Eq. (1), R_0 is the maximum correlation attainable ($R_0 = 0.995$); R is the correlation coefficient between the simulated and observed field; and δ is the standardized standard variation of the simulated field. In Eq. (2), $S_{i,j}$ is the skill score calculated according to Eq. (1); β is the weight coefficient of skill score for the climatological mean ($j = 1$), interannual variability ($j = 2$) and linear trend ($j = 3$); and α is the weight coefficient of skill score for summer SAT ($i = 1$), winter SAT ($i = 2$) and annual mean precipitation ($i = 3$).

2.3. *Ice sheet model*

SICOPOLIS (SImulation COde for POLythermal Ice Sheets) is a 3D, thermodynamically coupled ice sheet model based on the shallow ice approximation (SIA). It solves the polythermal ice sheet equations and utilizes the rheology of an incompressible, heat-conducting, power-law fluid to describe ice flow (Greve, 1997a, b). SICOPOLIS has been benchmarked in a number of international ice sheet modeling intercomparison projects and is widely used to simulate the temporal evolution of ice sheet mass balance in response to external forcing.

In this study, SICOPOLIS was run at a horizontal resolution of 20×20 km in a domain covering the entire land area of Greenland and the surrounding ocean. The present geometry was provided by the Sea-level Response to Ice Sheet Evolution project (http://websrv.cs.umt.edu/isis/index.php/SeaRISE_Assessment). The present-day temperature and precipitation over Greenland (i.e., the control climatology) were based on Fausto et al. (2009) and Ettema et al. (2009), respectively. The geothermal heat flux (Shapiro and Ritzwoller, 2004) was provided to the model as a spatially varying field and was fixed in all simulations. SMB was estimated by the positive degree-day (PDD) method (Reeh, 1991) with the semi-analytical solution (Calov and Greve, 2005). The elastic-lithosphere-relaxing-asthenosphere approach was employed to estimate the isostatic adjustment due to the ice load. Basal sliding was described by a Weertman-type sliding law in which sub-melt sliding is allowed (Greve, 2005). More information concerning SICOPOLIS is given by Greve (1995, 1997a, 1997b).

3. Experimental design

3.1. *Paleoclimate spin-up*

For ice sheet modeling, it is crucial to start a model run from accurate initial conditions because small errors in the initial state could systematically affect the projections for ice sheets and the corresponding sea level forecasts for the near future (Arthern and Gudmundsson, 2010). However, it is very difficult to reproduce the observed GrIS geometry without heavy tuning (Greve et al., 2011). Following Greve and Herzfeld (2013), we performed paleoclimate spin-up through the last glacial cycle with the GrIS topography fixed over time in order to obtain a modeled present-day GrIS close enough to observations [see Greve and Herzfeld (2013) for details].

3.2. *Future projection experiments*

3.2.1. *Climatic forcing*

Climate changes (monthly SAT and annual mean precipitation) for the 20th and 21st centuries (1951–2100) were derived from 20th century simulations of 20 CMIP5 models for the period 1951–2005 and future projection simulations under RCP 4.5 and RCP 8.5 scenarios beyond 2005. In order to reduce systematic errors in the global climate models (Huybrechts et al., 2004), the simulated climatic changes were considered in the anomaly mode. In other words, we subtracted the climatological mean over the period 1951–1980 from the simulated climate changes. These anomalies were then interpolated onto the SICOPOLIS grid, before being added to the control climatology used by the ice sheet model to create the climate forcing for the period 1951–2100.

3.2.2. *Experiments*

To estimate GrIS changes in the 20th and 21st centuries (1951–2100), the following experiments were performed. In the control run ($\mathrm{EXP_{cnt}}$), the ice sheet model was integrated for 150 years with the climate forcing fixed at present. In $\mathrm{EXP_{rcp45}}$ and $\mathrm{EXP_{rcp85}}$, the ice sheet model ran for the period 1951–2100, with climatic forcing derived from the 20 CMIP5 models and their ensemble mean under RCP 4.5 and RCP 8.5 scenarios, respectively (see section 3.2.1). In $\mathrm{EXP_{rcp45\_2B}}$ and $\mathrm{EXP_{rcp85\_2B}}$, the climatic forcing was the same as in $\mathrm{EXP_{rcp45}}$

Table 2. Experimental design.

	Climatic forcing	Basal sliding coefficient (m $\mathrm{yr^{-1}Pa^{-1}}$)	Number of runs	Integration period
$\mathrm{EXP_{cnt}}$	Modern	11.2	1	/
$\mathrm{EXP_{rcp45}}$	RCP 4.5[a]	11.2	21	1951 – 2100
$\mathrm{EXP_{rcp85}}$	RCP 8.5[a]	11.2	21	1951 – 2100
$\mathrm{EXP_{rcp45\_2B}}$	RCP 4.5[a]	22.4[b]	21	1951 – 2100
$\mathrm{EXP_{rcp85\_2B}}$	RCP 8.5[a]	22.4[b]	21	1951 – 2100

[a]Climatic anomalies derived from the 20 CMIP5 models and their ensemble mean.

[b]For the period 2006–2100.

and EXP_{rcp85}, but with 2× basal sliding (implemented by doubling the value of the sliding parameter) over the period 2006–2100 to consider the possible influence of enhanced basal sliding in the future (Greve and Herzfeld, 2013). In total, we carried out 85 experiments (Table 2).

4. Results

4.1. *CMIP5 model performance over Greenland*

Figure 1 displays the degree of correspondence of each model with the ERA-interim reanalysis in depicting the modern climate over Greenland. A "perfect" model would reside in the "REF" point in the δ, R-plane of the Taylor diagram. It is shown that the CMIP5 models perform well in reproducing the spatial pattern of climatological mean (Figs. 1a–c), exhibiting high spatial correlation coefficients ($R > 0.8$) and relatively small RMSE. Furthermore, the models differ with each other primarily in the modeled standard deviation, especially for summer SAT (Fig. 1a). In contrast, the CMIP5 models perform worse and vary more widely in simulating the interannual variability and linear trend for the period 1979–2005 (Figs. 1d–f). For example, seven out of 20 CMIP5 models show negative correlation in simulating the linear trend of annual mean precipitation. Besides, the CMIP5 model performance also varies with the evaluated variables. For example, model 9 performs best in simulating the linear trend of annual mean precipitation over Greenland ($R = 0.76$), but shows lower skill in simulating the linear trend of summer SAT ($R = 0.16$).

The multimodel ensemble mean (MEM) performs better in simulating the climatology mean of SAT and precipitation relative to most of the individual CMIP5 models (Figs. 1a–c), showing quite high spatial correlation coefficients ($R > 0.95$). In simulating the interannual variability and linear trend, the MEM also exhibits higher correlation coefficients than individual models (Figs. 1d–f). However, the MEM tends to greatly underestimate the amplitude of variation, which could be attributed to the fact that the MEM performs like a smooth function and hence reduces the variance of temporal evolution.

4.2. *Model rankings*

The aforementioned results indicate a substantial spread in CMIP5 model performance over Greenland, leading to great difficulty in setting up a criterion for optimal model selection. With the aim of selecting the most suitable model outputs for ice sheet modeling, we ranked the CMIP5 models based on their abilities in simulating summer SAT (ice sheet models are generally more sensitive to temperature changes than precipitation changes, and ablation mainly occurs in the summer season over GrIS). As part of the process, we assumed that the CMIP5 model capabilities to depict the climatological mean and temporal evolution are equally important (C1 in Table 3). According to the calculated skill scores, the top three models are GFDL-CM3, CSIRO-Mk3-6-0 and GISS-E2-R (Fig. 2).

To investigate the sensitivity of these top-performing models to the model-selection criterion, we defined another two criteria under which the model capabilities in reproducing winter SAT and annual mean precipitation over Greenland were also considered (Table 3). Based on the model-selection criterion C2 (C3), the skill scores showed that the top three models are GISS-E2-R, MPI-ESM-LR and MIROC5 (GISS-E2-R, MPI-ESM-LR and CCSM4) (Fig. 2).

4.3. *Sea-level changes in the 21st century*

Figure 3 shows the estimated global SLR due to GrIS mass loss in the 21st century under RCP 4.5 and RCP 8.5 scenarios. According to the results, which are based on the outputs of the 20 CMIP5 models, global sea level will rise by approximately 0–16 cm by 2100 under the RCP 4.5 scenario and 0–27 cm under the RCP 8.5 scenario. The upper and lower bounds are associated with GFDL-CM3 and the INMCM4, respectively. In response to the MEM result, the ice sheet model projects a global SLR of approximately 3 cm and 7 cm under the RCP 4.5 and RCP 8.5 scenarios, respectively. Considering the possible influence of enhanced basal sliding in the future, global SLR by 2100 increases to 7–22 (7–33) cm under the RCP 4.5 (RCP 8.5) scenario; the ice sheet model driven by the MEM result estimates a global SLR of 10 (13) cm. The large ranges of projected sea level change simply reflect inter-model differences in response to the same RCP scenario. In addition, the uncertainty range of sea level projections is much larger than that reported in IPCC AR4 (Meehl et al., 2007b) and other projections based on IPCC AR4 model outputs (e.g., Graversen et al., 2011).

To narrow the range of uncertainty in projected SLR caused by the large spread in climate projections, one can decide to only trust the results of the ice sheet model driven by the model outputs of those CMIP5 models judged to be more reliable. Based on the outputs of the top three models in simulating summer SAT (i.e., C1), GrIS mass loss contributes 4–16 cm and 7–27 cm (10–22 cm and 13–33 cm with 2× basal sliding) to global SLR by 2100 under the RCP 4.5 and

Table 3. Criteria for model selection.

	Coefficients in Eq.(2)	Notes
Criterion 1 (C1)	$\alpha_1 = 1, \alpha_2 = \alpha_3 = 0; \beta_i = 1/3$	Summer SAT is assumed to be the most important variable for GrIS mass balance.
Criterion 2 (C2)	$\alpha_1 = 0.5, \alpha_2 = 0.2, \alpha_3 = 0.3; \beta_i = 1/3$	Summer SAT is relatively more important and the influences of winter SAT and precipitation are also considered.
Criterion 3 (C3)	$\alpha_1 = \alpha_2 = \alpha_3 = 1/3; \beta_i = 1/3$	Summer SAT, winter SAT and annual mean precipitation are assumed to be equally important.

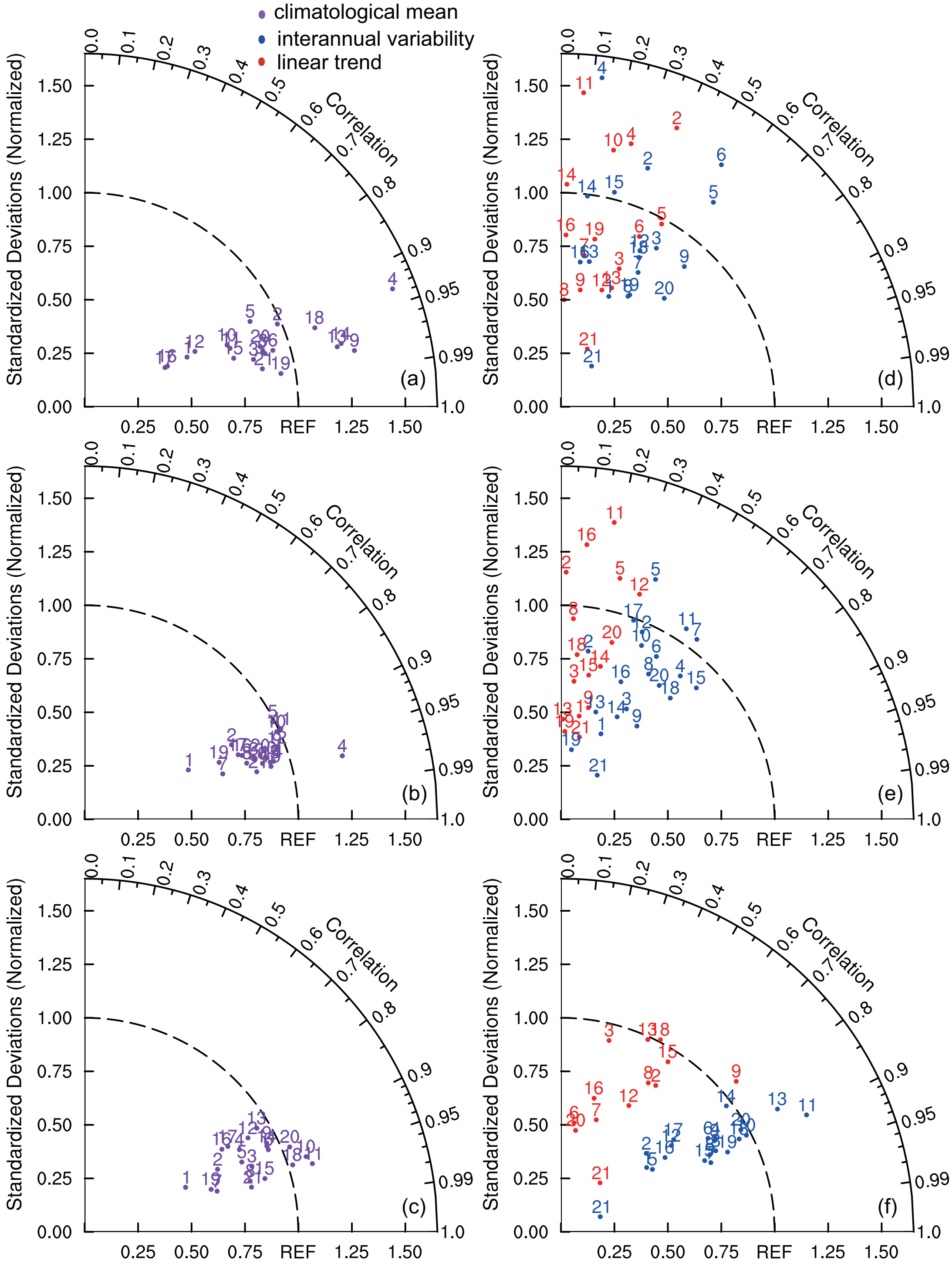

Fig. 1. Taylor diagram for displaying the spatial pattern statistics of the CMIP5 models in simulating the climatological mean (purple), interannual variability (blue) and linear trend (red) of (a, d) the summer SAT, (b, e) winter SAT and (c, f) annual mean precipitation. The numbers represent the CMIP5 models listed in Table 1 and number 21 represents the MEM. The standard deviation of the modeled field is the radial distance from the origin; the RMSE is the distance to the observed point ("REF"); the azimuthal position gives the correlation coefficient. Note that any model with a negative correlation coefficient or standard variation larger than 1.65 is not shown.

RCP 8.5 scenarios, respectively (Fig. 4). Compared to the results based on the outputs of the full 20 CMIP5 models, the uncertainty range of sea level projections is subsequently reduced. Based on the outputs of those models selected according to criteria C2 and C3, the uncertainty range of sea level projections is approximately 3–6 cm, which is much smaller

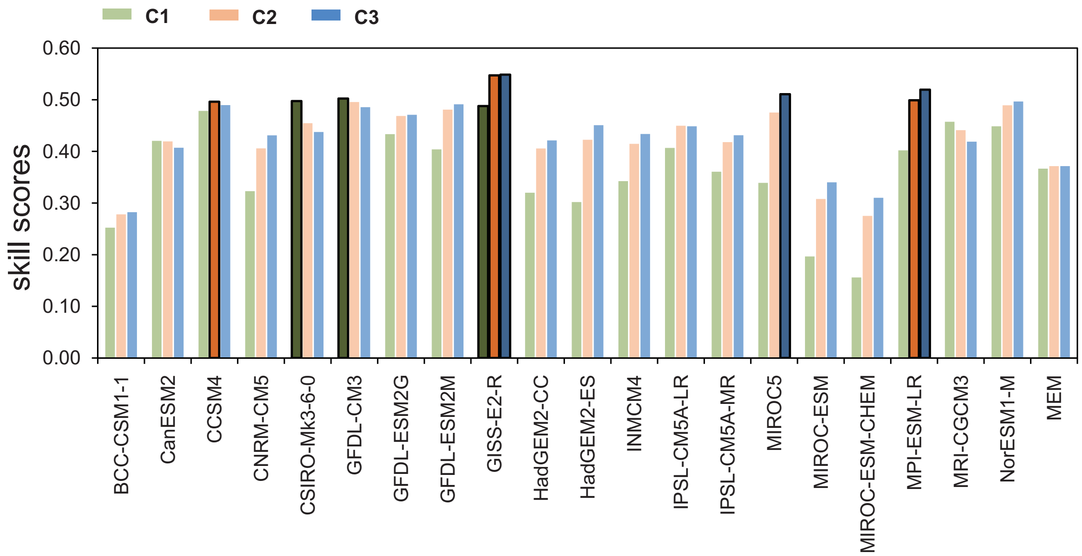

Fig. 2. Skill scores of CMIP5 models in simulating modern climate over Greenland based on different model-selection criteria (Table 3). The top three models are highlighted with the corresponding dark color.

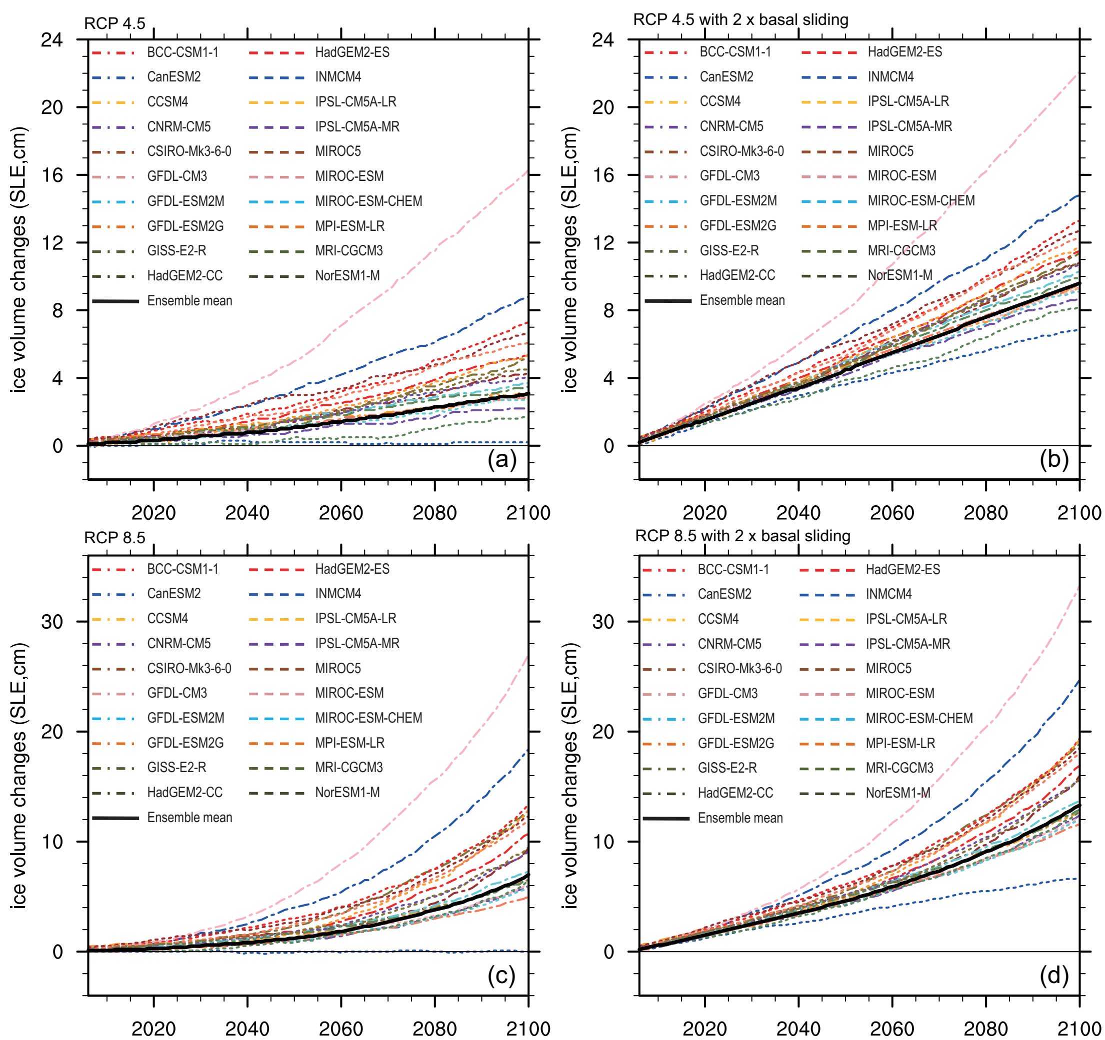

Fig. 3. Simulated ice volume changes of the GrIS (sea level equivalent, cm) in the 21st century (2006–2100) relative to 1986–2005 without/with 2×basal sliding under the RCP 4.5 (a, b) and RCP 8.5 (c, d) scenarios in the future projection experiments, which have been subtracted from the control run to remove unrelated post-initialization adjustments. The thick black line represents the MEM.

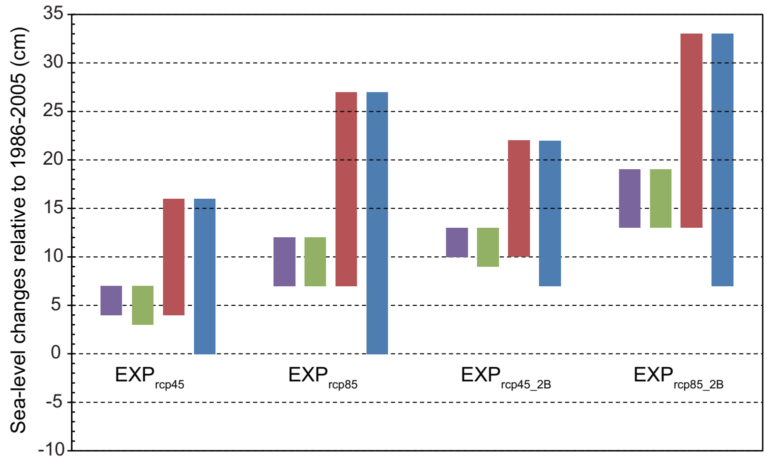

Fig. 4. The projected SLR by 2100 due to GrIS mass loss in the future projection experiments based on 20 CMIP5 model outputs (blue) and the selected top three model outputs according to model-selection criteria C1 (red), C2 (green) and C3 (purple).

than that based on the non-selective approach (Fig. 4). These results indicate that, although different criteria could lead to different model rankings, and hence different top-performing models being selected, such a selective approach in terms of model outputs is a possible method for reducing the level of uncertainty in sea level projections.

5. Discussion and conclusions

In this paper we have presented new estimates of the contribution of GrIS to 21st century SLR based on the latest CMIP5 model outputs. In addition, our results have revealed a large spread in climate projections simulated by CMIP5 models, which then leads to great uncertainty in terms of future sea level projection. However, with an evaluation of models and subsequent selection of the relatively more reliable model outputs, we have shown that the range of uncertainty in future sea level projection can be narrowed to a certain degree.

There are, however, limitations to be considered. The ranking process utilized in this study was targeted at the forcing of an ice sheet model, and hence contained arbitrary elements. If we aim to select an optimal subset of models for regional dynamical downscaling, the emphasis should be placed upon the model's capability to simulate atmospheric circulation (Franco et al., 2011). Furthermore, the projected SLR depends on the number of top-performing models selected. We hope our approach may stimulate improvements or a comprehensive and fully objective criterion for optimal model selection. Besides, the simple MEM (i.e., arithmetic average) may not be appropriate taking into account the wide spread in CMIP5 model performance. Thus, the use of model weighting could be a useful option in the calculation of MEM (Xu et al., 2010).

Equally, the uncertainty in sea level projection arising from the ice sheet model should also be considered. Because of the limitations of SIA (Calov et al., 2010) and the PDD scheme (Bougamont et al., 2007), SICOPOLIS cannot reproduce the fast-flowing ice streams and outlet glaciers very well, nor can it accurately simulate the ablation over the GrIS. These errors can affect the simulation of present-day ice calving and melting rates and hence influence projected sea level change. Bindschadler et al. (2013) highlighted the uncertainty in sea level projection from seven ice sheet models driven by a single climate forcing; they found that GrIS mass loss will contribute approximately 5–66 cm to global SLR by 2100 under a climate scenario approximation to RCP 8.5, which is comparable to the uncertainty range (7-33 cm) caused by the spread in climate projection in our study. Seddik et al. (2012) pointed out that, compared to an ice sheet model based on SIA, including more physics in the model projects a larger dynamical mass loss of the ice sheet in the 21st century. Furthermore, a high-order/full-stokes ice sheet model can reproduce the observed ice stream and outlet glaciers over the GrIS well and hence produce more reliable future projections (Price et al., 2011; Gillet-Chaulet et al., 2012).

Additionally, the effect of ocean temperature change on the GrIS (e.g., Holland et al., 2008) was not considered in our study, as few ice sheet models incorporate an ocean component enabling full ocean–ice interaction. However, the acceleration of outlet glaciers in Greenland (Joughin et al., 2010; Moon et al., 2012), which is responsible for a substantial increase in ice discharge, could be largely attributed to ocean warming (Bindschadler, 2006). Besides, Winkelmann and Levermann (2012) indicated that by including an annual incursion of warm ocean water, the solid ice discharge of the GrIS by 2100 could be up to 42 cm. Thus, ignoring the effect of ocean temperature change on the GrIS could lead to an underestimation of projected SLR. To provide more reliable sea level projection, a new generation of ice sheet models is required, in which rapid ice flow, the SMB and the effect of the ocean should all be better represented.

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