



HAL
open science

Future sea level change under CMIP5 and CMIP6 scenarios from the Greenland and Antarctic ice sheets

Antony Payne, Sophie Nowicki, Ayako Abe-ouchi, Cécile Agosta, Patrick Alexander, Torsten Albrecht, Xylar Asay-davis, Andy Aschwanden, Alice Barthel, Thomas Bracegirdle, et al.

► To cite this version:

Antony Payne, Sophie Nowicki, Ayako Abe-ouchi, Cécile Agosta, Patrick Alexander, et al.. Future sea level change under CMIP5 and CMIP6 scenarios from the Greenland and Antarctic ice sheets. *Geophysical Research Letters*, 2021, 48 (16), pp.e2020GL091741. 10.1029/2020GL091741 . hal-03228366

HAL Id: hal-03228366

<https://hal.science/hal-03228366>

Submitted on 14 Jun 2021

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution 4.0 International License

Future sea level change under CMIP5 and CMIP6 scenarios from the Greenland and Antarctic ice sheets

Antony J. Payne ¹, Sophie Nowicki ^{2,3}, Ayako Abe-Ouchi ⁴, Cécile Agosta ⁵, Patrick Alexander ^{6,7}, Torsten Albrecht ⁸, Xylar Asay-Davis ⁹, Andy Aschwanden ¹⁰, Alice Barthel ⁹, Thomas J. Bracegirdle ¹¹, Reinhard Calov ⁸, Christopher Chambers ¹², Youngmin Choi ¹³, Richard Cullather ², Joshua Cuzzone ¹⁴, Christophe Dumas ⁵, Tamsin L. Edwards ¹⁵, Denis Felikson ^{2,16}, Xavier Fettweis ¹⁷, Benjamin K. Galton-Fenzi ^{18,19}, Heiko Goelzer ^{20,21,22}, Rupert Gladstone ²³, Nicholas R. Golledge ²⁴, Jonathan M. Gregory ^{25,26}, Ralf Greve ^{11,27}, Tore Hattermann ^{28,29}, Matthew J. Hoffman ⁹, Angelika Humbert ^{30,31}, Philippe Huybrechts ³², Nicolas C. Jourdain ³³, Thomas Kleiner ³⁰, Peter Kuipers Munneke ²⁰, Eric Larour ¹⁴, Sebastien Le clec'h ³², Victoria Lee ¹, Gunter Leguy ³⁴, William H. Lipscomb ³⁴, Christopher M. Little ³⁵, Daniel P. Lowry ³⁶, Mathieu Morlighem ¹³, Isabel Nias ^{2,37}, Frank Pattyn ²¹, Tyler Pelle ¹³, Stephen F. Price ⁹, Aurélien Quiquet ⁵, Ronja Reese ⁸, Martin Rückamp ³⁰, Nicole-Jeanne Schlegel ¹⁴, Hélène Seroussi ¹⁴, Andrew Shepherd ³⁸, Erika Simon ², Donald Slater ³⁹, Robin S. Smith ²⁵, Fiammetta Straneo ³⁹, Sainan Sun ²¹, Lev Tarasov ⁴⁰, Luke D. Trusel ⁴¹, Jonas Van Breedam ³², Roderik van de Wal ^{20,42}, Michiel van den Broeke ²⁰, Ricarda Winkelmann ^{8,43}, Chen Zhao ¹⁹, Tong Zhang ⁹, Thomas Zwinger ⁴⁴

¹Centre for Polar Observation and Modelling, University of Bristol, Bristol, UK

²Cryospheric Sciences Laboratory, Code 615, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA

³Geology Department and RENEW Institute, University at Buffalo, Buffalo, NY, USA

⁴Atmosphere and Ocean Research Institute, The University of Tokyo, Kashiwa-shi, Japan

⁵Laboratoire des Sciences du Climat et de l'Environnement, LSCE-IPSL, CEA-CNRS-UVSQ, Université Paris-Saclay, Gif-sur-Yvette, France

⁶Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY, USA

⁷NASA Goddard Institute for Space Studies, New York, NY, USA

⁸Potsdam Institute for Climate Impact Research (PIK), Member of the Leibniz Association, Potsdam, Germany

⁹Theoretical Division, Los Alamos National Laboratory, Los Alamos, NM, USA

¹⁰Geophysical Institute, University of Alaska, Fairbanks, AK 99775, USA

¹¹British Antarctic Survey, Cambridge, UK

¹²Institute of Low Temperature Science, Hokkaido University, Sapporo, Japan

¹³Department of Earth System Science, University of California Irvine, Irvine, USA

¹⁴Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA

¹⁵Department of Geography, Kings College London, London, UK

¹⁶Universities Space Research Association, Goddard Earth Sciences Technology and Research Studies and Investigations, Columbia, MD 21044, USA

¹⁷Laboratory of Climatology, Department of Geography, University of Liège, Liège, Belgium

¹⁸Australian Antarctic Division, Kingston, Tasmania, Australia

¹⁹Australian Antarctic Program Partnership, Institute for Marine and Antarctic Studies, University of Tasmania, Hobart, Tasmania, Australia

²⁰Institute for Marine and Atmospheric research Utrecht, Utrecht University, Utrecht, the Netherlands

²¹Laboratoire de Glaciologie, Université Libre de Bruxelles, Brussels, Belgium

²²NORCE Norwegian Research Centre, Bjerknes Centre for Climate Research, Bergen, Norway

²³Arctic Centre, University of Lapland, Finland

²⁴Antarctic Research Centre, Victoria University of Wellington, New Zealand

²⁵National Center for Atmospheric Science, University of Reading, Reading, UK

²⁶Met Office, Hadley Centre, Exeter, UK

²⁷Arctic Research Center, Hokkaido University, Sapporo, Japan

²⁸Norwegian Polar Institute, Tromsø, Norway

²⁹Department of Physics and Technology, The Arctic University University of Tromsø, Norway

³⁰Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany

³¹Department of Geoscience, University of Bremen, Bremen, Germany

³²Earth System Science and Département Géographie, Vrije Universiteit Brussel, Brussels, Belgium

³³Univ. Grenoble Alpes/CNRS/IRD/G-INP, Institut des Géosciences de l'Environnement, France

³⁴Climate and Global Dynamics Laboratory, National Center for Atmospheric Research, Boulder, CO, USA

³⁵Atmospheric and Environmental Research, Inc., Lexington, Massachusetts, USA

³⁶GNS Science, Lower Hutt, New Zealand

³⁷School of Environmental Sciences, University of Liverpool, Liverpool, UK

³⁸Centre for Polar Observation and Modelling, University of Leeds, LS2 9JT, UK

This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the [Version of Record](#). Please cite this article as [doi: 10.1029/2020GL091741](#).

This article is protected by copyright. All rights reserved.

65 ³⁹Scripps Institution of Oceanography, University of California San Diego, La Jolla, CA, USA
66 ⁴⁰Dept of Physics and Physical Oceanography, Memorial University of Newfoundland, Canada
67 ⁴¹Department of Geography, Pennsylvania State University, University Park, PA, USA
68 ⁴²Geosciences, Physical Geography, Utrecht University, Utrecht, The Netherlands
69 ⁴³Department of Physics and Astronomy, University of Potsdam, Potsdam, Germany
70 ⁴⁴CSC-IT Center for Science, Espoo, Finland

71 **Key Points:**

- 72
- 73 • We compare results from an ice sheet model inter-comparison forced using CMIP6
74 and CMIP5 climate projections
 - 75 • Projected sea level at 2100 is higher for Greenland under CMIP6 scenarios than
76 CMIP5, but similar for Antarctica under both scenarios
 - 77 • CMIP6 warmer climate results in increased Greenland surface melt while increased
snowfall mitigates loss from ocean warming for Antarctica

Corresponding author: Tony Payne and Sophie Nowicki, a.j.payne@bristol.ac.uk
sophien@buffalo.edu

Abstract

Projections of the sea level contribution from the Greenland and Antarctic ice sheets rely on atmospheric and oceanic drivers obtained from climate models. The Earth System Models participating in the Coupled Model Intercomparison Project phase 6 (CMIP6) generally project greater future warming compared with the previous CMIP5 effort. Here we use four CMIP6 models and a selection of CMIP5 models to force multiple ice sheet models as part of the Ice Sheet Model Intercomparison Project for CMIP6 (ISMIP6). We find that the projected sea level contribution at 2100 from the ice sheet model ensemble under the CMIP6 scenarios falls within the CMIP5 range for the Antarctic ice sheet but is significantly increased for Greenland. Warmer atmosphere in CMIP6 models results in higher Greenland mass loss due to surface melt. For Antarctica, CMIP6 forcing is similar to CMIP5 and mass gain from increased snowfall counteracts increased loss due to ocean warming.

Plain Language Summary

The melting of the Greenland and Antarctic ice sheets will result in higher sea level in the future. How sea level will change depends in part on how the atmosphere and ocean warm and how this affects the ice sheets. We use multiple ice sheet models to estimate possible future sea levels under climate scenarios from the models participating in the new Coupled Model Intercomparison Project phase 6 (CMIP6), which generally indicate a warmer world than the previous effort (CMIP5). Our results show that the possible future sea level change due Antarctica is similar for CMIP5 and CMIP6, but the warmer atmosphere in CMIP6 models leads to higher sea-level contributions from Greenland by the end of the century.

1 Introduction

The overall aim of this paper is to assess whether the stronger future warming shown by many CMIP6 models (Forster et al., 2019; Meehl et al., 2020) compared with CMIP5 has a significant impact on future Global Mean Sea Level Rise (GMSLR). We compare projections for the sea-level contribution of the Greenland and Antarctic ice sheets (GrIS and AIS) under climate forcing from a small group of models from the CMIP6 ensemble (Eyring et al., 2016) with that of models using forcing from the CMIP5 model ensemble (Taylor et al., 2012). Goelzer et al. (2020b) and Seroussi et al. (2020) present detailed analyses of the latter set of experiments for GrIS and AIS, respectively. In both cases, a great deal of attention was paid to sampling the CMIP5 ensemble effectively, so that the CMIP5 models used to provide climate forcing both represented the present-day climate of the ice sheets well and sampled the range of future projections of the overall ensemble. Details of this procedure can be found in Barthel et al. (2020).

Global warming as manifested in regional atmospheric and oceanic change can impact the ice sheet mass budget, and hence contribution to GMSLR, in a number of ways. Warming of the atmosphere over the ice sheet promotes increased melt from snow and ice surfaces leading to increased mass loss in the form of runoff to the oceans. It may also be associated with increased precipitation because of the increased moisture-carrying capacity of warmer air. The relationship between global warming and the warmth of Polar ocean water masses impinging on the ice sheets is likely to be more complex. The warming of these water masses is expected to increase GMSLR by increasing mass loss from the marine-terminating outlet glaciers of the GrIS, and by processes associated with Marine Ice Sheet Instability (Schoof, 2007) for the AIS. An additional complexity for GrIS is that marine mass loss is partly controlled by freshwater fluxes from the surface melt (Slater et al., 2019). Finally, Marine Ice Sheet Instability could also be triggered by atmospheric warming leading to the fracture and collapse of floating ice shelves (Trusel et al., 2015). This process may in turn lead to the subsequent rapid retreat of the exposed

128 marine ice cliffs (DeConto & Pollard, 2016). In summary, the range and complexity of
129 the ways in which climate affects ice-sheet mass budget suggests that the greater global
130 warming found in CMIP6 models may not necessarily lead to increased GMSLR.

131 2 The CMIP6 ensemble

132 We compare a small ensemble of four Earth System Models (ESMs) submitted to
133 the CMIP6 exercise. These models are UKESM1-0-LL, CESM2, CNRM-CM6-1 and CNRM-
134 ESM2-1, which were the only ones available for downscaling at the time. Because the sam-
135 ple is small and based on availability only, it is important to understand the difference
136 between the selected models and the larger CMIP6 model ensemble. Effective Climate
137 Sensitivity (ECS)(IPCC, 2013) is a convenient measure of this. ECS estimates the global
138 mean temperature response to doubled atmospheric carbon dioxide concentration (Flato
139 et al., 2013). The four selected models all have ECS at the upper end of the CMIP6 en-
140 semble (CESM2, CNRM-CM6-1, CNRM-ESM2-1 and UKESM1-0-LL have ECS of 5.2,
141 4.8, 4.8 and 5.3 °C, respectively). Roughly half of the CMIP6 ensemble has an ECS of
142 between 4.6 and 5.6 °C, while there is a second similarly-sized group with markedly lower
143 ECS in the range 2.3 to 3.2 °C (Meehl et al., 2020). In contrast, the CMIP5 ensemble
144 exhibited a fairly continuous range of ECS between 2.1 and 4.7 °C (Flato et al., 2013).
145 The CMIP5 models used in Goelzer et al. (2020b) and Seroussi et al. (2020) were typ-
146 ically drawn from the upper end of this distribution (e.g., MIROC-ESM, HadGEM2-ES,
147 CSIRO-Mk3-6-0 and IPSL-CM5A-LR with ECS of 4.7, 4.6, 4.1 and 4.1 °C, respectively)
148 or lay close to the median (e.g., CCSM4, NorESM1-M and MIROC5 with ECS of 2.9,
149 2.8 and 2.7 °C, respectively).

150 Summaries of the atmospheric and ocean forcing for the two ice sheets are shown
151 in Figures 1 and 2, respectively. Surface warming exhibited over the AIS in CMIP6 lies
152 at or above the high end of the CMIP5 range. A similar pattern is evident in projected
153 changes in Surface Mass Balance (SMB, the annual difference between mass addition,
154 such as snowfall and refrozen rainfall, and mass loss, such as melt and subsequent runoff)
155 over the ice sheet. Neither quantity is, however, significantly higher than the CMIP5 range.
156 For GrIS, SMB was derived by forcing the MAR regional climate model of Greenland
157 (Fettweis et al., 2013) with CMIP6-derived boundary conditions. In this case, the CMIP6-
158 forced SMB is significantly more negative (i.e., higher GMSLR rise) than is the case for
159 CMIP5 forcing. Indeed, all four SSP585 ESMs fall outside the CMIP5 range and, by 2100,
160 anomalies from UKESM1-0-LL and CESM2 approach twice that of largest CMIP5 ESM.
161 The oceanic forcing of the AIS is described in detail by Jourdain et al. (2020) and for
162 the GrIS by Slater et al. (2020). The thermal forcing derived from the CMIP6 models
163 for both ice sheets lies within the range of the CMIP5 models with the exception of UKESM1-
164 0-LL SSP585, which is occasionally higher. In many cases, the forcing lies towards the
165 centre of the CMIP5 range despite the higher ECS of the CMIP6 models. As would be
166 expected thermal forcing from CNRM-CM6-1 SSP126 is less than that from CNRM-CM6-
167 1 SSP585, however the difference is similar to the difference between the four SSP585
168 models.

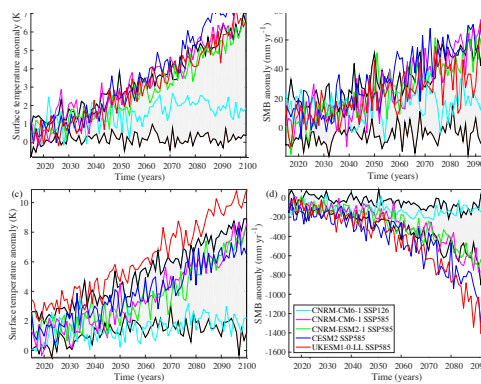


Figure 1. Atmospheric forcing used in CMIP6-forced experiments. (a) and (b) mean annual surface air temperature and Surface Mass Balance (SMB) anomalies over AIS. (c) and (d) mean annual surface air temperature and SMB anomaly for GrIS. Individual CMIP6 experiments are as shown as coloured lines (legend in panel (d)). Grey shading reflects range of CMIP5 forcing encompassed by all of the CMIP5 experiments used by ISMIP6 (i.e., highest and lowest CMIP5 forcing for each year).

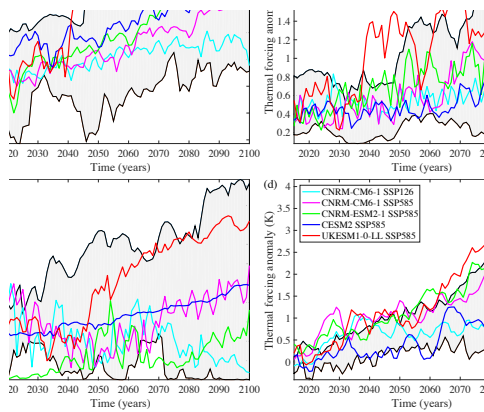


Figure 2. Ocean thermal forcing used in CMIP6-forced experiments for AIS sectors (a) Pine Island and Thwaites Glaciers, (b) Filchner-Ronne ice shelf, (c) Ross ice shelf and (d) for GrIS. Individual CMIP6 experiments are as shown as coloured lines (legend in panel (d)). Grey shading reflects range of CMIP5 forcing encompassed by all of the CMIP5 experiments used by ISMIP6 (i.e., highest and lowest CMIP5 forcing for each year).

Table 1. Overview of experiments and modelling groups participating in the CMIP6-forced exercise for AIS. Please refer to Seroussi et al. (2020) for model and group details. Symbols are those used in Figure 3.

Group	Model	Open	Standard	Symbol
AWI	PISM	1-5	1-5	◦
ILTS_PIK	SICOPOLIS		1-5	◁
JPL	ISSM		1-5	▷
NCAR	CISM	1-5	1-5	△
LSCE	GRISLI		1-5	□
UCIJPL	ISSM		1-5	▽
VUB	AISMPALEO		1-3	◇
Total		2	7	

3 Summary of ISMIP6 experimental procedure

The procedures used to convert the climate information summarised in Figures 1 and 2 into forcing imposed on ice sheet models are summarised in a series of papers for Antarctic ocean (Jourdain et al., 2020; Favier et al., 2019), Greenland ocean (Slater et al., 2019, 2020) and Greenland atmosphere (Fettweis et al., 2013; Goelzer et al., 2020a). Details of the experimental protocols employed can be found in Nowicki et al. (2016) and Nowicki et al. (2020) and employed a carefully chosen sub-sample of six CMIP5 models for each ice sheet.

These protocols were primarily employed by ice sheet modelling groups to generate projections using forcing from the CMIP5 ensemble, which are reported in Goelzer et al. (2020b) for GrIS and Seroussi et al. (2020) for AIS, however groups also conducted experiments using forcing from the CMIP6 ensemble as summarised in Tables 1 and 2. Both tables refer to experiments using the following numbering: 1) The CNRM-CM6-1 model run with scenario SSP585 (roughly equivalent to RCP8.5 of CMIP5), 2) CNRM-CM6-1 with SSP126 (roughly equivalent to RCP2.6 of CMIP5), and SSP585 with 3) UKESM1-0-LL, 4) CESM2, 5) CNRM-ESM2-1. Within the ISMIP6 design, experiments could be performed under ‘standard’ or ‘open’ configurations (see Nowicki et al., 2020). The former refers to the full implementation of ISMIP6 protocols for converting climate forcing into the mass fluxes experienced by the ice sheets, while in the latter individual groups used their own previously existing methods to do this.

4 GMSLR projections

Figure 3 shows projections for the AIS from the seven participating ice sheet models for each CMIP6-forced experiment along with ranges from the equivalent CMIP5-forced experiments (Seroussi et al., 2020). Figure 3 b to d compares these projections with ranges derived for the CMIP5 ensemble at 2100. The equivalent ranges for the whole AIS are -14 to 155 mm for RCP2.6, and -76 to 300 mm for RCP8.5. The regional contributions from West and East AIS are within or below the ranges reported for CMIP5 forcing. In many cases, they sit in the lower half of this range. This, however, is likely to reflect the high GMSLR associated with one ESM in CMIP5 ensemble of six (HadGEM2-ES), whose projected GMSLR was typically much higher (roughly twice that of the other ESMs for West AIS and positive rather than negative for East AIS). The projected GMSLR for all three AIS regions for CMIP6 and CMIP5 is very compatible if HadGEM2-ES is excluded from the latter.

Table 2. Overview of experiments and modelling groups participating in the CMIP6-forced exercise for GrIS. Please refer to Goelzer et al. (2020b) for model and group details. Symbols are those used in Figure 4. ‘f’ refers to filled symbol.

Group	Model	Open	Standard	Symbol
AWI	ISSM1		1-5	○
AWI	ISSM2		1-5	◁
AWI	ISSM3		1-5	▷
BGC	BISICLES	1-3		*
GSFC	ISSM		1-2	□
ILTS_PIK	SICOPOLIS1		1-5	△
ILTS_PIK	SICOPOLIS2		1-5	▽
IMAU	IMAUICE2		1-3,5	◇
JPL	ISSM		1-5	○ f
JPL	ISSMPALEO		1-3,5	◁ f
LSCE	GRISLI		1-5	▷ f
NCAR	CISM		1-5	□ f
UAF	PISM1		1-3,5	△ f
UAF	PISM2	1-3,5		▽ f
UCIJPL	ISSM1		1-3	◇ f
VUB	GISM		1-5	+
Total		2	14	

202 Comparing projections for SSP126 (one ESM only) and SSP585 (four ESMs) sug-
 203 gests that there is little impact of emission scenario on projected GMSLR for AIS. This
 204 is, again, most likely to be related to the contrasting impacts for global warming on the
 205 ice sheet’s mass budget through increases in both mass loss by ice-sheet discharge and
 206 gain by snow accumulation.

207 The relationship between forcing and GMSLR for each CMIP6 ESM is complicated.
 208 For instance, ocean thermal forcing (Figure 2), air temperature anomalies (Figure 1) tend
 209 to be larger for UKESM1-0-LL; however, this is not reflected in their projected GMSLR.
 210 This is most likely to be associated with the compensatory effect of increased precipi-
 211 tation (Figure 1) in these ESMs.

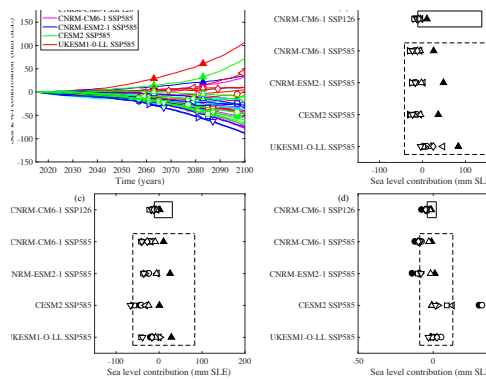


Figure 3. GMSLR contribution from the AIS to 2100. (a) Time series of contribution between 2015 and 2100 (in mm) for whole ice sheet as a function of ice sheet model (symbol) and experiment (see legend). Contribution at 2100 for (b) West AIS, (c) East AIS and (d) Antarctic Peninsula. Symbols refer to ice sheet models and are given in Table 1. Filled symbols refer to ‘open’ experiments and unfilled for ‘standard’. Boxes in panels (b) to (d) refer to ranges from equivalent CMIP5-forced experiments (see Seroussi et al. (2020)).

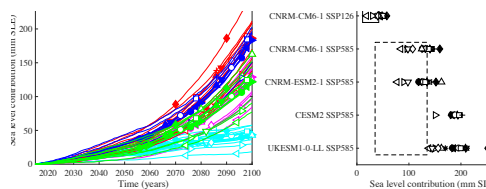


Figure 4. GMSLR contribution from the GrIS to 2100. (a) Time series of contribution between 2015 and 2100 (in mm) for whole ice sheet as a function of ice sheet model (symbol) and experiment (see legend) and (b) contribution at 2100. Symbols refer to ice sheet models and are given in Table 2. Boxes in panel (b) refers to ranges from equivalent CMIP5-forced experiments (see Goelzer et al. (2020b)).

212 Figure 4 shows projections for the GrIS from the fourteen participating ice-sheet
 213 models for each CMIP6-forced experiment along with ranges from the equivalent CMIP5-
 214 forced experiments (Goelzer et al., 2020b). Projected GMSLR is either at the upper end
 215 of the CMIP5-forced range or well above it. Indeed, both CESM2 and UKESM1-0-LL-
 216 based projections do not overlap with the CMIP5 range at all and, in the latter case, are
 217 almost double. In contrast to the AIS, projections for SSP126 (one ESM) are consider-
 218 ably lower than SSP585 (four ESMs) such that the ranges for CMIP6 SSP126 and SSP585
 219 do not overlap. The trajectory of GMSLR associated with SSP126 starts to become dis-
 220 tinct from SSP585 around 2060 but is not entirely separate until 2090. There is also a
 221 suggestion that GMSLR may stabilise (or at least increase at a far reduced rate) beyond
 222 2100 for SSP126, which is certainly not the case for SSP585.

5 Discussion

We present the first comparison between CMIP5 and CMIP6-based projections of the contribution of ice sheets to future GMSLR up to 2100. This comparison is particularly interesting because many CMIP6 ESMs have higher climate sensitivity than their CMIP5 counterparts (Forster et al., 2019; Meehl et al., 2020) and their projections of future global warming are therefore higher. The comparison is hampered by the use of a relatively small ensemble of available CMIP6 ESMs, which are all at the upper end of CMIP6's range of climate sensitivity.

The comparison between CMIP5 and CMIP6 is markedly different for the two ice sheets, reflecting the very different ways in which the ice sheets are impacted by and respond to changes in the global climate system. For the GrIS, our results suggest that GMSLR contributions under CMIP6 are much higher than for CMIP5 perhaps by a factor of two. They also suggest a significant difference between SSP585 and SSP126, with the former experiencing accelerating rates of mass loss in marked contrast to the tendency towards stabilization of the latter.

Goelzer et al. (2020b) demonstrate that in excess of 80% of GrIS' contribution to GMSLR can be explained by changing SMB (primarily by surface melt and subsequent runoff), which is mostly controlled by atmospheric processes. The link between global warming and mass loss from the ice sheet is therefore fairly direct and a strong relationship between the two should be expected. The higher climate sensitivity of the sampled CMIP6 ESMs will therefore manifest itself as a larger GMSLR contribution in comparison to CMIP5. It should also be noted that for GrIS (in contrast to AIS), global warming is likely to favour increased mass loss by both atmospheric (i.e. SMB) and ocean forcing (i.e., discharge). However it appears that, at least within the ISMIP6 experimental design, ocean forcing plays a secondary role to the atmosphere.

For AIS, our results up to 2100 suggest little difference between CMIP6 and CMIP5-forced projections. This reflects the more complex interactions between this ice sheet and the global climate system. Global warming is likely to favour mass loss through changes in discharge resulting from increased ocean thermal forcing; however, the opposite is expected of the atmospheric forcing where warming is likely to favour mass gain (as a consequence of increased snow accumulation). The higher climate sensitivity of the sampled CMIP6 ESMs is therefore associated with both increased mass gain (snowfall) and mass loss (discharge) resulting in little net change in comparison to CMIP5 forcing. The complicated regional nature of interactions between ocean thermal forcing and AIS' discharge (e.g., Jenkins et al., 2018) is also likely to weaken any link between global warming and AIS mass loss.

The experimental design of the CMIP6-forced experiments reported here does not include the fracture and collapse of AIS' floating ice shelves resulting from meltwater ponding due to significant atmospheric warming (Trusel et al., 2015). This process has been cited as a necessary precursor to rapid ice loss by the retreat of marine ice cliffs (DeConto & Pollard, 2016). As ice shelf fracture was included in the CMIP5-forced experiments, an initial assessment can be made by comparing the amount of atmospheric warming projected to occur under CMIP5 and CMIP6. Figure 1 suggests that CMIP6 ESMs lie close to or above the maximum CMIP5 surface temperature warming for AIS. For CMIP5 forcing, this process is limited to the Antarctic Peninsula and areas around George VI ice shelf and Totten glacier and its impact on GMSLR is ~ 28 mm (Seroussi et al., 2020). Ice-shelf fracture and associated processes may therefore be important under some CMIP6 forcing, in particular for CESM2 and UKESM1-0-LL, and likely be enhanced beyond 2100.

Acknowledgments

The data analysed in this paper are from available on Zenodo with digital object identifier <https://doi.org/10.5281/zenodo.4498331>. We would like to thank the Climate and Cryosphere (CliC) project for providing support for ISMIP6 through the sponsorship of workshops and hosting the ISMIP6 website. We acknowledge the University at Buffalo for their help with ISMIP6 data distribution, and the multiple agencies that support CMIP5, CMIP6 and the ESGF. This is ISMIP6 contribution number 12. This project received funding from the European Unions Horizon 2020 research and innovation programme under grant agreement No 869304, PROTECT contribution number 4.

References

- Barthel, A., Agosta, C., Little, C. M., Hatterman, T., Jourdain, N. C., Goelzer, H., ... Bracegirdle, T. J. (2020). C mip5 model selection for ismip6 ice sheet model forcing: Greenland and antarctica. *The Cryosphere*, *14*, 855–879. doi: 10.5194/tc-14-855-2020
- DeConto, R., & Pollard, D. (2016). Contribution of antarctica to past and future sea-level rise. *Nature*, *531*(7596), 591-597. doi: 10.1038/nature17145
- Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J., & Taylor, K. E. (2016). Overview of the coupled model intercomparison project phase 6 (cmip6) experimental design and organization. *Geosci. Model Dev.*, *9*(5), 1937-1958. doi: 10.5194/gmd-9-1937-2016
- Favier, L., Jourdain, N. C., Jenkins, A., Merino, N., Durand, G., Gagliardini, O., ... Mathiot, P. (2019). Assessment of sub-shelf melting parameterisations using the oceanice-sheet coupled model nemo(v3.6)elmer/ice(v8.3). *Geosci. Model Dev.*, *12*, 2255-2283. doi: 10.5194/gmd-12-2255-2019
- Fettweis, X., Franco, B., Tedesco, M., van Angelen, J. H., Lenaerts, J. T. M., van den Broeke, M. R., & Galle, H. (2013). Estimating the greenland ice sheet surface mass balance contribution to future sea level rise using the regional atmospheric climate model mar. *The Cryosphere*, *7*(2), 469-489. doi: 10.5194/tc-7-469-2013
- Flato, G., Marotzke, J., Abiodun, B., Braconnot, P., Chou, S., Collins, W., ... Rummukainen, M. (2013). Evaluation of climate models. In T. Stocker et al. (Eds.), *Climate change 2013: The physical science basis. contribution of working group i to the fifth assessment report of the intergovernmental panel on climate change* (p. 741866). Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press. doi: 10.1017/CBO9781107415324.020
- Forster, P., Maycock, A., McKenna, C., & Smith, C. (2019). Latest climate models confirm need for urgent mitigation. *Nature Climate Change*.
- Goelzer, H., Noel, B., Edwards, T. L., Fettweis, X., Gregory, J. M., Lipscomb, W. H., ... van den Broeke, M. R. (2020a). Remapping of greenland ice sheet surface mass balance anomalies for large ensemble sea-level change projections. *The Cryosphere*, *14*(6), 1747–1762. doi: 10.5194/tc-14-1747-2020
- Goelzer, H., Nowicki, S., Payne, A., Larour, E., Seroussi, H., Lipscomb, W., ... van den Broeke, M. (2020b). The future sea-level contribution of the greenland ice sheet: a multi-model ensemble study of ismip6. *The Cryosphere*, *14*(9), 3071–3096. doi: 10.5194/tc-14-3071-2020
- IPCC. (2013). Annex iii: Glossary. In T. Stocker et al. (Eds.), *Climate change 2013: The physical science basis. contribution of working group i to the fifth assessment report of the intergovernmental panel on climate change* (p. 14471466). Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press. doi: 10.1017/CBO9781107415324.031
- Jenkins, A., Shoosmith, D., Dutrieux, P., Jacobs, T. W., Stan Kim, Lee, S. H., Ha, H. K., & Stammerjohn, S. (2018). West antarctic ice sheet retreat in the amundsen sea driven by decadal oceanic variability. *Nature Geoscience*,

- 324 11(10), 733-738. doi: 10.1038/s41561-018-0207-4
- 325 Jourdain, N., Asay-Davis, X., Hattermann, T., Straneo, F., Seroussi, H., Little, C.,
326 & Nowicki, S. (2020). A protocol for calculating basal melt rates in the is-
327 mip6 antarctic ice sheet projections. *The Cryosphere*, 14(9), 3111–3134. doi:
328 10.5194/tc-14-3111-2020
- 329 Meehl, G., Senior, C., Eyring, V., Flato, G., Lamarque, J.-F., Stoffer, R., & Schlund,
330 M. (2020). Context for interpreting equilibrium climate sensitivity and tran-
331 sient climate response from the cmip6 earth system models. *Science Advances*,
332 6(26). doi: 10.1126/sciadv.aba1981
- 333 Nowicki, S., Goelzer, H., Seroussi, H., Payne, A. J., Lipscomb, W. H., Abe-Ouchi,
334 A., . . . van de Wal, R. (2020). Experimental protocol for sea level projections
335 from ismip6 standalone ice sheet models. *The Cryosphere*, 14(7), 2331–2368.
336 doi: 10.5194/tc-14-2331-2020
- 337 Nowicki, S., Payne, A., Larour, E., Seroussi, H., Goelzer, H., Lipscomb, W., . . .
338 Shepherd, A. (2016). Ice sheet model intercomparison project (ismip6) con-
339 tribution to cmip6. *Geoscientific Model Development*, 9(12), 4521-4545. doi:
340 10.5194/gmd-9-4521-2016
- 341 Schoof, C. (2007). Ice sheet grounding line dynamics: Steady states, stability, and
342 hysteresis. *Journal of Geophysical Research-Earth Surface*, 112(F3). doi: 10
343 .1029/2006JF000664
- 344 Seroussi, H., Nowicki, S., Payne, A. J., Goelzer, H., Lipscomb, W. H., Abe-Ouchi,
345 A., . . . Zwinger, T. (2020). Ismip6 antarctica: a multi-model ensemble of the
346 antarctic ice sheet evolution over the 21st century. *The Cryosphere*, 14(9),
347 3033–3070. doi: 10.5194/tc-14-3033-2020
- 348 Slater, D. A., Felikson, D., Straneo, F., Goelzer, H., Little, C., Morlighem, M., . . .
349 Nowicki, S. (2020). 21st century ocean forcing of the greenland ice sheet for
350 modeling of sea level contribution. *The Cryosphere*, 14(3), 985–1008. doi:
351 10.5194/tc-14-985-2020
- 352 Slater, D. A., Straneo, F., Felikson, D., Little, C. M., Goelzer, H., Fettweis,
353 X., & Holte, J. (2019). Estimating greenland tidewater glacier retreat
354 driven by submarine melting. *The Cryosphere*, 13(9), 2489-2509. doi:
355 10.5194/tc-13-2489-2019
- 356 Taylor, K., Stouffer, R., & Meehl, G. (2012). An overview of cmip5 and the ex-
357 perimnt design. *Bulletin of the American Meteorological Society*, 93(4), 485-
358 498. doi: 10.1175/BAMS-D-11-00094.1
- 359 Trusel, L. D., Frey, K. E., Das, S. B., Karnauskas, K. B., Kuipers Munneke, P., van
360 Meijgaard, E., & van den Broeke, M. R. (2015). Divergent trajectories of
361 antarctic surface melt under two twenty-first-century climate scenarios. *Nature*
362 *Geoscience*, 8(12), 927-932. doi: 10.1038/ngeo2563