ARTICLE

Projected land ice contributions to 21st century sea level rise

Tamsin L. Edwards[1]*, Sophie Nowicki[2,58], Ben Marzeion[6,7], Regine Hock[14,52], Heiko Goelzer[3,4,53], Hélène Seroussi[5], Nicolas C. Jourdain[9], Donald Slater[10,51], Fiona Turner[1], Christopher J. Smith[8], Christine M. McKenna[8], Erika Simon[2], Ayako Abe-Ouchi[11], Jonathan M. Gregory[12,13], Eric Larour[5], William H. Lipscomb[15], Antony J. Payne[16], Andrew Shepherd[17], Cécile Agosta[18], Patrick Alexander[19,20], Torsten Albrecht[21], Brian Anderson[22], Xylar Asay-Davis[23], Andy Aschwanden[14], Alice Barthel[23], Andrew Bliss[24], Reinhard Calov[21], Christopher Chambers[25], Nicolas Champollion[6,9], Youngmin Choi[26,5], Richard Cullather[2], Joshua Cuzzone[5], Christophe Dumas[18], Denis Felikson[2,57], Xavier Fettweis[28], Koji Fujita[29], Benjamin K. Galton-Fenzi[27,44], Rupert Gladstone[47], Nicholas R. Golledge[22], Ralf Greve[25,56], Tore Hattermann[30,31], Matthew J. Hoffman[23], Angelika Humbert[32,48], Matthias Huss[33,34,35], Philippe Huybrechts[36], Walter Immerzeel[37], Thomas Kleiner[32], Philip Kraaijenbrink[37], Sébastien Le clec'h[36], Victoria Lee[38], Gunter R. Leguy[15], Christopher M. Little[39], Daniel P. Lowry[49], Jan-Hendrik Malles[6,7], Daniel F. Martin[50], Fabien Maussion[40], Mathieu Morlighem[26], James F. O'Neill[1], Isabel Nias[2,55], Frank Pattyn[4], Tyler Pelle[26], Stephen Price[23], Aurélien Quiquet[18], Valentina Radić[41], Ronja Reese[21], David R. Rounce[14], Martin Rückamp[32], Akiko Sakai[29], Courtney Shafer[50], Nicole-Jeanne Schlegel[5], Sarah Shannon[16], Robin S. Smith[12], Fiammetta Straneo[10], Sainan Sun[4], Lev Tarasov[42], Luke D. Trusel[43], Jonas Van Breedam[36], Roderik van de Wal[3,37], Michiel van den Broeke[3], Ricarda Winkelmann[21,54], Harry Zekollari[45,4,33,34], Chen Zhao[44], Tong Zhang[23], Thomas Zwinger[46]

* Corresponding author

1 Department of Geography, King's College London, London, UK

2 NASA Goddard Space Flight Center, Greenbelt, MD, USA

3 Institute for Marine and Atmospheric research Utrecht, Utrecht University, The Netherlands

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

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

6 Institute of Geography, University of Bremen, Germany

7 MARUM – Center for Marine Environmental Sciences, University of Bremen, Germany

8 Priestley International Centre for Climate, University of Leeds, Leeds, UK

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

10 Scripps Institution of Oceanography, University of California San Diego, La Jolla, CA, USA

11 Atmosphere and Ocean Research Institute, The University of Tokyo, Kashiwa-shi, Chiba 277-8564, Japan

12 National Centre for Atmospheric Science, University of Reading, Reading, UK

13 Met Office, Hadley Centre, Exeter, UK

14 Department of Civil and Environmental Engineering, Carnegie Mellon University, USA

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

16 School of Geographical Sciences, University of Bristol, Bristol, UK

17 Centre for Polar Observation and Modelling, School of Earth and Environment, University of Leeds, Leeds, LS2 9JT, UK

18 Laboratoire des sciences du climat et de l'environnement, LSCE-IPSL, CEA-CNRS-UVSQ, Université Paris-Saclay, France

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

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

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

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

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

24 Department of Anthropology and Geography, Colorado State University, USA

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

26 Department of Earth System Science, University of California Irvine, Irvine, CA, USA

27 Australian Antarctic Division, Kingston, Tasmania, Australia

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

29 Graduate School of Environmental Studies, Nagoya University, Nagoya, Japan

30 Norwegian Polar Institute, Tromsø, Norway

31 Energy and Climate Group, Department of Physics and Technology, The Arctic University – University of Tromsø, Tromsø, Norway

32 Alfred-Wegener-Institut Helmholtz-Zentrum für Polar- und Meeresforschung, Bremerhaven, Germany

33 Laboratory of Hydraulics, Hydrology and Glaciology (VAW), ETH Zurich, Switzerland

34 Swiss Federal Institute for Forest, Snow and Landscape Research (WSL), Birmensdorf, Switzerland

35 Department of Geosciences, University of Fribourg, Switzerland

36 Earth System Science and Departement Geografie, Vrije Universiteit Brussel, Brussels, Belgium

37 Department of Physical Geography, Utrecht University, The Netherlands

70   38 Centre for Polar Observation and Modelling, School of Geographical Sciences, University of Bristol,

71   Bristol, UK

72   39 Atmospheric and Environmental Research, Inc., Lexington, Massachusetts, USA

73   40 Department of Atmospheric and Cryospheric Sciences, University of Innsbruck, Austria

74   41 Department of Earth, Ocean and Atmospheric Sciences, University of British Columbia, Canada

75   42 Dept of Physics and Physical Oceanography, Memorial University of Newfoundland, Canada

76   43 Department of Geography, Pennsylvania State University, University Park, PA, USA

77   44 Australian Antarctic Program Partnership, Institute for Marine and Antarctic Studies, University of

78   Tasmania, Hobart, Tasmania

79   45 Department of Geoscience and Remote Sensing, Delft University of Technology, The Netherlands

80   46 CSC-IT Center for Science, Espoo, Finland

81   47 Arctic Centre, University of Lapland, Finland

82   48 Department of Geoscience, University of Bremen, Bremen, Germany

83   49 GNS Science, Lower Hutt, New Zealand

84   50 Computational Research Division, Lawrence Berkeley National Laboratory, Berkeley, CA, USA

85   51 School of Geography and Sustainable Development, University of St Andrews, UK

86   52 Department of Geosciences, University of Oslo, Norway

87   53 NORCE Norwegian Research Centre, Bjerknes Centre for Climate Research, Bergen, Norway

88   54 Department of Physics and Astronomy, University of Potsdam, Potsdam, Germany

89   55 School of Environmental Sciences, University of Liverpool, Liverpool, UK

90   56 Arctic Research Center, Hokkaido University, Sapporo, Japan

91   57 Universities Space Research Association, Goddard Earth Sciences Technology and Research Studies

92   and Investigations, Columbia, MD 21044, USA

93   58 Geology Department and RENEW Institute, University at Buffalo, Buffalo, NY, USA

94

95   **The land ice contribution to global mean sea level rise has not yet been predicted[1] with**

96   **ice sheet and glacier models for the latest set of socio-economic scenarios, nor with**

97   **coordinated exploration of uncertainties arising from the various computer models**

98   **involved. Two recent international projects generated a large suite of projections using**

99   **multiple models[2-3,5,8,14-16], but mostly used previous generation scenarios[9] and climate**

100   **models[21], and could not fully explore known uncertainties. Here we estimate probability**

101   **distributions for these projections under the new scenarios[19,30] using statistical**

102   **emulation of the ice sheet and glacier models, and find that limiting global warming to**

103   **1.5°C would halve the land ice contribution to 21st century sea level rise, relative to**

104   **current emissions pledges. The median decreases from 25 to 13 cm sea level equivalent**

105   **(SLE) by 2100, with glaciers responsible for half the sea level contribution. The**

106   **Antarctic contribution does not show a clear response to emissions scenario, due to**

competing processes of increasing ice loss and snowfall accumulation in a warming climate. However, under risk-averse (pessimistic) assumptions, Antarctic ice loss could be five times higher, increasing the median land ice contribution to 42 cm SLE under current policies and pledges, with the upper end (95th percentile) exceeding half a metre even under 1.5°C warming. This would severely limit the possibility of mitigating future coastal flooding. Given this large range (13 cm main projections under 1.5°C warming; 42 cm risk-averse projections under current pledges), adaptation must plan for a factor of three uncertainty in the land ice contribution to 21st century sea level rise until climate policies and the Antarctic response are further constrained.

Land ice has contributed around half of all sea level rise since 1993, and this fraction is expected to increase[1]. The Ice Sheet Model Intercomparison Project (ISMIP6[2,3]) for CMIP6[4] and the Glacier Model Intercomparison Project (GlacierMIP[5]) provide the Intergovernmental Panel on Climate Change (IPCC) with projections of Earth's ice sheet and glacier contributions to future sea level. Both projects use suites of numerical models[6,7,8] and greenhouse gas emission scenarios[9] as the basis of their projections, and a variety of treatments are considered for the interaction between the ice sheets and the ocean[10,11,12,13]. In total, the projects provide 256 simulations of the Greenland ice sheet, 344 simulations of the Antarctic ice sheet, and 288 simulations of the global glacier response to climate change [8,14,15,16] (see also Extended Data Table 1). Although these simulations represent an unprecedented effort [3,6,7,8,10-18], their computational expense and complexity has meant that they (i) focus mainly on previous generation emissions scenarios (Representation Concentration Pathways[9], RCPs) developed for the IPCC's Fifth Assessment Report, not the more diverse and policy-relevant Shared Socioeconomic Pathways (SSPs[19,20]) that underpin the IPCC's Sixth Assessment Report, (ii) are driven mostly by a relatively small number of older generation global climate models developed before CMIP6[21], and (iii) have incomplete and limited ensemble designs.

To address these limitations, we emulate the future sea level contribution of the 23 regions comprising the world's land ice (see Extended Data Table 2) as a function of global mean surface air temperature change and as a consequence of marine-terminating glacier retreat in Greenland and ice-shelf basal melting and collapse in Antarctica. The ensembles of ice sheet and glacier models are emulated all at once for each region, using their simulations as

140   multiple estimates of sea level contribution for a given set of uncertain input values, and we

141   incorporate the ensemble spread through the use of a 'nugget 'term in Gaussian Process

142   emulation[22,23]. Gaussian Process regression requires minimal assumptions about the

143   functional form, and provides uncertainty estimates for the emulator predictions[24]; most

144   previous emulator-type approaches for sea level rise use parametric models, where the

145   functional form is assumed[25-29]. We then use the emulators to make probabilistic projections

146   for the glacier and ice sheet sea level contributions under five SSPs and under an additional

147   scenario reflecting current climate pledges (Nationally Determined Contributions, NDCs)[30]

148   made under the Paris Agreement. Most projections presented are for the year 2100, but we

149   also estimate a full timeseries by emulating each year from 2016 to 2100. The details of our

150   emulation approach are described in the Methods.

151

Response to temperature and parameters

153

154   Most land ice regions show a fairly linear relationship of increasing mass loss with global

155   mean surface air temperature. Figure 1 shows the temperature-dependence of the sea level

156   contribution at 2100 for the ice sheets and peripheral glaciers (Fig. 1 a-f) and eleven other

157   glacier regions: four with large maximum contributions (Alaska, Arctic Canada North and

158   South, Russian Arctic: Fig. 1g-j), two with non-linear temperature-dependence, giving near

159   or total disappearance at high temperatures (Central Europe and Caucasus: Fig. 1k, l), and the

160   three regions comprising High Mountain Asia (Fig. 1m-o), which are important for local

161   water supply[32]. Values of ice sheet parameters are fixed at two possible values for Greenland

162   glacier retreat and Antarctic basal melting, with no Antarctic ice shelf collapse; only

163   simulations using these values are shown. The ensemble designs are not complete – for

164   example, many fewer ice sheet simulations were performed under RCP2.6 than RCP8.5 – so

165   some of the apparent patterns in the simulation data are artefacts of the gaps, which the

166   emulator is intended to account for.

167

168   Greenland and the glaciers, which are dominated by surface melting[8,14,16], show clear

169   dependence on temperature. Fourteen of the nineteen glacier regions show approximately

170   linear relationships, and five are nonlinear (Fig. 1f, k, l; also Western Canada & U.S. and

171   North Asia, which have weaker nonlinearity: not shown). In contrast, East Antarctica (Fig.

172   1c) shows a slight decrease in sea level contribution with temperature: snowfall increases,

173 because warmer air can hold more water vapour, and this dominates over the increase in mass

174 loss due to melting[15,16]. Finally, West Antarctica and the Peninsula (b, e) show little

175 detectable temperature-dependence, due to an approximate cancellation across varying

176 climate and ice sheet model predictions of snowfall accumulation and ice loss. Antarctic ice

177 sheet results are discussed in detail later (see 'Antarctic focus').

178

179 The ice sheet contributions depend strongly on the Greenland glacier retreat and Antarctic

180 sub-shelf basal melting parameters, which determine the sensitivity of the marine-terminating

181 glaciers to ocean temperatures (and surface meltwater runoff for Greenland). Figure 2 shows

182 these relationships; the Greenland parameter is defined such that more negative values

183 correspond to further retreat inland.

184

Land ice contributions in 2100

186

187 We use probability distributions for global mean surface air temperature (Fig. 3a: FaIR

188 simple climate model[30]) and ice-ocean parameters (Figs. 3b and 3c show κ and γ, which are

189 derived from the original parameterisation studies; ice shelf collapse is assigned equal

190 probability off/on) as inputs to the emulators. Time series projections for the land ice

191 contribution under all scenarios are shown in Fig. 3d, and probability density functions at

192 2100 for the Greenland ice sheet, Arctic Canada North, the glacier total, and West and East

193 Antarctica in Fig. 3e-i. The Antarctic ice sheet total under the NDCs is shown in (j). ('Risk-

194 averse' projections in (d) and (j) are discussed later.) Density estimates are less smooth for the

195 glacier and Antarctica totals than individual regions, because sums of regions are estimated

196 by random sampling rather than deterministic integration; these samples are shown for

197 Antarctica (j).

198

199 Our projections show that reducing greenhouse gas emissions from current and projected

200 pledges under the Paris Agreement (NDCs) enough to limit warming to 1.5 °C (SSP1-19)

201 would nearly halve the land ice contribution to sea level at 2100 (Table 1: median decreases

202 from 25 cm to 14 cm SLE). This halving is not evenly distributed across the three ice

203 sources: Greenland ice sheet mass losses would reduce by 70%, glacier mass losses by about

204 half, and Antarctica shows no significant difference between scenarios; this is not due to a

205 lack of change in the Antarctica simulations themselves, but rather to the cancellation of mass

206 gains and losses mentioned above.

207

208 Average rates of mass loss for each ice sheet and the glacier total are within 1-2 cm/century,

209 of those of the 2013 IPCC Fifth Assessment Report[25] (see Methods: Comparison with IPCC

210 assessments), and the updated assessment for RCP2.6 in the 2019 IPCC Special Report on

211 the Oceans and Cryosphere in a Changing Climate (SROCC)[1]. However, SROCC revised the

212 projection for Antarctica under RCP8.5 up to 11 cm/century, close to the upper end of our

213 66% interval for SSP5-85 (though our projections may omit a commitment contribution of up

214 to about 2 cm/century; see Methods). Our results are therefore closer to the 2013 than 2019

215 IPCC assessment regarding the magnitude and unclear scenario-dependence for Antarctica.

216 Our 66% uncertainty intervals are narrower than the IPCC 66% (SROCC) and $\geq$ 66% (AR5)

217 uncertainty intervals, as would be expected from the latter being open-ended, except those for

218 Greenland under SSP1-26: too few Greenland simulations were performed under low

219 scenarios (RCP2.6, SSP1-26) to constrain the emulator variance (see Fig. 1a; Methods:

220 'Parameter interactions').

221

222 Emulation allows us to additionally assess the sensitivity of projections to uncertainties in

223 their inputs as well as their robustness. If we use CMIP6 global climate models for the

224 projections (Extended Data Figure 3), instead of FaIR, we find a slight increase in sea level

225 contributions due to the larger proportion of models with high climate sensitivity to carbon

226 dioxide[33,34]: the 95th percentile increases by 7 cm under SSP5-85. We estimate the potential

227 impact of reducing uncertainty with future knowledge by using fixed values for temperature,

228 or for the ice sheet retreat and basal melt parameters: the width of the 5-95% ranges reduce

229 by up to 13% and 17% respectively (tests 2-4 in Methods: Sensitivity tests; Extended Data

230 Table 3 and Extended Data Figure 4). In other words, the ice-ocean interface is a similar

231 magnitude contributor to, or larger, uncertainty for these projections as global warming under

232 a particular emissions scenario. When we assess the robustness of the projections to different

233 selections and treatments of the ice sheet simulations, we find this makes very little

234 difference (tests 2-4 in Methods: Robustness checks; Extended Data Table 4; Extended Data

235 Figure 5).

236

237 ## Antarctic focus

238

239 No clear dependence on emissions scenario emerges for Antarctica. This is partly due to the

240 opposite scenario-dependencies of West and East Antarctica regions (Fig. 3f and g). But the

241 average response to emissions scenario for each region is also small. A key reason is the wide

242 variety of changes in the atmosphere and ocean in the global climate models. Figure 4 shows

243 ice sheet model simulations where both the high and low emissions scenario were run (two

244 climate models for Greenland, three for Antarctica). For the Greenland ice sheet, all

245 simulations predict increased mass loss under higher emissions (Fig. 4a: red shaded region).

246 For Antarctica, the picture is more complex, and mostly clustered according to the climate

247 model. Many West Antarctica simulations show the same straightforward response as

248 Greenland (Fig. 4b), particularly those that do not use the ISMIP6 basal melting

249 parameterisation (see Methods). However, the West Antarctica simulations driven by

250 CNRM-CM6-1 show the reverse, where mass gain through snowfall accumulation increases

251 more under high emissions than mass loss (which is predominantly ocean-induced). (Note

252 fewer simulations were driven by IPSL-CM5A-MR and CNRM-CM6-1 than by NorESM1-

253 M, so their spread is necessarily smaller). East Antarctica and the Peninsula mostly also show

254 this latter response, though some simulations show other combinations: more mass loss under

255 low emissions than high, or mass loss under low emissions and mass gain under high.

256

257 It is challenging to evaluate which of these three climate models, or others used by ISMIP6,

258 are most reliable for Antarctic climate change. Ocean conditions and accumulation show

259 large spatio-temporal variability and are sparsely observed; models imperfectly represent

260 important processes, and it is unclear whether the newer CMIP6 models have improved

261 relative to CMIP5[13,35-38]. Most of the climate models were from CMIP5, including

262 NorESM1-M and IPSL-CM5A-MR, and were selected by their success at reproducing

263 southern climatological observations (while also sampling a range of future climate

264 responses)[18]. NorESM-1M has a lower than average atmospheric warming, hence less

265 snowfall, while IPSL-CM5A-MR is higher than average (particularly for East Antarctica)[18].

266 The newer CMIP6 models, including CNRM-CM6-1, were selected only by their availability.

267 Changing the selection or treatment of Antarctica simulations – e.g. using subsets of climate

268 models, or rejecting simulations with net mass gain early in the projections – do not result in

269 any substantial scenario-dependence (see tests 7-10 in Methods: Robustness checks;

270 Extended Data Table 4; Extended Data Figure 5).

271

272 Uncertainty about the scenario-dependence of Antarctic projections is not new. The IPCC

273 Fifth Assessment Report (2013) stated 'the current state of knowledge does not permit an

274 assessment' of the dependence of rapid dynamical change on scenario. Some studies that

275 show strong scenario-dependence neglect the compensating accumulation part[26,39], use

276 extreme[1] ice shelf collapse scenarios[24], or the basal melt parameterisation uncertainty is the

277 same order as, or larger than, the scenario-dependence[27,40,41]. To be clear, we do not assert

278 that Antarctica's future does not depend on future greenhouse emissions or global warming:

279 only that the relationship between global and Antarctic climate change, and the ice sheet's

280 response, are complex, only partially understood, and involve compensating factors of

281 increasing mass loss and gain which result in a balance we are not yet confident about.

282

283 We test the sensitivity of the Antarctica projections to the basal melting parameter. The main

284 projections combine two distributions[13] for γ derived from observations of mean Antarctic

285 basal melt rates or the ten highest melt rates for Pine Island Glacier (see Methods). Using the

286 mean distribution decreases the median to ~0 cm SLE and the 95th percentile to ~8 cm SLE

287 for all scenarios; using the high distribution has less effect, increasing the median to 6 cm

288 SLE and the 95th percentile to ~16 cm SLE (Extended Data Table 3 and Extended Data

289 Figure 4: tests 5 and 6). We also try and reproduce the higher projections of ref. [26] using a

290 similar approach to sampling basal melt (see Methods), and find we only obtain similar

291 projections when using extreme values of our parameter range (Extended Data Table 3 and

292 Extended Data Figure 4: tests 7 and 8). This suggests ref. [26] could be interpreted as more

293 pessimistic projections: they use values of basal melt sensitivity to ocean temperature

294 consistent with those estimated for the Amundsen Sea region[39], which is currently

295 undergoing most change.

296

297 However, other factors can lead to similarly high projections. In particular, the sensitivity of

298 an individual ice sheet model to the basal melt parameter can have a large effect. This differs

299 widely across ice sheet models, and also depends on the climate model (Extended Data

300 Figure 6). Emulator projections based on a single model with high or low sensitivity are

301 shown in Extended Data Figure 5 (tests 4 and 5; Extended Data Table 4). These also do not

302 show strong scenario-dependence – just a 2-3 cm decrease under high emissions for the low

303 sensitivity model, because the snowfall effect is more apparent – but instead predict a high or

304 low sea level contribution, respectively, regardless of scenario (95th percentiles: 29-30 cm

305 and 7-9 cm, respectively). The high sensitivity of the first model (SICOPOLIS) is probably

306 due to the way that sub-shelf melting is applied: over entire grid cells along the grounding

307 line, rather than just the parts detected as floating[26]. We also show results from the four most

308 sensitive models, which are similarly high (Extended Data Table 4 and Extended Data Figure

309 5: test 6). We do not have sufficient observations to evaluate which ice sheet models have the

310 most realistic response, nor sufficient understanding to confidently predict how basal melt

311 sensitivity might change in future[13,36], and therefore use all models in the main projections

312 (see also 'Risk-averse projections' below).

313

314 The ice shelf collapse scenario has little effect on our projections. Switching it on increases

315 the Antarctic Peninsula and East Antarctic median contributions by 1 cm and 0-1 cm SLE

316 from 2015-2100, with no change for West Antarctica (Extended Data Table 3 and Extended

317 Data Figure 4: test 9-10). This is similar, within uncertainties, to the ice sheet simulations

318 (Extended Data Figure 7). The effect is small because surface meltwater is not projected to be

319 enough to cause collapses until the second half of the century, and even then only for small

320 number of shelves, mostly around the Peninsula[15]. Some combinations of climate and ice

321 sheet models do project larger sea level contributions – in particular, 5 cm for East Antarctica

322 from the SICOPOLIS ice sheet model driven by HadGEM2-ES. The HadGEM2-ES climate

323 model projects extreme ocean warming in the Ross Sea[18], while SICOPOLIS has one of the

324 largest responses among the ice sheet models (as described above). If these two were found

325 to be the most realistic models, then the ISMIP6 ensemble and emulator may underestimate

326 the effect of ice shelf collapse by a few centimetres. Further results are in the Methods

327 ('Parameter interactions').

328

Risk-averse projections

330

331 Given the wide range and cancellations of responses across models and parameters, we

332 present alternative 'pessimistic but physically plausible' Antarctica projections for risk-averse

333 stakeholders, by combining a set of assumptions that lead to high sea level contributions.

334 These are: the four ice sheet models most sensitive to basal melting; the four climate models

335 that lead to highest Antarctic sea level contributions, and the one used to drive most of the ice

336 shelf collapse simulations; the high basal melt (Pine Island Glacier) distribution; and with ice

337 shelf collapse 'on' (i.e. combining robustness tests 6 and 7 and sensitivity tests 6 and 10). This

338 storyline would come about if the high basal melt sensitivities currently observed at Pine

339 Island Glacier soon become widespread around the continent; the ice sheet responds to these

340   with extensive retreat and rapid ice flow; and atmospheric warming is sufficient to

341   disintegrate ice shelves, but does not substantially increase snowfall. The risk-averse

342   projections are more than five times the main estimates: median 21 cm (95th percentile range

343   7 to 43 cm) under the NDCs (Fig. 3j), and essentially the same under SSP5-85 (Table 1;

344   regions shown in Extended Data Figure 4: test 11), with the 95th percentiles emerging above

345   the main projections after 2040 (Fig. 3d). This is very similar to projections[24] under an

346   extreme scenario of widespread ice shelf collapses for RCP8.5 (median 21 cm; 95th percentile

347   range 9 to 39 cm). The median is higher than ref. [26] for RCP8.5, though the 95th percentile

348   is smaller. No models that include a representation of rapid ice cliff collapse through the

349   proposed 'Marine Ice Cliff Instability'[43] mechanism participated in ISMIP6. This hypothesis

350   is the process with the largest estimated systematic impact on projections: it could increase

351   projections by tens of centimetres, if both the mechanism and projections of extreme ice shelf

352   collapse are found to be robust[24,44].

353

354   Our risk-averse Antarctica projections increase the total land ice sea level contribution to 42

355   cm (95th percentile 25 to 67 cm) SLE under current policies and pledges (NDCs), and to 30

356   cm (95th percentile 12 to 56 cm) SLE even under SSP1-19. This means that plausible

357   modelling choices for Antarctica could change the median land ice contribution by more (17

358   cm SLE) than the difference between these emissions scenarios (12 cm SLE). This ambiguity

359   limits confidence in assessing the effectiveness of mitigation on the response of global land

360   ice to climate change. When combined, the effects of uncertain emissions and Antarctic

361   response lead to a threefold spread in median projections of the land ice contribution to sea

362   level rise, ranging from 13 to 42 cm SLE over 2015-2100, implying that flexible adaptation

363   under substantial uncertainty will be essential until either can be further constrained.

364

365   Not all modelling uncertainties could be systematically assessed here. Aside from the ice cliff

366   instability hypothesis, these include ice sheet basal hydrology and sliding; glacier model

367   parameters, ice-water interactions, and meltwater routing; model initialisation; and the use of

368   coarse resolution global climate models (and a single high-resolution regional model for the

369   Greenland ice sheet). The probabilities we present are therefore specific to our ensembles,

370   and adding new climate and ice sheet models, or exploration of new parameters, could shift

371   or broaden their distributions[45]. However, our projections demonstrate the importance of

372   systematic design to assess as many uncertainties as feasible, and represent the current state-

373   of-the art in estimating the land ice contribution to global mean sea level rise.

Sea level contribution from 2015-2100 (cm SLE)	Main projections		Risk-averse projections	
	50 [5, 95]% percentiles	**[17, 83]% percentiles**	**50 [5, 95]% percentiles**	**[17, 83]% percentiles**
Global glaciers				
SSP119	7 [4, 10]	[5, 9]		
SSP126	8 [5, 12]	[6, 10]		
SSP245	11 [7, 15]	[9, 13]		
NDCs	**13 [9, 18]**	**[11, 16]**		
SSP370	14 [10, 19]	[12, 17]		
SSP585	16 [12, 21]	[14, 19]		
Greenland ice sheet				
SSP1-19	2 [-6, 11]	[-2, 7]		
SSP1-26	3 [-4, 12]	[-1, 8]		
SSP2-45	5 [-2, 14]	[1, 10]		
NDCs	**7 [0, 16]**	**[3, 12]**		
SSP3-70	8 [0, 17]	[4, 13]		
SSP5-85	10 [2, 20]	[5, 15]		
Antarctic ice sheet				
SSP1-19	4 [-5, 14]	[-1, 10]	21 [6, 42]	[12, 32]
SSP1-26	4 [-5, 14]	[-1, 10]	21 [7, 43]	[12, 31]
SSP2-45	4 [-5, 14]	[-1, 9]	21 [7, 43]	[12, 31]
NDCs	**4 [-5, 14]**	**[-1, 10]**	**21 [7, 43]**	**[13, 31]**
SSP3-70	4 [-5, 14]	[-1, 10]	21 [8, 43]	[13, 31]
SSP5-85	4 [-5, 14]	[-1, 10]	22 [8, 43]	[14, 32]
Land ice				
SSP1-19	13 [0, 28]	[6, 21]	30 [12, 56]	[20, 43]
SSP1-26	16 [3, 30]	[8, 24]	33 [15, 58]	[22, 45]
SSP2-45	20 [7, 35]	[13, 28]	38 [20, 63]	[28, 50]
NDCs	**25 [11, 40]**	**[17, 33]**	**42 [25, 67]**	**[32, 54]**
SSP3-70	27 [13, 41]	[19, 35]	44 [27, 70]	[34, 56]
SSP5-85	30 [16, 46]	[22, 39]	48 [30, 75]	[38, 61]

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459 **Author contributions**

460

461 T.L.E. conceived the idea, carried out all statistical analysis except the random effects model,

462 produced the figures, and wrote the manuscript. S.N. led ISMIP6, including experimental

463 design, organisation and analysis, and provided scientific interpretation. B.M and R.H. co-led

464 GlacierMIP and contributed simulations (below), and provided data and interpretation. H. G.

465 and H.S. led the processing and analysis in ISMIP6 for the Greenland and Antarctic ice

466 sheets, respectively, contributed simulations (below), and provided scientific interpretation

467 and advice. N.J. and. D.S. co-derived with T.L.E. the ice sheet continuous parameter

468 distributions for the emulator, and also derived the corresponding ocean forcing

469 parameterisation studies with X.A.-D. and T.H. for Antarctica and F.S., D.F. and M.M. for

470 Greenland. F.T. performed the random effects model cross-check for Antarctica. C.S.

471 provided the FaIR projections and C.M. provided the CMIP5 and CMIP6 projection data for

472 the emulator. E.S. led the ISMIP6 data processing. A.A.O., J.M.G., E.L., W.H.L., A.J.P.,

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631

632 **Figure 1. Ice sheet and glacier mass loss generally increases linearly with global mean**

633 **temperature.** Projected mass changes from 2015-2100 in sea level equivalent (SLE) as a function of

634 global mean surface air temperature change over the same period for (a) Greenland ice sheet, (b, c)

635 West and East Antarctic ice sheets, (d) Greenland peripheral glaciers, (e, f) the Antarctic Peninsula

636 and Antarctic peripheral glaciers, (g-j) four glacier regions with large maximum sea level

637 contributions (Alaska, Arctic Canada North and South, Russian Arctic), (k, l) two regions with

638 nonlinear temperature-dependence and total or near-total disappearance projected at high

639 temperatures (Central Europe and Caucasus); and (m-o) three regions comprising High Mountain

640 Asia. Central solid lines show the emulator mean, and shaded regions the mean ± 2 s.d.. For the ice

641 sheets (a-c, e), darker shaded regions use parameter values fixed at their default values (Greenland

642 glacier retreat: median; Antarctic sub-shelf basal melting: median of Mean Antarctic distribution;

643 Antarctic ice shelf collapse off), and lighter shaded regions use alternative values (Greenland: 75th

644 percentile; Antarctica: median of Pine Island Glacier distribution). See Methods for details. Points

645 show ice sheet and glacier simulations under RCP2.6/SSP1-26 (blue), RCP4.5 (yellow), RCP6.0

646 (orange) and RCP8.5/SSP5-85 (red). Solid circles for the ice sheets use the default ice-ocean

647 parameter value and open circles use the alternative value (other simulations are not shown). Glacier

648   simulations are change in total volume, not volume above flotation; the estimated maximum sea level

649   contribution (i.e. current total glacier volume above flotation)[31] is shown (horizontal dashed line).

650

651   **Figure 2. Ice sheet mass loss strongly depends on ice-ocean parameters.** Projections of sea level

652   contribution from 2015-2100 as a function of (a) Greenland glacier retreat parameter (κ), and basal

653   melt parameter (γ) for (b) West Antarctica, (c) East Antarctica, (d) Peninsula. Solid line shows

654   emulator mean estimate using fixed global temperature (projected by the global climate model most

655   used for simulations, under RCP8.5), and shaded regions show the mean $\pm$ 2 s.d. Symbols show ice

656   sheet models forced by this climate model for which simulations for at least three (Greenland) or four

657   (Antarctic) melt parameter values were available: circles use the ISMIP6 parameterisation for the ice-

658   ocean interface; crosses use other representations, and are assigned ensemble mean values of the

659   parameter; triangles show the Greenland ice sheet model for which two additional values of κ were

660   run.

661

662   **Figure 3. Projected land ice contribution to 21st century sea level rise and for selected regions at**

663   **2100.** (a) Probability distributions for global mean surface air temperature change from 2015-2100

664   from the FaIR simple climate model under the five Shared Socioeconomic Pathways (SSPs) and

665   current Nationally Determined Contributions (NDCs) (N = 5000 each). (b) Greenland ice sheet retreat

666   parameter (κ) distribution (N = 10,000): vertical lines show the five values used for simulations:

667   median (solid), 25th and 75th percentiles (dashed), and 5th and 95th percentiles (dotted). (c) Antarctic

668   basal melt parameter (γ) distribution (N = 8200): vertical lines show the six values used for

669   simulations: median (solid), 5th and 95th percentiles (dashed) of the Mean Antarctic (black) and Pine

670   Island Glacier (grey) distributions (see Methods). (d) Projected land ice contribution to sea level (cm

671   SLE) from 2015-2100 under the five SSPs and NDCs. Solid lines and shaded regions: median and 5-

672   95th percentiles (N = 11,500 per year per scenario): 5 year smoothing applied, with original data

673   shown as dots (interannual variation arises from annual sampling of emulator uncertainties). Pale

674   solid lines: 95th percentiles of risk-averse projections. Box and whiskers show [5, 25, 50, 75, 95][th]

675   percentiles at 2100 (N = 115,000 per scenario) for main projections (left) and risk-averse projections

676   for Antarctica (right). (e-j). Probability density functions for 2100 estimated for: (e) Greenland ice

677   sheet, (f) Arctic Canada North, (g) total for glaciers, (h, i) West and East Antarctica for all scenarios,

678   and (j) total for Antarctic ice sheet under main and risk-averse projections for the NDCs. Glacier and

679   Antarctic totals are less smooth because they are estimated from a sum of Monte Carlo samples from

680   each region, rather than deterministic integration (see Methods); these samples are shown for SSP1-19

681   and NDCs (N = 5000). Ice sheet projections do not include pre-2015 response, which is estimated to

682   add less than 1 cm to the Greenland contribution and up to ~2 cm to the Antarctic (see Methods).

683

684 **Figure 4. Climate and ice sheet projections show a wide range of responses to greenhouse gas**

685 **emissions scenario.** Sea level contribution at 2100 under high greenhouse gas emissions scenarios

686 (RCP8.5 or SSP5-85) versus low scenarios (RCP2.6 or SSP1-26), categorised by climate model

687 forcing (NorESM1-M and IPSL-CM5A-MR use RCPs; CNRM-CM6-1 use SSPs), without ice shelf

688 collapse. a, Greenland. b, West Antarctica. c, East Antarctica. d, Antarctic Peninsula. Filled circles

689 show ice sheet models that use the ISMIP6 parameterisations of the ice-ocean interface, while open

690 circles show models that used their own. Simulations in the red shaded regions have more mass loss

691 under high emissions (RCP8.5/SSP5-85) than low (RCP1-26/SSP1-26); those in the green shaded

692 regions have more mass gain under high emissions scenarios than low. Two regions with other

693 possible combinations are also labelled.

694

695 **Table 1. Projected land ice contributions to sea level rise in 2100 under different greenhouse gas**

696 **scenarios and Antarctic modelling assumptions.** Projected changes to global glaciers, Greenland

697 and Antarctic ice sheets and land ice total from 2015-2100 in sea level equivalent (cm SLE) for five

698 Shared Socioeconomic Pathways (SSPs) and predicted emissions under the 2019 Nationally

699 Determined Contributions (NDCs). Ice sheet projections do not include pre-2015 response, which is

700 estimated to add less than 1 cm to the Greenland contribution and ~2 cm to the Antarctic (see

701 Methods). The glaciers include the Greenland and Antarctic ice sheet peripheral glaciers; the overlap

702 of Antarctic periphery glaciers with the ice sheet contribution is estimated to be less than 1 cm SLE.

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Methods

Simulations

Ice sheet and glacier model simulations

Ice sheet and glacier simulations are from the Ice Sheet Model Intercomparison Project 6 (ISMIP6)[2,3] and Glacier Model Intercomparison Project Phase 2[8]. Most are published elsewhere[8,14-16]. Additional simulations were run for this analysis (Extended Data Table 1) as follows, where the names are group/model: 22 new Greenland experiments using [5th, 95th] percentile values of the retreat parameter under different climate model forcings with IMAU/IMAUICE1, and 113 Antarctic experiments with CPOM/BISICLES (N = 16), ILTS_PIK/SICOPOLIS (N = 31), JPL1/ISSM (N = 10), LSCE/GRISLI (N = 30) and NCAR/CISM (N = 26). Eight of the new Antarctic simulations were previous experiments described in ref. [15] using a new model (CPOM/BISICLES), and the rest (105) used 37 new combinations of previous uncertainties for additional exploration of basal melt (29) and ice shelf collapse (5) under different climate model forcings, and the interaction of ice shelf collapse and basal melt (3). CPOM/BISICLES is described in the ISMIP6 Antarctic initialisation study[7]: here the B variant is used, but with minimum resolution 1 km rather than 0.5 km. All ice sheet projections are calculated relative to a control simulation with constant present day climate (see 'Comparison with IPCC assessments' for an estimate of the 'committed' contribution this removes).

The glacier regions are listed in Extended Data Table 2 and all simulations are described in ref [8]. Greenland ice sheet projections have the peripheral glaciers (region 5) masked out, so there is no double-counting. The Antarctic periphery glaciers (region 19) are located only on the surrounding islands, not on the mainland ice sheet; ice sheet models include some of the larger islands, so there is some overlap in area, but the effect of this is estimated to be small (see 'Comparison with IPCC assessments' for an estimate of this and other limitations).

All projections are calculated as annual global mean sea level contributions since 2015, converting mass (for the glaciers) or mass above flotation (for the ice sheets) to sea level contribution using 362.5 Gt per mm SLE.

Global climate model simulations
745

746   We use projections of annual global mean surface air temperature change since 2015 from

747   the CMIP5 and CMIP6 global climate models used to drive the ice sheet and glacier models

748   to build the emulator. If multiple realisations (different initial conditions) for a model were

749   available, we use the mean of these. Data from 1850-2100 were downloaded from the

750   JASMIN/CEDA archive and ESGF on the 7th November 2019 and and 4th December 2019;

751   the CMIP6 snapshot was updated 28th-29th July 2020.

752

753   **Emulation**
754

755   An emulator is a fast statistical approximation of a computationally expensive simulator. This

756   can be used to predict the simulator response at untried input values – to explore the

757   uncertain input space far more thoroughly – for sensitivity analysis, to adjust the chosen

758   inputs, and to estimate probability distributions. We construct statistical models of the

759   simulated ice sheet and glacier sea level contribution as a function of the global mean surface

760   air temperature of the driving climate models – and also different representations of the ice

761   sheet-ocean interface – to make predictions under new emissions scenarios that incorporate

762   these uncertainties, as well as those arising from the different structures of the climate and ice

763   sheet models (and the emulators themselves).

764

765   Typically emulation is performed for one model at a time[24], but here we emulate each multi-

766   model ensemble all at once. This is made possible by the systematic design of the ISMIP6

767   and GlacierMIP projects, which explore uncertainties in global climate change and three ice-

768   ocean parameters simultaneously, and by our approach of applying emulation to multiple

769   models rather than (as is usual) one. The three ice-ocean parameters control: (1) how much

770   Greenland marine-terminating glaciers retreat (κ) with increasing local ocean temperatures

771   and meltwater runoff; (2) how much Antarctic ice-shelf basal melting (γ) increases with

772   increasing local ocean temperature; and (3) an on/off scenario of Antarctic ice shelf collapse

773   (C), which can increase glacier flow into the ocean when atmospheric temperatures rise[46].

774

775   We predict the 23 land ice regions separately – the Greenland ice sheet, the West and East

776   Antarctic ice sheets and Antarctic Peninsula, and 19 glacier regions – so the spatial

777   distribution of meltwater can be used in regional sea level projections.

778

779   We choose and evaluate emulator structures using the year 2100 (Extended Data Table 2;

780   Extended Data Figures 1 and 2). Global mean surface air temperature projections are taken

781   from the FaIR simple climate model[30], because it can explore uncertainties more thoroughly

782   than the relatively small CMIP6 ensemble of (computationally expensive) general circulation

783   models. We use the same global mean temperature value across all land ice sources for each

784   individual estimate: in other words, we include any co-dependence arising from global

785   temperature. Full details are described in the following sections.

786

787   *Global mean surface air temperature*
788

789   Previous sea level emulation studies[25,26,28,29] have typically used global mean temperature as

790   the main input, rather than regional climate variables. We follow this approach for several

791   reasons: to include correlation of land ice regions induced by global climate change (i.e. no

792   need to assume/estimate their correlations, or to treat them as independent), and to have a

793   larger sample of climate change projections. Using regional climate variables would improve

794   the signal to noise for the emulator, but would restrict us to using computationally expensive

795   general circulation models from CMIP5/6, for which there only a few tens of models. The

796   simple climate model FaIR can be used to explore uncertainties in each scenario thoroughly,

797   using the latest assessments of equilibrium climate sensitivity.

798

799   Global mean temperature is the only regressor for the glacier regions. For the ice sheets, there

800   are additional terms derived from the ISMIP6 parameterisations of ice-ocean interactions.

801

802   *Ice sheet model parameters*
803

804   The Greenland glacier retreat parameter κ (Fig. 3a; units km $(m^3\ s^{-1})^{-0.4}\ °C^{-1}$) is a scaling

805   coefficient relating marine-terminating glacier retreat to ocean temperatures and meltwater

806   runoff[10,11], where larger negative values indicate greater retreat of the glacier terminus in

807   response to warming. This is a continuous variable, but most simulations use one of three

808   values: the default, which is the median of the distribution in the parameterisation[11], $\kappa_{50} =$

809   -0.17, and the quartiles $\kappa_{25} = -0.37$ and $\kappa_{75} = -0.06$. One model uses 5th and 95th percentile

810   values, $\kappa_5 = -0.9705$ and $\kappa_{95} = 0.0079$. For ice sheet models that did not use this

811   parameterisation (N = 29 simulations)[14], we assign the mean value from the other simulations

812   to minimise the impact on the emulator (κ = -0.2073). One of these models (BISICLES) also

813   ran 'high' and 'low' retreat experiments by doubling and halving the ocean thermal forcing, to

814   which we assign the κ_{25} and κ_{75} values.

815

816   The Antarctic sub-shelf basal melt parameter γ (Fig. 3b; units m a^{-1}) is the 'ocean heat

817   exchange velocity' scaling coefficient relating sub-shelf basal melting to ocean

818   temperatures[12,13]. Two alternative distributions for γ were derived in the parameterisation[13]:

819   the first from mean Antarctic melt rates, and the second from the 10 highest observations of

820   melt rate at the grounding line of Pine Island Glacier, where melt rates are currently highest.

821   The values of γ estimated from Pine Island Glacier are an order of magnitude larger, and the

822   two distributions do not overlap. This is a continuous variable, but most simulations use one

823   of three values: the default, which is the median of the Mean Antarctic distribution,

824   MeanAnt$_{50}$ = 14477, and the 5th and 95th percentiles, MeanAnt$_5$ = 9619 and MeanAnt$_{95}$ =

825   21005. Further simulations used the same percentiles from the Pine Island Glacier

826   distribution: PIG$_{50}$ = 159188, PIG$_5$ = 86984 and PIG$_{95}$ = 471264. Some models[15] used an

827   alternative variant of the parameterisation in which only local ocean temperatures were used,

828   rather than a combination of local and regional, which uses a different tuning for γ. However,

829   the values used are also the 50 [5, 95]th percentiles of those distributions, so we consider them

830   equivalent. For ice sheet models that did not use this parameterisation (N = 62 simulations),

831   we again assign the ensemble mean value (γ = 59317).

832

833   The Antarctic ice shelf collapse parameter C is a switch that indicates whether a scenario of

834   ice shelf collapse was used, which can lead to glacier speed-up. A timeline of collapses was

835   derived according to the presence of surface meltwater on ice shelves above a threshold (725

836   mm a^{-1}) for 10 years, estimated from surface air temperature projections[46] in the global

837   climate model driving the ice sheet model (mostly CCSM4). This method does not predict

838   whether meltwater may be efficiently drained from the surface for a given ice shelf[47], thus

839   avoiding collapse. We use values of 1 or 0 indicating whether the scenario is implemented or

840   not.

841

842   *Gaussian Process emulation*

843

844   Gaussian Process emulation[48] is non-parametric, treating the simulator as an unknown

845   mathematical function of its inputs. We use the R package RobustGaSP[49] for its numerically

846   robust parameter estimation[50]. There are 23 emulators for the 2100 projections (Greenland ice
847   sheet, three Antarctic ice sheet regions, and 19 glacier regions) and 1955 emulators for the
848   full land ice time series (23 regions for each year from 2016 to 2100). An alternative to
849   predicting each year separately would be to model the temporal correlation explicitly, but we
850   prefer to use the simpler method, with fewer judgments, and allow temporal correlation to
851   emerge.

852

853   *Nugget*
854

855   We use a 'nugget 'term to incorporate simulations from each multi-model ensemble. The
856   nugget is usually zero for deterministic models – the emulator predicts each simulation in the
857   ensemble exactly, i.e. the regression curve goes through all points – or a very small value, to
858   improve numerical stability or other properties[22,23]. Here we allow the emulator to estimate
859   the nugget, and treat each multi-model ensemble as a set of outputs from a single stochastic
860   simulator or set of noisy observations. This approach has previously been used for emulating
861   stochastic simulators[51] and for emulating climate models accounting for internal variability,
862   other inert inputs (uncertainties not explicitly modelled in the emulator), and approximations
863   of the model outputs[52-57]. Our method is similar to the use of 'emergent constraints' for
864   climate models[44,58], seeking relationships between past and future simulations across multi-
865   model ensembles to constrain them with observations, but here the predictors are inputs to the
866   models rather than their outputs for the past.

867

868   This approach does not require the simulations to be normally distributed but does assume
869   they are independent, which has been a long-standing difficulty of interpreting multi-model
870   climate ensembles. But with ice sheet models, although model names may be the same across
871   groups, each one has a very different set up, including physics approximations,
872   parameterisations, tuning, grid resolution, and – in particular – initialisation methods, which
873   have been shown to produce very different results even for simulations produced by the same
874   group[6,7,14,15,59-61]. For glacier models, their structures are also vastly different, ranging from
875   simple scaling parameterisations to dynamic physical models[8]. We test two approaches to
876   account for any model dependence: a dummy variable (see below) and random effects
877   ('Antarctic cross-check model').

878

Statistical model
880

881 Let y denote the simulated global mean sea level contribution for given region and year (in

882 cm SLE), and $\mathbf{x}$ the simulator inputs (see below). Following ref. [22], we write the simulator

883 as a function $y = f(\mathbf{x})$, for which the Gaussian Process emulator is described by a mean

884 function:

885 $$E[f(\mathbf{x})] = h(\mathbf{x})^T \beta,$$

886

887 where $h(\mathbf{x})$ is a vector of regression functions and β the corresponding regression coefficients,

888 and a covariance function, with variance σ^2 and correlation function $c(\mathbf{x}, \mathbf{x}')$,

889

890 $$Cov[\ f(\mathbf{x}),\ f(\mathbf{x}')\ ] = \sigma^2(c(\mathbf{x}, \mathbf{x}') + \nu I),$$

891

892 where ν is the nugget term and I the identity matrix. So the prior for $f(\mathbf{x})$ is:

893

894 $$p(f(\mathbf{x}) \mid \beta, \sigma^2, \delta, \nu)) \sim N(h(\mathbf{x})^T \beta, \sigma^2(c(\mathbf{x},\mathbf{x}') + \nu I)),$$

895

896 where $\mathbf{x}$ are whichever model inputs are used for a given region, δ are the correlation lengths

897 of the covariance function, and $\sigma^2\nu$ is the variability not explained by the inputs. Parameters

898 $(\beta, \sigma^2, \delta, \nu)$ are estimated from the simulation data.

899

900 The inputs $\mathbf{x}$ used in the regression functions are global mean temperature change, T, and, for

901 the ice sheets, the ice-ocean parameter values (κ for Greenland; γ, C for Antarctica), plus a

902 dummy variable denoting whether Greenland models used the retreat parameterisation. These

903 are discussed in the next section. All inputs are rescaled to have zero mean and unit variance.

904

905 *Mean functions*
906

907 The Gaussian Process mean function describes the large-scale response of the simulator to its

908 inputs, usually specified as a linear trend with the remainder described by a zero-mean

909 Gaussian process.

910

911 For the glaciers, the linear regressor is simply global mean temperature in the same year (T).

912 For the ice sheets, the additional ice sheet model parameters are κ for Greenland, and γ and C

913   for Antarctica. We also try two types of dummy variable. The first is for the ice sheet and

914   glacier model names, so these can be treated distinctly in the emulator, but this leads to clear

915   overfitting (i.e. the model is too flexible in Figs. 1 and 2). The second represents whether an

916   ice sheet model uses the ISMIP6 retreat or basal melt parameterisation, to absorb any

917   misalignment between the imputed value and the effective value. Bayesian Information

918   Criterion (BIC) from a stepwise model selection (testing up to first-order interactions)

919   suggests this dummy variable is informative for Greenland, so we retain it (o, for open

920   parameterisation), but not for the Antarctic regions. The stepwise model selection suggests

921   we could reasonably include terms for the interaction between temperature and retreat for

922   Greenland, temperature and basal melt for West Antarctica, and temperature and collapse for

923   East Antarctica, but we choose not to, to avoid the risk of overfitting. The selection also

924   shows that collapse strongly dominates the Antarctic Peninsula response, and is may not be

925   needed for West Antarctica, but we retain all terms (i.e. T_i, γ_0, C) because we otherwise find

926   the covariance matrix is poorly conditioned. The resulting mean functions are $h_{GrIS}(\mathbf{x})_i \sim (T_i,$

927    $k, o)$ for Greenland, $h_{AIS}(\mathbf{x})_i \sim (T_i, \gamma_0, C)$ for the Antarctic regions, and $h_{Glaciers}(\mathbf{x})_i \sim (T_i)$ for the

928   glaciers, where $h \sim (a,b)$ means h is a linear function of a and b, and i is the index for the

929   year.

930

931   *Covariance functions*

932

933   The covariance function describes the smoothness of the Gaussian Process. As in any

934   statistical modelling, there is a trade-off between improving accuracy and over-fitting. We

935   assess this using the usual leave-one-out procedure[62,63]. We fit the emulator to all ensemble

936   members but one, then predict the sea level contribution from this simulation; we repeat this

937   for every combination, noting the emulator error (residual) and uncertainty for each

938   prediction. We perform this for each of the 23 regional emulators for the year 2100 with five

939   covariance functions of varying smoothness – Matérn(5/2), which is the default in

940   RobustGaSP, Matérn (3/2), and three members of the power exponential family with high,

941   medium and low exponent values ($\alpha = 1.9$, i.e. close to a squared exponential, the default

942   value; $\alpha = 1.0$, exponential, and $\alpha = 0.1$, for which the covariance function has a small effect

943   so the emulator approaches linear regression).

944

945   For 18 of the 19 glacier regions, we use the covariance function with the smallest

946   standardised Euclidean distance between the emulator predictions and simulations

947 (standardised because, unlike simpler metrics such as root mean square error or mean

948 absolute error, it does not penalise larger errors if the emulator uncertainty intervals are

949 sufficiently large), as in ref [24]. For the Southern Andes (region 17), all covariance functions

950 give identical distances, so we use the default for RobustGaSP. For the ice sheets, we use the

951 covariance function that gives close to linear regression (power exponential, $\alpha = 0.1$), rather

952 than the one with the minimum Euclidean distance, for various reasons. For Greenland, West

953 Antarctica, and the Antarctic Peninsula, the minimum distance covariance functions (power

954 exponential $\alpha = 1.0$ for Greenland; Matérn(3/2) for the Antarctic regions) result in overfitting

955 for temperature (i.e. too much flexibility in Fig. 1). For East Antarctica, the minimum

956 distance covariance functions (Matérn(5/2)) result in an incorrect sign prediction under the

957 ice shelf collapse switch. Using the alternative covariance function solves all of these issues

958 and does not increase the standardised Euclidean distance by much: 4% for the Peninsula,

959 and 0.4-1% for the other three regions. The resulting covariance functions are given in

960 Extended Data Table 2.

961

962 *Evaluating the emulators*

963

964 After selecting the covariance functions for each regional emulator at 2100, we evaluate the

965 emulators further by plotting the emulator predictions against the simulations from the leave-

966 one-out procedure, and the standardised residuals (the difference between the emulator

967 prediction and the simulator, divided by the emulator standard deviation), and calculating the

968 percentage of simulations falling within ± 2 s.d. (Extended Data Table 2 and Extended Data

969 Figures 1 and 2). We would not expect exactly 95% of the simulations to fall within 2 s.d., in

970 part because the predictions are not independent, but very low or high values would suggest

971 emulator over- or under-confidence. The region with the lowest percentage of predictions

972 within the uncertainty intervals is North Asia (region 10) with 89%, indicating slightly too

973 small emulator uncertainty estimates, and the highest is 98% (Scandinavia: region 8),

974 indicating the reverse.

975

976 Mean absolute errors for each emulator are given in Extended Data Table 2 and Extended

977 Data Figures 1 and 2: for the ice sheet regions they are 0.28 cm (Peninsula), 1.4 cm

978 (Greenland) and 1.5 cm (East Antarctica) and 2.0 cm (West Antarctica), and for the

979 individual glacier regions they range from 0.0020 cm to 0.87 cm (Antarctic periphery: region

980 19). Mean absolute standardised errors are all less than 0.006.

981

982 The emulator underestimates the three to four highest West and East Antarctic contributions

983 by around 10-15 cm (Extended Data Figure 1b and 1c). The five highest of these are from the

984 SICOPOLIS model, which has a much greater sensitivity to basal melting than other models

985 (see main text, *Robustness checks* and Extended Data Figure 6), and use the highest value of

986 this parameter ($\gamma = PIG_{95}$). These simulations are therefore extreme: 1% of the 344

987 simulations, and the 97.5th percentile value of the basal melt parameter. There are process-

988 based reasons to expect that SICOPOLIS is an upper bound or overestimate (see main text).

989 When the emulator is calibrated with this model alone, it does not underestimate its highest

990 contributions (not shown). The resulting projections under the NDC scenario are shown in

991 *Robustness checks* (test 4); the difference with the main projections may be interpreted as the

992 maximum possible impact of this emulator underestimate, if SICOPOLIS were the sole

993 realistic ice sheet model. These are lower than the 'risk-averse' projections, which are made

994 with a subset of high sensitivity ice sheet models and other pessimistic assumptions (see main

995 text).

996

997 We therefore consider the emulators to be adequate for the predictions of large-scale sea level

998 contribution presented here.

999

1000 *Antarctic cross-check model*

1001

1002 We perform a cross-check for the Antarctic ice sheet regions at 2100 using a linear mixed

1003 model, with the ice sheet model name included as a random effect to deal with any systematic

1004 uncertainty arising from dependence of ensemble members. This attributes some of the

1005 uncertainty in the response to the ice sheet model used, and this uncertainty can then be

1006 removed from the predicted PDF. We thus model the ensemble members as 'similar but not

1007 identical', using a mean function of temperature and ice sheet parameters, plus a structured

1008 error term which includes a systematic component according to the ice sheet model and a

1009 noise component to capture other sources of variability such as initialisation.

1010

1011   For the mean function (also linear), we use the logarithm of γ as a regressor, so it is always

1012   positive. Consequently we use the geometric mean as the missing value, rather than the

1013   arithmetic mean. We use a dummy variable to denote these models, as for Greenland in the

1014   GP emulator. The full global mean temperature change trajectories are used instead of only

1015   the total change at 2100. To increase the signal-to-noise ratio, the annual means are reduced

1016   to decadal means (2015–2029, 2030–2039, . . . , 2090–2100). There are thirteen distinct

1017   forcings, each one the product of a global climate model and a scenario, so we represent the

1018   forcing variables as twelve bisquare basis functions. These start as thirteen bisquare basis

1019   functions, each one centred at one of the thirteen forcings, but one is dropped because

1020   otherwise the model matrix becomes rank deficient when a constant is added. The one

1021   dropped is the one with the smallest mean Euclidean distance to the other twelve. We use

1022   bisquare kernels, where the standard deviation of each kernel is set to one tenth of the

1023   maximum Euclidean distance between all pairs of forcings, to cover the forcing space with

1024   non-zero values for the forcing regressors. We use the same distributions for temperature,

1025   basal melt and collapse as the main projections, and set the dummy variable to represent

1026   standard parameterisation models.

1027

1028   This emulator predicts 50 [5, 95][th] percentiles for the West Antarctic sea level contribution at

1029   2100 of 2 [-4, 8] cm SLE for SSP1-26 and 3 [-4, 10] cm SLE for SSP5-85, which are very

1030   similar to the GP emulator predictions of 2 [-5, 10] cm SLE and 3 [-4, 11] cm SLE. We test

1031   the effect of changing the kernel standard deviation to one twelfth or one fourteenth of the

1032   maximum Euclidean distance; the largest change is a 2 cm decrease in the 95th percentile

1033   under SSP5-85. For East Antarctica, the emulator with random effects predicts 2 [-3, 6] cm

1034   SLE for both scenarios; the GP emulator predicts a small scenario-dependence, 2 [-4, 7] cm

1035   SLE for the low emissions scenario and 0 [-5, 6] cm SLE for the high. For the Antarctic

1036   Peninsula, the random effects predictions are 0 [-1, 2] cm SLE for both scenarios, and the GP

1037   are the same. These similarities give us confidence that model dependence is not substantially

1038   affecting our projections – i.e. that differences in model structure, resolution, calibration and

1039   initialisation dominate over the similarities – although it would be worth investigating this in

1040   more detail.

1041

1042   **Sea level projections**

1043

1044 We use probability distributions for global temperature and the ice sheet model parameters as
1045 inputs to each emulator to make the projections.

1046

1047 *Global mean temperature projections*
1048

1049 We use projections of global annual mean surface air temperature change since 2015 from
1050 the FaIR (Finite amplitude Impulse Response) simple climate model for the main projections.
1051 We take the 500-member ensemble from reference [30]: SSP1-19, SSP1-26, SSP3-70, SSP5-
1052 85 and a scenario estimated for the 2019 Nationally Determined Contributions. We also use
1053 projections for SSP-245 generated with the same ensemble.

1054

1055 *Ice sheet model parameter distributions*
1056

1057 For Greenland, we sample from a kernel density estimate of the original k distribution (N =
1058 191) with the same bandwith used in deriving the parameterisation[10,11] (0.0703652) (Fig. 1b).
1059 The dummy variable is always set to represent the standard ISMIP6 parameterisation.

1060

1061 For Antarctica, we combine the Mean Antarctic and Pine Island Glacier γ distributions (N =
1062 10,000 each), and sample from a kernel density estimate using three times the automatic
1063 bandwidth (Silverman's 'rule of thumb'[64]) to merge and smooth them into a near-unimodal
1064 distribution that we truncate at zero (Fig. 1c). For the collapse switch C, we sample randomly
1065 from 0 or 1 with equal probability (8% of the ISMIP6 simulations have ice shelf collapse).
1066 The ice shelf collapse scenario does not include the possibility of surface meltwater draining
1067 efficiently from some ice shelves under certain conditions, thereby avoiding collapse, so we
1068 feel this is a reasonable judgement.

1069

1070 *Sampling*
1071

1072 For the 2100 projections, we sample from the FaIR ensemble (N=500) with replacement (N =
1073 5000 for main and risk-averse projections; N = 1000 for robustness and sensitivity tests). For
1074 the full time series, we use the 500 FaIR projections directly without resampling. We make
1075 one set of emulator predictions (23 regions) for each temperature value in a given year,
1076 randomly sampling the relevant ice-ocean parameters (k, γ_0, C) once for each FaIR ensemble
1077 member.

1078

1079 We integrate over the uncertain inputs (temperature in a given year, and ice-ocean

1080 parameters) to obtain the final probability density functions (PDFs). Each regional emulator

1081 predicts a Student-t distribution for a given set of these input values, defined by a mean and

1082 standard deviation; we approximate this with a normal distribution, as in refs [55, 57], which

1083 is accurate enough for this application. We use different integration methods for the 23

1084 individual regional PDFs compared with the regional sums (Antarctica, global glaciers, and

1085 land ice total). For the individual regional estimates, we use deterministic numerical

1086 integration (the midpoint rule: we sum the Gaussian distributions for each emulator

1087 prediction, then normalise). For regional sums we must use Monte Carlo sampling, because

1088 the three ice sources (Greenland, Antarctica and glaciers) have different parameters, and we

1089 also desire traceability of predictions to input values within a given ice source. We sample

1090 once from the Gaussian distribution for each emulator prediction, then sum the regional

1091 samples for a given temperature to estimate the PDF, smoothing with kernel density

1092 estimation for figures (again using Silverman's 'rule of thumb'[64] for the bandwidth). Sampling

1093 is a more noisy method of integration than deterministic methods, so the PDFs for regional

1094 sums are less smooth than those for individual regions.

1095

1096 *Glacier maximum cap*
1097

1098 We apply a cap to the glacier projections using estimates of their maximum sea level

1099 contribution[31]. Glacier model projections often exceed this cap in some regions, if near or

1100 total loss is projected under high emissions, either because they report changes in total mass,

1101 not mass above flotation, or because of errors in initial mass[8], or both. We restrict values to

1102 the maximum in the emulator mean predictions and then the PDFs (the latter exceeding the

1103 cap due to emulator uncertainty).

1104

1105 *Time series smoothing*
1106

1107 Interannual variability arises in the time series due to sampling the emulator uncertainty for

1108 each annual regional prediction. We apply a five year running mean in Fig. 3d to visualise the

1109 expected smoothness of sea level contributions; projections provided in the Supplementary

1110 Information are unsmoothed.

1111

Comparison with IPCC assessments

The ice sheet projections are made relative to control simulations with a constant recent climate. This control includes both the model drift and, depending on the initialisation method, any background contribution arising from forcing before 2015. This background contribution should be added to the ice sheet projections, but is difficult to quantify. Five year mean rates of sea level contribution since 1992/3 range from 0.1-0.8 mm/yr for the Greenland ice sheet[65] and 0.1-0.6 mm/yr for Antarctica[66], but they would decrease in the absence of forcing after 2014. Modelling work to quantify the background contribution from Greenland[67] suggests a contribution of 0.6 ± 0.2 cm SLE by 2100. Estimates made for this study range from 0.3-0.8 cm under a range of retreat parameter values, κ_{75} - κ_{25} (IMAU/IMAUICE1: 0.3-0.4 cm; CISM variant similar to NCAR/CISM: 0.4-0.8 cm). For Antarctica, the dynamic commitment has been estimated to be 2 cm SLE at 2100 for the Amunden Sea Embayment region of West Antarctica, where most mass loss is currently occurring[68]. Part of these trends may still be due to residual model drift. The committed contribution could therefore add up to ~1 cm/century to our Greenland projections and ~2 cm/century to the Antarctic.

The Antarctic ice sheet models include some of the larger islands that are also included in region 19, potentially leading to double-counting. However, median projections for region 19 range from 1-2 cm under different emissions scenarios, and the ice sheet models are much lower resolution (i.e. the glaciers are likely less responsive), so the effect is expected to be of order 0.5-1 cm SLE or less.

We average our projections over the 86 years and compare them with the average IPCC AR5[25] and SROCC[1] projections over 95 years (the midpoints of 1986-2005 to 2081-2100) as rates of cm SLE per century. For the glaciers, we project 8 cm/century SLE for SSP1-26 and 16 cm/century for SSP5-85 excluding the Antarctic peripheral glaciers (region 19: 1 cm and 2 cm, respectively), compared with 10 cm for RCP2.6 and 17 cm for RCP8.5 in AR5. For the Greenland ice sheet, we project 4 cm/century SLE for SSP1-26 and 11 cm for SSP5-85, compared with 6 cm for RCP2.6 and 13 cm for RCP8.5 in AR5. For Antarctica, we project 5 cm/century SLE for both scenarios; the AR5 projections are 5 cm/century SLE for RCP2.6 and 4 cm for RCP8.5, while those for SROCC are 4 cm/century SLE for RCP2.6 and 11 cm

1145   for RCP8.5. The difference between scenarios for Antarctica in AR5 arises only from

1146   additional accumulation, because the dynamic contributions are assumed to be the same.

1147

1148   Glacier projections could be overestimated because meltwater routing to the ocean is not

1149   accounted for (not all volume lost from the glaciers reaches the oceans), or underestimated

1150   because only one glacier model includes ice-water interactions (i.e. frontal ablation of

1151   marine- and lake-terminating glaciers). For the latter, we compare mean projections for the

1152   GloGEM model to the emulator for RCP8.5/SSP5-85 and RCP4.5/SSP2-45 for key regions,

1153   and find they are larger by less than 1 cm for Alaska and Russian Arctic (regions 1 and 9), by

1154   less than 0.5 cm for Svalbard (7) and Arctic Canada South (4), and smaller than the emulator

1155   for Arctic Canada North (3). All are within the emulator 95th percentile estimates. We may

1156   slightly underestimate uncertainty in the global glacier total due to correlated errors across

1157   models[8] by emulating the regions independently, though there are compensating advantages

1158   (more accurate emulation; spatial pattern of meltwater); a similar argument applies to

1159   Antarctica.

1160

Sensitivity tests

1161

1162

1163   We perform a number of checks to test the sensitivity of the ice sheet projections to changes

1164   in the chosen inputs, predominantly the input distributions, but also the dataset in the final

1165   test (see Extended Data Table 3 and refs [25, 26,30, 34, 39]). All results are shown for the

1166   SSP5-85 scenario in Extended Data Figure 4 under the index given (where 1 is the main

1167   projection); numerical values in the text refer to changes in the median and [5,95[th]] percentile

1168   estimates for the ice sheet under this scenario unless otherwise stated.

1169

Robustness checks

1170

1171

1172   We perform a number of checks to test robustness of the ice sheet projections to changes in

1173   the simulation dataset (see Extended Data Table 4 and refs [14, 16, 24, 66]). Results are

1174   shown for the NDCs scenario in Extended Data Figure 5 under the test index given (where 1

1175   is the main projection); numerical values in the text refer to changes in the median and

1176   [5,95[th]] percentile estimates under this scenario unless otherwise stated. The full datasets are

1177   256 simulations for Greenland and 344 simulations for Antarctica.

1178

Parameter interactions

Retreat and basal melt vs temperature

Ice sheet projection uncertainties are constant across scenarios. However, tests with three ice sheet models show that the range of projections from high to low values of the retreat parameter (κ_{95} - κ_5) and basal melt parameter (PIG_{95} - $MeanAnt_{50}$) is consistently smaller under RCP2.6 than RCP8.5, so the emulator uncertainty should be smaller at lower temperatures. The ratios of ranges, RCP2.6/RCP8.5, for each group/model + GCM are:

Greenland
- IMAU/IMAUICE + MIROC5 = 1.4097/8.3069 = 0.17
- IMAU/IMAUICE + CNRM-CM6-1 = 2.4813/9.7187 = 0.26

West Antarctica
- JPL1/ISSM + NorESM1-M = 0.40
- CPOM/BISICLES + NorESM1-M = 0.57

East Antarctica
- JPL1/ISSM + NorESM1-M = 0.73
- CPOM/BISICLES + NorESM1-M = 0.32

The emulator does not have sufficient data from lower emissions scenarios to reduce the variance, particularly for Greenland. If other ice sheet models respond the same way as the above, then adding more simulations may reduce the uncertainty for low SSPs.

Ice shelf collapse vs basal melt

The contribution due to ice shelf collapse does not increase with higher values of the basal melt parameter in the models JPL1/ISSM and CPOM/BISICLES (0.1 cm difference for the Peninsula in BISICLES; all other regional differences for both models ≤ 0.02 cm).

Code availability

1213   R code and input data are available at https://github.com/tamsinedwards/emulandice. Each

1214   simulation in the sea level projections file has a label in the 'publication' column for the

1215   reference (Goelzer2020, Seroussi2020, Nowicki2020 or Marzeion2020), or 'New' if

1216   previously unpublished.

1217

Data availability

1219

1220   All global climate, simple climate, ice sheet and glacier model data used as inputs to this

1221   study are provided with the code as described above. Main and risk-averse projections from

1222   the analysis are provided in the Supplementary Information as annual quantiles for each of

1223   the 23 regions, and the Antarctic, glacier and land ice sums.

1224

Author information

1226

1227   The authors declare no competing financial or non-financial interests. Correspondence and

1228   requests for materials should be addressed to T.L.E. (tamsin.edwards@kcl.ac.uk). Reprints

1229   and permissions information is available at www.nature.com/reprints.

1230

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1289
1290

Extended Data

Extended Data Table 1. The additional 22 Greenland and 37 Antarctic ice sheet model experiments not previously described elsewhere. Retreat parameter values κ_5 and κ_{95} are the 5th and 95th percentile values of the retreat (κ) distribution; basal melt parameter values MeanAnt$_{[5, 50, 95]}$ and PIG$_{[5, 50, 95]}$ are the 5th, 50th and 95th percentile values of the Mean Antarctic and Pine Island Glacier basal melt (γ) distributions (see Methods).

Extended Data Table 2. Emulator structure and validation. Emulator covariance functions, and the results of the leave-one-out procedure for each: the percentage of simulations that fall within the emulator 95% uncertainty intervals, and the mean absolute error.

Extended Data Figure 1. Emulator leave-one-out validation for ice sheets and 8 glacier regions. Left of each subpanel: Emulator predictions versus simulations for each regional sea level contribution in the year 2100, with percentage of predictions falling outside ± 2 emulator standard deviations and mean absolute error in cm SLE. Right of each subpanel: standardised residuals (emulated minus simulated, divided by emulator standard deviation). Predictions falling outside ± 2 emulator standard deviations are shown in orange.

Extended Data Figure 2. Emulator leave-one-out validation for 11 glacier regions. As for Extended Data Figure 1, but for the remaining glacier emulators.

Extended Data Figure 3. Temperature projections for 2015-2100 from FaIR and CMIP6 ensembles. Global surface air temperature projections under different greenhouse gas scenarios (see main text) from the (a) FaIR simple climate model ensemble (N = 5000; same as Figure 3a) and (b) CMIP6 global climate model ensemble (N ~30 models per scenario: see Methods) sampled with a kernel density estimate (N = 1000).

Extended Data Table 3. Sensitivity tests. Tests of the sensitivity of the ice sheet projections to changes in the chosen inputs. The test index, name, description and impact are detailed. Numerical values refer to changes in the median and [5th, 95th] percentile estimates for the ice sheet under SSP5-85, unless otherwise stated; results for this scenario are shown in Extended Data Figure 4.

Extended Data Figure 4. Sensitivity of ice sheet projections at 2100 under SSP5-85 to uncertain inputs. a, Greenland. b, West Antarctica. c, East Antarctica. d, Antarctic Peninsula. Indices refer to test (see Extended Data Table 3). Box and whiskers show [5, 25, 50, 75, 95]th percentiles. 1: Default; 2: CMIP6 global climate model ensemble projections of global mean surface air temperature, instead of FaIR simple climate model; 3: fixed global mean surface air temperature; 4: fixed glacier retreat (Greenland) or

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1329   basal melt (Antarctica) parameter. Antarctic regions only: basal melt parameter has 5: 'Mean Antarctic'

1330   distribution; 6: 'Pine Island Glacier' distribution; 7: uniform, high distribution; 8: uniform, very high

1331   distribution. Ice shelf collapse scenario: 9: off and 10: on. 11: Risk-averse projections using the high 'Pine

1332   Island Glacier' distribution for basal melt (test 6), ice shelf collapse on (test 10), and the ice sheet and

1333   climate models that give the highest sea level contributions (Extended Data Figure 5: test 6, 7).

1334

1335   **Extended Data Table 4. Robustness checks.** Checks performed to test the robustness of the ice sheet

1336   projections to changes in the simulation dataset. The test index, name, description and impact are detailed.

1337   Numerical values refer to changes in the median and [5th, 95th] percentile estimates for the ice sheet under

1338   the NDCs scenario, unless otherwise stated; results for this scenario are shown in Extended Data Figure 5.

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Extended Data Figure 5. Robustness of ice sheet projections under Nationally Determined Contributions to ice sheet/climate model simulation selection and treatment. a, Greenland. b, West Antarctica. c, East Antarctica. d, Antarctic Peninsula. Indices refer to test (see Extended Data Table 4). Box and whiskers show [5, 25, 50, 75, 95]th percentiles. 1: Default; 2: Higher resolution ice sheet models; 3: Ice sheet models with the most complete sampling of uncertainties (10 models for Greenland, 4 for Antarctica); 4: Single ice sheet model with the most complete sampling of uncertainties and (coincidentally) high sensitivity to retreat or basal melting parameter. Antarctic regions only: 5: Alternative single ice sheet model with nearly as complete sampling but low sensitivity to basal melt parameter. 6: Ice sheet models with the highest sensitivity to basal melt parameter; 7: Climate models that lead to highest sea level contributions. 8: Ice sheet models with 2015-2020 mass change in the range 0-0.6 cm. 9: Only ice sheet models that use the standard ISMIP melt parameterisations. 10: Higher basal melt value assigned to ice sheet models that do not use the standard ISMIP6 melt parameterisations.

Extended Data Figure 6. Sensitivity to basal melting by Antarctic ice sheet and climate model. Vertical lines show ice sheet models that do not use the ISMIP6 basal melt parameterisation, and the basal melt value they are assigned. Ice sheet models includes the high and low sensitivity models in Extended Data Figure 5: test 4 (ILTS_PIK/SICOPOLIS) and test 5 (LSCE/GRISLI).

Extended Data Figure 7. Effect of Antarctic ice shelf collapse by climate model. Additional sea level contribution at 2100 when using ice shelf collapse for six climate models, ordered by maximum impact on the Peninsula contribution. (a) West and (b) East Antarctica, and (c) Peninsula.

a Greenland

- MIROC5
- CNRM−CM6−1
- ○ Not using parameterisation

MASS LOSS DOMINATES
More mass loss under high emissions

b West Antarctica

- NorESM1−M
- CNRM−CM6−1
- IPSL−CM5A−MR
- ○ Not using parameterisation

MASS LOSS DOMINATES
More mass loss under high emissions

More mass loss under low emissions

Mass loss under low emissions, mass gain under high emissions

ACCUMULATION DOMINATES
More mass gain under high emissions

c East Antarctica

- NorESM1−M
- CNRM−CM6−1
- IPSL−CM5A−MR
- ○ Not using parameterisation

MASS LOSS DOMINATES
More mass loss under high emissions

More mass loss under low emissions

Mass loss under low emissions, mass gain under high emissions

ACCUMULATION DOMINATES
More mass gain under high emissions

d Antarctic Peninsula

- NorESM1−M
- CNRM−CM6−1
- IPSL−CM5A−MR
- ○ Not using parameterisation

MASS LOSS DOMINATES
More mass loss under high emissions

More mass loss under low emissions

Mass loss under low emissions, mass gain under high emissions

ACCUMULATION DOMINATES
More mass gain under high emissions

Sea level contribution at 2100 for RCP2.6/SSP1−26 (cm SLE)

Sea level contribution at 2100 for RCP8.5/SSP5−85 (cm SLE)