

Projected land ice contributions to twenty-first-century sea level rise

Article

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1 **ARTICLE**

2 **Projected land ice contributions to 21st**

3 **century sea level rise**

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94
95 **The land ice contribution to global mean sea level rise has not yet been predicted 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, but mostly used previous generation scenarios and climate models, and**
100 **could not fully explore known uncertainties. Here we estimate probability distributions**
101 **for these projections under the new scenarios using statistical emulation of the ice sheet**
102 **and glacier models, and find that limiting global warming to 1.5°C would halve the land**
103 **ice contribution to 21st century sea level rise, relative to current emissions pledges. The**
104 **median decreases from 25 to 13 cm sea level equivalent (SLE) by 2100, with glaciers**
105 **responsible for half the sea level contribution. The Antarctic contribution does not show**
106 **a clear response to emissions scenario, due to competing processes of increasing ice loss**

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

116

117 Land ice has contributed around half of all sea level rise since 1993, and this fraction is
118 expected to increase¹. The Ice Sheet Model Intercomparison Project (ISMIP6^{2,3}) for CMIP6⁴
119 and the Glacier Model Intercomparison Project (GlacierMIP⁵) provide the Intergovernmental
120 Panel on Climate Change (IPCC) with projections of Earth's ice sheet and glacier
121 contributions to future sea level. Both projects use suites of numerical models^{6,7,8} and
122 greenhouse gas emission scenarios⁹ as the basis of their projections, and a variety of
123 treatments are considered for the interaction between the ice sheets and the ocean^{10,11,12,13}. In
124 total, the projects provide 256 simulations of the Greenland ice sheet, 344 simulations of the
125 Antarctic ice sheet, and 288 simulations of the global glacier response to climate change
126 ^{8,14,15,16} (see also Extended Data Table 1). Although these simulations represent an
127 unprecedented effort ^{3,6,7,8,10-18}, their computational expense and complexity has meant that
128 they (i) focus mainly on previous generation emissions scenarios (Representation
129 Concentration Pathways⁹, RCPs) developed for the IPCC's Fifth Assessment Report, not the
130 more diverse and policy-relevant Shared Socioeconomic Pathways (SSPs^{19,20}) that underpin
131 the IPCC's Sixth Assessment Report, (ii) are driven mostly by a relatively small number of
132 older generation global climate models developed before CMIP6²¹, and (iii) have incomplete
133 and limited ensemble designs.

134

135 To address these limitations, we emulate the future sea level contribution of the 23 regions
136 comprising the world's land ice (see Extended Data Table 2) as a function of global mean
137 surface air temperature change and as a consequence of marine-terminating glacier retreat in
138 Greenland and ice-shelf basal melting and collapse in Antarctica. The ensembles of ice sheet
139 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 predictions²⁴; most
144 previous emulator-type approaches for sea level rise use parametric models, where the
145 functional form is assumed²⁵⁻²⁹. 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

152 **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 supply³². 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

185 **Land ice contributions in 2100**

186

187 We use probability distributions for global mean surface air temperature (Fig. 3a: FaIR
188 simple climate model³⁰) 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 Report²⁵ (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. NorESM1M 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 extreme¹ ice shelf collapse scenarios²⁴, 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 distributions¹³ 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 region³⁹, 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 floating²⁶. 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 Peninsula¹⁵. 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 Sea¹⁸, 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

329 **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 projections²⁴ 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 distributions⁴⁵. However, our projections demonstrate the importance of
372 systematic design to assess as many uncertainties as feasible, and represent the current state-
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374

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

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]

688 **Table 1. Projected land ice contributions to sea level rise in 2100 under different greenhouse gas**
689 **scenarios and Antarctic modelling assumptions.** Projected changes to global glaciers, Greenland
690 and Antarctic ice sheets and land ice total from 2015-2100 in sea level equivalent (cm SLE) for five
691 Shared Socioeconomic Pathways (SSPs) and predicted emissions under the 2019 Nationally
692 Determined Contributions (NDCs). Ice sheet projections do not include pre-2015 response, which is
693 estimated to add less than 1 cm to the Greenland contribution and ~2 cm to the Antarctic (see
694 Methods). The glaciers include the Greenland and Antarctic ice sheet peripheral glaciers; the overlap
695 of Antarctic periphery glaciers with the ice sheet contribution is estimated to be less than 1 cm SLE.

696

697

698 **Figure 4. Climate and ice sheet projections show a wide range of responses to greenhouse gas**
699 **emissions scenario.** Sea level contribution at 2100 under high greenhouse gas emissions scenarios
700 (RCP8.5 or SSP5-85) versus low scenarios (RCP2.6 or SSP1-26), categorised by climate model
701 forcing (NorESM1-M and IPSL-CM5A-MR use RCPs; CNRM-CM6-1 use SSPs), without ice shelf
702 collapse. a, Greenland. b, West Antarctica. c, East Antarctica. d, Antarctic Peninsula. Filled circles
703 show ice sheet models that use the ISMIP6 parameterisations of the ice-ocean interface, while open
704 circles show models that used their own. Simulations in the red shaded regions have more mass loss
705 under high emissions (RCP8.5/SSP5-85) than low (RCP1-26/SSP1-26); those in the green shaded
706 regions have more mass gain under high emissions scenarios than low. Two regions with other
707 possible combinations are also labelled.

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715

716 **Methods**

717 **Simulations**

718

719 *Ice sheet and glacier model simulations*

720

721 Ice sheet and glacier simulations are from the Ice Sheet Model Intercomparison Project 6
722 (ISMIP6)^{2,3} and Glacier Model Intercomparison Project Phase 2⁸. Most are published
723 elsewhere^{8,14-16}. Additional simulations were run for this analysis (Extended Data Table 1) as
724 follows, where the names are group/model: 22 new Greenland experiments using [5th, 95th]
725 percentile values of the retreat parameter under different climate model forcings with
726 IMAU/IMAUICE1, and 113 Antarctic experiments with CPOM/BISICLES (N = 16),
727 ILTS_PIK/SICOPOLIS (N = 31), JPL1/ISSM (N = 10), LSCE/GRISLI (N = 30) and
728 NCAR/CISM (N = 26). Eight of the new Antarctic simulations were previous experiments
729 described in ref. [15] using a new model (CPOM/BISICLES), and the rest (105) used 37 new
730 combinations of previous uncertainties for additional exploration of basal melt (29) and ice
731 shelf collapse (5) under different climate model forcings, and the interaction of ice shelf
732 collapse and basal melt (3). CPOM/BISICLES is described in the ISMIP6 Antarctic
733 initialisation study⁷: here the B variant is used, but with minimum resolution 1 km rather than
734 0.5 km. All ice sheet projections are calculated relative to a control simulation with constant
735 present day climate (see 'Comparison with IPCC assessments' for an estimate of the
736 'committed' contribution this removes).

737

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

744

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

748

749

750 *Global climate model simulations*

751

752 We use projections of annual global mean surface air temperature change since 2015 from
753 the CMIP5 and CMIP6 global climate models used to drive the ice sheet and glacier models
754 to build the emulator. If multiple realisations (different initial conditions) for a model were
755 available, we use the mean of these. Data from 1850-2100 were downloaded from the
756 JASMIN/CEDA archive and ESGF on the 7th November 2019 and and 4th December 2019;
757 the CMIP6 snapshot was updated 28th-29th July 2020.

758

759 **Emulation**

760

761 An emulator is a fast statistical approximation of a computationally expensive simulator. This
762 can be used to predict the simulator response at untried input values – to explore the
763 uncertain input space far more thoroughly – for sensitivity analysis, to adjust the chosen
764 inputs, and to estimate probability distributions. We construct statistical models of the
765 simulated ice sheet and glacier sea level contribution as a function of the global mean surface
766 air temperature of the driving climate models – and also different representations of the ice
767 sheet-ocean interface – to make predictions under new emissions scenarios that incorporate
768 these uncertainties, as well as those arising from the different structures of the climate and ice
769 sheet models (and the emulators themselves).

770

771 Typically emulation is performed for one model at a time²⁴, but here we emulate each multi-
772 model ensemble all at once. This is made possible by the systematic design of the ISMIP6
773 and GlacierMIP projects, which explore uncertainties in global climate change and three ice-
774 ocean parameters simultaneously, and by our approach of applying emulation to multiple
775 models rather than (as is usual) one. The three ice-ocean parameters control: (1) how much
776 Greenland marine-terminating glaciers retreat (κ) with increasing local ocean temperatures
777 and meltwater runoff; (2) how much Antarctic ice-shelf basal melting (γ) increases with
778 increasing local ocean temperature; and (3) an on/off scenario of Antarctic ice shelf collapse
779 (C), which can increase glacier flow into the ocean when atmospheric temperatures rise⁴⁶.

780

781 We predict the 23 land ice regions separately – the Greenland ice sheet, the West and East
782 Antarctic ice sheets and Antarctic Peninsula, and 19 glacier regions – so the spatial
783 distribution of meltwater can be used in regional sea level projections.

784

785 We choose and evaluate emulator structures using the year 2100 (Extended Data Table 2;
786 Extended Data Figures 1 and 2). Global mean surface air temperature projections are taken
787 from the FaIR simple climate model³⁰, because it can explore uncertainties more thoroughly
788 than the relatively small CMIP6 ensemble of (computationally expensive) general circulation
789 models. We use the same global mean temperature value across all land ice sources for each
790 individual estimate: in other words, we include any co-dependence arising from global
791 temperature. Full details are described in the following sections.

792

793 *Global mean surface air temperature*

794

795 Previous sea level emulation studies^{25,26,28,29} have typically used global mean temperature as
796 the main input, rather than regional climate variables. We follow this approach for several
797 reasons: to include correlation of land ice regions induced by global climate change (i.e. no
798 need to assume/estimate their correlations, or to treat them as independent), and to have a
799 larger sample of climate change projections. Using regional climate variables would improve
800 the signal to noise for the emulator, but would restrict us to using computationally expensive
801 general circulation models from CMIP5/6, for which there only a few tens of models. The
802 simple climate model FaIR can be used to explore uncertainties in each scenario thoroughly,
803 using the latest assessments of equilibrium climate sensitivity.

804

805 Global mean temperature is the only regressor for the glacier regions. For the ice sheets, there
806 are additional terms derived from the ISMIP6 parameterisations of ice-ocean interactions.

807

808 *Ice sheet model parameters*

809

810 The Greenland glacier retreat parameter κ (Fig. 3a; units $\text{km} (\text{m}^3 \text{s}^{-1})^{-0.4} \text{ }^\circ\text{C}^{-1}$) is a scaling
811 coefficient relating marine-terminating glacier retreat to ocean temperatures and meltwater
812 runoff^{10,11}, where larger negative values indicate greater retreat of the glacier terminus in
813 response to warming. This is a continuous variable, but most simulations use one of three
814 values: the default, which is the median of the distribution in the parameterisation¹¹, $\kappa_{50} =$
815 -0.17 , and the quartiles $\kappa_{25} = -0.37$ and $\kappa_{75} = -0.06$. One model uses 5th and 95th percentile
816 values, $\kappa_5 = -0.9705$ and $\kappa_{95} = 0.0079$. For ice sheet models that did not use this
817 parameterisation (N = 29 simulations)¹⁴, we assign the mean value from the other simulations

818 to minimise the impact on the emulator ($\kappa = -0.2073$). One of these models (BISICLES) also
819 ran 'high' and 'low' retreat experiments by doubling and halving the ocean thermal forcing, to
820 which we assign the κ_{25} and κ_{75} values.

821

822 The Antarctic sub-shelf basal melt parameter γ (Fig. 3b; units m a^{-1}) is the 'ocean heat
823 exchange velocity' scaling coefficient relating sub-shelf basal melting to ocean
824 temperatures^{12,13}. Two alternative distributions for γ were derived in the parameterisation¹³:
825 the first from mean Antarctic melt rates, and the second from the 10 highest observations of
826 melt rate at the grounding line of Pine Island Glacier, where melt rates are currently highest.
827 The values of γ estimated from Pine Island Glacier are an order of magnitude larger, and the
828 two distributions do not overlap. This is a continuous variable, but most simulations use one
829 of three values: the default, which is the median of the Mean Antarctic distribution,
830 MeanAnt₅₀ = 14477, and the 5th and 95th percentiles, MeanAnt₅ = 9619 and MeanAnt₉₅ =
831 21005. Further simulations used the same percentiles from the Pine Island Glacier
832 distribution: PIG₅₀ = 159188, PIG₅ = 86984 and PIG₉₅ = 471264. Some models¹⁵ used an
833 alternative variant of the parameterisation in which only local ocean temperatures were used,
834 rather than a combination of local and regional, which uses a different tuning for γ . However,
835 the values used are also the 50 [5, 95]th percentiles of those distributions, so we consider them
836 equivalent. For ice sheet models that did not use this parameterisation (N = 62 simulations),
837 we again assign the ensemble mean value ($\gamma = 59317$).

838

839 The Antarctic ice shelf collapse parameter C is a switch that indicates whether a scenario of
840 ice shelf collapse was used, which can lead to glacier speed-up. A timeline of collapses was
841 derived according to the presence of surface meltwater on ice shelves above a threshold (725
842 mm a^{-1}) for 10 years, estimated from surface air temperature projections⁴⁶ in the global
843 climate model driving the ice sheet model (mostly CCSM4). This method does not predict
844 whether meltwater may be efficiently drained from the surface for a given ice shelf⁴⁷, thus
845 avoiding collapse. We use values of 1 or 0 indicating whether the scenario is implemented or
846 not.

847

848 *Gaussian Process emulation*

849

850 Gaussian Process emulation⁴⁸ is non-parametric, treating the simulator as an unknown
851 mathematical function of its inputs. We use the R package RobustGaSP⁴⁹ for its numerically

852 robust parameter estimation⁵⁰. There are 23 emulators for the 2100 projections (Greenland ice
853 sheet, three Antarctic ice sheet regions, and 19 glacier regions) and 1955 emulators for the
854 full land ice time series (23 regions for each year from 2016 to 2100). An alternative to
855 predicting each year separately would be to model the temporal correlation explicitly, but we
856 prefer to use the simpler method, with fewer judgments, and allow temporal correlation to
857 emerge.

858

859 *Nugget*

860

861 We use a 'nugget' term to incorporate simulations from each multi-model ensemble. The
862 nugget is usually zero for deterministic models – the emulator predicts each simulation in the
863 ensemble exactly, i.e. the regression curve goes through all points – or a very small value, to
864 improve numerical stability or other properties^{22,23}. Here we allow the emulator to estimate
865 the nugget, and treat each multi-model ensemble as a set of outputs from a single stochastic
866 simulator or set of noisy observations. This approach has previously been used for emulating
867 stochastic simulators⁵¹ and for emulating climate models accounting for internal variability,
868 other inert inputs (uncertainties not explicitly modelled in the emulator), and approximations
869 of the model outputs⁵²⁻⁵⁷. Our method is similar to the use of 'emergent constraints' for
870 climate models^{44,58}, seeking relationships between past and future simulations across multi-
871 model ensembles to constrain them with observations, but here the predictors are inputs to the
872 models rather than their outputs for the past.

873

874 This approach does not require the simulations to be normally distributed but does assume
875 they are independent, which has been a long-standing difficulty of interpreting multi-model
876 climate ensembles. But with ice sheet models, although model names may be the same across
877 groups, each one has a very different set up, including physics approximations,
878 parameterisations, tuning, grid resolution, and – in particular – initialisation methods, which
879 have been shown to produce very different results even for simulations produced by the same
880 group^{6,7,14,15,59-61}. For glacier models, their structures are also vastly different, ranging from
881 simple scaling parameterisations to dynamic physical models⁸. We test two approaches to
882 account for any model dependence: a dummy variable (see below) and random effects
883 ('Antarctic cross-check model').

884

885 *Statistical model*

886

887 Let y denote the simulated global mean sea level contribution for given region and year (in
888 cm SLE), and \mathbf{x} the simulator inputs (see below). Following ref. [22], we write the simulator
889 as a function $y = f(\mathbf{x})$, for which the Gaussian Process emulator is described by a mean
890 function:

891
$$E[f(\mathbf{x})] = h(\mathbf{x})^T \beta,$$

892

893 where $h(\mathbf{x})$ is a vector of regression functions and β the corresponding regression coefficients,
894 and a covariance function, with variance σ^2 and correlation function $c(\mathbf{x}, \mathbf{x}')$,

895

896
$$\text{Cov}[f(\mathbf{x}), f(\mathbf{x}')] = \sigma^2(c(\mathbf{x}, \mathbf{x}') + vI),$$

897

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

899

900
$$p(f(\mathbf{x}) | \beta, \sigma^2, \delta, v) \sim N(h(\mathbf{x})^T \beta, \sigma^2(c(\mathbf{x}, \mathbf{x}') + vI)),$$

901

902 where \mathbf{x} are whichever model inputs are used for a given region, δ are the correlation lengths
903 of the covariance function, and $\sigma^2 v$ is the variability not explained by the inputs. Parameters
904 $(\beta, \sigma^2, \delta, v)$ are estimated from the simulation data.

905

906 The inputs \mathbf{x} used in the regression functions are global mean temperature change, T , and, for
907 the ice sheets, the ice-ocean parameter values (κ for Greenland; γ, C for Antarctica), plus a
908 dummy variable denoting whether Greenland models used the retreat parameterisation. These
909 are discussed in the next section. All inputs are rescaled to have zero mean and unit variance.

910

911 *Mean functions*

912

913 The Gaussian Process mean function describes the large-scale response of the simulator to its
914 inputs, usually specified as a linear trend with the remainder described by a zero-mean
915 Gaussian process.

916

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

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

919 for Antarctica. We also try two types of dummy variable. The first is for the ice sheet and
920 glacier model names, so these can be treated distinctly in the emulator, but this leads to clear
921 overfitting (i.e. the model is too flexible in Figs. 1 and 2). The second represents whether an
922 ice sheet model uses the ISMIP6 retreat or basal melt parameterisation, to absorb any
923 misalignment between the imputed value and the effective value. Bayesian Information
924 Criterion (BIC) from a stepwise model selection (testing up to first-order interactions)
925 suggests this dummy variable is informative for Greenland, so we retain it (o , for open
926 parameterisation), but not for the Antarctic regions. The stepwise model selection suggests
927 we could reasonably include terms for the interaction between temperature and retreat for
928 Greenland, temperature and basal melt for West Antarctica, and temperature and collapse for
929 East Antarctica, but we choose not to, to avoid the risk of overfitting. The selection also
930 shows that collapse strongly dominates the Antarctic Peninsula response, and is may not be
931 needed for West Antarctica, but we retain all terms (i.e. T_i, γ_0, C) because we otherwise find
932 the covariance matrix is poorly conditioned. The resulting mean functions are $h_{\text{GrIS}}(\mathbf{x})_i \sim (T_i,$
933 $k, o)$ for Greenland, $h_{\text{AIS}}(\mathbf{x})_i \sim (T_i, \gamma_0, C)$ for the Antarctic regions, and $h_{\text{Glaciers}}(\mathbf{x})_i \sim (T_i)$ for the
934 glaciers, where $h \sim (a, b)$ means h is a linear function of a and b , and i is the index for the
935 year.

936

937 *Covariance functions*

938

939 The covariance function describes the smoothness of the Gaussian Process. As in any
940 statistical modelling, there is a trade-off between improving accuracy and over-fitting. We
941 assess this using the usual leave-one-out procedure^{62,63}. We fit the emulator to all ensemble
942 members but one, then predict the sea level contribution from this simulation; we repeat this
943 for every combination, noting the emulator error (residual) and uncertainty for each
944 prediction. We perform this for each of the 23 regional emulators for the year 2100 with five
945 covariance functions of varying smoothness – Matérn(5/2), which is the default in
946 RobustGaSP, Matérn (3/2), and three members of the power exponential family with high,
947 medium and low exponent values ($\alpha = 1.9$, i.e. close to a squared exponential, the default
948 value; $\alpha = 1.0$, exponential, and $\alpha = 0.1$, for which the covariance function has a small effect
949 so the emulator approaches linear regression).

950

951 For 18 of the 19 glacier regions, we use the covariance function with the smallest
952 standardised Euclidean distance between the emulator predictions and simulations

953 (standardised because, unlike simpler metrics such as root mean square error or mean
954 absolute error, it does not penalise larger errors if the emulator uncertainty intervals are
955 sufficiently large), as in ref [24]. For the Southern Andes (region 17), all covariance functions
956 give identical distances, so we use the default for RobustGaSP. For the ice sheets, we use the
957 covariance function that gives close to linear regression (power exponential, $\alpha = 0.1$), rather
958 than the one with the minimum Euclidean distance, for various reasons. For Greenland, West
959 Antarctica, and the Antarctic Peninsula, the minimum distance covariance functions (power
960 exponential $\alpha = 1.0$ for Greenland; Matérn(3/2) for the Antarctic regions) result in overfitting
961 for temperature (i.e. too much flexibility in Fig. 1). For East Antarctica, the minimum
962 distance covariance functions (Matérn(5/2)) result in an incorrect sign prediction under the
963 ice shelf collapse switch. Using the alternative covariance function solves all of these issues
964 and does not increase the standardised Euclidean distance by much: 4% for the Peninsula,
965 and 0.4-1% for the other three regions. The resulting covariance functions are given in
966 Extended Data Table 2.

967

968 *Evaluating the emulators*

969

970 After selecting the covariance functions for each regional emulator at 2100, we evaluate the
971 emulators further by plotting the emulator predictions against the simulations from the leave-
972 one-out procedure, and the standardised residuals (the difference between the emulator
973 prediction and the simulator, divided by the emulator standard deviation), and calculating the
974 percentage of simulations falling within ± 2 s.d. (Extended Data Table 2 and Extended Data
975 Figures 1 and 2). We would not expect exactly 95% of the simulations to fall within 2 s.d., in
976 part because the predictions are not independent, but very low or high values would suggest
977 emulator over- or under-confidence. The region with the lowest percentage of predictions
978 within the uncertainty intervals is North Asia (region 10) with 89%, indicating slightly too
979 small emulator uncertainty estimates, and the highest is 98% (Scandinavia: region 8),
980 indicating the reverse.

981

982 Mean absolute errors for each emulator are given in Extended Data Table 2 and Extended
983 Data Figures 1 and 2: for the ice sheet regions they are 0.28 cm (Peninsula), 1.4 cm
984 (Greenland) and 1.5 cm (East Antarctica) and 2.0 cm (West Antarctica), and for the

985 individual glacier regions they range from 0.0020 cm to 0.87 cm (Antarctic periphery: region
986 19). Mean absolute standardised errors are all less than 0.006.

987

988 The emulator underestimates the three to four highest West and East Antarctic contributions
989 by around 10-15 cm (Extended Data Figure 1b and 1c). The five highest of these are from the
990 SICOPOLIS model, which has a much greater sensitivity to basal melting than other models
991 (see main text, *Robustness checks* and Extended Data Figure 6), and use the highest value of
992 this parameter ($\gamma = \text{PIG}_{95}$). These simulations are therefore extreme: 1% of the 344
993 simulations, and the 97.5th percentile value of the basal melt parameter. There are process-
994 based reasons to expect that SICOPOLIS is an upper bound or overestimate (see main text).
995 When the emulator is calibrated with this model alone, it does not underestimate its highest
996 contributions (not shown). The resulting projections under the NDC scenario are shown in
997 *Robustness checks* (test 4); the difference with the main projections may be interpreted as the
998 maximum possible impact of this emulator underestimate, if SICOPOLIS were the sole
999 realistic ice sheet model. These are lower than the 'risk-averse' projections, which are made
1000 with a subset of high sensitivity ice sheet models and other pessimistic assumptions (see main
1001 text).

1002

1003 We therefore consider the emulators to be adequate for the predictions of large-scale sea level
1004 contribution presented here.

1005

1006 *Antarctic cross-check model*

1007

1008 We perform a cross-check for the Antarctic ice sheet regions at 2100 using a linear mixed
1009 model, with the ice sheet model name included as a random effect to deal with any systematic
1010 uncertainty arising from dependence of ensemble members. This attributes some of the
1011 uncertainty in the response to the ice sheet model used, and this uncertainty can then be
1012 removed from the predicted PDF. We thus model the ensemble members as 'similar but not
1013 identical', using a mean function of temperature and ice sheet parameters, plus a structured
1014 error term which includes a systematic component according to the ice sheet model and a
1015 noise component to capture other sources of variability such as initialisation.

1016

1017 For the mean function (also linear), we use the logarithm of γ as a regressor, so it is always
1018 positive. Consequently we use the geometric mean as the missing value, rather than the
1019 arithmetic mean. We use a dummy variable to denote these models, as for Greenland in the
1020 GP emulator. The full global mean temperature change trajectories are used instead of only
1021 the total change at 2100. To increase the signal-to-noise ratio, the annual means are reduced
1022 to decadal means (2015–2029, 2030–2039, . . . , 2090–2100). There are thirteen distinct
1023 forcings, each one the product of a global climate model and a scenario, so we represent the
1024 forcing variables as twelve bisquare basis functions. These start as thirteen bisquare basis
1025 functions, each one centred at one of the thirteen forcings, but one is dropped because
1026 otherwise the model matrix becomes rank deficient when a constant is added. The one
1027 dropped is the one with the smallest mean Euclidean distance to the other twelve. We use
1028 bisquare kernels, where the standard deviation of each kernel is set to one tenth of the
1029 maximum Euclidean distance between all pairs of forcings, to cover the forcing space with
1030 non-zero values for the forcing regressors. We use the same distributions for temperature,
1031 basal melt and collapse as the main projections, and set the dummy variable to represent
1032 standard parameterisation models.

1033

1034 This emulator predicts 50 [5, 95]th percentiles for the West Antarctic sea level contribution at
1035 2100 of 2 [-4, 8] cm SLE for SSP1-26 and 3 [-4, 10] cm SLE for SSP5-85, which are very
1036 similar to the GP emulator predictions of 2 [-5, 10] cm SLE and 3 [-4, 11] cm SLE. We test
1037 the effect of changing the kernel standard deviation to one twelfth or one fourteenth of the
1038 maximum Euclidean distance; the largest change is a 2 cm decrease in the 95th percentile
1039 under SSP5-85. For East Antarctica, the emulator with random effects predicts 2 [-3, 6] cm
1040 SLE for both scenarios; the GP emulator predicts a small scenario-dependence, 2 [-4, 7] cm
1041 SLE for the low emissions scenario and 0 [-5, 6] cm SLE for the high. For the Antarctic
1042 Peninsula, the random effects predictions are 0 [-1, 2] cm SLE for both scenarios, and the GP
1043 are the same. These similarities give us confidence that model dependence is not substantially
1044 affecting our projections – i.e. that differences in model structure, resolution, calibration and
1045 initialisation dominate over the similarities – although it would be worth investigating this in
1046 more detail.

1047

1048 **Sea level projections**

1049

1050 We use probability distributions for global temperature and the ice sheet model parameters as
1051 inputs to each emulator to make the projections.

1052

1053 *Global mean temperature projections*

1054

1055 We use projections of global annual mean surface air temperature change since 2015 from
1056 the FaIR (Finite amplitude Impulse Response) simple climate model for the main projections.
1057 We take the 500-member ensemble from reference [30]: SSP1-19, SSP1-26, SSP3-70, SSP5-
1058 85 and a scenario estimated for the 2019 Nationally Determined Contributions. We also use
1059 projections for SSP-245 generated with the same ensemble.

1060

1061 *Ice sheet model parameter distributions*

1062

1063 For Greenland, we sample from a kernel density estimate of the original k distribution ($N =$
1064 191) with the same bandwidth used in deriving the parameterisation^{10,11} (0.0703652) (Fig. 1b).
1065 The dummy variable is always set to represent the standard ISMIP6 parameterisation.

1066

1067 For Antarctica, we combine the Mean Antarctic and Pine Island Glacier γ distributions ($N =$
1068 10,000 each), and sample from a kernel density estimate using three times the automatic
1069 bandwidth (Silverman's 'rule of thumb'⁶⁴) to merge and smooth them into a near-unimodal
1070 distribution that we truncate at zero (Fig. 1c). For the collapse switch C , we sample randomly
1071 from 0 or 1 with equal probability (8% of the ISMIP6 simulations have ice shelf collapse).
1072 The ice shelf collapse scenario does not include the possibility of surface meltwater draining
1073 efficiently from some ice shelves under certain conditions, thereby avoiding collapse, so we
1074 feel this is a reasonable judgement.

1075

1076 *Sampling*

1077

1078 For the 2100 projections, we sample from the FaIR ensemble ($N=500$) with replacement ($N =$
1079 5000 for main and risk-averse projections; $N = 1000$ for robustness and sensitivity tests). For
1080 the full time series, we use the 500 FaIR projections directly without resampling. We make
1081 one set of emulator predictions (23 regions) for each temperature value in a given year,
1082 randomly sampling the relevant ice-ocean parameters (k, γ_0, C) once for each FaIR ensemble
1083 member.

1084

1085 We integrate over the uncertain inputs (temperature in a given year, and ice-ocean
1086 parameters) to obtain the final probability density functions (PDFs). Each regional emulator
1087 predicts a Student-t distribution for a given set of these input values, defined by a mean and
1088 standard deviation; we approximate this with a normal distribution, as in refs [55, 57], which
1089 is accurate enough for this application. We use different integration methods for the 23
1090 individual regional PDFs compared with the regional sums (Antarctica, global glaciers, and
1091 land ice total). For the individual regional estimates, we use deterministic numerical
1092 integration (the midpoint rule: we sum the Gaussian distributions for each emulator
1093 prediction, then normalise). For regional sums we must use Monte Carlo sampling, because
1094 the three ice sources (Greenland, Antarctica and glaciers) have different parameters, and we
1095 also desire traceability of predictions to input values within a given ice source. We sample
1096 once from the Gaussian distribution for each emulator prediction, then sum the regional
1097 samples for a given temperature to estimate the PDF, smoothing with kernel density
1098 estimation for figures (again using Silverman's 'rule of thumb'⁶⁴ for the bandwidth). Sampling
1099 is a more noisy method of integration than deterministic methods, so the PDFs for regional
1100 sums are less smooth than those for individual regions.

1101

1102 *Glacier maximum cap*

1103

1104 We apply a cap to the glacier projections using estimates of their maximum sea level
1105 contribution³¹. Glacier model projections often exceed this cap in some regions, if near or
1106 total loss is projected under high emissions, either because they report changes in total mass,
1107 not mass above flotation, or because of errors in initial mass⁸, or both. We restrict values to
1108 the maximum in the emulator mean predictions and then the PDFs (the latter exceeding the
1109 cap due to emulator uncertainty).

1110

1111 *Time series smoothing*

1112

1113 Interannual variability arises in the time series due to sampling the emulator uncertainty for
1114 each annual regional prediction. We apply a five year running mean in Fig. 3d to visualise the
1115 expected smoothness of sea level contributions; projections provided in the Supplementary
1116 Information are unsmoothed.

1117

1118 **Comparison with IPCC assessments**

1119

1120 The ice sheet projections are made relative to control simulations with a constant recent
1121 climate. This control includes both the model drift and, depending on the initialisation
1122 method, any background contribution arising from forcing before 2015. This background
1123 contribution should be added to the ice sheet projections, but is difficult to quantify. Five year
1124 mean rates of sea level contribution since 1992/3 range from 0.1-0.8 mm/yr for the Greenland
1125 ice sheet⁶⁵ and 0.1-0.6 mm/yr for Antarctica⁶⁶, but they would decrease in the absence of
1126 forcing after 2014. Modelling work to quantify the background contribution from
1127 Greenland⁶⁷ suggests a contribution of 0.6 ± 0.2 cm SLE by 2100. Estimates made for this
1128 study range from 0.3-0.8 cm under a range of retreat parameter values, $\kappa_{75} - \kappa_{25}$
1129 (IMAU/IMAUICE1: 0.3-0.4 cm; CISM variant similar to NCAR/CISM: 0.4-0.8 cm). For
1130 Antarctica, the dynamic commitment has been estimated to be 2 cm SLE at 2100 for the
1131 Amunden Sea Embayment region of West Antarctica, where most mass loss is currently
1132 occurring⁶⁸. Part of these trends may still be due to residual model drift. The committed
1133 contribution could therefore add up to ~ 1 cm/century to our Greenland projections and ~ 2
1134 cm/century to the Antarctic.

1135

1136 The Antarctic ice sheet models include some of the larger islands that are also included in
1137 region 19, potentially leading to double-counting. However, median projections for region 19
1138 range from 1-2 cm under different emissions scenarios, and the ice sheet models are much
1139 lower resolution (i.e. the glaciers are likely less responsive), so the effect is expected to be of
1140 order 0.5-1 cm SLE or less.

1141

1142 We average our projections over the 86 years and compare them with the average IPCC
1143 AR5²⁵ and SROCC¹ projections over 95 years (the midpoints of 1986-2005 to 2081-2100) as
1144 rates of cm SLE per century. For the glaciers, we project 8 cm/century SLE for SSP1-26 and
1145 16 cm/century for SSP5-85 excluding the Antarctic peripheral glaciers (region 19: 1 cm and 2
1146 cm, respectively), compared with 10 cm for RCP2.6 and 17 cm for RCP8.5 in AR5. For the
1147 Greenland ice sheet, we project 4 cm/century SLE for SSP1-26 and 11 cm for SSP5-85,
1148 compared with 6 cm for RCP2.6 and 13 cm for RCP8.5 in AR5. For Antarctica, we project 5
1149 cm/century SLE for both scenarios; the AR5 projections are 5 cm/century SLE for RCP2.6
1150 and 4 cm for RCP8.5, while those for SROCC are 4 cm/century SLE for RCP2.6 and 11 cm

1151 for RCP8.5. The difference between scenarios for Antarctica in AR5 arises only from
1152 additional accumulation, because the dynamic contributions are assumed to be the same.
1153
1154 Glacier projections could be overestimated because meltwater routing to the ocean is not
1155 accounted for (not all volume lost from the glaciers reaches the oceans), or underestimated
1156 because only one glacier model includes ice-water interactions (i.e. frontal ablation of
1157 marine- and lake-terminating glaciers). For the latter, we compare mean projections for the
1158 GloGEM model to the emulator for RCP8.5/SSP5-85 and RCP4.5/SSP2-45 for key regions,
1159 and find they are larger by less than 1 cm for Alaska and Russian Arctic (regions 1 and 9), by
1160 less than 0.5 cm for Svalbard (7) and Arctic Canada South (4), and smaller than the emulator
1161 for Arctic Canada North (3). All are within the emulator 95th percentile estimates. We may
1162 slightly underestimate uncertainty in the global glacier total due to correlated errors across
1163 models⁸ by emulating the regions independently, though there are compensating advantages
1164 (more accurate emulation; spatial pattern of meltwater); a similar argument applies to
1165 Antarctica.

1166

1167 **Sensitivity tests**

1168

1169 We perform a number of checks to test the sensitivity of the ice sheet projections to changes
1170 in the chosen inputs, predominantly the input distributions, but also the dataset in the final
1171 test (see Extended Data Table 3 and refs [25, 26, 30, 34, 39]). All results are shown for the
1172 SSP5-85 scenario in Extended Data Figure 4 under the index given (where 1 is the main
1173 projection); numerical values in the text refer to changes in the median and [5, 95th] percentile
1174 estimates for the ice sheet under this scenario unless otherwise stated.

1175

1176 **Robustness checks**

1177

1178 We perform a number of checks to test robustness of the ice sheet projections to changes in
1179 the simulation dataset (see Extended Data Table 4 and refs [14, 16, 24, 66]). Results are
1180 shown for the NDCs scenario in Extended Data Figure 5 under the test index given (where 1
1181 is the main projection); numerical values in the text refer to changes in the median and
1182 [5, 95th] percentile estimates under this scenario unless otherwise stated. The full datasets are
1183 256 simulations for Greenland and 344 simulations for Antarctica.

1184

1185 **Parameter interactions**

1186 *Retreat and basal melt vs temperature*

1187

1188 Ice sheet projection uncertainties are constant across scenarios. However, tests with three ice
1189 sheet models show that the range of projections from high to low values of the retreat
1190 parameter ($\kappa_{95} - \kappa_5$) and basal melt parameter ($\text{PIG}_{95} - \text{MeanAnt}_{50}$) is consistently smaller
1191 under RCP2.6 than RCP8.5, so the emulator uncertainty should be smaller at lower
1192 temperatures. The ratios of ranges, RCP2.6/RCP8.5, for each group/model + GCM are:

1193

1194 Greenland

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

1197

1198 West Antarctica

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

1201

1202 East Antarctica

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

1205

1206 The emulator does not have sufficient data from lower emissions scenarios to reduce the
1207 variance, particularly for Greenland. If other ice sheet models respond the same way as the
1208 above, then adding more simulations may reduce the uncertainty for low SSPs.

1209

1210 *Ice shelf collapse vs basal melt*

1211

1212 The contribution due to ice shelf collapse does not increase with higher values of the basal
1213 melt parameter in the models JPL1/ISSM and CPOM/BISICLES (0.1 cm difference for the
1214 Peninsula in BISICLES; all other regional differences for both models ≤ 0.02 cm).

1215

1216

1217 **Code availability**

1218

1219 R code and input data are available at <https://github.com/tamsinedwards/emulandice>. Each
1220 simulation in the sea level projections file has a label in the 'publication' column for the
1221 reference (Goelzer2020, Seroussi2020, Nowicki2020 or Marzeion2020), or 'New' if
1222 previously unpublished.

1223

1224 **Data availability**

1225

1226 All global climate, simple climate, ice sheet and glacier model data used as inputs to this
1227 study are provided with the code as described above. Main and risk-averse projections from
1228 the analysis are provided in the Supplementary Information as annual quantiles for each of
1229 the 23 regions, and the Antarctic, glacier and land ice sums.

1230

1231 **Author information**

1232

1233 The authors declare no competing financial or non-financial interests. Correspondence and
1234 requests for materials should be addressed to T.L.E. (tamsin.edwards@kcl.ac.uk). Reprints
1235 and permissions information is available at www.nature.com/reprints.

1236

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1295

1296

1297 **Extended Data**

1298

1299 **Extended Data Table 1. The additional 22 Greenland and 37 Antarctic ice sheet model experiments**
1300 **not previously described elsewhere.** Retreat parameter values κ_5 and κ_{95} are the 5th and 95th percentile
1301 values of the retreat (κ) distribution; basal melt parameter values $\text{MeanAnt}_{[5, 50, 95]}$ and $\text{PIG}_{[5, 50, 95]}$ are the
1302 5th, 50th and 95th percentile values of the Mean Antarctic and Pine Island Glacier basal melt (γ)
1303 distributions (see Methods).

1304

1305 **Extended Data Table 2. Emulator structure and validation.** Emulator covariance functions, and the
1306 results of the leave-one-out procedure for each: the percentage of simulations that fall within the emulator
1307 95% uncertainty intervals, and the mean absolute error.

1308

1309 **Extended Data Figure 1. Emulator leave-one-out validation for ice sheets and 8 glacier regions.** Left
1310 of each subpanel: Emulator predictions versus simulations for each regional sea level contribution in the
1311 year 2100, with percentage of predictions falling outside ± 2 emulator standard deviations and mean
1312 absolute error in cm SLE. Right of each subpanel: standardised residuals (emulated minus simulated,
1313 divided by emulator standard deviation). Predictions falling outside ± 2 emulator standard deviations are
1314 shown in orange.

1315

1316 **Extended Data Figure 2. Emulator leave-one-out validation for 11 glacier regions.** As for Extended
1317 Data Figure 1, but for the remaining glacier emulators.

1318

1319 **Extended Data Figure 3. Temperature projections for 2015-2100 from FaIR and CMIP6 ensembles.**
1320 Global surface air temperature projections under different greenhouse gas scenarios (see main text) from
1321 the (a) FaIR simple climate model ensemble ($N = 5000$; same as Figure 3a) and (b) CMIP6 global climate
1322 model ensemble ($N \sim 30$ models per scenario: see Methods) sampled with a kernel density estimate ($N =$
1323 1000).

1324

1325 **Extended Data Table 3. Sensitivity tests.** Tests of the sensitivity of the ice sheet projections to changes in
1326 the chosen inputs. The test index, name, description and impact are detailed. Numerical values refer to
1327 changes in the median and [5th, 95th] percentile estimates for the ice sheet under SSP5-85, unless otherwise
1328 stated; results for this scenario are shown in Extended Data Figure 4.

1329

1330 **Extended Data Figure 4. Sensitivity of ice sheet projections at 2100 under SSP5-85 to uncertain**
1331 **inputs.** a, Greenland. b, West Antarctica. c, East Antarctica. d, Antarctic Peninsula. Indices refer to test
1332 (see Extended Data Table 3). Box and whiskers show [5, 25, 50, 75, 95]th percentiles. 1: Default; 2:
1333 CMIP6 global climate model ensemble projections of global mean surface air temperature, instead of FaIR
1334 simple climate model; 3: fixed global mean surface air temperature; 4: fixed glacier retreat (Greenland) or

1335 basal melt (Antarctica) parameter. Antarctic regions only: basal melt parameter has 5: 'Mean Antarctic'
1336 distribution; 6: 'Pine Island Glacier' distribution; 7: uniform, high distribution; 8: uniform, very high
1337 distribution. Ice shelf collapse scenario: 9: off and 10: on. 11: Risk-averse projections using the high 'Pine
1338 Island Glacier' distribution for basal melt (test 6), ice shelf collapse on (test 10), and the ice sheet and
1339 climate models that give the highest sea level contributions (Extended Data Figure 5: test 6, 7).

1340

1341 **Extended Data Table 4. Robustness checks.** Checks performed to test the robustness of the ice sheet
1342 projections to changes in the simulation dataset. The test index, name, description and impact are detailed.
1343 Numerical values refer to changes in the median and [5th, 95th] percentile estimates for the ice sheet under
1344 the NDCs scenario, unless otherwise stated; results for this scenario are shown in Extended Data Figure 5.

1345

1346

1347 **Extended Data Figure 5. Robustness of ice sheet projections under Nationally Determined**
1348 **Contributions to ice sheet/climate model simulation selection and treatment.** a, Greenland. b,
1349 West Antarctica. c, East Antarctica. d, Antarctic Peninsula. Indices refer to test (see Extended Data
1350 Table 4). Box and whiskers show [5, 25, 50, 75, 95]th percentiles. 1: Default; 2: Higher resolution ice
1351 sheet models; 3: Ice sheet models with the most complete sampling of uncertainties (10 models for
1352 Greenland, 4 for Antarctica); 4: Single ice sheet model with the most complete sampling of
1353 uncertainties and (coincidentally) high sensitivity to retreat or basal melting parameter. Antarctic
1354 regions only: 5: Alternative single ice sheet model with nearly as complete sampling but low
1355 sensitivity to basal melt parameter. 6: Ice sheet models with the highest sensitivity to basal melt
1356 parameter; 7: Climate models that lead to highest sea level contributions. 8: Ice sheet models with
1357 2015-2020 mass change in the range 0-0.6 cm. 9: Only ice sheet models that use the standard ISMIP
1358 melt parameterisations. 10: Higher basal melt value assigned to ice sheet models that do not use the
1359 standard ISMIP6 melt parameterisations.

1360

1361 **Extended Data Figure 6. Sensitivity to basal melting by Antarctic ice sheet and climate model.**
1362 Vertical lines show ice sheet models that do not use the ISMIP6 basal melt parameterisation, and the
1363 basal melt value they are assigned. Ice sheet models includes the high and low sensitivity models in
1364 Extended Data Figure 5: test 4 (ILTS_PIK/SICOPOLIS) and test 5 (LSCE/GRISLI).

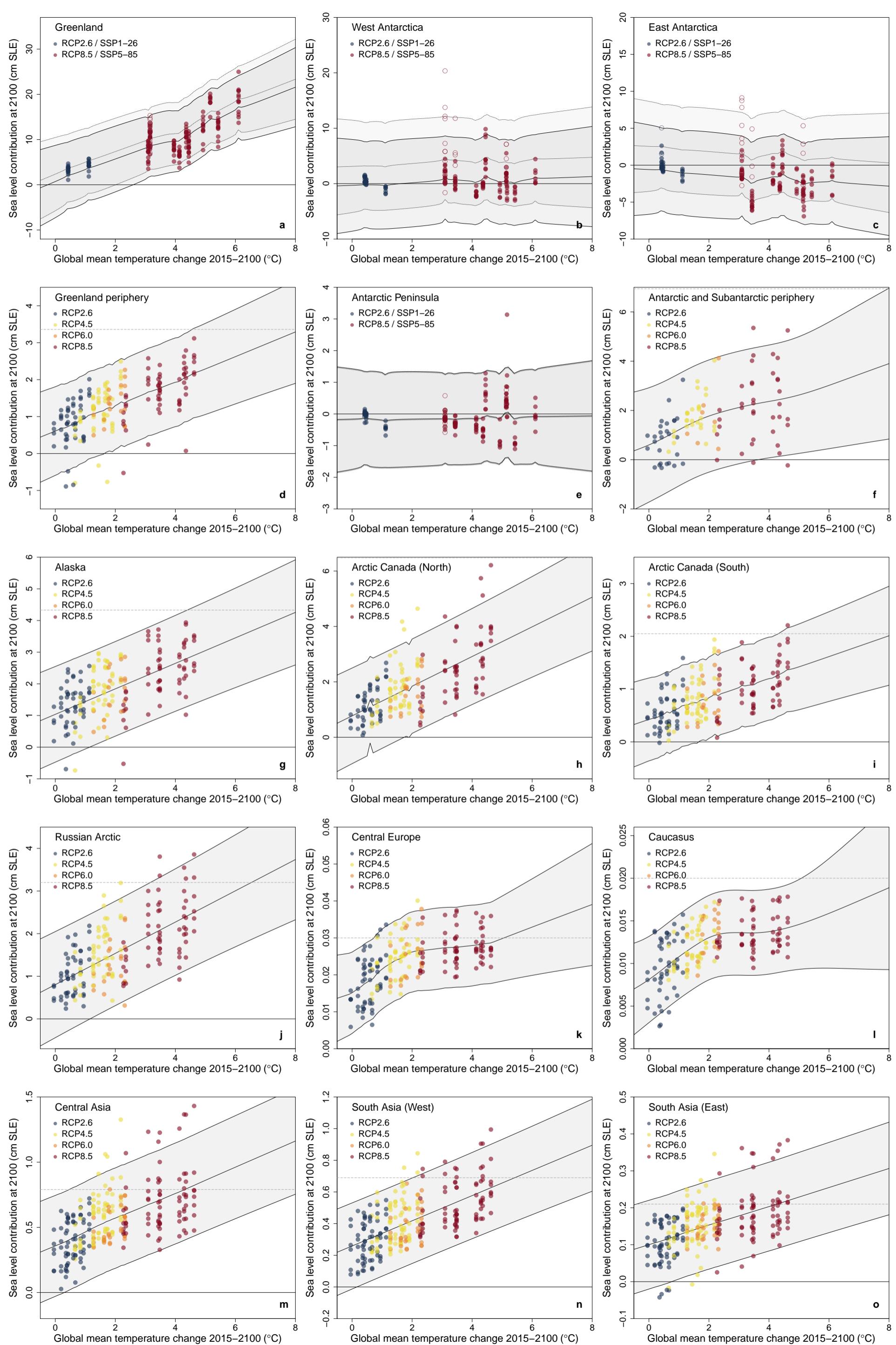
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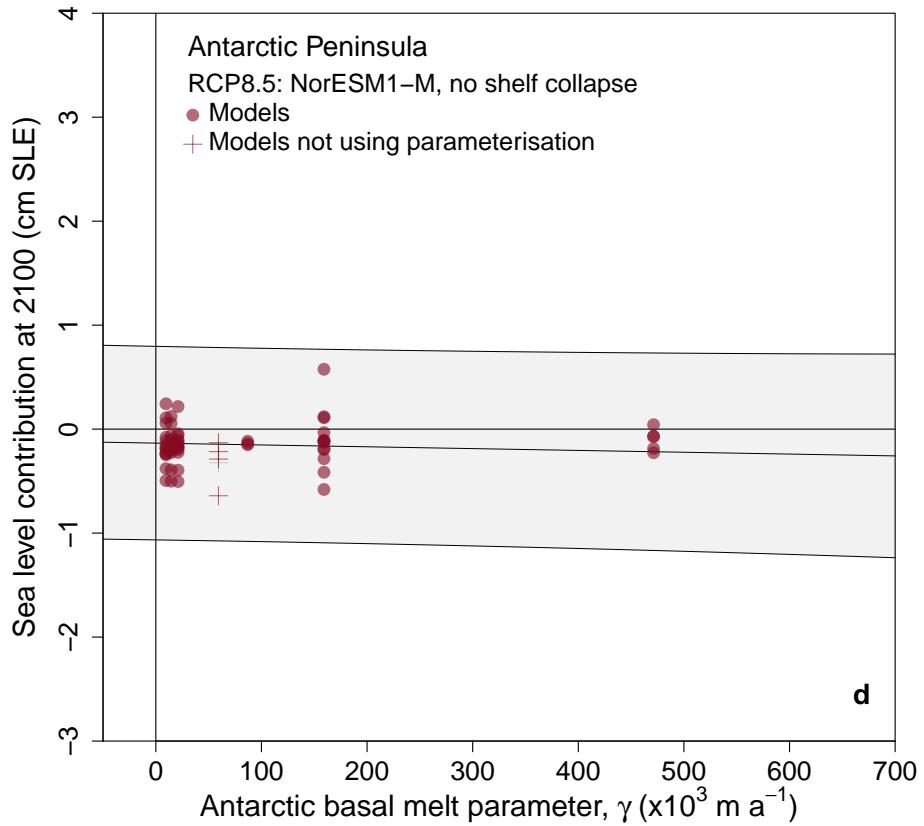
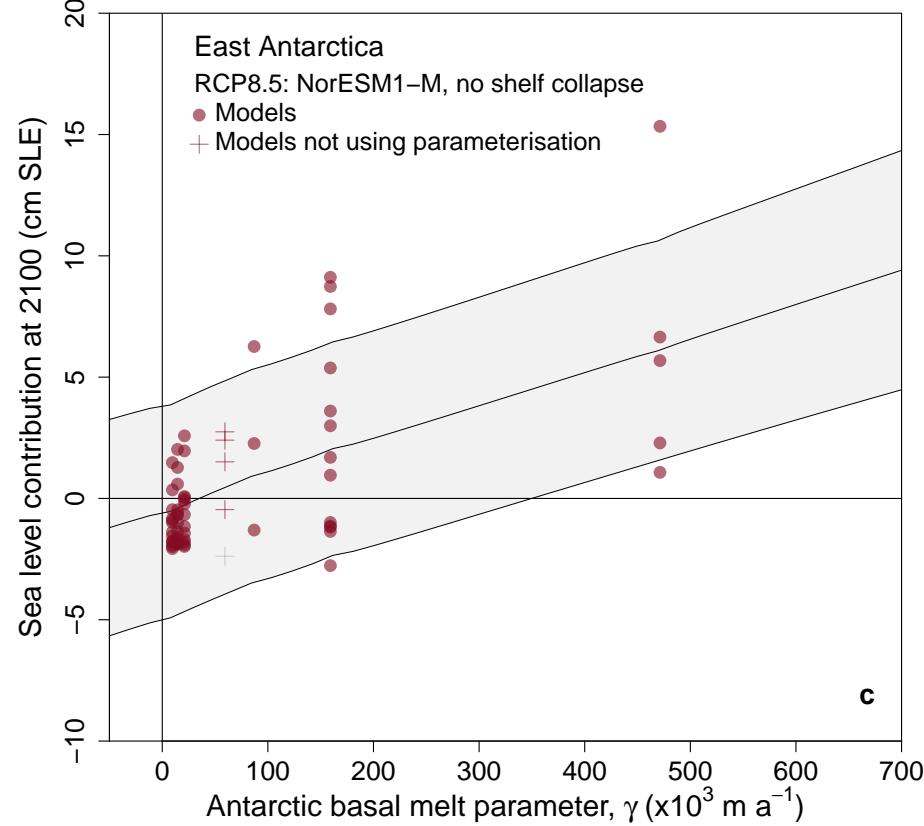
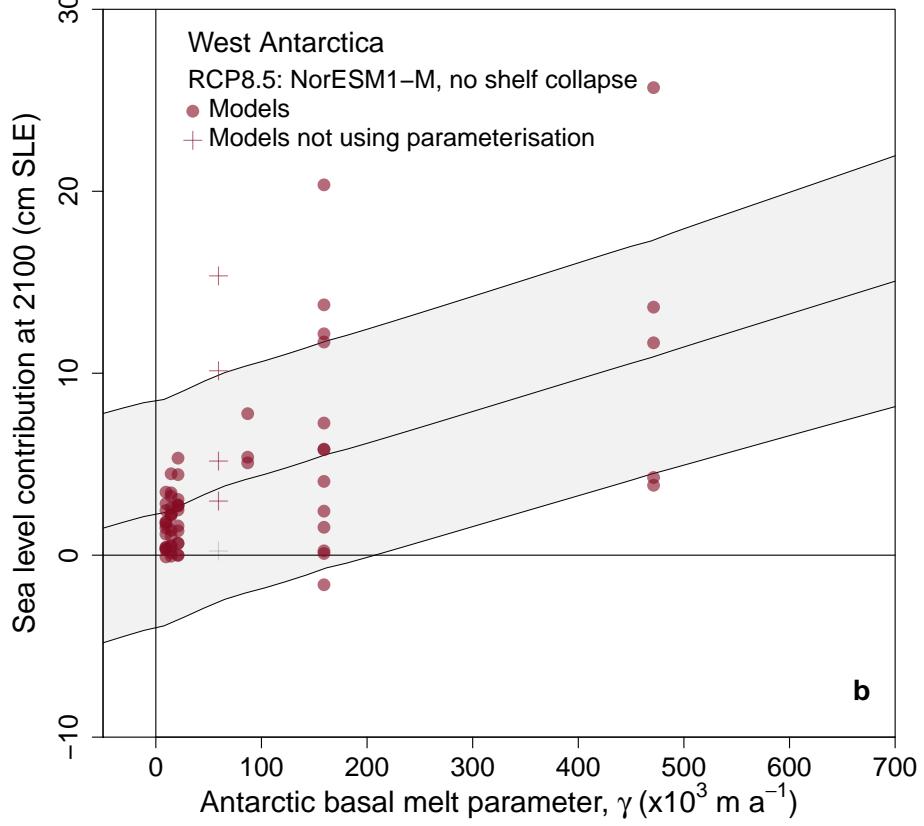
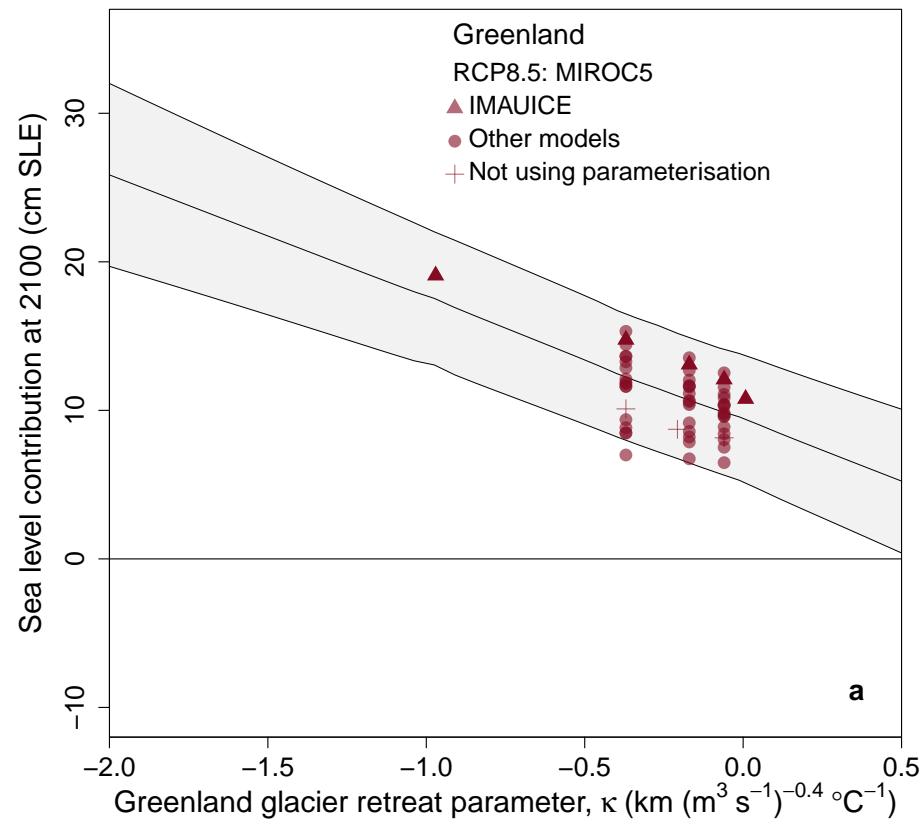
1366 **Extended Data Figure 7. Effect of Antarctic ice shelf collapse by climate model.** Additional sea
1367 level contribution at 2100 when using ice shelf collapse for six climate models, ordered by maximum
1368 impact on the Peninsula contribution. (a) West and (b) East Antarctica, and (c) Peninsula.

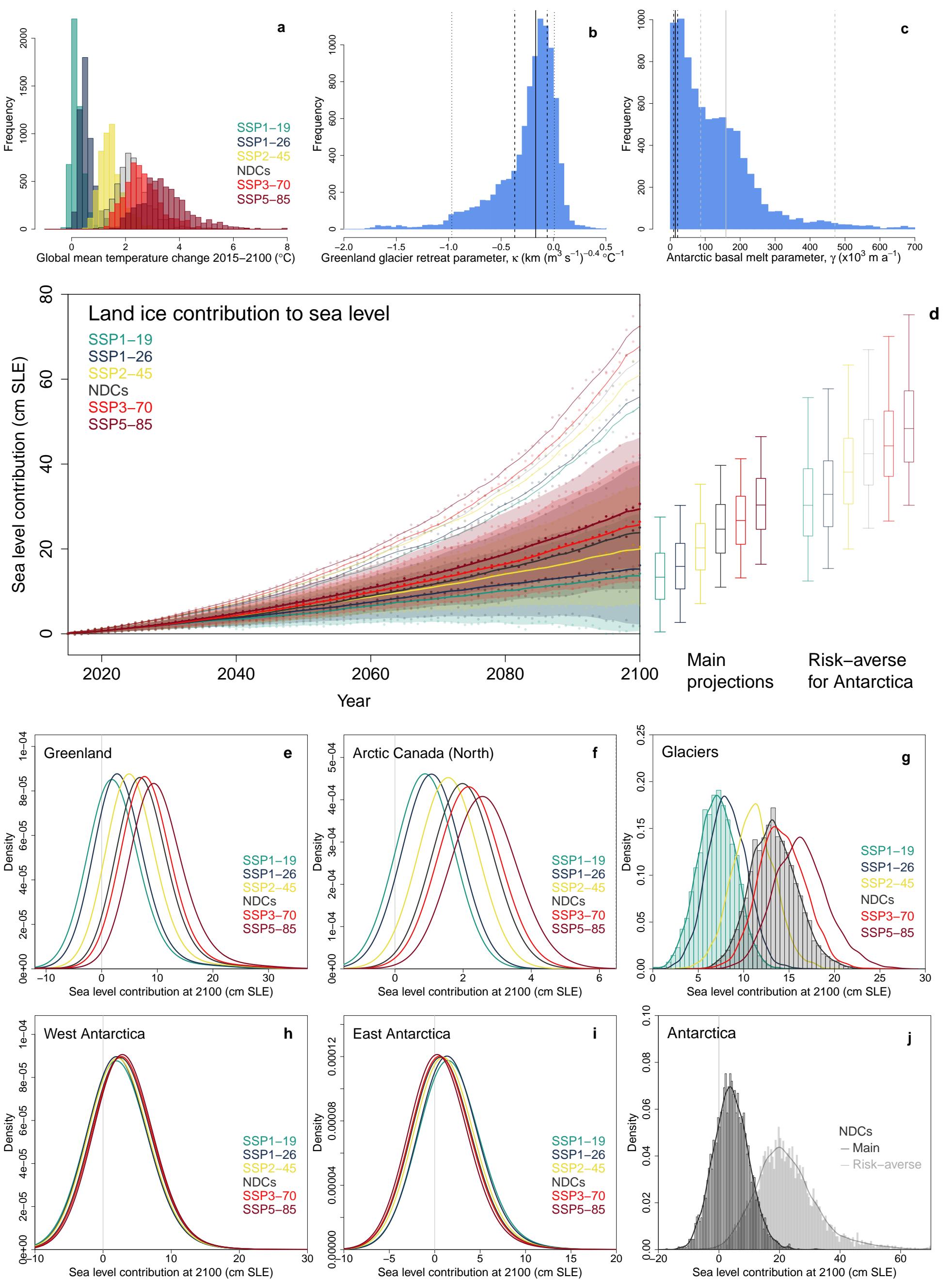
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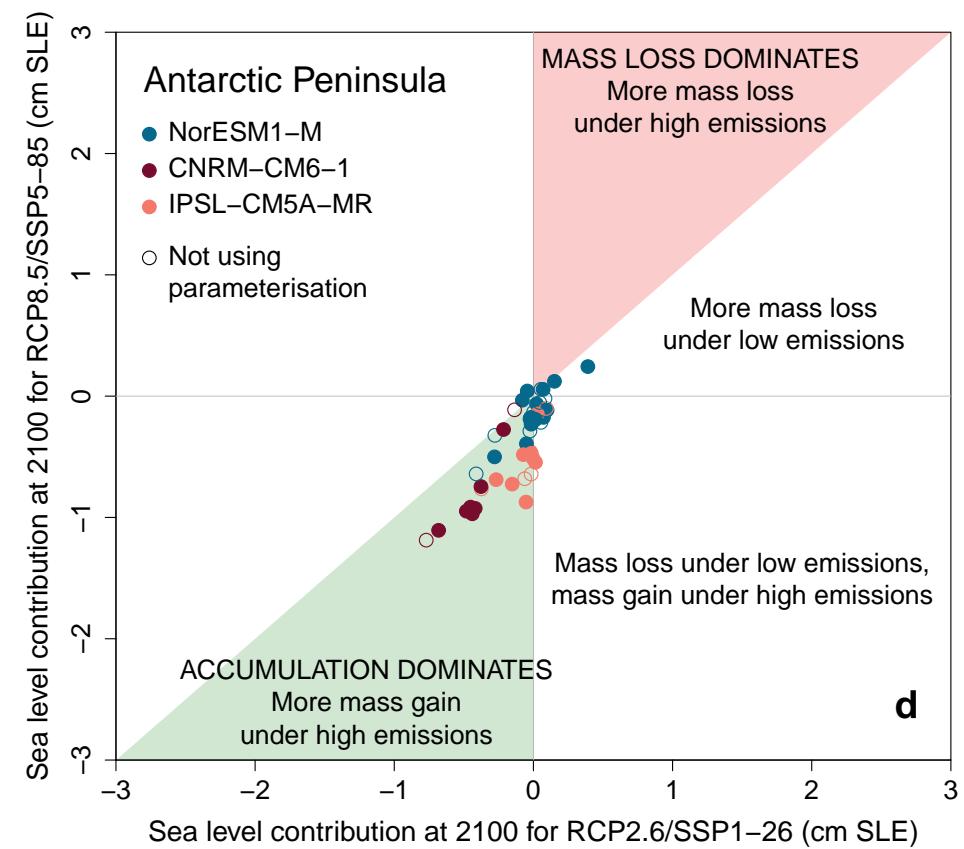
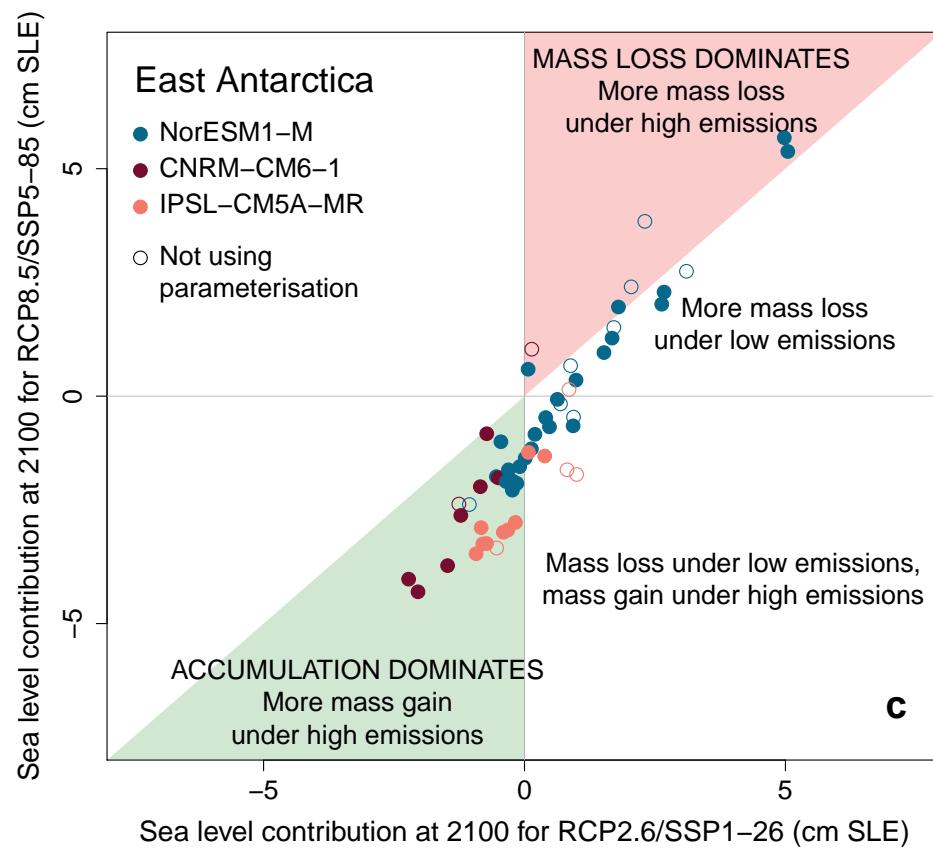
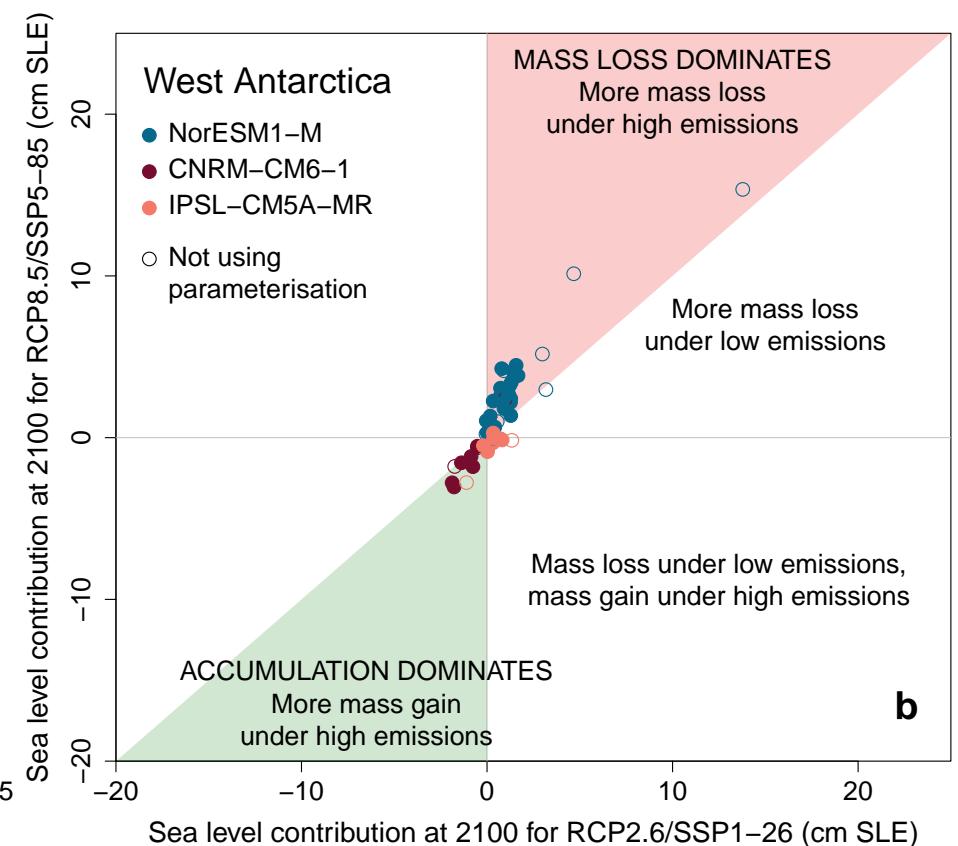
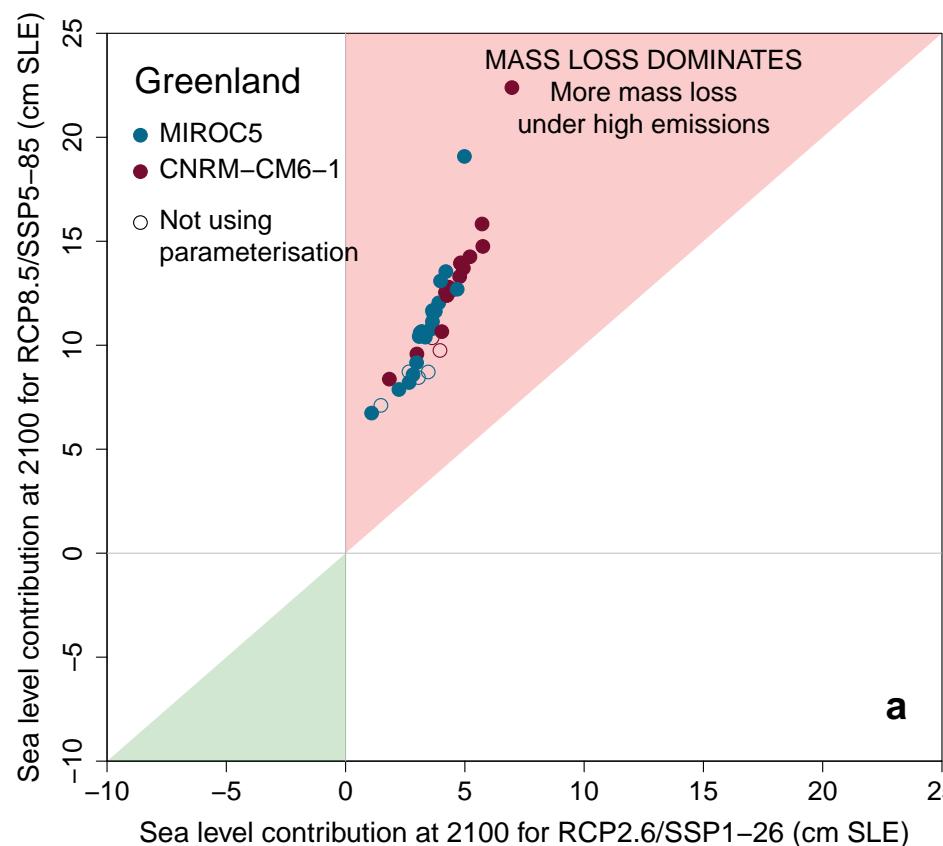
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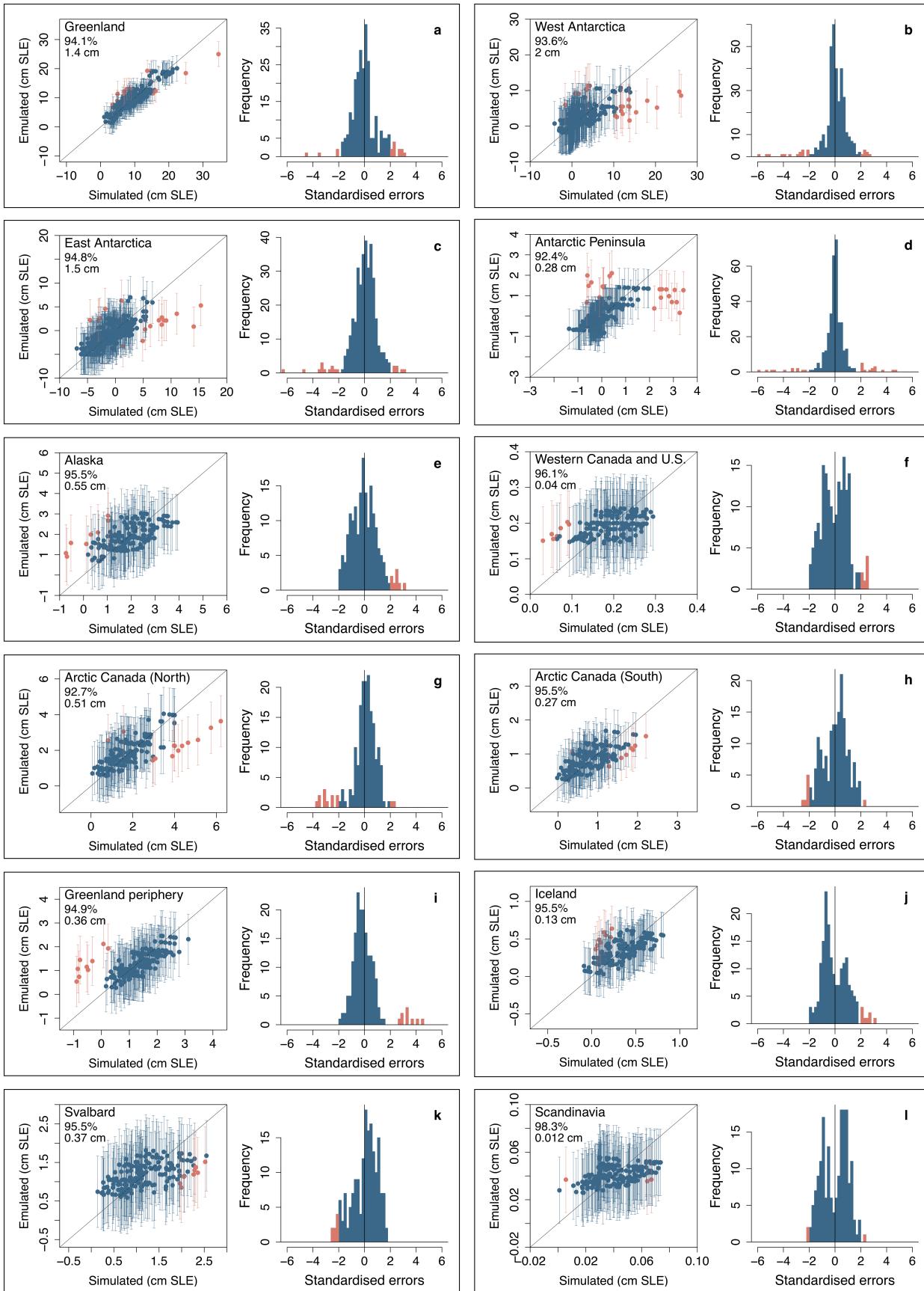
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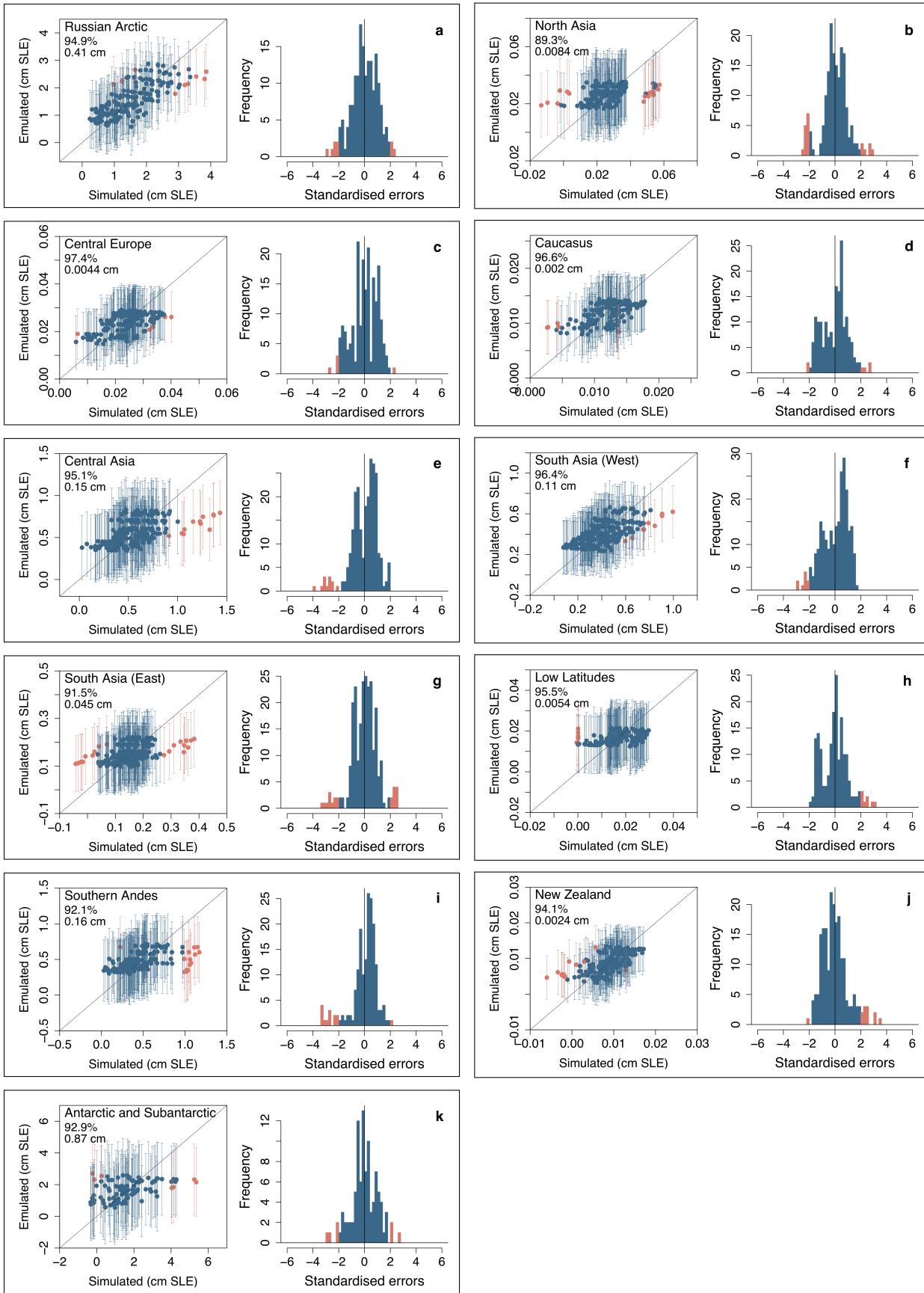


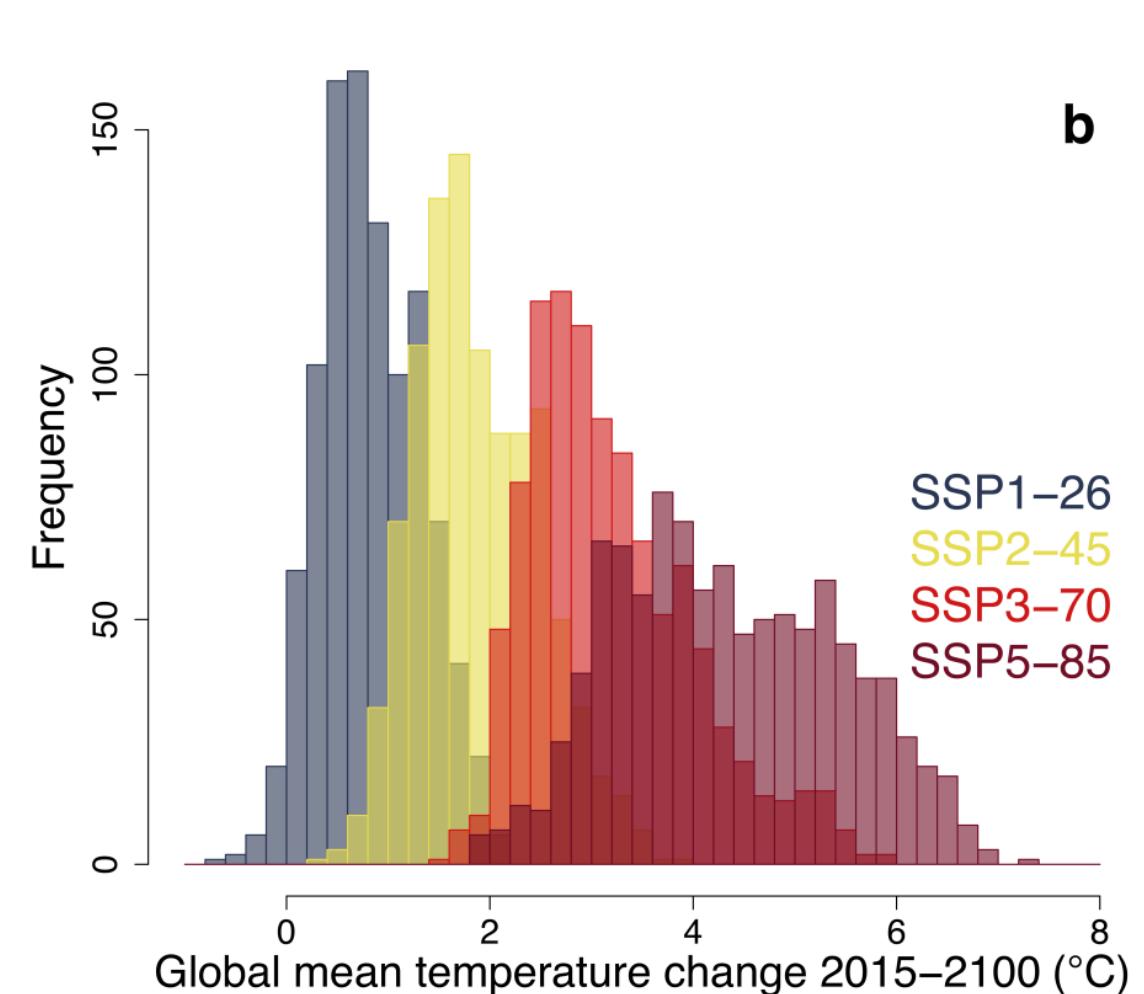
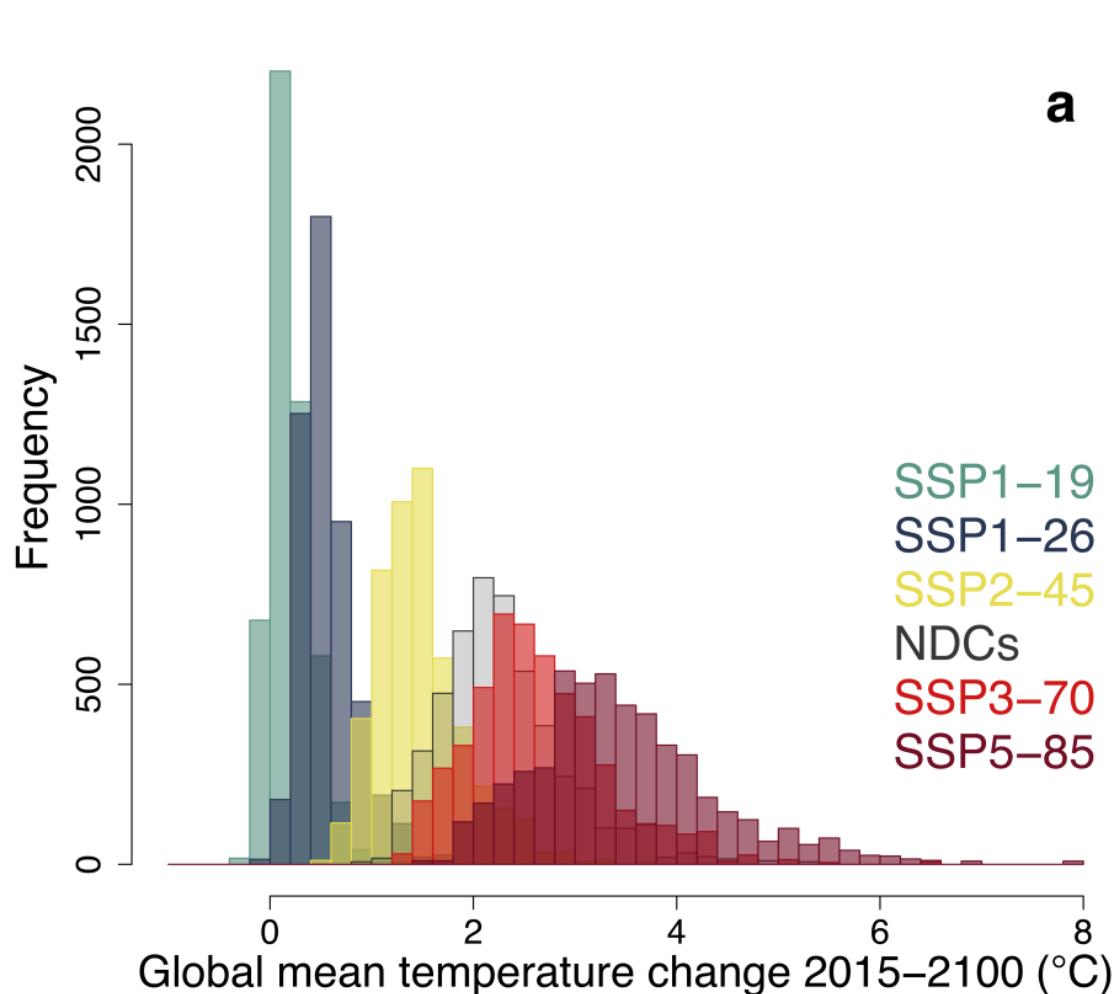


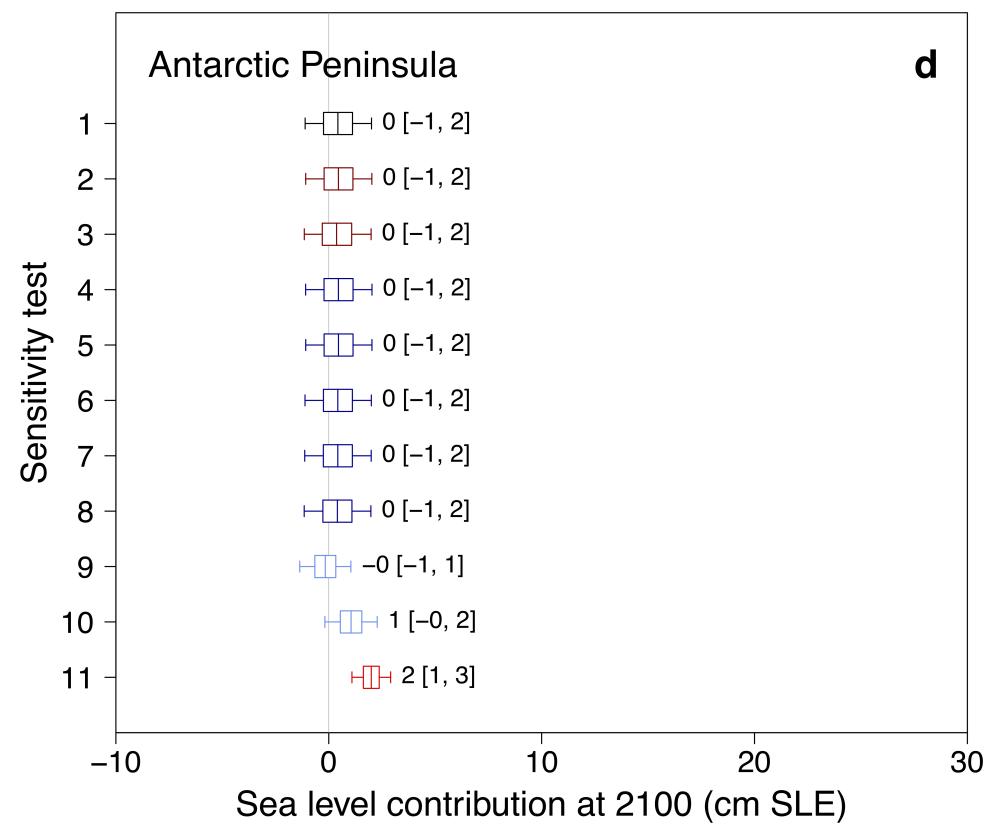
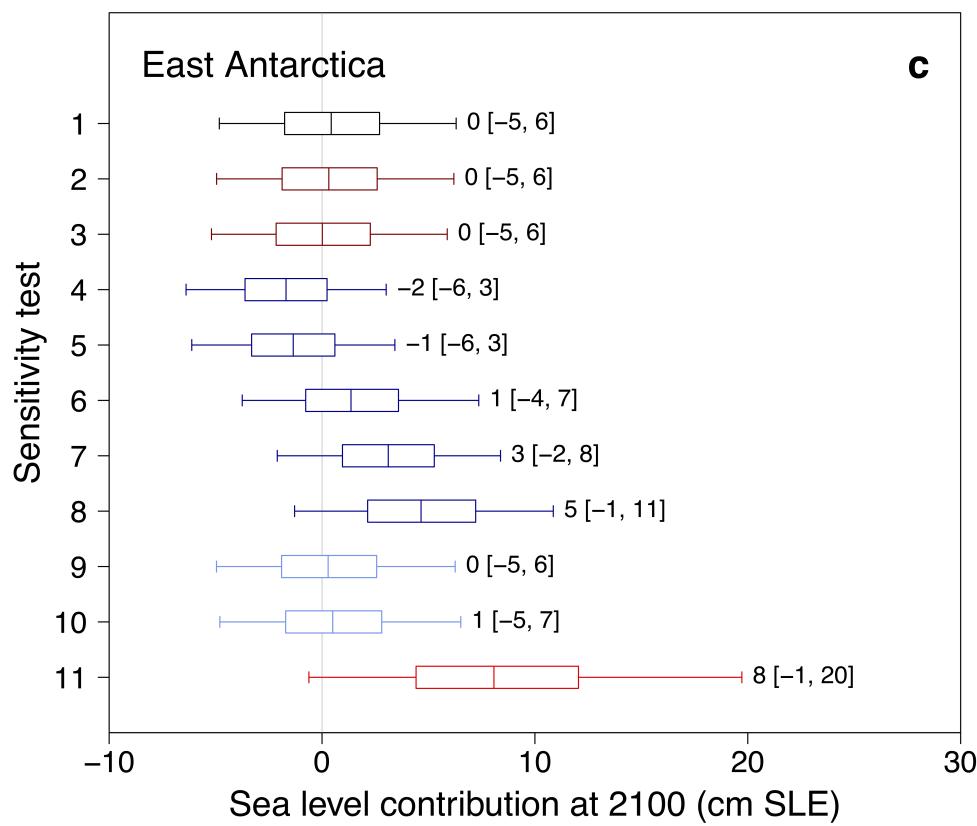
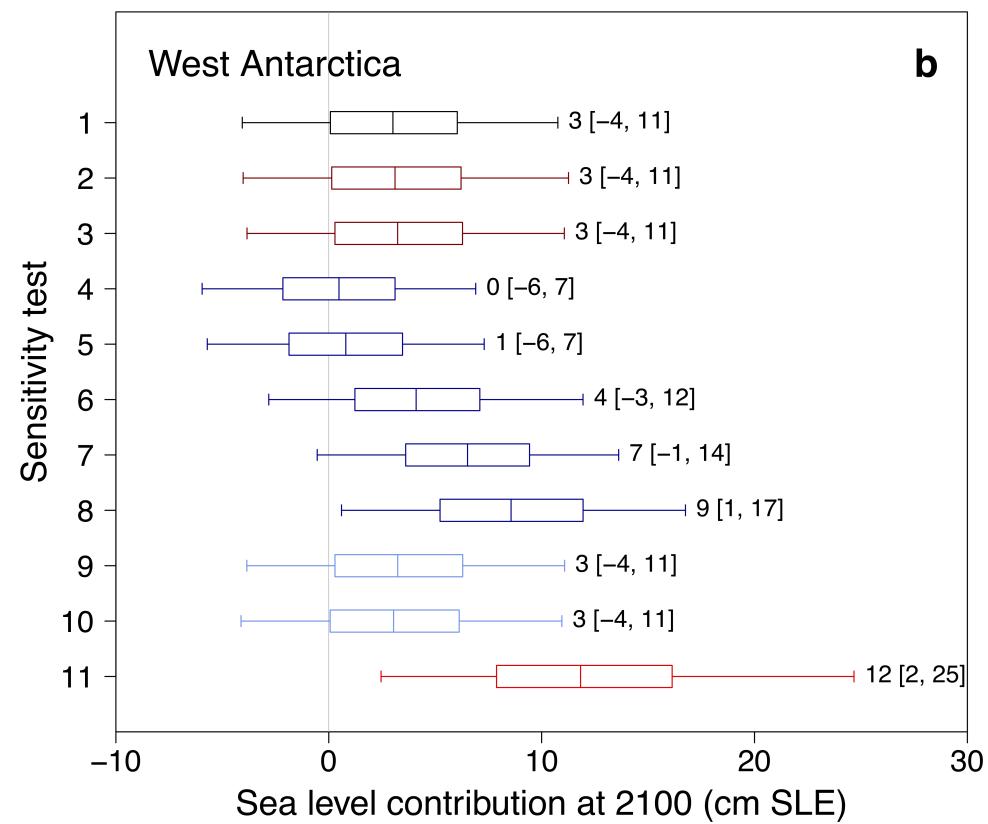
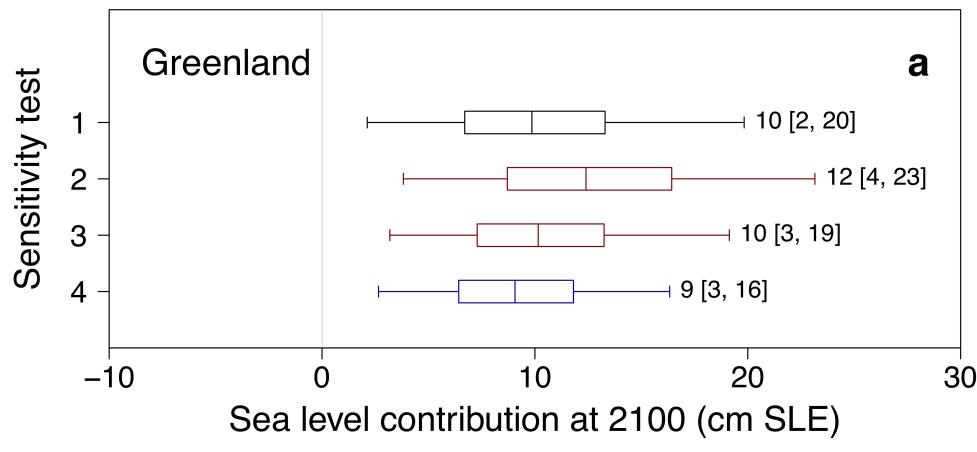


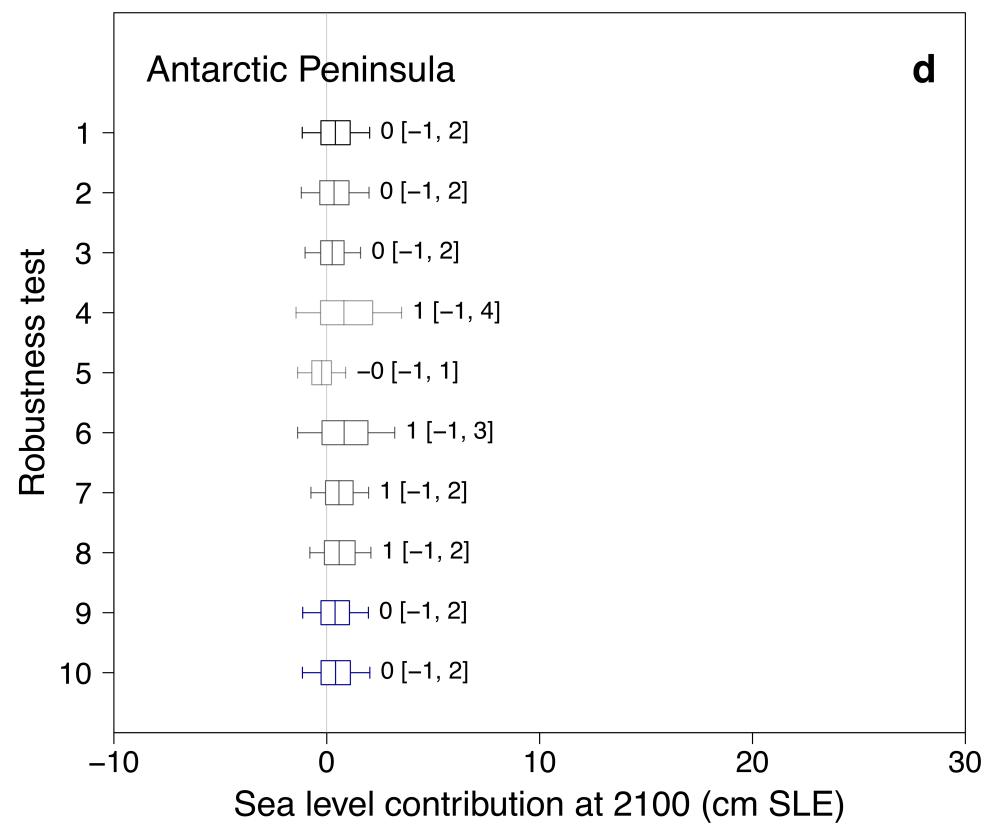
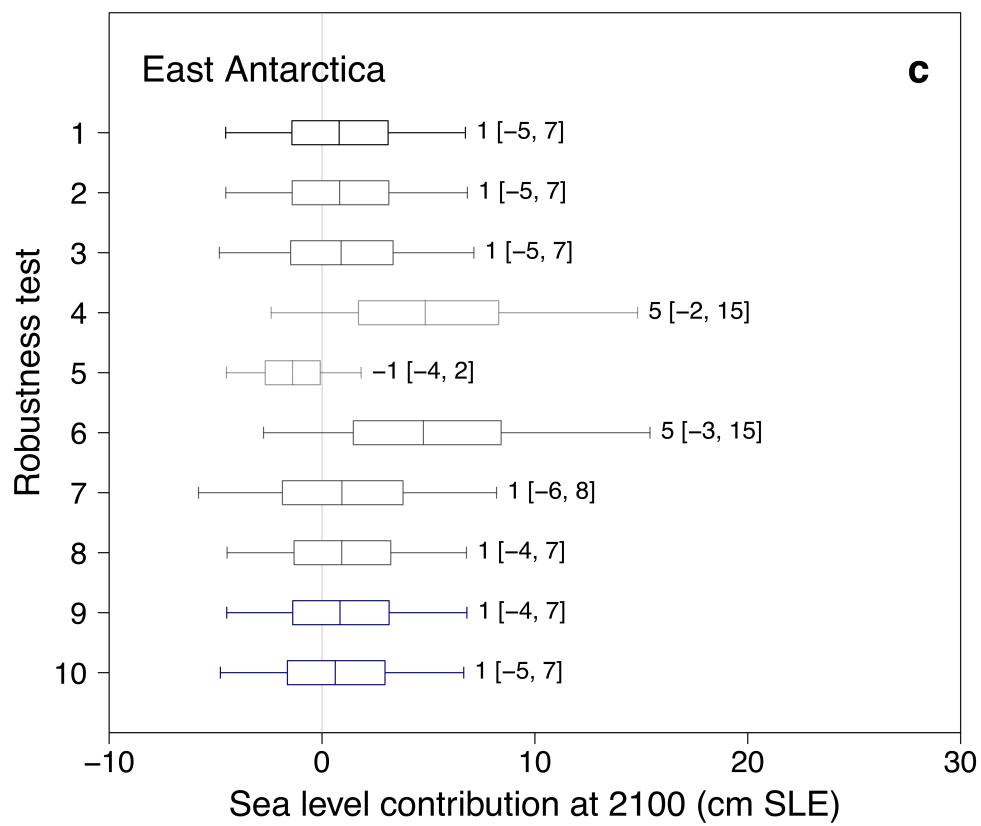
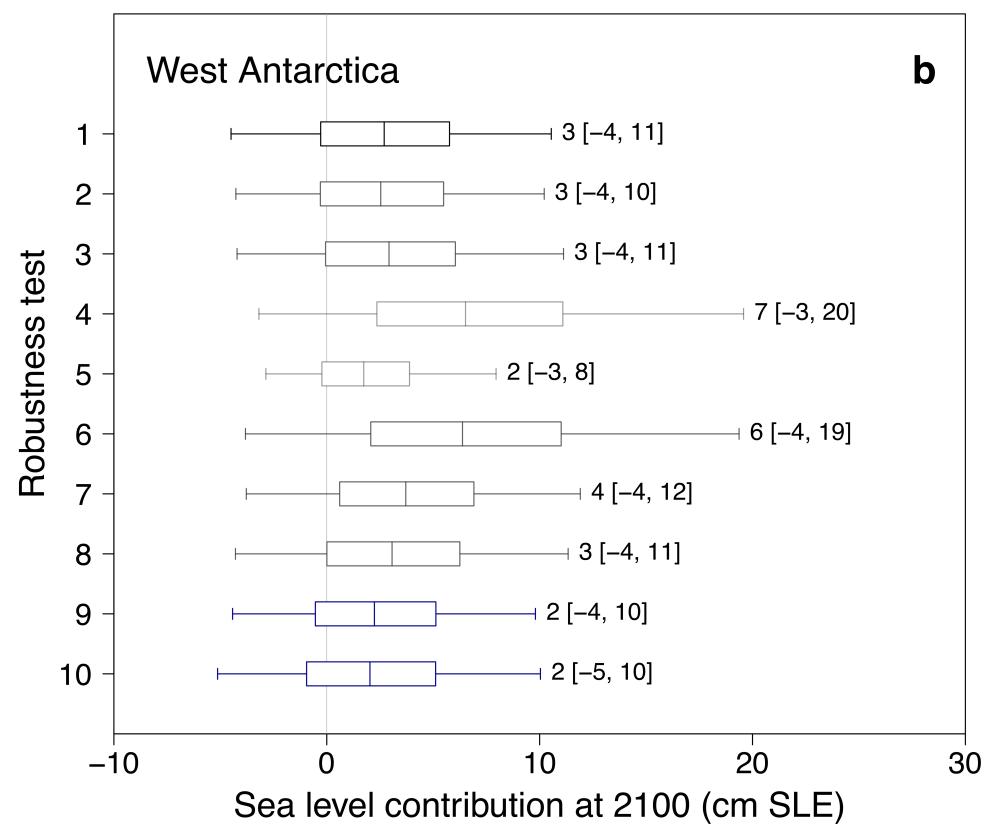
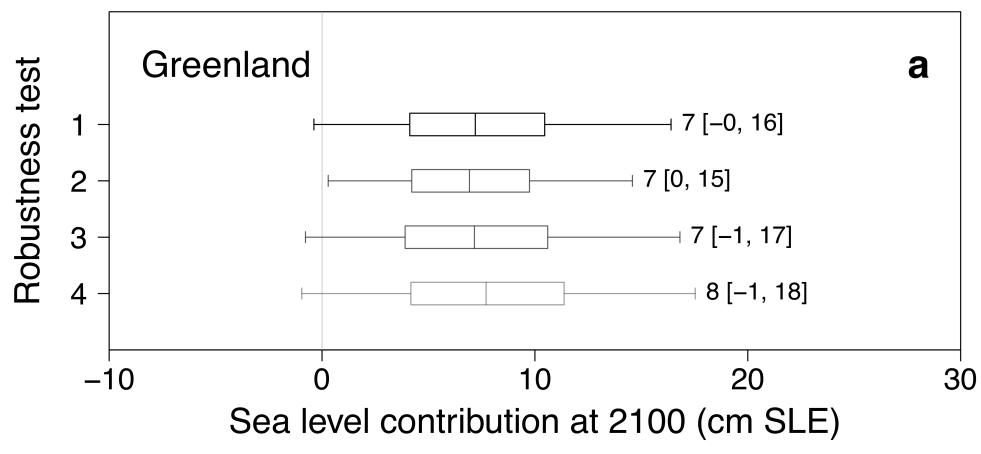


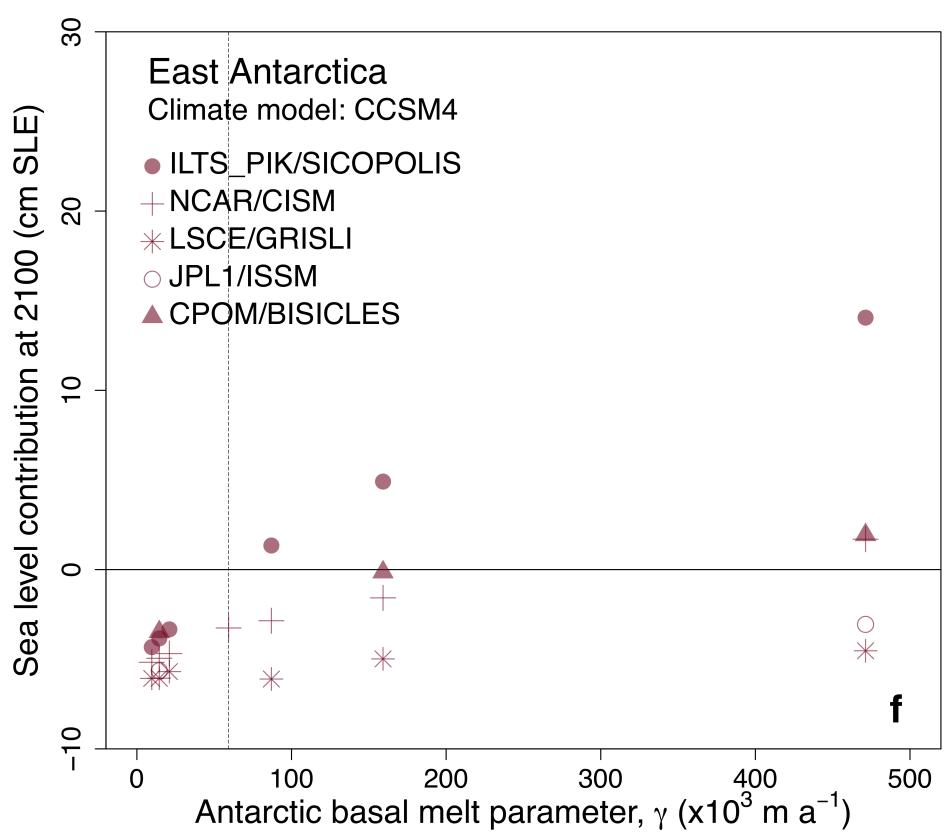
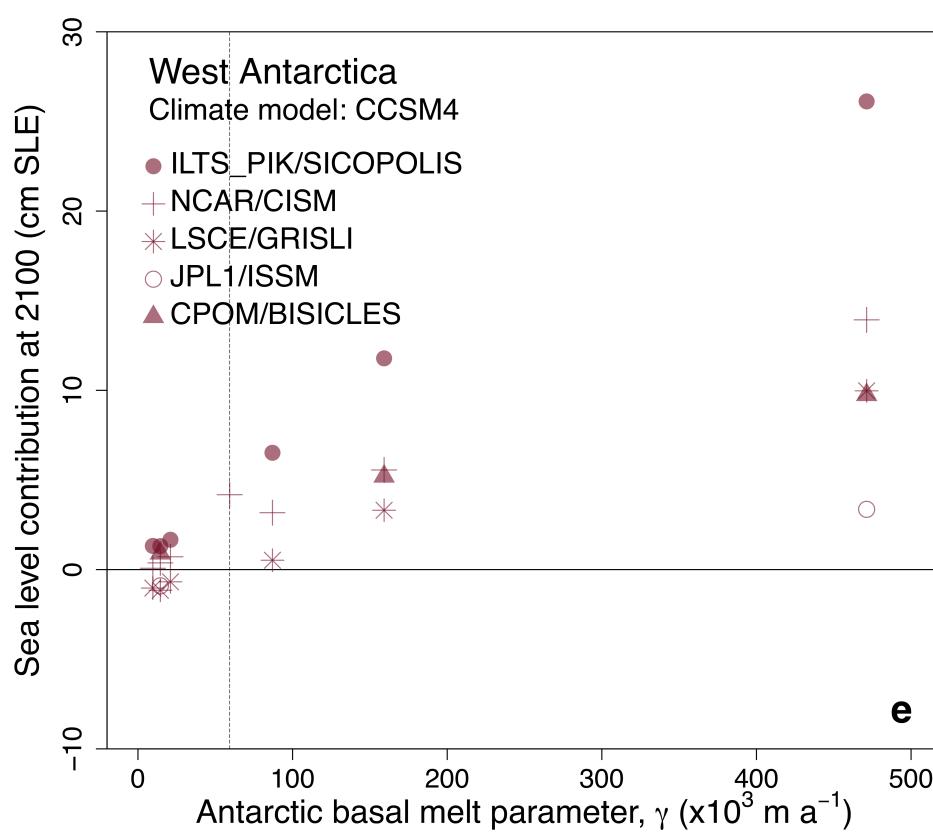
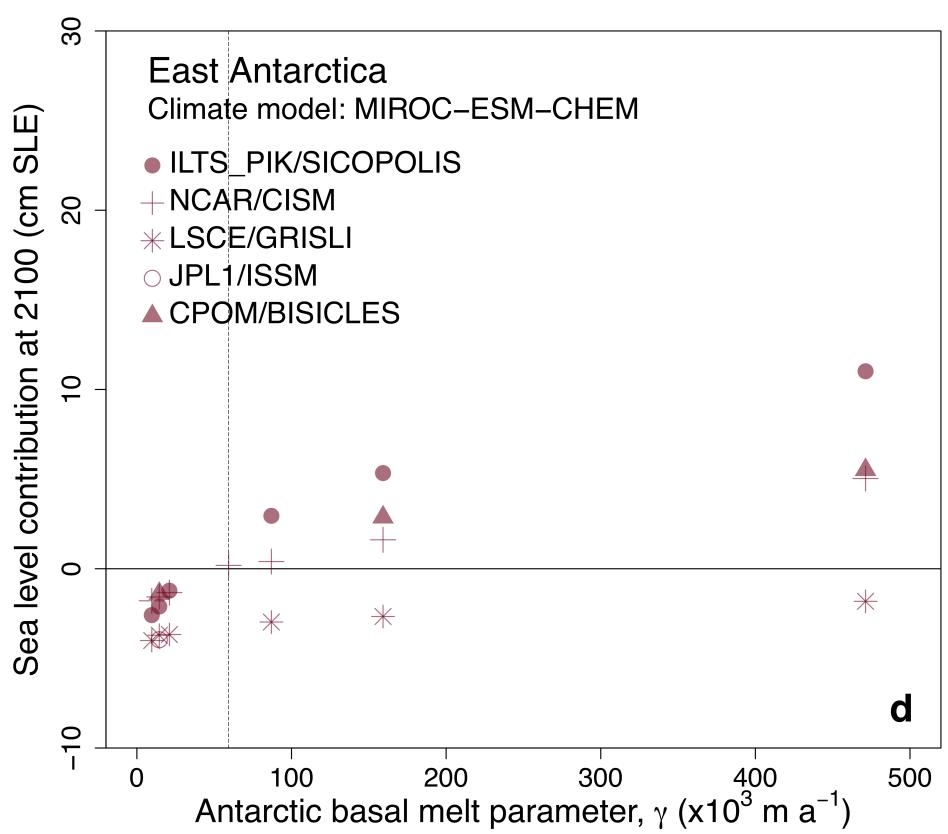
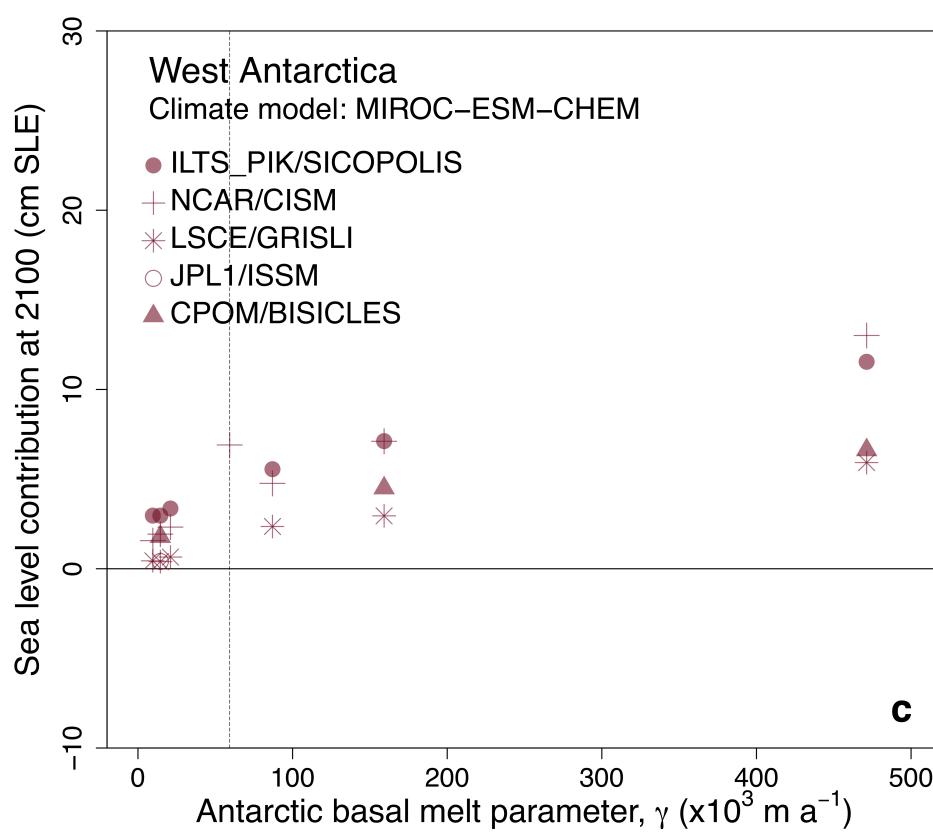
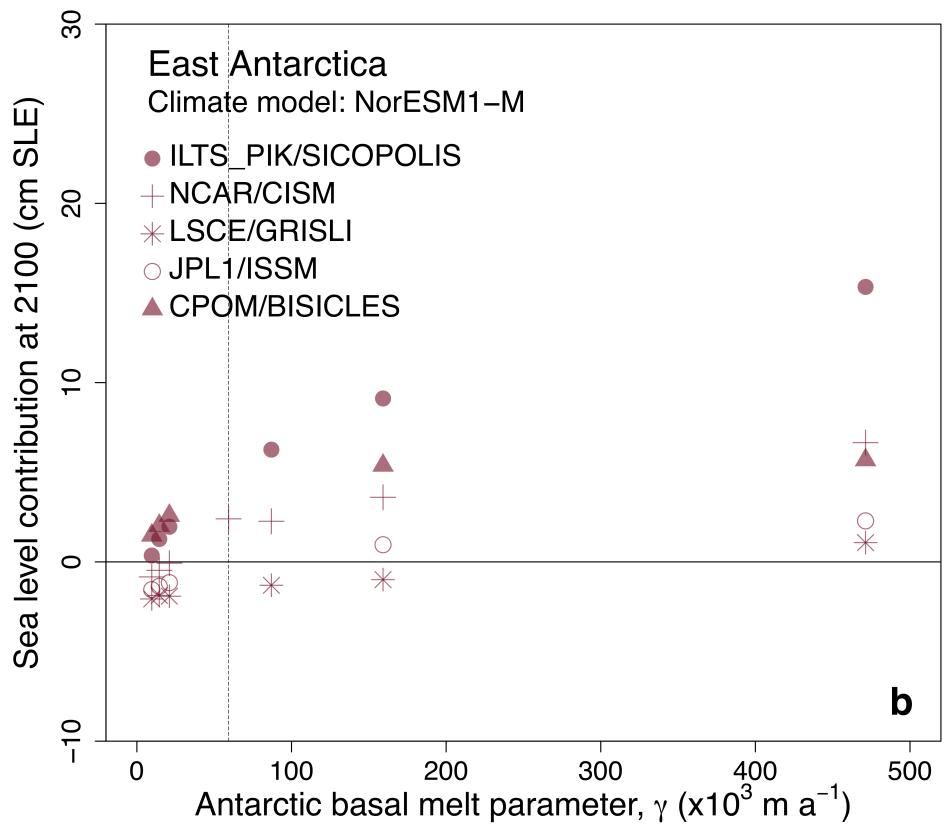
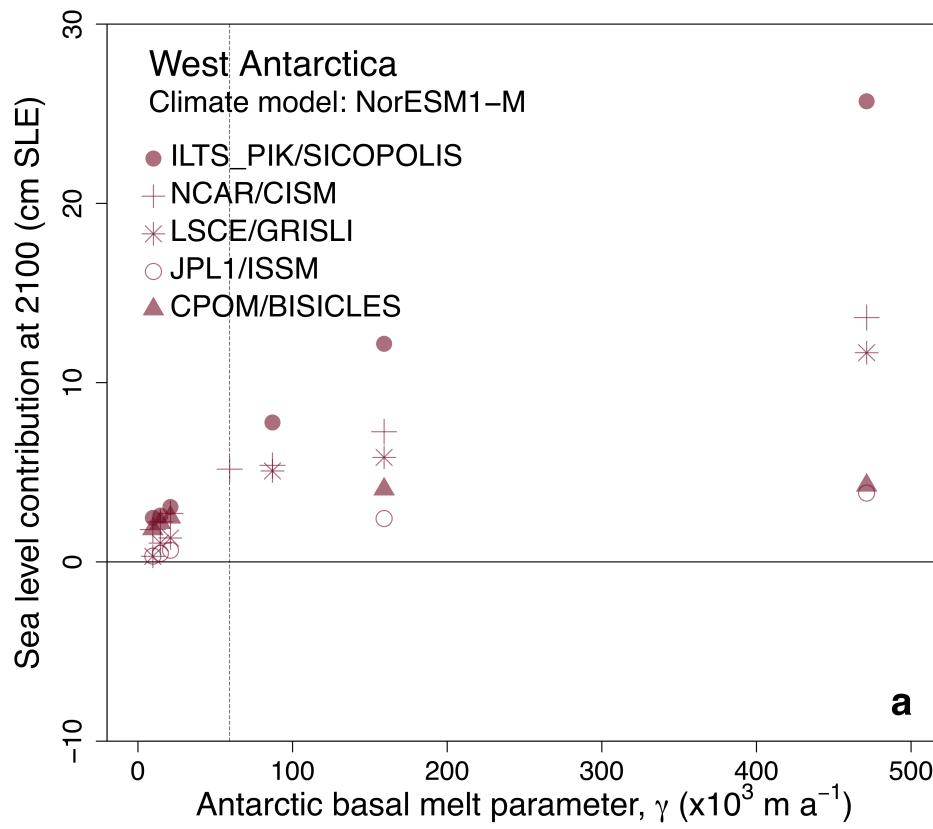


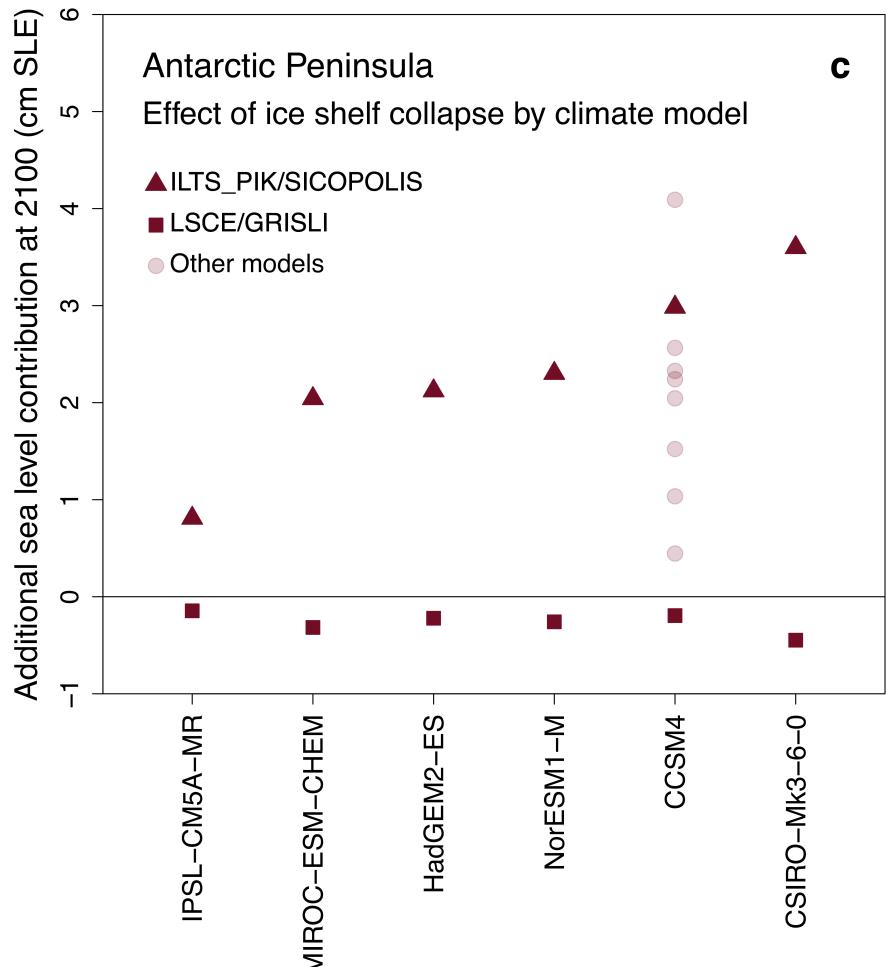
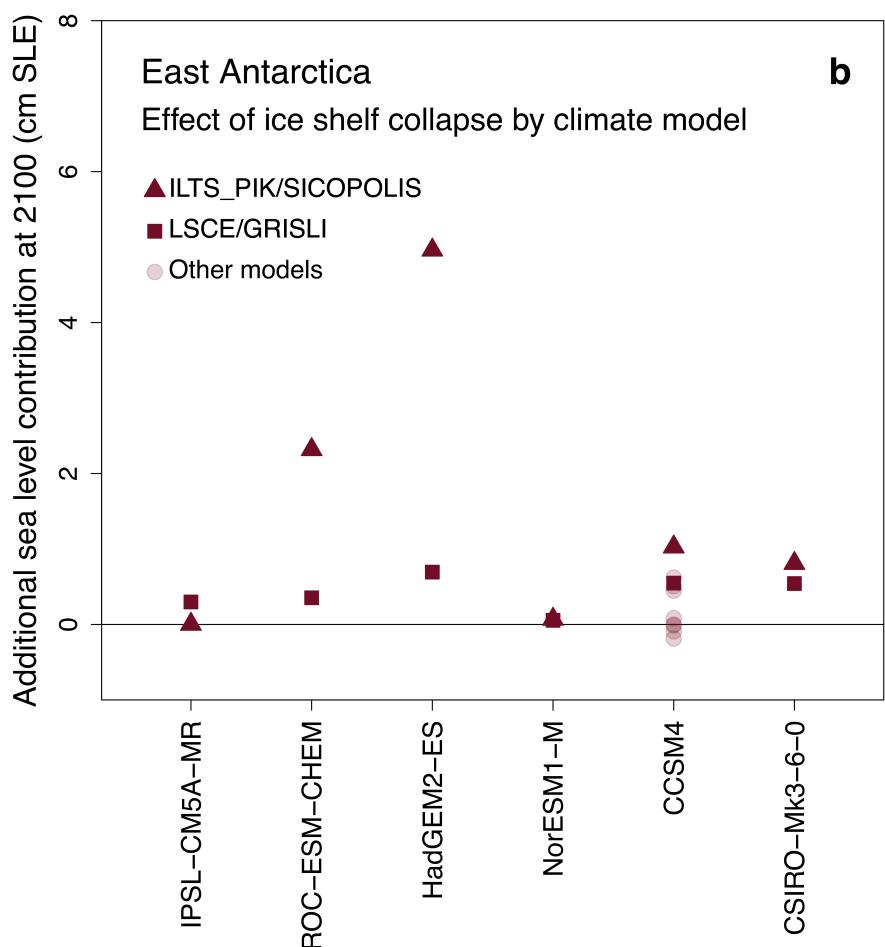
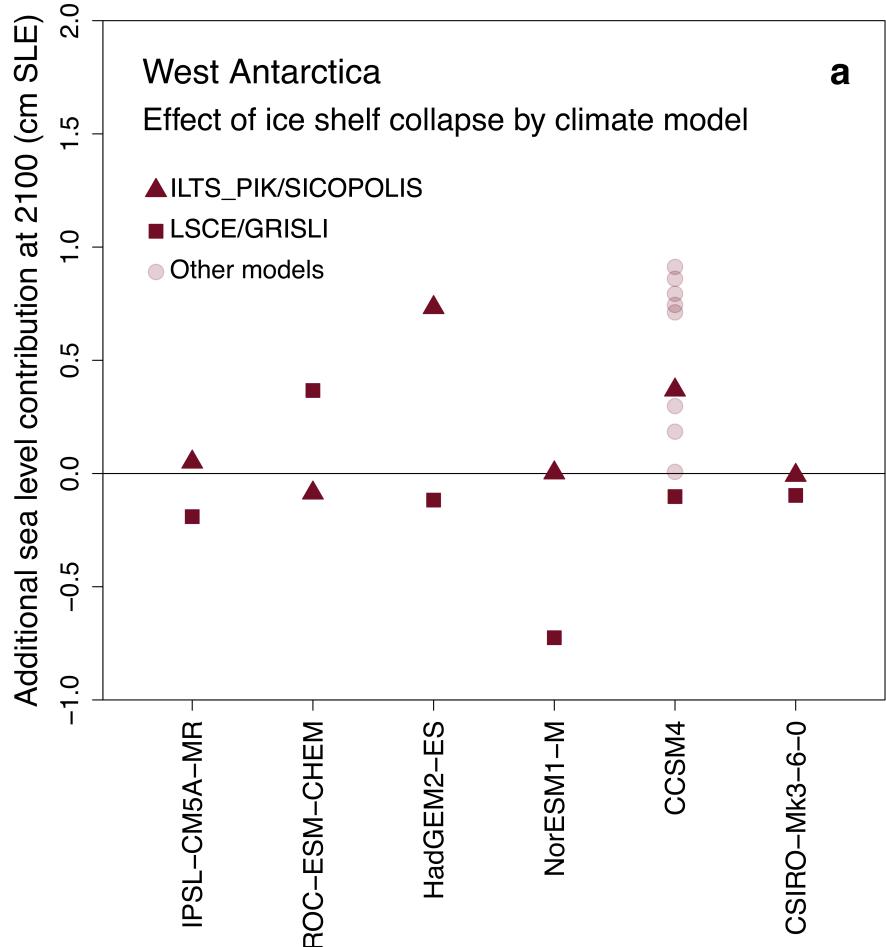












Additional Greenland experiments				
Experiment name	Scenario	Climate model	Retreat parameter	
expe01	RCP8.5	NorESM1-M	K95	
expe02	RCP8.5	NorESM1-M	K5	
expe03	RCP8.5	HADGEM2-ES	K95	
expe04	RCP8.5	HADGEM2-ES	K5	
expe05	RCP2.6	MIROC5	K95	
expe06	RCP2.6	MIROC5	K5	
expe07	RCP8.5	IPSL-CM5A-MR	K95	
expe08	RCP8.5	IPSL-CM5A-MR	K5	
expe09	RCP8.5	CSIRO-Mk3-6-0	K95	
expe10	RCP8.5	CSIRO-Mk3-6-0	K5	
expe11	RCP8.5	ACCESS1-3	K95	
expe12	RCP8.5	ACCESS1-3	K5	
expe13	SSP5-85	CNRM-CM6-1	K95	
expe14	SSP5-85	CNRM-CM6-1	K5	
expe15	SSP1-26	CNRM-CM6-1	K95	
expe16	SSP1-26	CNRM-CM6-1	K5	
expe17	SSP5-85	UKESM1-0-LL	K95	
expe18	SSP5-85	UKESM1-0-LL	K5	
expe21	SSP5-85	CNRM-ESM2-1	K95	
expe22	SSP5-85	CNRM-ESM2-1	K5	
expe23	RCP8.5	MIROC5	K95	
expe24	RCP8.5	MIROC5	K5	
Additional Antarctic experiments				
Experiment name	Scenario	Climate model	Basal melt (%)	Ice shelf collapse (C)
Basal melt parameter values				
expD1	RCP8.5	MIROC-ESM-CHEM	MeanAnt ₉₅	Off
expD2	RCP8.5	MIROC-ESM-CHEM	MeanAnt ₅	Off
expD3	RCP2.6	NorESM1-M	MeanAnt ₉₅	Off
expD4	RCP2.6	NorESM1-M	MeanAnt ₅	Off
expD5	RCP8.5	CCSM4	MeanAnt ₉₅	Off
expD6	RCP8.5	CCSM4	MeanAnt ₅	Off
expD7	RCP8.5	HADGEM2-ES	MeanAnt ₉₅	Off
expD8	RCP8.5	HADGEM2-ES	MeanAnt ₅	Off
expD9	RCP8.5	CSIRO-Mk3-6-0	MeanAnt ₉₅	Off
expD10	RCP8.5	CSIRO-Mk3-6-0	MeanAnt ₅	Off
expD11	RCP8.5	IPSL-CM5A-MR	MeanAnt ₉₅	Off
expD12	RCP8.5	IPSL-CM5A-MR	MeanAnt ₅	Off
expD13	SSP5-85	CNRM-CM6-1	MeanAnt ₉₅	Off
expD14	SSP5-85	CNRM-CM6-1	MeanAnt ₅	Off
expD15	SSP5-85	UKESM1-0-LL	MeanAnt ₉₅	Off
expD16	SSP5-85	UKESM1-0-LL	MeanAnt ₅	Off
expD17	SSP5-85	CESM2	MeanAnt ₉₅	Off
expD18	SSP5-85	CESM2	MeanAnt ₅	Off
expD51	RCP8.5	NorESM1-M	PIG ₅	Off
expD52	RCP8.5	NorESM1-M	PIG ₉₅	Off
expD53	RCP8.5	MIROC-ESM-CHEM	PIG ₅₀	Off
expD54	RCP8.5	MIROC-ESM-CHEM	PIG ₅	Off
expD55	RCP8.5	MIROC-ESM-CHEM	PIG ₉₅	Off
expD56	RCP8.5	CCSM4	PIG ₅₀	Off
expD57	RCP8.5	CCSM4	PIG ₅	Off
expD58	RCP8.5	CCSM4	PIG ₉₅	Off
expT071	RCP2.6	NorESM1-M	PIG ₅₀	Off
expT072	RCP2.6	NorESM1-M	PIG ₅	Off
expT073	RCP2.6	NorESM1-M	PIG ₉₅	Off
Ice shelf collapse under different climate forcings				
expE6	RCP8.5	NorESM1-M	MeanAnt ₅₀	On
expE7	RCP8.5	MIROC-ESM-CHEM	MeanAnt ₅₀	On
expE8	RCP8.5	HADGEM2-ES	MeanAnt ₅₀	On
expE9	RCP8.5	CSIRO-Mk3-6-0	MeanAnt ₅₀	On
expE10	RCP8.5	IPSL-CM5A-MR	MeanAnt ₅₀	On
Ice shelf collapse and basal melt interactions				
expTD5	RCP8.5	CCSM4	MeanAnt ₉₅	On
expTD56	RCP8.5	CCSM4	PIG ₅₀	On
expTD58	RCP8.5	CCSM4	PIG ₉₅	On

Region	Covariance function and hyperparameters (α : exponent; v : roughness parameter)	% predictions within emulator 95% interval	Mean absolute error (cm)
Greenland ice sheet	power exp ($\alpha = 0.1$)	94.1	1.4
West Antarctica	power exp ($\alpha = 0.1$)	93.6	2.0
East Antarctica	power exp ($\alpha = 0.1$)	94.8	1.5
Antarctic Peninsula	power exp ($\alpha = 0.1$)	92.4	0.28
1: Alaska	power exp ($\alpha = 1.0$)	95.5	0.55
2: Western Canada and U.S.	power exp ($\alpha = 1.9$)	96.1	0.040
3: Arctic Canada North	power exp ($\alpha = 1.9$)	92.7	0.51
4: Arctic Canada South	power exp ($\alpha = 0.1$)	95.5	0.27
5: Greenland periphery	power exp ($\alpha = 0.1$)	94.9	0.36
6: Iceland	power exp ($\alpha = 1.0$)	95.5	0.13
7: Svalbard	power exp ($\alpha = 0.1$)	95.5	0.37
8: Scandinavia	power exp ($\alpha = 1.0$)	98.3	0.012
9: Russian Arctic	power exp ($\alpha = 1.0$)	94.9	0.41
10: North Asia	power exp ($\alpha = 1.0$)	89.3	0.0084
11: Central Europe	power exp ($\alpha = 1.0$)	97.4	0.0044
12: Caucasus	Matérn ($v = 3/2$)	96.6	0.0020
13: Central Asia	power exp ($\alpha = 0.1$)	95.1	0.15
14: South Asia (West)	power exp ($\alpha = 1.9$)	96.4	0.11
15: South Asia (East)	power exp ($\alpha = 0.1$)	91.5	0.045
16: Low Latitudes	power exp ($\alpha = 0.1$)	95.5	0.0054
17: Southern Andes	Matérn ($v = 5/2$)	92.1	0.16
18: New Zealand	power exp ($\alpha = 0.1$)	94.1	0.0024
19: Antarctic and Subantarctic periphery	Matérn ($v = 5/2$)	92.9	0.87

Sensitivity tests	
Description	Impact
2: CMIP6 temperature projections Around 30 CMIP6 models are available at the time of analysis for four SSPs (31 for SSP1-26, 30 for SSP2-45, 27 for SSP3-70 and 31 for SSP5-85). Simulations are obtained and processed in the same way as the subset used for the emulator calibration. We set missing 2100 values to that of 2099 (for CAMS-CSM1-0, and two additional models for SSP3-70). We smooth the temperature changes with a kernel density estimator and sample from this with replacement (N = 1000; Extended Data Figure 3).	We find a slight increase in projected sea level rise: median and 95 th percentile land ice contributions increase by 1-5 cm and 4-7 cm across scenarios SSP1-26 to SSP5-85. This is likely due to the greater number of simulations with high equilibrium climate sensitivity in CMIP6 than FaIR (and a wider range than several recent past generations, 1.8-5.6°C ³⁴). The FaIR ensemble is constructed to have a climate sensitivity distribution in line with latest understanding from multiple lines of evidence (5-95% range 2-5°C ³⁰).
3, 4: Fixed global mean temperature and ice sheet melt parameters We replace the input distributions with single values, to test the potential for reducing uncertainties with improved knowledge	Using the FaIR ensemble mean for global temperature, the width of the 5-95% range for SSP5-85 reduces from 30 cm to 26 cm. Using default values of the Greenland retreat and Antarctic basal melt parameters ($\kappa = \kappa_{50}$; $\gamma_0 = \text{MeanAnt}_{50}$), the 5-95% range decreases from 30 cm to 25 cm.
5, 6: Antarctic basal melt - Mean Antarctic and Pine Island Glacier distributions We use the Mean Antarctic (test 5), or Pine Island Glacier (test 6) distribution for basal melt γ , rather than the combined distribution, sampling from the original distributions with replacement.	Results are discussed in the main text.
7, 8: Antarctic basal melt - uniform distributions We use two uniform distributions to reproduce the sampling strategy of ref [26]. This is an emulation-type study based on a similar ensemble of climate and Antarctic ice sheet models to ISMIP6, which uses a uniform distribution for basal melt sensitivity consistent with values estimated for the Amundsen Sea region ³⁹ . If we add projections of dynamic change from ref. [26] to IPCC AR5 ²⁵ projections for surface mass balance (SMB), neglecting differences in time period, the median projections are ~11 and ~13 cm under RCP2.6 and RCP8.5, and the 95 th percentiles are ~35 and ~54 cm (using median SMB values in both).	We reach similar values only with extreme values of the basal melt parameter: we show here $\gamma \sim \text{unif}[\text{PIG}_{50}, \text{PIG}_{95}]$ and $\gamma \sim \text{unif}[\text{PIG}_{50}, 700000]$, where 700000 is 98.7th percentile of the Pine Island Glacier distribution, which give median projections of 10 cm and ~14 cm across all scenarios. The 95 th percentiles are roughly half those of the other study: ~19 cm and ~24 cm.
9, 10: Antarctic ice shelf collapse off and on We use only $C = 0$ or $C = 1$, rather than a random sample of the two.	Results are discussed in the main text.
11: Risk-averse Antarctic projections We use the five global climate models with highest sea level contribution or for which ice shelf collapse projections are available (Robustness test 7), the four Antarctic ice sheet models with highest sensitivity to basal melting (Robustness test 6), the Pine Island Glacier distribution for basal melt γ (Sensitivity test 6) and ice shelf collapse on (Sensitivity test 10). We also use the same γ value for all three regions in a given projection, i.e. fully correlated rather than sampled independently, to explore the tails more fully: this aspect broadens the distribution, increasing the 95 th percentile by 2-4 cm and decreasing the 5 th by 1 cm, and also decreases the median by 1 cm. We use N = 5000 temperature samples, as for the main projections. We do not use the combinations that lead to the highest possible sea level contribution – i.e. the single most sensitive ice sheet model (Robustness test 4), or the extreme distributions for basal melt (Sensitivity test 7-8) – because we aim to provide plausible high-end projections, rather than relying on a single model or unrealistic assumptions.	Results are discussed in the main text.

Robustness checks	
Description	Impact
2: High resolution models We use only Greenland ice sheet models with minimum spatial resolution less than 8 km (N = 215) and Antarctic ice sheet models with resolution less than 32 km (N = 303).	This results in differences of 0-1 cm for each ice sheet.
3: More balanced design We restrict the input dataset to only the models with the most complete designs (i.e. the most experiments). For Greenland, we use 10 of the 21 models: one with 28 experiments (IMAU/IMAUICE1) and the nine models that ran all 14 experiments presented by refs. [14] and [16] (AWI/ISSM1, ISSM2 and ISSM3, ILTS_PIK/SICOPOLIS1 and SICOPOLIS2, JPL/ISSM, LSCE/GRISLI2, NCAR/CISM, VUB/GISMHOMv1), removing the dummy variable from the emulator as there are no 'open' models in this set (N = 154). For Antarctica, we use four of the 16 models (ILTS_PIK/SICOPOLIS: N = 55, of which 13 do not use the ISMIP6 parameterisation; JPL1/ISSM: N = 48; LSCE/GRISLI: N = 47; NCAR/CISM: N = 27) (total N = 177).	This results in differences of 0-1 cm for each ice sheet.
4, 5: Single ice sheet models We use only the Greenland model with the most simulations (IMAU/IMAUICE1: N = 28), and a single model for Antarctica (test 4: ILTS_PIK/SICOPOLIS, N = 48; test 5: LSCE/GRISLI, N = 47). The two Antarctic models have high and low sensitivity to the basal melting parameter, respectively (Extended Data Figure 6).	Using one Greenland model has little impact: the largest change is 2 cm increase in the 95 th percentile, due to this model being at the upper end of the range in sensitivity to the retreat parameter (Figure 2a: triangles). Using one Antarctic model has far more effect: results are discussed further in the main text.
6: Highest sensitivity Antarctic ice sheet models We use the four Antarctic models with highest sensitivity to basal melting, i.e. largest 2100 contribution for $\gamma = \text{PIG}_{50}$, ice shelf collapse off and RCP8.5/SSP5-85 (decreasing order: ILTS_PIK/SICOPOLIS: N = 48; ULB/fETISH_16km: N = 21; ULB/fETISH_32km: N = 21; DOE/MALI: N = 8) (total N = 98).	Results are discussed in the main text.
7: Select climate models that result in highest Antarctic sea level contributions We use only results from the climate models that lead to highest sea level contributions at 2100 under $\gamma = \text{MeanAnt}_{50}$, ice shelf collapse off and RCP8.5/SSP5-85 (in decreasing order: HadGEM2-ES, UKESM1-0-LL, MIROC-ESM-CHEM, NorESM1-M). We also include CCSM4, to retain information on the effect of ice shelf collapse (N = 241). We also test the impact of using only two of these climate models (not shown in Extended Data Figure 5): NorESM1-M (discussed in the main text regarding scenario-dependence: Figure 4) and CCSM4 (for shelf collapse) (N = 164).	Using these five climate models results in +1 cm change to median from SSP1-19 to SSP5-85 for West Antarctica, -1 cm for East Antarctica, and +1 cm for the total. NDCs median increases by +2 cm relative to main projections. Using only NorESM1-M and CCSM4 leads to +2 cm from SSP1-19 to SSP5-85 for West Antarctica, -3 cm for East Antarctica, and -3 cm decrease for the total, i.e. a weak scenario dependence; no change to NDCs median.
8: Exclude Antarctic ice sheet models far from observed trend We exclude simulations with 2015-2020 sea level contributions outside the range 0.00-0.60 cm, motivated by recent observations. We use a satellite estimate ⁶⁶ of the mass trend from 2012-2017 (-219 \pm 43 Gt a ⁻¹) and reject simulations for which the mean trend over 2015-2020 is outside the mean \pm 5 s.d. interval (N = 181). We choose this interval to allow for the trend changing from one time period to the other, and for tolerance to model discrepancy ²⁴ , and because it coincides with zero at the bottom end so is informative for excluding models with mass gain at the start of the projections (as well as those with very rapid mass loss).	This results in +1 cm scenario-dependence for West Antarctica and -2 cm for East Antarctica, and none for the total; the NDCs median increases by 1 cm.
9: Exclude Antarctic ice sheet models that do not use ISMIP6 melt parameterisation We exclude the ice sheet models that do not use the ISMIP6 basal melt parameterisation. (N = 282).	No scenario-dependence for West Antarctica or the total; -2 cm for East Antarctica. No change to NDCs median.
10: Impute higher basal melt value for Antarctic ice sheet models that do not use the ISMIP6 melt parameterisation We assign models that do not use the ISMIP6 parameterisations a higher value for γ (150,000; slightly less than PIG_{50}), rather than the ensemble mean (59,317), reflecting the fact that such models are often tuned to Amundsen Sea (high) melt observations, and approximately in line with NCAR/CISM which was run in both modes (Extended Data Figure 6).	This results in +1 cm scenario-dependence for West Antarctica, -1 cm decrease for East Antarctica, and no change for the total; the NDCs median projection decreases by 1 cm.