Scoring Antarctic surface mass balance in climate models to refine future projections

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1 Empirical Orthogonal Functions

The top three modes of SMB variability in the reconstruction are the only three modes with the percent of variance explained above 10% (Fig. 1). In total, these top three modes explain about 77% of the total variance in AIS SMB in the reconstruction.

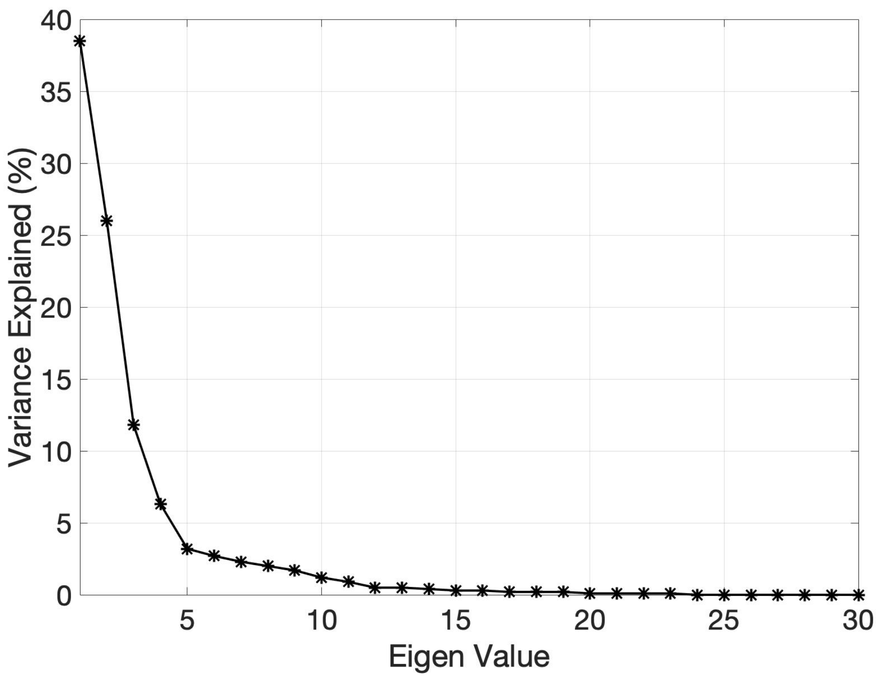

Figure 1. The top 30 Eigen values out of 200 total for SMB in the reconstruction. The top three Eigenvalues explain 76.3% of the total SMB variance.

To gain insight into what atmospheric conditions may lead to the dominant modes of SMB spatial variability, we performed the same EOF analysis on the reconstructed sea level pressure (Fig. 2). The top mode of atmospheric variability shows high variability around the Amundsen Sea region. Similarly, mode 2 also reflects strong variability in the Amundsen Sea region but with more zonal symmetry. The third mode of atmospheric variability represents a quadripolar pattern in variability about the 0-180° and 90°E/W longitude lines.

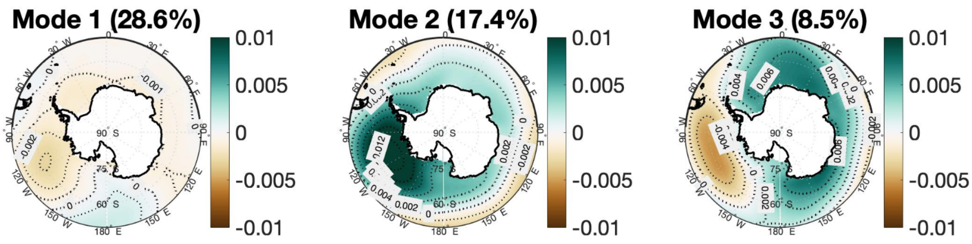

Figure 2. EOFs of the top 3 modes of the reconstruction for sea level pressure.

2 Sample Size Monte Carlo

The average final score for CMIP5 is 3.7 and the average final score for CMIP5 is 5.6. To determine if this difference is generated by the smaller CMIP6 sample size, we performed a Monte Carlo-type simulation. Randomly selecting 22 of the 41 total CMIP5 model scores 10,000 times, we then tested whether those 10,000 selections were statistically different from all 41 using a two-sided t-test. The t-test generates results of 0 if we cannot reject the null hypothesis that the two samples are different at the 95% confidence level or 1 if we can. Averaging the t-test over all 10,000 selections yields a 0.042% chance that we can reject the null hypothesis. From this, we determine that we cannot reasonably reject the null hypothesis that these two scores are statistically different at the 95% confidence level. This means that 22 models is representative of the total CMIP5 suite of models from which we hypothesize that the same can be said for the current 22 models being representative of the full CMIP6 suite of models in terms of average final score.

3 Temperature Trends

To assess how much of the model sensitivity to forcing scenario is attributable to spread in ΔT versus spread in $\frac{\Delta \mathrm{SMB}}{\Delta \mathrm{T}}$, we compared the relative spreads of each. For RCPs 2.6, 4.5, and 8.5, respectively, $\frac{\Delta \mathrm{SMB}}{\Delta \mathrm{T}}$ ranged between -116% to + 305%, 21% to 264%, and 52% to 223% about their respective means. By comparison, ΔT ranged between 56% to 156%, 30% to 141%, and 45% to 135% about their relative means for RCPs 2.6, 4.5, and 8.5, respectively. In short, ΔT ranged about 100% about the mean in each scenario while $\frac{\Delta \mathrm{SMB}}{\Delta \mathrm{T}}$ ranged about 200% to 300% about the mean depending on scenario. With that, we conclude that much of the variation in $\frac{\Delta \mathrm{SMB}}{\Delta \mathrm{T}}$ between models stems from differences in how the models react to different forcing scenarios rather than owing to large spread in modeled temperature change over the 21st century.

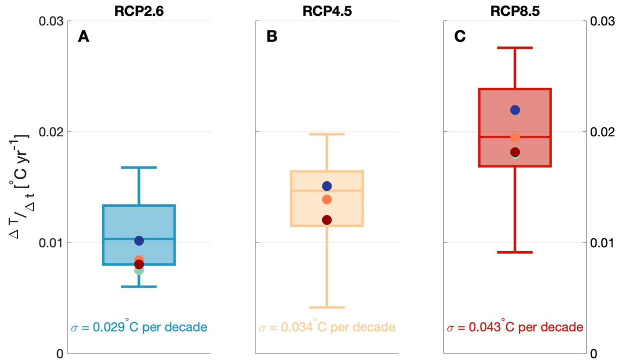

Figure 3. Box plots of the temperature trends in °C yr^{-1} for **A** RCP2.6 (blue), **B** RCP4.5 (yellow), and **C** RCP8.5 (red). The four best scoring models are shown as colored circles: GISS E2 H (dark blue), GISS E2 R (green), MPI ESM LR (coral), and MPI ESM MR (dark red).

4 Data Tables

This section includes tables with model resolutions and scores for all CMIP5 and CMIP6 models as well as a table with projected SMB and related variables for the various RCPs.

	Model	Resolution ($^\circ$lat$\times^\circ$lon)	Total Score
1	ACCESS1-0	1.2414×1.875	3.02
2	ACCESS1-3	1.2414×1.875	2.66
3	BCC-CSM1.1	2.8125×2.8125	4.05
4	BCC-CSM1.1-m	2.8125×2.8125	4.99
5	BNU ESM	2.8125×2.8125	8.18
6	CanESM2	2.8125×2.8125	4.01
7	CCSM4	0.9375×1.25	7.02
8	CESM1 BGC	0.9375×1.25	5.83
9	CESM1 CAM5 FV2	0.9375×1.25	2.82
10	CESM1 CAM5	0.9375×1.25	4.55
11	CESM1 FASTCHEM	0.9375×1.25	9.56
12	CESM1 WACCM	0.9375×1.25	5.59
13	CMCC CESM	0.75×0.75	3.14
14	CMCC CM	0.75×0.75	3.86
15	CNRM CM5	1.4063×1.4063	3.98
16	CSIRO	1.875×1.875	3.32
17	FGOALS	3×2.8125	1.36
18	FIO ESM	2.8125×2.8125	7.91
19	GFDL CM3	2×2.5	3.42
20	GFDL ESM2G	2×2.5	3.26
21	GFDL ESM2M	2×2.5	5.87

Table 1. Model names, resolutions and final score for the first half of the CMIP5 suite of models.

	Model	Resolution (°lat×°lon)	Total Score
22	GISS E2 H CC	2×2.5	1.56
23	GISS E2 H	2×2.5	3.21
24	GISS E2 R CC	2×2.5	1.25
25	GISS E2 R	2×2.5	1.00
26	HadGEM2 CC	1.2414×1.875	4.42
27	HadGEM2 ES	1.2414×1.875	4.50
28	INMCM4	1.5×2	2.28
29	IPSL CM5A LR	1.875×3.75	2.87
30	IPSL CM5A MR	1.2587c2.5	2.59
31	IPSL CM5B LR	1.875×3.75	4.87
32	MIROC ESM CHEM	1.4063×1.4063	2.58
33	MIROC ESM	2.8125×2.8125	2.33
34	MIROC5	2.8125×2.8125	1.62
35	MPI ESM LR	1.875×1.875	1.26
36	MPI ESM MR	1.875×1.875	1.28
37	MPI ESM P	1.875×1.875	1.28
38	MRI CGCM3	1.125×1.125	3.59
39	MRI ESM1	1.125×1.125	4.28
40	NorESM1 M	1.875×2.5	2.73
41	NorESM1 ME	1.875×2.5	3.18

Table 2. Model names, resolutions and final score for the second half of the CMIP5 suite of models.

	Model	Resolution (°lat×°lon)	Total Score
1	BCC CSM2 MR	1.125×1.125	6.33
2	BCC ESM1	2.8125×2.8125	4.47
3	CAMS CSM1	1.125×1.125	6.92
4	CanESM5	2.8125×2.8125	6.23
5	CESM2 WACCM	1.25×0.9375	5.21
6	CESM2	1.25×0.9375	5.20
7	CNRM CM6	1.4063×1.4063	4.41
8	CNRM ESM2	1.4063×1.4063	3.70
9	E3SM1	1.0×1.0	5.45
10	FGOALS G3	2.0×2.25	5.66
11	GFDL ESM4	1.25×1.0	5.95
12	GISS E2 G	2.5×2.0	6.66
13	GISS E2 H	2.5×2.0	6.88
14	HadGEM3 GC3	1.875×1.25	7.42
15	IPSL CM6A	2.5×1.2587	3.54
16	MCM UA1	3.75×2.25	6.85
17	MIROC ES2L	1.4063×1.4063	6.53
18	MIROC6	2.8125×2.8125	4.97
19	MRI ESM2	1.125×1.125	5.22
20	NorCPM1	2.5×1.875	3.02
21	SAM0 UNICON	1.25×0.9375	5.92
22	UKESM1	1.875×0.9375	7.17

Table 3. Model names, resolutions and final score for the CMIP6 suite of models.

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Competing interests. The authors declare no competing interests.

		RCP2.6		RCP4.5		RCP8.5	
	Years	All	Best	All	Best	All	Best
SMB (Gt yr^{-1})	2070 - 2100	2295 $\pm$ 1222	2246 $\pm$ 268	2382 $\pm$ 1316	2358 $\pm$ 331	2648 $\pm$ 1530	2495 $\pm$ 335
GMSL rise buffering (cm)	2000 - 2100	1.8 $\pm$ 0.7	1.3 $\pm$ 0.6	3.5 $\pm$ 0.8	3.2 $\pm$ 0.7	6.6 $\pm$ 1.1	5.0 $\pm$ 0.7
$\frac{\Delta \mathrm{SMB}}{\Delta \mathrm{t}}$ (Gt yr^{-2})	2000 - 2100	0.9 $\pm$ 2.4	0.9 $\pm$ 0.1	2.5 $\pm$ 3.5	1.9 $\pm$ 1.0	6.0 $\pm$ 7.2	3.8 $\pm$ 1.8
$\frac{\Delta \mathrm{SMB}}{\Delta \mathrm{T}}$ (Gt yr^{-1} °C^{-1})	2000 - 2100	95 $\pm$ 152	64 $\pm$ 80	102 $\pm$ 124	57 $\pm$ 33	120 $\pm$ 103	78 $\pm$ 15
Δ T (°C 100yr^{-1})	2000 - 2100	1.1 $\pm$ 0.5	0.8 $\pm$ 0.3	1.4 $\pm$ 0.8	1.2 $\pm$ 0.4	2.0 $\pm$ 0.9	1.8 $\pm$ 0.6

Table 4. Projected values for SMB, GMSL rise buffering, SMB trend, SMB temperature sensitivity, and change in 21st century temperature for all CMIP5 models compared to the best scoring CMIP5 models for RCP2.6, RCP4.5, and RCP8.5.

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References