

Observation-based constraint suggests larger ocean carbon uptake and stronger climate feedbacks

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S1 Supplementary Figures

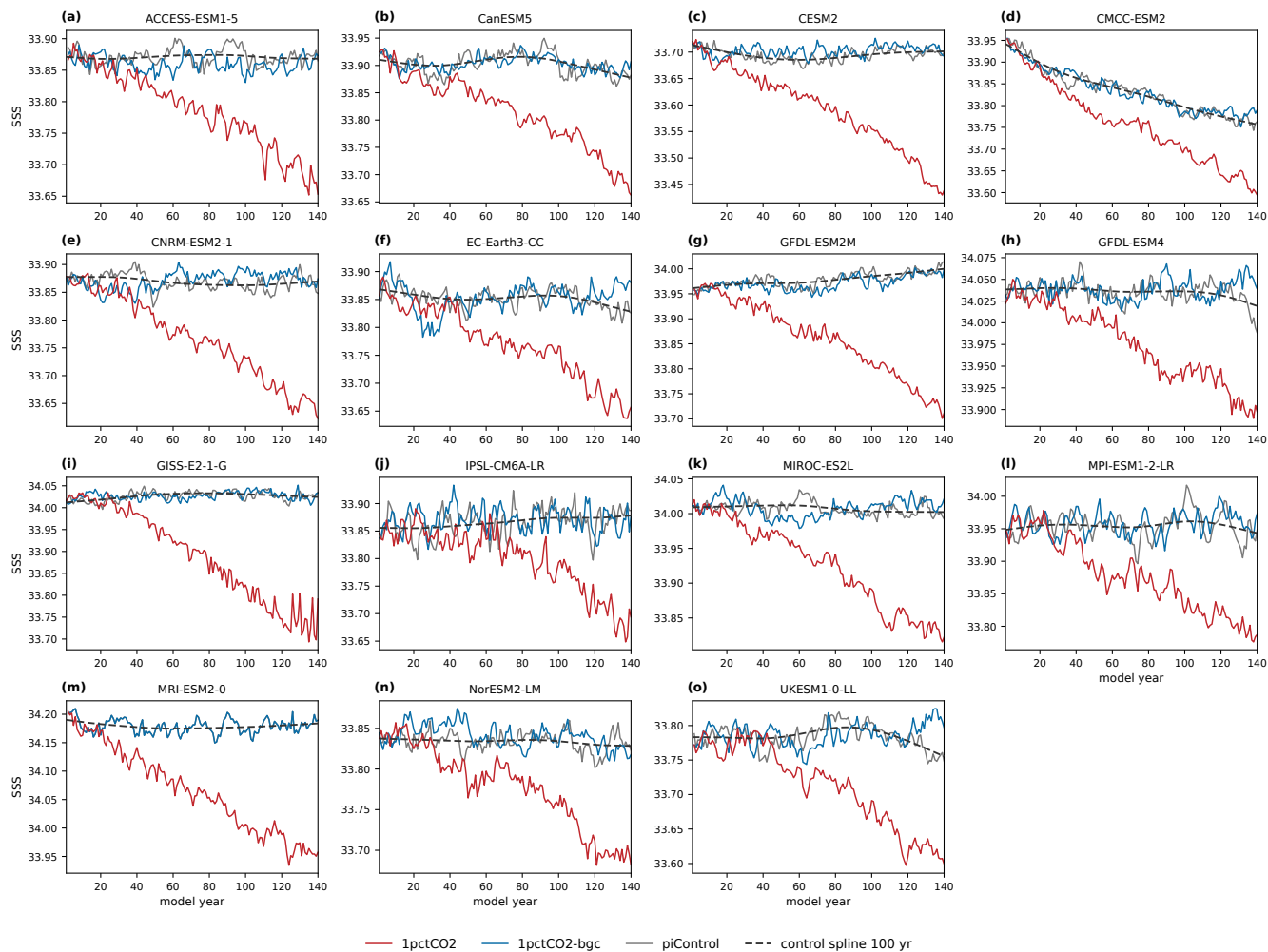


Figure S1. Inter-frontal sea surface salinity (SSS) of the Southern Ocean in the fully coupled (1pctCO₂, red line) and biogeochemically coupled (1pctCO₂-bgc, blue line) 1 % yr⁻¹ simulations, and in the pre-industrial control simulation (grey line). The dashed black line is the Enting spline of the control with a 100-year cut-off period to quantify the drift.

S2 Supplementary Tables

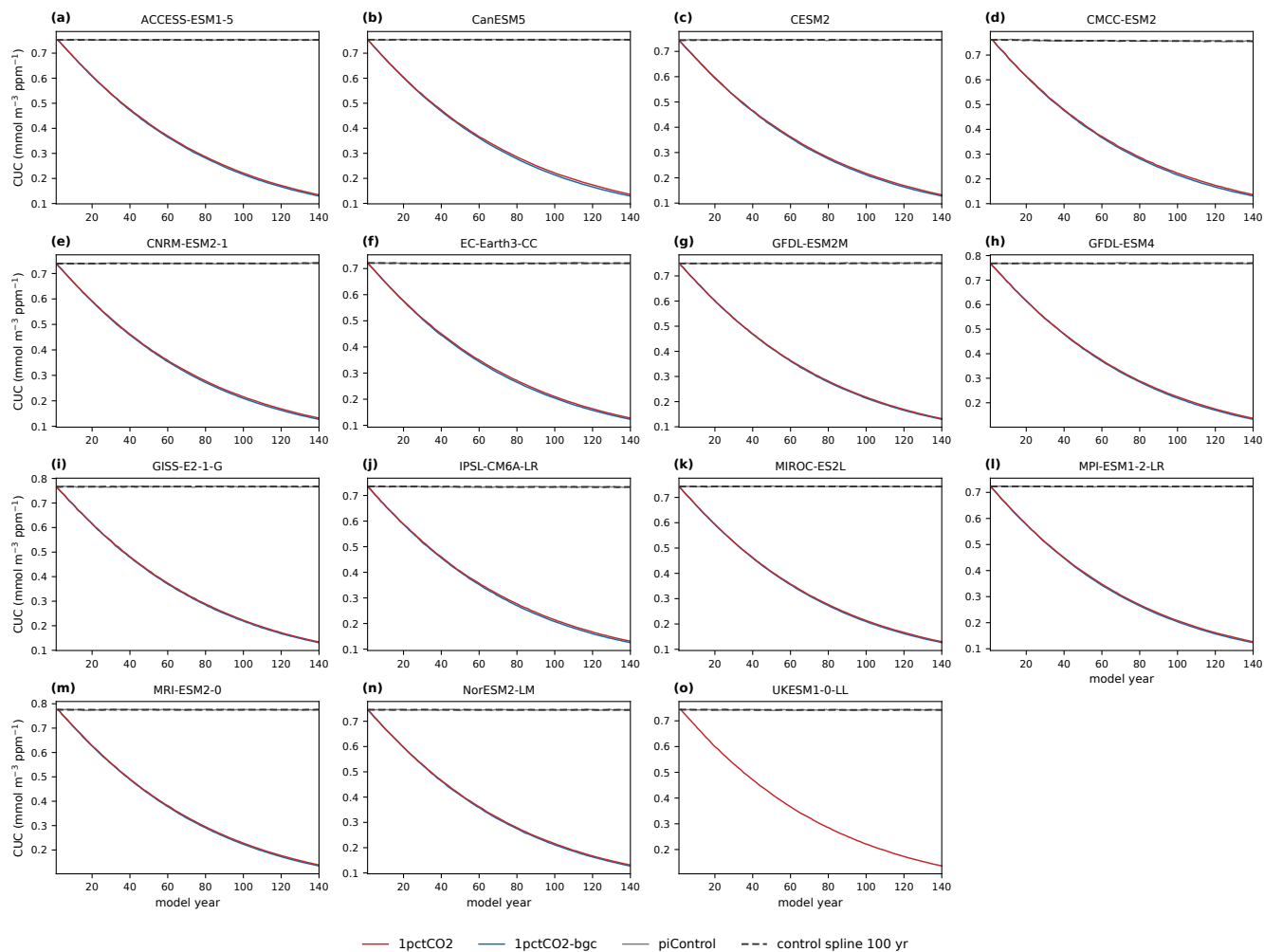


Figure S2. Chemical uptake capacity (CUC) in the fully coupled (1pctCO_2 , red line) and biogeochemically coupled ($1\text{pctCO}_2\text{-bgc}$, blue line) $1\% \text{yr}^{-1}$ simulations, and in the pre-industrial control simulation (grey line). The dashed black line is the Enting spline of the control with a 100-year cut-off period to quantify the drift.

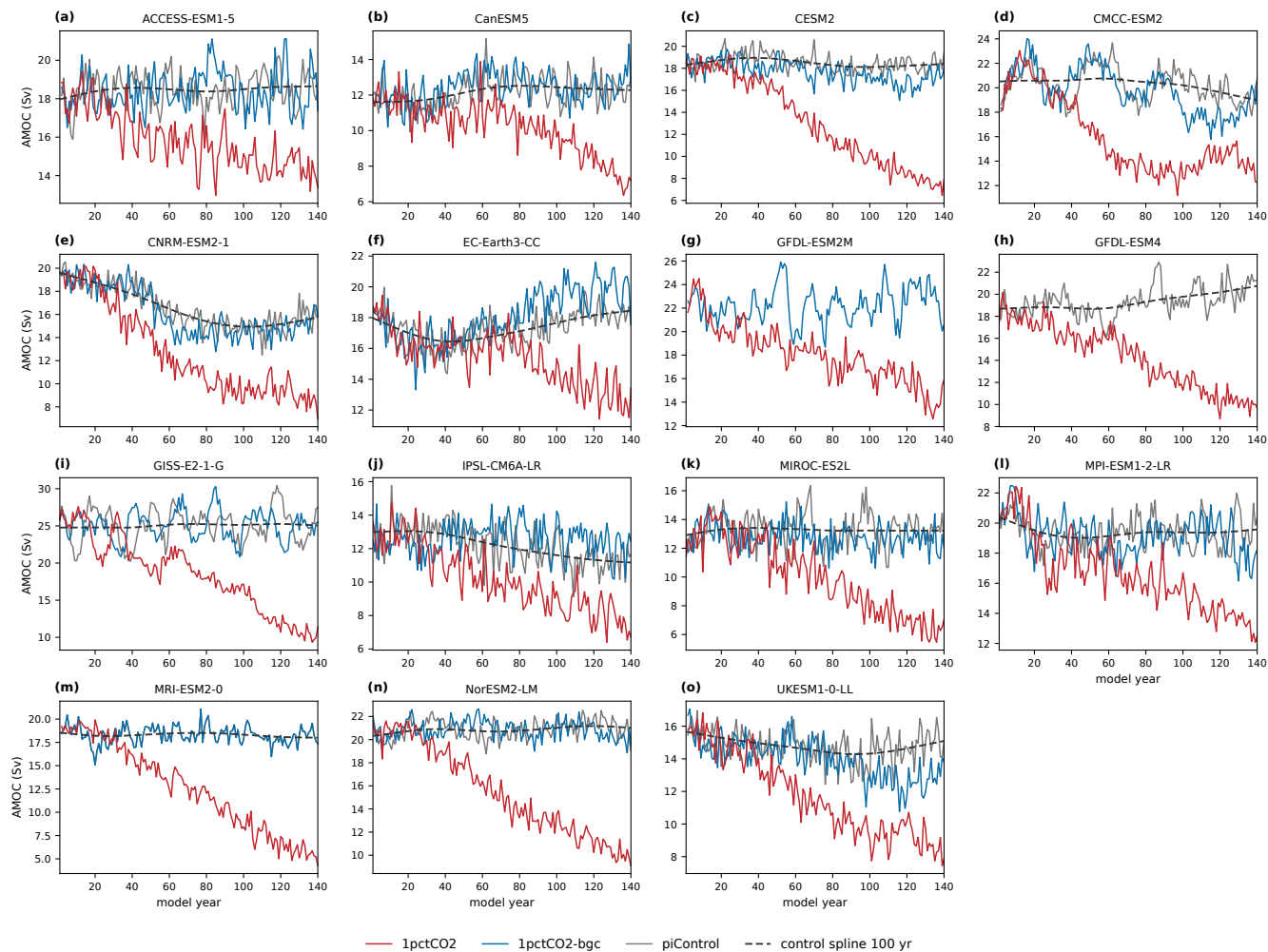


Figure S3. The Atlantic Meridional Overturning Circulation (AMOC) at 26.5° N in the fully coupled (1pctCO₂, red line) and biogeochemically coupled (1pctCO₂-bgc, blue line) 1 % yr⁻¹ simulations, and in the pre-industrial control simulation (grey line). The dashed black line is the Enting spline of the control with a 100-year cut-off period to quantify the drift.

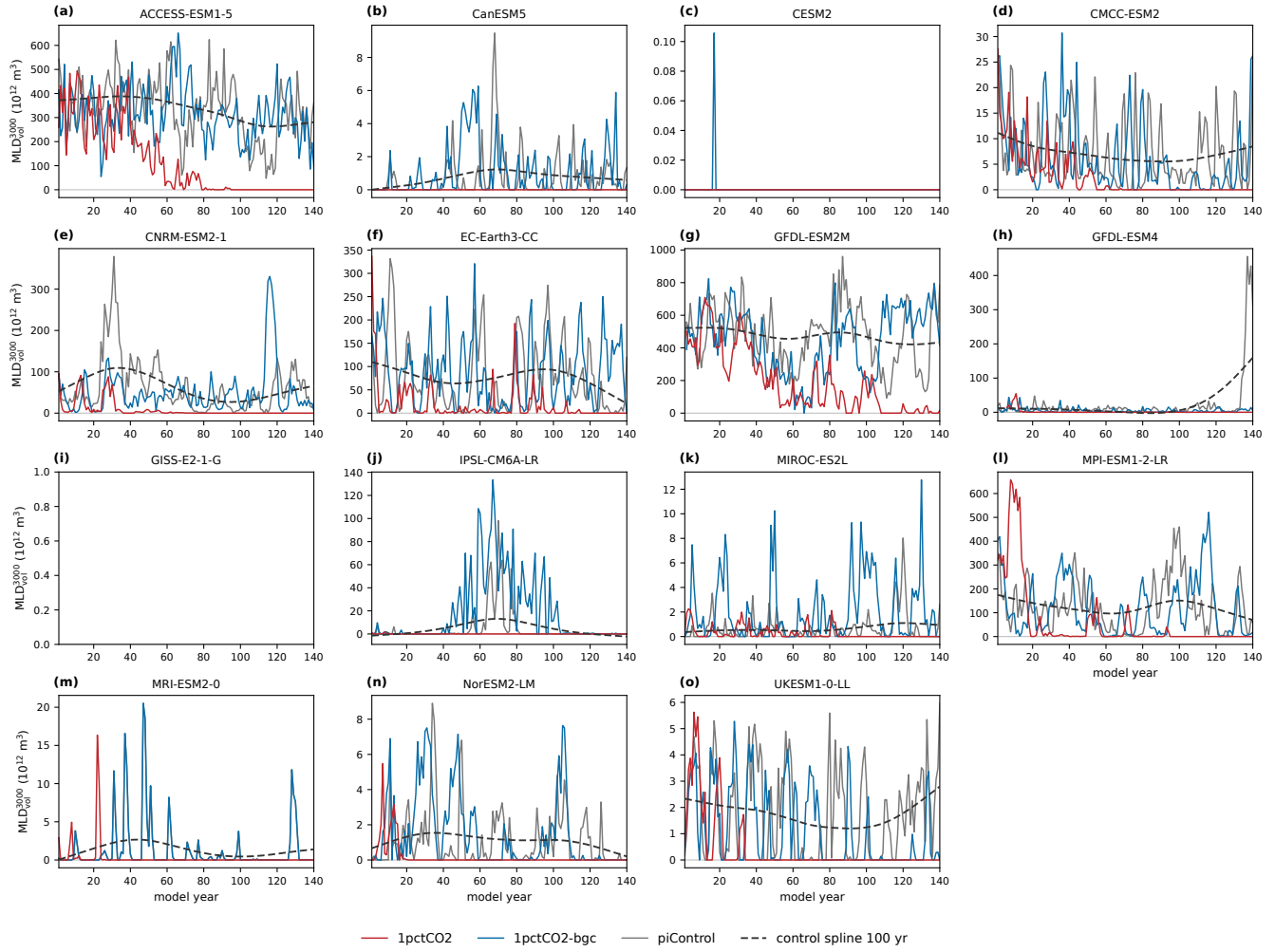


Figure S4. The volume of water mixed deeper than 3000 m (MLD_{vol}^{3000}) in the fully coupled (1pctCO₂, red line) and biogeochemically coupled (1pctCO₂-bgc, blue line) 1 % yr⁻¹ simulations, and in the pre-industrial control simulation (grey line). The dashed black line is the Enting spline of the control with a 100-year cut-off period to quantify the drift.

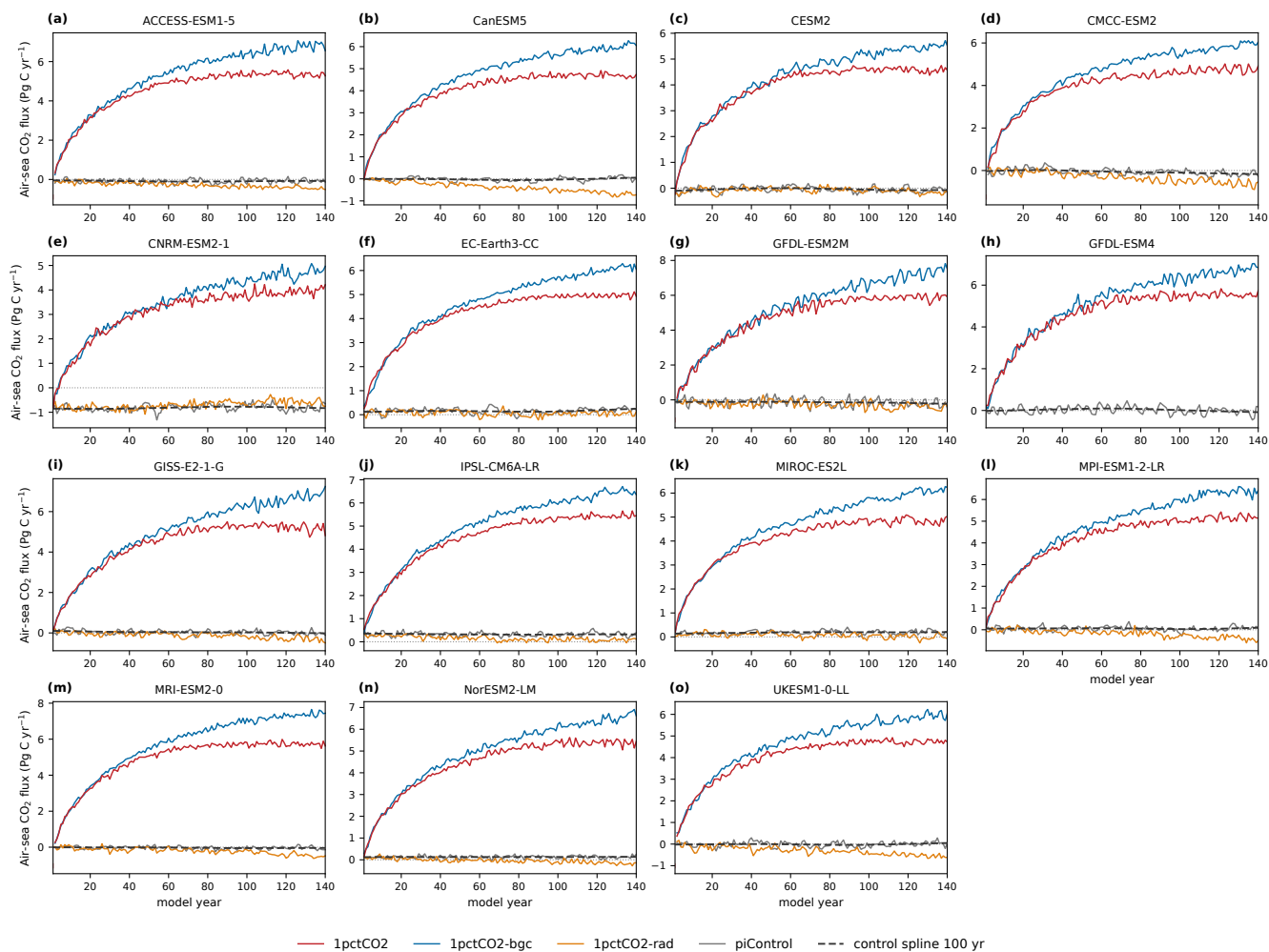


Figure S5. The annual air-sea CO₂ flux in the fully coupled (1pctCO₂, red line), biogeochemically coupled (1pctCO₂-bgc, blue line), and radiatively coupled (1pctCO₂-rad, orange line) 1% yr⁻¹ simulations, and in the pre-industrial control simulation (grey line). The dashed black line is the Enting spline of the control with a 100-year cut-off period to quantify the drift.

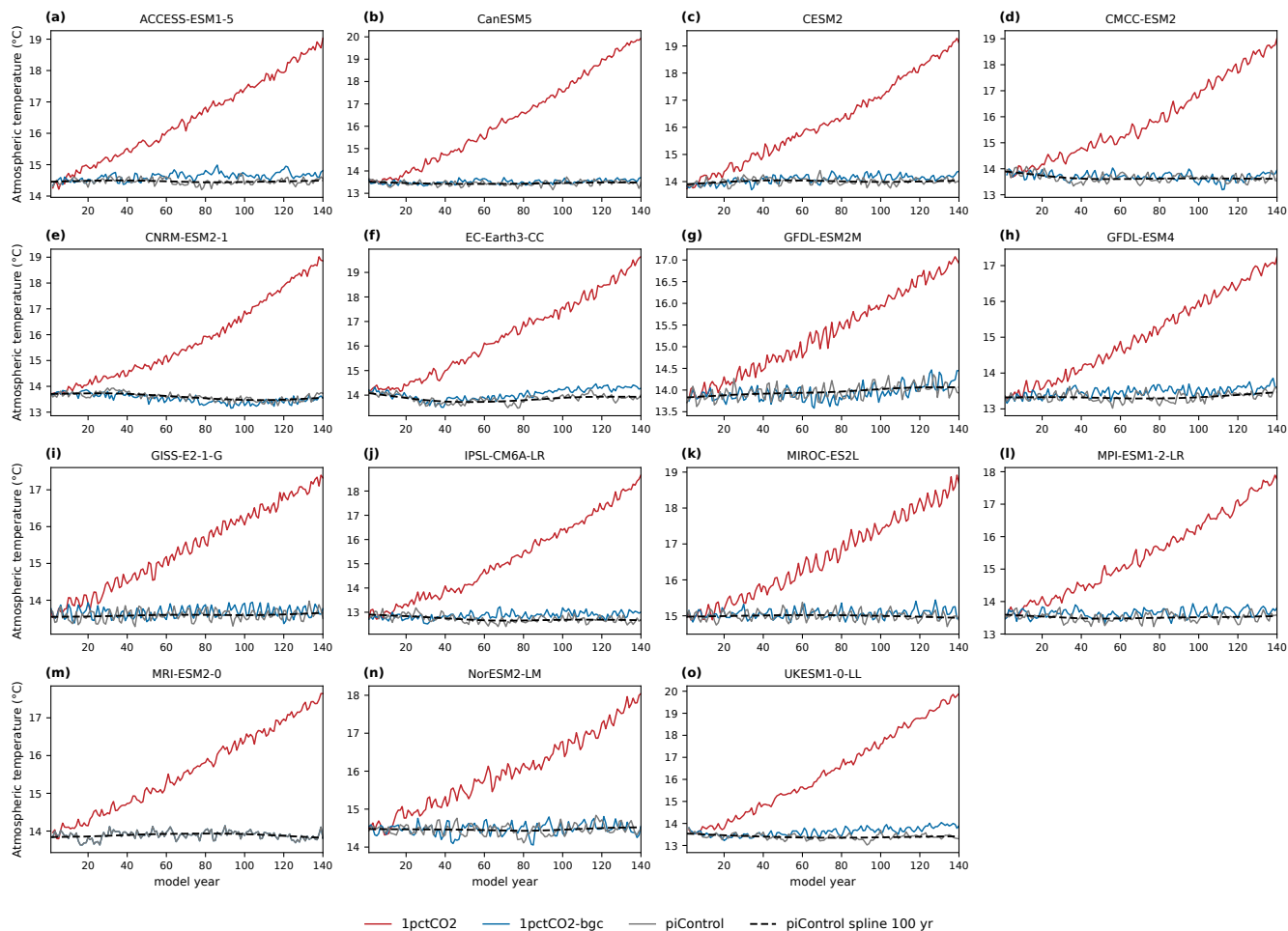


Figure S6. Global mean surface air temperature in the fully coupled (1pctCO₂, red line) and biogeochemically coupled (1pctCO₂-bgc, blue line) 1 % yr⁻¹ simulations, and in the pre-industrial control simulation (grey line). The dashed black line is the Enting spline of the control with a 100-year cut-off period to quantify the drift.

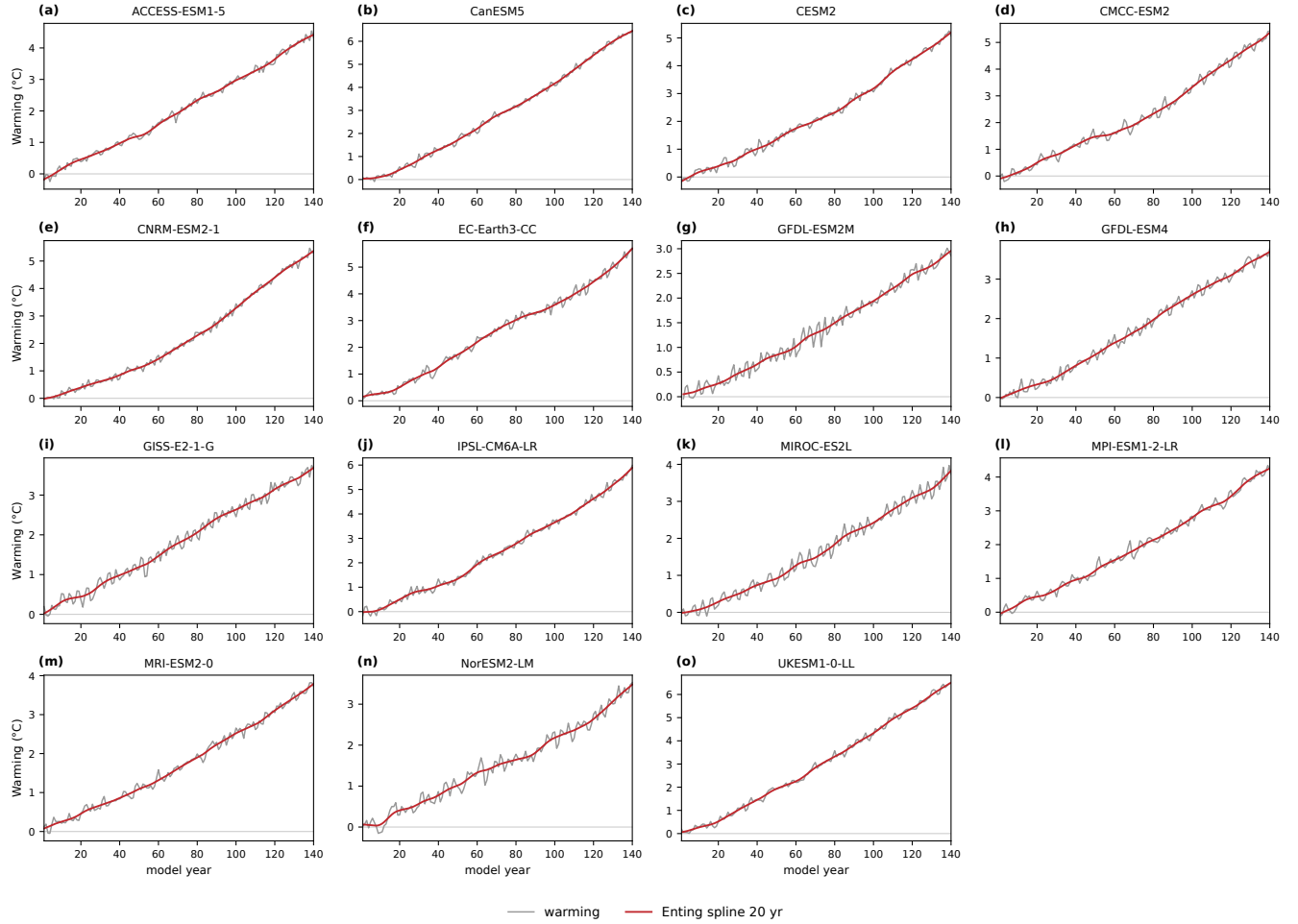


Figure S7. Global atmospheric warming in the fully coupled simulation after removing the control drift, before (grey) and after (red) smoothing with an Enting spline of 20-year cut-off period.

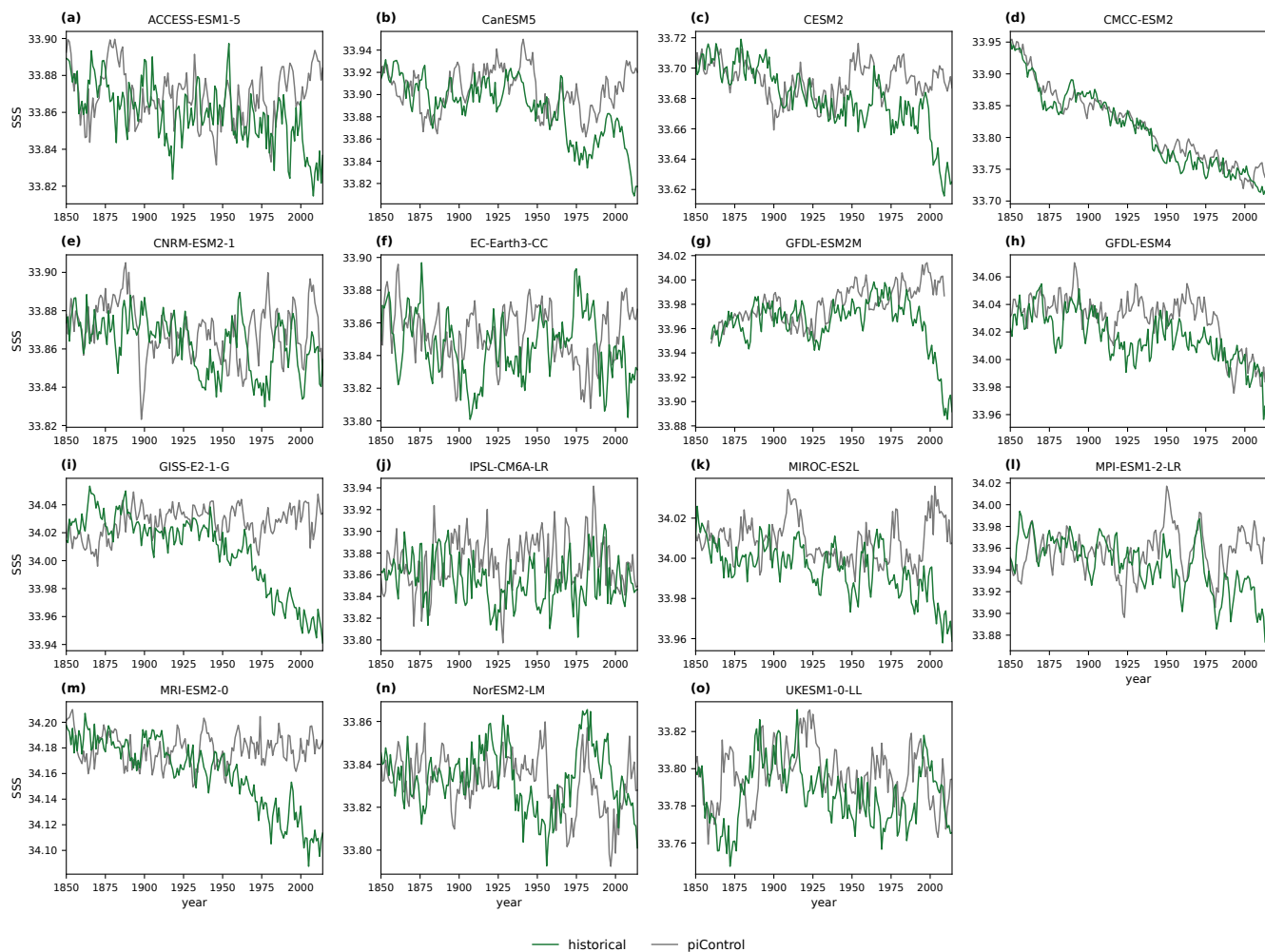


Figure S8. The inter-frontal sea surface salinity (SSS) of the Southern Ocean in the historical simulation (green line) and in the pre-industrial control (grey line).

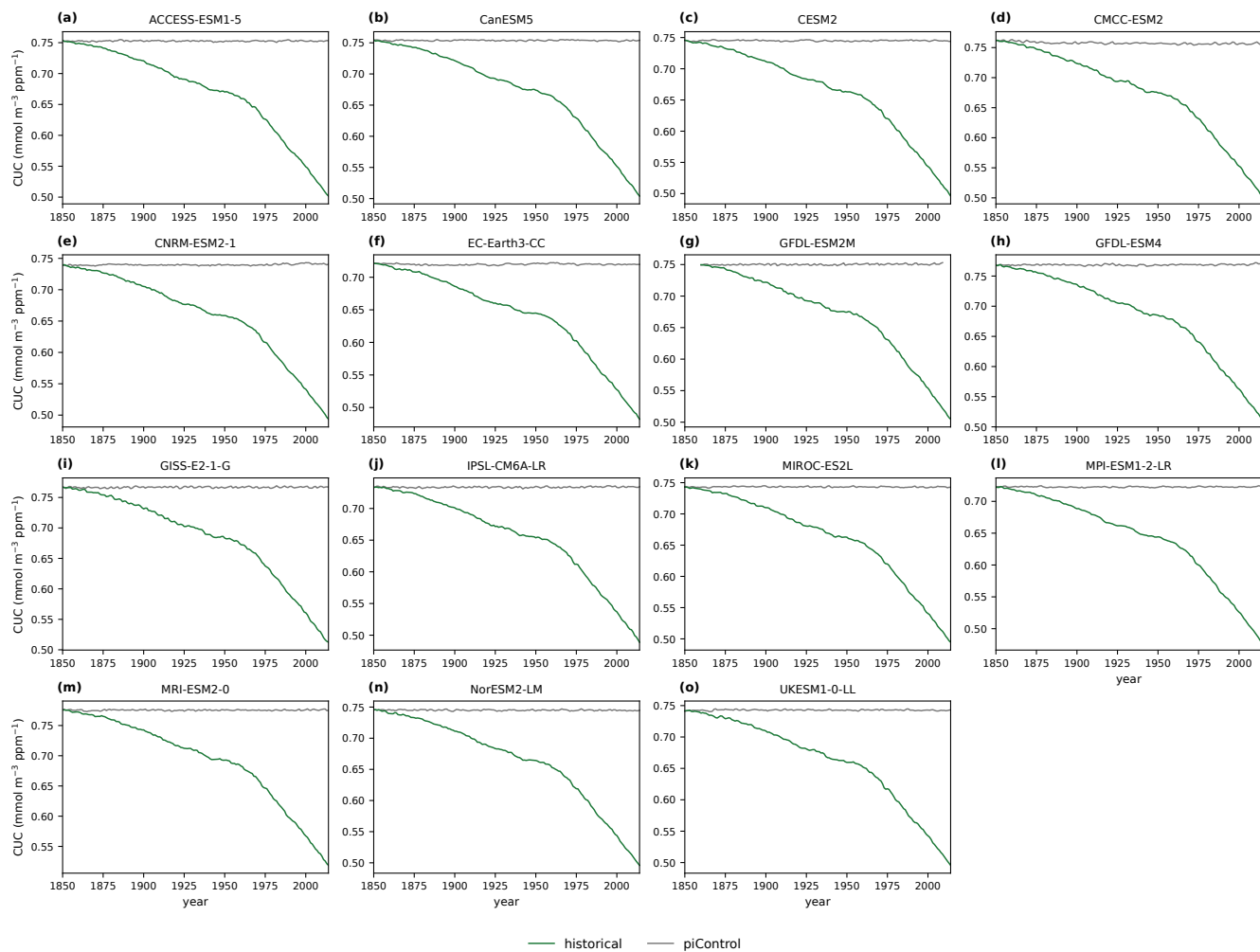


Figure S9. Chemical uptake capacity (CUC) in the historical simulation (green line) and in the pre-industrial control (grey line).

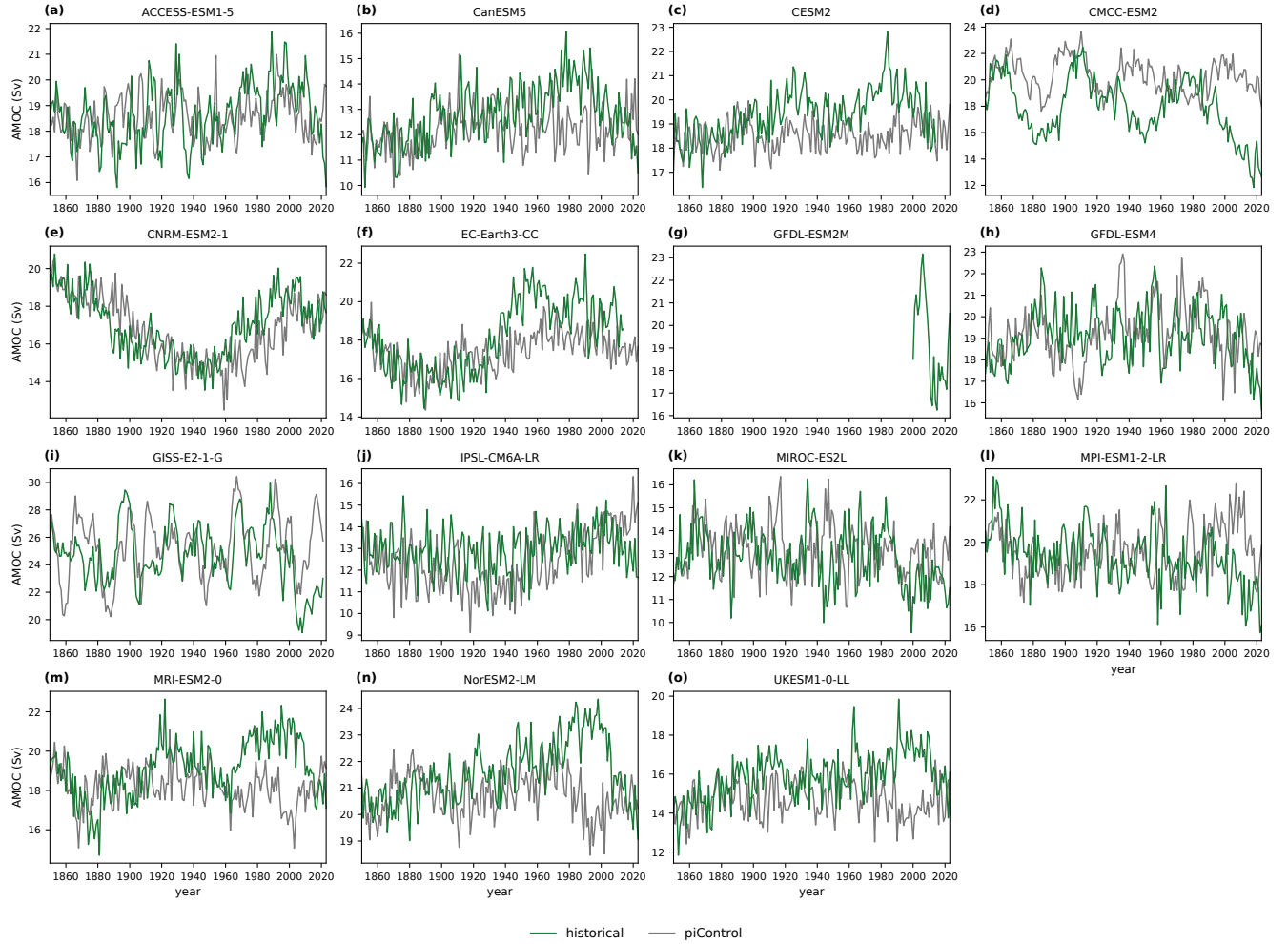


Figure S10. The AMOC at 26.5° N in the historical simulation (green line) and in the pre-industrial control (grey line).

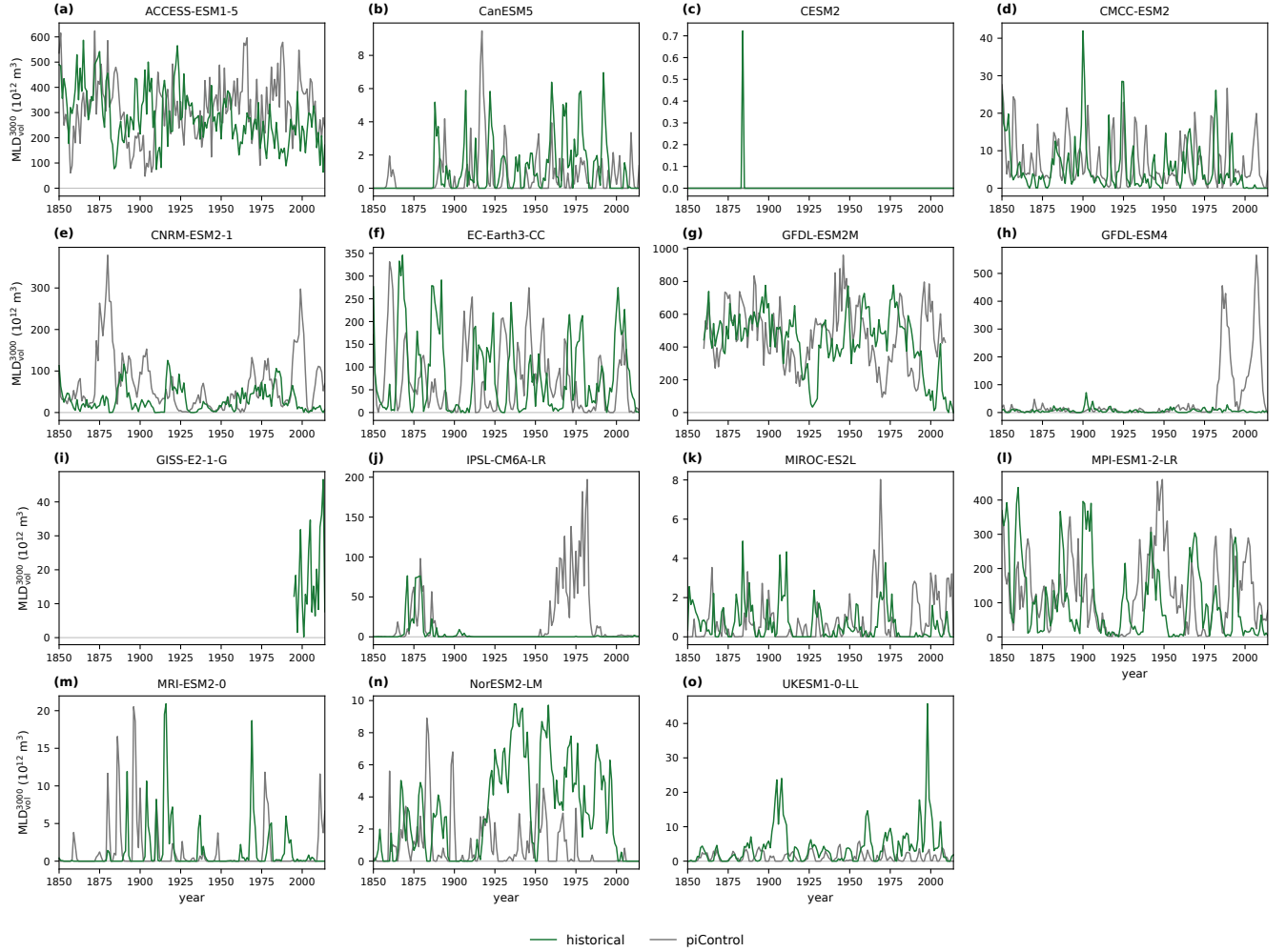


Figure S11. The volume of water mixed deeper than 3000 m (MLD_{vol}^{3000}) in the historical simulation (green line) and in the pre-industrial control (grey line).

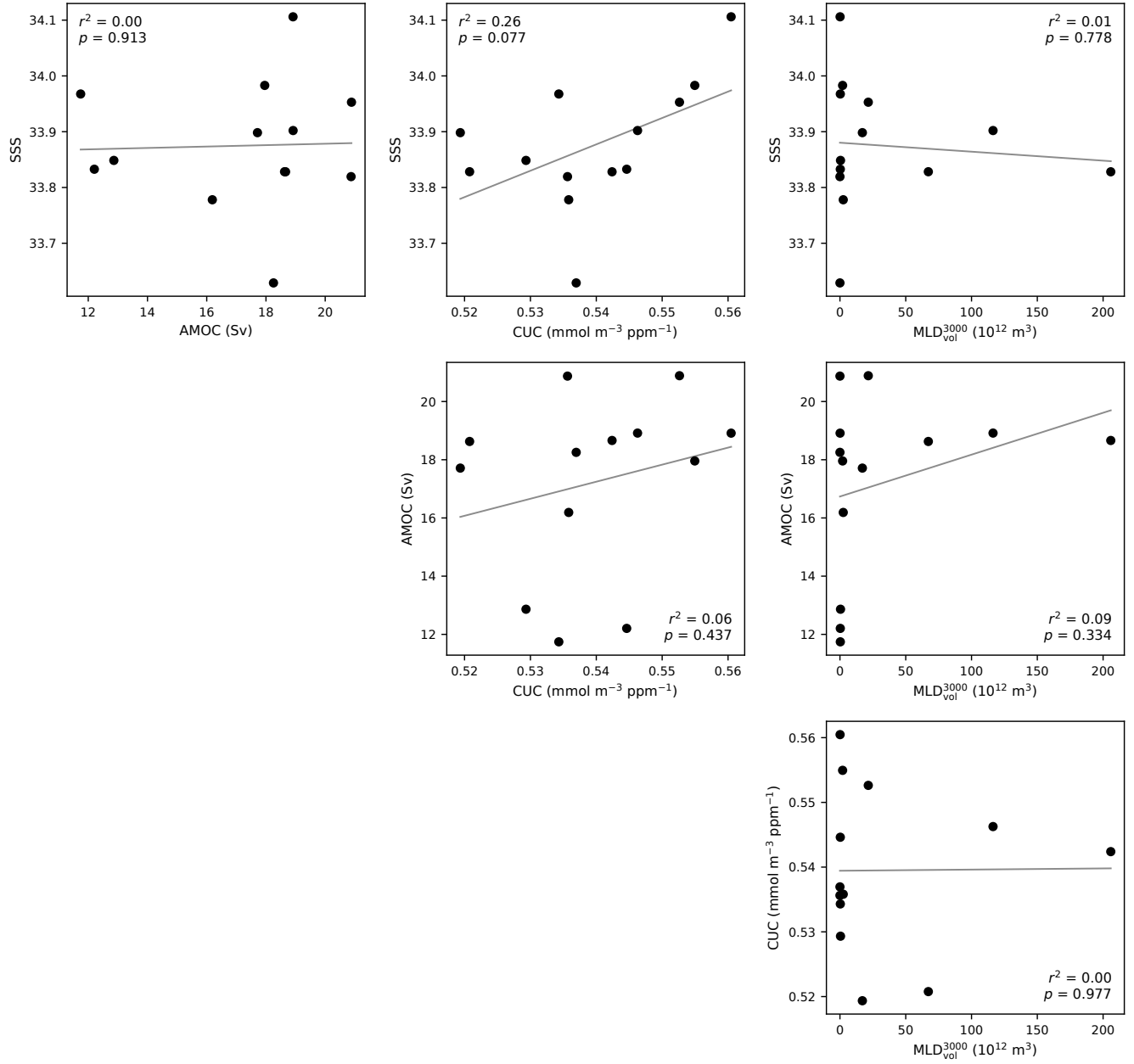


Figure S12. Each predictor against each of the others across the 13 Earth system models. Rows are the inter-frontal sea surface salinity (SSS), the AMOC at 26.5° N, and the chemical uptake capacity (CUC); columns are the AMOC, the CUC and the volume of water mixed deeper than 3000 m (MLD³⁰⁰⁰). Grey lines are least-squares fits, and the coefficient of determination and the two-sided p value of the correlation are given in each panel.

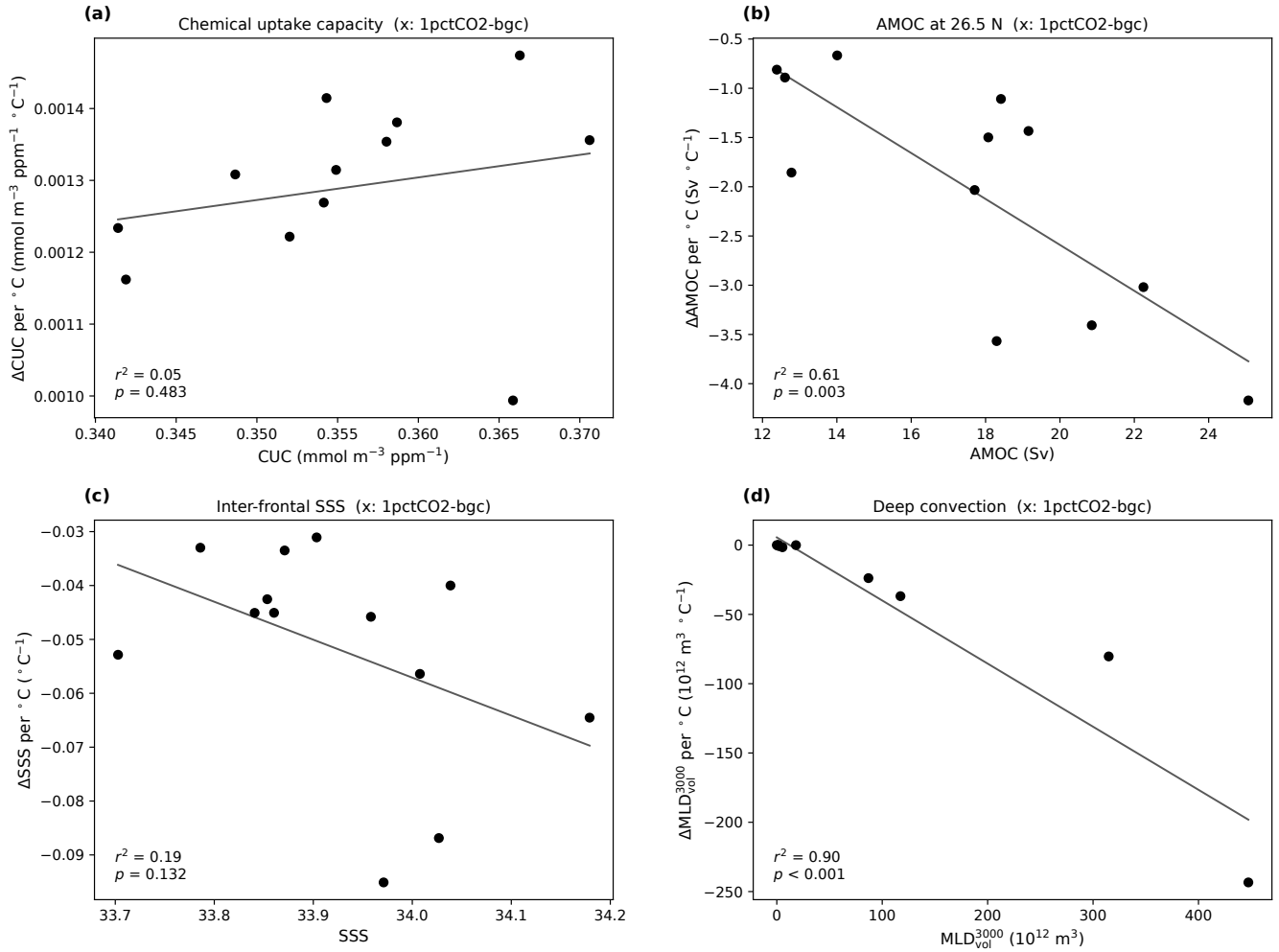


Figure S13. Mean value of each predictor over the biogeochemically coupled 1 % yr⁻¹ simulation (1pctCO₂-bgc), which has no global warming, against its change under warming, across the ESMs. **(a)** the chemical uptake capacity (CUC), **(b)** the AMOC at 26.5° N, **(c)** the inter-frontal sea surface salinity (SSS), and **(d)** the volume of water mixed deeper than 3000 m (MLD³⁰⁰⁰_{vol}). The change under warming is calculated as the difference between the fully coupled (1pctCO₂) and biogeochemically coupled (1pctCO₂-bgc) simulations, averaged over the last 30 years of the 140-year ramp and divided by the difference in their global mean warming. Grey lines are least-squares fits, and the coefficient of determination and the two-sided p value of the correlation are given in each panel. Simulated changes in the predictors per warming for each model are listed in Table S5.

Table S1. Effect of including CMCC-ESM2 and CNRM-ESM2-1 on the constrained carbon-concentration (β) and carbon-climate (γ) feedback parameters, at year 70 and year 140 of the 1 % yr⁻¹ simulation.

	Models kept	n	Prior	$\pm$	Constrained	$\pm$	R^2
<i>Year 70</i>							
β (Pg C ppm ⁻¹)	excluded (standard)	13	0.925	0.073	0.961	0.048	0.78
	+ CNRM-ESM2-1	14	0.918	0.075	0.956	0.051	0.76
	+ CMCC-ESM2	14	0.924	0.070	0.959	0.046	0.78
	both included	15	0.917	0.072	0.955	0.049	0.75
γ (Pg C °C ⁻¹)	excluded (standard)	13	-8.26	2.39	-10.15	2.36	0.48
	+ CNRM-ESM2-1	14	-7.93	2.59	-9.87	2.61	0.44
	+ CMCC-ESM2	14	-8.47	2.42	-9.88	2.68	0.33
	both included	15	-8.15	2.63	-9.59	2.87	0.33
<i>Year 140</i>							
β (Pg C ppm ⁻¹)	excluded (standard)	13	0.804	0.069	0.847	0.037	0.86
	+ CNRM-ESM2-1	14	0.797	0.071	0.842	0.043	0.80
	+ CMCC-ESM2	14	0.802	0.067	0.846	0.035	0.85
	both included	15	0.796	0.069	0.840	0.042	0.80
γ (Pg C °C ⁻¹)	excluded (standard)	13	-19.06	6.23	-24.46	3.58	0.83
	+ CNRM-ESM2-1	14	-18.36	6.53	-23.88	4.42	0.75
	+ CMCC-ESM2	14	-18.89	6.02	-24.19	3.69	0.80
	both included	15	-18.25	6.30	-23.60	4.43	0.72

Predictors of the two models. CMCC-ESM2: AMOC 14.04 Sv, SSS 33.72, MLD_{vol}³⁰⁰⁰ 0.1×10^{12} m³, CUC 0.546 mmol m⁻³ ppm⁻¹. CNRM-ESM2-1: AMOC 17.89 Sv, SSS 33.86, MLD_{vol}³⁰⁰⁰ 8.3×10^{12} m³, CUC 0.534 mmol m⁻³ ppm⁻¹.

Table S2. Predictor variables averaged over the idealised 1 % yr⁻¹ CO₂ simulations for the fully coupled (1pctCO₂) and biogeochemically coupled (1pctCO₂-bgc) configurations, with the drift of the branch-aligned pre-industrial control removed by an Enting spline with a 100-year cut-off period. These are the values of the y-axes in Fig. 3; the corresponding historical values are the predictors themselves and are given in Table 3. A dash means the field could not be computed. GFDL-ESM4 has no overturning streamfunction archived for 1pctCO₂-bgc; UKESM1-0-LL has no surface dissolved inorganic carbon and alkalinity archived for 1pctCO₂-bgc; GISS-E2-1-G has no three-dimensional temperature and salinity fields for the idealised simulations.

Model	SSS		AMOC (Sv)		CUC (mmol m ⁻³ ppm ⁻¹)		MLD _{vol} ³⁰⁰⁰ (10 ¹² m ³)	
	1pct	1pct-bgc	1pct	1pct-bgc	1pct	1pct-bgc	1pct	1pct-bgc
ACCESS-ESM1-5	33.785	33.860	15.34	17.94	0.3626	0.3587	153.5	352.4
CanESM5	33.821	33.910	9.59	11.82	0.3636	0.3580	-0.7	0.3
CESM2	33.610	33.721	12.88	17.53	0.3575	0.3535	0.0	0.0
EC-Earth3-CC	33.787	33.870	15.98	18.73	0.3474	0.3426	51.5	121.0
GFDL-ESM2M	33.842	33.954	18.07	22.25	0.3569	0.3544	236.5	495.9
GFDL-ESM4	33.978	34.041	13.62	—	0.3694	0.3661	-9.5	-5.2
GISS-E2-1-G	33.877	34.012	18.18	24.80	0.3683	0.3655	—	—
IPSL-CM6A-LR	33.789	33.861	10.97	13.42	0.3549	0.3502	-5.9	12.2
MIROC-ES2L	33.927	34.009	9.67	12.43	0.3543	0.3517	-0.0	1.7
MPI-ESM1-2-LR	33.870	33.952	17.59	20.15	0.3457	0.3424	110.2	168.8
MRI-ESM2-0	34.076	34.190	12.68	18.52	0.3741	0.3706	-1.0	0.0
NorESM2-LM	33.781	33.844	14.95	20.31	0.3578	0.3547	-0.3	1.0
UKESM1-0-LL	33.711	33.785	12.55	14.87	0.3606	—	1.0	1.7
Multi model mean	33.835	33.924	14.01	17.73	0.3595	0.3557	44.6	95.8
Standard deviation	0.118	0.122	2.97	3.98	0.0083	0.0088	80.1	166.0

Table S3: Coefficients of the emergent-constraint relationship $a \cdot \text{AMOC} + b \cdot \text{SSS} + c \cdot \text{CUC} + e = \beta$, fitted across the 13 models at every year of the ramp. Each coefficient is the change in β per unit change in that predictor with the others held fixed. The intercept e is the value at zero in every predictor, far outside the range of the ensemble, and carries no interpretation on its own. Units are $\text{Pg C ppm}^{-1} \text{ Sv}^{-1}$ for a , Pg C ppm^{-1} per unit of SSS for b , Pg C ppm^{-1} per $\text{mmol m}^{-3} \text{ ppm}^{-1}$ for c , and Pg C ppm^{-1} for e .

Year	a (AMOC)	b (SSS)	c (CUC)	e	r^2
2	0.0038	-0.157	1.701	4.537	0.06
3	0.0028	-0.165	2.003	4.669	0.12
4	0.0027	-0.188	1.781	5.602	0.12
5	0.0019	-0.176	1.687	5.319	0.10
6	0.0006	-0.169	2.172	4.871	0.15
7	-0.0001	-0.155	2.392	4.299	0.19
8	-0.0013	-0.154	2.454	4.283	0.19
9	-0.0020	-0.153	2.328	4.370	0.17
10	-0.0012	-0.130	2.081	3.727	0.13
11	-0.0006	-0.118	2.042	3.358	0.13
12	-0.0004	-0.112	2.033	3.170	0.14
13	-0.0004	-0.102	2.040	2.864	0.14
14	-0.0002	-0.114	2.169	3.205	0.15
15	-0.0001	-0.115	2.309	3.201	0.18
16	-0.0003	-0.105	2.388	2.844	0.19
17	-0.0005	-0.100	2.520	2.606	0.21
18	-0.0003	-0.093	2.592	2.352	0.23
19	0.0000	-0.086	2.671	2.077	0.25
20	0.0001	-0.075	2.688	1.705	0.26
21	0.0005	-0.062	2.722	1.276	0.28
22	0.0007	-0.053	2.768	0.944	0.29
23	0.0009	-0.044	2.858	0.618	0.31
24	0.0013	-0.037	2.867	0.359	0.33
25	0.0016	-0.027	2.821	0.081	0.33
26	0.0016	-0.017	2.780	-0.252	0.33
27	0.0020	-0.009	2.812	-0.523	0.36
28	0.0023	-0.003	2.874	-0.742	0.39
29	0.0025	0.006	2.861	-1.059	0.40
30	0.0025	0.011	2.911	-1.228	0.42
31	0.0026	0.019	2.892	-1.477	0.43
32	0.0026	0.027	2.909	-1.769	0.45
33	0.0027	0.038	2.856	-2.091	0.45
34	0.0029	0.051	2.778	-2.496	0.46
35	0.0029	0.067	2.702	-2.970	0.45
36	0.0030	0.079	2.696	-3.390	0.47
37	0.0031	0.087	2.687	-3.645	0.48
38	0.0033	0.091	2.696	-3.775	0.49
39	0.0034	0.095	2.711	-3.921	0.50
40	0.0035	0.099	2.788	-4.076	0.52
41	0.0036	0.100	2.849	-4.159	0.52

Year	a (AMOC)	b (SSS)	c (CUC)	e	r^2
42	0.0037	0.101	2.894	-4.191	0.53
43	0.0039	0.107	2.882	-4.400	0.53
44	0.0040	0.117	2.851	-4.707	0.54
45	0.0040	0.122	2.865	-4.878	0.55
46	0.0040	0.126	2.865	-5.002	0.55
47	0.0040	0.129	2.884	-5.136	0.55
48	0.0040	0.132	2.934	-5.236	0.56
49	0.0040	0.134	2.957	-5.322	0.56
50	0.0041	0.136	2.932	-5.362	0.56
51	0.0041	0.138	2.923	-5.434	0.56
52	0.0042	0.140	2.922	-5.512	0.56
53	0.0041	0.140	2.950	-5.496	0.56
54	0.0042	0.140	2.980	-5.522	0.57
55	0.0043	0.142	2.991	-5.582	0.57
56	0.0044	0.147	2.964	-5.755	0.58
57	0.0045	0.153	2.959	-5.940	0.58
58	0.0046	0.157	2.950	-6.094	0.59
59	0.0047	0.161	2.940	-6.217	0.59
60	0.0047	0.163	2.944	-6.270	0.59
61	0.0048	0.164	2.954	-6.321	0.59
62	0.0050	0.164	2.975	-6.345	0.59
63	0.0051	0.163	2.997	-6.292	0.59
64	0.0052	0.164	3.014	-6.360	0.60
65	0.0051	0.167	3.031	-6.471	0.60
66	0.0051	0.169	3.058	-6.525	0.61
67	0.0052	0.170	3.098	-6.585	0.61
68	0.0052	0.172	3.110	-6.666	0.62
69	0.0051	0.175	3.112	-6.783	0.62
70	0.0051	0.179	3.107	-6.905	0.62
71	0.0052	0.183	3.090	-7.029	0.62
72	0.0053	0.185	3.081	-7.110	0.63
73	0.0053	0.187	3.075	-7.172	0.63
74	0.0054	0.188	3.079	-7.208	0.63
75	0.0053	0.188	3.084	-7.186	0.63
76	0.0054	0.189	3.072	-7.241	0.63
77	0.0055	0.191	3.065	-7.301	0.63
78	0.0056	0.192	3.066	-7.345	0.63
79	0.0057	0.194	3.062	-7.403	0.64
80	0.0057	0.197	3.043	-7.503	0.64
81	0.0058	0.198	3.048	-7.513	0.64
82	0.0058	0.199	3.035	-7.544	0.64
83	0.0059	0.201	3.030	-7.617	0.64
84	0.0060	0.205	3.022	-7.756	0.64
85	0.0060	0.208	3.013	-7.849	0.64
86	0.0060	0.211	2.999	-7.947	0.64
87	0.0061	0.211	3.013	-7.948	0.65
88	0.0061	0.210	3.018	-7.936	0.65

Year	a (AMOC)	b (SSS)	c (CUC)	e	r^2
89	0.0061	0.211	3.009	-7.940	0.65
90	0.0061	0.212	3.004	-7.997	0.65
91	0.0062	0.214	2.998	-8.049	0.65
92	0.0062	0.214	2.992	-8.067	0.65
93	0.0063	0.215	2.980	-8.081	0.65
94	0.0063	0.215	2.980	-8.081	0.65
95	0.0063	0.216	2.994	-8.141	0.66
96	0.0063	0.217	2.987	-8.162	0.66
97	0.0064	0.220	2.951	-8.242	0.66
98	0.0064	0.221	2.928	-8.279	0.66
99	0.0065	0.224	2.903	-8.358	0.67
100	0.0065	0.225	2.878	-8.386	0.67
101	0.0066	0.228	2.851	-8.461	0.67
102	0.0066	0.231	2.825	-8.551	0.67
103	0.0067	0.232	2.797	-8.599	0.67
104	0.0067	0.232	2.789	-8.590	0.68
105	0.0067	0.234	2.776	-8.653	0.68
106	0.0067	0.235	2.759	-8.683	0.68
107	0.0067	0.236	2.758	-8.705	0.68
108	0.0068	0.236	2.746	-8.704	0.68
109	0.0068	0.236	2.732	-8.696	0.68
110	0.0068	0.238	2.702	-8.743	0.68
111	0.0068	0.238	2.712	-8.775	0.68
112	0.0068	0.240	2.702	-8.830	0.69
113	0.0069	0.240	2.693	-8.829	0.69
114	0.0069	0.241	2.677	-8.849	0.69
115	0.0069	0.241	2.664	-8.862	0.69
116	0.0069	0.242	2.650	-8.878	0.69
117	0.0070	0.243	2.626	-8.890	0.69
118	0.0070	0.244	2.610	-8.917	0.69
119	0.0070	0.245	2.585	-8.964	0.69
120	0.0070	0.247	2.567	-9.008	0.69
121	0.0070	0.247	2.550	-9.013	0.69
122	0.0070	0.247	2.536	-9.009	0.69
123	0.0070	0.247	2.521	-8.993	0.69
124	0.0070	0.247	2.505	-8.994	0.69
125	0.0070	0.247	2.492	-8.991	0.69
126	0.0070	0.248	2.479	-9.009	0.69
127	0.0071	0.248	2.463	-9.016	0.70
128	0.0070	0.248	2.449	-8.996	0.70
129	0.0071	0.248	2.435	-8.990	0.70
130	0.0071	0.249	2.422	-9.018	0.70
131	0.0072	0.248	2.407	-9.004	0.70
132	0.0072	0.249	2.390	-9.011	0.70
133	0.0072	0.249	2.361	-9.009	0.70
134	0.0072	0.249	2.355	-8.992	0.70
135	0.0072	0.249	2.343	-8.993	0.70

Year	a (AMOC)	b (SSS)	c (CUC)	e	r^2
136	0.0072	0.249	2.336	-9.007	0.70
137	0.0072	0.249	2.338	-9.013	0.70
138	0.0071	0.249	2.335	-9.014	0.70
139	0.0072	0.248	2.332	-8.983	0.71
140	0.0072	0.249	2.324	-9.004	0.71

Table S4: Coefficients of the emergent-constraint relationship $a \cdot \text{AMOC} + b \cdot \text{SSS} + c \cdot \text{CUC} + d \cdot \text{MLD} + e = \beta$, fitted across the 13 models at every year of the ramp. Each coefficient is the change in β per unit change in that predictor with the others held fixed. The intercept e is the value at zero in every predictor, far outside the range of the ensemble, and carries no interpretation on its own. Units are Pg C ppm⁻¹ Sv⁻¹ for a , Pg C ppm⁻¹ per unit of SSS for b , Pg C ppm⁻¹ per mmol m⁻³ ppm⁻¹ for c , Pg C ppm⁻¹ per 10¹² m³ of MLD_{vol}³⁰⁰⁰ for d , and Pg C ppm⁻¹ for e .

Year	a (AMOC)	b (SSS)	c (CUC)	d (MLD)	e	r^2
2	0.0003	-0.130	1.749	0.000575	3.625	0.18
3	0.0002	-0.144	2.039	0.000428	3.991	0.24
4	-0.0000	-0.166	1.819	0.000455	4.881	0.26
5	0.0002	-0.163	1.711	0.000280	4.875	0.16
6	-0.0006	-0.160	2.190	0.000205	4.546	0.19
7	-0.0014	-0.144	2.410	0.000216	3.957	0.24
8	-0.0026	-0.144	2.473	0.000217	3.940	0.24
9	-0.0033	-0.143	2.346	0.000220	4.020	0.21
10	-0.0029	-0.117	2.104	0.000270	3.299	0.20
11	-0.0023	-0.105	2.066	0.000279	2.915	0.20
12	-0.0022	-0.097	2.058	0.000303	2.690	0.23
13	-0.0026	-0.085	2.070	0.000359	2.294	0.27
14	-0.0023	-0.097	2.198	0.000345	2.658	0.27
15	-0.0023	-0.098	2.338	0.000351	2.645	0.31
16	-0.0024	-0.089	2.417	0.000348	2.293	0.32
17	-0.0025	-0.084	2.548	0.000330	2.082	0.32
18	-0.0024	-0.076	2.622	0.000355	1.789	0.35
19	-0.0023	-0.068	2.703	0.000375	1.482	0.39
20	-0.0022	-0.057	2.720	0.000372	1.115	0.40
21	-0.0016	-0.046	2.751	0.000351	0.720	0.40
22	-0.0014	-0.036	2.798	0.000354	0.383	0.42
23	-0.0013	-0.027	2.889	0.000363	0.043	0.44
24	-0.0008	-0.020	2.896	0.000343	-0.185	0.44
25	-0.0005	-0.011	2.850	0.000347	-0.469	0.44
26	-0.0004	-0.001	2.808	0.000332	-0.778	0.44
27	-0.0001	0.007	2.841	0.000346	-1.071	0.48
28	0.0001	0.014	2.905	0.000365	-1.321	0.52
29	0.0003	0.024	2.892	0.000366	-1.640	0.53
30	0.0002	0.029	2.943	0.000373	-1.818	0.56
31	0.0003	0.037	2.924	0.000372	-2.067	0.57
32	0.0003	0.045	2.941	0.000375	-2.364	0.58
33	0.0004	0.056	2.889	0.000383	-2.698	0.59
34	0.0006	0.069	2.810	0.000377	-3.093	0.59
35	0.0005	0.085	2.734	0.000382	-3.575	0.59
36	0.0007	0.098	2.729	0.000389	-4.006	0.61
37	0.0008	0.106	2.720	0.000391	-4.266	0.62
38	0.0010	0.109	2.729	0.000388	-4.389	0.63
39	0.0011	0.114	2.743	0.000384	-4.530	0.63
40	0.0011	0.118	2.821	0.000394	-4.701	0.65
41	0.0011	0.120	2.883	0.000405	-4.800	0.67

Year	a (AMOC)	b (SSS)	c (CUC)	d (MLD)	e	r^2
42	0.0012	0.120	2.929	0.000415	-4.849	0.68
43	0.0014	0.127	2.918	0.000422	-5.069	0.68
44	0.0014	0.137	2.887	0.000432	-5.392	0.69
45	0.0014	0.142	2.901	0.000434	-5.565	0.70
46	0.0013	0.146	2.901	0.000435	-5.692	0.70
47	0.0014	0.150	2.921	0.000437	-5.829	0.71
48	0.0013	0.153	2.972	0.000439	-5.932	0.72
49	0.0013	0.155	2.995	0.000451	-6.036	0.72
50	0.0013	0.157	2.970	0.000452	-6.078	0.72
51	0.0014	0.160	2.961	0.000454	-6.155	0.72
52	0.0014	0.162	2.961	0.000461	-6.242	0.73
53	0.0013	0.162	2.989	0.000464	-6.231	0.73
54	0.0014	0.162	3.019	0.000461	-6.253	0.73
55	0.0015	0.163	3.030	0.000460	-6.312	0.73
56	0.0016	0.169	3.003	0.000463	-6.490	0.74
57	0.0017	0.175	2.998	0.000469	-6.682	0.74
58	0.0017	0.180	2.990	0.000472	-6.841	0.75
59	0.0018	0.184	2.980	0.000474	-6.969	0.75
60	0.0018	0.185	2.984	0.000476	-7.024	0.75
61	0.0019	0.187	2.994	0.000478	-7.078	0.75
62	0.0020	0.188	3.016	0.000485	-7.114	0.76
63	0.0021	0.186	3.039	0.000492	-7.071	0.76
64	0.0022	0.188	3.056	0.000494	-7.144	0.77
65	0.0022	0.191	3.072	0.000492	-7.251	0.77
66	0.0022	0.192	3.099	0.000488	-7.300	0.77
67	0.0022	0.193	3.139	0.000489	-7.361	0.77
68	0.0022	0.195	3.152	0.000489	-7.441	0.78
69	0.0021	0.199	3.153	0.000490	-7.559	0.78
70	0.0022	0.202	3.149	0.000489	-7.680	0.78
71	0.0023	0.206	3.131	0.000489	-7.805	0.78
72	0.0024	0.209	3.123	0.000492	-7.889	0.79
73	0.0023	0.211	3.117	0.000496	-7.958	0.79
74	0.0023	0.212	3.121	0.000497	-7.996	0.79
75	0.0023	0.211	3.126	0.000494	-7.969	0.79
76	0.0024	0.213	3.114	0.000492	-8.021	0.79
77	0.0025	0.215	3.107	0.000496	-8.087	0.79
78	0.0025	0.216	3.108	0.000500	-8.137	0.80
79	0.0026	0.218	3.105	0.000504	-8.201	0.80
80	0.0027	0.221	3.086	0.000504	-8.302	0.80
81	0.0027	0.222	3.090	0.000507	-8.317	0.80
82	0.0027	0.223	3.078	0.000511	-8.355	0.81
83	0.0028	0.225	3.073	0.000509	-8.424	0.81
84	0.0029	0.229	3.065	0.000511	-8.566	0.81
85	0.0029	0.232	3.057	0.000513	-8.662	0.81
86	0.0029	0.235	3.043	0.000513	-8.760	0.81
87	0.0029	0.235	3.056	0.000515	-8.764	0.81
88	0.0029	0.235	3.062	0.000514	-8.750	0.81

Year	a (AMOC)	b (SSS)	c (CUC)	d (MLD)	e	r^2
89	0.0030	0.235	3.052	0.000511	-8.750	0.81
90	0.0030	0.237	3.047	0.000514	-8.813	0.81
91	0.0031	0.238	3.042	0.000519	-8.872	0.81
92	0.0031	0.239	3.036	0.000521	-8.893	0.81
93	0.0031	0.240	3.023	0.000517	-8.901	0.82
94	0.0032	0.239	3.024	0.000514	-8.896	0.82
95	0.0032	0.241	3.037	0.000511	-8.951	0.82
96	0.0033	0.241	3.030	0.000509	-8.969	0.82
97	0.0034	0.244	2.994	0.000504	-9.040	0.82
98	0.0034	0.245	2.971	0.000504	-9.079	0.83
99	0.0034	0.248	2.946	0.000504	-9.157	0.83
100	0.0035	0.249	2.920	0.000499	-9.178	0.83
101	0.0036	0.251	2.893	0.000498	-9.250	0.83
102	0.0036	0.254	2.866	0.000496	-9.338	0.83
103	0.0037	0.256	2.839	0.000494	-9.382	0.83
104	0.0037	0.256	2.830	0.000490	-9.366	0.83
105	0.0038	0.257	2.818	0.000489	-9.429	0.83
106	0.0038	0.259	2.801	0.000489	-9.458	0.83
107	0.0038	0.259	2.799	0.000486	-9.475	0.83
108	0.0038	0.259	2.787	0.000485	-9.472	0.83
109	0.0039	0.259	2.773	0.000481	-9.459	0.83
110	0.0039	0.260	2.743	0.000478	-9.501	0.83
111	0.0039	0.261	2.753	0.000479	-9.534	0.84
112	0.0039	0.263	2.742	0.000478	-9.588	0.84
113	0.0040	0.263	2.733	0.000477	-9.585	0.84
114	0.0040	0.264	2.718	0.000478	-9.606	0.84
115	0.0040	0.264	2.704	0.000476	-9.618	0.84
116	0.0040	0.265	2.690	0.000477	-9.633	0.84
117	0.0041	0.265	2.666	0.000478	-9.647	0.84
118	0.0041	0.266	2.650	0.000474	-9.668	0.84
119	0.0041	0.268	2.625	0.000474	-9.716	0.84
120	0.0041	0.269	2.607	0.000474	-9.759	0.84
121	0.0041	0.270	2.590	0.000473	-9.762	0.84
122	0.0041	0.270	2.576	0.000470	-9.754	0.84
123	0.0042	0.269	2.560	0.000467	-9.733	0.84
124	0.0042	0.269	2.545	0.000466	-9.732	0.84
125	0.0042	0.269	2.532	0.000468	-9.732	0.84
126	0.0042	0.270	2.519	0.000468	-9.750	0.85
127	0.0042	0.270	2.502	0.000464	-9.752	0.85
128	0.0042	0.270	2.488	0.000462	-9.729	0.85
129	0.0043	0.270	2.474	0.000461	-9.720	0.85
130	0.0043	0.271	2.461	0.000460	-9.747	0.85
131	0.0044	0.270	2.446	0.000460	-9.734	0.85
132	0.0044	0.271	2.429	0.000459	-9.739	0.85
133	0.0044	0.271	2.399	0.000455	-9.731	0.85
134	0.0044	0.270	2.394	0.000455	-9.713	0.85
135	0.0044	0.270	2.382	0.000454	-9.713	0.85

Year	a (AMOC)	b (SSS)	c (CUC)	d (MLD)	e	r^2
136	0.0044	0.271	2.375	0.000454	-9.726	0.85
137	0.0044	0.271	2.376	0.000453	-9.731	0.85
138	0.0044	0.271	2.373	0.000450	-9.728	0.85
139	0.0044	0.270	2.370	0.000448	-9.693	0.85
140	0.0045	0.270	2.362	0.000446	-9.710	0.86

Table S5. Change in each predictor per degree of warming, averaged over the last 30 years of the 1 % yr⁻¹ CO₂ simulation. For each model the difference between the fully coupled (1pctCO₂) and biogeochemically coupled (1pctCO₂-bgc) run is divided by the difference in their global mean warming. A dash means the model lacks one of the two runs for that quantity.

Model	CUC (mmol m ⁻³ ppm ⁻¹) °C ⁻¹	AMOC (Sv) °C ⁻¹	SSS °C ⁻¹	MLD _{vol} ³⁰⁰⁰ (10 ¹² m ³) °C ⁻¹
ACCESS-ESM1-5	0.00138	-1.109	-0.0451	-80.33
CanESM5	0.00135	-0.811	-0.0311	-0.20
CESM2	0.00127	-2.033	-0.0529	0.00
EC-Earth3-CC	0.00123	-1.499	-0.0425	-23.82
GFDL-ESM2M	0.00131	-3.019	-0.0951	-243.40
GFDL-ESM4	0.00147	–	-0.0400	-1.53
GISS-E2-1-G	0.00099	-4.170	-0.0869	–
IPSL-CM6A-LR	0.00131	-0.891	-0.0335	-0.03
MIROC-ES2L	0.00122	-1.856	-0.0564	-0.62
MPI-ESM1-2-LR	0.00116	-1.434	-0.0458	-36.83
MRI-ESM2-0	0.00136	-3.567	-0.0645	-0.34
NorESM2-LM	0.00141	-3.407	-0.0451	-0.01
UKESM1-0-LL	–	-0.666	-0.0330	-0.06
Multi model mean	0.00129	-2.039	-0.0517	-32.26
Standard deviation	0.00013	1.205	0.0199	70.79

Table S6: Coefficients of the emergent-constraint relationship $a \cdot \text{AMOC} + b \cdot \text{SSS} + c \cdot \text{CUC} + d \cdot \text{MLD} + e = \gamma$, fitted across the 13 models at every year of the ramp. Each coefficient is the change in γ per unit change in that predictor with the others held fixed. The intercept e is the value at zero in every predictor, far outside the range of the ensemble, and carries no interpretation on its own. Units are $\text{Pg C } ^\circ\text{C}^{-1} \text{ Sv}^{-1}$ for a , $\text{Pg C } ^\circ\text{C}^{-1}$ per unit of SSS for b , $\text{Pg C } ^\circ\text{C}^{-1}$ per $\text{mmol m}^{-3} \text{ ppm}^{-1}$ for c , $\text{Pg C } ^\circ\text{C}^{-1}$ per 10^{12} m^3 of $\text{MLD}_{\text{vol}}^{3000}$ for d , and $\text{Pg C } ^\circ\text{C}^{-1}$ for e .

Year	a (AMOC)	b (SSS)	c (CUC)	d (MLD)	e	r^2
1	0.0808	-0.330	25.106	0.000408	-4.236	0.07
2	0.4534	-15.780	297.557	0.012670	363.228	0.58
3	2.3564	11.427	-17.608	-0.014067	-418.238	0.29
4	-0.1975	45.027	-5.471	0.019577	-1518.472	0.06
5	3.8443	-147.428	889.155	-0.066461	4450.375	0.26
6	-0.8206	53.167	-147.108	0.127905	-1711.115	0.81
7	-0.2988	38.826	-156.802	-0.018504	-1226.651	0.59
8	-1.0427	26.051	-171.247	0.000301	-771.403	0.33
9	-0.5990	20.678	-107.225	0.005121	-632.298	0.32
10	-0.3646	15.997	-75.734	0.003794	-495.207	0.28
11	-0.3067	12.919	-77.303	-0.003170	-390.868	0.28
12	-0.0797	11.042	-93.066	-0.013713	-322.576	0.28
13	0.0191	10.852	-102.533	-0.014915	-312.762	0.27
14	0.0253	11.685	-98.287	-0.011455	-343.433	0.26
15	-0.0048	11.477	-100.921	-0.009158	-334.701	0.27
16	-0.0403	11.294	-94.596	-0.003205	-331.508	0.26
17	-0.0335	10.609	-89.117	-0.003629	-311.461	0.26
18	-0.0057	9.980	-77.368	-0.006379	-297.234	0.25
19	-0.0329	9.207	-71.900	-0.006347	-273.698	0.26
20	-0.0567	9.248	-65.847	-0.003534	-278.182	0.27
21	-0.1152	9.228	-63.190	0.000171	-278.112	0.33
22	-0.1451	8.702	-52.233	-0.000336	-265.782	0.34
23	-0.1742	7.575	-51.321	-0.001344	-227.697	0.36
24	-0.1890	6.218	-39.097	-0.000209	-188.070	0.31
25	-0.1644	5.878	-30.244	-0.000151	-181.742	0.27
26	-0.1642	5.352	-38.348	0.000476	-159.883	0.28
27	-0.1765	5.137	-46.089	0.002123	-148.601	0.31
28	-0.1754	5.034	-44.522	0.001198	-146.117	0.33
29	-0.1812	4.090	-42.226	0.000177	-115.537	0.32
30	-0.1420	4.176	-39.979	0.000163	-120.484	0.27
31	-0.1323	4.151	-39.478	0.000164	-120.263	0.30
32	-0.1252	3.698	-31.886	-0.000511	-109.173	0.25
33	-0.1076	2.362	-29.956	-0.002469	-65.337	0.21
34	-0.1292	1.561	-24.065	-0.000829	-41.126	0.21
35	-0.1128	0.980	-16.084	-0.000798	-26.073	0.13
36	-0.1101	-0.066	-14.298	-0.002408	8.207	0.14
37	-0.1086	-1.162	-13.046	-0.002594	44.463	0.14
38	-0.1198	-2.095	-8.255	-0.000443	73.392	0.13
39	-0.1372	-2.408	-5.479	-0.000302	82.681	0.15
40	-0.1242	-2.171	-13.483	-0.001428	78.641	0.17

Year	a (AMOC)	b (SSS)	c (CUC)	d (MLD)	e	r^2
41	-0.1219	-2.383	-14.568	-0.001859	86.167	0.18
42	-0.0985	-2.159	-15.272	-0.002611	78.540	0.15
43	-0.0793	-2.729	-11.061	-0.002281	95.018	0.12
44	-0.0569	-3.689	-3.884	-0.001815	123.175	0.11
45	-0.0443	-3.995	-0.423	-0.001160	131.361	0.10
46	-0.0285	-4.276	-3.168	-0.001686	141.902	0.12
47	-0.0134	-4.990	-2.667	-0.002815	165.491	0.15
48	-0.0050	-6.046	-0.433	-0.002410	199.710	0.19
49	0.0218	-6.863	2.139	-0.004545	225.455	0.21
50	0.0425	-7.387	7.886	-0.005372	239.687	0.22
51	0.0521	-7.949	4.069	-0.007164	260.519	0.26
52	0.0564	-8.487	-0.227	-0.008043	280.816	0.32
53	0.0677	-8.835	-7.282	-0.008949	296.142	0.36
54	0.0470	-8.878	-13.009	-0.008646	300.860	0.37
55	0.0325	-8.943	-15.920	-0.007729	304.712	0.38
56	0.0232	-9.060	-15.306	-0.006963	308.416	0.37
57	0.0253	-9.345	-18.027	-0.007376	319.392	0.39
58	0.0350	-9.596	-19.236	-0.007624	328.270	0.41
59	0.0375	-9.956	-18.476	-0.007602	339.931	0.41
60	0.0360	-10.190	-18.723	-0.007823	347.928	0.41
61	0.0230	-10.190	-17.808	-0.007195	347.570	0.41
62	0.0095	-10.016	-20.204	-0.006743	343.076	0.40
63	-0.0097	-9.793	-22.538	-0.006042	336.976	0.39
64	-0.0158	-10.385	-22.197	-0.006126	356.772	0.41
65	-0.0017	-11.196	-21.093	-0.006279	383.314	0.44
66	-0.0020	-11.490	-19.311	-0.006744	392.222	0.44
67	0.0009	-11.813	-20.267	-0.007623	403.500	0.45
68	0.0116	-12.062	-18.648	-0.008214	410.756	0.46
69	0.0194	-12.265	-21.708	-0.008616	419.021	0.48
70	0.0188	-12.604	-21.910	-0.008823	430.492	0.48
71	0.0165	-12.838	-22.318	-0.009165	438.593	0.50
72	0.0103	-13.017	-25.441	-0.009572	446.305	0.51
73	0.0098	-13.334	-29.898	-0.010513	459.282	0.53
74	0.0025	-13.424	-30.743	-0.010613	462.800	0.52
75	0.0069	-13.262	-32.685	-0.010611	458.194	0.51
76	0.0028	-13.335	-34.669	-0.011071	461.623	0.51
77	-0.0100	-13.802	-35.102	-0.011252	477.735	0.53
78	-0.0203	-13.995	-36.255	-0.011248	484.968	0.53
79	-0.0278	-14.150	-39.250	-0.011687	491.872	0.54
80	-0.0468	-14.464	-41.298	-0.010875	503.774	0.56
81	-0.0546	-14.661	-40.266	-0.010772	509.868	0.55
82	-0.0627	-14.785	-39.993	-0.011017	513.921	0.55
83	-0.0770	-14.959	-38.339	-0.011107	519.056	0.54
84	-0.0869	-15.537	-37.192	-0.011474	538.036	0.54
85	-0.0936	-15.640	-37.457	-0.011554	541.630	0.54
86	-0.1067	-15.988	-36.772	-0.011608	553.136	0.55
87	-0.1176	-16.149	-38.225	-0.012630	559.467	0.56

Year	a (AMOC)	b (SSS)	c (CUC)	d (MLD)	e	r^2
88	-0.1217	-16.365	-40.433	-0.013094	567.896	0.56
89	-0.1227	-16.687	-39.307	-0.013333	578.065	0.56
90	-0.1181	-17.121	-39.311	-0.013967	592.591	0.57
91	-0.1257	-17.832	-40.262	-0.014802	617.181	0.59
92	-0.1185	-18.294	-41.866	-0.015286	633.465	0.60
93	-0.1098	-18.668	-43.594	-0.015490	646.765	0.62
94	-0.1174	-19.049	-44.502	-0.015278	660.132	0.63
95	-0.1246	-19.524	-50.741	-0.015325	679.516	0.66
96	-0.1319	-19.802	-53.875	-0.015642	690.585	0.67
97	-0.1400	-20.208	-53.778	-0.015952	704.272	0.68
98	-0.1384	-20.497	-54.543	-0.016582	714.333	0.69
99	-0.1407	-21.001	-56.700	-0.016489	732.429	0.70
100	-0.1511	-21.517	-57.573	-0.016337	750.368	0.71
101	-0.1627	-22.056	-59.175	-0.017126	769.519	0.72
102	-0.1695	-22.711	-59.349	-0.017138	791.783	0.72
103	-0.1847	-23.098	-59.027	-0.016920	804.830	0.72
104	-0.1961	-23.352	-60.423	-0.017306	814.209	0.73
105	-0.2087	-24.066	-61.155	-0.017618	838.858	0.74
106	-0.2204	-24.481	-62.242	-0.017968	853.564	0.74
107	-0.2384	-25.072	-62.926	-0.017903	874.096	0.74
108	-0.2564	-25.470	-63.113	-0.018315	887.822	0.74
109	-0.2627	-25.941	-64.222	-0.018345	904.377	0.75
110	-0.2794	-26.643	-61.058	-0.018417	926.539	0.75
111	-0.2965	-27.185	-62.178	-0.018706	945.624	0.75
112	-0.3182	-27.785	-60.436	-0.018824	965.218	0.76
113	-0.3289	-28.111	-59.470	-0.018986	975.763	0.76
114	-0.3403	-28.371	-59.386	-0.019194	984.557	0.76
115	-0.3615	-28.802	-59.653	-0.019189	999.491	0.77
116	-0.3766	-29.249	-60.118	-0.019535	1014.959	0.77
117	-0.3938	-29.271	-59.186	-0.019965	1015.377	0.77
118	-0.4018	-29.389	-59.791	-0.019411	1019.686	0.77
119	-0.4071	-29.771	-60.720	-0.019284	1033.079	0.78
120	-0.4108	-29.927	-64.339	-0.019452	1040.262	0.78
121	-0.4127	-30.075	-67.935	-0.019579	1047.078	0.79
122	-0.4152	-30.472	-69.325	-0.019558	1061.212	0.79
123	-0.4151	-30.713	-71.216	-0.020002	1070.235	0.79
124	-0.4144	-31.159	-73.302	-0.020218	1086.294	0.79
125	-0.4134	-31.514	-77.089	-0.021119	1100.238	0.80
126	-0.4206	-32.020	-79.498	-0.021652	1118.615	0.80
127	-0.4208	-32.496	-80.651	-0.021842	1135.215	0.80
128	-0.4213	-32.713	-83.017	-0.022322	1143.707	0.80
129	-0.4222	-32.899	-84.807	-0.022508	1150.882	0.80
130	-0.4224	-33.440	-87.742	-0.023214	1170.646	0.81
131	-0.4319	-33.689	-92.352	-0.024022	1181.562	0.81
132	-0.4439	-34.042	-95.501	-0.024193	1195.263	0.82
133	-0.4596	-34.235	-96.799	-0.023933	1202.600	0.82
134	-0.4648	-34.350	-99.812	-0.024557	1208.084	0.82

Year	a (AMOC)	b (SSS)	c (CUC)	d (MLD)	e	r^2
135	-0.4712	-34.374	-102.651	-0.024842	1210.417	0.82
136	-0.4750	-34.536	-105.624	-0.025508	1217.446	0.82
137	-0.4877	-34.781	-109.479	-0.025831	1227.895	0.83
138	-0.5008	-34.856	-112.606	-0.025911	1232.232	0.83
139	-0.5158	-34.898	-115.994	-0.026005	1235.589	0.83
140	-0.5341	-35.083	-119.275	-0.026115	1243.801	0.83

Table S7. All predictor subsets for β , at year 70 and year 140 of the 1 % yr⁻¹ CO₂ simulation, across the 13 ESMs. n is the number of predictors. LOO is the leave-one-out root-mean-square prediction error (Pg C ppm⁻¹), in which each ESM in turn is predicted from a fit that excludes it; the intercept-only row is the reference against which it should be read. Δ AIC, Δ AICc and Δ BIC are differences from the best subset on each criterion, so zero is best and larger is worse.

Predictors	n	r^2	LOO	year 70			r^2	LOO	year 140		
				Δ AIC	Δ AICc	Δ BIC			Δ AIC	Δ AICc	Δ BIC
none (intercept only)	0	0.00	0.0757	13.32	7.91	11.63	0.00	0.0715	17.21	9.05	14.95
AMOC	1	0.12	0.0740	13.60	9.65	12.47	0.19	0.0665	16.49	9.80	14.79
CUC	1	0.53	0.0576	5.57	1.61	4.44	0.50	0.0552	10.12	3.43	8.43
MLD _{vol} ³⁰⁰⁰	1	0.18	0.0731	12.76	8.81	11.63	0.18	0.0672	16.59	9.90	14.89
SSS	1	0.32	0.0699	10.40	6.45	9.27	0.41	0.0589	12.26	5.57	10.57
AMOC + CUC	2	0.56	0.0584	6.58	4.96	6.02	0.58	0.0531	9.98	5.62	8.85
AMOC + MLD _{vol} ³⁰⁰⁰	2	0.24	0.0764	13.82	12.21	13.26	0.29	0.0652	16.80	12.44	15.67
CUC + MLD _{vol} ³⁰⁰⁰	2	0.70	0.0523	1.62	0.00	1.05	0.68	0.0516	6.38	2.02	5.25
SSS + AMOC	2	0.43	0.0697	10.10	8.48	9.53	0.59	0.0542	9.77	5.41	8.64
SSS + CUC	2	0.58	0.0593	6.11	4.49	5.54	0.61	0.0521	8.92	4.56	7.79
SSS + MLD _{vol} ³⁰⁰⁰	2	0.54	0.0699	7.25	5.63	6.68	0.65	0.0520	7.58	3.22	6.45
AMOC + CUC + MLD _{vol} ³⁰⁰⁰	3	0.71	0.0553	3.44	5.39	3.44	0.70	0.0511	7.34	6.56	6.78
SSS + AMOC + CUC	3	0.62	0.0602	6.68	8.63	6.68	0.71	0.0490	7.21	6.43	6.65
SSS + AMOC + MLD _{vol} ³⁰⁰⁰	3	0.58	0.0744	8.04	9.99	8.04	0.73	0.0503	6.21	5.43	5.65
SSS + CUC + MLD _{vol} ³⁰⁰⁰	3	0.77	0.0513	0.00	1.95	0.00	0.82	0.0404	0.79	0.00	0.22
SSS + AMOC + CUC + MLD _{vol} ³⁰⁰⁰	4	0.78	0.0562	1.58	8.96	2.14	0.86	0.0401	0.00	4.64	0.00

Table S8. All predictor subsets for γ , at year 70 and year 140 of the 1 % yr⁻¹ CO₂ simulation, across the 13 ESMs. n is the number of predictors. LOO is the leave-one-out root-mean-square prediction error (Pg C °C⁻¹), in which each ESM in turn is predicted from a fit that excludes it; the intercept-only row is the reference against which it should be read. Δ AIC, Δ AICc and Δ BIC are differences from the best subset on each criterion, so zero is best and larger is worse.

Predictors	n	r^2	LOO	year 70			r^2	LOO	year 140		
				Δ AIC	Δ AICc	Δ BIC			Δ AIC	Δ AICc	Δ BIC
none (intercept only)	0	0.00	2.48	5.11	3.64	4.54	0.00	6.49	15.02	9.23	12.76
AMOC	1	0.01	2.59	7.00	7.00	7.00	0.17	6.31	14.53	10.19	12.83
CUC	1	0.18	2.59	4.57	4.57	4.57	0.40	5.54	10.36	6.03	8.66
MLD _{vol} ³⁰⁰⁰	1	0.03	2.73	6.72	6.72	6.72	0.08	6.60	15.93	11.60	14.24
SSS	1	0.42	2.00	0.00	0.00	0.00	0.58	4.37	5.88	1.55	4.18
AMOC + CUC	2	0.18	2.76	6.57	8.90	7.14	0.48	5.62	10.59	8.59	9.46
AMOC + MLD _{vol} ³⁰⁰⁰	2	0.03	2.90	8.70	11.03	9.26	0.20	6.49	16.07	14.07	14.94
CUC + MLD _{vol} ³⁰⁰⁰	2	0.21	2.80	6.12	8.45	6.68	0.48	5.87	10.56	8.56	9.43
SSS + AMOC	2	0.43	2.11	1.89	4.23	2.46	0.73	3.65	2.00	0.00	0.87
SSS + CUC	2	0.43	2.26	1.74	4.08	2.31	0.66	4.22	5.05	3.05	3.92
SSS + MLD _{vol} ³⁰⁰⁰	2	0.47	2.37	0.77	3.10	1.33	0.70	4.16	3.41	1.42	2.28
AMOC + CUC + MLD _{vol} ³⁰⁰⁰	3	0.21	3.01	8.06	13.96	9.18	0.52	5.98	11.49	13.07	10.93
SSS + AMOC + CUC	3	0.43	2.44	3.70	9.61	4.83	0.77	3.86	2.03	3.61	1.47
SSS + AMOC + MLD _{vol} ³⁰⁰⁰	3	0.47	2.55	2.77	8.67	3.90	0.79	3.54	0.70	2.27	0.13
SSS + CUC + MLD _{vol} ³⁰⁰⁰	3	0.48	2.61	2.55	8.46	3.68	0.77	4.02	1.90	3.47	1.33
SSS + AMOC + CUC + MLD _{vol} ³⁰⁰⁰	4	0.48	2.86	4.54	15.87	6.24	0.83	3.74	0.00	7.00	0.00