



Supplement of

Evaluating the performance of CMIP6 models in simulating Southern Ocean biogeochemistry

Ming Cheng et al.

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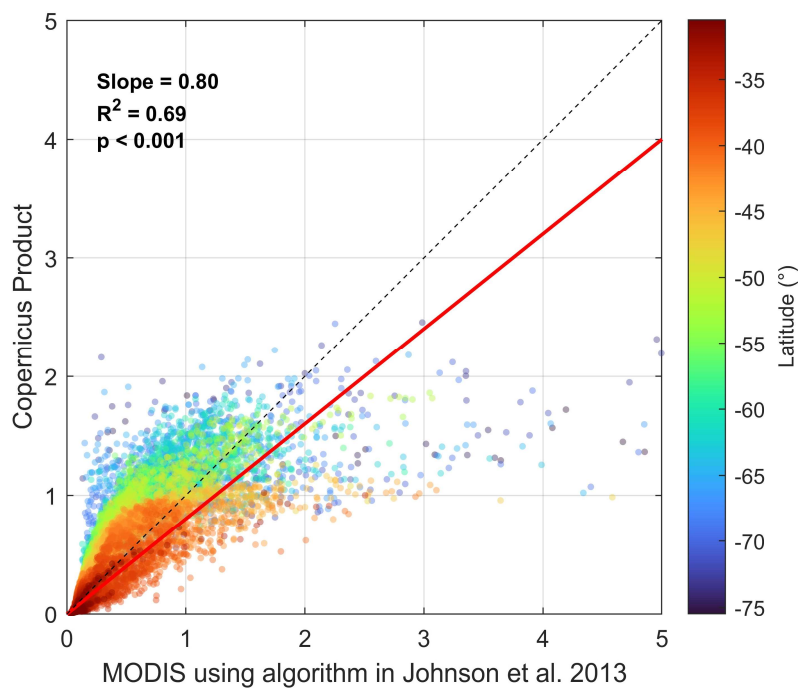


Figure S1: Comparison between surface chlorophyll concentrations from the Copernicus chlorophyll product (Sauzède et al., 2016) and Aqua-MODIS satellite estimates derived using the new algorithm of Johnson et al. (2013). Colours indicate the latitude of the data grid points. The 1:1 line is shown as a black dashed line and the regression line as a red solid line, with corresponding statistics shown in the upper-left corner. Approximately 30 data points where MODIS-derived chlorophyll concentrations exceeding 5 mg m⁻³ are excluded from the plot for clarity.

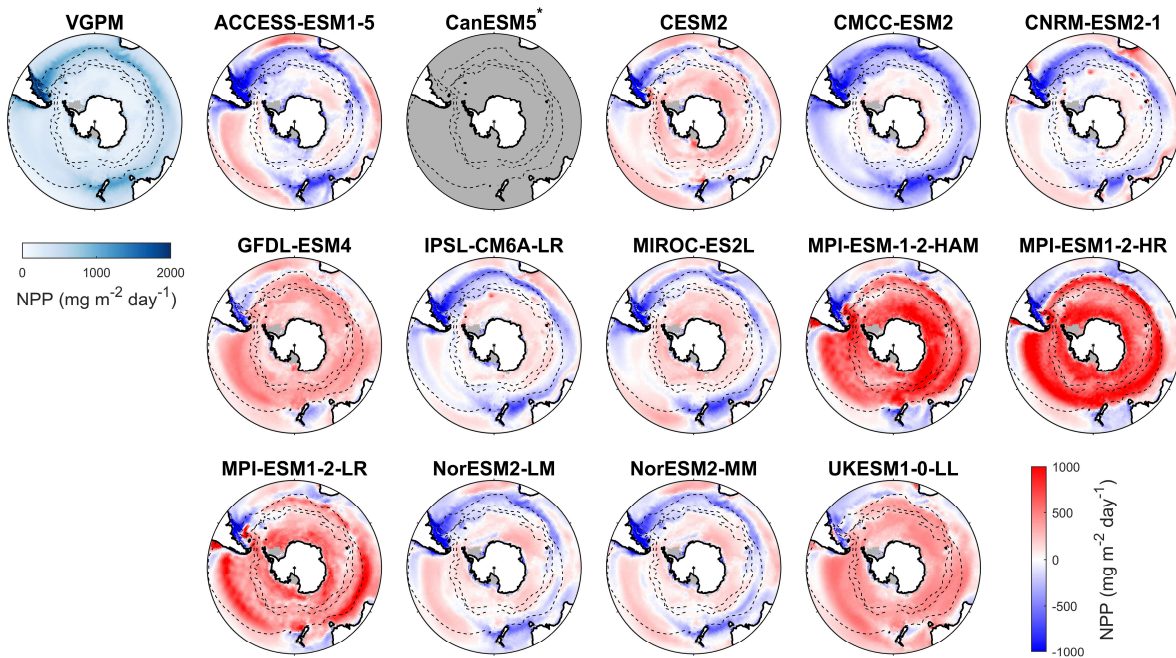


Figure S2: Net primary production estimated by VGPM algorithm and spatial biases of net primary production for 14 CMIP6 models (model NPP – VGPM NPP) for the Southern Ocean (>30°S). Models with unavailable NPP are labelled with *.

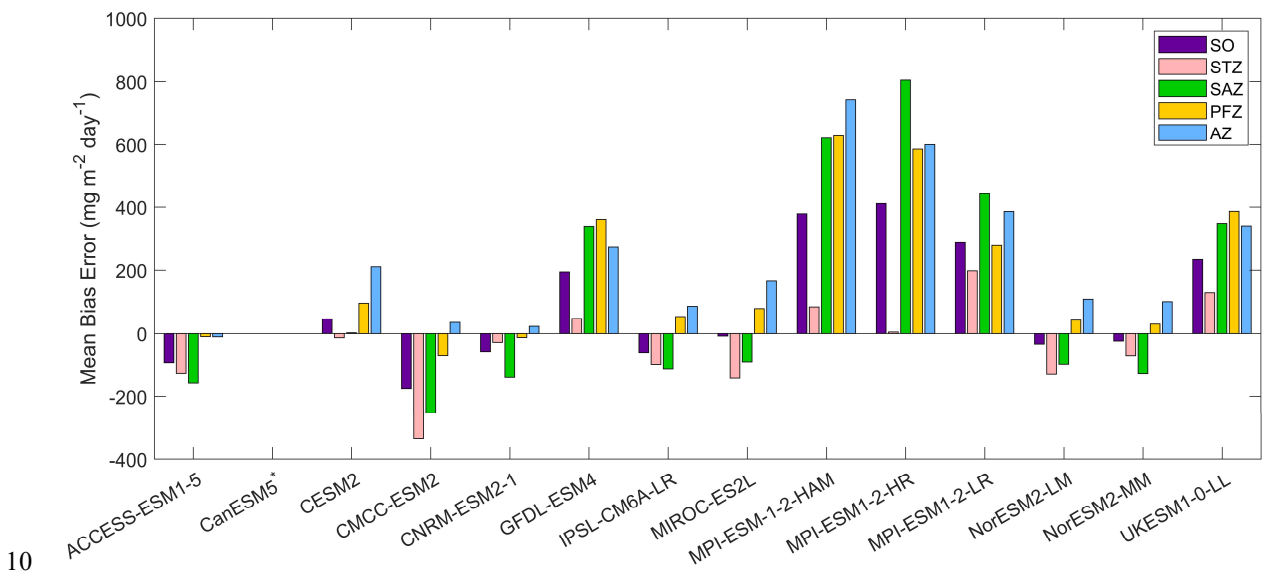
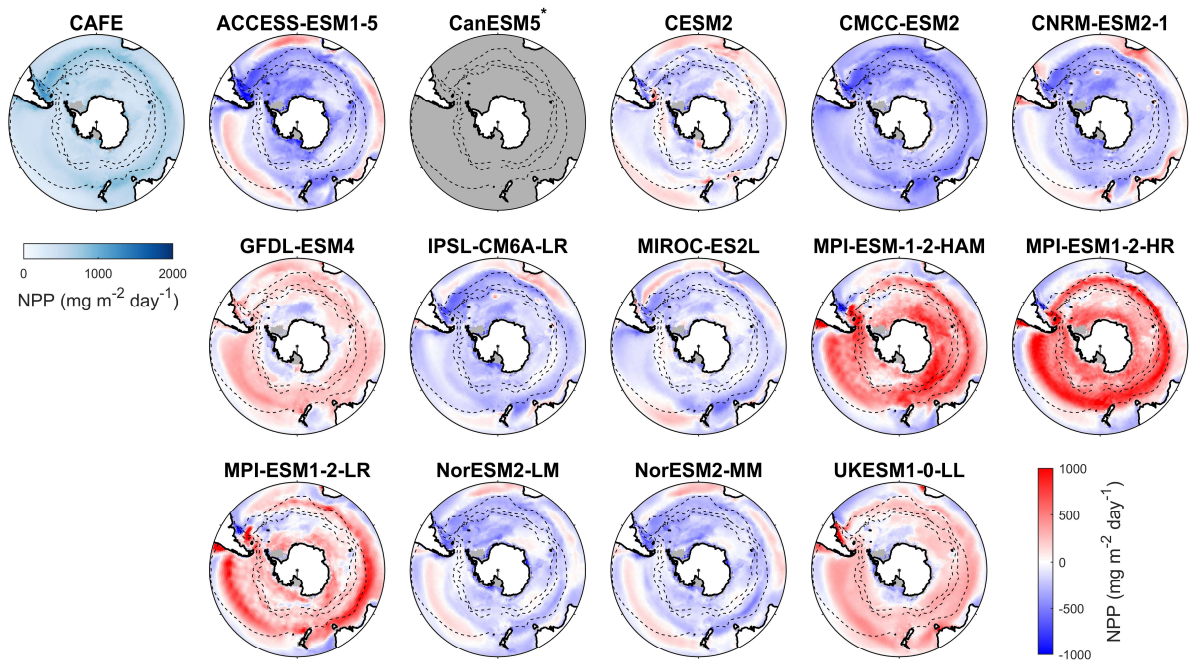
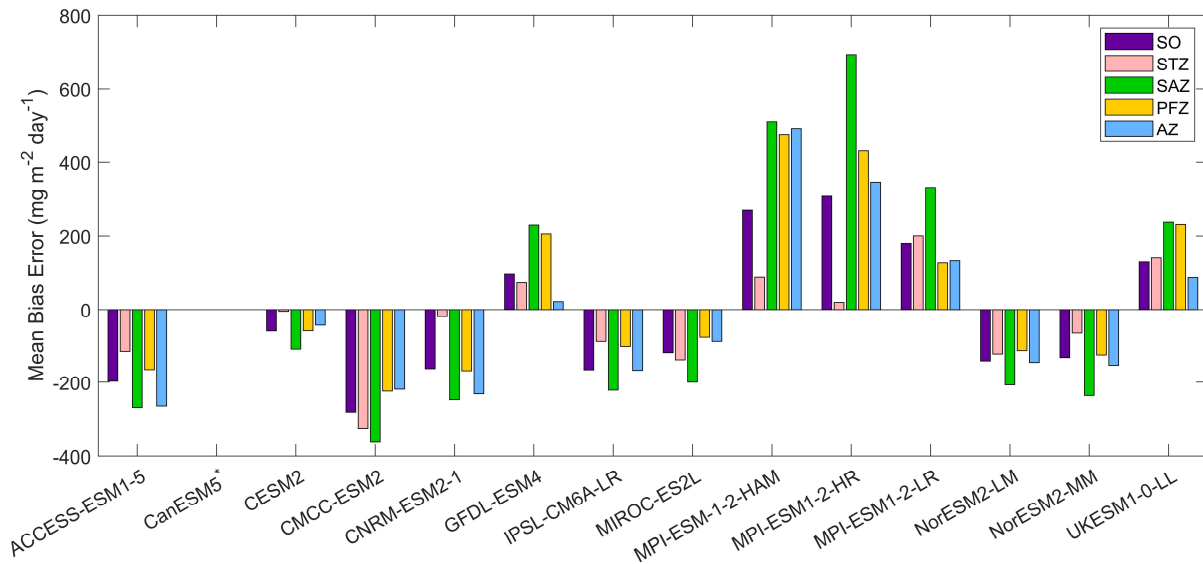


Figure S3: The mean bias errors in NPP estimated by VGPM algorithm for the Southern Ocean (SO), the subtropical zone (STZ), the subantarctic zone (SAZ), the polar front zone (PFZ), and the Antarctic zone (AZ) in DJF. Models with unavailable NPP are labelled with *.



15 **Figure S4: Net primary production estimated by CAFE algorithm and spatial biases of net primary production for 14 CMIP6 models (model NPP – CAFE NPP) for the Southern Ocean (>30°S). Models with unavailable NPP are labelled with *.**



20 **Figure S5: The mean bias errors in NPP estimated by CAFE algorithm for the Southern Ocean (SO), the subtropical zone (STZ), the subantarctic zone (SAZ), the polar front zone (PFZ), and the Antarctic zone (AZ) in DJF. Models with unavailable NPP are labelled with *.**

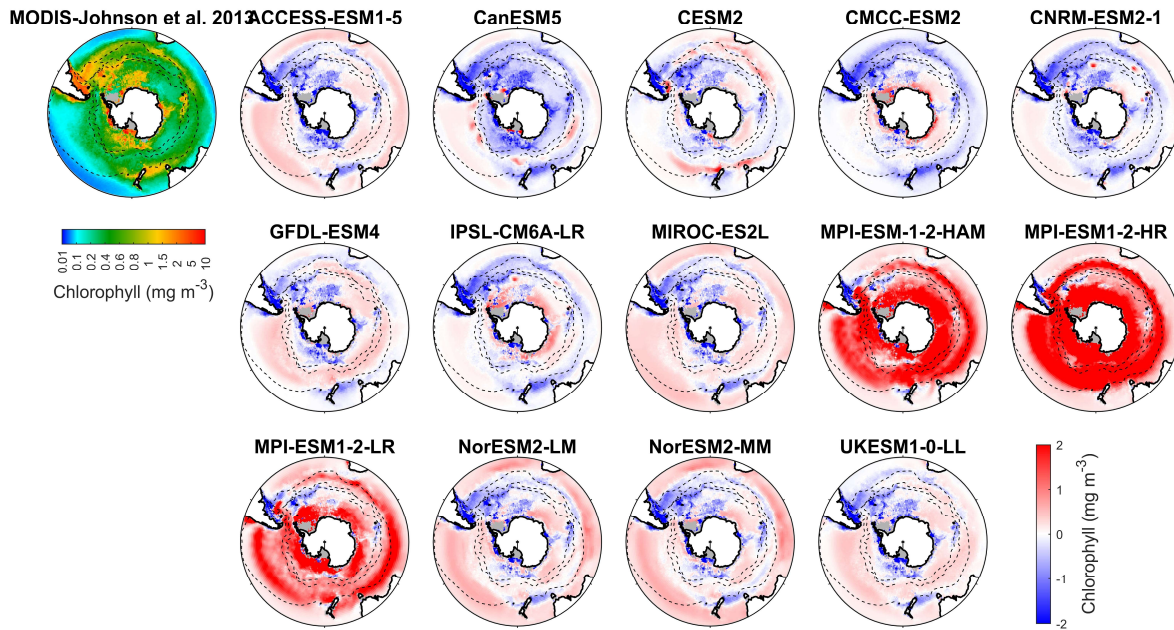


Figure S6: Observed surface chlorophyll concentrations from Aqua-MODIS derived using the new algorithms of Johnson et al. (2013) in DJF and spatial biases of surface chlorophyll concentrations for 14 CMIP6 models (model chlorophyll – MODIS chlorophyll) in DJF for the Southern Ocean ($>30^{\circ}\text{S}$). Black dashed lines in the maps denote the subtropical front, the subantarctic front, and the polar front, from north to south. Grey areas denote regions where no data are available.

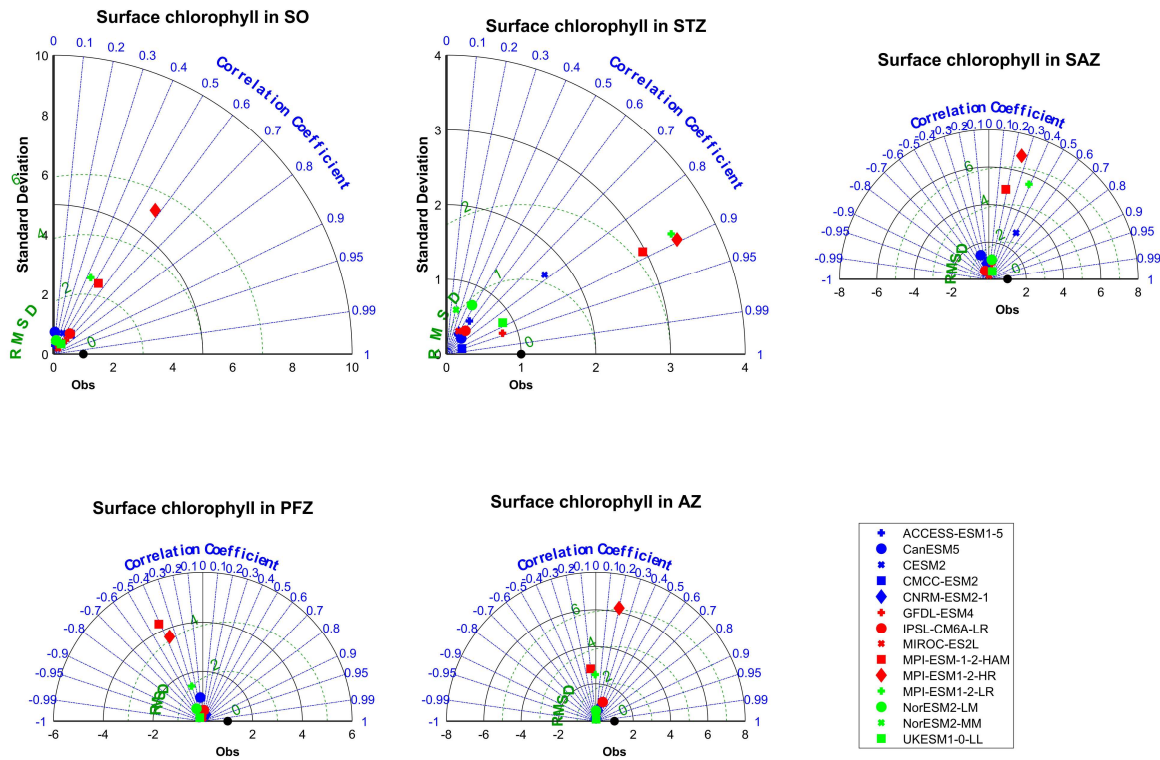


Figure S7: Taylor diagrams for surface chlorophyll in December-January-February (DJF) across the Southern Ocean (SO) and its subregions-the subtropical zone (STZ), the subantarctic zone (SAZ), the polar front zone (PFZ), and the Antarctic zone (AZ). The black circle denotes observational reference, while different colours and shapes represent individual CMIP6 models. The radius of each model's position on the diagram corresponds to its standardised standard deviation (SSD), indicating the model's variability relative to observations. The angle of the arc represents the correlation coefficient (CC), measuring the strength of agreement in spatial patterns between the model and observation. The Euclidean distance between a model's position and the observational reference reflects the root-mean-squared deviation (RMSD), where smaller distances indicate better agreement with observations.

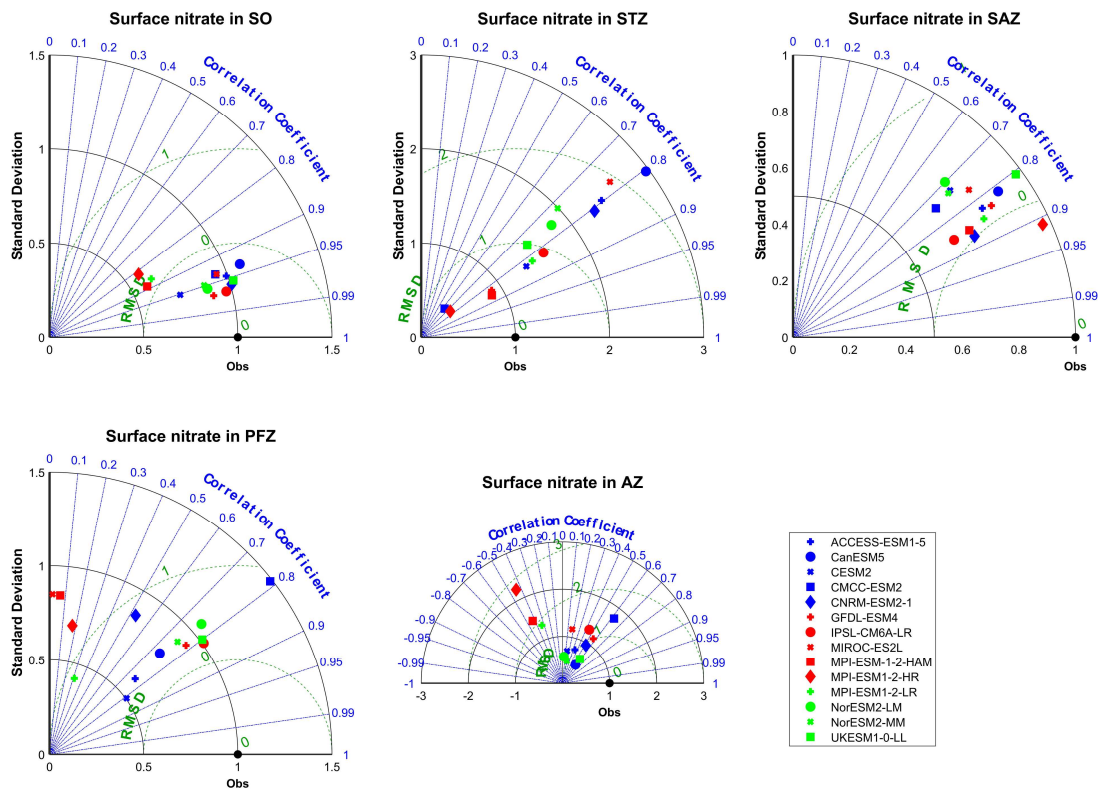
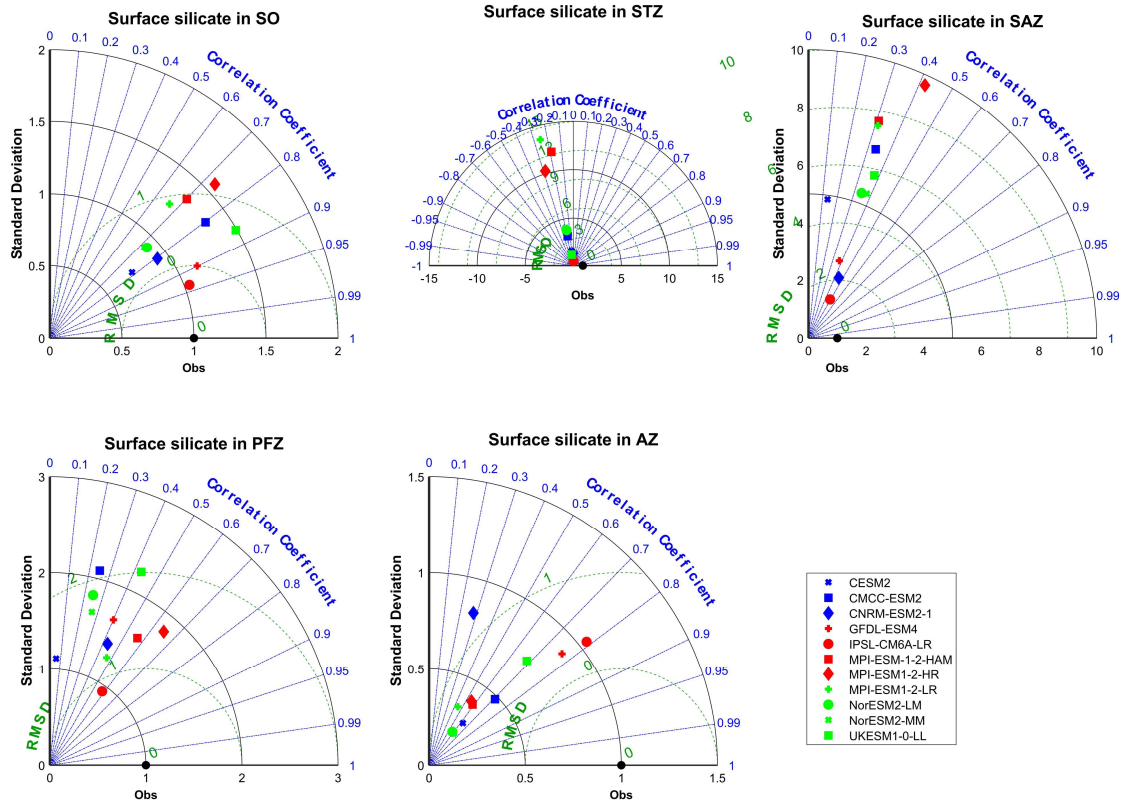


Figure S8: Taylor diagrams for surface nitrate in DJF across the Southern Ocean (SO) and its subregions-the subtropical zone (STZ), the subantarctic zone (SAZ), the polar front zone (PFZ), and the Antarctic zone (AZ).



40 Figure S9: Taylor diagrams for surface silicate in DJF across the Southern Ocean (SO) and its subregions-the subtropical zone (STZ), the subantarctic zone (SAZ), the polar front zone (PFZ), and the Antarctic zone (AZ).

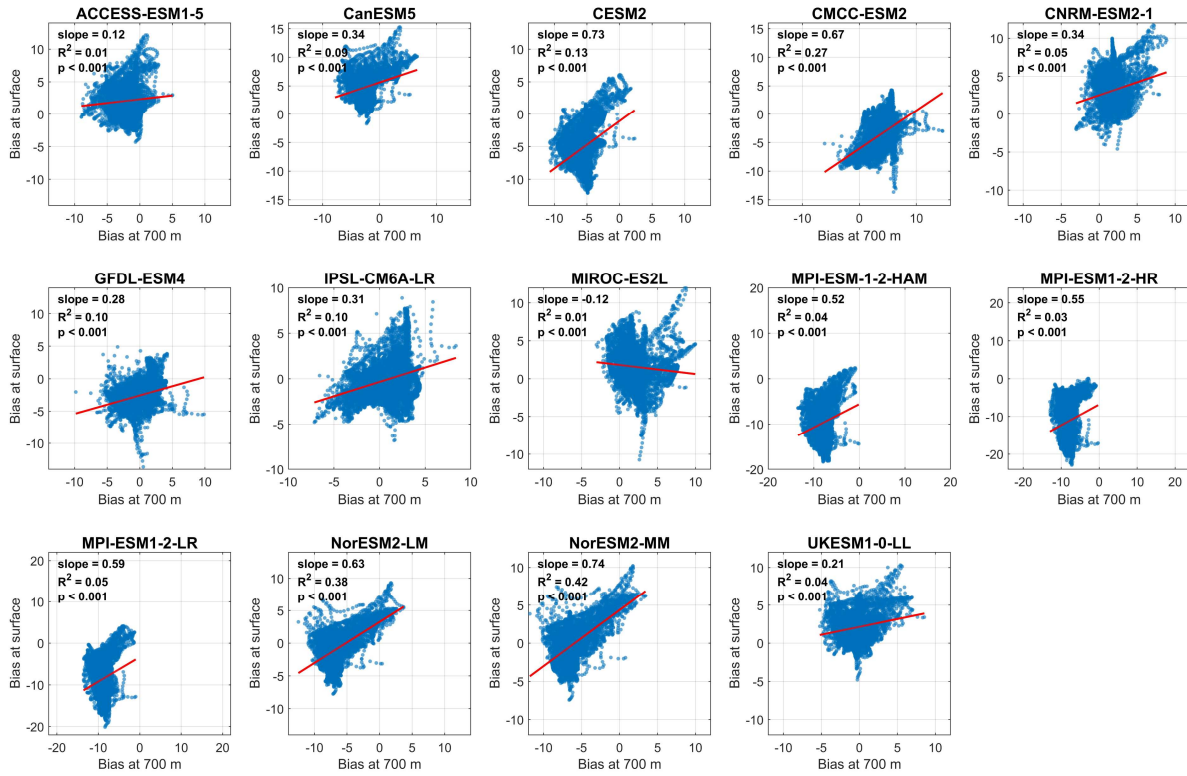


Figure S10: Scatterplots for nitrate bias (model-observation) at the surface versus nitrate bias (model-observation) at 700m for 14 CMIP6 models during DJF south of 50°S. Red lines indicate the linear regression for each model. The slope, R^2 and p value are shown in each panel.

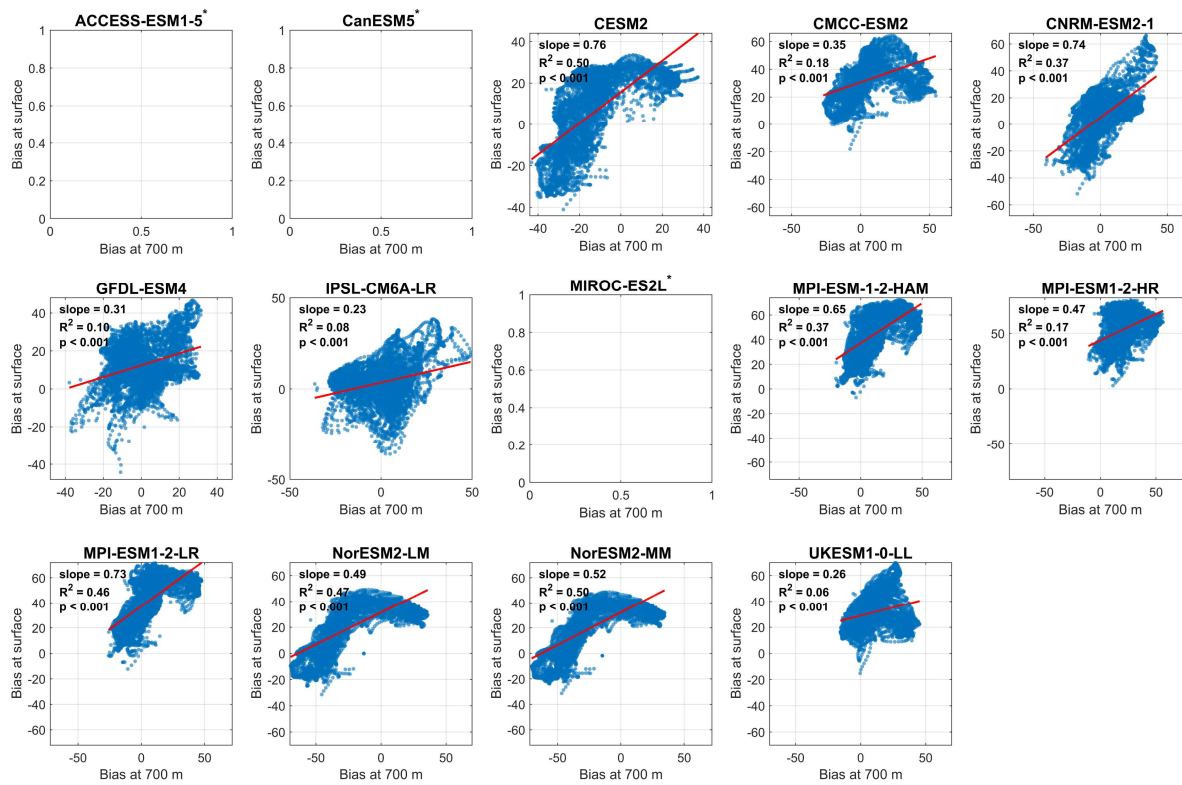


Figure S11: Scatterplots for silicate bias (model-observation) at the surface versus silicate bias (model-observation) at 700m for 14 CMIP6 models during DJF south of 50°S. Red lines indicate the linear regression for each model. The slope, R^2 and p value are shown in each panel.

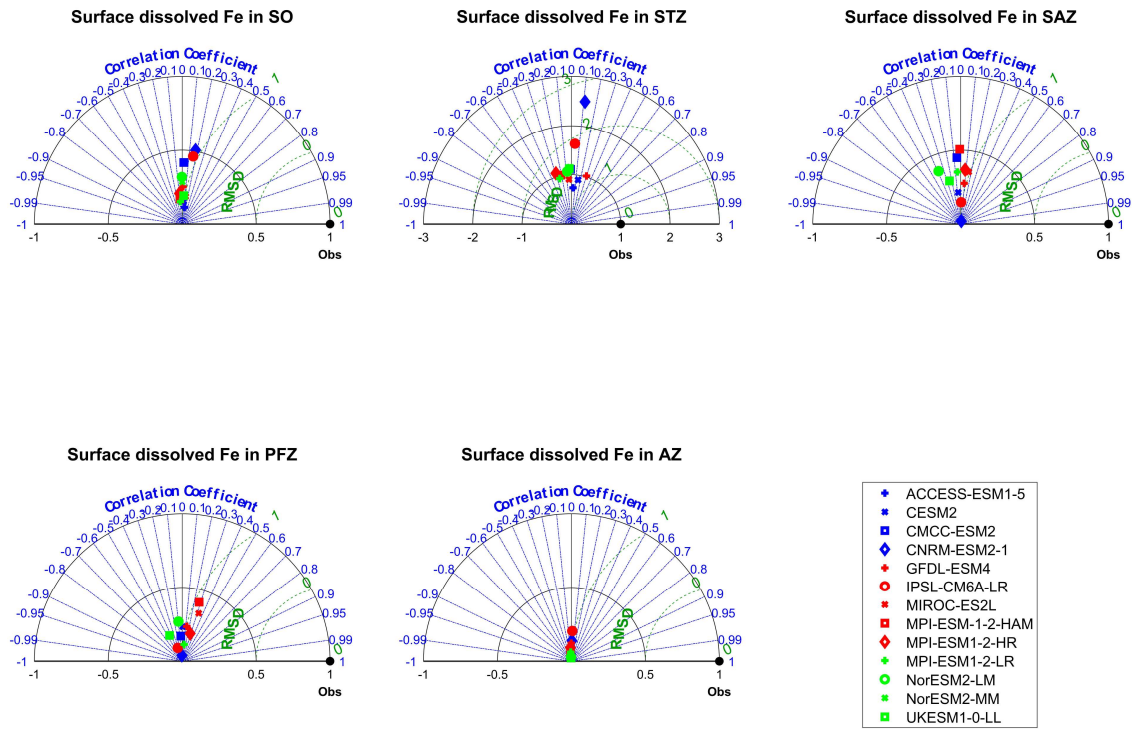
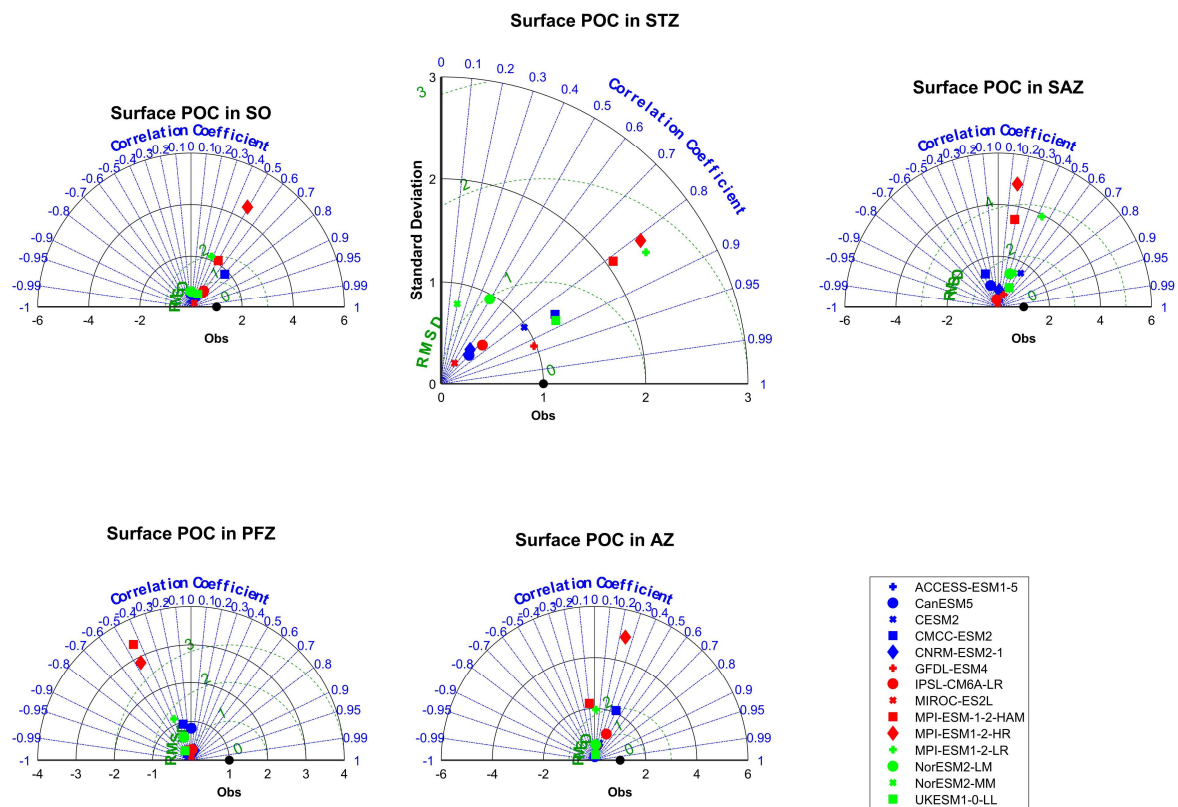


Figure S12: Taylor diagrams for surface dissolved iron in DJF across the Southern Ocean (SO) and its subregions-the subtropical zone (STZ), the subantarctic zone (SAZ), the polar front zone (PFZ), and the Antarctic zone (AZ).



55 **Figure S13: Taylor diagrams for surface particulate organic carbon (POC) in DJF across the Southern Ocean (SO) and its subregions-the subtropical zone (STZ), the subantarctic zone (SAZ), the polar front zone (PFZ), and the Antarctic zone (AZ).**

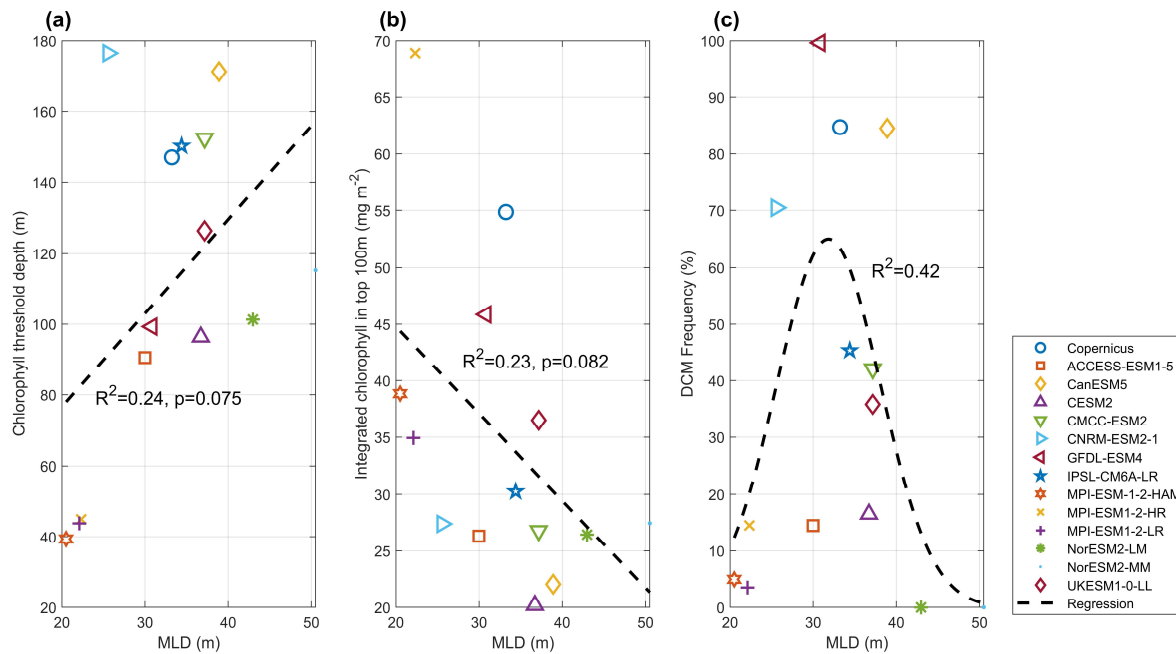


Figure S14: Relationships between (a) chlorophyll threshold depth, (b) integrated chlorophyll in the top 100m, (c) deep chlorophyll maximum (DCM) frequency and mixed layer depth (MLD) for observation and 14 CMIP6 models in the Southern Ocean during the period 2000-2014. Each point (colour/shape) represents a CMIP6 model (or the Copernicus reference), and dashed lines indicate regression fits where relevant. Corresponding P-values and R² statistics (for linear regressions) are displayed on each panel.

Table S1: Linear Fit Statistics (R^2 and slope) for different chlorophyll and particulate backscattering coefficient (bbp) products or algorithms when validated against *in situ* datasets from specific regions. “HPLC data” in the table refer pigment samples obtained using High Performance Liquid Chromatography (HPLC).

Data product/method	Data for validation	Region	R ²	Slope	Source
SeaWIFS with original algorithm	HPLC data for chlorophyll analysed in Australia	Southern Ocean	0.27	0.25	Johnson et al. (2013)
SeaWIFS with algorithm in Johnson et al. (2013)			0.46	0.76	
MODIS-Aqua with original algorithm			0.26	0.23	
MODIS-Aqua with algorithm in Johnson et al. (2013)			0.51	0.90	
GlobColour with original algorithm			0.25	0.50	
GlobColour with algorithm in Johnson et al. (2013)			0.26	0.46	
Method in Uitz et al. (2006)	HPLC data for chlorophyll analysed in France	Global	0.42	0.38	Sauzède et al. (2024)
SOCA2024			0.53	0.70	
SOCA2021	BGC-Argo data for chlorophyll	Southern Ocean	0.73	0.81	
SOCA2024			0.89	1.04	
SOCA2016	BGC-Argo data for bbp		0.72	0.84	
SOCA2021			0.92	0.89	
SOCA2024			0.93	0.89	

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Table S2: Statistics of standardised standard deviation (SSD), root-mean-squared deviation (RMSD), and correlation coefficient (CC) for surface chlorophyll of 14 CMIP6 models in December-January-February (DJF) across the Southern Ocean (SO) and its subregions- the subtropical zone (STZ), subantarctic zone (SAZ), polar front zone (PFZ), and Antarctic zone (AZ).

CMIP6 ESMs	SSD					RMSD					CC				
	SO	STZ	SAZ	PFZ	AZ	SO	STZ	SAZ	PFZ	AZ	SO	STZ	SAZ	PFZ	AZ
ACCESS-ESM1-5	0.29	0.54	0.37	0.18	0.26	1.00	0.82	1.01	1.15	1.07	0.15	0.57	0.15	-0.81	-0.17
CanESM5	0.74	0.29	1.38	0.96	0.15	1.21	0.83	1.94	1.45	1.00	0.06	0.69	-0.32	-0.11	0.09
CESM2	0.77	1.69	2.90	0.26	0.65	0.98	1.11	2.54	1.06	1.05	0.41	0.78	0.51	-0.09	0.24
CMCC-ESM2	0.87	0.22	0.41	0.29	1.06	0.79	0.80	1.18	1.09	1.20	0.65	0.94	-0.28	-0.16	0.32
CNRM-ESM2-1	0.39	0.32	0.88	0.28	0.58	0.91	0.87	1.42	0.92	1.07	0.43	0.53	-0.13	0.43	0.16
GFDL-ESM4	0.61	0.80	0.87	0.36	0.37	0.75	0.37	1.20	0.99	1.03	0.66	0.94	0.18	0.22	0.11
IPSL-CM6A-LR	0.87	0.40	0.50	0.44	1.09	0.82	0.81	1.28	1.05	1.20	0.63	0.63	-0.40	0.10	0.34
MIROC-ES2L	0.25	0.34	0.18	0.12	0.23	0.87	0.89	1.01	0.99	0.96	0.62	0.46	0.01	0.18	0.27
MPI-ESM-1-2-HAM	2.80	2.96	4.89	4.31	2.81	2.41	2.13	4.81	4.81	3.08	0.54	0.89	0.19	-0.41	-0.10
MPI-ESM1-2-HR	5.90	3.45	6.83	3.66	6.21	5.38	2.59	6.64	4.13	6.09	0.58	0.90	0.26	-0.36	0.20
MPI-ESM1-2-LR	2.84	3.41	5.52	1.47	2.49	2.56	2.58	5.21	2.02	2.70	0.44	0.88	0.39	-0.30	-0.01
NorESM2-LM	0.46	0.74	1.08	0.56	0.56	1.02	0.93	1.36	1.35	1.14	0.19	0.46	0.14	-0.45	0.01
NorESM2-MM	0.43	0.60	1.04	0.52	0.48	1.06	1.05	1.32	1.35	1.09	0.07	0.22	0.16	-0.54	0.05
UKESM1-0-LL	0.42	0.86	0.47	0.19	0.11	0.82	0.49	0.93	1.13	0.99	0.60	0.87	0.38	-0.66	0.16

Table S3: Statistics of standardised standard deviation (SSD), root-mean-squared deviation (RMSD), and correlation coefficient (CC) for surface nitrate of 14 CMIP6 models in December-January-February (DJF) across the Southern Ocean (SO) and its subregions- the subtropical zone (STZ), subantarctic zone (SAZ), polar front zone (PFZ), and Antarctic zone (AZ).

CMIP6 ESMs	SSD					RMSD					CC				
	SO	STZ	SAZ	PFZ	AZ	SO	STZ	SAZ	PFZ	AZ	SO	STZ	SAZ	PFZ	AZ
ACCESS-ESM1-5	0.99	2.40	0.81	0.60	0.77	0.33	1.72	0.56	0.68	1.03	0.95	0.80	0.83	0.75	0.35
CanESM5	1.08	2.97	0.89	0.79	0.48	0.39	2.24	0.58	0.68	0.83	0.93	0.80	0.81	0.74	0.57
CESM2	0.73	1.35	0.76	0.50	0.70	0.38	0.76	0.68	0.66	1.14	0.95	0.83	0.73	0.81	0.14
CMCC-ESM2	0.94	0.39	0.68	1.49	1.76	0.35	0.81	0.67	0.93	1.38	0.94	0.63	0.74	0.79	0.62
CNRM-ESM2-1	1.01	2.28	0.74	0.87	0.95	0.28	1.58	0.51	0.92	0.96	0.96	0.81	0.87	0.53	0.52
GFDL-ESM4	0.90	0.90	0.84	0.93	1.16	0.25	0.56	0.55	0.64	1.02	0.97	0.83	0.83	0.78	0.56
IPSL-CM6A-LR	0.97	1.58	0.67	1.01	1.28	0.25	0.95	0.55	0.62	1.22	0.97	0.82	0.86	0.81	0.44
MIROC-ES2L	0.95	2.60	0.81	0.85	1.17	0.35	1.93	0.64	1.30	1.40	0.94	0.77	0.77	0.02	0.18
MPI-ESM-1-2-HAM	0.58	0.87	0.73	0.84	1.47	0.55	0.51	0.53	1.26	2.11	0.89	0.86	0.85	0.07	-0.43
MPI-ESM1-2-HR	0.58	0.41	0.97	0.69	2.22	0.62	0.74	0.42	1.11	2.81	0.82	0.75	0.91	0.17	-0.44
MPI-ESM1-2-LR	0.62	1.43	0.80	0.42	1.31	0.55	0.83	0.53	0.96	1.90	0.87	0.83	0.85	0.31	-0.33
NorESM2-LM	0.88	1.83	0.77	1.06	0.57	0.30	1.25	0.72	0.72	1.13	0.96	0.76	0.70	0.76	0.05
NorESM2-MM	0.87	2.00	0.75	0.91	0.48	0.33	1.44	0.68	0.68	1.02	0.95	0.73	0.73	0.75	0.19
UKESM1-0-LL	1.02	1.49	0.98	1.01	0.64	0.30	0.99	0.61	0.64	0.82	0.96	0.75	0.81	0.80	0.58

75 **Table S4: Statistics of standardised standard deviation (SSD), root-mean-squared deviation (RMSD), and correlation coefficient (CC) for surface silicate of 14 CMIP6 models in December-January-February (DJF) across the Southern Ocean (SO) and its subregions- the subtropical zone (STZ), subantarctic zone (SAZ), polar front zone (PFZ), and Antarctic zone (AZ).**

CMIP6 ESMs	SSD					RMSD					CC				
	SO	STZ	SAZ	PFZ	AZ	SO	STZ	SAZ	PFZ	AZ	SO	STZ	SAZ	PFZ	AZ
ACCESS-ESM1-5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
CanESM5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
CESM2	0.73	1.65	4.86	1.11	0.28	0.62	2.02	4.82	1.45	0.85	0.78	-0.11	0.14	0.06	0.63
CMCC-ESM2	1.35	3.19	6.94	2.09	0.48	0.81	3.51	6.67	2.08	0.74	0.80	-0.18	0.34	0.25	0.71
CNRM-ESM2-1	0.93	1.28	2.33	1.40	0.82	0.61	1.65	2.08	1.32	1.10	0.81	-0.04	0.45	0.43	0.28
GFDL-ESM4	1.14	0.69	2.88	1.65	0.90	0.50	1.15	2.67	1.55	0.66	0.90	0.10	0.37	0.40	0.77
IPSL-CM6A-LR	1.04	0.47	1.53	0.94	1.04	0.37	1.08	1.36	0.89	0.67	0.94	0.06	0.49	0.58	0.79
MIROC-ES2L	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
MPI-ESM-1-2-HAM	1.35	12.06	7.90	1.61	0.39	0.97	12.29	7.65	1.33	0.83	0.70	-0.19	0.31	0.57	0.59
MPI-ESM1-2-HR	1.56	10.29	9.66	1.83	0.40	1.08	10.61	9.28	1.40	0.85	0.73	-0.28	0.42	0.65	0.55
MPI-ESM1-2-LR	1.25	13.54	7.74	1.27	0.34	0.95	13.83	7.49	1.19	0.90	0.67	-0.25	0.31	0.47	0.44
NorESM2-LM	0.92	3.83	5.36	1.82	0.21	0.71	4.13	5.10	1.85	0.90	0.73	-0.18	0.34	0.25	0.57
NorESM2-MM	0.91	4.08	5.40	1.65	0.21	0.72	4.39	5.11	1.69	0.89	0.72	-0.20	0.37	0.26	0.62
UKESM1-0-LL	1.49	1.15	6.09	2.22	0.74	0.80	1.62	5.79	2.01	0.73	0.86	-0.14	0.38	0.43	0.68

80 **Table S5: Statistics of standardised standard deviation (SSD), root-mean-squared deviation (RMSD), and correlation coefficient (CC) for surface dissolved iron of 14 CMIP6 models in December-January-February (DJF) across the Southern Ocean (SO) and its subregions- the subtropical zone (STZ), subantarctic zone (SAZ), polar front zone (PFZ), and Antarctic zone (AZ).**

CMIP6 ESMs	SSD					RMSD					CC				
	SO	STZ	SAZ	PFZ	AZ	SO	STZ	SAZ	PFZ	AZ	SO	STZ	SAZ	PFZ	AZ
ACCESS-ESM1-5	0.11	0.73	0.15	0.08	0.05	0.99	1.21	1.01	1.02	1.00	0.13	0.04	0.00	-0.26	-0.01
CanESM5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
CESM2	0.15	0.91	0.21	0.23	0.04	1.00	1.25	1.04	1.02	1.00	0.05	0.15	-0.08	0.01	-0.08
CMCC-ESM2	0.42	1.11	0.45	0.17	0.03	1.07	1.51	1.12	1.02	1.00	0.02	-0.02	-0.06	-0.06	0.04
CNRM-ESM2-1	0.51	2.50	0.02	0.04	0.14	1.04	2.59	1.00	1.00	1.01	0.18	0.11	0.21	-0.06	0.02
GFDL-ESM4	0.25	1.02	0.28	0.24	0.12	1.03	1.20	1.01	1.00	1.01	0.02	0.30	0.08	0.13	-0.01
IPSL-CM6A-LR	0.46	1.63	0.15	0.09	0.20	1.03	1.88	1.01	1.03	1.01	0.16	0.04	0.02	-0.32	0.03
MIROC-ES2L	0.19	0.90	0.36	0.34	0.05	0.99	1.32	1.01	0.95	1.00	0.12	-0.06	0.15	0.33	-0.02
MPI-ESM-1-2-HAM	0.17	1.01	0.51	0.42	0.06	1.03	1.57	1.13	0.97	1.01	-0.09	-0.21	-0.01	0.28	-0.11
MPI-ESM1-2-HR	0.21	1.07	0.37	0.19	0.09	1.04	1.67	1.04	0.96	1.01	-0.09	-0.29	0.08	0.28	-0.08
MPI-ESM1-2-LR	0.15	0.95	0.35	0.11	0.06	1.02	1.54	1.08	0.99	1.01	-0.08	-0.25	-0.06	0.11	-0.07
NorESM2-LM	0.32	1.07	0.39	0.27	0.03	1.05	1.52	1.20	1.06	1.00	-0.01	-0.08	-0.39	-0.10	-0.11
NorESM2-MM	0.29	1.15	0.39	0.26	0.03	1.04	1.55	1.20	1.05	1.00	0.00	-0.03	-0.37	-0.08	-0.07
UKESM1-0-LL	0.19	1.12	0.30	0.19	0.02	1.01	1.53	1.11	1.10	1.00	0.05	-0.04	-0.25	-0.44	-0.09

85 **Table S6: Statistics of standardised standard deviation (SSD), root-mean-squared deviation (RMSD), and correlation coefficient (CC) for surface particulate organic carbon (POC) in December-January-February (DJF) of 14 CMIP6 models across the Southern Ocean (SO) and its subregions- the subtropical zone (STZ), subantarctic zone (SAZ), polar front zone (PFZ), and Antarctic zone (AZ).**

CMIP6 ESMs	SSD					RMSD					CC				
	SO	STZ	SAZ	PFZ	AZ	SO	STZ	SAZ	PFZ	AZ	SO	STZ	SAZ	PFZ	AZ
ACCESS-ESM1-5	0.22	0.38	0.26	0.15	0.20	0.98	0.80	1.00	1.12	1.06	0.21	0.66	0.14	-0.76	-0.20
CanESM5	0.55	0.39	0.91	0.82	0.14	1.15	0.78	1.56	1.29	1.00	-0.02	0.70	-0.33	0.01	0.06
CESM2	0.58	0.98	1.60	0.27	0.69	0.85	0.58	1.35	1.09	1.04	0.53	0.83	0.55	-0.22	0.28
CMCC-ESM2	1.85	1.30	1.40	0.95	2.09	1.34	0.69	1.99	1.52	1.92	0.71	0.85	-0.36	-0.22	0.40
CNRM-ESM2-1	0.36	0.44	0.67	0.26	0.56	0.92	0.79	1.17	0.95	1.06	0.40	0.65	0.06	0.32	0.17
GFDL-ESM4	0.71	0.98	0.55	0.30	0.56	0.70	0.38	0.94	1.15	1.02	0.71	0.93	0.38	-0.38	0.24
IPSL-CM6A-LR	0.82	0.55	0.31	0.28	1.11	0.83	0.71	1.11	1.01	1.15	0.60	0.73	-0.21	0.11	0.41
MIROC-ES2L	0.19	0.24	0.13	0.09	0.18	0.90	0.89	1.02	0.99	0.96	0.62	0.54	-0.13	0.11	0.28
MPI-ESM-1-2-HAM	2.12	2.07	3.48	3.36	2.20	1.84	1.38	3.44	3.91	2.50	0.50	0.81	0.19	-0.45	-0.09
MPI-ESM1-2-HR	4.48	2.40	4.86	2.85	4.95	4.09	1.69	4.81	3.43	4.81	0.49	0.81	0.16	-0.46	0.24
MPI-ESM1-2-LR	2.15	2.38	3.93	1.15	1.96	2.00	1.63	3.61	1.79	2.17	0.38	0.84	0.44	-0.38	0.03
NorESM2-LM	0.62	0.95	1.39	0.62	0.61	1.16	0.98	1.43	1.32	1.13	0.02	0.50	0.33	-0.30	0.07
NorESM2-MM	0.63	0.79	1.48	0.58	0.53	1.25	1.15	1.41	1.32	1.08	-0.14	0.20	0.41	-0.34	0.11
UKESM1-0-LL	0.58	1.28	0.89	0.29	0.22	0.90	0.63	0.97	1.18	0.99	0.46	0.88	0.48	-0.55	0.17

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