Supplementary Information

Biogeochemistry of climate driven shifts in Southern Ocean primary producers

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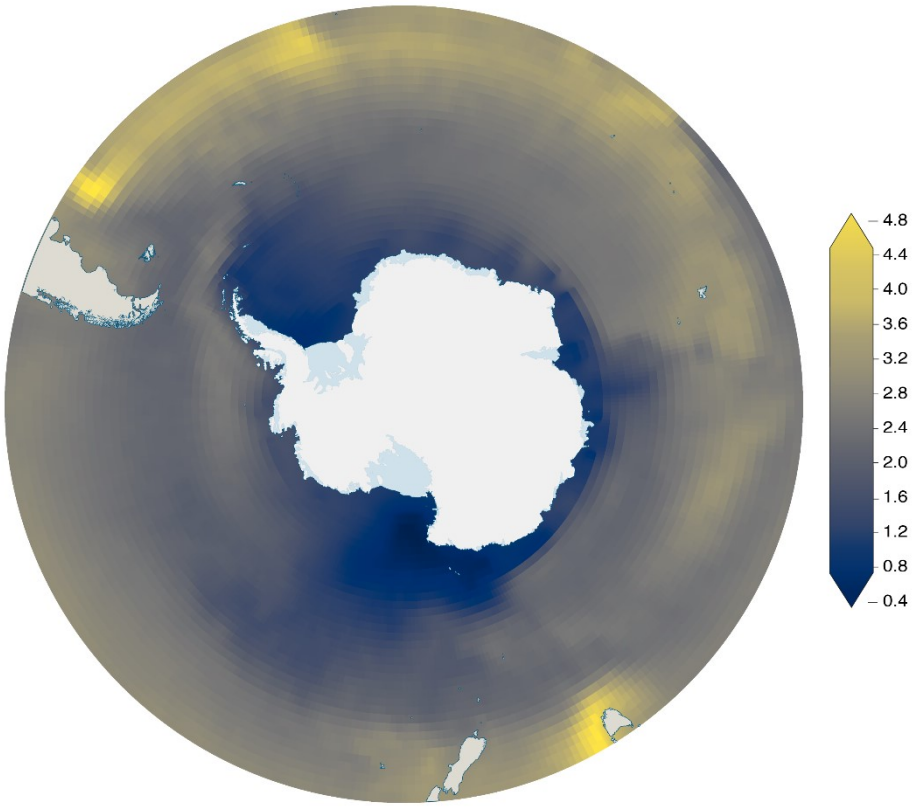

Figure S1: Anomaly in sea surface temperature (°C) between 2100 (SSP5-8.5) and a historical average (1985-2015). Representative of a multi-model ensemble of CMIP6 models, models included are detailed in Table S1.

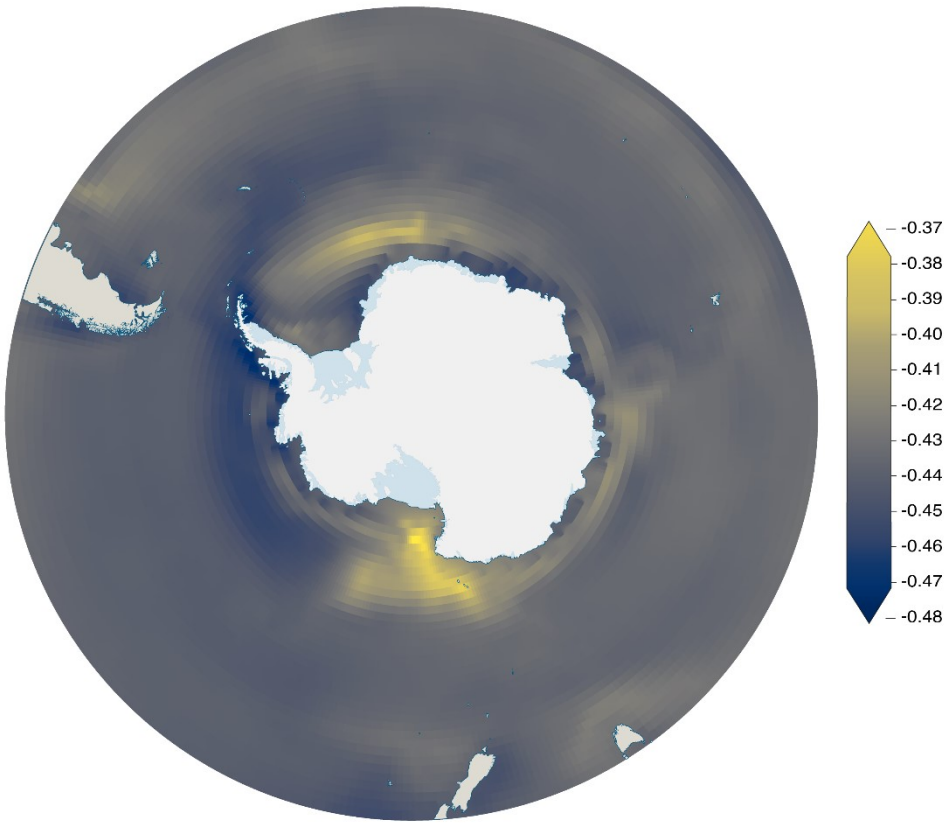

Figure S2: Anomaly in sea surface pH between 2100 (SSP5-8.5) and a historical average (1985-2015). Representative of a multi-model ensemble of CMIP6 models, models included are detailed in Table S1.

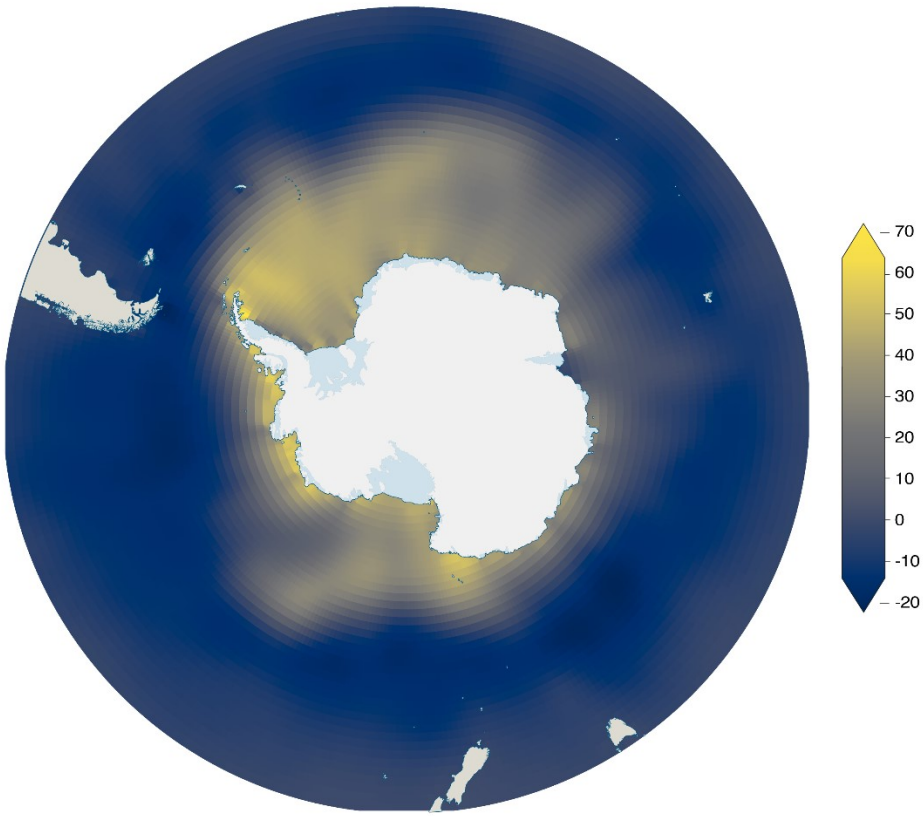

Figure S3: Si* ($[Si(OH)_4]$–$[NO_3^-]$) (µmol) across the Southern Ocean. According to the World Ocean Atlas data product 2018.

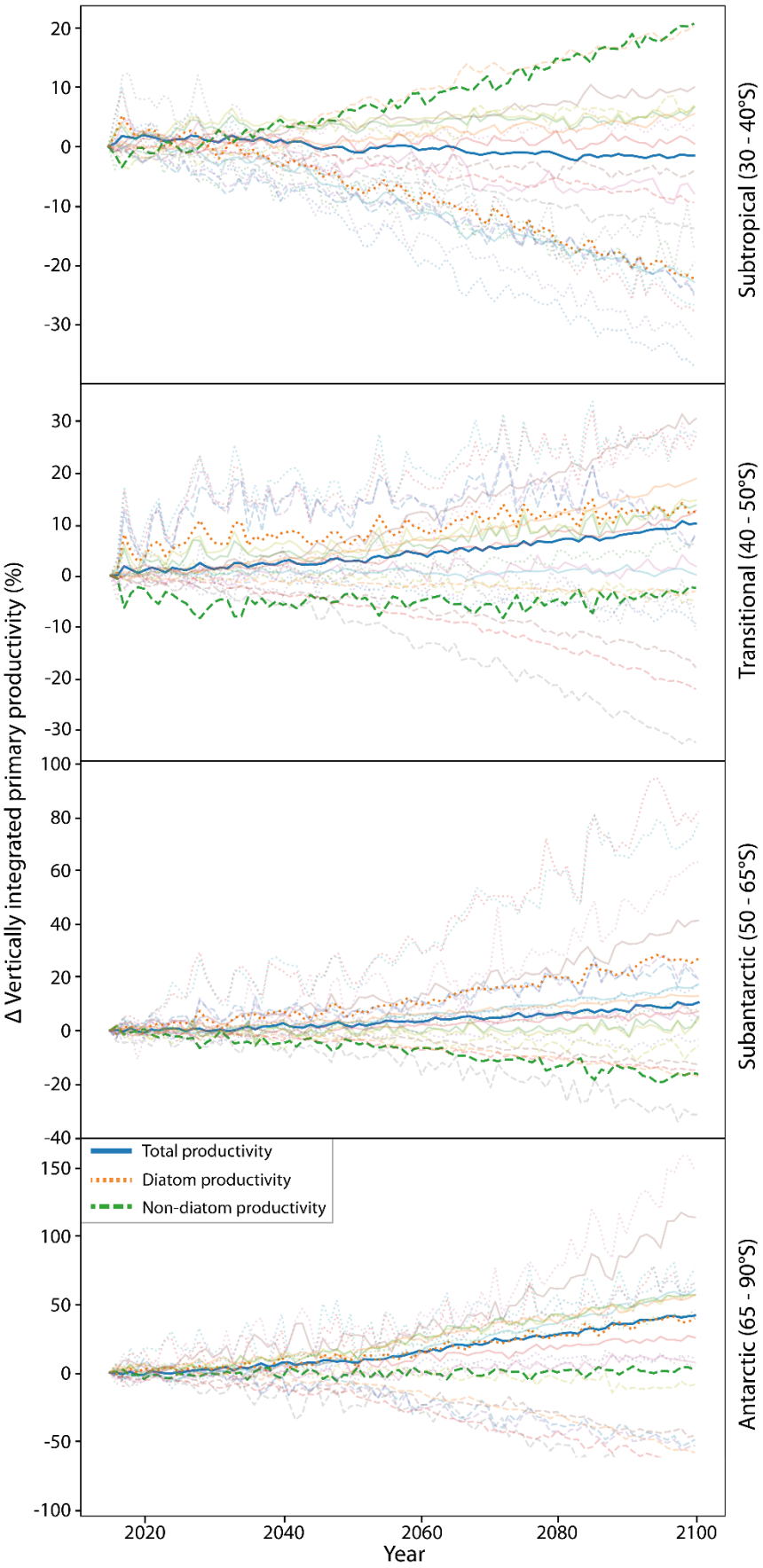

Figure S4: Changes in productivity (%) and the contribution of different phytoplankton classes to productivity 2015-2100. Adapted version of main figure 3 showing the relative change in productivity and phytoplankton group contributions compared to annual productivity at the first time point (2015) in the SSP585 run.

Table S1: **CMIP6 members assessed.**

Table S1 shows the CMIP6 productivity parameters used in this paper. Models shown correspond to CMIP6 models that contain a) the productivity parameter, b) both a historical and SSP5-8.5 scenario. For all models the final data selection represents a mean across all available member_ids, bnds, vertex and time parameters (following selection of desired time period). Model availability was determined from pangeo (https://pangeo.io/).

Variable ID	Parameter	Units	Data selection	Models containing
intpp	Primary organic carbon production by all types of phytoplankton.	gC m^{-2} yr^{-1}	Annual average	GFDL-ESM4, GFDL-CM4, CanESM5, CanESM5-CanOE, MPI-ESM1-2-HR, UKESM1-0-LL, CESM2-WACCM, CNRM-ESM2-1, NorESM2-LM, MIROC-ES2L, CMCC-ESM2, EC-Earth3-CC, ACCESS-ESM1-5, MRI-ESM2-0, IPSL-CM6A-LR.
intppdiat	Primary organic carbon production by diatoms	gC m^{-2} yr^{-1}	Annual average	GFDL-ESM4, CanESM5-CanOE, UKESM1-0-LL, CESM2-WACCM.IPSL-CM6A-LR, CNRM-ESM2-1.
chl	Mass concentration of total phytoplankton expressed as chlorophyll in sea water	kg m^{-3}	Annual average	GFDL-ESM4, GFDL-CM4, CanESM5, CanESM5-CanOE, MPI-ESM1-2-HR, UKESM1-0-LL, NorESM2-MM, CanESM5, MIROC-ES2L, CMCC-ESM2, ACCESS-ESM1-5,MRI-ESM2-0.
limirrpico	Irradiance limitation of picophytoplankton	Ratio of growth under environmental irradiance/growth under unlimited irradiance	Annual average (Combined with misc/diat/diaz)	GFDL-ESM4, CESM2-WACCM,
limirrmisc	Irradiance limitation of miscellaneous phytoplankton	Ratio of growth under environmental irradiance/growth under unlimited irradiance	Annual average (Combined with pico/diat/diaz)	GFDL-ESM4, IPSL-CM6A-LR, CNRM-ESM2-1, CanESM5,
limirrdiat	Irradiance limitation of diatoms	Ratio of growth under environmental irradiance/growth	Annual average (Combined with pico/diat/diaz)	GFDL-ESM4, CESM2-WACCM, CNRM-ESM2-1, IPSL-CM6A-LR, UKESM1-0-LL.

		under unlimited irradiance		
limirrdiaz	Irradiance limitation of diazotrophs	Ratio of growth under environmental irradiance/growth under unlimited irradiance	Annual average (Combined with pico/diat/misc)	GFDL-ESM4, CESM2-WACCM.
Limfediat/pico/misc	Iron limitation of diatoms/picophytoplankton/ miscellaneous phytoplankton.	Ratio of growth under environmental iron concentration/growth under unlimited iron concentration	Combined annual average	GFDL-ESM4.
Rsntds	Net Downward Shortwave Radiation at Sea Water Surface (IPAR)	W m^{-2} (Converted to µE m^{-2} s^{-1} by x4.599)	Summertime maximum	CNRM-CM6-1, CNRM-ESM2-1, CanESM5, CanESM5-CanOE, MPI-ESM1-2-LR, CESM2-WACCM, MIROC-ES2L, IPSL-CM6A-LR, ACCESS-CM2, CNRM-CM6-1-LR, MRI-ESM2-0, EC-Earth3, CMCC-CM2-SR5, ACCESS-ESM1-5, FIO-ESM-2-0, EC-Earth3-CC.
sfcWindmax	Daily Maximum Near-Surface Wind Speed	m s^{-1}	Annual average of daily maxima	GFDL-CM4, CNRM-CM6-1, BCC-CSM2-MR, CNRM-CM6-1, CNRM-ESM2-1, CanESM5, (AWI-CM-1-1-MR), INM-CM4-8, MPI-ESM1-2-LR, MPI-ESM1-2-HR, INM-CM5-0, UKESM1-0-LL, IPSL-CM6A-LR,KACE-1-0-G, CNRM-ESM2-1, MRI-ESM2-0, CNRM-CM6-1-HR, CMCC-CM2-SR5, HadGEM3-GC31-MM, EC-Earth3-Veg-LR, EC-Earth3-CC, CMCC-ESM2.
Mlotst	Ocean Mixed Layer Thickness Defined by σ_t	m	Summertime maximum	IPSL-CM6A-LR, GISS-E2-1-G, BCC-CSM2-MR, BCC-ESM1, CESM2,CanESM5, MPI-ESM-1-2-HAM, NESM3, MPI-ESM1-2-HR, GFDL-ESM4, CESM2-WACCM, GISS-E2-1-G-CC, EC-Earth3, ACCESS-CM2,NorESM2-MM, ACCESS-ESM1-5, CESM2-FV2, CESM2-WACCM-FV2, E3SM-1-1, MRI-ESM2-0, E3SM-1-1-ECA.

pH	Sea surface pH	pH units	Annual average	GFDL-ESM4, CanESM5, CanESM5-CanOE, CESM2-WACCM, IPSL-CM6A-LR, NorESM2-LM, NorESM2-MM, IPSL-CM6A-LR ,MRI-ESM2-0, CESM2, MIROC-ES2L
tos	Sea surface temperature	°C	Annual average	GFDL-ESM4, GFDL-CM4, CNRM-CM6-1, CNRM-ESM2-1, BCC-CSM2-MR, CanESM5-CanOE, INM-CM4-8, MIROC6, MPI-ESM1-2-LR, MPI-ESM1-2-HR, INM-CM5-0, UKESM1-0-LL, MCM-UA-1-0, NESM3, CESM2-WACCM, IPSL-CM6A-LR, CAM5-CSM1-0, FGOALS-f3-L, MRI-ESM2-0, NorESM2-0, IPSL-CM6A-LR, CNRM-CM6-1-HR, FIO-ESM-2-0, FGOALS-g3, HadGEM3-GC31-LL, GISS-E2-1-G, KACE-1-0-G, EC-Earth3-Veg ,EC -Earth3, MIROC-ES2L, ACCESS-ESM1-5.

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106 **Table S2**: **Models containing different classes of phytoplankton under SSP5-8.5 ScenarioMIP conditions.** (not assessed in this study).

chldiat	Mass concentration of diatoms expressed as chlorophyll in sea water	kg m^{-3}	N/A	CanESM5-CanOE, CESM2-WACCM, UKESM1-0-LL.
chlpico	Mass concentration of picophytoplankton expressed as chlorophyll in sea water	kg m^{-3}	N/A	CESM2-WACCM
chlmisc	Mass concentration of miscellaneous phytoplankton expressed as chlorophyll in sea water	kg m^{-3}	N/A	CanESM5-CanOE.
chldiaz	Mass concentration of diazotrophs expressed as chlorophyll in sea water	kg m^{-3}	N/A	CESM2-WACCM, MPI-ESM1-2-LR, MPI-ESM1-2-HR

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Table S3: Data descriptors for Figure 1.

Variable	Value	Detail	Reference
Warming at depth	+0.62 °C	Expected warming of Antarctic shelf bottom waters by 2100 across SSP5-8.5 in a CMIP6 multi-ensemble mean. (Purich & England 2021).	Purich, & England. (2021)
Changes in stratification.	CMIP6: -1.9 m/ -7.8% Uncertain, sign change within standard deviation.	Changes in mixed layer depth are highly spatially variable. In the coastal Southern Ocean (south of 60°) CMIP5 models disagree on the direction of MLD change due to the competing effects of freshwater input with increased upwelling and wind driven mixing. (Hauk et al., 2015). CMIP6 models similarly disagree but give an overall mean of -1.9 m. Melting of the Antarctic ice sheet is not a process considered within CMIP models.	Hauck et al. (2015)
pCO_2	+200%	Increase from ~500 µatm (GLODAP) to ~1000 µatm under RCP8.5.	Kawaguchi et al. (2013).
pH	-0.3 pH units	Decrease in Southern Ocean pH from 8.09 to 7.79 calculate using the CSIRO ocean carbon model from CC IS92a atmospheric CO_2 scenario.	McNeil and Matear.(2008).
Increased surface warming	+2.50°C	Spatial average taken from the temperature anomaly data shown in Figure S1. Representative of a CMIP6 multi-model ensemble anomaly between 2100 and (1985-2015) under SSP5-8.5.	This study

References:

Purich, A., & England, M. H. (2021). Historical and future projected warming of Antarctic Shelf Bottom Water in CMIP6 models. Geophysical Research Letters, 48.

Hauck, J., Völker, C., Wolf-Gladrow, D. A., Laufkötter, C., Vogt, M., Aumont, O., Bopp, L., Buitenhuis, E. T., Doney, S. C., Dunne, J., et al. (2015), On the Southern Ocean CO2 uptake and the role of the biological carbon pump in the 21st century, Global Biogeochem. Cycles, 29, 1451– 1470,

Kawaguchi, S., Ishida, A., King, R. et al. Risk maps for Antarctic krill under projected Southern Ocean acidification. Nature Clim Change 3, 843–847 (2013).

McNeil, B.I. and Matear, R.J., 2008. Southern Ocean acidification: A tipping point at 450-ppm atmospheric CO2. Proceedings of the National Academy of Sciences, 105(48), pp.18860-18864.