Supplementary Information - Enhanced Southern Ocean CO₂ outgassing as a result of stronger and poleward shifted southern hemispheric westerlies

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Changes in oceanic remineralised carbon concentration (C_{org}) between 1980 and 2021 are estimated as follows:

\[ \Delta C_{org} = R_{C/P} \Delta PO_{4\text{Reg}}, \]  

with

\[ \Delta PO_{4\text{Reg}} = R_{P/O_2} \Delta AOU. \]  

AOU is the apparent oxygen utilisation, and is the difference between the dissolved oxygen at saturation (as a function of temperature and salinity) and the simulated dissolved oxygen concentration. \( R_{C/P} \) and \( R_{P/O_2} \) are the Redfield ratios equal to 106/1 and 1/172, respectively.
References

Supplementary Fig. 1. Biogeochemical tracers distribution (left) as simulated in years 1990-2010 in the numerical model and compared to (right) the observed GLODAP v2 dataset (Olsen et al., 2016) for a,b, tDIC (µmol kg\(^{-1}\)), c,d, alkalinity (µmol kg\(^{-1}\)), and e,f, dissolved oxygen (µmol kg\(^{-1}\)), zonally averaged over the Indo-Pacific and Atlantic basins. The density of the AABW (≥1028.31 kg/m\(^3\)), the AAIW (1027.5 ≤ AAIW ≤ 1026.95 kg/m\(^3\)) and the SAMW (≤1026.95 kg/m\(^3\)) are overlaid. The core of PDW (1027.7 kg/m\(^3\)) and NADW (1027.75 kg/m\(^3\)) are also overlaid in the Indo-Pacific and Atlantic sectors respectively.
**Supplementary Fig. 2.** Zonally averaged a) windstress (N/m$^2$), b) Ekman pumping (m/s), and zonally integrated c) natural, d) anthropogenic and e) total ocean to atmospheric CO$_2$ flux (mol/m/yr) for years (black) 1980-1984 and (red) 2017-2021 of the numerical experiment.
Supplementary Fig. 3. Scatter plots of annual mean SO (left) natural, (middle) detrended anthropogenic and (right) detrended total CO$_2$ fluxes as a function of annual mean (top) SAM index calculated from JRA55-do dataset, (middle) SO zonal mean windstress, and (bottom) latitude of the maximum windstress. Black lines indicate the linear fit.
Supplementary Fig. 4. (from top to bottom) nCO$_2$, aCO$_2$ and tCO$_2$ anomalies (GtC/yr) compared to 1980 and integrated over the (blue) Atlantic, (red) Indian and (black) Pacific sectors of the Southern Ocean (south of 35°S).
**Supplementary Fig. 5.** Change in the latitude (°) of the maximum windstress in the (blue) Atlantic, (green) Indian and (red) Pacific sector of the Southern Ocean compared to the 1980-2021 mean. A negative change indicates a poleward shift. The thin lines represent annual mean data, while the thick lines are 5-years running means.
Supplementary Fig. 6. a) aCO$_2$ and b) tCO$_2$ flux (mol/m$^2$/yr) anomalies for a composite of positive phases of the SAM ($\geq 0.83$, i.e. 1998, 1999, 2010, 2015 and 2021) compared to a composite of negative SAM years (1980, 1991, 1992, 2002).
Supplementary Fig. 7. Zonally averaged (a-c) remineralized DIC (mmol/m$^3$), (d-f) saturated dissolved O$_2$ (mmol/m$^3$) and (g-i) ocean temperature ($^\circ$C) anomalies for years 2017-2021 compared to 1980-1982 over the (left) Atlantic, (middle) Indian and (right) Pacific basins.
Supplementary Fig. 8. Zonally averaged (a-c) natural DIC, (d-f) anthropogenic DIC and (g-i) total DIC anomalies (mmol/m$^3$) averaged over (left) the Atlantic, (middle) the Indian and (right) the Pacific for years 2017-2021 compared to 1980-1982. The density of the AABW ($\geq 1028.31$ kg/m$^3$), the AAIW ($1027.5 \geq$ AAIW $\geq 1026.95$ kg/m$^3$) and the SAMW ($\leq 1026.95$ kg/m$^3$) are overlaid.