Supplementary Information for

Marine heatwaves in a shifting Southern Ocean induce dynamical changes in primary production

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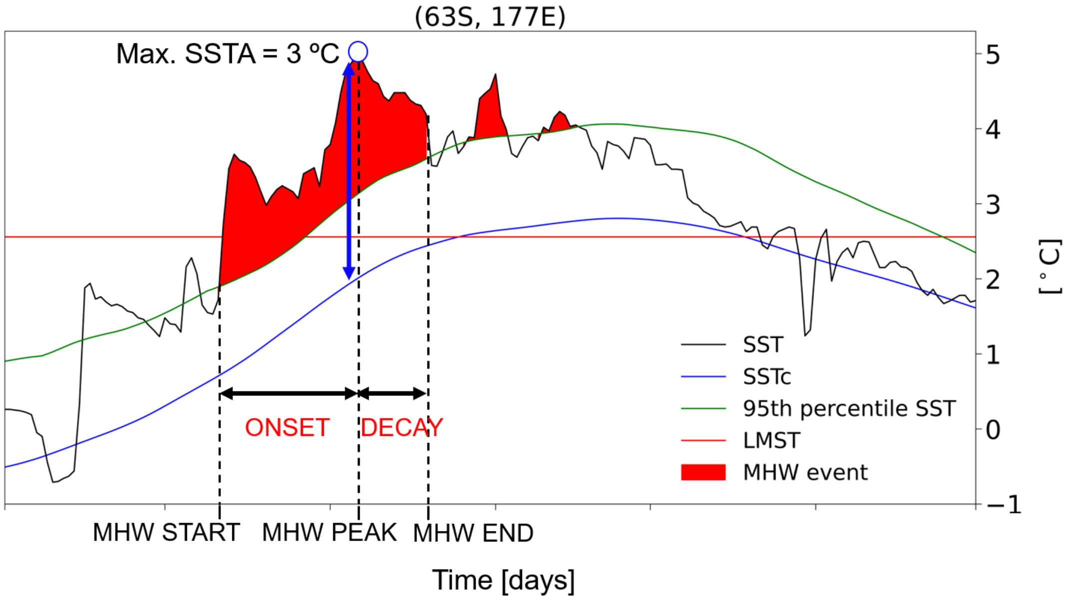
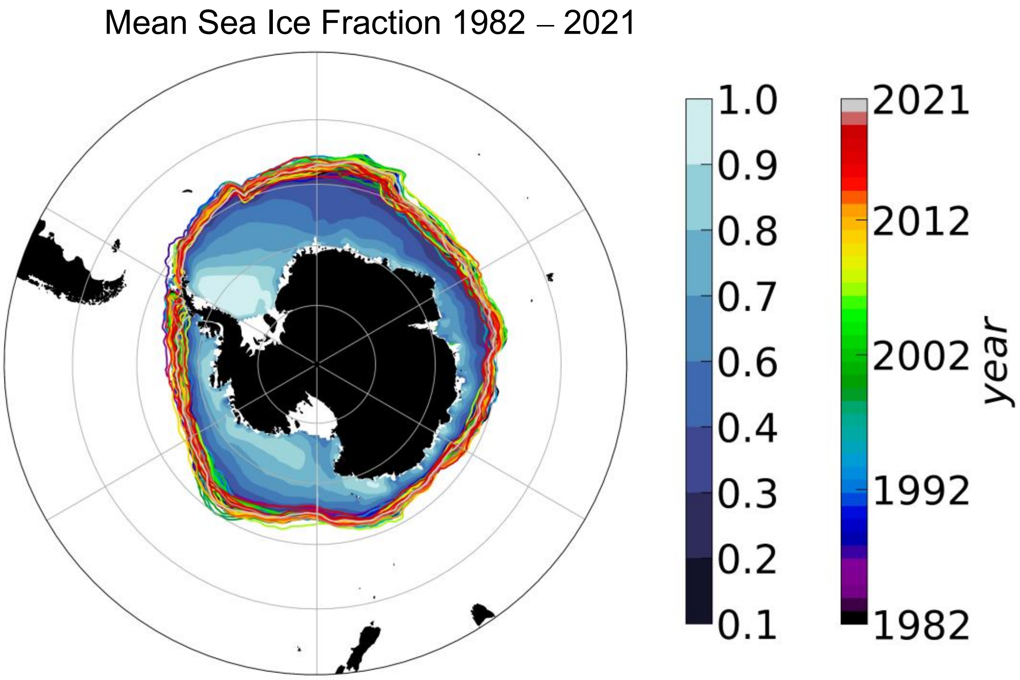
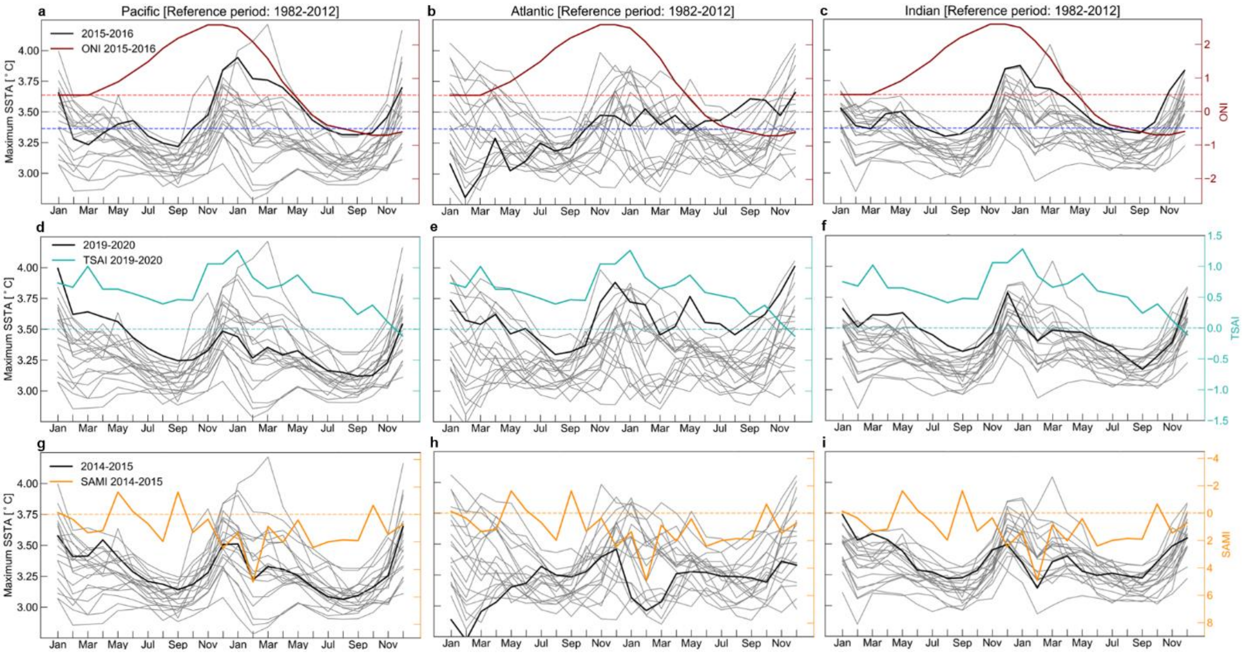


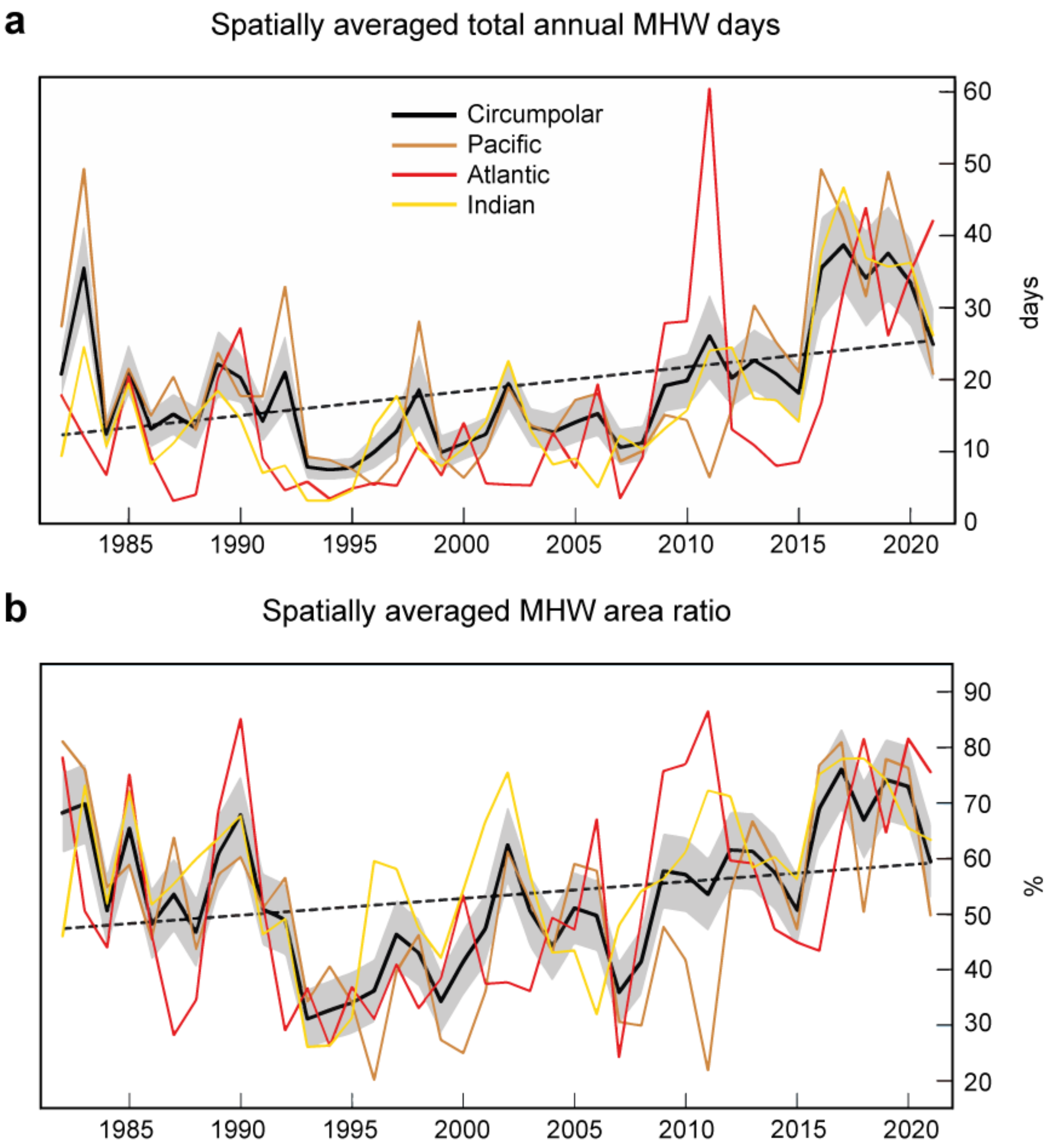
Supplementary Fig. S1 | Schematics outlining the approach for detecting marine heatwave (MHW) events, including the onset and decay periods. Following the criteria set by Hobday et al. (2016), a MHW event (red shading) was identified when the sea surface temperature (SST; black line) exceeded a seasonally varing threshold (green line), defined as the 95th percentile from a baseline of 11-day climatological average (blue line), for at least five consecutive days. In this study, we additionally introduced the criterion that the average temperature of the MHW event must surpass the long-term mean summer temperature (LMST, red line; see methods). From this methodology, various MHW metrics were derived, including the maximum magnitude of the event (maximum SST anomaly; Max. SSTA), which represents the peak anomaly. Frequency is the count of events within a year. In this case, three events were observed throughout the annual series. Duration is the number of days that elapse from the start to the end of a MHW. In this sense, the cumulative intensity (ºC·days) could be derived by integrating the area defined between the SST and the threshold during an event. The period between the start and the peak of the MHW was defined as the onset phase (i.e., the build-up of heat), while the period between the peak and the end of the event was specified as the decay phase (i.e., the dissipation of heat).



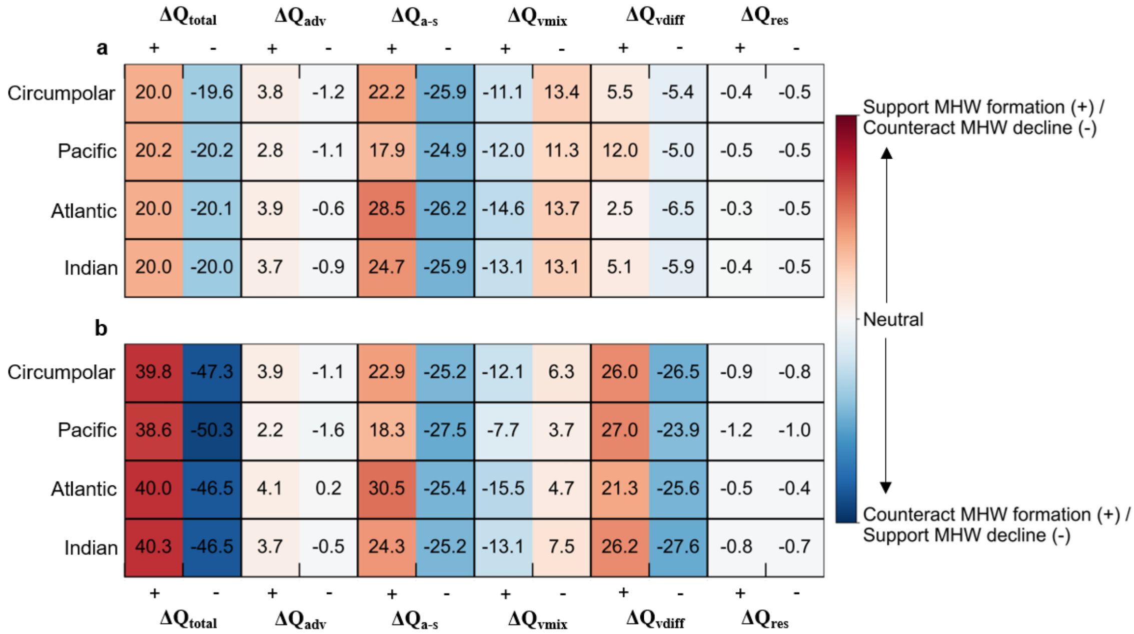
Supplementary Fig. S2 | Averaged Antarctic Sea Ice Extent. Mean Sea Ice Fraction (SIF) 1982 – 2021 from Climate Change Initiative (CCI) and Copernicus Climate Change Service (C3S) L4 daily reanalysis in the Southern Ocean. Note that areas with an averaged SIF lower than 0.2 have been masked out. Solid colored contour lines indicate the annually varying extent of 20% (0.2) sea ice concentration.



Supplementary Fig. S3 | Synergy between three climate indices (as metrics for climate modes) and regionally-averaged maximum sea surface temperature anomaly (SSTA) in the Southern Ocean. Monthly Oceanic Niño Index (ONI, **a**–**c**, solid dark red line), and Tropical Southern Atlantic Index (TSAI, **d**–**f**, solid turquoise) were derived from NOAA Climate Prediction Centre (CPC), while monthly observation-based Southern Annular Mode Index (SAMI, **g**–**i**, solid orange) was obtained from British Antarctic Survey. Monthly maximum SSTAs (reference period is from 1982 to 2012) from CCI C3S L4 SST product were averaged in the Pacific (**a**, **d**, **g**), Atlantic (**b**, **e**, **h**), and Indian sectors (**c**, **f**, **i**) south of 40ºS where mean SIC are lower than 20% (Supplementary Fig. S1). In **a**–**c**, red and blue dashed lines show El Niño and La Niña thresholds, respectively. Please, note that solid black lines show the maximum SSTA for the two-year period of the climate indices (2015–2016 for ONI, 2019–2020 for TSAI, and 2014–2015 for SAMI), whereas gray lines depict the signal for the remaining years. In **d**–**f**, also note that the SAMI scale is reversed.

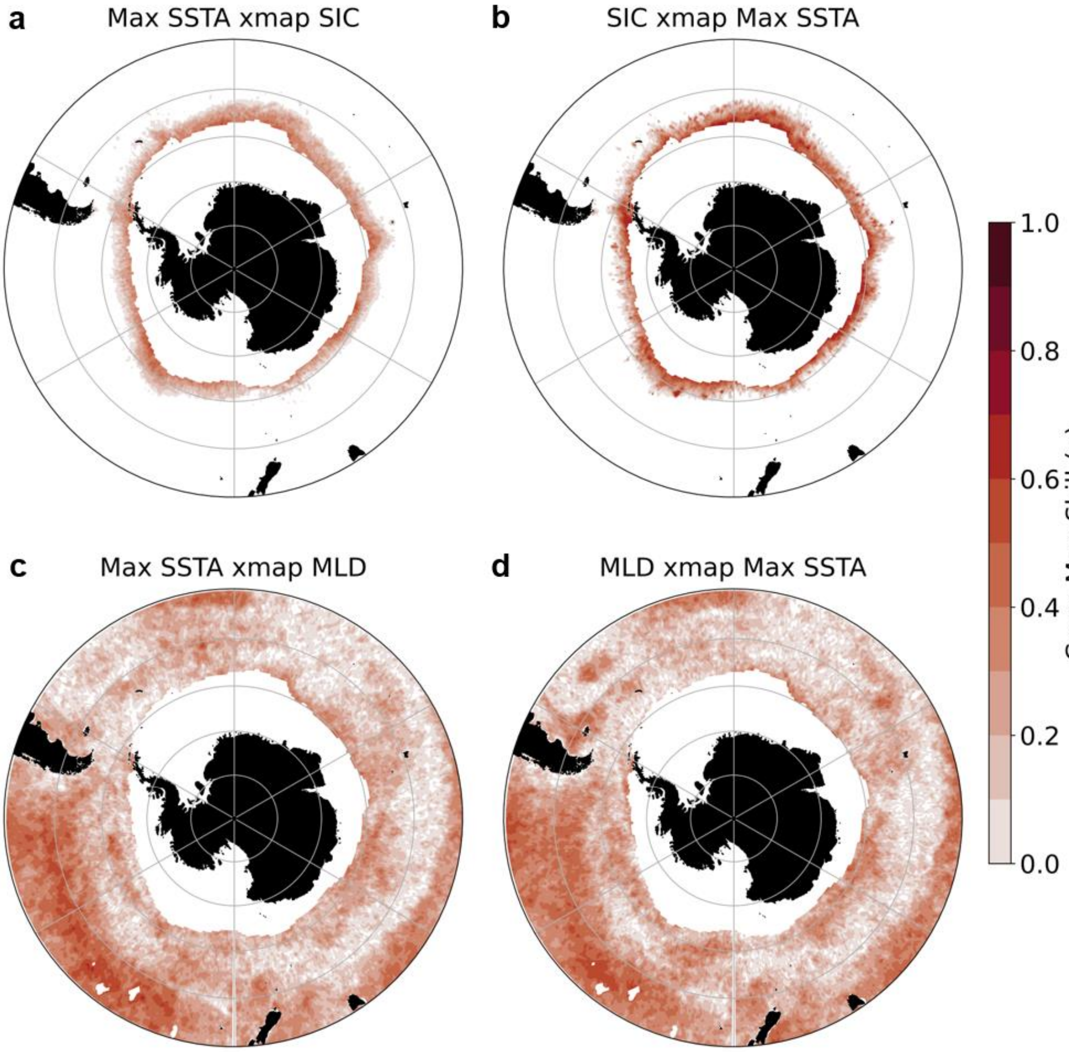


Supplementary Fig. S4 | Spatially averaged time series of total annual MHW days and MHW area ratio in the Southern Ocean. (**a**, **b**) Time series (1982–2021) of annual averaged (**a**) total MHW days and (**b**) MHW area ratio south of 40ºS where sea ice concentrations are lower than 20% (0.2, Supplementary Fig. S1) over the Pacific (brown), Atlantic (red) and Indian (yellow) sectors. Black lines show the circumpolarly-averaged time series, with their linear fitting represented by black dotted lines. Black shading indicates the standard error of the metrics.

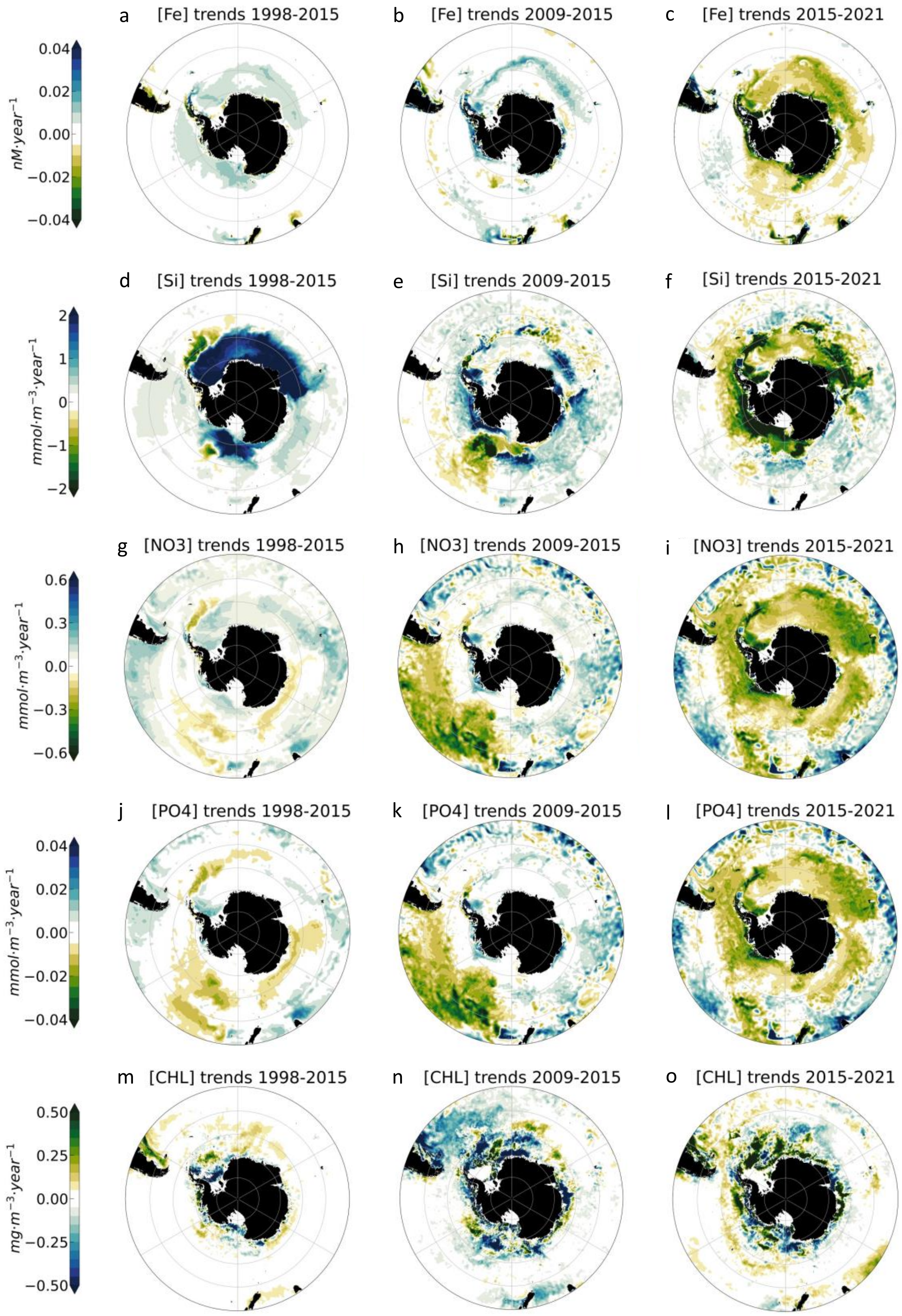


	ΔQ_total +	ΔQ_total -	ΔQ_adv +	ΔQ_adv -	ΔQ_a-s +	ΔQ_a-s -	ΔQ_vmix +	ΔQ_vmix -	ΔQ_vdiff +	ΔQ_vdiff -	ΔQ_res +	ΔQ_res -
a												
Circumpolar	20.0	-19.6	3.8	-1.2	22.2	-25.9	-11.1	13.4	5.5	-5.4	-0.4	-0.5
Pacific	20.2	-20.2	2.8	-1.1	17.9	-24.9	-12.0	11.3	12.0	-5.0	-0.5	-0.5
Atlantic	20.0	-20.1	3.9	-0.6	28.5	-26.2	-14.6	13.7	2.5	-6.5	-0.3	-0.5
Indian	20.0	-20.0	3.7	-0.9	24.7	-25.9	-13.1	13.1	5.1	-5.9	-0.4	-0.5
b												
Circumpolar	39.8	-47.3	3.9	-1.1	22.9	-25.2	-12.1	6.3	26.0	-26.5	-0.9	-0.8
Pacific	38.6	-50.3	2.2	-1.6	18.3	-27.5	-7.7	3.7	27.0	-23.9	-1.2	-1.0
Atlantic	40.0	-46.5	4.1	0.2	30.5	-25.4	-15.5	4.7	21.3	-25.6	-0.5	-0.4
Indian	40.3	-46.5	3.7	-0.5	24.3	-25.2	-13.1	7.5	26.2	-27.6	-0.8	-0.7

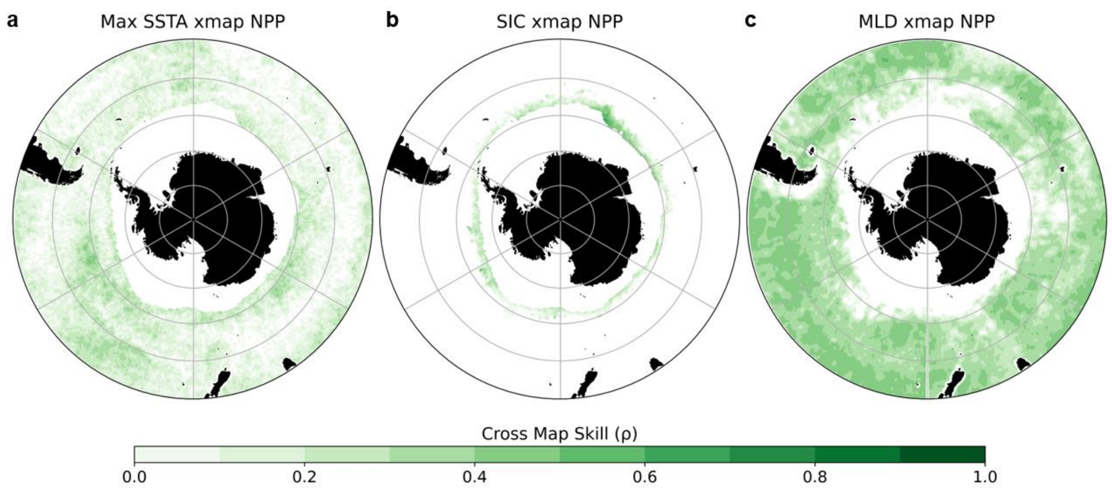
Supplementary Fig. S5 | Mean contributions of the different heat budget terms (in W m^{-2}) in MOM4p1[1] to the onset and decay of marine heatwaves (MHWs) averaged over the Southern Ocean. Heat flux anomalies for the temperature tendency terms (see Supplementary Methods S1 for further information) averaged over MHW onset (+) and decay (-) days within (**a**) the preindustrial control simulation and (**b**) the eight-member ensemble simulation for the present period 1982-2021 and for each sector of the Southern Ocean (see boundaries in Fig. 1b). Positive anomalies during the onset phases increase temperature anomalies, thereby supporting the formation of MHWs, whereas positive anomalies during the decay phases counteract the decline of an event. Please note that in **a**–**b**, the onset and decay values for ΔQ_{total} do not result in zero due to variations in the mean lengths of these phases. This fact arises because a shorter phase implies larger heat flux anomalies, and vice versa.



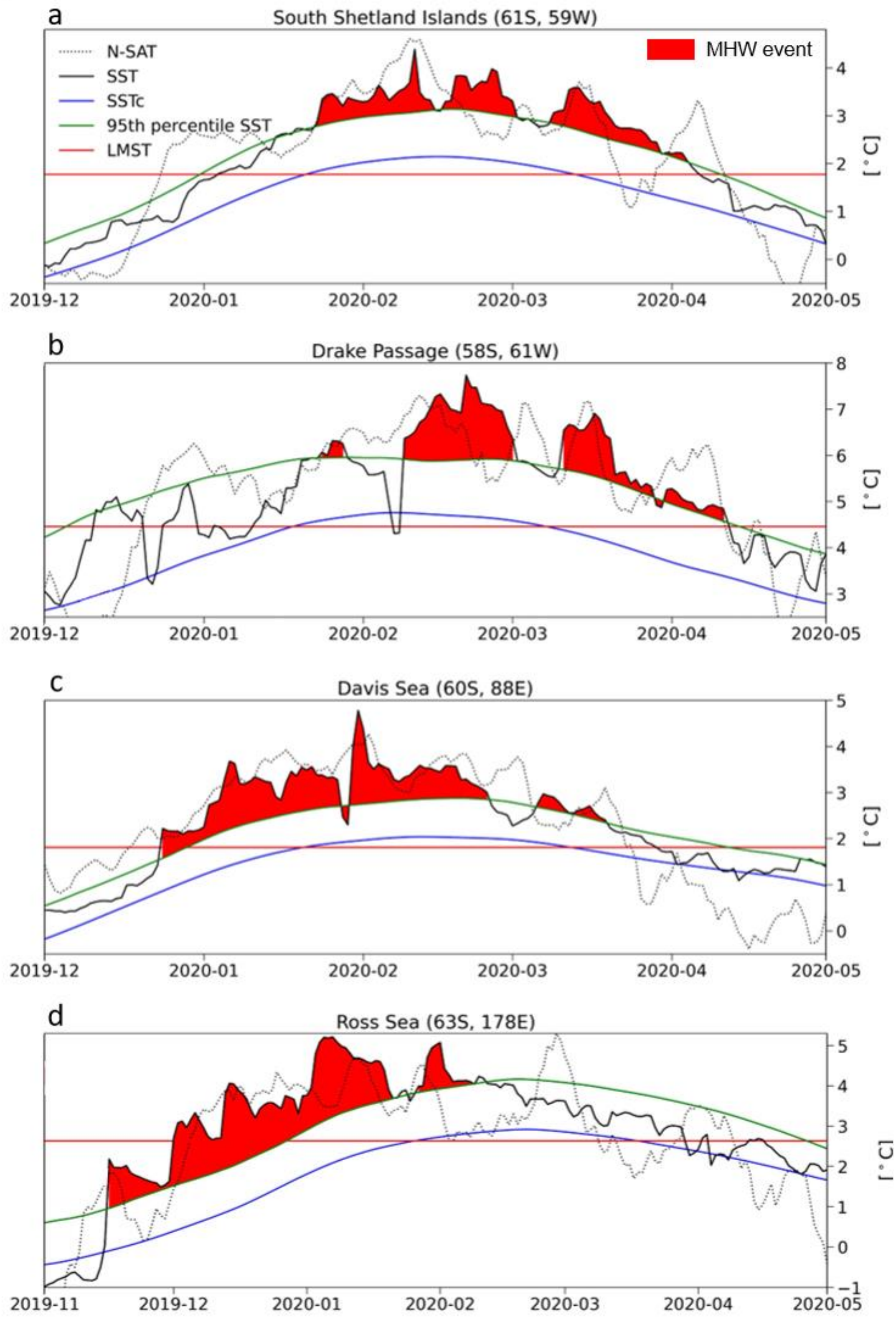
Supplementary Fig. S6 | Causal inferences between Maximum Sea Surface Temperature Anomalies (Max SSTA), Sea Ice Concentrations (SIC) and Mixed Layer Depth (MLD). Causation is detected in monthly time series of (**a–b**) Max SSTA versus SIC, and (**c–d**) Max SSTA versus MLD, through the Convergent Cross Mapping (CCM) method[2]. In this context, 'X xmap Y' indicates the forcing impact of Y on the variations of X. The predictive skill of cross map estimates is indicated by the correlation coefficient (ρ). In **a–d**, areas south of 40ºS with mean SIC greater than 20% have been masked out.



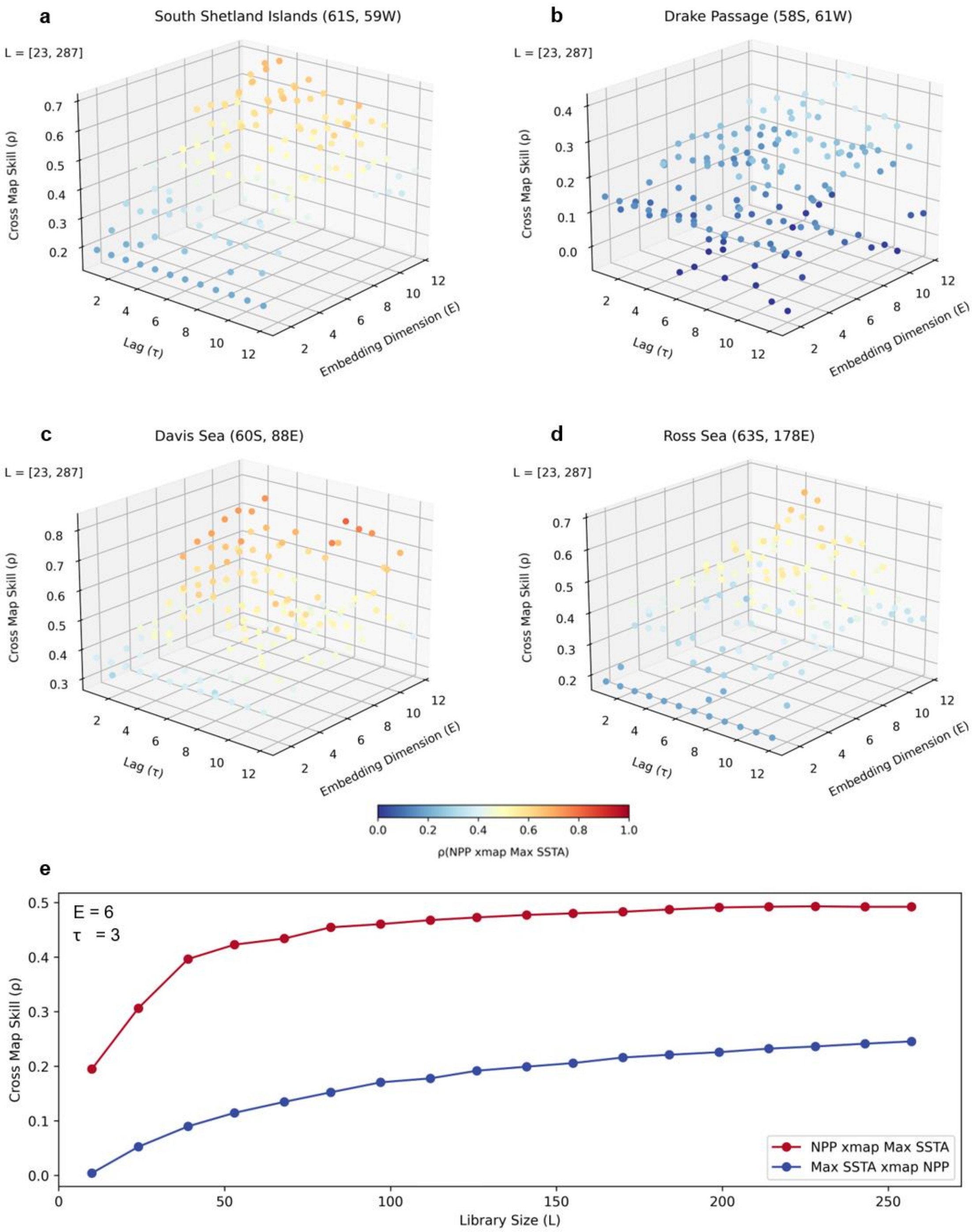
Supplementary Fig. S7 | Dominant surface (upper 30 m average) trace metal, nutrients and chlorophyll concentration trends in the Southern Ocean. (**a–o**) Trends in surface mole concentration of dissolved iron (**a–c**), silicate (**d–f**), nitrate (**g–i**), phosphate (**j–l**), and mass concentration of chlorophyll in sea water from C3S Global Ocean Biogeochemistry Hindcast, during 1998-2015 (**a**, **d**, **g**, **j**, and **m**), 2009–2015 (**b**, **e**, **h**, **k,** and **n**), and 2015–2021 (**c**, **f**, **i**, **l**, and **o**). Please, note that iron trends are expressed in nanomolar per year in **a–c**, and the color bar for chlorophyll trends (**m–o**) is reversed for clearer interpretation.



Supplementary Fig. S8 | Causal inferences between Net primary production (NPP) and Maximum Sea Surface Temperature (Max SSTA), Sea Ice Concentration (SIC) and Mixed Layer Depth (MLD). Convergent Cross Mapping (CCM)[2] (or lack thereof) of the impacts of monthly NPP on (**a**) Max SSTA, (**b**) SIC, and (**c**) MLD from 1998 to 2021 south of 40ºS where SIC is lower than 20%. The predictive skill (Cross Map Skill) estimates is indicated by the correlation coefficient (ρ).



Supplementary Fig. S9 | Temporal evolution of MHW events at different locations around the Southern Ocean. (**a-d**) MHWs (red shading) in (**a**) South Shetland Islands (61ºS, 59ºW), (**b**) Drake Passage (58ºS, 61ºW), (**c**) Davis Sea (60ºS, 88ºE), and (**d**) Ross Sea (63ºS, 178ºE) in 2019-2020 are indicated by ESA CCI C3S daily sea surface temperature (SST, solid black), climatological SST (SSTc, solid blue), MHW criterion (95th percentile SST, solid green), long-term mean summer temperature (LMST, solid red) and ECMWF ERA5 near-surface air temperature (N-SAT, dotted black). A 7-day running mean filter is applied to N-SAT.



Supplementary Fig. S10 | Detecting causation through Convergent Cross Mapping (CCM)[2] between monthly time series (1998-2021) of Maximum Sea Surface Temperature Anomalies (Max SSTA) and Net Primary Production (NPP) at various locations in the Southern Ocean. (**a-d**) Sensitivity test through mutual information analysis where cross-mapping skill (ρ) is shown as a function of cross-mapping lags (τ) and embedding dimensions (E). (**e**) With convergence (E = 6 and τ = 3), ρ increases with time series (library) length (L), where the effect of Max SST on NPP is stronger than in the reverse. Consequently, predictability of NPP using Max SSTA manifold (NPP xmap Max SSTA) is stronger than the predictability of Max SSTA using NPP manifold (Max SSTA xmap NPP).

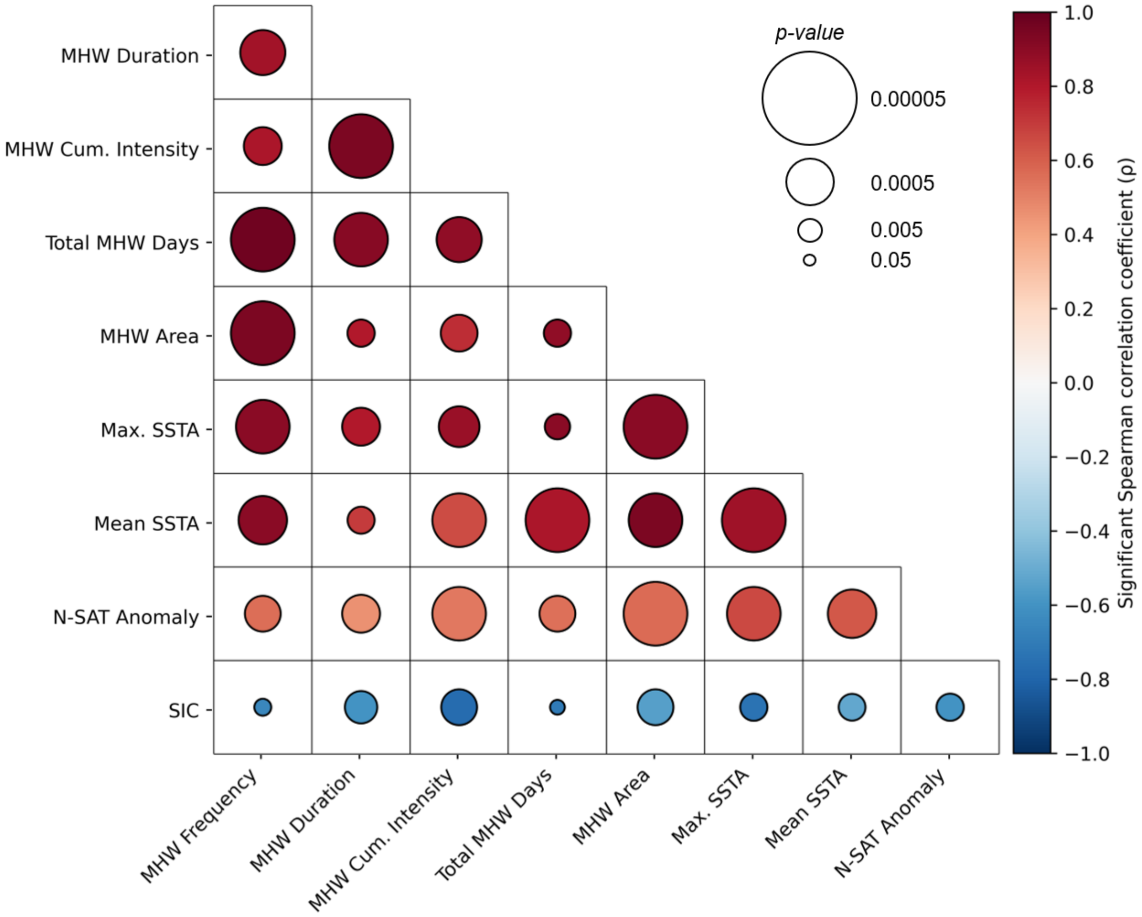
Supplementary Table S1 | Averaged (1982–2015, 2009–2015, and 2015–2021) marine heatwave (MHW) metrics from ESA CCI & C3S daily Sea Surface Temperature (SST) over the Southern Ocean (95th percentile threshold applied). 'Cir' refers to circumpolar mean, whereas 'Pac', 'Atl', and 'Ind' refer to averages in the Pacific, Atlantic, and Indian sectors, respectively.

MHW metric	**1982–2015**				**2009–2015**				**2015–2021**			
	Cir	Pac	Atl	Ind	Cir	Pac	Atl	Ind	Cir	Pac	Atl	Ind
Max SSTA [ºC]	3.19	3.11	3.35	3.12	3.29	3.14	3.55	3.21	3.70	3.56	3.78	3.50
Mean Frequency [number]	1.16	1.11	1.14	1.23	1.44	1.09	1.85	1.58	1.98	1.97	1.88	2.02
Mean Duration [days]	10.65	10.68	9.69	9.92	12.44	12.75	11.01	11.07	14.51	16.25	14.21	13.00
Cumulative intensity [ºC·days]	15.95	15.57	16.37	13.94	19.41	19.58	18.84	15.45	28.02	28.09	27.78	25.28
Total annual MHW days [days]	16.19	16.83	12.26	12.88	20.98	18.32	22.40	17.99	34.14	35.75	29.24	33.32
Area coverage ratio [%]	50.36	47.77	49.60	54.01	57.04	48.35	64.30	62.26	69.03	65.61	65.33	70.77

Supplementary Table S2 | Linear trends (1982–2021) and their fitting uncertainties of spatially-averaged marine heatwave (MHW) metrics derived from the ESA CCI & C3S daily Sea Surface Temperature (SST) in the Southern Ocean using the 95th percentile threshold. The trends are significant at the 95% confidence level of Student's t-test.

MHW metric	**Linear trends**	**Unit**
Max SSTA	0.49±0.23	ºC/decade
Mean Frequency	0.22±0.06	number/decade
Mean Duration	0.85±0.36	day/decade
Cumulative intensity	1.03±0.56	ºC·days/decade
Total annual MHW days	4.17±1.03	day/decade
Area coverage ratio	4.02±1.25	%/decade

Supplementary Table S3 | Correlation coefficients matrix (1982−2021) of relationship between the monthly averaged (from November to March) marine heatwave (MHW) metrics and averaged mean sea surface temperature (SSTA), near-surface air temperature (N–SAT) anomaly, and sea ice concentration (SIC) in the Southern Ocean. The MHW metrics and SIC are derived from the ESA CCI & C3S daily Sea Surface Temperature (SST); N-SAT is from ECMWF ERA-5. The averages are calculated south of 40ºS where mean SIC < 20% in Supplementary Fig. S1. The coefficients are significant at the 95% confidence level of Student's t-test. The size of the scatter is proportional to the significance of the correlation.



Supplementary Methods

Supplementary Methods S1. Heat budget in MOM4p1 (GFDL ESM2M)

The total heat flux (in W m^2) was performed over a time step at a given grid cell using MOM4p1, following Griffies et al.[1]:

$$\Delta Q_{total} = \Delta Q_{adv} + \Delta Q_{a\text{-}s} + \Delta Q_{vmix} + \Delta Q_{vdiff} + \Delta Q_{res}; \quad \text{(S1)}$$

where:

$$\Delta Q_{adv} = \Delta Q_{temp\_advection} + \Delta Q_{neutral\_gm\_temp} + \Delta Q_{temp\_submeso} \quad \text{(S2)}$$

$$\Delta Q_{a\text{-}s} = \Delta Q_{temp\_vdiffuse\_sbc} + \Delta Q_{sw\_heat} \quad \text{(S3)}$$

$$\Delta Q_{vmix} = \Delta Q_{temp\_nonlocal\_kpp} \quad \text{(S4)}$$

$$\Delta Q_{vdiff} = \Delta Q_{temp\_vdiffuse\_impl} - \Delta Q_{temp\_vdiffuse\_sbc} \quad \text{(S5)}$$

$$\Delta Q_{res} = \Delta Q_{sfc\_hflux\_pme} + \Delta Q_{neutral\_diffusion\_temp} + \Delta Q_{temp\_runoffmix} \quad \text{(S6)}$$

$$+ \Delta Q_{temp\_calvingmix} + \Delta Q_{frazil\_2d}.$$

Please, see a detailed description of the terms in Griffies et al.[1].

Supplementary References

1. Griffies, S. M. Working notes on the ocean heat budget in GFDL-ESM2M. https://mom-ocean.github.io/assets/pdfs/ESM2M_heat_budget.pdf [Accessed February 8, 2024]. (2015).

2. Sugihara, G. *et al.* Detecting Causality in Complex Ecosystems. *Science* **338**, 496–500 (2012).