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Oxygen minimum zones in the Indian Ocean and their response to changes in the Indian Ocean meridional circulation

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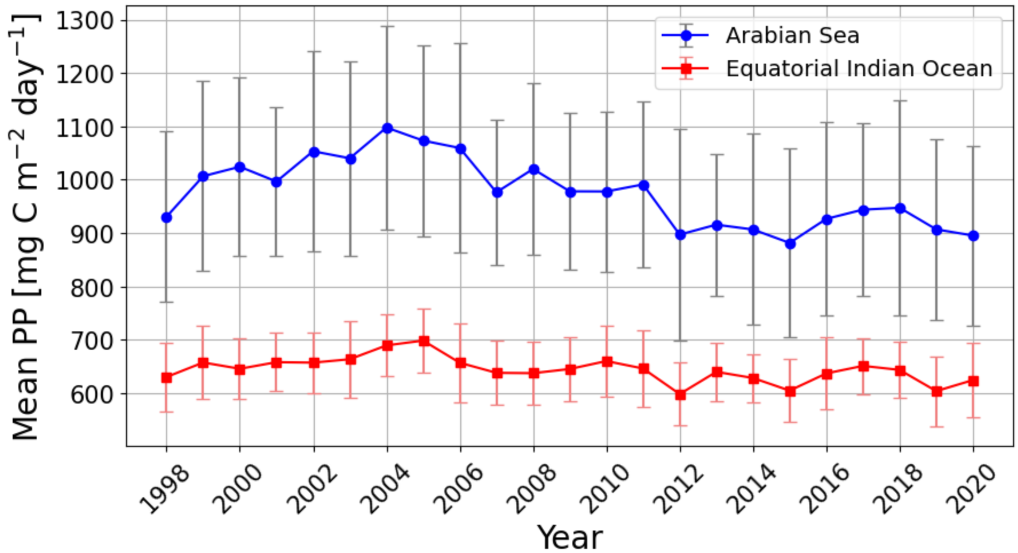


Figure S1: Mean and standard deviation of annual primary productivity (PP) in the Arabian Sea (5° N–25° N, 50° E–75° E) and equatorial Indian Ocean (8° S–8° N, 55° E–85° E).

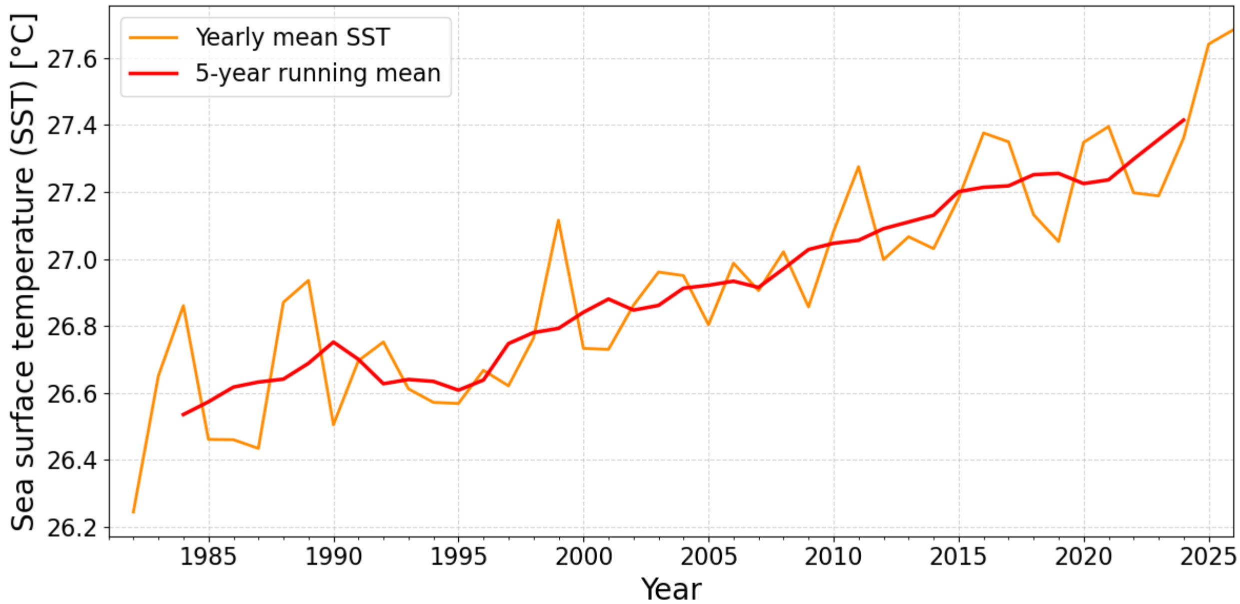


Figure S2: Mean sea surface temperature across the Indian Ocean (30° N–30° S, 30° E–120° E).

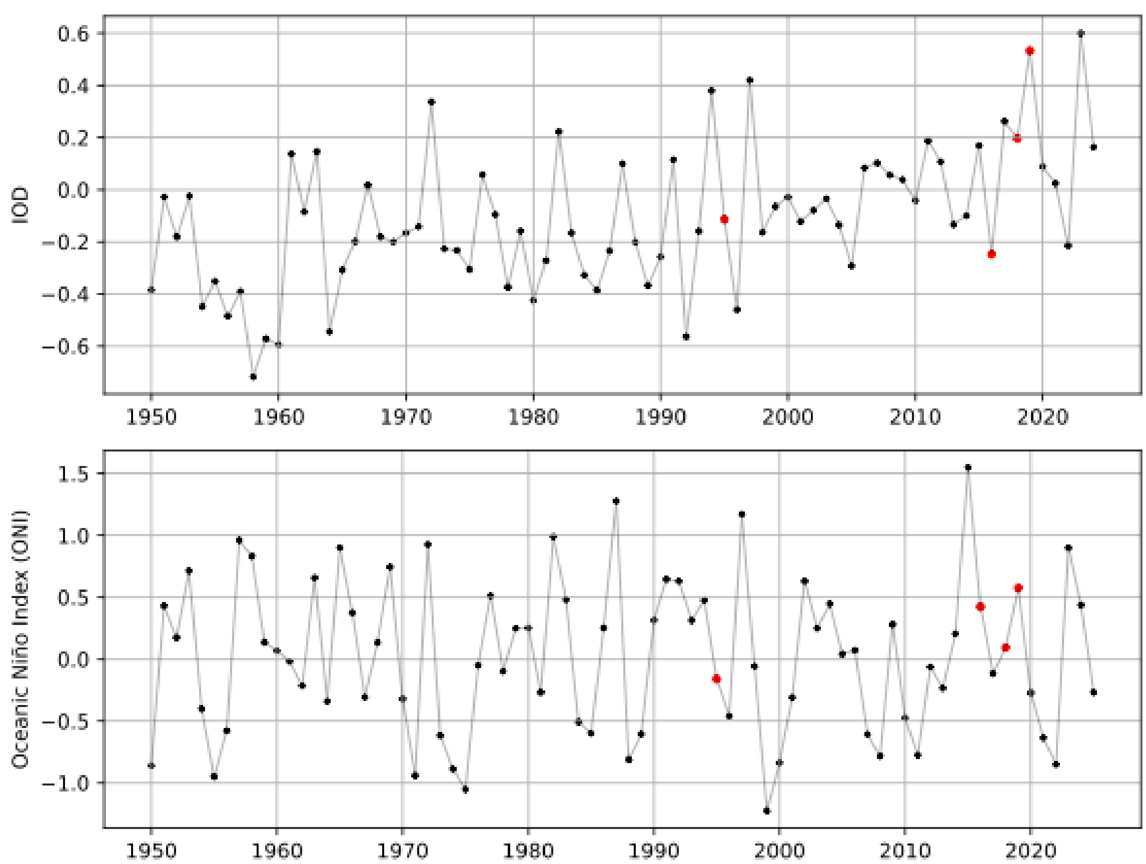
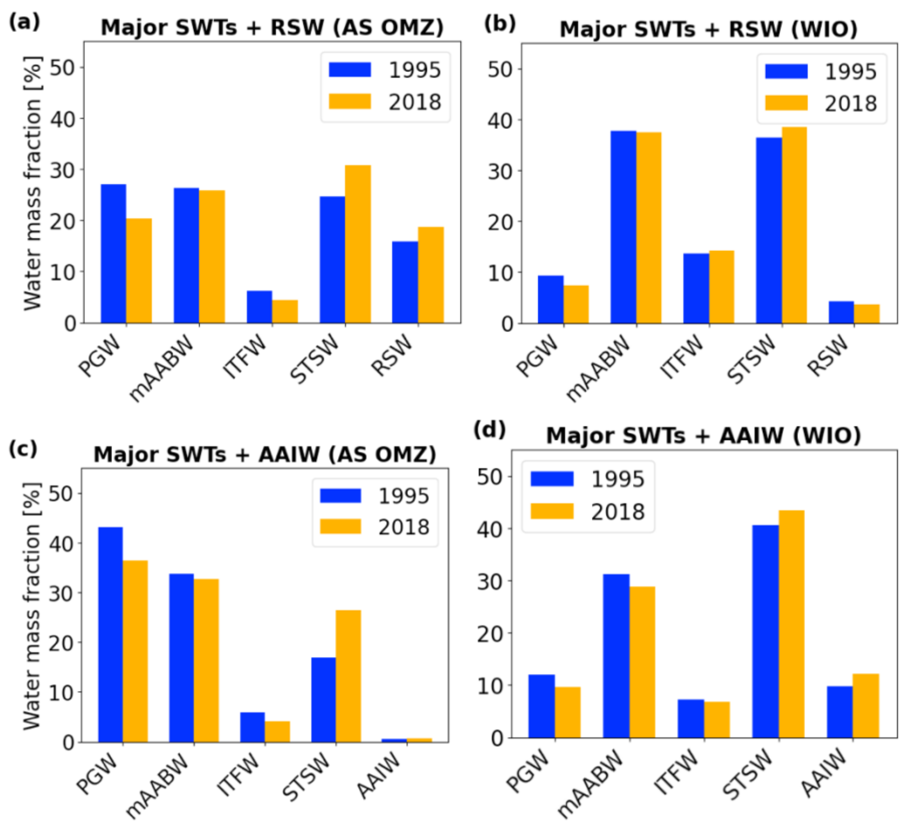


Figure S3: Mean Indian Ocean Dipole (IOD) Oceanic Niño Index (ONI). The ONI represents sea surface temperature (SST) anomalies in the tropical Pacific Ocean (5° N–5° S, 120° W–170° W) and the IOD shows anomalous in the SST gradient between the western (50° E–70° E and 10° S–10° N) and eastern Indian Ocean (90° E–110° E and 10° S–0° N).


(a)
Major SWTs + RSW (AS OMZ)
Water mass fraction [%]
1995
2018
PGW
mAABW
ITFW
STSW
RSW
(b)
Major SWTs + RSW (WIO)
1995
2018
PGW
mAABW
ITFW
STSW
RSW
(c)
Major SWTs + AAIW (AS OMZ)
Water mass fraction [%]
1995
2018
PGW
mAABW
ITFW
STSW
AAIW
(d)
Major SWTs + AAIW (WIO)
1995
2018
PGW
mAABW
ITFW
STSW
AAIW

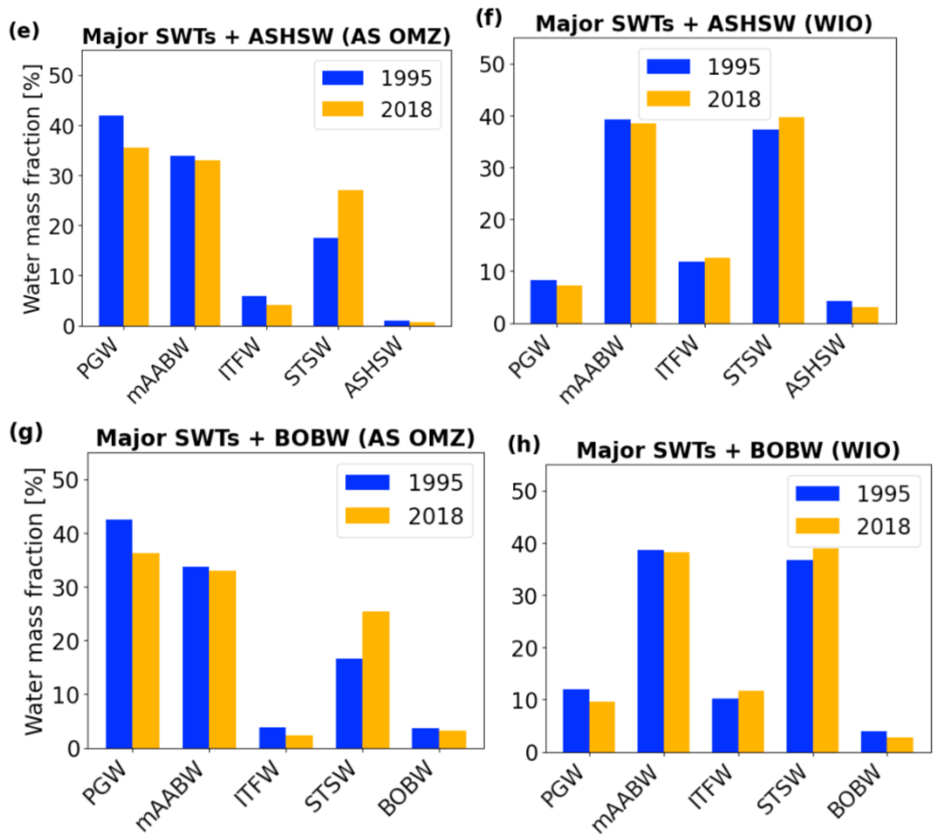
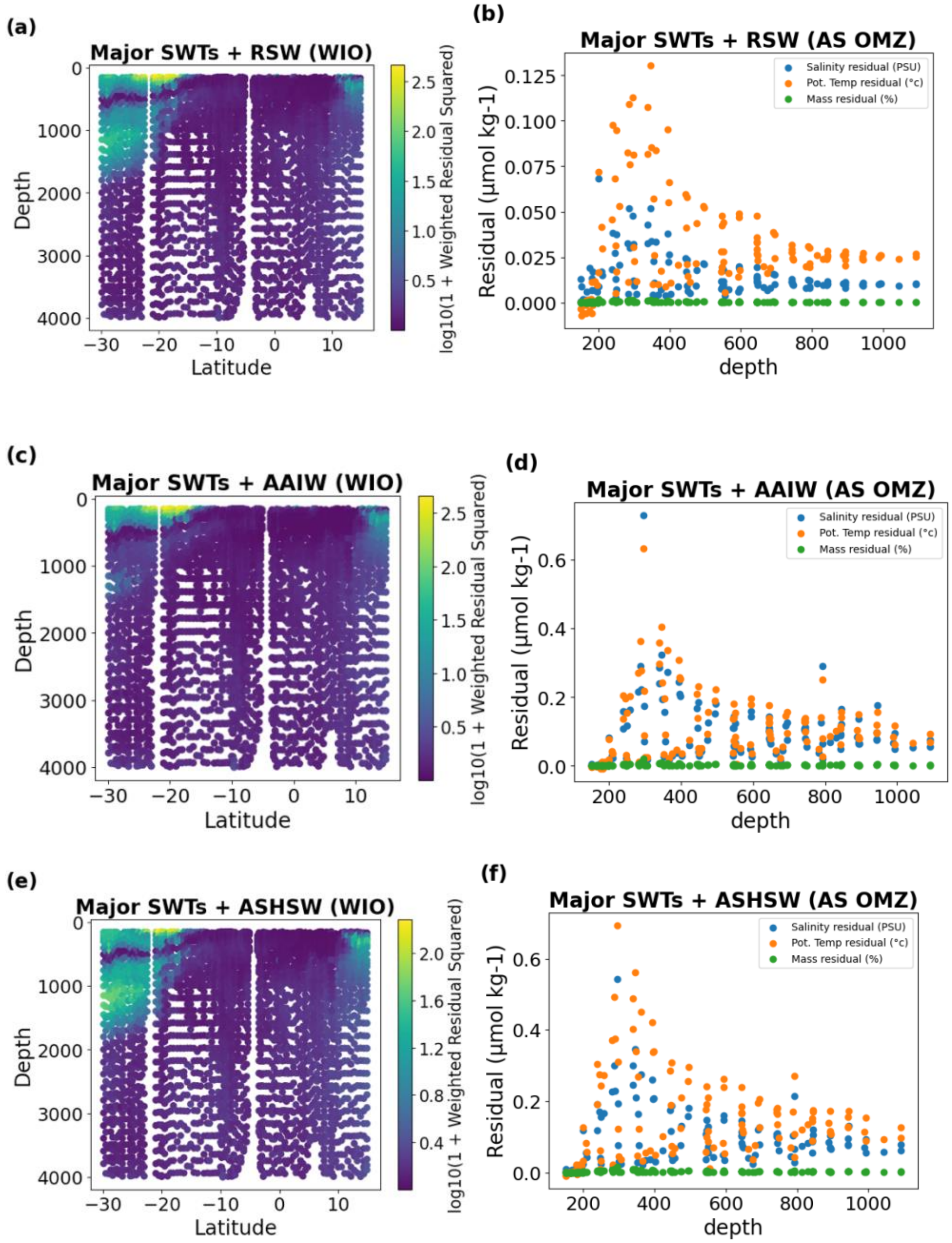


Figure S4: Source water type (SWT) fractions from overdetermined eOMP analysis using the western Indian Ocean (WIO, 150–1200 m) transect and Arabian Sea oxygen minimum zone (AS OMZ, O_2 < µmol kg^{-1}, 150–1000 m). Major source water types (SWTs) include Persian Gulf water, modified Antarctic bottom water, Subtropical surface water and Indonesian throughflow water. Showing results of eOMP analysis using major SWTs and (a, b) Red Sea water (RSW), (c, d) Antarctic intermediate water (AAIW), (e, f) Arabian Sea high salinity water (ASHSW), (g, h) Bay of Bengal water (BOBW)



(a)
Major SWTs + RSW (WIO)
Depth
Latitude
log10(1 + Weighted Residual Squared)
(b)
Major SWTs + RSW (AS OMZ)
Salinity residual (PSU)
Pot. Temp residual (°c)
Mass residual (%)
Residual (µmol kg-1)
depth
(c)
Major SWTs + AAIW (WIO)
Depth
Latitude
log10(1 + Weighted Residual Squared)
(d)
Major SWTs + AAIW (AS OMZ)
Salinity residual (PSU)
Pot. Temp residual (°c)
Mass residual (%)
Residual (µmol kg-1)
depth
(e)
Major SWTs + ASHSW (WIO)
Depth
Latitude
log10(1 + Weighted Residual Squared)
(f)
Major SWTs + ASHSW (AS OMZ)
Salinity residual (PSU)
Pot. Temp residual (°c)
Mass residual (%)
Residual (µmol kg-1)
depth

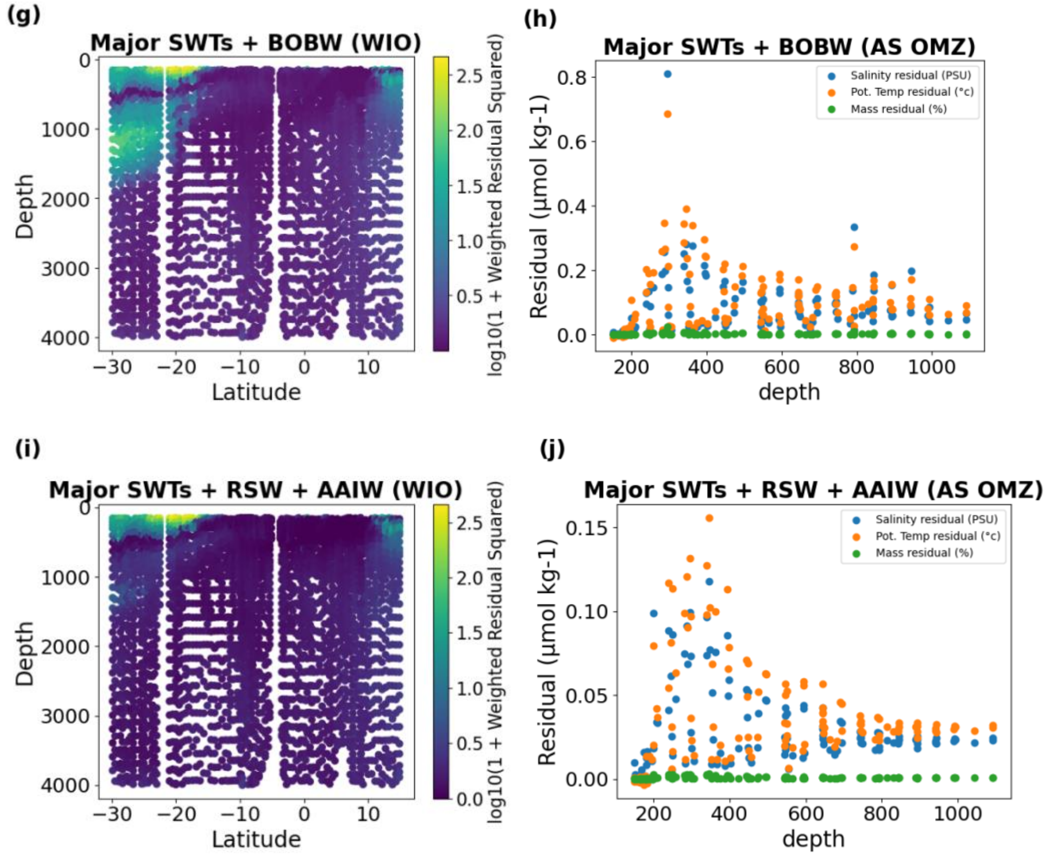


Figure S5: eOMP residual from overdetermined analysis using 1995 western Indian Ocean transect (WIO, 150–1200 m, including all parameter residual) and Arabian Sea oxygen minimum zone (AS OMZ, O_2 < µmol kg^{-1}, 150–1000 m). Major source water types (SWTs) include Persian Gulf water, modified Antarctic bottom water, Subtropical surface water and Indonesian throughflow water. Showing results of eOMP analysis using major SWTs and (a, b) Red Sea water (RSW), (c, d) Antarctic intermediate water (AAIW), (e, f) Arabian Sea high salinity water (ASHSW), (g, h) Bay of Bengal water (BOBW), (i, j) a combination of RSW and AAIW

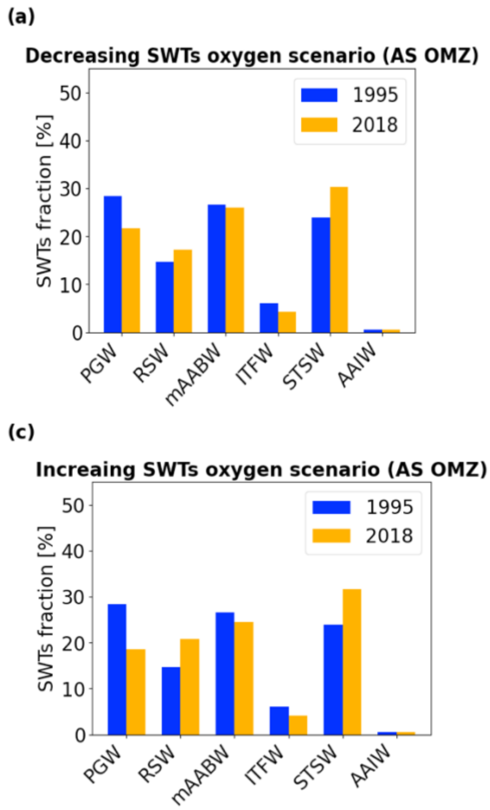


Figure S6. Source water type (SWT) fractions from oxygen variability sensitivity test in the Arabian Sea oxygen minimum zone (AS OMZ). (a) decreasing SWT oxygen scenario, (b) constant SWTs oxygen scenario and (d) increasing SWTs oxygen scenario

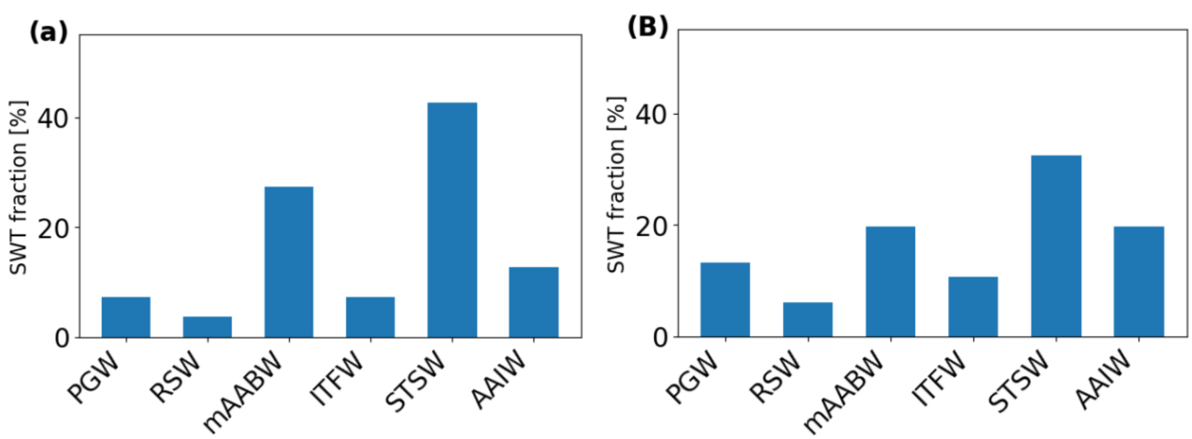


Figure S7: Source water type (SWT) fractions from SWT properties sensitivity test using 2018 western Indian Ocean transect, 15° N–30° S, at depth between 150–1200 m (a) study defined SWT properties according to table 2, (b) SWT properties defined from literature values according to supplementary table S1.

Table S1. Source water type definition from literature, used for source water types (SWTs) properties sensitivity analysis. See figure S5 for SWTs abbreviation meaning.

Source water types	Potential Temp. (°C)	Salinity	Oxygen ($\mu mol\ kg^{-1}$)	Phosphate ($\mu mol\ kg^{-1}$)	Nitrate ($\mu mol\ kg^{-1}$)	Silicate ($\mu mol\ kg^{-1}$)
PGW	18.11	36.5	43.75	2.12	21.05	14.64
RSW	12	36.2	28	2.55	30	31.29
mAABW	0.8	34.72	245	2.12	30.53	117
AAIW	7.04	34.48	233.97	1.59	28.57	34.19
ITFW	17	35.2	108.93	2.28	13.31	21.33
STSW	13.28	35.30	200	0.29	2.85	3.45
Weights	36	36	14	5	5	1

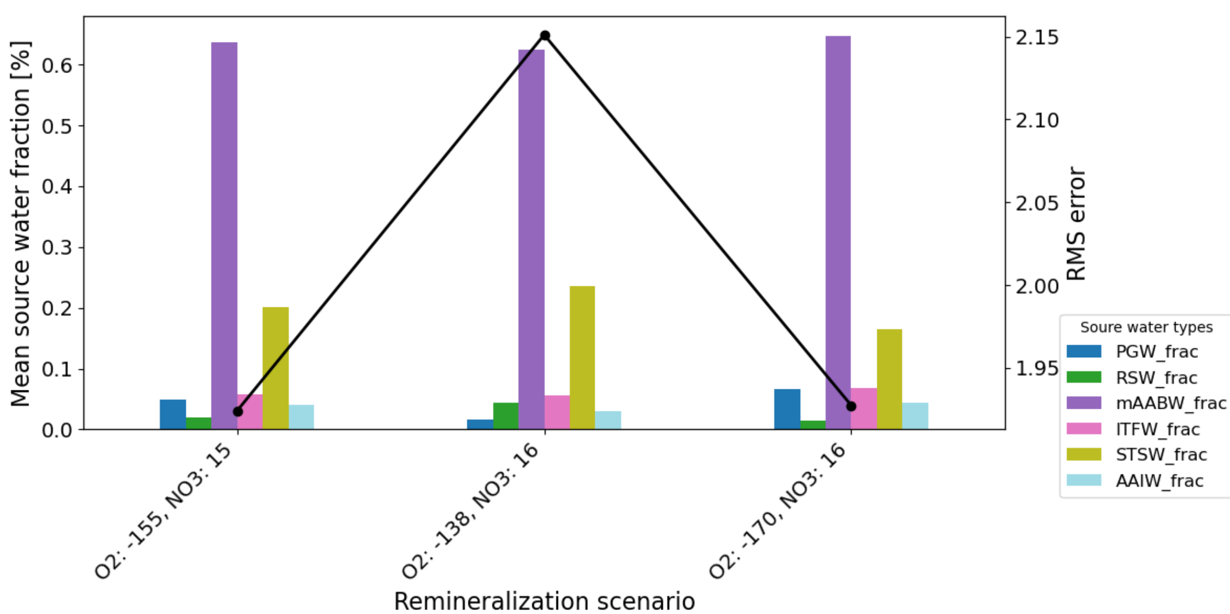


Figure S8: Sensitivity of eOMP solution to remineralization ratio (O_2:PO_4:NO_3). Showing variation in source water type fractions and root mean square (RMS) Error across different scenarios. PO_4 value equal 1 in all scenarios. Persian Gulf Water (PGW), Red Sea Water (RSW), Arabian Sea High Salinity Water (ASHSW), Bay of Bengal Water (BOBW),

Indonesian Throughflow Water (ITFW), Subtropical Surface Water (STSW), Antarctic Intermediate Water (AAIW), modified Antarctic Bottom Water (mAABW).

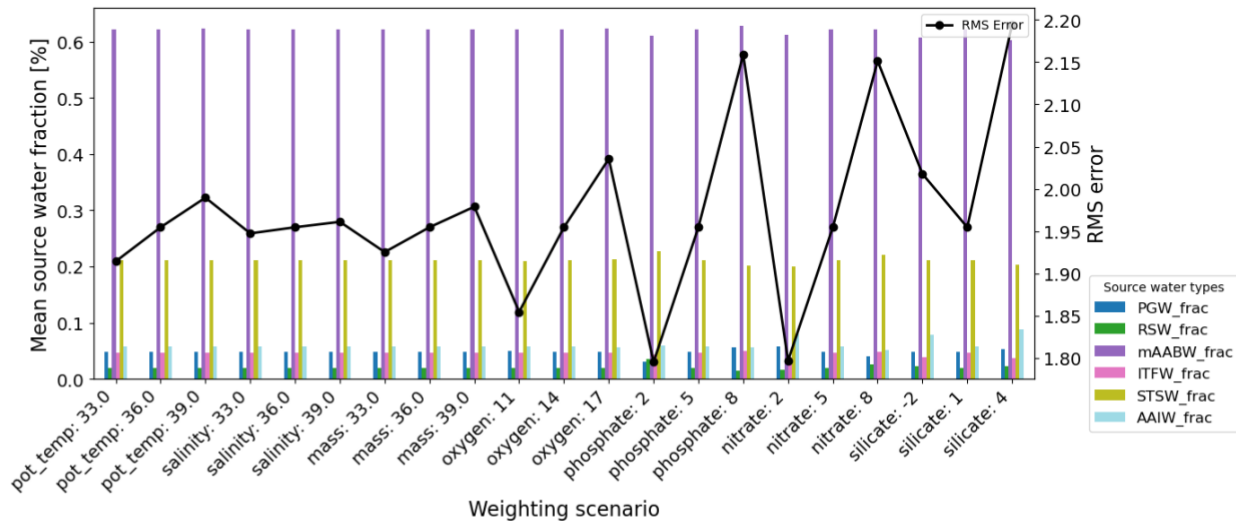


Figure S9: Sensitivity of eOMP solution to parameter weights. Showing variation in source water type fractions and root mean square (RMS) Error across different scenarios. Persian Gulf Water (PGW), Red Sea Water (RSW), Arabian Sea High Salinity Water (ASHSW), Bay of Bengal Water (BOBW), Indonesian Throughflow Water (ITFW), Subtropical Surface Water (STSW), Antarctic Intermediate Water (AAIW), modified Antarctic Bottom Water (mAABW).

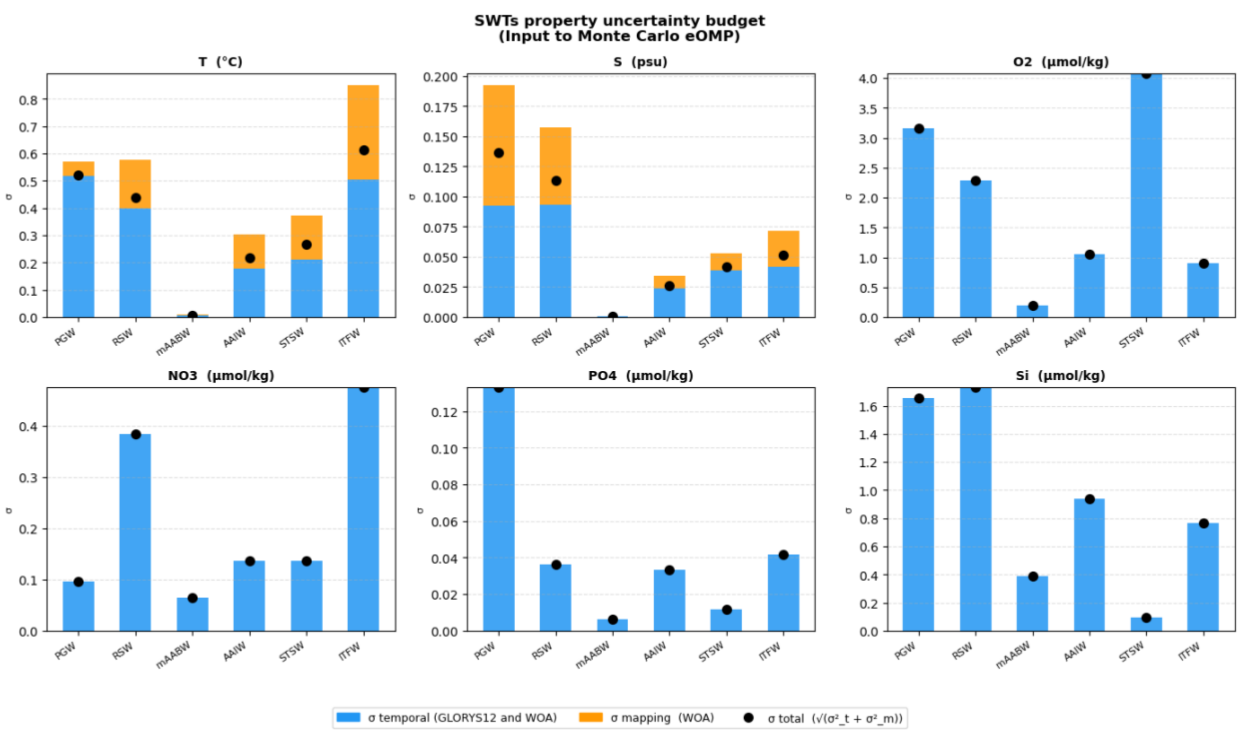


Figure S10: Source water property uncertainty budget. Each panel shows the uncertainty decomposition for one eOMP property across the six final SWTs. Blue bars: temporal uncertainty (σ_temporal), interannual standard deviation from GLORYS12 (1993–2020) for T and S, the WOA23 1971–2000 minus all-period difference for O_2, and the WOA23 sparsity-weighted standard error for nutrients. Orange bars: spatial-mapping uncertainty (σ_mapping), the WOA23 sparsity-weighted standard error, shown only for T and S (set to zero for O_2 and nutrients to avoid double-counting; Section 2.5.1). Black points: total uncertainty combined in quadrature.

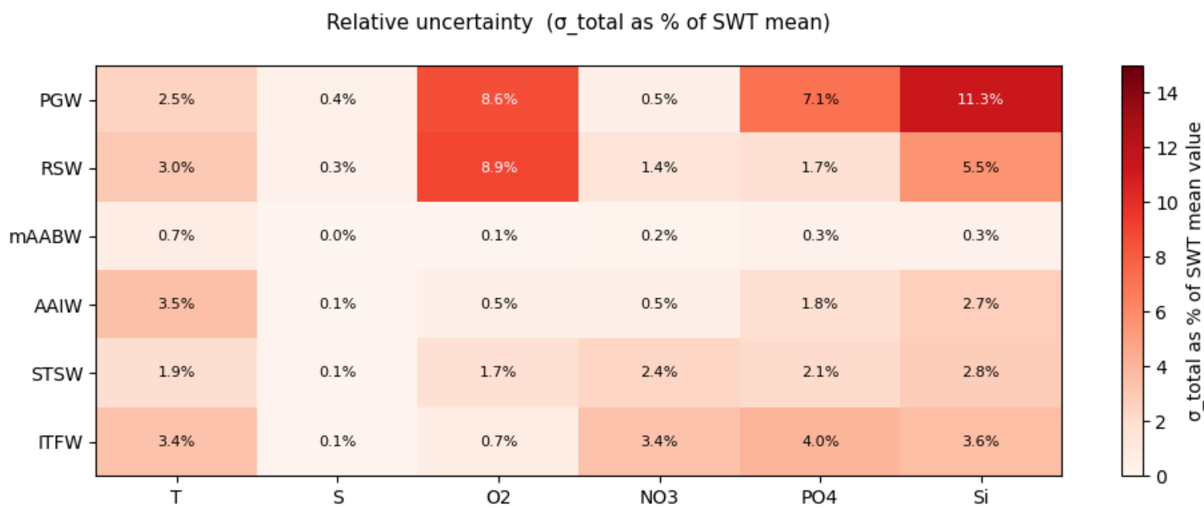


Figure S11: Relative uncertainty in the SWT property definitions. Each cell shows the ratio of the total uncertainty (σ_total) to the SWT's mean value for that property, expressed as a percentage.

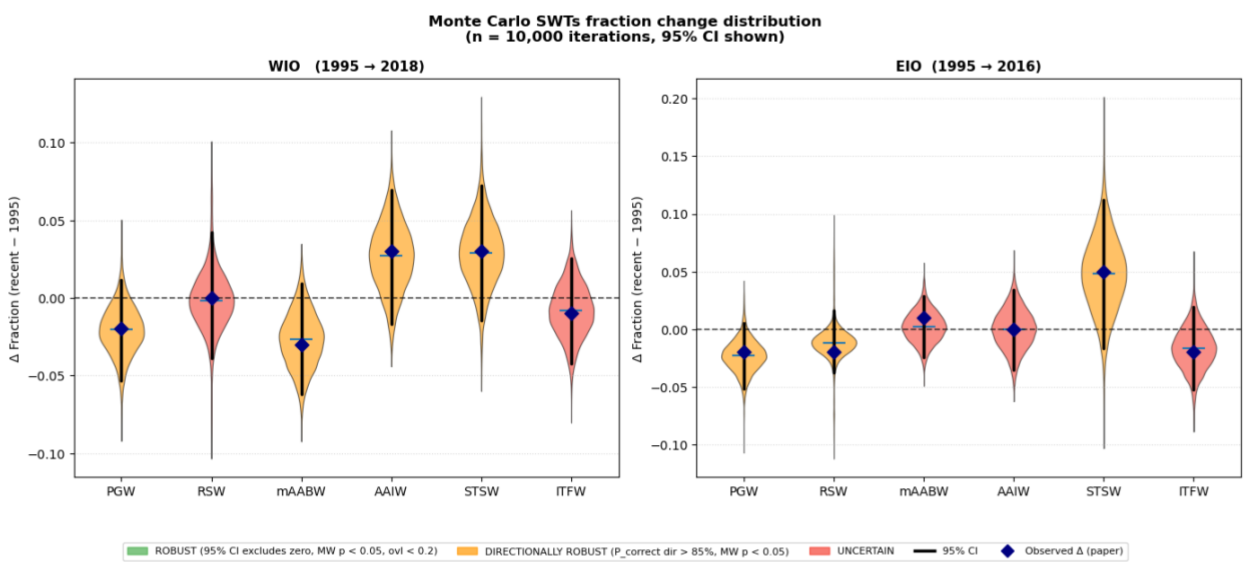


Figure S12: Monte Carlo distributions of the change in SWT mixing fractions (Δfraction = recent − 1995) for the full western (WIO, 1995 → 2018) and eastern (EIO, 1995 → 2016) Indian Ocean transects (150–1200 m), from 10,000 perturbation iterations. Each violin shows the probability distribution of Δfraction for one SWT; the black vertical bar marks the 95% confidence interval (CI) with the blue horizontal line representing Monte Carlo mean. The blue diamond represents the observed change from the eOMP solution. Violins are coloured by robustness verdict: green for robust (95% CI excludes zero, overlap coefficient OVL < 0.20, Mann-Whitney $p < 0.05$), orange for directionally robust (≥85% of iterations in the observed direction, $p < 0.05$, CI includes zero), and red for uncertain. The dashed line marks zero change.

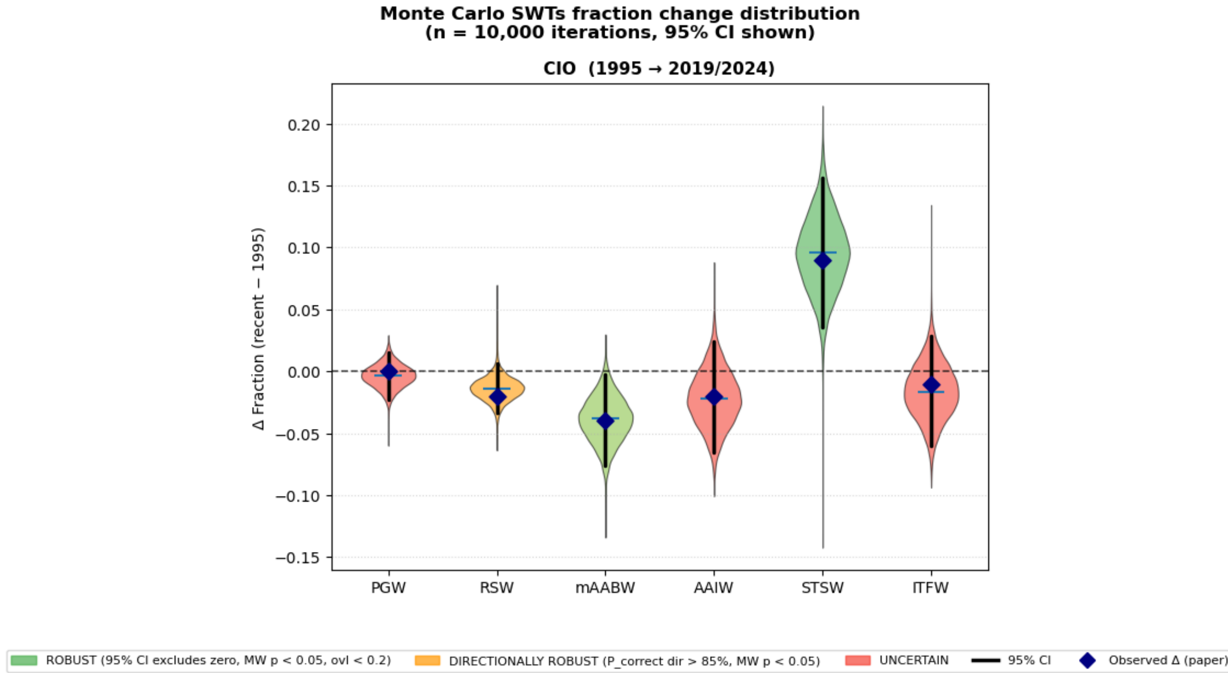


Figure S13: Monte Carlo distributions of the change in SWT mixing fractions (Δfraction = recent − 1995) for the central Indian Ocean (CIO) transect (150–1200 m), from 10,000 perturbation iterations (See Figure S13 for figure elements explanation).

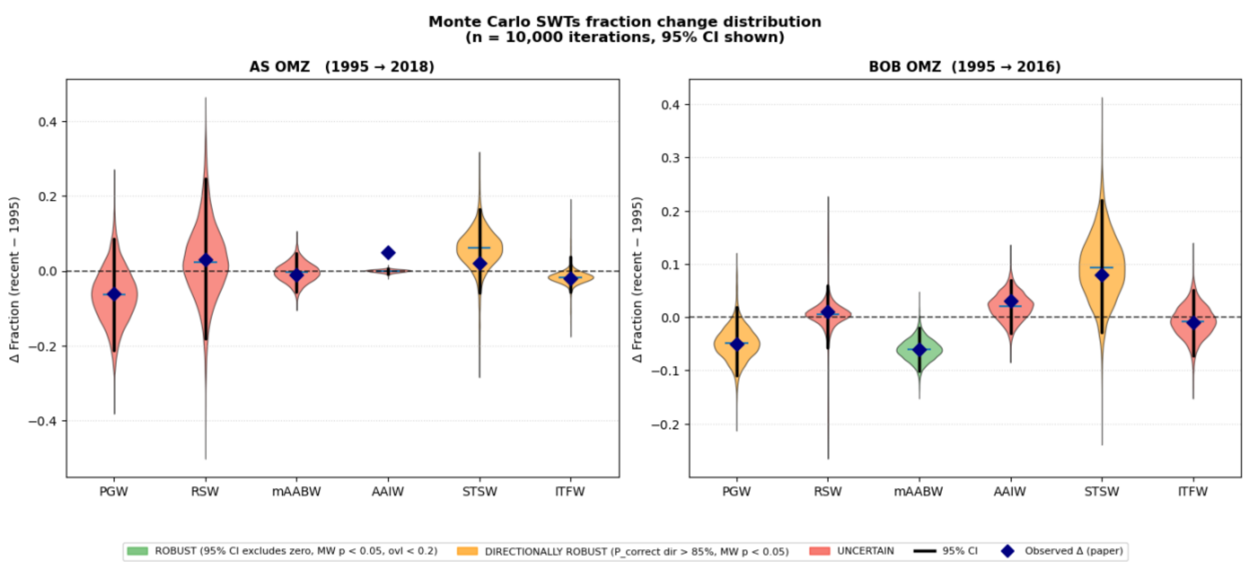


Figure S14: Monte Carlo distributions of the change in SWT mixing fractions (Δfraction = recent − 1995) for the Arabian Sea OMZ (AS OMZ) and Bay of Bengal OMZ (BOB OMZ) cores ($O_2 < 20$ µmol kg^{-1}), from 10,000 perturbation iterations (See Figure S13 for figure elements explanation).

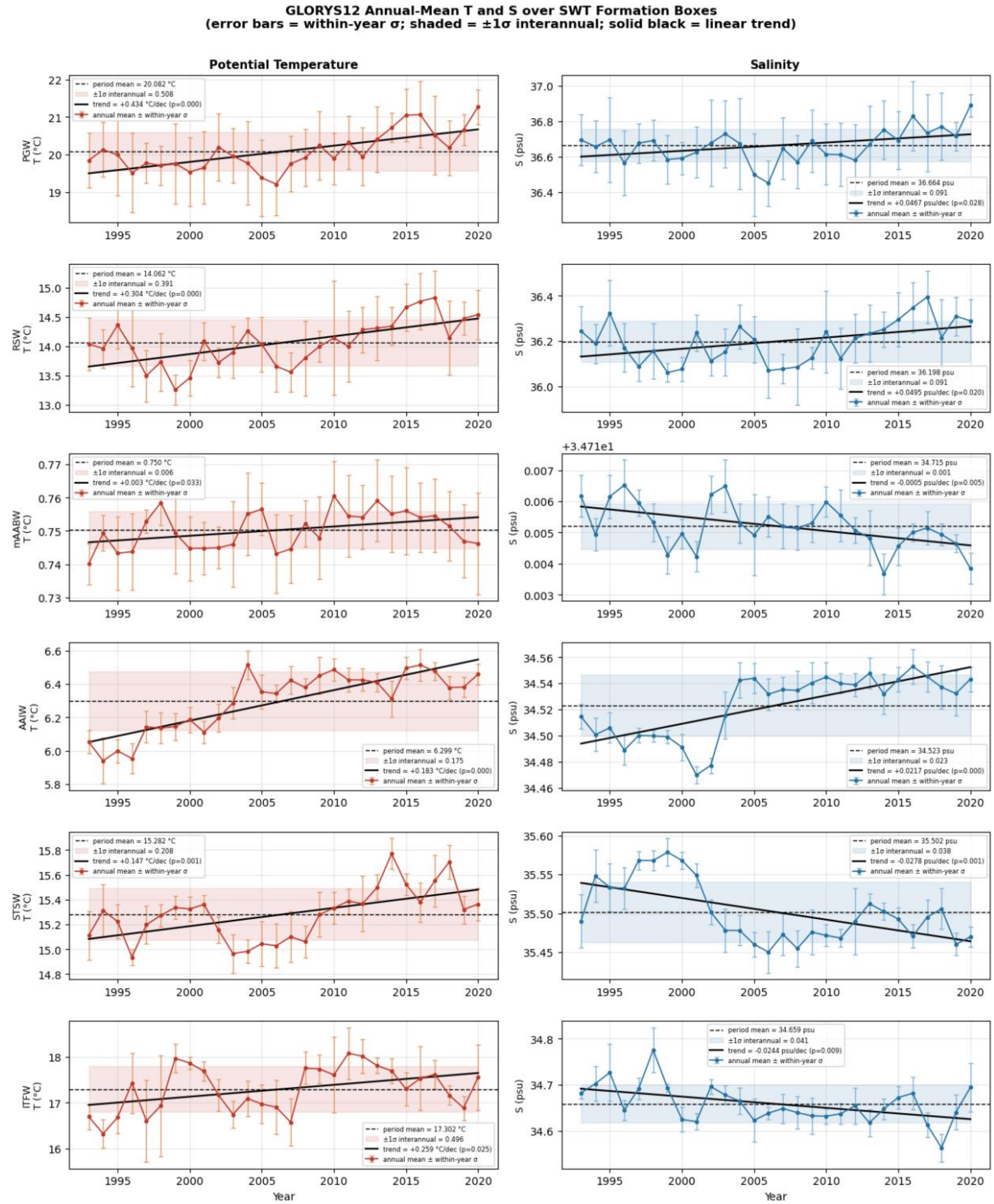


Figure S15: Monte Carlo Annual-mean potential temperature (left, red) and salinity (right, blue) over the six source water types (SWTs) formation boxes, derived from the GLORYS12 ocean reanalysis (1993–2020). Box-mean values were computed using cosine-latitude area weighting. Each marker is the annual mean and the orange/blue error bars denote

the within-year (seasonal) standard deviation. The dashed line marks the period mean and the shaded band shows ±1 standard deviation of the annual means (the interannual variability, σ_temporal, used in the Monte Carlo perturbation analysis; Section 2.5). The solid black line is the ordinary least-squares linear trend, with its slope (per decade) and p-value given in each panel legend. SWTs are shown in rows.

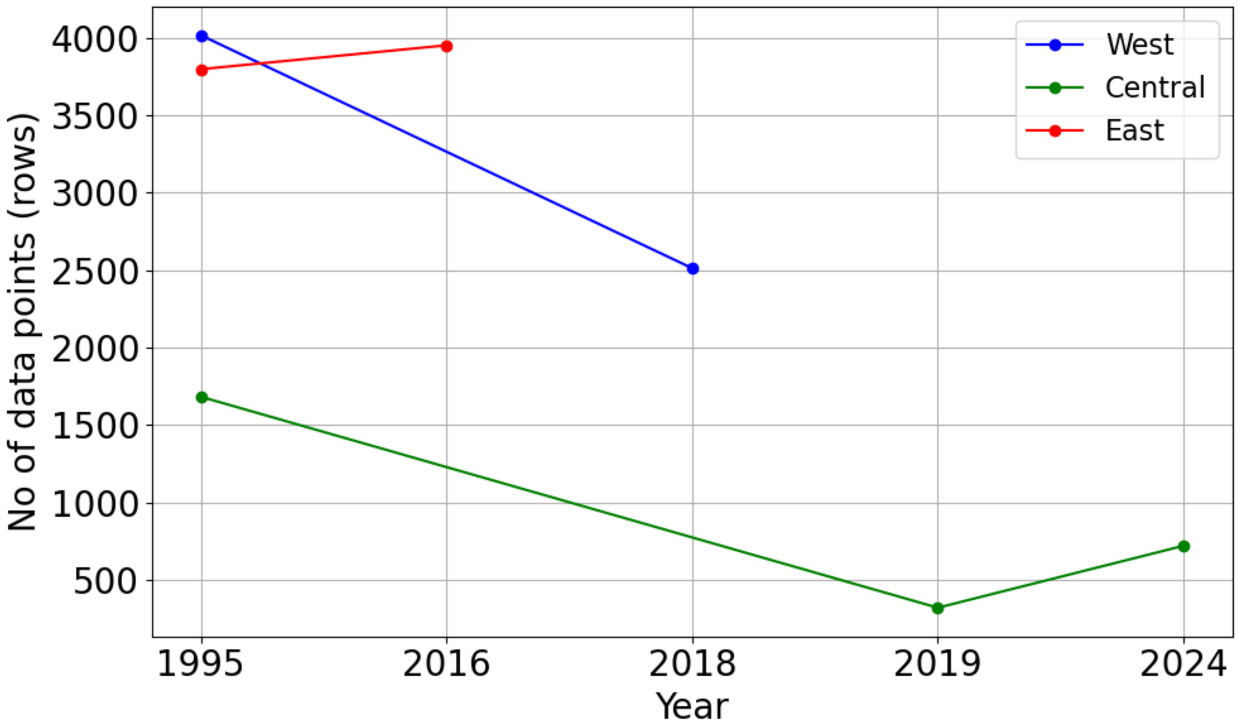


Figure S16: Number of data points across western Indian Ocean transect (west), eastern Indian Ocean transect (east), and central equatorial Indian Ocean transect (central).