Response to Reviewers

Manuscript: egusphere-2025-4712

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

General response

We thank the reviewers for their careful and constructive second review. The manuscript is substantially improved as a result. We have addressed all of the reviewer's comments below. Based on reviewer 1 comments, we have substantially revised the manuscript text and addressed all typos and vague statements. See point-by-point response below. Reviewer 2 identifies a core methodological concern: that the extended optimum multi-parameter (eOMP) analysis inherently assumes stationarity in source water types (SWTs) properties, and that without rigorous uncertainty quantification, the attribution of observed oxygen differences to changes in the Indian Ocean meridional overturning circulation (MOC) and global thermohaline circulation (THC) remains unsubstantiated. We take this concern seriously and have responded with a comprehensive uncertainty analysis as requested. Specifically, we have implemented a sparsity-weighted Monte Carlo perturbation analysis (n = 10,000 iterations), as suggested by the reviewer, that propagates two independent uncertainty components (1) temporal variability at SWTs formation regions and (2) spatial mapping error, through the full eOMP solution for all transects. The results are presented below and in revised supplementary figures (Figs. S10–S14). We note that the analysis yields mixed but honest results: some signals are statistically robust; others are directionally consistent but not formally confirmed at the 95% confidence level. We have revised the manuscript accordingly to integrate the Monte Carlo analysis. We believe this transparency strengthens rather than weakens the paper's contribution.

Response to Reviewer 1 Comments

Each comment is quoted in full, followed by our response.

General Point: MOC vs THC Terminology

Reviewer Comment	*Clarify MOC vs THC. One rarely sees both of these terms used in the same article, given that they often describe the same circulation system (e.g. Toggweiler and Russell 2008). If I understand correctly, you mean to use MOC to refer to both the shallow Indian Ocean overturning cell (which includes the transport by the western boundary current) and the deeper Indian Ocean overturning (flow of intermediate and deep waters from the southern ocean which then upwell in the northern Indian Ocean), while you use THC to refer exclusively to the global overturning circulation which also controls the intermediate and deep transport through the ITF. I appreciate that these are complex systems of ocean circulation and their labels and classification are very much up for interpretation. But I would urge you to be clear, consistent and careful about existing associations that the reader might have with each of these terms.*

Authors' Response	We thank the reviewer for this important clarification. We have adopted a consistent framework throughout the revised manuscript: Indian Ocean meridional overturning circulation (IO-MOC) = the regional Indian Ocean overturning circulation, comprising a shallow cell (upper 300–450 m), and a deep cell with an intermediate limb and an abyssal limb Regarding the Global thermohaline circulation (THC) we were more specific and referred on the warm water return flow of global thermohaline circulation linking the Atlantic, Indian, and Pacific basins via the ITF and Agulhas leakage. We have included such definitions for exactly how IO-MOC and THC are used in the manuscript in the "Study area" so readers can understand exactly what is meant by each terminology throughout the manuscript.

Reviewer Comment	*Regarding the title: while using 'MOC' to refer to the local shallow overturning isn't wrong, per se, I would guess that most readers will expect this to refer to the global overturning (AMOC, Southern MOC – what you call THC).*
Authors' Response	Addressed by title revision. The revised title now reads: "Oxygen minimum zones in the Indian Ocean and their response to changes in the Indian Ocean meridional circulation." This removes the ambiguity with the global MOC/AMOC that most readers would associate with 'MOC' alone. The explicit qualifier "Indian Ocean" signals to the reader that this refers to the regional overturning rather than the global AMOC.

Reviewer Comment	*Lines 152–157: It is strange to me to lump AAIW and AABW together here because AABW would generally be associated with the global THC, but not so much for AAIW. It also leads to confusing notions of 'deep' versus 'intermediate' ventilation throughout. For example, a 9 year transit time to the Indian Ocean might make sense for AAIW, but I would be very surprised if it held for AABW. You also end up with phrases like in lines 638–640, "deep cell of the Indian Ocean MOC at intermediate depths."*
Authors' Response	We agree that lumping AAIW and mAABW together was misleading. The relevant passage (Section 1.1) has been rewritten to distinguish clearly between the intermediate limb (AAIW) and the abyssal limb (mAABW) of the Indian Ocean deep MOC. The revised text now reads: "The deep Indian Ocean MOC comprises an intermediate limb ventilated by AAIW and an abyssal limb supplied by modified Antarctic Bottom Water (mAABW))."

	Transit times for AAIW and mAABW now correctly attributed.

Reviewer Comment	*Line 152: I would explicitly make the connection between the 'deep MOC' and the 'THC' here for clarity.*
Authors' Response	The manuscript has been revised accordingly.

Reviewer Comment	*Line 619: 'shallow MOC including PGW and RSW'. This is the first time we get the association of the marginal seas with the MOC. Is that justified? It might be clearer to simply talk about transport of waters by the western boundary current…*
Authors' Response	Agreed. The phrasing has been revised.

Reviewer Comment	*Section 4.1.2: Here you pile together the impacts of the shallow MOC, deeper MOC and THC here. And it seems like it is this full collection of systems that the title refers to. I appreciate the connections that you want to make; however, the concepts need to be more clear. It feels quite arbitrary when these structures are treated as distinct and when they are treated as related. Just make this very clear at the beginning.*
Authors' Response	Section 4 has been revised and now explicitly defines what is meant by "Indian Ocean MOC" and what is meant by "THC", as previously stated.

Minor Points

Reviewer Comment	*Line 136: 'is weakening' should be 'would weaken'.*
Authors' Response	Corrected.

Reviewer Comment	*Line 240: the term 'eOMP' has not been defined yet.*

Authors' Response	We note that eOMP is defined at first use in the abstract ("extended optimum multi-parameter (eOMP) analysis") and again in the introduction.

Reviewer Comment	*Line 252: SAMW is a primary water mass that has its own distinct formation regions (e.g. Sallée et al. 2006). It aligns with the spectrum of ICW, but is not itself formed by mixing of other endmembers. I think the interpretation in line 255 is too strong, 'Their influence is fully represented through their parent source components.' Using the endmembers to represent the spectrum of ICW is a way to mathematically represent the system, but it does not capture all of the information on water mass formation mechanisms. In other words, it is incorrect to say that all ICW (including SAMW) are formed by a mixing of STSW and AAIW.*
Authors' Response	We agree that using the endmembers to represent the spectrum of ICW is a way to mathematically represent ICW as it is identified by mixing line connecting AAIW and STSW in T/S diagrams (Schott and McCreary Jr, 2001). However, in the revised version we described its formation more clearly and it reads now as follows: "…. although ICW is formed by subduction in the Subtropical Front and advected northward (You and Tomczak, 1993), is not considered as an independent principal water mass as it mixes with STSW and is identified by a mixing T/S line connecting AAIW and STSW (Schott and McCreary Jr, 2001). Additionally it can get diluted with ASW, BoBW, and ITFW (Gordon et al., 1997). SAMW on the other hand, share the same density class and overlap with AAIW (Koch-Larrouy et al., 2010)."

Reviewer Comment	*Line 263: Please define all acronyms here.*
Authors' Response	All eight SWT acronyms are now spelled out in full.

Reviewer Comment	*Line 284: This feels like a big stretch, especially with no reference. Probably better to just acknowledge this limitation of the available data and move on.*
Authors' Response	Agreed. The original justification (invoking CO_2 uptake by the biological carbon pump) has been removed. The text now plainly acknowledges the limitation and how we quantified such uncertainties using the Monte Carlo analysis and SWTs oxygen sensitivity test.

Reviewer Comment	*Lines 294–303: I would say explicitly here that this oxygen adjustment should be reasonable for primary SWTs, even if it may neglect important factors for secondary SWTs. I would also acknowledge here or elsewhere that this is probably not a good assumption for your definitions of PSW and RSW, as those water masses have already undergone quite a lot of mixing when flowing out of the marginal seas.*
Authors' Response	We have added the following lines at the end of Section 2.2.2: "However, this method ignores the influence of deeper water masses on the properties of these SWTs, and it is probably a weaker assumption for PGW and RSW because both water masses already undergo substantial mixing when they flow out of the marginal seas, and their oxygen content reflects this outflow mixing in addition to solubility-driven change. To quantify uncertainty arising from variations in SWT oxygen concentration, we conducted Monte Carlo perturbation analysis and an oxygen sensitivity test as described in Sections 2.5 and 2.6, respectively."

Reviewer Comment	*Lines 305–316: Why is this paragraph in this section?*
Authors' Response	The paragraph placement has been revised.

Reviewer Comment	*Line 348: remind the reader here how many SWTs you consider and how many constraints you have.*
Authors' Response	The opening sentence of Section 2.3.1 now reads: "To achieve a determined eOMP solution, we reduced the number of SWTs using an exclusion process, resulting in six SWTs and seven constraints (temperature, salinity, nitrate, phosphate, silicate, and mass)."

Reviewer Comment	*Lines 442–444: Please list explicitly which SWTs are local, equatorial, and remote. Perhaps also add to Table 3.*
Authors' Response	The categories are now listed explicitly in the text

Reviewer Comment	*Line 448: 'SWTs composition' is a confusing term here. Perhaps 'SWT fraction'?*

Authors' Response	We adopted "SWTs fraction"

Reviewer Comment	*Lines 518–524: Probably need to be a bit more thorough here. Walk the reader through what the patterns are and how they are changing. It is also good practice to have a difference section (e.g., panel b minus panel a) as well for comparison.*
Authors' Response	We have included the difference section and the texts have been revised

Reviewer Comment	*Figure 8: Change colorscale and add a column of difference sections. There are ways to highlight the 0–20 range without saturating the rest of the sections.*
Authors' Response	Previous Figure 8 has been removed from the revised manuscript, as we already have a figure 9, which shows changes in oxygen due to mixing. We have also included an additional figure to show changes in the mAABW.

Reviewer Comment	*Line 631: '…OMZs indicates a reorganization of large-scale ocean circulation'. Really, this indicates a local reorganization of water masses. You need to make the connection to the large-scale circulation changes.*
Authors' Response	The discussion Section has been fully revised.

Reviewer Comment	*Line 635: 'cross-equatorial flow' means flow across the equator, not zonal flow.*
Authors' Response	Corrected. The phrase now reads: "Such a weakening of the cross-equatorial flow seems to have favored the northward (meridional) flow..."

Reviewer Comment	*Line 653–654: this sentence doesn't make sense to me. Please clarify what you mean.*
Authors' Response	The sentence has been rewritten and fully revised.

Reviewer Comment	*Line 654: 'benefit more' is unclear. What compared to what? Or when compared to when?*
Authors' Response	The sentence has been rewritten and fully revised.

Reviewer Comment	*Line 666: 'longer residence time of water masses…' Worth being precise here when you mean integrated oxygen consumption (e.g. AOU) and when you mean local oxygen consumption rate. Also, perhaps worth addressing that this is not in conflict with an overall younger OMZ (that is, a decline in water age) because of the distinction between local residence time and integrated age.*
Authors' Response	The paragraph has been revised; we have previously noted in the methods that the biological oxygen consumption is similar to AOU.

Reviewer Comment	*Line 675: 'the velocity of the MOC' is unclear. Do you mean transport by the MOC (and which MOC)? Or the climate velocity of the MOC?*
Authors' Response	Here we refer to the transport rate. The sentence now reads: "…Hence, how the OMZs develop in the future depends on both the reorganization of the SWTs contributions and the transport rate of the Indian Ocean MOC."

Reviewer Comment	*Lines 688–694: Clarify the connection between the ITF and sea levels. Why does global sea level control ITF transport? What periods are we talking about? Did the ITF exist during those periods?*
Authors' Response	The passage has been substantially revised to clarify the physical mechanism and historical context. The revised text now reads: "During the Last Glacial Maximum (~20,000 years ago), the sea level fell by approximately 120 m, exposing large areas of the Sunda and Sahul shelves and closing the shallow Java Sea ITF pathway (Dinezio and Tierney, 2013). The deeper main ITF straits (e.g., Makassar and Lombok) remained submerged and active; nevertheless, the ITF was reduced during this cooler glacial phase. This reduction in ITF transport would, in turn, have favored an enhanced meridional inflow into the northern Indian Ocean. In contrast, in the 21st century, the reduced influx of the ITF is not caused by a drop in sea level but is linked to the slowdown of the global THC in response to global warming. However, the mechanism appears to be similar: a reduction in cross-equatorial (ITF) transport increases the relative contribution of meridional, southern-sourced inflow to the Indian Ocean OMZs. …"

Reviewer Comment	*Line 695: 'These changes are not yet well understood…'. Perhaps, but there has been some recent work and some solid theories, e.g., Sun and Thompson (2020).*
Authors' Response	This section has been revised. See text above.

Reviewer Comment	*Line 696: '…an enhance(d) meridional circulation at the expense of a weaker zonal circulation…'. This is implying a casual link between the enhancing of one aspect and the weakening of another, which is not obvious (and may not be correct). Also, is the meridional circulation enhanced? Or just the oxygen supply from the circulation. I would expect that the volume transport rates are also slowing down. Please be more precise.*
Authors' Response	The causal implication has been removed and the phrasing made more precise. The revised text reads: "…However, the mechanism appears to be similar: a reduction in cross-equatorial (ITF) transport increases the relative contribution of meridional, southern-sourced inflow to the Indian Ocean OMZs, even as the absolute volume transport associated with the IO-MOC itself is likely also slowing." This separates the relative and absolute effects and avoids implying a direct causal trade-off between meridional and zonal transport.

Reviewer Comment	*Lines 713–714: How will your findings help improve the representation of OMZs in global models? If you are going to make the assertion, then back it up with specifics.*
Authors' Response	The conclusion has been revised.

In addition to the changes listed above, we have conducted a thorough pass for typos and unclear statements throughout the manuscript. The reviewer's note that the writing was "often unclear or confusing with many typos" has been taken seriously; all authors have reviewed the full revised manuscript. The list of specific points above is not exhaustive of all minor language corrections made, but every point raised has been addressed.

Response to Reviewer 2 Comments

Reviewer comment (major methodological flaws 1 & 2)

> *"The analytical framework still inherently assumes stationarity in source water properties. By failing to account for how interannual and decadal variability modulates these signals before they reach the transect, the authors' attribution of the observed oxygen differences exclusively to long-term changes in the MOC and THC is fundamentally unsupported... Relying on heavily smoothed climatologies like the World Ocean Atlas (WOA) to define SWT properties for specific synoptic snapshots (1995 and 2018) is highly problematic... the authors must rigorously quantify the uncertainty in their mixing ratios... I strongly recommend conducting a sensitivity analysis, such as a sparsity-weighted Monte Carlo perturbation analysis, to test if the mixing signals exceed the background noise. A robust uncertainty budget for the SWT definitions should ideally incorporate two major components: A) Temporal Variability... B) Spatial Mapping Error..."*

Our Response

We have implemented a sparsity-weighted Monte Carlo perturbation analysis as specifically recommended by the reviewer. The full methodology is described in the new Section 2.5 of the revised manuscript. Here we summarize the key results and respond to each sub-point of the reviewer's concern.

A. Temporal Variability of SWT Properties

We quantified temporal uncertainty in SWT properties using two independent sources: (1) interannual standard deviations of potential temperature and salinity from the GLORYS12 global ocean reanalysis (1993–2020, Mercator Ocean, 1/12° resolution) extracted over each SWT formation box (Table 3 of the paper); and (2) the absolute difference between the WOA23 1971–2000 oxygen climatology and the WOA23 all-period oxygen climatology at each SWT formation region, which represents the documented long-term deoxygenation signal at the source. For nutrients, the WOA23 sparsity-weighted standard error (SE) was used as the best available uncertainty estimate, as WOA23 does not provide decadal nutrient climatologies. The resulting temporal uncertainties (σ_temporal) are:

SWT	σ_T (°C)	σ_S (psu)	$σ\_O_2$ (μmol kg^{-1})	$σ\_NO_3$	$σ\_PO_4$	σ_Si
PGW	0.517	0.093	3.157	0.097	0.133	1.654
RSW	0.399	0.093	2.287	0.383	0.036	1.734
mAABW	0.006	0.001	0.199	0.065	0.007	0.392
AAIW	0.179	0.024	1.056	0.136	0.033	0.937
STSW	0.212	0.039	4.079	0.136	0.012	0.097
ITFW	0.506	0.042	0.909	0.475	0.041	0.764

The σ_O_2 values reflect genuine documented deoxygenation at each formation region since 1971. Notably, PGW (3.16 μmol kg^{-1}) and STSW (4.08 μmol kg^{-1}) show the largest oxygen uncertainties, consistent with their shallow formation depths and well-documented exposure to surface warming and deoxygenation trends (Schmidtko et al., 2017). The deep-water mass mAABW shows near-zero oxygen change (0.20 μmol kg^{-1}), consistent with the high stability of Antarctic Bottom Water properties.

B. Spatial Mapping Error and Sparsity Weighting

Mapping uncertainty (σ_mapping) was computed from the WOA23 formal standard error fields, weighted by the inverse square root of the local observation count ($w\_i = 1/\sqrt{\max(n\_obs\_i, 0.5)}$). This formulation penalizes data-sparse grid cells and directly addresses the reviewer's concern about pre-Argo observational sparsity.

Crucially, the analysis reveals 0% empty grid cells (sparsity index = 0.00) across all six SWTs formation regions for all variables examined. This directly contradicts the reviewer's concern that 'WOA grid cells in these regions are largely artifacts of statistical extrapolation'. All SWT formation boxes used in this study are well-observed in WOA23, and the sparsity weighting therefore did not inflate uncertainty beyond the formal WOA standard errors.

Since σ_temporal (O_2, nutrients) and σ_mapping (O_2, nutrients) were both derived from WOA23, they are not independent. To avoid double-counting, σ_mapping was set to zero for O_2 and nutrients; σ_total for these variables equals σ_temporal only. For temperature and salinity, σ_temporal (GLORYS12) and σ_mapping (WOA23 SE) are genuinely independent sources and were combined in quadrature: $\sigma\_total = \sqrt{(\sigma^2\_temporal + \sigma^2\_mapping)}$.

C. Monte Carlo Perturbation Design

The Monte Carlo analysis was designed with two perturbation components per iteration, following the reviewer's recommended approach:

δ_structural (mapping error): drawn once per iteration from N(0, σ_mapping) and applied equally to both the 1995 and recent-year SWT tables. This reflects that both periods use WOA-derived SWT definitions and share the same mapping error. For O_2 and nutrients σ_mapping = 0, so the structural component is zero for these variables.

δ_temporal: drawn independently for 1995 and the recent year from N(0, σ_temporal). This reflects that the source-region conditions in each observation year were subject to independent interannual variability.".

The combined perturbation δ_structural + δ_temporal is mathematically equivalent to drawing from N(0, σ_total), the quadrature sum, because the sum of two independent Gaussian draws is Gaussian with variance equal to the sum of variances. For each of the 10,000 iterations, perturbed SWT tables were passed to PYOMPA (Shrikumar et al., 2022) to solve the full eOMP system. Averaged mixing fractions were recorded, yielding probability distributions of Δfraction (recent minus 1995) for each SWT and region. For each iteration, the oxygen supply contribution of each SWT was computed for both years as the product of its mixing fraction and its oxygen concentration, yielding probability distributions of the change in each SWT oxygen contribution (positive or negative) per region.

Robustness was assessed using three criteria: (1) 95% confidence interval (CI) exclusion of zero; (2) overlap coefficient (OVL) between 1995 and recent distributions; and (3) Mann-Whitney U test (MW $p < 0.05$). Results were classified as robust (CI excludes zero, OVL < 0.20, $p < 0.05$), likely robust (CI excludes zero, OVL < 0.35, MW $p < 0.05$), directionally robust (≥85% of iterations in the observed direction (P_dir), MW $p < 0.05$, CI includes zero), or uncertain (when these conditions are not met, indicating no significant difference). Robustness of changes in physical oxygen contribution by individual SWTs was classified as robust (95% CI excludes zero and SNR > 2), directionally robust (SNR ≥ 1, P dir ≥ 0.85), or uncertain (none of the above criteria were met).

D. Monte Carlo Results

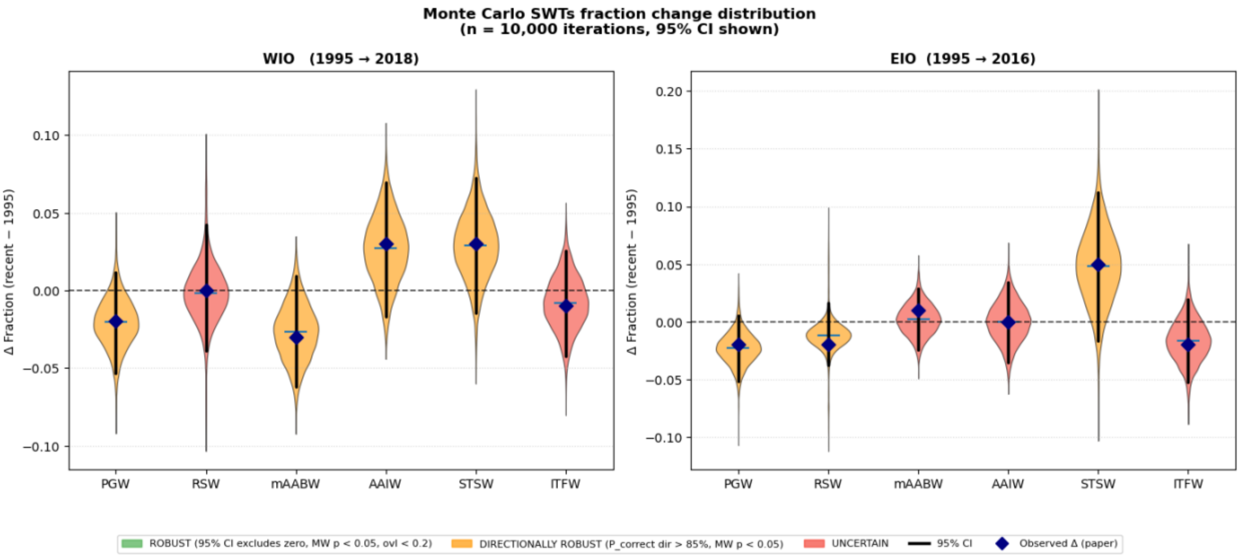

Figure 1: Monte Carlo distributions of the change in SWT mixing fractions (Δfraction = recent − 1995) for the full western (WIO, 1995 → 2018) and eastern (EIO, 1995 → 2016) Indian Ocean transects (150–1200 m), from 10,000 perturbation iterations. Each violin shows the probability distribution of Δfraction 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.

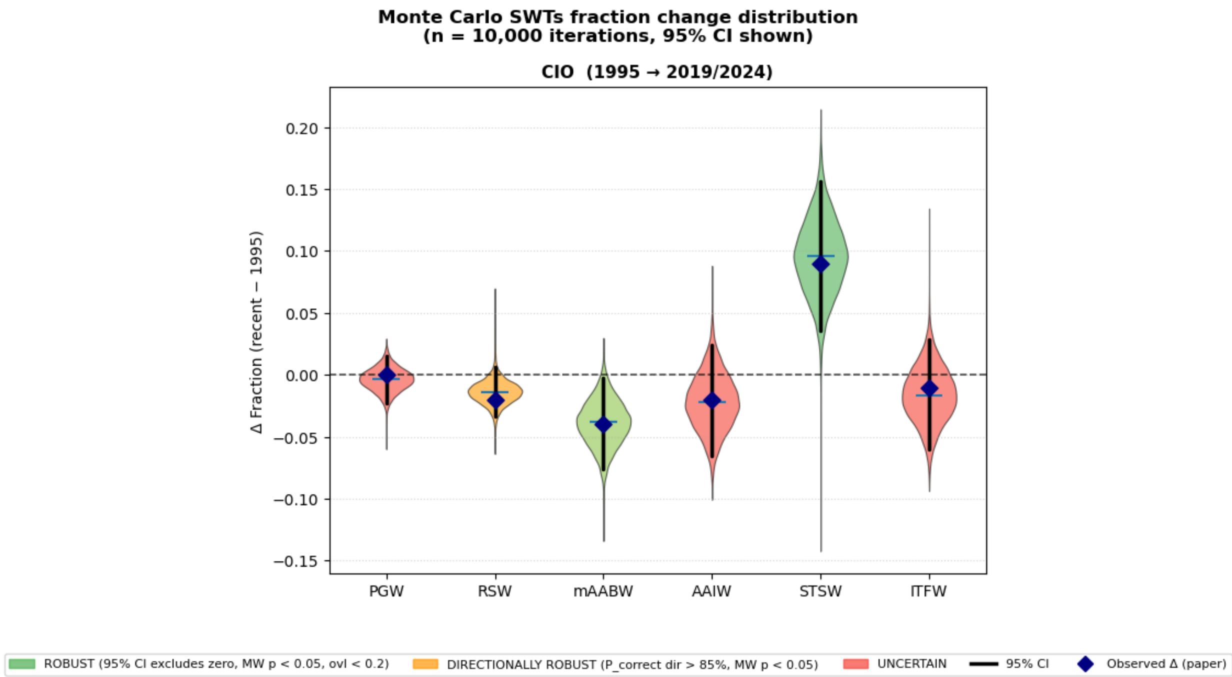

Figure 2: Monte Carlo distributions of the change in SWT mixing fractions (Δfraction = recent − 1995) for the central Indian Ocean (CIO) transect (150–1200 m), from 10,000 perturbation iterations (See Figure S13 for figure elements explanation).

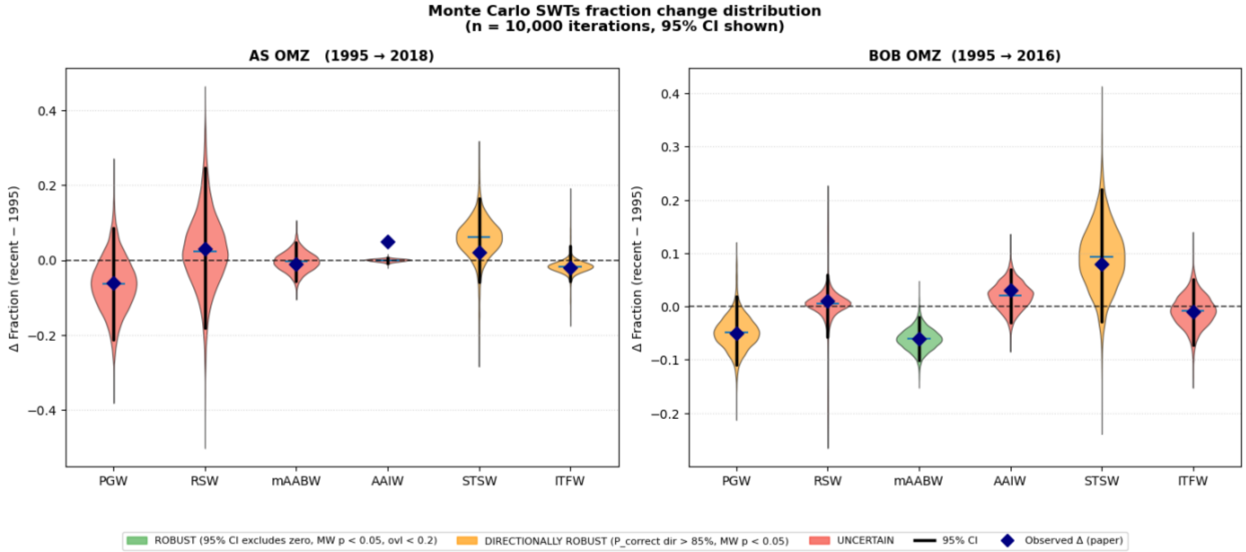

Figure 3: Monte Carlo distributions of the change in SWT mixing fractions (Δfraction = recent − 1995) for the Arabian Sea OMZ (AS OMZ) and Bay of Bengal OMZ (BOB OMZ) cores (O_2 < 20 µmol kg^{-1}), from 10,000 perturbation iterations (See Figure S13 for figure elements explanation).

Table 1. Monte Carlo (MC) robustness verdict of physical oxygen contribution change (recent year minus 1995) of individual source water types (SWTs) to combined uncertainty in SWTs properties from MC perturbation analysis (n = 10,000 iterations). MC verdict description: robust (RR) (95% CI excludes zero and SNR > 2), directionally robust (DR) (P dir ≥ 85% and SNR ≥ 1).

Transects	SWTs	O_2 Supply Δ (µmol kg^{-1})	MC std	MC 95% CI	P dir	SNR	MC verdict
AS OMZ	PGW	-2.7	2.7	-8, +2.7	0.9	1.0	DR
	STSW	+12.9	13.1	-14.7, +37.9	0.9	1.0	DR
BoB OMZ	PGW	-1.9	1.2	-4.1, +0.5	1	1.6	DR
	STSW	20.8	14.7	-7.7, +50.3	0.9	1.4	DR
	mAABW	-12.9	4.3	-21.2, -4.4	1	3.0	RR
WIO	PGW	-0.9	0.5	-2, 0.3	0.9	1.5	DR
	STSW	5.4	5.2	-4.8, +15.6	0.9	1.0	DR
	mAABW	-5.7	3.9	-13.1, +1.9	0.9	1.5	DR
	AAIW	5.5	4.6	-3.7, +14.5	0.9	1.2	DR
EIO	PGW	-0.9	0.5	-1.9, +0.1	1.0	1.8	DR
	STSW	10.2	7.7	-4.9, +25.3	0.9	1.3	DR
CIO	PGW	-1.3	0.9	-3.2, 0.7	0.9	1.3	DR
	STSW	18.1	12.8	-6.8, +43.8	0.9	1.4	DR
	mAABW	-4.1	3.0	-10, +1.9	0.9	1.4	DR

ITFW	-3.8	3.6	-11, +3.0	0.9	1.1	DR

SNR (signal-to-noise ratio).
P correct direction (P dir): the proportion of the mean of 10,000 iterations that reproduces the direction of the observed change (1 = 100%).

Scientific Interpretation of Monte Carlo Results

Monte Carlo analysis as described earlier revealed that the increase in STSW was formally robust in the CIO within the 95% confidence interval (CI [+0.035; +0.157], OVL = 0.05) and directionally robust (P dir = 0.9, MW $p < 0.05$) across all other transects and OMZ cores in the Monte Carlo analysis. Similarly, the decline in PGW is directionally robust (P dir = 0.9, MW $p < 0.05$) across all transects and OMZ cores (except in the CIO and AS OMZ) (Figs 1– 4). Furthermore, the decline in mAABW in the BoB OMZ core was formally robust within the 95% confidence interval (CI [−0.10; −0.02], OVL = 0.05) and is likely robust within the CIO (CI [−0.076; −0.003], OVL = 0.2). Additionally, the ITFW decline was directionally robust in ≥85% of iterations in the AS OMZ and uncertain in the other transects; however, with P dir values ranging from 0.7 to 0.9. Therefore, while not all eOMP results are statistically distinguishable from uncertainties in SWTs properties, the Monte Carlo analysis directionally supports the main results shown by the eOMP analyses (supplementary Fig. S10-14), that along selected GLODAPV2 sections the proportion of STSW has increased at the expense of local water masses such as the PGW, which was most likely also associated with a reduced contribution from ITFW and mAABW.

The results of the physical oxygen change from the Monte Carlo perturbation analysis (n = 10,000 iterations) show that the increase of the physical oxygen supply associated with STSW was directionally robust (SNR ≥ 1, P dir ≥ 0.85) across all transects; additionally, the increase in oxygen due to AAIW was directionally robust only in the WIO (SNR =1.2, P dir = 0.9). Furthermore, decrease in physical oxygen supply associated with PGW was directionally robust (SNR ≥ 1, P dir ≥ 0.85) across all transects and OMZs, while decrease in oxygen supply due mAABW was formally robust in the BoB OMZ (SNR =3.0, P dir = 1), and directionally robust in the WIO (SNR =1.5, P dir = 0.9) and CIO (SNR =1.4, P dir = 0.9) (Table 1).

Summary Statement for Reviewer 2

1. The data are not as sparse as the reviewer assumed. The WOA23 observation density analysis shows 0 % empty grid cells across all six SWT formation regions, confirming that the climatological means are supported by actual historical observations rather than statistical extrapolation.

2. Some signals survive uncertainty testing; others do not. The mAABW decline in the BoB OMZ is formally robust, the STSW increase in the CIO is formally robust, and the mAABW decline in the CIO is likely robust. These are statistically distinguishable from the combined uncertainty in the SWTs properties. The remaining signals are directionally consistent across the Monte Carlo iterations but do not reach formal significance at the 95% level.

3. We have included a sub-session in the methods to describe the Monte Carlo analysis and result session to show the robustness signal of our eOMP analysis to uncertainties, which would be useful when interpreting changes in SWTs fraction discussed in the manuscript.

4. We have revised the conclusions to accurately reflect the strength of the evidence with a focus on the robust changes.