Authors' Response to Reviews of

Divergent Sensitivities of Apparent Oxygen Utilization to Ventilation ~~Circulation~~ Changes in the Deep Ocean Across Earth System Models

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RC: ***Reviewers' Comment***, AR: Authors' Response, ☐ Manuscript Text

We thank the reviewer for following up with a second round of comments and suggestions. We revised the manuscript accounting for them. In particular, we expanded the results description and discussion on the divergent sensitivities of AOU to ventilation changes across models. In the revised title, as well in most of the revised manuscript, the term circulation has been replaced by ventilation. The supplementary figures and tables are now included in the appendix to the main manuscript, in accordance with the journal's guidelines.

1. Reviewer #1

RC: ***In the revised manuscript, the authors have improved the validation and clarification of their methodology and sharpened the focus on water age and AOU in the models using a consistent methodological framework across all models. These revisions enhance both the clarity of the manuscript and the robustness of the findings. I only have a few minor comments and suggestions before the manuscript can be considered for publication.***

1.1. General comments

RC: ***Across the manuscript and Discussion, I suggest reconsidering the use of the term 'circulation' and, where appropriate, replacing it with 'ventilation' Ventilation refers to the exchange of surface water properties with the ocean interior and is therefore directly linked to the cycling of oxygen and carbon. In contrast, circulation more generally describes the advective transport of water masses. Since water age (including ideal age and tracer-based age estimates such as TTD age) is fundamentally a measure of ventilation rather than circulation, using "ventilation" would be more precise and conceptually consistent.***

AR: We are using now the term ventilation age instead of age to clarify. We have replaced circulation by ventilation where appropriate. Circulation is now used only for general description, i.e., when not specific to exchanges between surface and interior.

RC: ***Section 3.2: Based on the title and the emphasis in the abstract, I expected a more detailed inter-model comparison of $S^{\Delta \mathrm{AOU}}_{\Delta \mathrm{age}}$. While the section presents relevant results, the discussion of inter-model differences and their implications appears somewhat limited.***

AR: We expanded the specific aspect of divergent $S^{\Delta \mathrm{AOU}}_{\Delta \mathrm{age}}$ between models in the revised version of the manuscript. In the "Results" section, we added some text to emphasize the diverging $S^{\Delta \mathrm{AOU}}_{\Delta \mathrm{age}}$ and the consequences on the ventilation-driven changes in AOU:

> Within each water-mass, $S_{\Delta\mathrm{age}}^{\Delta\mathrm{AOU}}$ varies substantially, increasing by at least a factor of two between the least and the most sensitive ESM.
>
> [...]
>
> The disparities in the contributions of ideal-age trends across models arise from differences in the both the ideal-age trends themselves and in $S_{\Delta\mathrm{age}}^{\Delta\mathrm{AOU}}$. MPI-ESM1.2-LR and ACCESS-ESM1.5 are the two models with the lowest contributions of ideal-age trends but for different reasons: MPI-ESM1.2-LR has the lowest $S_{\Delta\mathrm{age}}^{\Delta\mathrm{AOU}}$ and relatively strong ideal-age trends, while ACCESS-ESM1.5 has high $S_{\Delta\mathrm{age}}^{\Delta\mathrm{AOU}}$ and weak ideal-age trends. In contrast to these two models with compensating $S_{\Delta\mathrm{age}}^{\Delta\mathrm{AOU}}$ and ideal-age trends, MIROC-ES2L shows both a high $S_{\Delta\mathrm{age}}^{\Delta\mathrm{AOU}}$ and strong ideal-age trends. This combination leads to MIROC-ESL having the highest contribution of ideal-age trends to AOU trends.

In the "Discussion" section, we added a paragraph discussing the causes and implications of the inter-model differences in $S_{\Delta\mathrm{age}}^{\Delta\mathrm{AOU}}$:

> Our work shows that ESMs have substantially different sensitivities of AOU to ventilation changes, indicating uncertainty. The models that simulate the strongest slow down of the overturning circulation do not necessarily produce the strongest increase in AOU (Liu et al., 2023), complicating the interpretation of projections of carbon sequestration. Divergent model sensitivities may reflect different remineralization rate parametrizations (Maerz et al., 2026; Brabson et al., 2026), different organic matter fluxes into the interior (Henson et al., 2022) and more generally differences in the representation of marine biogeochemistry (Séférian et al., 2020; Fennel et al., 2022). The inter-model spread in the sensitivities might also indicate model dependent spatial distribution of water-masses and the differences in ventilation mechanisms (mixing, advection) and pathways. Additionally, the AOU response could be state dependent, varying with the physical and biogeochemical background (e.g., stratification, export production, remineralization depth).

The implication of the $S_{\Delta\mathrm{age}}^{\Delta\mathrm{AOU}}$ spread is also mentioned in another paragraph in the "Discussion" section, discussing the potential for constraining AOU changes:

> Constraining only ventilation changes may not be enough to identify the best ESMs at projecting changes in AOU in the interior ocean, since the divergent sensitivities of AOU to ventilation changes modulate ventilation-driven changes in AOU.

1.2. Specific comments

RC: ***Line 43: Suggest to change as "In contrast, greater accumulation of remineralised carbon in the ocean interior..." to avoid the potential confusion of "higher remineralisation rate".***

AR: Thanks for the suggestion. We have revised the sentence accordingly.

RC: ***Line 57: The authors may wish to consider including additional relevant references, such as Sonnerup et al. (1999, 2013, 2015).***

AR: Thanks for pointing these additional references out. To avoid extending an already long bibliography, we included only one and mentioned that the list of reference for this specific point was not exhaustive.

RC: ***Line 89: Please add the definition of the ideal age that you use.***

AR: We added this paragraph the definition of the ideal-age tracer as followed:

> The ideal-age tracer measures the time elapsed since a water parcel was last at the ocean surface. It is carried by the simulated ocean circulation and mixing. We use the ideal-age tracer to estimate the ventilation age of the ESMs.

RC: ***Lines 169-179: The authors may simply clarify the methodological distinction from the classical oxygen utilization rate (OUR) concept: In the OUR framework, aerobic respiration rates are estimated from the spatial gradients of AOU and water-mass age. In contrast, the approach used here appears to rely on the temporal trends of AOU and age within the same grid cell to diagnose the sensitivity of oxygen changes to changes in ventilation.***

AR: Indeed the main difference is that we used temporal trends while the classical OUR concept relies on scalar values of AOU and ventilation age (e.g. Sulpis et al. (2023)) or their gradient (e.g. Sonnerup et al. (2015)). As suggested, we clarified the methodological distinction as follows:

> 2) we want to avoid ambiguity with studies estimating OUR using AOU and ventilation age (e.g., Sulpis et al. (2023); Guo et al. (2023); Sonnerup et al. (2015); Feely et al. (2004); Sarmiento et al. (1990); Jenkins (1982)) and not their temporal trends.

RC: ***Figure 2: Please clarify why the trend in ideal age can exceed 1 year per year. This may result from the redistribution of water masses rather than literal aging at that rate, but this point is not immediately obvious and should be briefly explained for clarity.***

AR: We clarified in the first paragraph of subsection 3.2 as follows:

> When ideal-age increases or decreases due to changes in ventilation rates or redistribution of waters, AOU increases or decreases, respectively.

And it is also mentioned in the conclusions:

> ...the increase in ideal-age, due to changes in ventilation rates or redistribution of waters, contribute between...

We used the term "redistribution of waters" instead of "redistribution of water-masses" to avoid ambiguity with the water-masses defined specifically for the analyses in this work.

RC: ***Line 345-353: The authors may wish to consider including additional relevant references on studies that estimate temporal changes in ocean ventilation, such as Waugh et al. (2013), Gerke et al. (2024), Wefing et al., (2025), and Guo et al. (2026).***

AR: Thanks for pointing these out. We included these additional reference in the paragraph as follows:

> Our results suggest that the constraining of deep ocean ventilation changes in ESMs with observed ventilation changes (Waugh et al., 2013; Gerke et al., 2024; Wefing et al., 2025; Guo et al., 2026) is a prerequisite for constraining projections of deep ocean AOU.

RC: ***Lines 354–380: I am happy with what the manuscript is and do not recommend additional analysis. Still, it might be nice to further explain some technique details.***

AR: We thank the reviewer for this suggestion. We interpreted this comment as referring to methodological details related to the discussion in Lines 354–380. These aspects are described in detail in Section 2 (Methods), and we aimed to avoid repetition in the Discussion.

RC: ***In the first round of revision, I raised concerns regarding the use of age trends derived from a single-tracer constrained IG-TTD method, as this type of age estimate can exhibit spurious temporal trends (e.g., Guo et al., 2025). This issue is particularly relevant here because the metric is derived from the temporal trends of age and AOU; therefore, methodological uncertainties in the age trend may directly affect the inferred sensitivity. In this context, the comparison between observational estimates (based on single-tracer IG-TTD ages) and model results (based on ideal age) may not be entirely consistent.***

AR: Following the concerns raised during the first round of revision, we conducted analyses to quantify the uncertainties in the observation-based estimates. These uncertainties lead us to focus primarily on the results from the model. The analysis of the observations and the related methodological uncertainties are included in the revised manuscript in particular to discuss limitations preventing us from constraining the models.

The methodological uncertainties and their quantification are presented in Section 2.5 and Section 3.3. We mention specifically the difference between the trends in TTD-mean-age and the trends in ideal-age:

> When computed with CFC-12 outputs from NorESM2-LM, trends in TTD-mean-age are generally much stronger than trends in ideal-age (not shown). In some instances, trends may even oppose each other.

RC: ***Dual-tracer-based age estimates provide more robust and reliable temporal trends (Guo et al., 2025, 2026) and would generally be preferable in this context. However, since the authors now focus primarily on the ideal age in model simulations, this specific concern is substantially reduced.***

AR: The dual-tracer approach is mentioned as a promising approach in the discussion section:

> Approaches employing dual constraint are promising and should be further explored (Guo et al., 2025, 2026).

RC: ***For method comparison, previous OUR-based studies (e.g., Sonnerup et al., 1999, 2013, 2015; Sulpis, 2023) relied on spatial gradients of age and AOU rather than temporal trends, which makes their estimates less sensitive to potential spurious temporal variability in age diagnostics.***

The difference between the previous OUR studies has been clarified in the method section:

> 2) we want to avoid ambiguity with studies estimating OUR using AOU and ventilation age (e.g., Sulpis et al. (2023); Guo et al. (2023); Sonnerup et al. (2015); Feely et al. (2004); Sarmiento et al. (1990); Jenkins (1982)) and not their temporal trends.

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