Author response for egusphere-2025-2326

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Letter to the Editor and to the Reviewers

Dear Editor, and Reviewer 2,

We deeply appreciate the points raised by both of you to the second version of our manuscript. We have addressed these comments and have reflected the suggestions in a revised version of our manuscript.

Sincerely,

Fernanda D. A. O. Matos

(On behalf of the authors)

Response to the Editor

abstract: probably "...maximum is substantially stronger than THAT OF THE z-AMOC, ...
#Response#: We appreciate the comment and have corrected the sentence accordingly.

abstract: comma, before "which", "...mass transformations, which are concealed...
#Response#: We appreciate the comment and have corrected the sentence accordingly.

introduction: last sentence of paragraph 5 beginning "Moreover, deriving the overturning circulation in density space..." should be moved up. This is known, and if anything should be the motivating factor for the rest of the paragraph.
#Response#: We thank the reviewer for this helpful suggestion. We agree that the broader motivation should appear earlier. We have therefore repositioned the sentence from the end of the paragraph to an earlier position. It now follows the explanation that zonal averaging in depth space conceals the horizontal separation between the AMOC limbs in the subpolar North Atlantic and precedes the concluding statement.

This placement highlights the general applicability beyond the North Atlantic and present climate while preserving the logical sequence of the argument from the mechanism in the subpolar North Atlantic, broader relevance, conclusion, and observed community uptake. The paragraph is now written as:

"The choice of coordinate system becomes particularly relevant when comparing the overturning estimates in the SPNA with those in the subtropical North Atlantic (STNA). In the STNA, the strong stratification and relatively flat isopycnals allow the southward limb to flow directly beneath the northward upper limb, resulting in similar estimates of magnitude and variability of ρ- and z-AMOC (Moat et al., 2025). Conversely, in the SPNA, sloped isopycnals induce horizontal separation between the upper and lower limbs, resulting in divergence between ρ- and z-AMOC in terms of both strength and variability (Foukal and Chafik, 2024). This divergence arises because zonal averaging in depth space conceals this horizontal separation, which in turn compromises the accuracy of AMOC estimates under this representation, particularly in the SPNA. Moreover, deriving the overturning circulation in density space instead of depth space is advantageous beyond studies that focus mostly on the North Atlantic and on current climate change, as constant-depth averaging can lead to spurious features such as the Deacon cell in the Southern Ocean (Döös and Webb, 1994; Stevens and Ivchenko, 1997; Speer et al., 2000) and has been linked to discrepancies between modeled and observed AMOC variability across timescales (Liu et al., 2017). Thus, diagnosing AMOC in density space yields a more continuous and physically consistent representation of the AMOC and its underlying mechanisms (Megann, 2018; Xu et al., 2018; Sidorenko et al., 2020a, 2021; Megann et al., 2021; Foukal and Chafik, 2024)"

Introduction: paragraph 6 ordering of reasoning is back to front. The computation cost is high so people don't do it. As written it somewhat implies people don't do it for no particularly good reason when they should, but then justifies it by the computation cost, which is internally inconsistent.

#Response#: We thank the editor for this comment. We have revised the paragraph to the following:

"Although diagnosing AMOC in density space provides clear advantages, the establishment of ρ-AMOC as the standard diagnostic is still hindered by the research community's long-standing familiarity with z-AMOC, built over decades of studies employing the latter definition, with some articles providing a supplementary figure of ρ-AMOC remapped onto depth coordinates to facilitate comparisons between depth and density space AMOC representations (e.g. Xu et al., 2018; Tesdal et al., 2023; Foukal and Chafik, 2024). An additional caveat includes the higher computational cost associated with diagnosing ρ-AMOC (Sidorenko et al., 2021), which can discourage its implementation in studies that require long integration periods or high-resolution output. Furthermore, while the streamfunction in density space has been requested as output in CMIP6 (Griffies et al., 2016), it was not provided consistently for all experiments by all participating modelling centers (Baker et al., 2025; Jackson and Petit, 2023), which limits model intercomparison. While these barriers remain, the scientific gain through diagnosing ρ-AMOC outweighs these challenges, driving its increasing recognition in recent decades, with a strong momentum towards diagnosing AMOC in density space either in modelling studies or observational arrays at various latitudes (e.g. Frajka-Williams et al., 2023; Jackson and Petit, 2023; Fu et al., 2023; van Westen et al., 2025). In particular, observational arrays such as the OSNAP (Overturning in the Subpolar North Atlantic Program; Lozier et al., 2017) and RAPID-MOCHA (RAPID Climate Change - Meridional Overturning Circulation and Heatflux Array; McCarthy et al., 2015), already provide ρ-AMOC output and have, since their launch, changed our view on overturning in the subpolar and subtropical North Atlantic (Lozier et al., 2019; Moat et al., 2025; Frajka-Williams et al., 2023). Consequently, this dichotomy between the studies employing ρ- and/or z-AMOC frameworks introduces increased uncertainty regarding the occurrence and timing of a substantial AMOC weakening under a warming climate. At the inception of CMIP7, where both $\rho-$ and $z-$AMOC are requested (Fox-Kemper et al., 2025, in review), we see a timely opportunity to advertise the more widespread adoption of $\rho-$AMOC, at least as an additional, if not even the main, overturning diagnostic."

Same paragraph: grammar, "...and have, since their LAUNCH, changed..."
#Response#: We appreciate the comment and have corrected the sentence accordingly.

Eq (1): still unclear whether the w* resulting from GM scheme (which is active) is included here. (It shouldn't be in Eq. (2) if that is a diapycnal velocity)
#Response#: We thank the reviewer for pointing this out. In Eq.(1) we use the vertical velocity that includes the GM bolus contribution w^*. However, in Eq.(2), w_ρ as the GM transport is adiabatic, the w_ρ^* is not included in w_ρ. We have added clarifying sentence immediately below Eq.1.

"**where w denotes the vertical velocity that includes the GM bolus component w^*.**"

Below Eq (4): "...model drift was calculated and found TO BE negligible."
#Response#: We appreciate the comment and have corrected the sentence accordingly.

Paragraph above Sec 3: they are only mathematically equivalent if the flow is incompressible, but there is no mention of that property being satisfied by the present model explicitly (if it is hydrostatic I guess it's implied, but only implicitly)
#Response#: We agree that both MOC formulations are equivalent under incompressibility. FESOM2 solves the hydrostatic primitive equations under the Boussinesq (incompressible) approximation. Therefore the two formulations are formally equivalent in this model (up to negligible discretization error; see Banerjee et al. (2024)). We have modified the following paragraph to explicitly inform the readers about how FESOM2 solves primitive equations:

In the mathematical framework section (paragraph above section 3)

"Please note that, in our study, the AMOC is computed using vertical velocity, w, rather than the conventional approach based on meridional velocity (v; see Table A1 for the equations). We make this choice because the hydrostatic Boussinesq formulation used by FESOM2 implies incompressibility (Banerjee et al., 2024), which makes both methodologies mathematically equivalent (see Sidorenko et al., 2020b, for a detailed comparison) and because not using meridional velocity is advantageous with the spatial discretization used by FESOM2. Using the meridional velocity would require integration along the boundaries of the control volumes, which is less convenient for arbitrary unstructured meshes, and it would also neglect important information about diapycnal velocities. In contrast, the vertical velocity approach naturally yields the AMOC in density space, reduces noise introduced by the beforementioned integration along the boundaries of the control volumes, and enables more efficient online diagnostics in FESOM2 (Sidorenko et al., 2020a, 2021). Additionally, since model drift is negligible during model runtime and at the density range of the upper cell (Figure A2), surface and interior transformations constitute the only ρ-AMOC components in our simulations"

Sentence near Table 2: should just be "...oscillatING around 5 Sc, suggesting..."
#Response#: We appreciate the comment and have corrected the sentence accordingly.

if the authors deem it appropriate please acknowledge all those who provided comments accordingly.
#Response#: We thank the editor for drawing our attention to this, we have updated the last two sentences of the Acknowledgements section to:

"We also acknowledge the Nippon Foundation and the Partnership for the Observation of the Global Ocean (POGO) for support under the NF-POGO Centre of Excellence (NF-POGO CofE) programme. Finally, we thank Dr. Paul Gierz and Dr. Sergey Danilov for their valuable guidance during the preparation and revision of this article. We are extremely grateful to the editor, Dr. Julian Mak, the reviewer, Dr. Henri Drake, and one more anonymous reviewer for their constructive feedback and comments that have greatly increased the quality and comprehensibility of our manuscript."

Response to Reviewer 2

As explained in the response to reviewers, the author's method of diagnosing the density-based overturning streamfunction is only equivalent with the more conventional meridional transport-based method of diagnosing the density-based overturning if isopycnal drifts are taken into account. However, the authors provide zero evidence that the drift is negligible, either in the revised manuscript, in their response to my concern, or in the cited Sidorenko (2020) paper which establishes the methodology. Based on my experience performing similar calculations, I can confirm that mean isopycnal drifts are generally negligible contributions to piControl water mass budgets on multi-decadal timescales; in strongly-forced runs, however, I have found that the drift is a leading-order term in the water mass budget! For a manuscript focusing on the response of the density-based overturning to strong forcing, it is unacceptable to leave this key supporting evidence as "(not shown)".

#Response#: We thank the reviewer for emphasizing the role of isopycnal drift under strong forcing. We now display the isopycnal volume tendency ("drift term") in figure A2 (Figure 1 here) in the appendix. During model runtime at the latitude of stronger AMOC, Figure 1 reveals that the drift is negligible. Thus, the weakening and multidecadal variability of the upper overturning cell in the 4xCO_2 persist and remain consistent as a response to such an abrupt forcing.

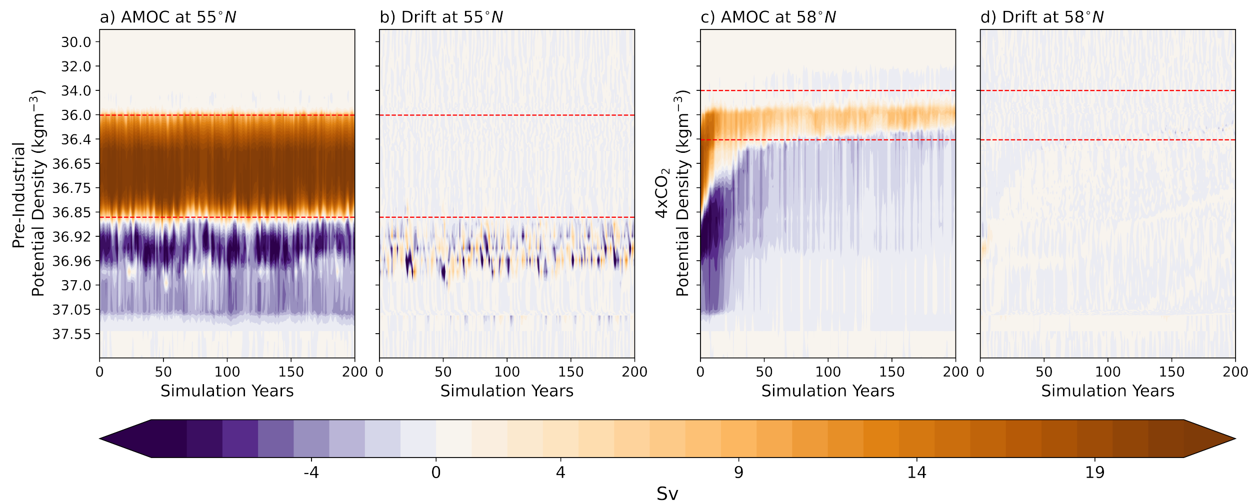
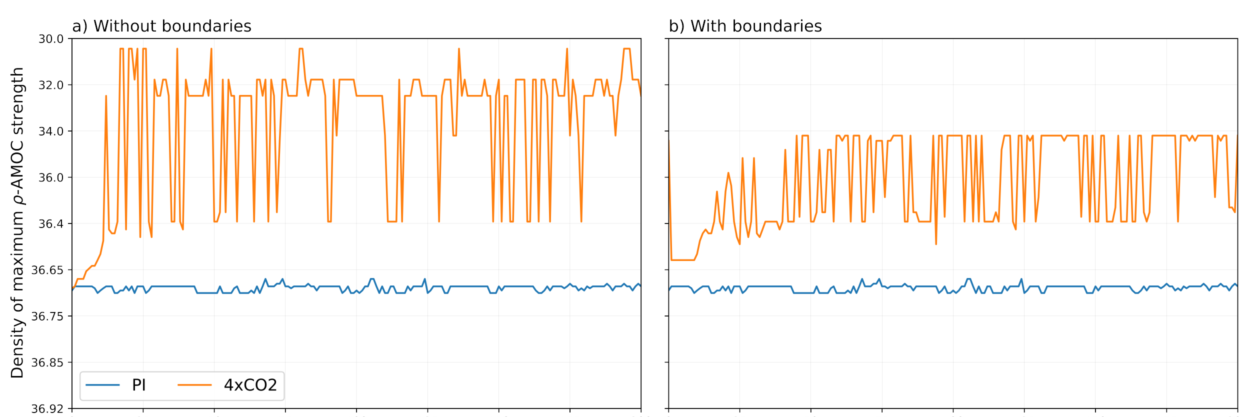


Figure 1: Hovmöller diagrams of ρ-AMOC (a,c) and model drift (b,d) in density space for PI (a,b) and 4xCO_2 (c,d). Red dashed lines denote the upper and lower density bounds of the ρ-AMOC upper limb, computed from the mean over the last 50 years of each simulation. The ρ-AMOC maximum latitude for both simulations is displayed in Table 1.

Figure 2 appears to reveal a fatal flaw in the methodology. The fact that the density of the maximum ρ-AMOC strength oscillations between about ∼31 kg/m-3 and 36.4 kg/m-3 suggests to me that this metric is not robustly picking up the AMOC cell. While the authors seem to recognize this and have thus constrained the range of valid densities (as shown in their Figure 2b reproduced below) to a fixed range. [Aside: The main text states that the upper boundary is 35, whereas this figure shows it to be 34. Which is the correct one?] However, the maximum density still jumps around, just now within the artificially constrained range. By visual inspection, it seems to me that these spurious multi-decadal jumps in the density of the rho-AMOC map onto the multi-decadal oscillations in the strength of the rho-AMOC streamfunction, which the authors argue is a key result of their paper, which is supposedly hidden by the z-AMOC streamfunction.



#Response#: We thank the reviewer for this constructive suggestion. In the revised manuscript we clarify that the variability captured by our indices reflects physical water–mass transformation processes rather than an artefact of index definition. Motivated by the comment, we extended the analysis to derive an index that considers the full density range and compared it with our original index (Figure 2 in this response). This additional comparison shows that incorporating the full density range does not affect the variability of z- and ρ-AMOC$_{max}$ during model runtime, it does only modify the strength of z-AMOC$_{max}$ (as expected). As the reviewer noted, the 4xCO_2 experiment represents a strongly forced climate, distinct from more weakly forced cases like *piControl*, which therefore alters the AMOC variability.Yet, based on the additional analyses that we show now we can explicitly state that the variability in AMOC in the 4xCO_2 experiment is not an artifact of the chosen density classes.

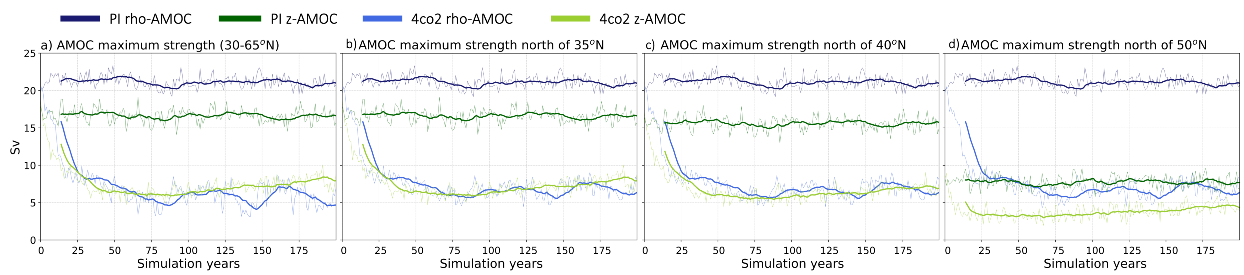


Figure 2: Comparison between AMOC$_{max}$ indices. In a) the original index, derived from the maximum AMOC strength between $30-65°$N. In (b, c, d) the indices derived within the entire density range but with different latitudinal boundaries.

AMOC$_{max}$ is now defined as the basin maximum of the overturning streamfunction over the full density range north of 50°N. This cutoff lies within the latitude window used in previous studies (e.g.; Cheng et al., 2013; Ackermann et al., 2020; Matos et al., 2020; Sidorenko et al., 2021) and targets the subpolar deep-water formation regions, while excluding subtropical contributions. By taking the maximum over the entire density axis, no upper or lower density bounds need to be prescribed, as evinced in Figure 3:

Figure 3: Density of maximum ρ-AMOC strength north of a) 35°N, b) 37°N, c) 40°N, d) 50°N

We are extremely grateful to the reviewer to have pointed out that our analysis, as presented in the previous version of the manuscript, where we had not discussed the impact of changes in density classes on our results, may lead to doubts regarding robustness of our inferences. Their comments have greatly improved presentation of our results towards robustness and comprehension of our study. Consequently, we have updated the text and the figure in the revised manuscript accordingly.

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