MS-No.: egusphere-2026-209

Version: Revision

Title: Interaction of AMOC and Intrinsic Multi-decadal Southern Ocean Variability

Author(s): Emma J.V. Smolders, René M. van Westen and Henk A. Dijkstra

Point-by-point reply to reviewer

April 16, 2026

We thank the reviewer for their careful reading and for the useful comments on the manuscript.

This study examines the impact of the AMOC on the intrinsic multi-decadal variability in the Southern Ocean, called the Southern Ocean Mode (SOM), using an eddy-resolving ocean model. The authors added the freshwater forcing in the North Atlantic and demonstrated that the SOM in the Atlantic sector gets weaker after the AMOC collapse, while in the Pacific sector, deep convection starts to emerge with multidecadal variability. The weakening of the SOM in the Atlantic sector may be related to the strengthening of the stratification and the weakening of deep convection in the upper ocean, while the emergence of the SOM in the Pacific sector may be linked to the weakening of the stratification and the strengthening of deep convection.

Although these results are solely based on the model simulations, the SOM changes driven by the AMOC collapse are intriguing and worth investigating, given a possible influence of the weakening AMOC on the Southern Ocean and sea ice under future global warming. However, the physical processes underlying the changes in the ocean stratification responsible for the SOM changes are not well examined and remain unclear. For example, the relative contributions of the ocean temperature and salinity to the stratification changes and their sources and pathways are not clarified. The weaker AMOC is expected to induce the weakening of the poleward advection of warm and saline subsurface water (i.e., Antarctic Circumpolar Deep Water) and hence weakening of the deep convection in the Weddell Sea. However, in the Pacific sectors, there are different stratification changes in the NZ, AU, and PA sectors. Why do these stratification changes happen and what are the links with the deep convection changes? This is worth further investigation in this study. Below are other major and specific comments to further improve this *study before possible publication in this journal.*

Thank you for this overall assessment.

Changing SOM variability (Section 3.1)

1. *It is interesting to find the change in the SOM variability before and after the freshwater input, but there are several concerns to be addressed before drawing conclusions. First, the model shows a gradual decrease in the AMOC strength until 300 years when the freshwater forcing is implemented. This gives me the impression that the model does not reach an equilibrium state and requires further spin-up period before conducting the freshwater forcing experiment.*

   Author's reply:

   The freshwater forcing is applied from the start of the simulations (model year 1), and not from model year 300 onwards. The quasi-equilibrium freshwater flux forcing simulation used in this study is branched from a multi-century control simulation by Le Bars et al. (2016) at model year 300, with a near-zero ocean surface heat flux upon initialisation (see Figure 8b in https://egusphere.copernicus.org/preprints/2025/egusphere-2025-5102/). The gradual decrease in AMOC strength in Figure 1 in the manuscript prior to model year 300 is therefore a direct response to the imposed freshwater forcing, causing a slow weakening of the circulation. More information on the quasi-equilibrium freshwater flux forcing simulation can be found in van Westen et al. (2025).

   - *Le Bars, D., J. P. Viebahn, and H. A. Dijkstra (2016), A Southern Ocean mode of multidecadal variability, Geophys. Res. Lett., 43, 2102–2110, doi:10.1002/2016GL068177.*
   - *van Westen, R. M., Kliphuis, M., & Dijkstra, H. A. (2025). Collapse of the Atlantic Meridional Overturning Circulation in a strongly eddying ocean-only model. Geophysical Research Letters, 52(6). doi:10.1029/2024GL114532*
   - *van Westen, R. M., Katsman, C. A., and Le Bars, D.: Dynamic and Steric Sea-level Changes due to a Collapsing AMOC*

in the Community Earth System Model, EGUsphere [preprint], https://doi.org/10.5194/egusphere-2025-5102, 2025.

Changes in manuscript:

We will better clarify the freshwater forcing experiment in the Methods section.

2. *Second, the authors discuss the changes in the frequency of the SOM and Drake Passage transport qualitatively (e.g., L136 and L141), but are these changes statistically significant? I would recommend the authors should conduct wavelet power spectrum analysis with statistical test to the timeseries and describe how the period of the timeseries change before and after the freshwater input.*

   Author's reply:

   We agree with the reviewer that a wavelet power spectrum analysis would be a good addition to support the mentioned changes in frequency (Figure R1). Indeed, the results show that the (significant) dominant period of the ACC transport increases following the onset of the AMOC collapse. Prior to the collapse, this dominant period closely matches that of the SOM index, which disappears completely after the AMOC has collapsed. In contrast, a clear significant period of the SOM-P emerges right after the onset of the AMOC collapse, with a period about 20 years larger than that of the SOM index. The dominant period of the ACC transport aligns with that of the SOM-P after the collapse of the AMOC.

   Changes in manuscript:

   We will include the wavelet power spectrum analysis and discuss the results in the revised text.

3. *Third, the authors applied the EOF analysis to the SST anomalies in the Southern Ocean, but are the SST anomalies used in the EOF analysis monthly or yearly mean values? I would recommend the authors should consider strong seasonality of the SST variability in the Southern Ocean.*

   Author's reply:

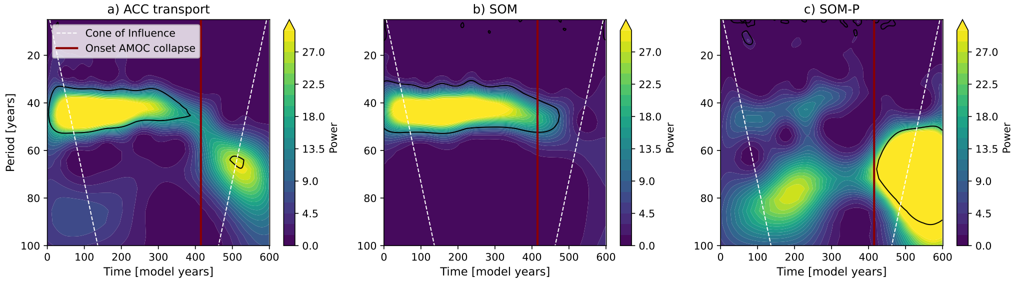

Figure R1: **Wavelet power spectra for the ACC transport, SOM and SOM-P index**. Wavelet (Morlet) power spectra for (a) the ACC transport, (b) the SOM index, and (c) the SOM-P index. Black contours indicate power significant at the 95% level relative to an AR(1) red-noise background. The vertical red line marks the onset of the AMOC collapse, and the white dashed lines indicate the cone of influence.

The SST anomalies used in the EOF analysis are derived from annual mean values, such that seasonality is averaged out. This is justified because we focus on multidecadal variability.

Changes in manuscript:

We will clarify the use of annual mean data for the EOF analysis in the revised text.

4. *Fourth, the explained variances of the first EOF mode are very small at 13% and 7% before and after the freshwater forcing. Are these EOF modes well separated from the corresponding second EOF modes? I would recommend the authors should perform a statistical test introduced by North et al. (1982).*

   Author's reply:

   The explained variances of the corresponding second EOF modes for the AMOC on- and off-state are 10% and 6%, respectively. According to the statistical test from North et al. (1982), the EOF modes in the AMOC off-state are indeed not well separated. We therefore applied a 5-year moving average to the data prior to the EOF analysis to enhance the coherence of the signal. This results in explained variances of 25% and 18% for the first EOF modes in the AMOC on- and off-state, respectively (see Figure R2), and 18% and 13% for the second EOF modes.

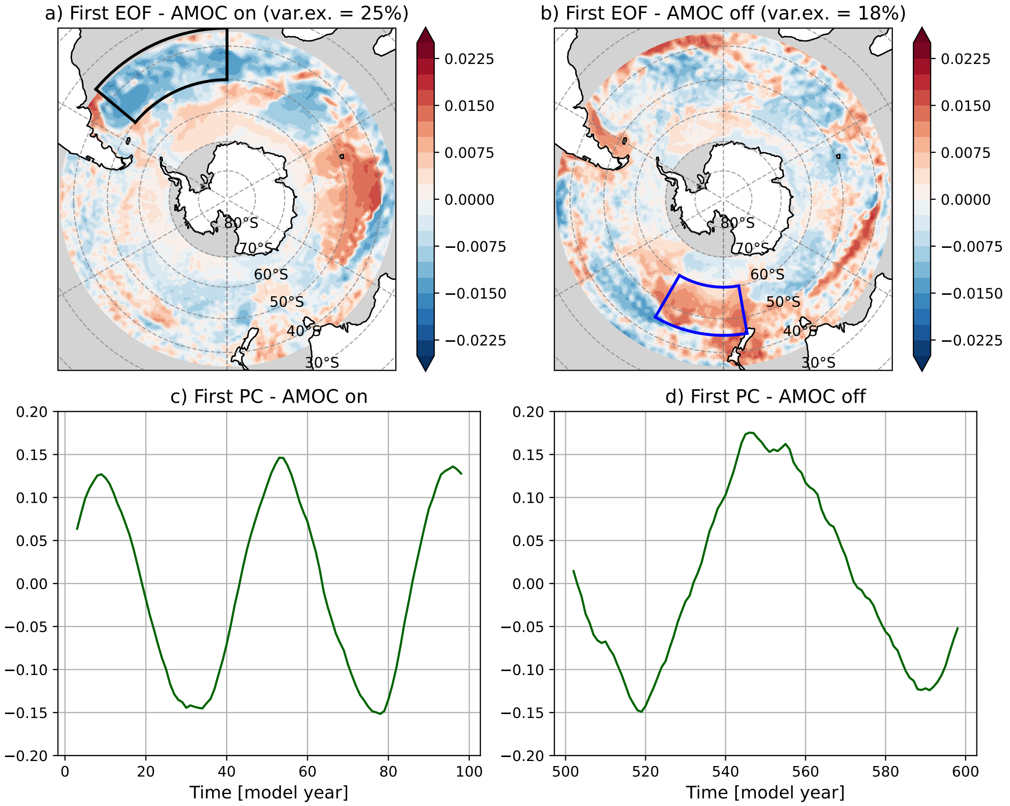

Figure R2: **First EOFs and PCs of Southern Ocean SST.** First EOFs of SSTs south of 30°S for the first 100 model years (a) and the last 100 model years (b), with the explained variance indicated. A moving average of 5 years has been applied to the data prior to the EOF analysis. The black (blue) outlined region shows the region used to determine the SOM (SOM-P) index. Panels (c) and (d) show the corresponding first PCs.

Changes in manuscript:

We will include the EOF analysis using the 5-year moving averaged data, and update the text and figure accordingly. Note that the results are not affected by the new EOF analysis.

5. *Lastly, the blue outlined region used for the SOM-P index includes the negative SST variability, so it would be better to modify the box that covers a core region of the positive SST variability, for example, 60-45ºS, 170ºE-150ºW.*

   Author's reply:

   Agreed. It is better to not include the negative SST variability and focus solely on the positive SST variability. Using the modified SOM-P region (60-45°S, 170°E-150°W, see also Figure R2) does not change anything regarding the SOM-P period, and results only in a slight decrease in amplitude.

   Changes in manuscript:

   We will modify the area used for the SOM-P and change the figures accordingly.

AMOC-SOM coupling (Section 3.2)

1. *This subsection discusses the impact of the freshwater input on the ocean background mean state in the Atlantic sector, but does not discuss the coupling between the AMOC and SOM. The authors mention that the density anomalies associated with the SOM influence the AMOC through their northward propagation within the Atlantic basin (van Westen & Dijkstra 2017). If this is true in the model world, the change in the SOM variability after the freshwater input can also affect the AMOC strength. Is there any feedback processes between the SOM and AMOC changes?*

   Author's reply:

   Indeed, sea surface height, subsurface (300-700 m) temperature and salinity anomalies propagate northward within the Atlantic basin (Figure A1 in manuscript), thereby imprinting the variability generated by the SOM onto the AMOC (Figure R3a). After the collapse, the disappearance of the SOM variability leads to the disappearance of multidecadal variability in the AMOC strength (Figure R3b).

   Changes in manuscript:

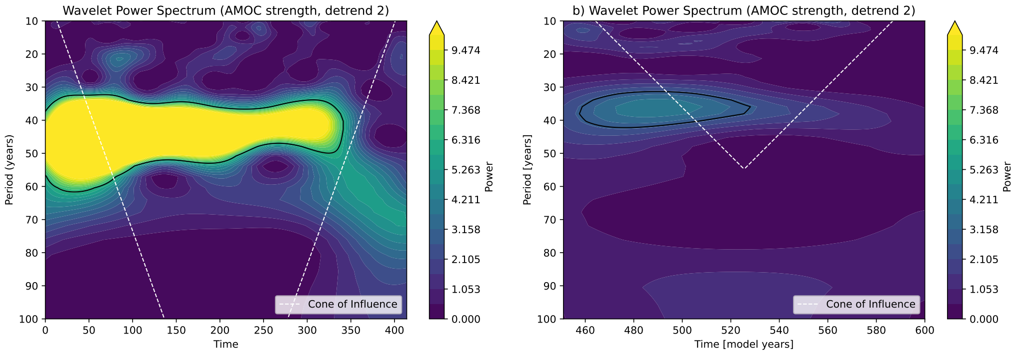

Figure R3: **Wavelet power spectra for the AMOC strength.** Wavelet (Morlet) power spectra for the quadratically detrended AMOC strength from (a) model year 0 - 415, and for (b) model year 450 to 600. Black contours indicate power significant at the 95% level relative to an AR(1) red-noise background, and the white dashed lines indicate the cone of influence.

We will elaborate on the influence of the SOM on the AMOC in the revised manuscript, and include Figure R3.

2. *Second, the subsurface ocean gets warmer and saltier after the AMOC collapse, while the deeper ocean gets cooler and fresher (Fig. 3). Are these changes statistically significant and large enough compared to the intrinsic variability? The authors should carefully explain why these temperature and salinity changes occur in the subsurface and deep oceans after the freshwater input.*

   Author's reply:

   The substantially weakened AMOC leads to a pronounced reduction in meridional heat transport (van Westen et al., 2025), resulting in the accumulation of heat in the Southern Hemisphere ocean interior (up to 1000m) north of the ACC. As the AMOC transports salt northward, a strong reduction in strength will lead to salt convergence in the South Atlantic. The freshening and slight cooling of the deep oceans are related to a reduced formation of North Atlantic Deep Water (NADW), which is characterised by relatively high salinity compared to deep ocean waters. Hence, a reduced formation of NADW, together with a reorganisation of the water masses in the Southern Ocean (e.g. deepening of AAIW, or increased influence of Antarctic Bottom Waters) leads to the freshening and slight cooling of the deep Atlantic.

   - *van Westen, R. M., Kliphuis, M., & Dijkstra, H. A. (2025). Collapse of the Atlantic meridional overturning circulation in a strongly eddying ocean-only model. Geophysical Research Letters, 52(6), e2024GL114532.*

   Changes in manuscript:

   We will apply a two-sided Welch's t-test to the data to test for statistical significance at the 95% level, and include this in the figures. Next to that, we will elaborate on the mechanisms of the temperature and salinity changes in the revised text.

3. *Third, the authors describe three different isopycnals in Fig. 3c. However, some of the values before and after the AMOC collapse (i.e., 1026.2 vs 1025.7, 1027.7 vs 1027.6) are different and hard to compare with each other. Could the authors plot the same isopycnals in the figure?*

Author's reply:

We agree with the reviewer that plotting the same isopycnals is more informative.

Changes in manuscript:

We will change the figures accordingly.

4. *Fourth, which of the ocean temperature and salinity changes is more important for the meridional density gradient changes? This can be further investigated by decomposing the density anomalies into the temperature and salinity-driven components.*

   Author's reply:

   We decomposed the density anomalies into temperature and salinity-driven components using a linear decomposition, i.e. $\Delta\rho \approx \frac{\delta\rho}{\delta T}\Delta T + \frac{\delta\rho}{\delta S}\Delta S$. It appears that Atlantic density changes in the upper 1000 m north of the ACC are a combination of salinity- and temperature-driven changes, while the decrease in density in the deeper layers ($>$ 1000 m) is primarily caused by the freshening driven by the hosing in the North Atlantic (see Figure R4). The density anomalies in the Pacific and Indian sector have a stronger salinity-driven component, where the increased densities in the upper 1000 m are now mainly caused by the salinification of the upper layers (not shown).

   Changes in manuscript:

   We will mention the importance of temperature and salinity for the density changes in the revised manuscript, and add density, N^2 and salinity-driven N^2 difference subplot to the figure (e.g. Figure R5).

5. *Lastly, the ACC does not uniformly change in response to the AMOC collapse. For example, the ACC gets stronger north of 40^{o}S and south of 50^{o}S, while it gets weaker between 40-50^{o}S. This may be related to the meridional density gradient change, but why does this heterogeneous change in the ACC happen?*

   Author's reply:

   Indeed, changes in isopycnal slopes, driven by variations in meridional density gradients, modify the baroclinicity, thereby influencing

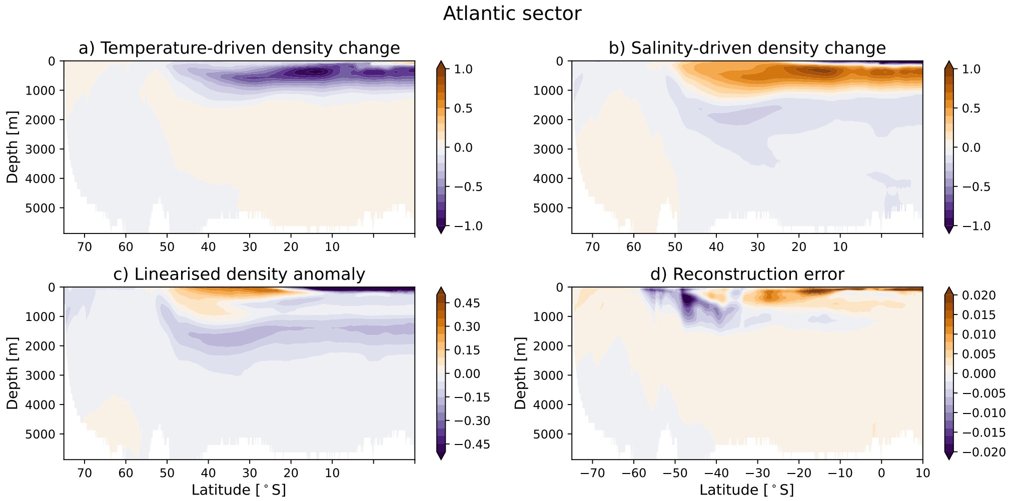

Figure R4: **Linear density decomposition in the Atlantic sector.** Zonal-averaged (60°W – 25°E) (a) temperature-driven and (b) salinity-driven density changes (model year (500 – 600) minus model year (1 – 100)). (c) Linearised density anomaly, obtained as the sum of the temperature- and salinity-driven contributions. (d): Reconstruction error of the linearised density anomaly relative to the actual density anomaly.

the strength of the ACC. These changes in meridional density gradients are not uniform across the ACC latitude band (Figure 3c in manuscript), and therefore they may lead to a spatially heterogeneous change of the ACC.

Changes in manuscript:

We will remove the zonal velocity subplot from Figure 3 in the manuscript and instead include a difference plot showing changes in density, N^2 and salinity-driven N^2 (e.g. Figure R5). This will provide stronger support for the claim about changes in vertical density structure and better connect this section to the eddy-driven responses discussed in Section 3.3 and the deep convection changes in Section 3.4. We will also mention in the revised text that zonal velocity changes within the ACC latitude band are spatially heterogeneous.

Mechanisms of SOM changes (Section 3.3)

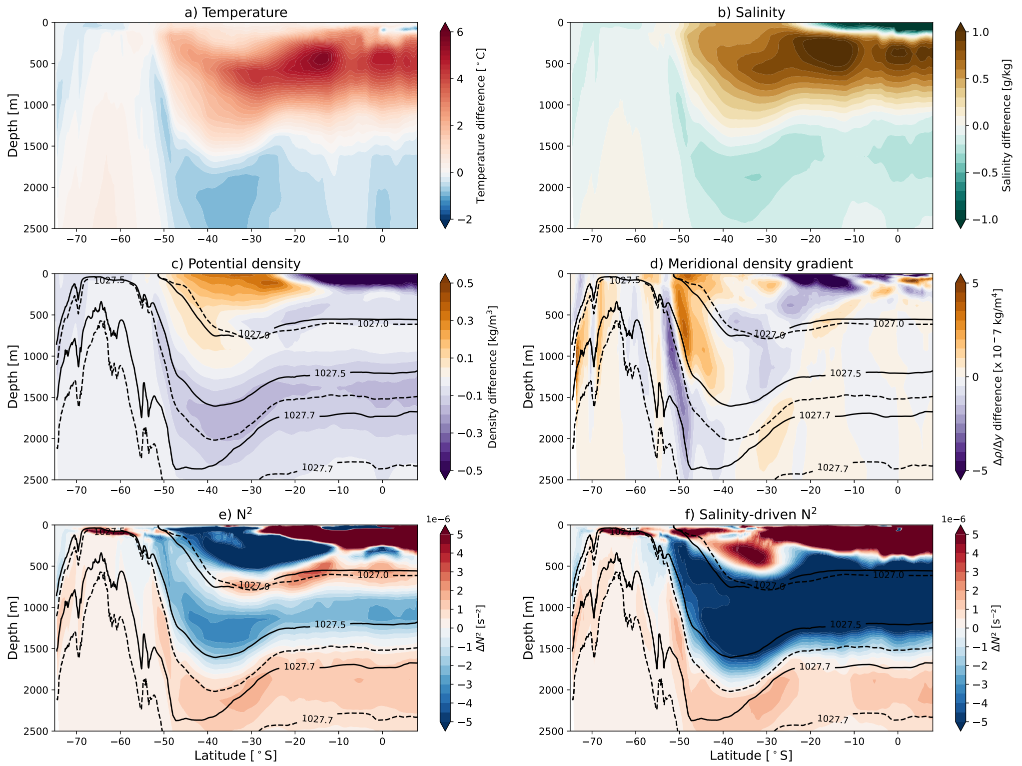

Figure R5: **Temperature, salinity, density, meridional density gradient and N^2 differences in the Atlantic sector.** Zonally averaged (60°W – 25°E) (a) temperature, (b) salinity, (c) density, (d) meridional density gradient, (e) N^2, and (f) salinity-driven N^2 differences in the upper 2500 m before and after the AMOC collapse (model year (500 – 600) minus model year (1 – 100)). In (c,d,e,f), the solid (dashed) black lines denote isopycnals of model year 1 – 100 (500 – 600). Plotted isopycnals are (from top to bottom): 1027.0, 1027.5, and 1027.7 kg/m^3 for model year 1 – 100 (500 – 600).

1. *The authors draw conclusions from the energetics of three different SOM cycles that the increase in P at the end of the simulation is not driven by enhanced mean wind energy input (i.e., G), but instead is a consequence of changes in the density field associated with the AMOC collapse (i.e., C). This appears to be true, but the relationship with the non-zonality parameter is unclear. For example, the decrease in*

G and C over time indicates less zonal flow with narrower isopycnals and reduced eddy generation through baroclinic instability, respectively. However, the non-zonality parameter increases, indicating more eddy generation through baroclinic instability. This looks puzzling and contradictory results. Is my understanding correct?

Author's reply:

Your understanding is partly correct. The non-zonality parameter increases after the AMOC collapses, indicating a more non-zonal flow. This is consistent with a reduction in mean wind energy input, as the correlation between the wind forcing and the zonal flow weakens. While a more non-zonal flow is typically also associated with enhanced baroclinic generation through eddies, this is not reflected in an overall increase of $C(P_e, K_e)$. The non-zonality parameter loses its multidecadal variability entirely after the AMOC collapse, suggesting that the mean increase is not primarily driven by eddy variability and mean wind energy input, but rather by changes in the mean state. For example, the mean reduction of the ACC or a shift in its position could lead to increased meandering of the zonal flow, thereby increasing the non-zonality parameter.

Changes in manuscript:

We will elaborate on the possible mechanisms of the mean increase of the non-zonality parameter in the revised text.

2. *Another intriguing aspect is the periodicity of the cycle and time lag among the variables. In the SOM cycle 1 and 2, P shows a clear cycle with a period of 40-50 years, but what determines the timescale of this cycle? According to Eq. (4), G and C should contribute to the rate of P, and both G and C show similar cycles with a period of 40-50 years. Also, there is 10-yr lag between K and C (L224), but what causes this time lag? By definition in Eq. (5), C should contribute to the rate of K, so the time lag looks very long.*

   Author's reply:

   The vertical stratification plays a key role in setting the timescale of the SOM cycle. Changes in the vertical stratification can therefore lead to either an increase or a reduction of the SOM period. For example, Van

Westen and Dijkstra (2020) showed that increased meridional isopycnal slopes in their CESM simulation led to enhanced baroclinic flow, resulting in a reduced period of the SOM compared to the stand-alone POP configuration used in this study.

We agree that a time-lag of 10 years between $C(P_e, K_e)$ and K appears rather large. Upon closer examination, this time is actually closer to 5 years, and becomes smaller during regime A and B of SOM cycle 1, and even smaller in SOM cycle 2 and 3. According to the theory of Hogg and Blundell (2006), changes in $C(P_e, K_e)$ should be closely linked to changes in K, with only a small time lag, as a large transfer of potential to kinetic energy feeds almost directly into the eddy kinetic energy field. Consistent with this, the time-lag between K (or K_e) and $C(P_e, K_e)$ of the entire time series varies between 1 and 6 years. It might be possible that during regime C and D of SOM cycle 1, other energy transfer pathways or processes temporarily play a prominent role in governing the evolution of K, resulting in a slightly larger time lag.

- *van Westen, R. M. and Dijkstra, H. A.: Multidecadal preconditioning of the Maud Rise polynya region, Ocean Sci., 16, 1443–1457, https://doi.org/10.5194/os-16-1443-2020, 2020*
- *Hogg, A. M. C., & Blundell, J. R. (2006). Interdecadal variability of the Southern Ocean. Journal of physical oceanography, 36(8), 1626-1645.*

Changes in manuscript:

We will elaborate on this in the revised manuscript.

Changes in the Southern Ocean deep convection (Section 3.4)

1. *It is interesting to find different responses of the ocean stratification in different sectors to the AMOC collapse. However, the underlying mechanisms need to be clarified. In the NZ and WGKP regions, the stratification increases in the upper 100 m, decreases in the middle layer (250-500 m), and increases again in the deeper layer down to 1500 m.*

I am speculating that poleward advection of warm and saline subsurface water (i.e., Antarctic Circumpolar Deep Water) should decrease after the AMOC collapse thereby increasing the stratification in the deeper layer and inducing the shallower mixed-layer. Despite this expectation, why does the middle layer show the weaker stratification in both sectors? Does it also affect the initiation of multidecadal oscillation in the NZ sector?

Author's reply:

We agree with the reviewer that the mechanisms underlying the stratification changes and multidecadal variability should be clarified in more detail. The vertically non-uniform response of stratification in the NZ and WGKP regions reflects a reorganisation of the water-column structure after the AMOC collapse (Figure R6).

The reviewer's expectation that a reduced poleward advection of CDW would explain the increased deep stratification and shoal the mixed layer is broadly consistent with our results. In both regions, we indeed find enhanced stratification possibly related to a reduction or deepening of the CDW. The decrease in stratification in the intermediate layer (approximately 250-500 m), however, originates from salinity-driven changes in the water masses north of 60°S. We find a reduction in the vertical salinity gradient, consistent with a downward displacement or reorganisation of Antarctic Intermediate Water (AAIW). This reduces the density contrast between the upper and intermediate layers and thereby weakens stratification in this depth range. While this signal only barely penetrates into the NZ region (Figure R6a), it is more clearly expressed in the WGKP region (Figure R6b). In both cases, the weakened stratification in this depth range is dominant over the overall increasing stratification in the water column. The vertical structure of the spatial averaged N^2 anomalies in Figure 8 in the manuscript are therefore sensitive to the chosen region. Small changes in the latitudinal or longitudinal extent might give a more coherent stratification signal related to the deep convection changes.

Overall, the stratification changes in the NZ and WGKP region reflect a salinity-driven reorganisation of water masses, consistent with possibly a downward displacement/reorganisation of AAIW and a reduced influence or deepening of CDW. The negative stratification anomalies

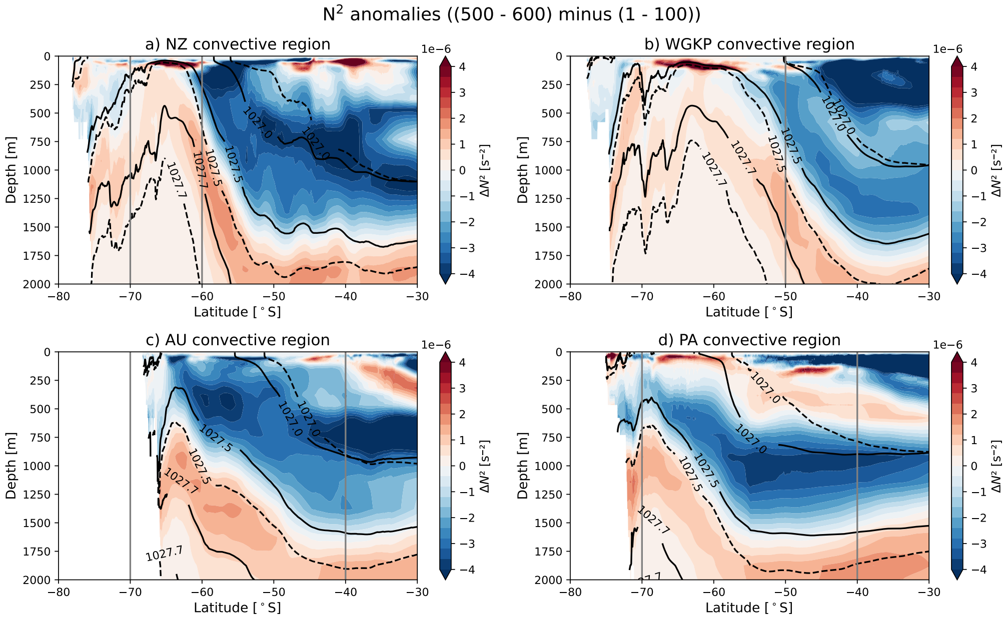

Figure R6: **Zonally averaged N^2 anomalies in SO30 convective regions.** (a) Zonally averaged (150°E – 170°E) N^2 in the NZ convective region (model year (500 – 600) minus (1 – 100)). (b) Same as (a), but now zonally averaged over the WGKP convective region (35°W – 80°W), (c) for the AU convective region (80°E – 150°E), and (d) for the PA convective region (110°W – 160°W). The solid (dashed) black lines denote zonally averaged isopycnals of model year 1 – 100 (500 – 600). Plotted isopycnals are (from top to bottom): 1027.0, 1027.5, and 1027.7 kg/m^3. The grey vertical lines denote the meridional boundaries of the respective convective regions.

in the upper 100 m in the NZ region are closely associated with the onset of multidecadal oscillation in the NZ region. Note that the above interpretation of Southern Ocean water mass changes remains speculative, as a complete understanding of the underlying mechanisms and pathways would require a detailed water mass budget analysis, which is beyond the scope of this study. However, the consistent salinity-driven stratification changes support our interpretation in terms of a reorganisation of AAIW and CDW.

Changes in manuscript:

We will include a more detailed explanation of the potential sources of the stratification changes in the revised manuscript.

2. *In contrast, both AU and PA regions show a steady decrease in the ocean stratification thereby inducing the deeper mixed-layer. What causes this weaker stratification in these regions? The mixed-layer depths in the AU and PA regions appear to oscillate on a multidecadal timescale after the AMOC collapse. Is it related to the initiation of the multidecadal oscillation in the NZ sector or is there any time lag in the multidecadal oscillation among the different sectors? Potential sources of multidecadal oscillation and their influence on the pathway to other sectors should be carefully examined and described in this paper.*

   Author's reply:

   The weaker stratification in the AU and PA regions arises from the same mechanisms as the reduced stratification in the intermediate waters of the WGKP and NZ regions, but in this case the signal penetrates more deeply into the water column, extending down to 1000–1500 m within the convective regions (Figure R6c,d). This weakening is primarily driven by a reduction in the vertical salinity gradient, associated with an increase in salinity in the upper 1000 m north of 60°S and a freshening of the waters below. The associated pattern is consistent with a downward displacement or reorganisation of AAIW.

   Indeed, multidecadal oscillations in the mixed layer depths of the PA and AU regions occur on similar timescales to those in the NZ region, and have therefore a comparable period as the SOM-P. The maximum MLD variations in the NZ and AU regions are largely in phase, likely reflecting their close spatial proximity. In contrast, the MLD variability in the PA region is approximately 180° out of phase with that in the NZ region, indicating an opposing response between the Pacific and NZ regions (Figure R7).

   Changes in manuscript:

   We will elaborate on the possible potential sources of stratification changes in the revised manuscript.

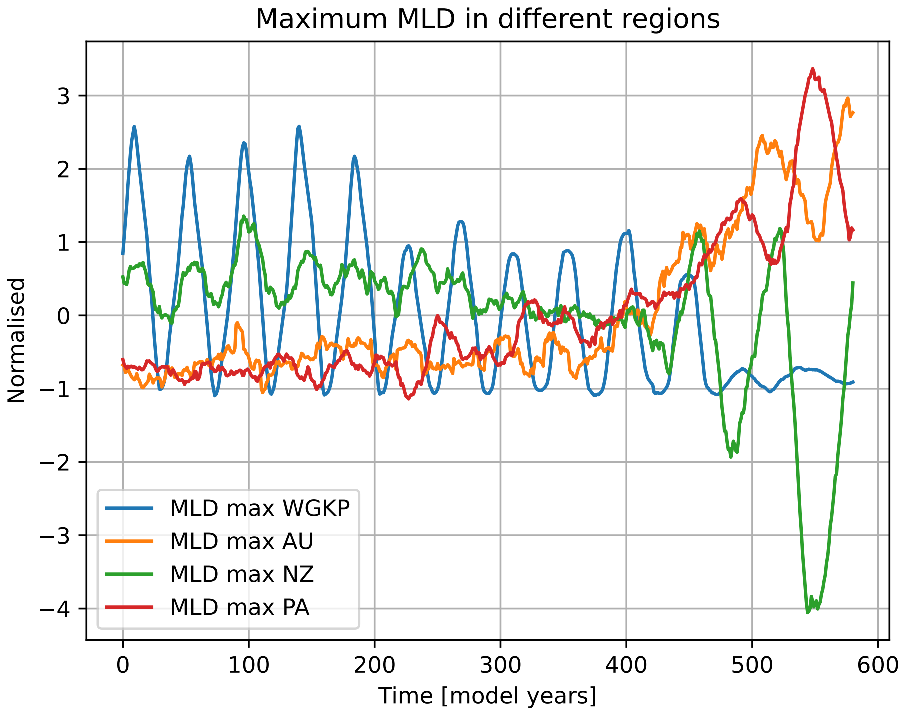

Figure R7: **Normalised maximum MLD in the convective regions.** The MLD time series are smoothed using a 20-year moving average. Each series is then normalised by subtracting its mean and scaling by its standard deviation.

Conclusions (Section 4)

1. *Some of the statements are not yet examined in this study. For example, a weakening of the AMOC increases the stratification in the WGKP region, mainly due to reduced upper-layer salinities (L304-305). However, the relative contribution of temperature and salinity to the density anomalies and the potential sources of them are unexplored in this study. In the Pacific sector, the deep convection events begin to emerge only after the AMOC has collapsed (L307). It remains unclear why the deep convection events start to emerge after the AMOC has collapsed, while it does not appear before the AMOC collapse. Although the role*

of deep convection in driving multi-decadal oscillations in the Southern Ocean remains uncertain, the reasons for the changes in the deep convection should be clarified in this study.

Author's reply:

We agree that some statements in the Conclusions need further clarification. The revisions described above will allow us to address this more clearly.

Changes in manuscript:

We will better justify the statements in the revised Conclusions.

Specific comments:

1. *L31: The timescale of ENSO is much shorter than the SOM, so I am wondering if the interdecadal variability of ENSO such as the Interdecadal Pacific Oscillation (IPO; Power et al. 1999) may affect the SOM through the atmospheric teleconnection to the South Atlantic, known as the Pacific-South American pattern (PSA; Mo and Paegle 2001)*

   - Power, S., Casey, T., Folland, C., Colman, A., & Mehta, V. (1999). Inter-decadal modulation of the impact of ENSO on Australia. Climate Dynamics, 15(5), 319-324.

   - Mo, K. C., & Paegle, J. N. (2001). The Pacific–South American modes and their downstream effects. International Journal of Climatology: A Journal of the Royal Meteorological Society, 21(10), 1211-1229.

   Author's reply:

   Indeed, Chang et al. (2020) largely attributed the pronounced multi-decadal variation in the upper-ocean temperatures in their high-resolution CESM1.3 simulation to a super-charged IPO in the model. Preliminary analysis suggested a link between SO sea-ice variability and the IPO, in which a decrease in sea-ice extent in the SO leads to a warming in the tropical Pacific. This negative correlation between the IPO and SO sea-ice is consistent with previous studies arguing that tropical Pacific SST anomalies can remotely force variability in the SO through stationary Rossby waves excited by convective heat anomalies in the tropics, e.g., Meehl et al., (2019).

- *Chang, P., Zhang, S., Danabasoglu, G., Yeager, S. G., Fu, H., Wang, H., ... & Wu, L. (2020). An unprecedented set of high-resolution earth system simulations for understanding multiscale interactions in climate variability and change. Journal of Advances in Modeling Earth Systems, 12(12), e2020MS002298.*
- *Meehl, G. A., Arblaster, J. M., Chung, C. T., Holland, M. M., DuVivier, A., Thompson, L., Yang, D., & Bitz, C. M. (2019). Sustained ocean changes contributed to sudden Antarctic sea ice retreat in late 2016. Nature Communications, 10(1), 14–19. https://doi.org/10.1038/s41 018-07865-9*

Changes in manuscript:

No changes needed.

2. *L35-37: How do the effects of the SOM extend into the North Atlantic? Does the SOM affect the tropical Atlantic SST thereby inducing the atmospheric teleconnection to the North Atlantic or influence the ocean circulation in the tropical Atlantic and the North Atlantic, but how?*

   Author's reply:

   The effects of the SOM extend into the North Atlantic through temperature and salinity anomalies propagating northward, thereby inducing multidecadal variations in the subsurface waters and AMOC strength (Figure A1 in manuscript). This was mentioned already in the original version of the paper.

   Changes in manuscript:

   No changes needed.

3. *L43: The role of convection is unclear. Do you mean the Southern Ocean deep convection (south of 60S in Antarctic Sea) is modified along this cycle? I am wondering how the Southern Ocean deep convection affects the mid-latitude phenomenon of the SOM (35-50S).*

Author's reply:

We refer here to deep convection episodes in the WGKP region (80°S to 50°S and 35°W to 80°E) which have the same multidecadal variability as the SOM. Anomalies in surface heat flux in the South Atlantic lead to anomalous temperatures that propagate eastward with the ACC and enter the Weddell gyre. These anomalies fill up the Weddell gyre and lead to significant changes in the ACC transport. The exact relation between the SOM and the deep convective episodes in the WGKP region needs much more analysis, which is outside the scope of the paper.

Changes in manuscript:

We mention this issue in the revised discussion.

4. *L70: I think the 300-yr simulation is not sufficiently long for the ocean model to reach the equilibrium state in the Southern Ocean where the deep convection plays a key role in formation of Antarctic Bottom Water and ocean background mean state. Ideally, a few thousand years are required, but it would not be feasible to run such a long simulation using the eddy-resolving ocean model because of the computational constraint. Can the authors examine to what extent the model is spun up by checking the Southern Ocean temperature and salinity from the surface to bottom?*

   Author's reply:

   Indeed, to equilibrate the entire ocean we would need simulations on millennial time scales, so there is still model drift, which is also reflected in the near-zero globally-averaged surface heat flux (Figure 8b in https://egusphere.copernicus.org/preprints/2025/egusphere-2025-5102/). The drift is, however, much slower than the time scale over which the AMOC declines and is hence not that relevant for the change in multidecadal variability we study here.

   - *van Westen, R. M., Katsman, C. A., and Le Bars, D.: Dynamic and Steric Sea-level Changes due to a Collapsing AMOC in the Community Earth System Model, EGUsphere [preprint], https://doi.org/10.5194/egusphere-2025-5102, 2025.*

Changes in manuscript:

We will make a statement about the model drift in the revised Methods.

5. *L76-77: Eastward propagation of the temperature anomalies from the South Atlantic to the Indian Ocean Sector along the ACC is also reported in another study by Morioka et al. (2017). However, it is unclear how these signals propagate southward and enter the Weddell Gyre. Is there any mechanism for the poleward migration?*

   - Morioka, Y., Taguchi, B., & Behera, S. K. (2017). Eastward propagating decadal temperature variability in the South Atlantic and Indian Oceans. Journal of Geophysical Research: Oceans, 122(7), 5611-5623.

   Author's reply:

   The temperature anomalies of the SOM that occur in the South Atlantic propagate eastward with the ACC. The propagation is smooth in the South Atlantic, but it is interrupted south of Africa around 30°E due to the interaction with the Agulhas Current retroflection (Le Bars et al. (2016)). In this area, the anomalies split into two parts. The first part continues along the ACC and slowly dissipates and reaches latitudes south of 58°S in the western Indian Ocean, in accordance with the findings of Morioka et al. (2017). The second part enters the Weddell Gyre (Le Bars et al. (2016)). This might be possible through an increase in cross-stream eddy diffusivity within this area compared to the South Atlantic (Sallée et al., 2008).

   - *Le Bars, D., J. P. Viebahn, and H. A. Dijkstra (2016), A Southern Ocean mode of multidecadal variability, Geophys. Res. Lett., 43, 2102–2110, doi:10.1002/2016GL068177.*
   - *Sallée, J. B., K. Speer, R. Morrow, and R. Lumpkin (2008), An estimate of Lagrangian eddy statistics and diffusion in the mixed layer of the Southern Ocean, J. Mar. Res., 66(4), 441–463, doi:10.1357/002224008787157458.*

   Changes in manuscript:

   This will be mentioned in more detail in the revised manuscript.

6. *L79: What is 60 ZJ?*

   Author's reply:

   ZJ stands for zettajoule, which is 10^{21} joules.

   Changes in manuscript:

   This will be clarified in the revised manuscript.

7. *L124: Why did you take the 5-yr time average? Is there any objective criterion for the length of the average? Are the results sensitive to this selection?*

   Author's reply:

   The 5-year time average is used to be consistent with earlier studies working on the SOM (Le Bars et al. (2016), Jüling et al. (2021)). The analysis is not sensitive to small changes in window length (tested using window lengths of 3-10 years). Using shorter window lengths results, however, in more noisy patterns, making it harder to visualize the lags between minima and maxima of the energetic terms.

   Changes in manuscript:

   A note on the sensitivity of the results to the window length will be added in the revised Methods section.

8. *L133: Is the AMOC strength during the first 50 model years reasonable compared to the observation?*

   Author's reply:

   The present-day AMOC strength is 16.9 ± 1.2 Sv over the period 2004 - 2024 (Johns et al. (2023)) and the AMOC strenght in the HR-POP is therefore slightly higher compared to observations.

   - *Johns, W. E., Elipot, S., Smeed, D. A., Moat, B., King, B., Volkov, D. L., & Smith, R. H. (2023). Towards two decades of Atlantic Ocean mass and heat transports at 26.5○N. Philosophical Transactions of the Royal Society A, 381(2262), 20220188. doi:10.1098/rsta.2022.0188*

Changes in manuscript:

No changes needed.

9. *Figure 3: I would recommend plotting only significant values in color or with dots and adding the vertical dashed lines that denote the mean ACC latitude band for Figs. 3a-c to compare against Fig. 3d.*

   Author's reply:

   Agreed.

   Changes in manuscript:

   Will be corrected.

10. *L162: Could the authors elaborate more on how the SOM influences the AMOC?*

    Author's reply:

    The effects of the SOM extend into the North Atlantic through temperature and salinity anomalies propagating northward, thereby inducing multidecadal variations in the subsurface waters and AMOC strength (Figure A1 in manuscript).

    Changes in manuscript:

    We will elaborate on this in the revised text.

11. *L212-213: In Fig. 6a, Regime A does not correspond well with this statement. The end of Regime A does not correspond to the minimum of the total kinetic energy K.*

    Author's reply:

    Agreed. The end or regime A should be around model year 92 where the minimum of K is located.

    Changes in manuscript:

    Will be corrected.

12. *L231, 233: Please show the figures on the energetics of the Atlantic and Pacific sectors as the supplementary figures.*

    Author's reply:

    Agreed.

    Changes in manuscript:

    These figures will be added.

13. *L254: I guess AU stands for Australia, but there is no mention in the sentence. Please specify the acronym.*

    Author's reply:

    Indeed, AU is an acronym for Australia.

    Changes in manuscript:

    This will be mentioned in the revised text.

14. *L264: It looks to me that the MLD response is deepening in association with the weakened stratification, although the amplitude is smaller than the other sectors.*

    Author's reply:

    Agreed.

    Changes in manuscript:

    This will be mentioned in the revised text.