Replies to Reviewer #1:

The authors present an AMOC mechanism studies using ensemble experiments in 2-dimensional ocean model. Their study shows dominant role of salinity in AMOC, whose magnitude and period are sensitive to four AMOC regions (week/strong and deep/shallow) due to different forcing and horizontal and vertical mixing. These results are consistent with their theoretical study and provide more features in our understanding the AMOC features and mechanisms. The manuscript is written well and can be published after major revision.

My major concerns are:

1. *The selection of surface salinity forcing in equation (4b) is kind of overly simplified, which missed the maxima near 15°S and 30°N and a minimum near the equator. If more realistic salinity forcing is selected, how will the simulated AMOC vary?*

Responses: Thank you for pointing this out. Indeed, Eq. (4b) represents an idealized forcing designed to facilitate mechanistic understanding.

Following your suggestion, we implemented a more realistic surface salinity forcing scheme. Specifically, we used the monthly net water flux data from the Ocean Reanalysis System 5 (ORAS5) for the period 2015–2025 (up to June) to calculate the forcing. These data were processed into zonal-mean values over the Atlantic basin. The salinity flux forcing input to the model was then calculated using the following formula:

$$Q_s = \frac{S_{ref}}{\rho_{ref}\delta_{ekman}}(EMP - < EMP >)$$

where EMP is the net upward water flux, $< EMP >$ is the mean of EMP over the period, which is to ensure the overall conservation of salinity. S_{ref} and ρ_{ref} are the reference values of the ocean, set to 35 psu and 1025 kg/m³, respectively. δ_{ekman} denotes the thickness of the Ekman layer, which is set to 50 m in our model.

As shown in Fig. R1, the red line represents the net flux forcing derived from ORAS5, which captures the observed maxima near subtropical and the equatorial minimum, while the black line shows the simplified forcing used in our CTRL experiment. We noticed that the net flux derived from ORAS5 is not symmetric between the Northern and Southern Atlantic, in contrast to the idealized flux, which was designed to be symmetric.

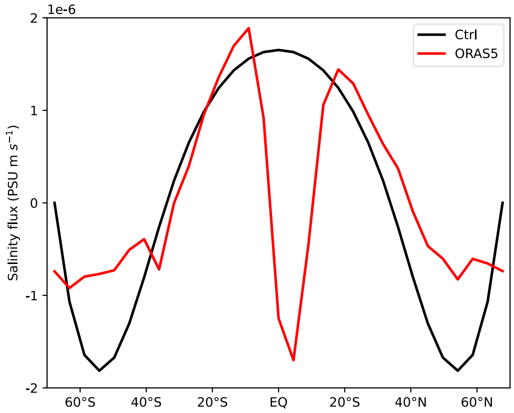

FIG. R1 Net surface virtual salinity flux. The black line represents the flux given in our CTRL experiment, and the red line is derived from ORAS5.

The corresponding AMOC are shown in Fig. R2. Panel (a) is from the CTRL; panel (b) shows result from the ORAS5 flux; and panel (c) shows their AMOC power spectrum. The AMOC structures are nearly identical, except that the AMOC intensity under ORAS5 is slightly stronger (by 2 Sv) than the CTRL. This small difference does not affect the period of AMOC's multicentennial oscillation (MCO), as illustrated in panel (c). This suggests the robustness of the AMOC MCO.

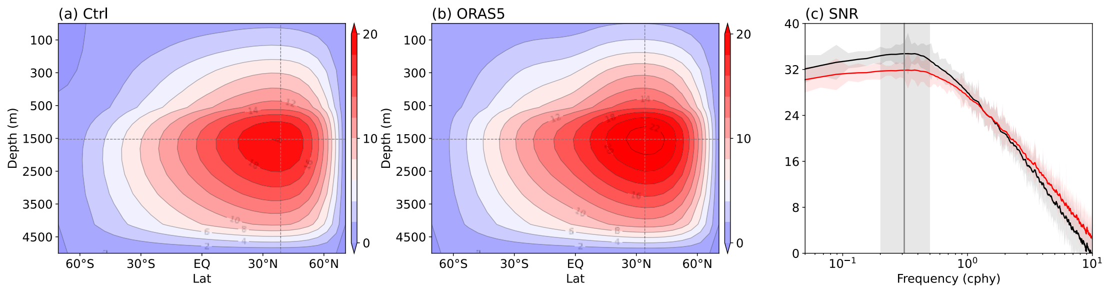

FIG. R2 AMOC situation under different flux forcings. (a) for Ctrl experiment, (b) for ORAS5 flux. Gray dotted lines in (a)-(b) cross the point of the maximum value of the streamfunction. (c) The ratios of the AMOC spectrum to the noise spectrum (units: dB), i.e., signal-noise ratio (SNR), with peaks around 0.2-0.5 cphy (200-500 years) that are specified by pale-gray shadow. Black and red lines represent the CTRL experiment and the ORAS5 condition, respectively.

References:

Copernicus Climate Change Service, Climate Data Store, (2021): ORAS5 global ocean reanalysis monthly data from 1958 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). DOI: 10.24381/cds.67e8eeb7.

2. The propagation of salinity and temperature anomalies looks clear in Figure 7, but I have a kind of feeling that the anomalies may have something to do with the surface forcing. Is there a way that the authors can look into the changes in surface salinity and heat flux?

Responses: We appreciate the reviewer's insight regarding the potential link between subsurface anomalies and surface forcing.

Here we would like to say that that our model employs fixed surface flux boundary conditions (Eq. 4a–4c):

$$Q_H = \frac{\Delta Z}{\tau}(T_0 - T), \quad \mathrm{Q_S} = \frac{\Delta Z}{\tau}(S_0 - S) \tag{4a}$$

$$T_0 = T_L + T_*\left(1 + \cos\frac{\pi y}{L}\right), \quad S_0 = S_L + S_*\left(1 + \cos\frac{\pi y}{L}\right) \tag{4b}$$

$$Q_H = \frac{\Delta Z}{\tau}(T_0 - T), \quad Q_S = Q_S(y) \tag{4c}$$

which meaning that heat and freshwater fluxes are prescribed as constants.

Stochastics freshwater flux is only applied in the subpolar North Atlantic region. Therefore, the anomalies in Figure 7 can be generated or modulated by the stochastic freshwater flux, and have nothing on the constant surface fluxes. The propagating signals observed in Figure 7 are purely driven by internal ocean dynamics, specifically advective feedback.

Figure R3 shows power spectrum of sea surface temperature (SST) and sea surface salinity (SSS) averaged over the subpolar North Atlantic (40-50°N, which is the primary region where stochastic forcing is applied) and over the global. The SST and SSS in the subpolar North Atlantic exhibit clear MCO (indicated by the grey shaded region), whereas global SST and SSS do not show this type of variability.

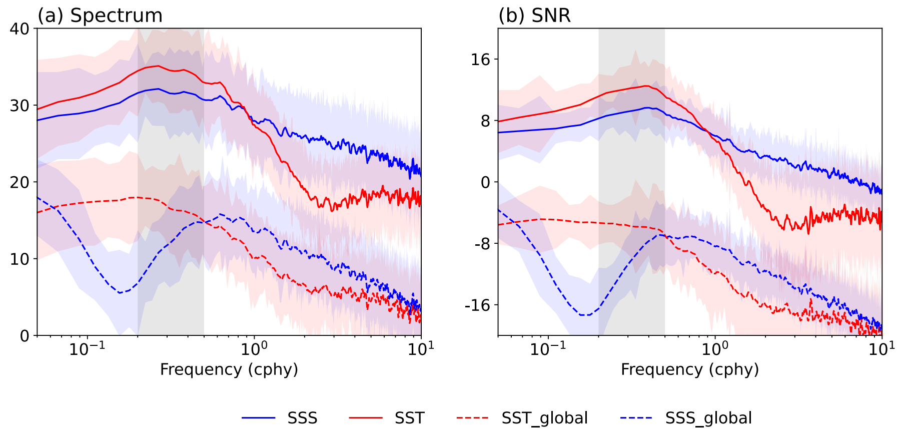

FIG. R3 (a) The power spectrum and (b) the signal-to-noise ratio (SNR, units: dB) of sea surface salinity (SSS) and sea surface temperature (SST). The shaded pale-gray region highlights the 0.2-0.5 cycles per hundred years (cphy), corresponding to periods of 200-500 years. The thick blue and red curves represent the ensemble mean of 50 realizations of SSS and SST forced by white noise. The pale red, blue, and green shaded regions indicate the spread of the 50 realizations. The x-axis represents frequency in units of cycles per hundred years (cphy).

3. *L64: This study = Their study?* Revised.

4. *L71: organically, what does this really mean?*

Responses: Thanks for the question. This word "organically" is removed.

5. *L126, what is the difference between Qs in equations (4c) and (4a) (4b)?*

Responses: Thank you for your question. The difference between Qs in equations (4c) and (4a)/(4b) lies in the boundary conditions used for temperature and salinity.

$$Q_H = \frac{\Delta Z}{\tau}(T_0 - T), \quad Q_S = \frac{\Delta Z}{\tau}(S_0 - S) \tag{4a}$$

$$T_0 = T_L + T_* \left(1 + \cos\frac{\pi y}{L}\right), \quad S_0 = S_L + S_* \left(1 + \cos\frac{\pi y}{L}\right) \tag{4b}$$

$$Q_H = \frac{\Delta Z}{\tau}(T_0 - T), \quad Q_S = Q_S(y) \tag{4c}$$

Equation (4a) represents a restoring boundary condition for both temperature and salinity, where both variables are restored to a prescribed value. Equation (4c) represents a mixed boundary condition, where temperature is restored to a prescribed value, but salinity is treated with a fixed salinity flux condition. The restoring boundary condition in (4a) is only used during the spin up experiment to initialize the model and achieve a balanced state. Equation (4b) provides the numerical representation of the temperature and salinity restoring conditions. After the spin up experiment, the fixed salinity flux condition in (4c) is used for subsequent experiments (including to get equilibrium states and perturbation experiment). The salinity flux Qs in (4c) is diagnosed from the surface salinity distribution (Fig. R1).

6. *L123, what is the direction of "y" in the equations? It may be good to mention the latitudinal changes from 70°S to 70°N as indicated in Figure 1. T0 as a function of y looks very reasonable, but S0 as a function of y may not be a good approximation either for the Atlantic or the global average (Peixoto and Oort, 1991 page 189, see attached).*

Responses: We appreciate the reviewer's valid point about y direction and regarding the idealized salinity profile.

Our approach is based on the following methodological considerations: The meridional coordinate y is defined such that y = –L corresponds to 70°S and y = +L to 70°N. Regarding the salinity profile S_0, we would like to emphasize that this profile is only used in the spin-up phase of experiments employing restored boundary condition. Its role is to help the model reach a quasi-equilibrium state before applying the mixed boundary condition. Thus, S_0 serves as an idealized initial condition rather than a persistent forcing throughout the simulation. As for the concern about its idealized nature, we have already addressed this in response to the first major comment, the overall AMOC structure remains qualitatively robust (Figs. R1 and R2).

7. *L160-161, Northern Hemisphere, Southern Hemisphere= North Atlantic, South Atlantic?*

Responses: Thank you very much for this suggestion. Revised

8. *L173-176, How are the "a" and "b" selected in a specific experiments or ensemble run? This should be stated clearly as in the next paragraph.*

Responses: Thank you very much for this suggestion. We used the “a” and “b” selected here in all subsequent perturbation experiments. A clarifying statement has been added to the manuscript at line 176: “All subsequent stochastic experiments in this study are conducted using the parameters specified here."

9. L190, it is interesting to see that Figure 3b is almost symmetric to the lead-lag of 0 year, any insight about this feature?

Responses: Thank you for your insightful comment regarding Fig. 3b.

We would like to say that the asymmetry seen in Fig. 3b is physically reasonable, as the periodicity of AMOC, SST, and SSS in Fig. 3a is notably irregular, reflecting the influence of stochastic forcing. In fact, symmetric oscillations should not be expected, since the ocean—or the coupled climate system—is inherently nonlinear. The pattern in Fig. 3b likely captures the intrinsic nonlinear dynamics of the system, particularly the time-asymmetric response of AMOC to salinity anomalies. This interpretation is consistent with our discussion in Line 518, where we emphasize that "nonlinearities in the response of the oceanic circulation to salinity and temperature anomalies may contribute to asymmetry."

Moreover, similar asymmetric behavior has been documented in previous studies. For instance, Figure R4 shows lagged regressions from earlier works using three different models, all exhibiting varying degrees of lead–lag asymmetry between AMOC strength and associated oceanic variables (Jiang et al. 2021; Mehling et al. 2022; Meccia et al. 2023). These results support the notion that asymmetry is an intrinsic and robust feature of AMOC variability across different modeling frameworks.

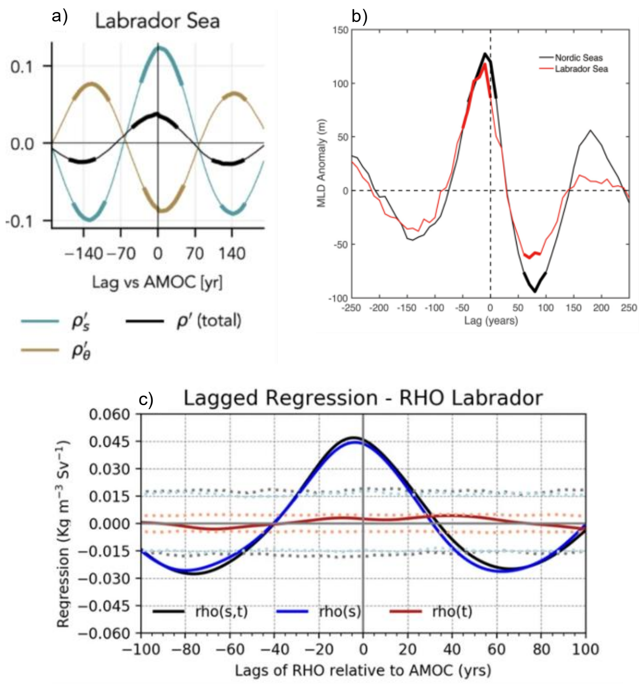

FIG. R4 Lagged regressions related to AMOC variability across different models. (a) Density anomalies regressed onto AMOC index (PlaSim-LSG; Mehling et al. 2022).(b) Mixed layer depth regressed onto AMOC LFC1 (IPSL-CM6-LR; Jiang et al. 2021).(c) Density, salinity, and temperature contributions regressed onto the AMOC index (EC-Earth3; Meccia et al. 2023).

References:

Jiang, W., G. Gastineau, and F. Codron, 2021: Multicentennial Variability Driven by Salinity Exchanges Between the Atlantic and the Arctic Ocean in a Coupled Climate Model. *J. Adv. Model. Earth Syst.*, **13,** e2020MS002366, https://doi.org/10.1029/2020MS002366.

Meccia, V. L., R. Fuentes-Franco, P. Davini, K. Bellomo, F. Fabiano, S. Yang, and J. von Hardenberg, 2022: Internal multi-centennial variability of the Atlantic Meridional Overturning Circulation simulated by EC-Earth3. *Climate Dyn.*, **60,** 1-18, https://doi.org/10.1007/s00382-022-06534-4.

Mehling, O., K. Bellomo, M. Angeloni, C. Pasquero, and J. Von Hardenberg, 2022: High-latitude precipitation as a driver of multicentennial variability of the AMOC in a climate model of intermediate complexity. *Climate Dyn.*, **61,** 1519-1534, https://doi.org/10.1007/s00382-022-06640-3.

10. L223, with that under white noise forcing stronger than that under red noise forcing =, which is stronger under white noise forcing than that under red noise forcing.

Responses: Thank you very much for this suggestion. Revised

11. L224-227, why is the SNR stronger white noise?

Responses: Thanks for this question. The higher SNR under white noise forcing is because of lower energy in the low frequency range under white noise forcing.

As shown in Fig. 4a, the power spectrum of the red noise (longer e-folding times) exhibits significantly more energy at low frequencies compared to the spectrally flat white noise. Crucially, our experiments are designed such that the total standard deviation of the AMOC variability induced by these different noises is comparable (approximately 5 Sv in CTRL run). This implies that the overall power level in the AMOC spectra (Fig. 4b) is similar across noise experiments. Therefore, higher SNR under white noise forcing.

12. L236, Lag -150 = Lag -160? Revised.

13. L236-238, It is not immediately clear how the "peak" is identified, by the max/min regression coefficients?

Responses: Thanks for this comment. The peak is identified by the max/min regression coefficients.

14. L258, why are the orange dashed arrows plotted in (c), (g), and (l) only, why not all, or why just one panel only?

Responses: Thanks for the question. The orange dashed arrows are plotted in panels (c), (g), and (l) to highlight the key features of the process in different phases (positive and negative) of the northward-to-southward propagation of the salinity anomalies. These panels were selected because they most clearly illustrate the salinity anomaly propagation from the high latitudes of the North Atlantic, downwelling, and the subsequent southward transport. Of course, this is just one way to visualize the process. It would also be ok to include arrows in all panels, but we think it is not that necessary.

15. L246, "200-0" = -200 to 0? Revised.

16. L248-250, "propagate northward", it is not very clear about the propagation? Is it possible that the increase of salinity in the high latitudes is due to surface forcing?

Responses: Thank you for your question. It is unlikely that the increase in salinity in the high latitudes is due to surface forcing, which is constant. As shown in Figure R1, the black line represents the surface salinity forcing used in the CTRL, which actually leads to a continuous loss of surface salinity in the high latitudes. Therefore, the propagation of salinity anomalies northward is not driven by surface forcing, but rather by the internal dynamics of the ocean, such as advective feedbacks and the interaction of salinity anomalies with the AMOC.

17. L285: "a couple of years" is how many years? My visual estimate is at least about 10-20 years in Fig. 7a.

Responses: Thank you very much for this suggestion. Revised to 10-20 year.

18. Figures 5, 6, 8, Why the Lag 20 panel is included, which makes the lag interval not equal?

Responses: Thanks for this question. The main reason of including the Lag-20 panel is to make these figures having even number of subplots, so these figures consist of 3 columns and 4 rows, which improves the overall visual appeal. Otherwise, there would be 11 subplots, which is hard to organize. Also, inclusion of the Lag 20 panel in Figs. 5, 6, and 8 allows us to better observe shorter-term variations in the salinity anomalies and their impact on the AMOC.

19. Figure 8, why does the current anomaly change so much from (d) to (e)?

Responses: Thank you for raising this question. The MCO is inherent in simple model driven by stochastic forcing, so the regression coefficient of the system varies significantly during different phases of the oscillation. Specifically, the coefficient is greater when the phase is closer to lead/lag 0.

The transition from (d) to (e) represents the shift from a neutral phase to a stronger phase of the AMOC, which leads to a stronger current anomaly. This change occurs because, in the context of the MCO, when the system is closer to the neutral phase, the feedback processes are weakest, resulting in smallest anomalies. As the AMOC enters the stronger phase (moving from (d) to (e)), the positive feedback mechanisms become more pronounced, driving a larger response in the current anomaly.

20. Table 2. It is not clear how the experiments are designed with those changes in parameters: e.g. Why Ah and Kh are the largest/smallest among the experiments in comparison with Ctrl? The changes in Av and Kv are more reasonable.

Responses: Thank you for your comment. The changes in the parameters in our experiments were designed to explore the effects of ideal values on the AMOC structure and its variability, particularly in comparison to CTRL. These experiments are simplified to isolate the effects of changes in AMOC structure and strength, assuming only differences in depth and strength, in line with the theoretical equation $T = 2\pi\sqrt{V_1 V_2/\bar{q}}$ from Yang et al. (2022), V_1 and V_2 are volumes of upper tropical and Atlantic, $\bar{q}$ is equilibrium AMOC strength.

During the adjustment process, we found that although changes in vertical mixing parameters (*Av* and *Kv*) significantly influence the magnitude of $\bar{q}$, they also affect the spatial structure—namely, the effective volumes V_1 and V_2. To better control these volumes and maintain the structural balance, we also adjusted the horizontal parameters *Ah* and *Kh*. Although these values may appear extreme, this was done intentionally to construct clean experiments that isolate the effect of AMOC structure on the MCO.

In general, we aim to investigate the impact of depth and strength of AMOC on the MCO, as described in line 160 of the manuscript. We acknowledge that this approach may seem extreme but is intentionally designed to better understand the theoretical behavior under such conditions.

References:

Li, Y., and H. Yang, 2022: A Theory for Self-Sustained Multicentennial Oscillation of the Atlantic Meridional Overturning Circulation. *J. Climate*, **35**, 5883–5896, https://doi.org/10.1175/JCLI-D-21-0685.1.

21. L372-374, How are these numbers derived?

Responses: Thank you for this question. The reported values are derived from the peak frequencies in the power spectra shown in Figs. 10b and 10d, which represent the statistically significant dominant periods of AMOC variability under different parameters.

These periods are then compared to the equilibrium (mean-state) AMOC index from each experiment to assess the relationship between the strength of the AMOC index and the oscillation timescale. This comparison supports the conclusion that both the period and amplitude of the MCO are sensitive to the background AMOC structure.

22. L397, delete "easily", "simply" Revised.

Replies to Reviewer #2:

In this manuscript, the authors study the AMOC multi-centennial oscillations (MCO) using a zonally averaged simple model. They found the AMOC MCO is intrinsic to the system, they also tested to add different noises and found that these different noises do not affect the existence of the AMOC MCO, and the period of the MCO depends on the AMOC vertical structure and the strength. They also found that by adding wind effect, it has limited influence on MCO periods. In general, the results are interesting and worth to be published, but some revision is needed.

1. *The authors may need to state the model more clearly. Such as this model is assumed a width of 6000 km, but in reality, this is a zonally averaged model.*

Responses: Thanks very much for this suggestion. We have clarified that our model is a zonally averaged 2D ocean model with an assumed basin width of 6000 km. The updated statement in the revised manuscript Line 135-137: "*In this study, the 2-dimensional model domain extends from 70°S to 70°N, with an ocean depth of 5000 m. Since this configuration is used to simulate the thermohaline circulation in the Atlantic Ocean, a basin width of 6000 km is further adopted for the calculation of the streamfunction*."

2. *Since this is a zonally averaged model, it will be good to increase the meridional resolution. Now it is about 220 km. I wonder if the meridional resolution is 100 or 50 or 25 km, will these lead to changes in the results?*

Responses: Thanks very much for your thoughtful suggestion. We agree that increasing the meridional resolution could be beneficial, particularly for capturing finer-scale dynamics. In our current model, the meridional resolution is approximately 220 km.

To assess the impact of finer resolutions, we conducted additional experiments with resolutions that are 2 times (about 110 km) and four times (about 55 km) finer than the current grid. Our results indicate that the changes in the meridional resolution did not lead to significant differences in the overall outcomes of the simulations (Fig. R5). Specifically, the AMOC index maximum values across different resolutions were all close to 20 Sv, with the differences being less than 1% (approximately 0.2 Sv). Furthermore, the resolution does not also affect the timescale of AMOC MCO. The mean AMOC and its MCO are planetary-scale problem, so we think the model resolution is not a serious issue in this work.

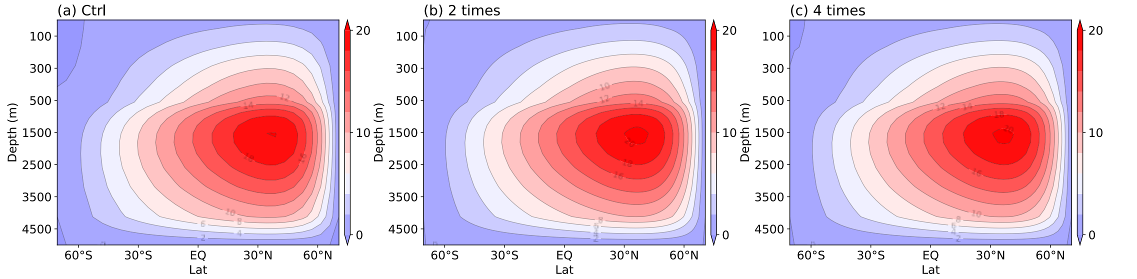

FIG. R5 AMOC equilibrium state at different resolutions. (a) Control run; (b) 2 times resolution; (c) 4 times resolution.

3. *What is the vertical resolution?*

Responses: Thank you for this question. In our simple 2D model, the vertical resolution is non-uniform. The model employs a vertical grid that stretches more densely in the upper ocean and coarser deeper down. This setup allows for better resolution of surface processes, such as the Ekman layer, while maintaining computational efficiency in the deeper ocean. The vertical depth for each layer, in meters , is as follows：0, 50, 166, 286, 415, 556, 710, 880, 1069, 1281, 1525, 1812, 2157, 2594, 3187, 4118, 5000.

4. *It seems that the MCO may be a function of the relaxation timescale of the mixed boundary condition. What if you alter the relaxation timescale from 1 year to 6 months or 2 years?*

Responses: Thank you for your question. In Yang et al. (2024), the impact of the relaxation timescale on the AMOC MCO has been investigated theoretically in a box model framework.

As shown in Figure R6, the relationship between the relaxation timescale and the eigenvalues of the system was analyzed. Specifically, Figure R6a shows the imaginary part of the eigenvalue, which is related to the oscillation frequency (i.e., period), while Figure R6b shows the real part, which indicates the growth or decay rate of the mode and thus the system’s stability. The results indicate that the relaxation timescale has a relatively limited influence on the MCO—it only slightly modulates the period and stability within a certain range, and the overall impact is not substantial.

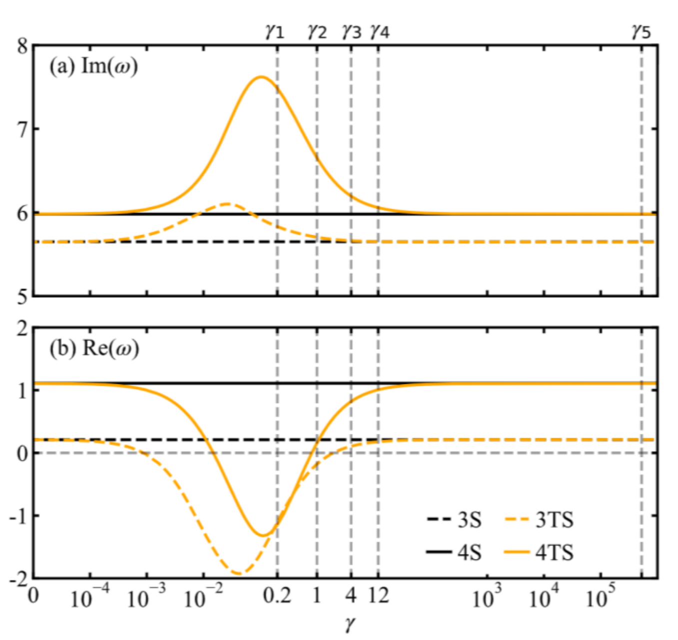

FIG. R6 Dependences of (a) positive imaginary parts and (b) real parts of the conjugate eigenvalues ω on γ (units: yr^{-1}) in box models. The units of the ordinate are $10^{-10}\ S^{-1}$ (Yang et al. 2024). The vertical dashed lines from left to right denote the situations under relaxation timescales of 5 years, 1 year, 1/4 year and 1 month, respectively.

In response to your inquiry, we conducted additional experiments with relaxation timescales of 6 months and 2 years under the same experimental setup as the CTRL. In these experiments, we used 50 sets of white noise to perform 50 stochastic forcing experiments, similar to the CTRL.

As shown in Fig. R7, compared to the CTRL (Fig. R7a), the experiments with a 6-month relaxation time (Fig. R7b) shows a larger upper control region in the AMOC, and the AMOC becomes slightly stronger. When the relaxation timescale is extended to 2 years (Fig. R6c), the AMOC does not exhibit significant changes. Based on theoretical estimates from Li and Yang (2022), the oscillation period in the 6-month relaxation experiment is approximately 1.2 times that of the 1-year relaxation period, while the period in the 2-year experiment is approximately 1.5 times that of the 1-year relaxation period. This is consistent with the power spectra shown in Fig. R7d, where the peak value for the 6-month experiment (yellow line) is slightly higher than that for the 1-year experiment (red line), and the peak value for the 2-year experiment (blue line) is greater than that for both the 1-year and 6-month experiments. However, the significant periods still fall within the range of 250-500 years for the MCO (grey shading).

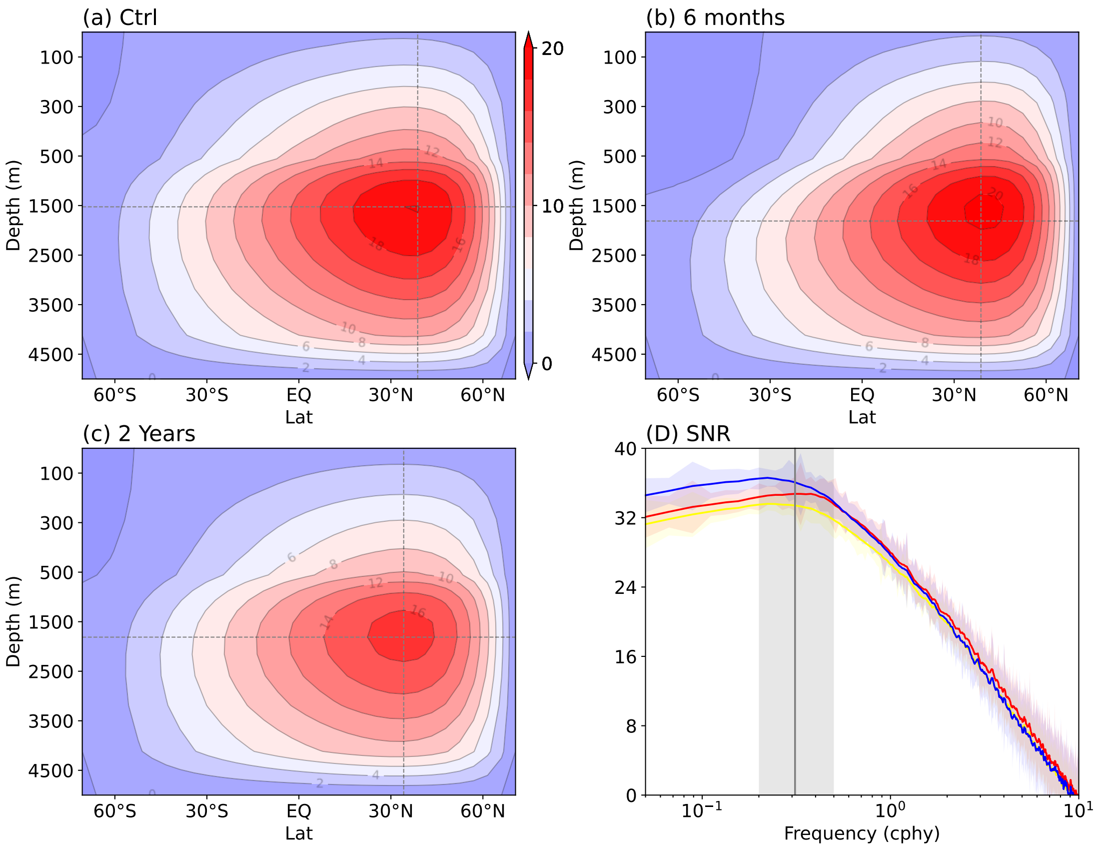

FIG. R7 AMOC equilibrium state at different relaxation timescale. (a) CTRL (1 year); (b) 6 months ; (c) 2 years; (d) The ratios of the AMOC spectrum to the noise spectrum (units: dB), i.e., signal-noise ratio. The red line represents experiments with relaxation timescale of 1 year, the yellow line represents experiments with a relaxation timescale of 6 months, and the blue line represents experiments with relaxation timescale of 2 years.

In summary, we find that while the MCO is influenced by the relaxation timescale in 2d model, but it is still mainly controlled by the equilibrium state of the system. The relaxation time influences the AMOC's response slightly, but the underlying mechanism driving the MCO remains consistent.

References:

Li, Y., and H. Yang, 2022: A Theory for Self-Sustained Multicentennial Oscillation of the Atlantic Meridional Overturning Circulation. *J. Climate*, **35**, 5883–5896, https://doi.org/10.1175/JCLI-D-21-0685.1.

Yang, K., H. Yang, and Y. Li, 2024: A Theory for Self-Sustained Multicentennial Oscillation of the Atlantic Meridional Overturning Circulation. Part II: Role of Temperature. J. Climate, 37, 913–926, https://doi.org/10.1175/JCLI-D-22-0755.1.

5. *Although the authors mentioned the advection of the salinity anomalies as a mechanism driving the AMOC MCO, it is not clear what induces these salinity anomalies.*

Responses: Thank you for your insightful comment. The origin of the salinity anomalies is induced by stochastic surface virtual salt flux in our simple model. Stochastic forcing act as perturbations to excite the system and drive the internal dynamics, including the propagation of anomalies.

Since in reality, stochastic perturbation is always available in a couple system. So, in this work, we focus on how these anomalies propagate and influence the AMOC oscillations once they are introduced by the stochastic forcing. A coupled model might be better suited to fully explain the mechanisms that induce salinity anomalies, as it can account for more complex interactions between the atmosphere, ocean, and other components. However, coupled models come with significantly higher computational costs and greater model complexity, which leads to larger differences between models. This is precisely where the advantage of our simplified model lies. By focusing on the internal dynamics of the ocean and using stochastic forcing, we can isolate and study the essential mechanisms of the AMOC oscillations without the added computational burden.

6. *It seems that the MCO also exists in control run, is it right?*

Responses: Thank you for the question. The MCO is present in both the control run and in various sensitivity experiments conducted at different equilibrium states. However, it is important to note that the MCO is only excited when stochastics salinity forcing is added to the simple model. Without this stochastic forcing, the system remains in a stable equilibrium.

7. *What is the pattern of T, S used for the restoration?*

Responses: The SST and SSS profiles used for the restoration are primarily based on Equation (4b):

$$T_0 = T_L + T_* \left(1 + \cos\frac{\pi y}{L}\right), \quad S_0 = S_L + S_* \left(1 + \cos\frac{\pi y}{L}\right) \tag{4b}$$

where the parameter settings are as follows: $T_L = 0°\mathrm{C}$, $S_L = 35$ psu, $S_* = 1$ psu, $T_* = 12.5°\mathrm{C}$. These parameters ensure that the SST is restored from the poles to the equator within a range of 0–25°C, and the SSS is restored within a range of 35–37 psu.

The overall temperature and salinity profiles are symmetric, as shown in Fig. R8. This symmetric structure is consistent with the findings of many 2D models that also use restoring boundary conditions (Marotzke et al. 1988; Wright and Stocker 1992).

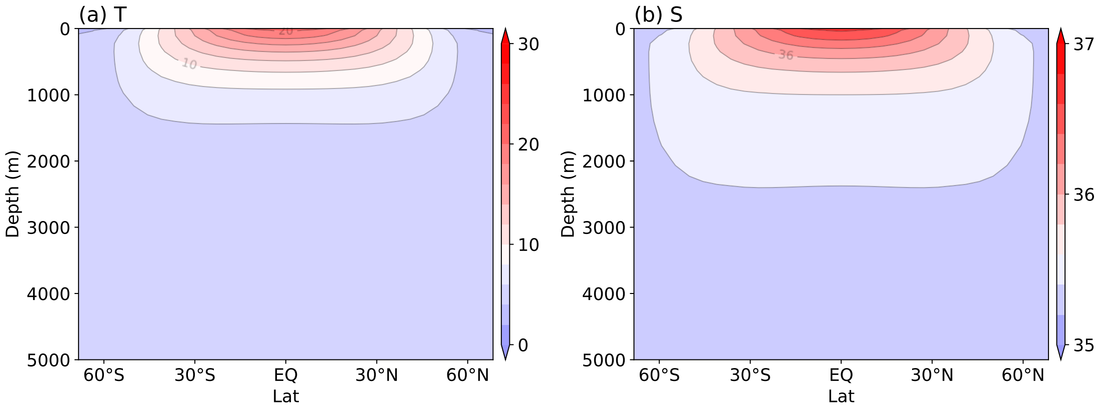

FIG. R8 The pattern is obtained by using the restoring boundary condition spin up. (a) T; (b) S.

References:

Marotzke, J., P. Welander, and J. Willebrand, 1988: Instability and multiple steady states in a meridional-plane model of the thermohaline circulation. Tellus, 40, 162-172, https://doi.org/10.3402/tellusa.v40i2.11790.

Wright, D. G., and T. F. Stocker, 1991: A Zonally Averaged Ocean Model for the Thermohaline Circulation. Part I: Model Development and Flow Dynamics. J. Phys. Oceanogr., 21, 1713–1724, https://doi.org/10.1175/1520-0485(1991)021<1713:AZAOMF>2.0.CO;2.

8. What if a model domain is defined with two longitudes, instead of a rectangular domain? does this will change the model results?

Responses: Thank you for your suggestion. The current model assumes a zonal averaged y-z domain. Extending to a domain defined by two longitudes is an interesting future direction. We believe that, while finer geometrical representation could affect results to some extent, the core oscillation mechanism should remain similar due to its internal nature. This expectation is supported by studies using more complex model geometries—for example, coupled models such as CESM have also exhibited similar AMOC MCO (Yang et al. 2024).

Therefore, we think that domain complexity (rectangular or latitude-longitude domain) would not eliminate the underlying mechanism. In future work, we plan to extend this research by implementing 3D ocean-only models to further investigate the persistence and modulation of the MCO under more realistic boundary and geometric settings. This stepwise approach will help bridge the gap between idealized and comprehensive modeling frameworks.

References:

Yang, K., H. Yang, Y. Li, and Q. Zhang, 2024: North Atlantic Ocean–Originated Multicentennial Oscillation of the AMOC: A Coupled Model Study. J. Climate, 37, 2789–2807, https://doi.org/10.1175/JCLI-D-23-0422.1.