Reviewer 2:

The authors designed an idealized numerical model setup to mimic the South China Sea (SCS) and its connection with the west Pacific Ocean in order to understand the control of the slope topography in the three-layer circulation system in the SCS.

In my opinion, the numerical design is too simplified to reflect the complexity in the interactions between the three layered circularions, the setup is flawed and does not provide convincing results to support their quantitative conclusions.

Response: Thank you for the thoughtful suggestions and comments, which have significantly helped us refine and clarify our work. We have carefully considered your comments and revised our manuscript accordingly.

We acknowledge that this process-oriented study adopts certain simplifications, such as boundary conditions, topographic features, and turbulent mixing intensity. Our primary objective is to use these simplified simulations to isolate and better understand the key processes driving layered circulation. This approach allows us to clearly demonstrate how variations in the strong upper-layer circulation influence the overall layered circulation over the slope. Similar approaches were applied in previous studies and successfully obtained insights into the circulation dynamics. The results also show that the processes observed in this simulation are consistent with established understandings from previous studies. We have improved the description of model configuration to avoid misunderstanding.

Below, we have provided detailed responses to your specific concerns, particularly the details and explanations on configuration of the boundary condition, the turbulent mixing intensity, and the stability of the simulation.

The major flaws of the numerical setup are listed below:

1. The depth of the west pacific ocean is set to the same of the SCS (4000 m), and adopts the same initial temperature and salinity profile. This means that there is no density gradient in the deep layer between the pacific ocean and the SCS which is needed to form the

intrusion of the denser western paficic water into the SCS and the resultant cyclonic deep layer circulation. I don't understand how can the model reproduce this deep circulation in this case?

Response: Yes, the maximum depths of the SCS and Pacific basins are set as 4000 m to represent the deep basins. These two basins are connected through the Luzon Strait (LS), which has a depth of only 2500 m. Although the initial temperature and salinity distributions are horizontally uniform, the intensified turbulent mixing within the deep SCS basin gradually leads to a density difference between the two sides of the LS (Figure R1). Specifically, the deep SCS exhibits lower density compared to the Pacific basin. The formation of this cross-strait density difference is consistent with previous understandings and is widely recognized as the source of the deep pressure gradient between the SCS and the Pacific. This gradient subsequently drives the deep intrusion and the development of deep cyclonic circulation (e.g., Tian et al., 2009; Zhou et al, 2023; Zhu et al.2019, Cai et al., 2021, 2023). Associated with the layered exchange current in LS, the layered circulations were developed accordingly inside the SCS basin (Figure R2)

We apology for the misunderstanding caused by the initial description. In the revised manuscript, Figure R1 and R2 will be used as the supplementary figure to better clarify the configuration details.

Line 99-100: The SCS and Pacific basins were connected by a narrow strait (representing the LS) with a depth of 2500 m.

Line 142-151: Although the initial temperature and salinity distributions are horizontally uniform, the intensified turbulent mixing within the deep SCS basin gradually leads to a density difference between the two sides of the LS. Specifically, the deep SCS exhibits lower density compared to the Pacific basin (Figure S1). Under the density difference, the westward pressure gradient was formed that drives the deep intrusion from the open ocean towards the SCS. Those features are consistent with established understandings from previous studies (e.g., Wang, Xie et al. 2011, Zhu et al., 2017, 2019; Cai, Chen et al. 2023; Zhou et al., 2023). Associated with the simulated layered exchanging current, the layered circulations developed inside the SCS basin. The upper, middle, and deep layers exhibit circulation in cyclonic, anticyclonic, and cyclonic directions, respectively (Figure S1).

Reference:

Cai, Z., D. Chen and J. Gan (2023). "Formation of the Layered Circulation in South China Sea With the Mixing Stimulated Exchanging Current Through Luzon Strait." Journal of Geophysical Research: Oceans 128(3).

Cai, Z. and J. Gan (2021). "Dynamics of the Layered Circulation Inferred from Kinetic Energy Pathway in the South China Sea." Journal of Physical Oceanography 51(5): 1671-1685.

Tian, J., Q. Yang, and W. Zhao, 2009: Enhanced Diapycnal Mixing in the South China Sea. J. Phys. Oceanogr., 39, 3191–3203, https://doi.org/10.1175/2009JPO3899.1.

Zhou, C., Xiao, X., Zhao, W. et al. Increasing deep-water overflow from the Pacific into the South China Sea revealed by mooring observations. Nat Commun 14, 2013 (2023). https://doi.org/10.1038/s41467-023-37767-4

Zhu, Y., Sun, J., Wang, Y., Li, S., Xu, T., Wei, Z. and Qu, T., 2019. Overview of the multi-layer circulation in the South China Sea. *Progress in Oceanography*, *175*, pp.171-182.

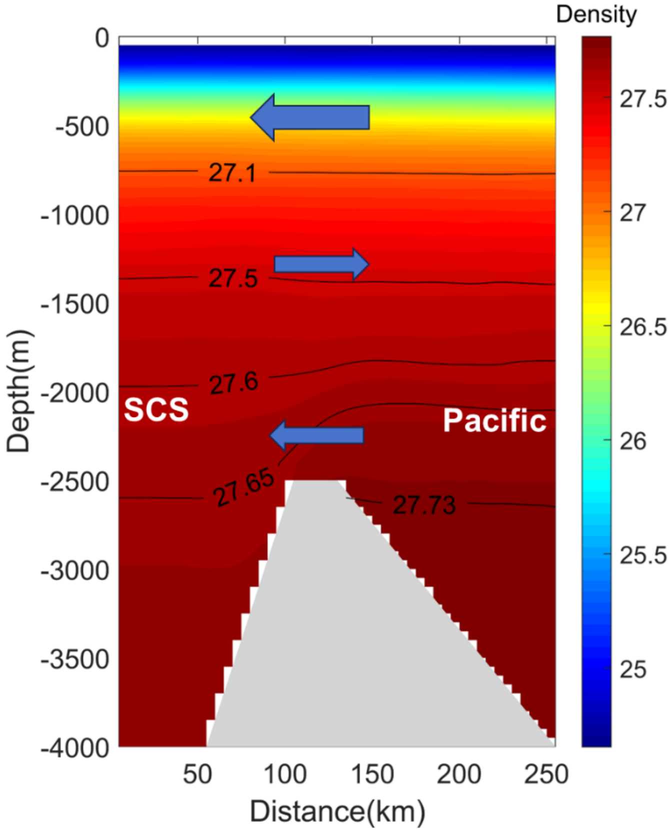


Figure R1. Vertical transect of density (represented by color shading and contour lines) across the Luzon Strait. The left side represents the SCS basin, while the right side corresponds to the Pacific basin. Schematic arrows indicate the direction of the exchange flow between the two basins.

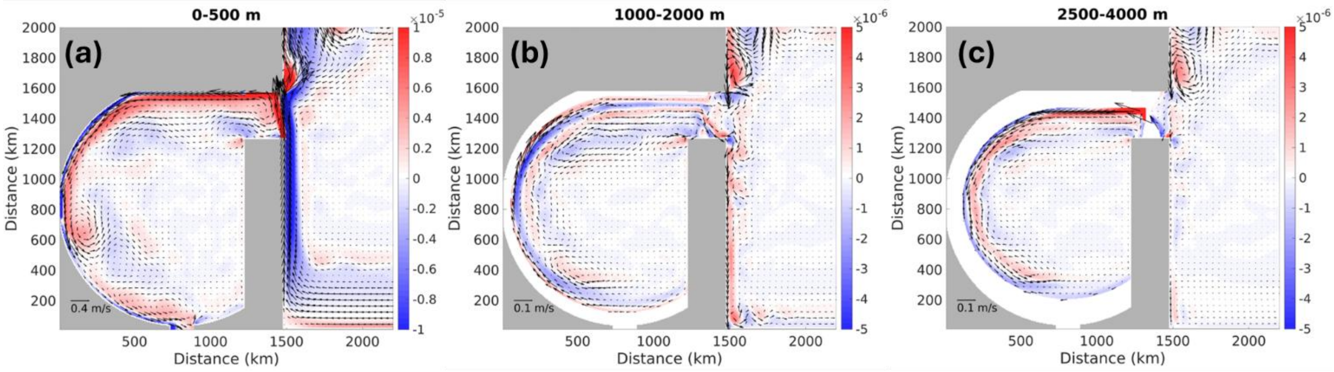


Figure R2. The horizontal circulation (arrows) and depth averaged vorticity (color) of (a) upper layer 0-500 m, (b) middle layer 1000-2000 m and (c) deep layer 2500-4000 m in the standard case.

2. What is the reason for setting three values of Kv for surface, middle and deep water layers, respectively? There is not even a linear transition between the three values in the setting. It is unclear how sensitive is the model to such artificial setting, and whether an abrupt jump of the values at the bounday cause instability of the flows and their interactions.

Response: Thank you for your question regarding the parameterization of vertical diffusivity (Kv). The Kv profile in our model is mainly based on observational work by Yang et al. (2016) (Figure R3). Yang et al. (2016) provide estimates of Kv for specific depth intervals: 500–1500 m, 1500 m to the bottom, and 500 m above the seafloor. Similarly, Wang et al. (2017) report Kv values of O(10^{-4} m^2 /s^2) in the continental shelf break region and O(10^{-3} m^2 /s^2) in deep waters. Those values are “generally consistent with diapycnal diffusivity estimates from turbulence microstructure measurements and finescale parameterizations” (Wang et al., 2017).

In this study, we focused on exploring the response of the layered slope current, particularly in the semi-enclosed middle and deep layers, to changes in the upper-layer circulation. Thus, we designed the mixing intensity based on those observed findings to form and maintain the deep/middle circulations. But did not delve into the detailed processes of the intensified turbulent mixing. Similar approaches were also adopted in our previous work and other studies (e.g., Cai et al., 2023; Emile-Geay and Madec, 2009; Huang and Jin, 2002; Quan and Xue, 2019; Zhao et al., 2020).

Regarding concerns about discontinuities in the Kv profile, we examined model outputs, including density and velocity distributions over the slope. While there is discontinuity in Kv, the larger Kv primarily helps to homogenize the density gradient. No significant instabilities or disruptions were observed in the slope currents or density profiles (Figure R4).

In the revised manuscript, we clarified those points:

Line 114-118: The K_v was designed based on observational work by Yang et al. (2016) and estimations by Wang et al. (2017) to form the circulation in the semi-enclosed middle and deep layers. Then, simulations were conducted to explore the response of the layered slope current, particularly in the semi-enclosed middle and deep layers, to changes in the upper-layer circulation.

Reference:

Cai, Z., D. Chen and J. Gan (2023). "Formation of the Layered Circulation in South China Sea With the Mixing Stimulated Exchanging Current Through Luzon Strait." Journal of Geophysical Research: Oceans 128(3).

Emile-Geay, J., and G. Madec, 2009: Geothermal heating, diapycnal mixing and the abyssal circulation. Ocean Sci., 5, 203-217, doi:10.5194/os-5-203-2009.

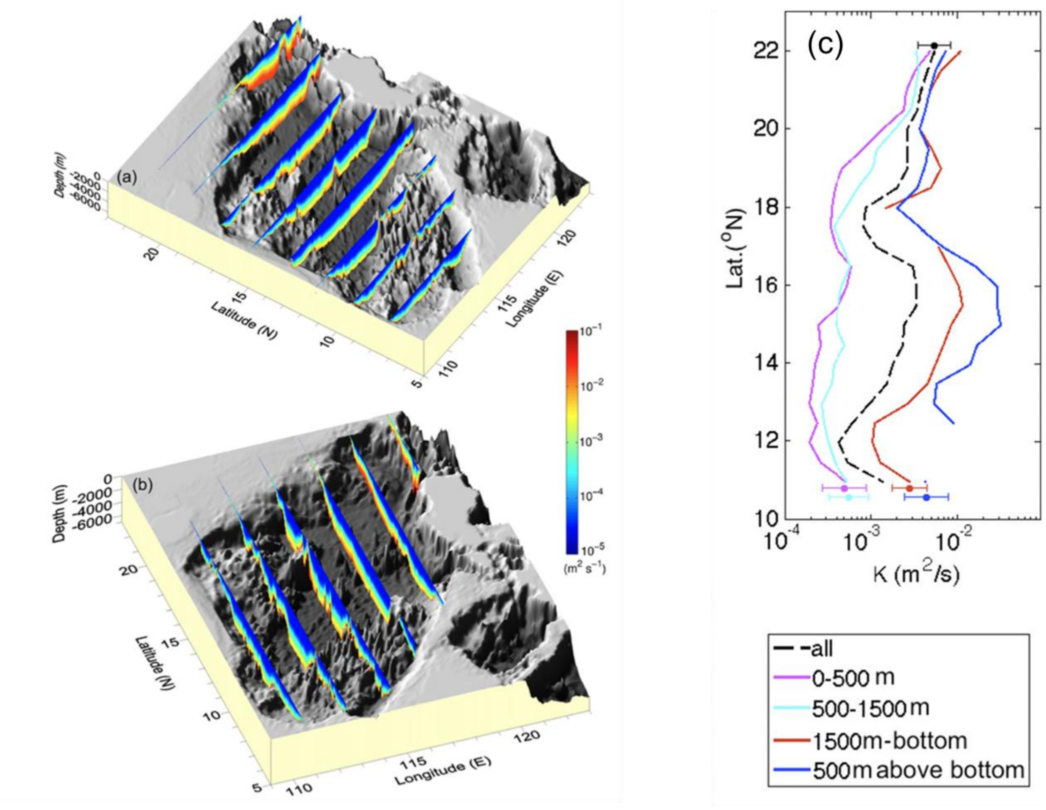
Huang, R. X., and X. Jin, 2002: Deep Circulation in the South Atlantic Induced by Bottom-Intensified Mixing over the Midocean Ridge. Journal of Physical Oceanography, 32, 1150-1164, doi:https://doi.org/10.1175/1520-0485(2002)032<1150:DCITSA>2.0.CO;2.

Quan, Q., and H. Xue, 2019: Influence of Abyssal Mixing on the Multilayer Circulation in the South China Sea. Journal of Physical Oceanography, 49, 3045-3060, doi:https://doi.org/10.1175/JPO-D-19-0020.1.

Yang, Q., W. Zhao, X. Liang, and J. Tian, 2016: Three-Dimensional Distribution of Turbulent Mixing in the South China Sea. J. Phys. Oceanogr., 46, 769–788, https://doi.org/10.1175/JPO-D-14-0220.1.

Wang, X., Z. Liu, and S. Peng, 2017: Impact of Tidal Mixing on Water Mass Transformation and Circulation in the South China Sea. J. Phys. Oceanogr., 47, 419–432, https://doi.org/10.1175/JPO-D-16-0171.1.

Zhao, X., C. Zhou, X. Xu, R. Ye, and W. Zhao, 2020: Deep circulation in the South China Sea simulated in a regional model. Ocean Dynamics, 70, 1461-1473, doi:10.1007/s10236-020-01411-2.



Wang et al., 2017

Yang et al., 2016

Figure R3. (a-b) The spatial distributions of the tide-induced diapycnal diffusivity estimated from internal tide energetics along the (a) zonal sections and (b) meridional sections. From Wang et al, 2017; (c) Depth-averaged diffusivity ($m^2\ s^{-1}$) for different layers in the meridional direction. The error bars indicate the uncertainty of standard deviation. From Yang et al., 2016

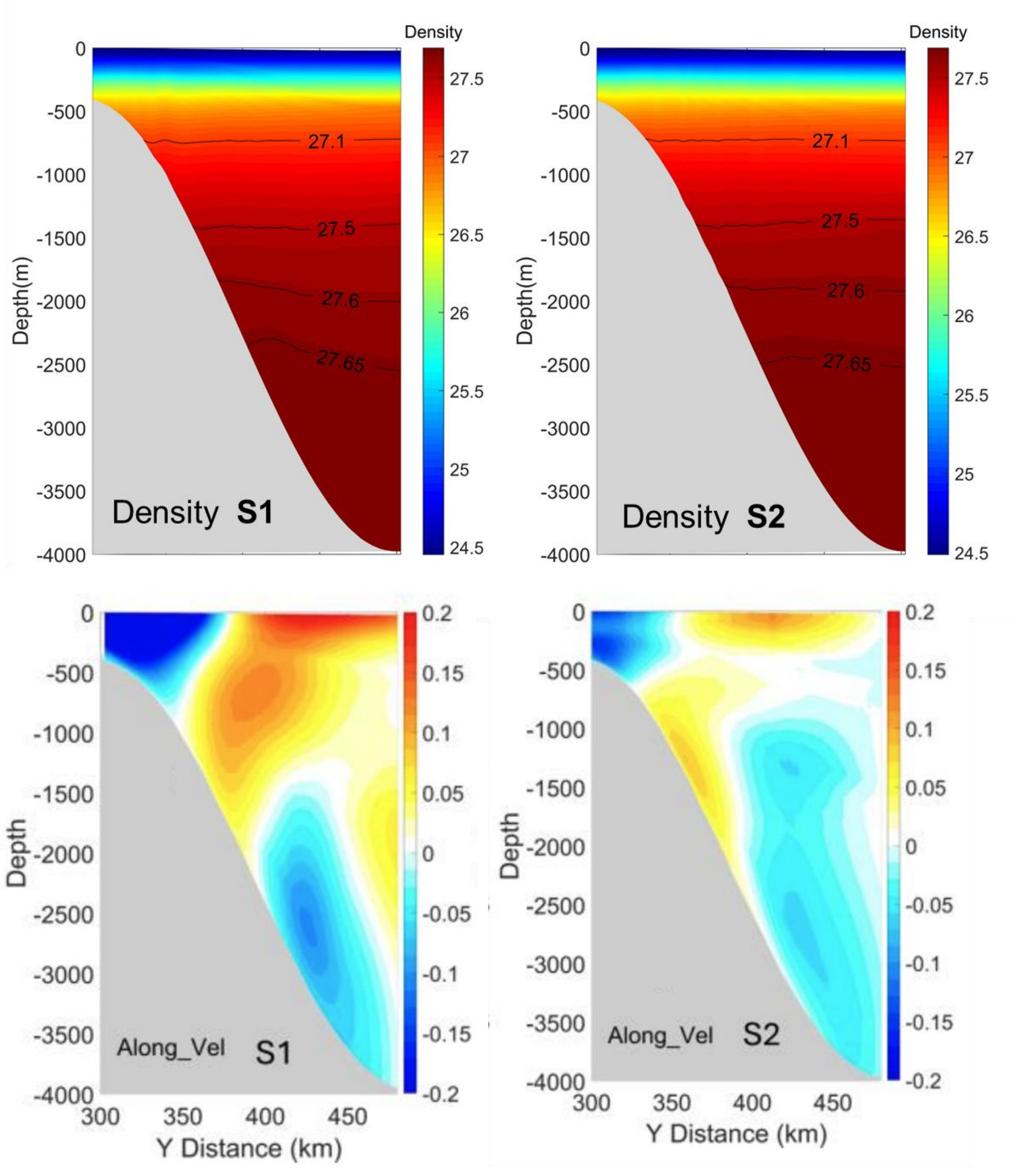


Figure R4. Vertical transects of (upper panel) density and (lower panel) along-slope velocity (Along_Vel) over sections S1 and S2.

3. The simulation is run for 25 years only. This is probably sufficient for a shallow shelf sea but is definitely too short for the SCS and west pacific ocean to develop a stable or quasi-stable states of the circulations, especially for the middle and deep layers. This means the system is still in a fast developing phase with instable states, and I have serious concern on using the results for quantative analysis of the three-layer circulations.

Response: We understand the reviewer's concern on the stability of simulation. Following reviewer's concerns, we've checked the time series of the vorticity in different layers (Figure R5). Generally, even for the middle and deep layers, the simulation time is sufficient to reach a stable or quasi-stable state. Since the mixing intensity inside the SCS is two orders of magnitude larger than the Pacific (Tian et al., 2009; Yang et al., 2016), under the intensified density difference crossing the LS, the layered circulations are quickly generated and reached the stable state.

In the revised manuscript, we clarified this point:

Line 126-127. The simulation ran for 25 years, with the analysis was conducted on the results from the final 5 years average after the layered circulation reached a stable state.

Reference:

Tian, J., Q. Yang, and W. Zhao, 2009: Enhanced Diapycnal Mixing in the South China Sea. J. Phys. Oceanogr., 39, 3191–3203, https://doi.org/10.1175/2009JPO3899.1.

Yang, Q., W. Zhao, X. Liang, and J. Tian, 2016: Three-Dimensional Distribution of Turbulent Mixing in the South China Sea. J. Phys. Oceanogr., 46, 769–788, https://doi.org/10.1175/JPO-D-14-0220.1.

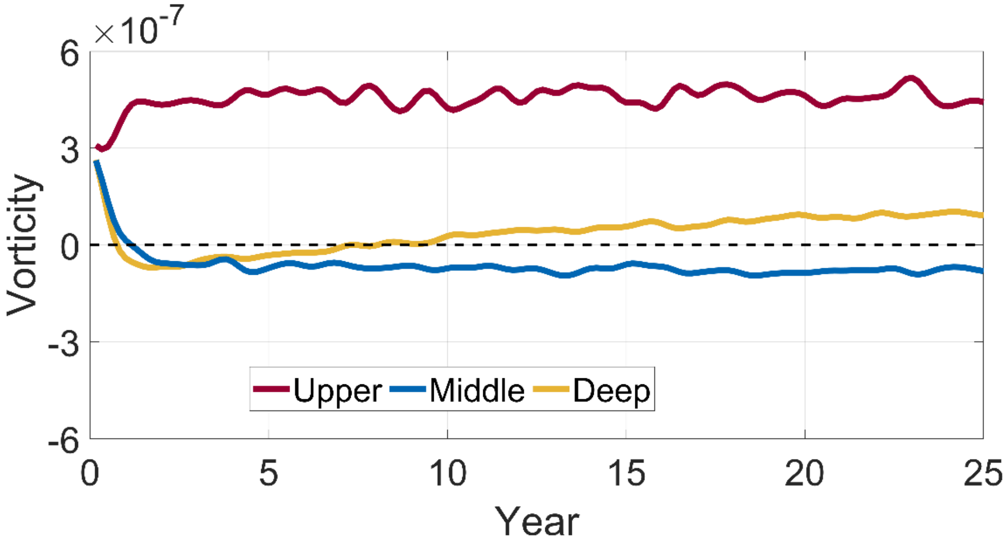


Figure R5. Time series of the domain-averaged vorticity averaged in the upper 500 m (Upper), 1000-2000 m (Middle), and below 2500 m (Deep)

4. It seems the authors mix the desciptions of the simulation results with results from existing literature for formation of the three-layer circulations, see line 123-129. As the authors described, density differences between the SCS and the pacific ocean is needed to drive the deep intrusion, but such feature was not implemented in the model setup (see point 1).

Response: Thank you for your comment. We apologize for the confusion caused by the initial description. The citations included in the manuscript are intended to highlight that, although an idealized configuration was used, the results and processes observed in this simulation are consistent with established understandings from previous studies. They help prove that the model successfully captures the key processes, thereby ensuring the reliability of the results in exploring the underlying dynamics.

To address this concern and prevent further misunderstanding, we have revised the manuscript as:

Line 142-148: Although the initial temperature and salinity distributions are horizontally uniform, the intensified turbulent mixing within the deep SCS basin gradually leads to a density difference between the two sides of the LS. Specifically, the deep SCS exhibits lower density compared to the Pacific basin (Figure S1). Under the density difference, the westward pressure gradient was formed that drives the deep intrusion from the open ocean towards the SCS. Those features are consistent with established understandings from previous studies (e.g., Wang, Xie et al. 2011, Zhu et al., 2017, 2019; Cai, Chen et al. 2023; Zhou et al., 2023).

For the density difference, we responded in your comments 1, thanks!

5. It is unclear to me how the authors managed to adjust the outflux and influx at the open boundary to these exact values. My concern is that the model results may be largely driven by the speficied input/output at the boundary, rather by the internal dynamics of the system. The authors need to justity why such configuration is reasonable. For instance, it is stated that the influx/outflux was defined in the **upper water layer** at the **southeastern** and **northwestern** boundaries of the open ocean (line 99-100). What is set for the deeper water layers in these open boundaries, and for other parts of the open boundary in the pacific ocean? Please clarify these and justify that the system is not purely driven by the boundary setting.

Response: Thank you for the comment on the model configurations.

Based on current understanding, the upper-layer influx through the Luzon Strait (LS) is induced by the western boundary current (Kuroshio Current) as it passes through the strait (Nan et al., 2015). The middle-layer outflux and deep-layer intrusion, on the other hand, are largely driven by density differences caused by contrasting turbulent mixing intensities (e.g., Tian et al 2007; Zhu et al, 2019; Zhou et al.,2023). Thus, the upper layer intrusion, as noted by the reviewer, is related to the boundary flux, while the middle and deep layer exchanging current are governed by internal dynamics. These established understandings guided the design of our model configuration.

In this study, we focused on the influence of upper layer circulation intensity on the layered current. For the upper layer circulation, the key is to provide the western boundary current in Pacific and the intrusion through LS. Thus, the upper influx (25 Sv)/outflux (20 Sv) was defined at the southeastern/northeastern boundary of the open ocean (Figure R6). The other regions of the southern, eastern and northern boundaries are set as walls. In the SCS basin, the southern strait was opened, allowing the intrusion through LS, which subsequently drives the upper-layer circulation. By changing the influx and outflux through the southeastern and northeastern boundaries, the upper intrusion and upper SCS circulation can be modified intrinsically.

In the deep and middle layer, the exchange current is generated and maintained by the contrasting turbulent mixing intensity as we responded above (Figure R1).

We acknowledge that the idealized configuration is used in this process-oriented simulation. However, it captures the major processes involved in the layered circulation and helps explore how changes in the upper-layer circulation influence the layered currents. Following reviewer's concerns, the Figure R6 was added in the revised manuscript, and we refine the manuscript to clarify the configuration of boundary current:

Line 60-64: Based on current understanding, the upper-layer influx through the Luzon Strait (LS) is induced by the Kuroshio Current as it passes through the strait (Nan et al., 2015). The middle-layer outflux and deep-layer intrusion, on the other hand, are largely driven by density differences caused by contrasting turbulent mixing intensities (e.g., Tian et al., 2009; Zhu et al., 2019; Zhou et al., 2023).

Line 104-110: In the upper layer, an influx of 25 Sv and an outflux of 20 Sv were specified at the southeastern and northeastern boundaries of the open ocean, respectively (Figure 2c). The SCS was opened to the south with the depth of 400 m (Figure 2a), to allow the upper-layer intrusion to develop intrinsically during the simulation. To simulate the density differences and exchange currents in the middle and deep layers of the LS, the model incorporated variable contrasting mixing coefficients (Kv) between the SCS and the Western Pacific Ocean (Tian, Yang et al. 2009, Yang, Zhao et al. 2016).

Reference:

Nan, F., Xue, H. and Yu, F., 2015. Kuroshio intrusion into the South China Sea: A review. *Progress in Oceanography*, *137*, pp.314-333.

Tian, J., Q. Yang and W. Zhao (2009). "Enhanced diapycnal mixing in the South China Sea." Journal of Physical Oceanography **39**(12): 3191-3203.

Zhu, Y., Sun, J., Wang, Y., Li, S., Xu, T., Wei, Z. and Qu, T., 2019. Overview of the multi-layer circulation in the South China Sea. *Progress in Oceanography*, *175*, pp.171-182.

Zhou, C., Xiao, X., Zhao, W. et al. Increasing deep-water overflow from the Pacific into the South China Sea revealed by mooring observations. Nat Commun 14, 2013 (2023). https://doi.org/10.1038/s41467-023-37767-4

Yang, Q., W. Zhao, X. Liang and J. Tian (2016). "Three-Dimensional Distribution of Turbulent Mixing in the South China Sea." Journal of Physical Oceanography **46**(3): 769-788.

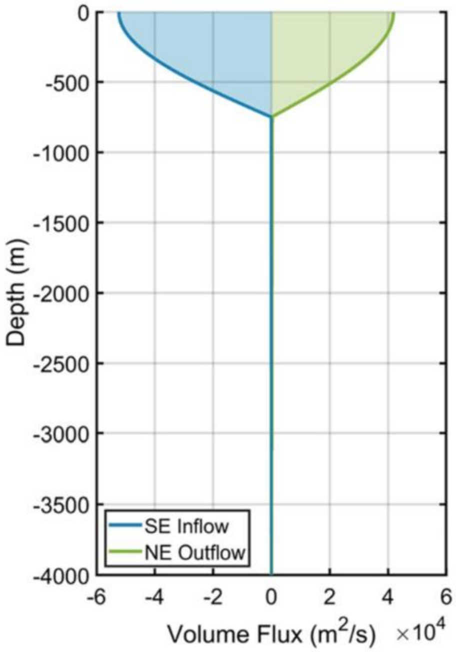


Figure R6. Vertical profile of the volume inflow/outflux ($m^2\ s^{-1}$) through the southern/northern part of the eastern boundary. The total volume transports are set as 25 and 20 Sv, respectively.

Given the major flaws mentioned above, I am not convinced by the quantative numbers, e.g. 10% increase in the intensity of the middle anticyclonic circulation and 27% increase in the deep cyclonic circulation (line 299-300) given in the summary. A more comprehensive sensitivity study on how a change in the specific configurations would affect such numbers is needed. This includes not only the influx/outflux setting in the surface layer at the open boundary but also the run time, the setting of Kv and the intitial temperature&salinity profile.

Response: Thanks for the comment. We agree with the reviewer that the quantitative values provided in the summary are reliable only under the current simulation configuration. In the revised manuscript, we did not highlight those quantitative numbers. In the description of the results, we clarified that the values are based on the idealized simulation with specific settings. Realistic simulations would provide more reliable quantitative results, which require future investigation.

As addressed in previous comments, the runtime of the simulation is sufficiently long to ensure a steady-state solution. The Kv used in the model are based on observational estimates, and the initial temperature and salinity profiles are derived from reanalysis data. These configurations have also been used in our previous investigations to explore the dynamics of the layered circulation in SCS.

In the revised manuscript, we removed the quantitative numbers and clarified the results are based on the simplification configuration

Line 120-123: This model simplifies the configurations to focus on the fundamental dynamics of the system. While these simplifications are essential for isolating key mechanisms, they may not capture the complexity of real-world conditions, potentially limiting its quantitative applicability to realistic processes.

Line 330-332: it was found that the intensification of the upper-layer circulation resulted in the increase in the intensity of the middle anticyclonic circulation and deep cyclonic circulation.

Line 352-355: It should be noted that those understandings are based on process-oriented simulation with simplified configurations. In the following analysis, a more realistic simulation will provide more quantitative insights into the topographic modulation on the layered circulation in the marginal seas.

Besides a more comprehensive sensitity study, I suggest the authors to perform analysis using more realistic simulation/reanalysis results that are readily available, e.g. from the global HYCOM. The multi-year averaged results (climatology) should provide a more convincing dataset for the analysis, and it has a more realistic representation of the complex topography and the three-layer circulations. A result comparison between the idealized model setup and the more realistic setup would provide more insights into the topographic modulation on the layered circulation in the SCS.

Response: We totally agreed that the realistic simulation or reanalysis dataset would give more details in those processes. However, as all factors change simultaneously in such setups, it may be challenging to isolate specific processes carefully. The process-oriented simulations offer a different perspective by isolating individual processes and illustrating the role of upper-layer circulation more clearly.

Besides, the intensified mixing intensity in the SCS was related to the dissipation of internal waves over complicated topography, which was not well resolved by the global models. Thus, the global model, such as HYCOM or OFES, did not capture the layered circulation features in the SCS (Figure R7). We are refining a regional high-resolution realistic simulation in this region (part of the work was under review in Journal of Physical Oceanography) and prefer to explore the topographic modulation on the layered circulation in the SCS using realistic simulation in our following work.

In the revised manuscript, we clarify this point.

Line 352-355: It should be noted that those understandings are based on process-oriented simulation with simplified configurations. In the following analysis, a more realistic simulation will provide more quantitative insights into the topographic modulation on the layered circulation in the SCS.

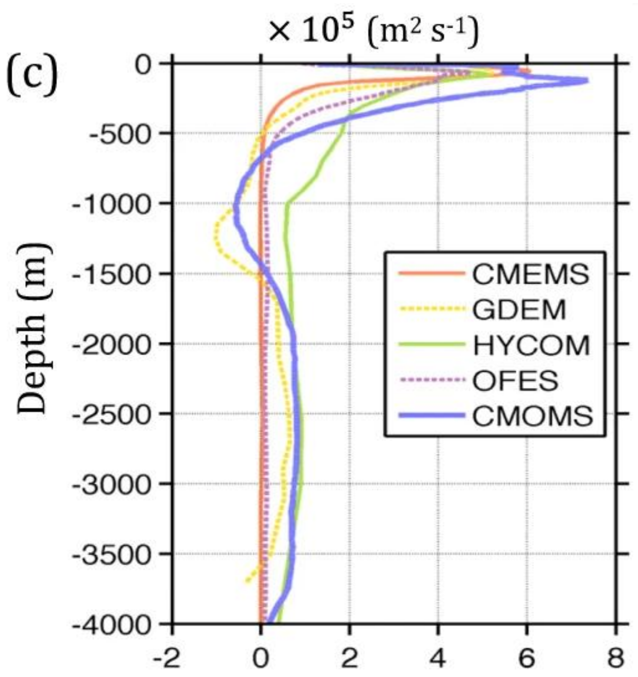


Figure R7. Vertical profile of the 20-year time domain-integrated relative vorticity obtaining from geostrophic currents based on hydrographic data from GDEM (Generalized Digital Environmental Model; yellow dashed line), global models of CMEMS (The European Copernicus Marine Environment Monitoring Service; solid orange line), HYCOM (Hybrid Coordinate Ocean Model; green solid line) and OFES (Ocean General Circulation Model For the Earth Simulator; purple dashed line), and CMOMS (China Sea Multi-scale Modeling System; blue solid line) as a function of depth. From Gan et al., 2022.

References:

Gan, J., Kung, H., Cai, Z. et al. Hotspots of the stokes rotating circulation in a large marginal sea. Nat Commun 13, 2223 (2022). https://doi.org/10.1038/s41467-022-29610-z