Reviewer 2 #

Although the authors have addressed some of my questions and concerns, three major ones are not satisfactorily addressed.

1. The setting of Kv: I understand that the measured values of Kv in different water layers in the SCS are used to setup the model, however, this seens to me more like a parameter over-tune in order to fit the model results to observation, but not a result from internal dynamics of the system. The larger values of Kv in the SCS compared to the western pacific ocean is due to the enhanced mixing in the SCS caused by the complext topography there. There exists a lot of seamounts and islands in the SCS, that are responsible for enhancement of the mixing. But these features are not implemented in the model of this study! I don't think it is appropriate to artificially change the profile of Kv and prescribe a vertical difference between the SCS and the western pacific ocean to mimic the impact of the complex topography. Rather, I suggest the authors to respect the complex topography in their model setup by introducing certain amount of seamounts/islands in the SCS and an initial uniform Kv profile to check whether the observed difference in Kv can be reproduced in the simplified model. This is not trivial since the development of the bottom layer circulation is directly driven by density difference between the SCS and pacific ocean that is closely linked to variation of Kv.

Response: We sincerely thank the reviewer for the thoughtful comment regarding the configuration on the turbulent diffusivity (Kv). We appreciate the opportunity to further explain our approach and respond to the important points raised.

We fully agree with the reviewer that the intensified mixing intensity inside the SCS is intrinsically related to the complex topography. These bathymetric features, such as seamounts and islands, play a significant role in sustaining the intensified mixing observed in this region. For studies specifically focus on the generation and maintenance dynamics of enhanced mixing, as rightly pointed out by reviewer, incorporating realistic topography is necessary and would provide deeper insight into how these features influence mixing.

Once this contrasting mixing intensity between SCS and open ocean is established, it would support the development of layered circulation, where different layers interact dynamically along the slope. Our view is that, for the purpose of examining inter-layer dynamics, the detailed formation mechanisms of mixing, while certainly important, may not be so critical for analysis. By prescribing a background mixing profile and the resulting layered circulation, the fundamental coupling mechanisms between layers can be reasonably examined.

We fully understand and appreciate the reviewer's concern, and we believe there is no fundamental disagreement between us. In this study, we hope to pay more attention to the dynamical interactions between layered circulations under the existing mixing contrast, rather than on the detailed formation mechanisms of mixing itself. In this context, the use of intensified mixing, whether through prescribed values or topographic features, was intended to approximate the observed structure and provide a basis for analyzing inter-layer coupling. We hope this explanation helps clarify the rationale behind our model configuration for the reviewer's consideration. We also clarified this in the revised manuscript:

Line 126-129: "While it may be viewed as parameter tuning, our intention was not to simulate the mixing generation mechanisms explicitly, but rather to approximate the existing background structure that sustains the observed layered circulation."

Following reviewer's concern, we would like to use new models with realistic topographic features in future work (as noted in the next response below) to investigate how these features influence both mixing intensity and layered circulation. The current study serves as a foundation for understanding how layered circulation interacts with slope dynamics and offers valuable insights for future research.

Once again, we thank the reviewer for the helpful feedback, which has guided us in refining the scope of this study and identifying meaningful directions for future work.

2. I am not convinced by the authors' statement that "global model, such as HYCOM or OPES, did not capture the layered circulation features in the SCS ". The three-layer circulation has been reproduced in global models such as HYCOM reanalysis and others, as demonstrated in existing literature, e.g. Shu, Y., H. Xue, D. Wang, F. Chai, Q. Xie, J. Yao, and J. Xiao (2014), Meridional overturning circulation in the South China Sea envisioned from the high-resolution global reanalysis data GLBa0.08, J. Geophys. Res. Oceans, 119, 3012–3028, doi:10.1002/2013JC009583. Therefore, I still stick to my comment from last review that a result

Response: We sincerely apologize for the confusion caused by our previous response. What we intended to convey was that, based on the vertical profile of domain-averaged vorticity, previous analysis did not reveal a layered pattern characterized by alternating positive and negative values (Figure R1). However, we agree with the reviewer that circulation patterns do exhibit notable variation with depth, as illustrated in earlier studies such as Shu et al. (2014). These global models have indeed provided valuable insights into the meridional overturning and stratified circulation dynamics of the South China Sea, and we greatly respect the contributions made by these works.

We also appreciate the reviewer's suggestion to consider layered circulation coupling within more realistic modeling frameworks. However, in such realistic simulations, multiple dynamic processes, such as changes in surface circulation and lateral exchange through the Luzon Strait, often evolve concurrently. These interlinked processes make it not easy to isolate and clearly diagnose the specific mechanisms during the inter-layer interactions when using the global model results directly.

To better address this issue and respond to the reviewer's concern, we prefer to use our locally refined numerical model that incorporates realistic bathymetry and external forcings, allowing for a more detailed investigation (Figure R2). Preliminary results from this model suggest that variations in upper-layer circulation influence the deep circulation (Figure R3). The more in-depth exploration of these interactions will benefit from a carefully structured modeling framework and systematic numerical experiments, which we think would be best presented in a separate manuscript.

In this study, we adopted a simplified framework to explicitly investigate the interactions between layered circulations in isolation. It provides valuable foundation for understanding interaction among layers over the slope and serves as a complement to more realistic simulations. The work is also inspired by previous process-oriented efforts to understand the dynamics of SCS circulation. For instance, Chen and Xue (2014) used an idealized model to explore the presence of a strong western boundary current in the South China Sea; Quan and Xue (2018) developed a three-layer model to investigate coupling between the upper and middle layers; Wang et al. (2018) employed a simplified bottom-layer reduced gravity model to examine the influences of upwelling/downwelling pattern on the deep circulation; and others (e.g., Huang and Zhou 2022).

We hope this explanation clarifies our thinking for the reviewer's consideration. We truly respect the reviewer's suggestions, which have helped us refine the positioning of this study and identify meaningful directions for continued research. In the updated manuscript, we refined it as follows:

Line 99-102: which employs a simplified setup and allows for a clearer examination of the dynamical coupling between layers. Similar strategies have been applied in previous studies of SCS circulation [*Chen and Xue*, 2014; *Huang and Zhou*, 2022; *Quan and Xue*, 2018; *Wang et al.*, 2018], and have provided valuable insights into specific dynamic mechanisms.

Line 361-364: Based on the obtained understanding, a more realistic simulation in our following study, incorporating detailed topography and external forcings, will offer more quantitative insights and help further validate and extend the findings presented here

Reference:

Chen, G., and H. Xue (2014), Westward intensification in marginal seas, Ocean Dynamics, 64(3), 337-345, doi:10.1007/s10236-014-0691-z.

Huang, -. R. X., and -. H. Zhou (2022), - Circulation in the South China Sea is in a state of forced oscillation: Results from a simple reduced gravity model with a closed boundary, - Acta Oceanologica Sinica, - 41(- 7), - 1, doi:- 10.1007/s13131-022-2013-5.

Quan, Q., and H. Xue (2018), Layered model and insights into the vertical coupling of the South China Sea circulation in the upper and middle layers, Ocean Modelling, 129, 75-92, doi:https://doi.org/10.1016/j.ocemod.2018.06.006.

Wang, A., Y. Du, S. Peng, K. Liu, and R. X. Huang (2018), Deep water characteristics and circulation in the South China Sea, Deep Sea Research Part I: Oceanographic Research Papers, 134, 55-63, doi:https://doi.org/10.1016/j.dsr.2018.02.003.

Gan, J., H. Kung, Z. Cai, Z. Liu, C. Hui, and J. Li (2022), Hotspots of the stokes rotating circulation in a large marginal sea, Nature Communications, 13(1), 2223, doi:10.1038/s41467-022-29610-z.

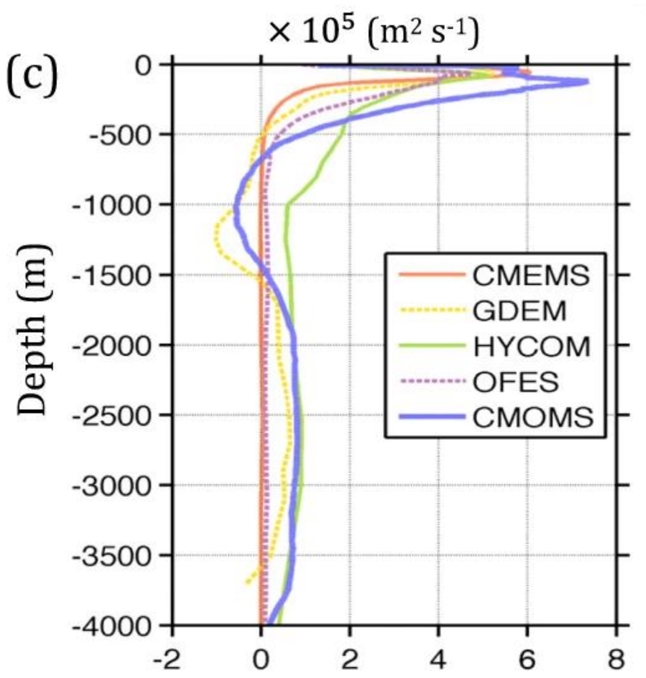

Figure R1. Vertical profile of the 20-year time domain-integrated relative vorticity obtaining from geostrophic currents based on hydrographic data from GDEM (Generalized Digital Environmental

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]

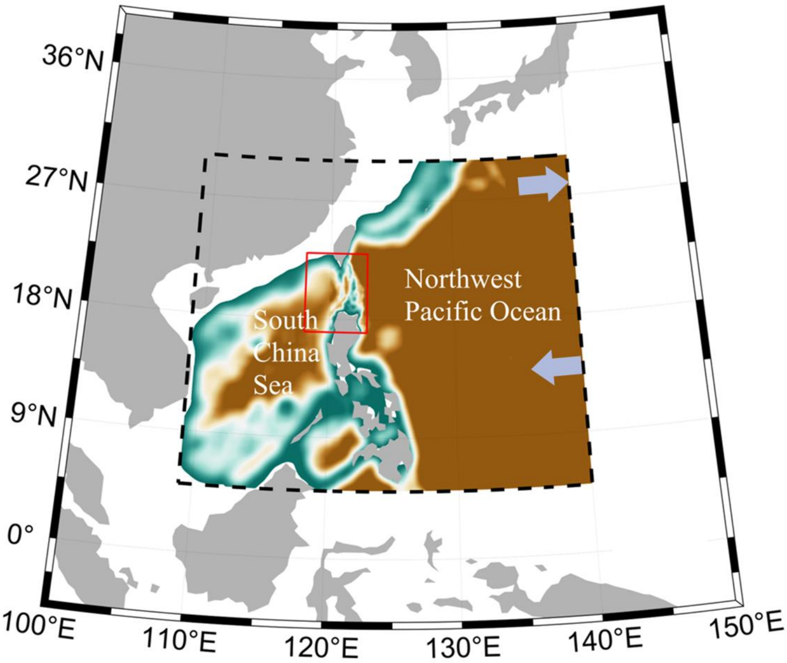

Figure R2. Domain of the simulation incorporating the realistic topographic features. It covers the SCS basin and the western pacific.

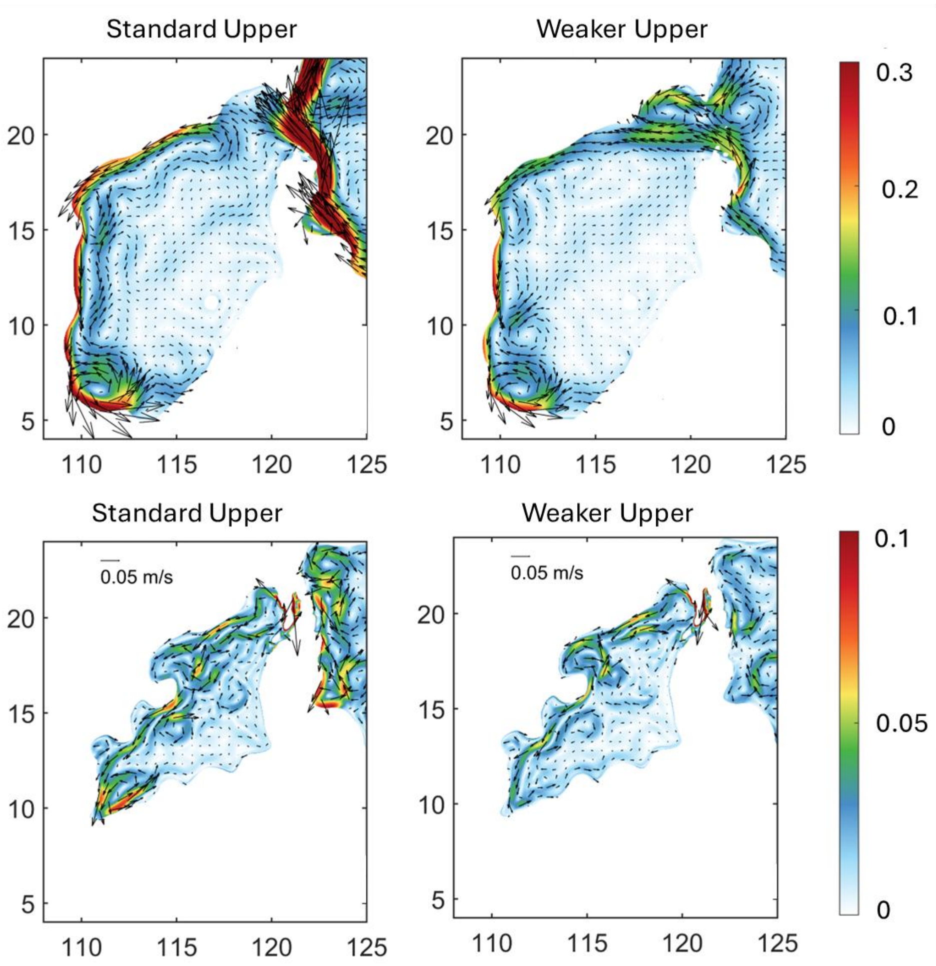

Figure R3. Changes of the deep circulation intensity (at 2500 m as example) associated with the weakening of the upper layer circulation. Color represents the magnitude of the velocity

3. I noticed that the authors already published one study in 2020 to investigate the formation dynamics of the layered circulation in the South China Sea: Cai et al. 2020. Progress on the formation dynamics of the layered circulation in the South China Sea. Progress in Oceanography. https://doi.org/10.1016/j.pocean.2019.102246. There, the influence of vorticity was already concluded, e.g. "In the middle and deep layers, the vertical vorticity flux is the major response to the external forcing and its spatial pattern has a strong impact on the regional structures of the circulation, while the vertical vorticity flux has a relatively smaller influence on the upper layer circulation. Through vertical coupling, the changes in the surface wind forcing and lateral external forcing can be transmitted through the water column and affect the entire layered circulation." In the current manuscript, the findings are not quantitative since the model setup is not based on realistic setting, therefore, it is unclear to me what new insights could this much simplified model study provide to deepen the existing knowledge? This must be clearly clarified in a revised version.

Response: We thank the reviewer for highlighting our previous work (*Cai et al., 2020*) and for raising an important point regarding the novelty and contribution of the current study in relation to our earlier findings.

Cai et al. (2020) is a review-style overview paper that synthesized existing knowledge on the circulation dynamics in the South China Sea (SCS) and speculated that there is strong coupling among circulation layers. The statement referenced by the reviewer is primarily based on the analysis of net horizontal and vertical vorticity fluxes in each layer. While that study emphasized the likelihood of strong vertical coupling, it did not address how changes in dominant upper-layer circulation affect the overall layered structure.

Although the current work did not provide quantitative estimations, it offered clear processes for understanding vertical coupling among circulation layers. Through numerical experiments, we show that pressure patterns over the slope modulate the stretching term, which is a key mechanism linking circulations across layers. Motions in one layer influence others by modifying the along-slope pressure distribution and associated stretching, thereby facilitating inter-layer interaction. This study thus provides a more mechanistic interpretation of vertical coupling, offering new insights beyond those presented in our previous work.

Following reviewer’s concern, we modified the manuscript to clarify this point.

Line 74-76: Previous studies have advanced our understanding of the major features of the mean layered circulation and have highlighted the potential for strong coupling among layers, particularly over sloping topography.

Line 333-337: Inside the basin, the intensification of upper-layer inflow directly enhances the upper-layer cyclonic circulation, which in turn strengthens the middle anticyclonic slope current,…. Furthermore, even though the deep cyclonic slope current is not directly connected to the upper layer, it also exhibits increased strength.

Line 357-360: The results from this process-oriented study offered clear processes for understanding vertical coupling among circulation layers. The motions in one layer influence others by modifying the along-slope pressure distribution and associated stretching, thereby facilitating inter-layer interaction.

Reviewer 3 #

I thank the authors for their close attention to the points I raised in the previous version of the manuscript. I believe the new version adresses most of my major concerns. Below are responses to remaining points I would like the authors to address.

Response: Thanks for your kind suggestions and comments. They helped us to improve our work.

M1 (pressure gradient errors): The authors' response shows a much weaker spurious flow in the unforced case, and that adds confidence to the results. I assume figures R1 and R2 are also based on 5-year averages after a 25-year spinup?

Response: Yes, in our simulation, the magnitude of spurious flow is quite small and it has limited impact on the results. Thanks for the reminder from the reviewer, which helps us to add confidence to the results. As suggested, we have included a note on the magnitude of the spurious flow in the revised manuscript.

Line 111-112: In this simulation, the magnitude of the spurious flow is in the order of 10^{-2} m/s, which has limited impact on the results presented in this study

The authors should add a brief sentence specifying the size of the maximum (not depth- or laterally-averaged) spurious velocities in the five-year averages, as it is difficult to eyeball that in Figure R1's lower panels (and these panels are not included in the manuscript's revised version or the supplementary materials).

Response: Thanks for the suggestion from the reviewer. We revised the manuscript to address the magnitude of the spurious velocities.

Line 111-112: In this simulation, the magnitude of the spurious flow is in the order of 10^{-2} m/s, which has limited impact on the results presented in this study

M7 (lateral and vertical viscosity terms): I see from Figure R7 in the authors' response that the lateral turbulent frictional torque term is much smaller compared to the vertical friction term, and Figure R8 shows the dominance of bottom pressure torque over both frictional terms.

Verifying that these two results found in other model fields and other ocean basins (e.g., the ECCO analysis from Liang et al., 2017) also show in the present SCS model fields is an insightful step. But considering the fact that the vertical torque is the physically-relevant term and the lateral torque is numerical, I still see no point in including both in the vorticity budget. The best approach is to plot the terms separately.

Response: Thank you for the suggestion and the insightful explanations of the two terms. Following the reviewer's recommendation, we have updated the figure to plot them separately.

Line 204-207: $\overbrace{\int_A [\nabla \times \int_{H_1}^{H_2} (\overrightarrow{PGF})\, dz] dA}^{\zeta\_PGF} + \overbrace{\int_A [\nabla \times \int_{H_1}^{H_2} (\overrightarrow{ADV})\, dz] dA}^{\zeta\_ADV} + \overbrace{\underbrace{\int_A \left[-f\nabla \cdot \int_{H_1}^{H_2} \left(\vec{V}_h\right) dz \right] dA}_{\zeta\_DIV} + \underbrace{\int_A \left[-\beta \cdot \int_{H_1}^{H_2} (v)\, dz \right] dA}_{\zeta\_BETA}}^{\zeta\_COR} +$

$\overbrace{\int_A [\nabla \times \int_{H_1}^{H_2} (\overrightarrow{HVIS})\, dz] dA}^{\zeta\_HVIS} + \overbrace{\int_A [\nabla \times \int_{H_1}^{H_2} (\overrightarrow{VVIS})\, dz] dA}^{\zeta\_VVIS} = 0$ (1)

where $\overrightarrow{PGF}$ is pressure gradient force, $\overrightarrow{ADV}$ is nonlinear advection, $\overrightarrow{HVIS}$ and $\overrightarrow{VVIS}$ are the horizontal and vertical turbulent viscosity, respectively

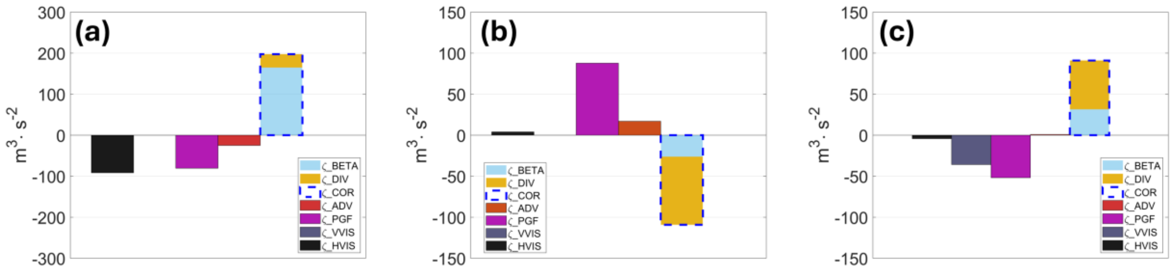

Figure R1. The layered-integrated vorticity budget (Equation 1) for the standard case in the layers of (a) 0–500, (b) 1,000–2,000, and (c) 2,500–4,000 m. Updated figure 5 in the revised manuscript.

M12: I appreciate the authors' response and willingness to share their source code on a personal contact basis. However, Ocean Science Discussions and all Copernicus journals follow the "findable, accessible, interoperable, and reusable" (FAIR) data curation framework (see https://www.ocean-science.net/policies/data_policy.html). This policy specifies that data sets and model code should also be linked to the article through DOIs. While the model output is likely beyond Zenodo's repository storage limits

Response: Thank you for the helpful suggestion. We have updated the source code in the repository accordingly.

Data availability. All data and source code used in this paper are available at
https://doi.org/10.5281/zenodo.15081223.