Author's General Response

We sincerely thank the reviewer for their thoughtful evaluation and constructive comments. We greatly appreciate the reviewer's recognition of the scientific merit and clarity of our work, as well as the insightful suggestions that have helped us strengthen the manuscript.

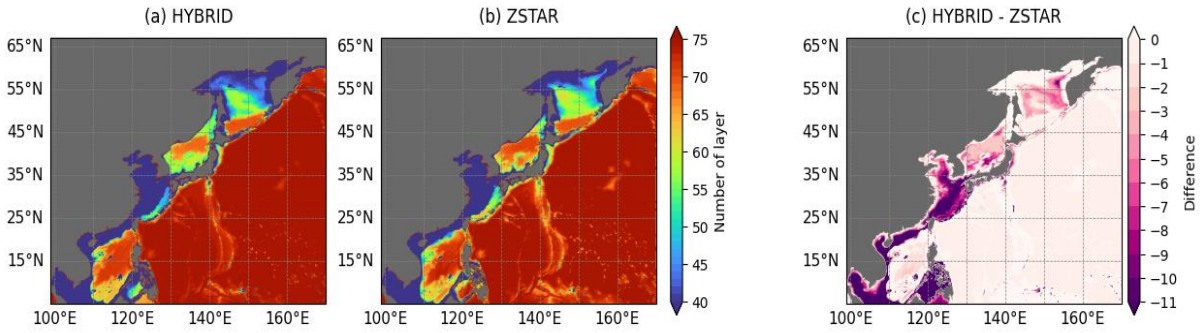

Figure S5. Spatial distribution of active layers in HYBRID and ZSTAR on December 22, 2012. (a, b) Number of active layers in HYBRID and ZSTAR, respectively, where an active layer is defined as having a thickness greater than 0.001 m. (c) Difference (HYBRID - ZSTAR).

In particular, we fully agree with the reviewer's main remark regarding the use of a global target density range for the HYBRID configuration. Following this valuable suggestion, we conducted an additional simulation using a regional target density array tailored to the hydrographic characteristics of the Northwest Pacific domain. This modification significantly improved the vertical discretization in HYBRID, increasing the number of active layers (as shown in the revised Fig. S5). As a result, the revised HYBRID configuration better captured the vertical structure of the North Pacific Intermediate Water and reduced the positive temperature bias in the subtropical region. In particular, the regional target density setup enhanced the simulation of the East Sea Intermediate Water, which was previously too weak in the global-density configuration.

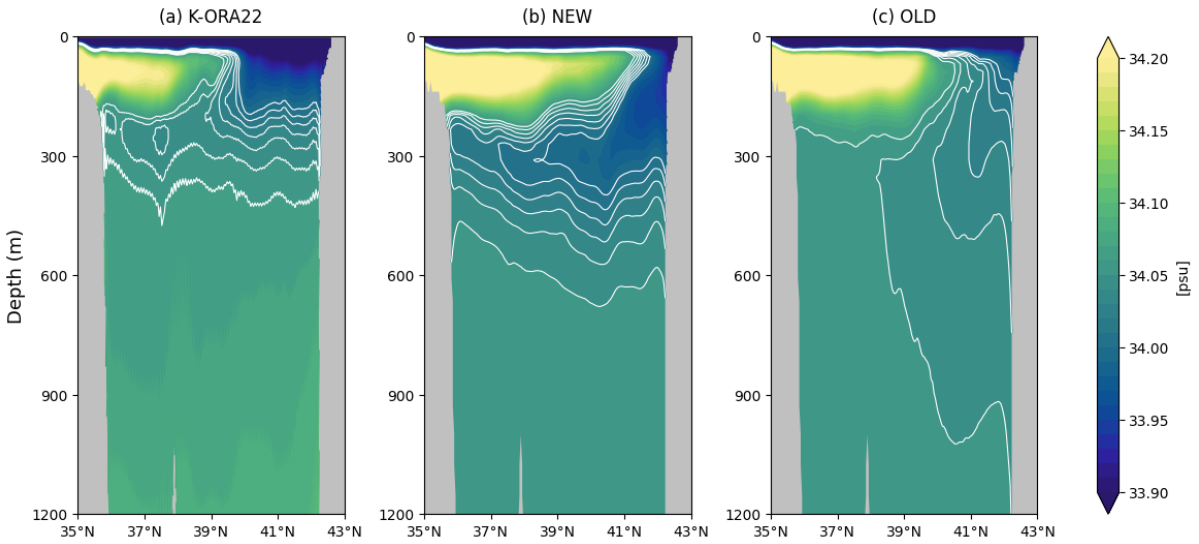

Figure 1 Meridional salinity section along 131˚E from (a) GLORYS12 reanalysis, (b) HYBRID simulation, and (c) ZSTAR simulation, showing vertical salinity distribution.

We have incorporated these new results into the revised manuscript. Overall, the reviewer's comments have led to a more balanced and comprehensive assessment of the vertical coordinate sensitivity in the regional MOM6 framework.

The detailed responses to the reviewer's specific comments are provided below.

L89: MOM6 introduces a "significantly different algorithm" compared to previous versions -> can you be a bit more specific?

➔ Thank you for pointing this out. We have revised the sentence to clarify the specific algorithmic differences introduced in MOM6 compared to previous versions. In addition to the adoption of a vertically Lagrangian finite-volume framework, MOM6 transitions from a B-grid to a C-grid discretization, which improves the representation of momentum and tracer advection. Furthermore, the ocean boundary layer mixing parameterization has been updated from the traditional K-Profile Parameterization (Large et al. 1994) to the energetics based planetary boundary layer (Reichl and Hallberg, 2018) scheme, enhancing the simulation of vertical mixing and surface boundary processes. These algorithmic and physical updates collectively contribute to the improved numerical stability and physical realism of MOM6. (line 84-90)

L149: "layer thickness of 2 meters extending to a depth of 14 meters in the ZSTAR space." -> does it mean that the thickness of the upper layer is 2m? If yes, I think it could be too thick – e.g. Bernie et al 2005 and Siddorn & Furner 2012 recommend a resolution of ~1m to properly model diurnal SST variability – and this could possibly be one of the causes behind the SST biases you are seeing in both ZSTAR and HYBRID, please clarify.

➔ In this study, the uppermost layer in the ZSTAR vertical grid configuration has a thickness of 2 m, extending to a depth of 14 m. While this design provides a reasonable balance between computational efficiency and representation of the mixed layer, it may be relatively coarse for capturing processes that operate at sub-daily scales. Previous studies (e.g., Bernie et al., 2005; Siddorn & Furner, 2012) have shown that vertical resolutions of ~1 m or finer are required in the surface ocean to adequately resolve diurnal warming and associated SST variability. Therefore, the 2 m upper layer thickness employed here may contribute to the persistent SST warm biases identified in both the ZSTAR and HYBRID simulations. We note that although our primary focus was on large-scale circulation and stratification, rather than diurnal processes, this limitation could influence the realism of the surface heat budget, particularly under strong insolation conditions. Future experiments employing enhanced vertical resolution in the upper ocean (e.g., 1 m thickness for the first few layers) will be necessary to further assess the extent to which layer thickness impacts the SST biases and to determine whether improving vertical discretization can reduce the discrepancy between model results and observations. We will clarify this point and discuss its possible link to the SST biases in the Discussion section. (line 693-697)

L151-155: "The transition depth between the isopycnal and ZSTAR coordinates deepened toward higher latitudes (Adcroft et al., 2019)" -> could you please clarify how the hybrid vertical coordinate works – a sketch or plot showing a vertical section with grid layers and the topography would be very helpful. Also, it is not clear to me what happens on the shelf: because of the shallow depths, the unstratified bottom boundary layer can be quite thick, and is not unusual that it merges with the upper mixed layer, generating a well mixed water column, especially in regions where tides are strong. In such a regime, I see the usage of isopycnal coordinates quite challenging … for example, according to Fig. S4 it seems that in shallow areas HYBRID has much less active layers than ZSTAR …

➔ We thank the reviewer for the helpful suggestions. We have revised the Methods to clarify how the MOM6 hybrid vertical coordinate works and we added a vertical section with grid interfaces over topography (new Fig. 2).

➔ In each water column we first form a stable, monotonic density profile from temperature, salinity, and pressure and map it to a prescribed set of target densities to obtain isopycnal candidate interface depths. Independently, we define a nominal z-star (z*) grid; in the hybrid this grid is used as a one-sided lower-bound ("floor") constraint. At each level the model takes the deeper of the isopycnal candidate and the z* floor, and then applies the bottom and any optional thickness/depth limits. There is no hard switch between coordinates: the "transition depth" is simply where an isopycnal surface would otherwise lie above the z* floor. Because mixed layers are generally deeper and stratification weaker at higher latitudes, the isopycnal candidates remain shallow for longer and the crossing with the z* floor occurs deeper; hence the transition tends to deepen poleward (consistent with Adcroft et al., 2019).

➔ Regarding shelves, the effective strength of the z* floor is scaled by the local depth in MOM6. Where the bathymetry is shallow, this scaling makes the z* floor very shallow—often only a few meters—so even in winter, if residual stratification exists, interfaces typically follow the target isopycnals over much of the column. Conversely, in fully mixed columns or where the effective z* penetration approaches the local depth, the hybrid reduces to z*. This also explains the reviewer's observation about "active layers": on shallow shelves many target isopycnals collapse to nearly the same depth and fall below the remapping thickness tolerance, so HYBRID may count fewer active layers than a pure ZSTAR grid, which retains its prescribed z* layers regardless of stratification. We now state this explicitly and clarify in the caption that "active layers" are layers whose thickness exceeds the remapping tolerance.

(Fig.2 and line 169-184)

L148-157: what formulation of bottom friction is used by the two configurations? What type of lateral boundary conditions are used in the case of the ZSTAR model? How is represented the bottom topography with ZSTAR, with full or partial steps?

➔ We thank the reviewer for pointing out these missing details. In both ZSTAR and HYBRID configurations, bottom friction is represented using a quadratic drag formulation with a coefficient of Cd = 0.003. For the lateral solid boundaries, free-slip boundary conditions are applied (NOSLIP = False), allowing tangential flow along the walls while preventing normal flow. In the ZSTAR configuration, bottom topography is represented using partial-step layers, ensuring a more realistic bathymetric representation and smoother pressure gradients over steep slopes. (line 202-204)

L251: "where u′ and v′ represent deviations of the zonal and meridional velocity components from their respective means." -> averages over which period?

➔ We thank the reviewer for this question. The averages were computed over the evaluation period of 2003–2012. We have clarified this point in the revised manuscript. (line 280)

L322-324: It seems to me that in the South China Sea and across the open ocean it is actually the contrary - i.e., HYBRID has a slightly larger positive bias than ZSTAR - see Fig 4 – please clarify.

➔ We thank the reviewer for the careful reading. We agree that, as shown in Fig. 4, HYBRID tends to have slightly larger positive biases than ZSTAR in the South China Sea and across the open ocean, whereas ZSTAR exhibits larger positive biases in the Yellow Sea. We have revised the sentence to correct this inconsistency. (line 351-353)

L336: ", with ZSTAR showing stronger positive biases in the open ocean and …" -> It seems to me that in the open ocean the two model are in the same ballpark, with ZSTAR sightly better than HYBRID in terms of warm bias … please clarify.

➔ We thank the reviewer for pointing this out. We agree that in the open ocean the two models perform similarly, with ZSTAR showing slightly smaller positive biases than HYBRID. We have corrected the sentence accordingly in the revised manuscript. (line 366)

L341-344: you already said this at L336-337 - you may want to merge and simplify the text here.

➔ We thank the reviewer for this suggestion. We agree that the statements at L336–337 and L341–344 were redundant. We have merged them into a single simplified description in the revised manuscript.

L356: "15 m compared to ZSTAR in the open ocean" -> perhaps "Southern open ocean"?

➔ We thank the reviewer for the suggestion. We agree that "Southern open ocean" is a more precise description, and we have revised the sentence accordingly in the manuscript.

L362: Perhaps you were meaning Fig. S2?

➔ We thank the reviewer for noticing this mistake. Yes, the correct reference is to Fig. S2, and we have corrected it in the revised manuscript.

Fig. 9 -> Vectors are not clear (I can not see them), perhaps you may consider avoiding plotting them …

➔ We thank the reviewer for this helpful suggestion. We agree that the vectors in Fig. 9 were not clearly visible. In the revised manuscript, we have removed the vectors and retained only the shading to improve clarity. (Fig.10)

L456: "HYBRID achieved a slightly lower RMSE (138.46 cm^2/s^2) than ZSTAR (138.86 cm^2/s^2)" -> to me, they are very similar …

➔ We thank the reviewer for this comment. We agree that the RMSE values of HYBRID and ZSTAR are nearly identical, and therefore the statement does not add significant value. We have removed this sentence from the revised manuscript.

L478: "The Yellow Sea is characterized by the Yellow Sea Bottom Cold Water Mass (YBCWM), a cold and dense water mass that forms near the bottom. However, both configurations showed positive temperature biases exceeding 2°C near the bottom, suggesting limitations in accurately representing YBCWM" -> is this an indication that actually in the Yellow Sea the two models are using a similar vertical discretization – mainly z* levels? Fig. S4 seems to support this conclusion (the difference in active layers in the Yellow Sea is <= 6). This links to the previous comment: it would be great if you could clarify how the hybrid vertical coordinate works in shallow areas (a plot would be very helpful).

➔ We thank the reviewer for this insightful comment. In MOM6, the HYBRID vertical coordinate system determines the layer interfaces by selecting the deeper of two surfaces—the isopycnal candidate or the ZSTAR floor—at each grid point. This approach allows a continuous transition from z*-like layers near the surface to isopycnal layers in the stratified interior, combining the strengths of both coordinate systems. To examine its behavior in shallow regions such as the Yellow Sea, we compared the model interfaces between HYBRID and ZSTAR during both winter and summer. The results indicate that in winter, isopycnal layers appear mainly in the deeper portion of the water column, whereas in summer they emerge in stratified regions associated with internal wave structures. Thus, the difficulty in reproducing the Yellow Sea Bottom Cold Water Mass (YBCWM) is unlikely to be directly attributable to the vertical coordinate system. Instead, recent studies (e.g., Seelanki et al.,

2025, GMD preprint) have shown that the shear-driven mixing parameterization in MOM6 (Jackson et al., 2008) is sensitive to the decay scale, and certain configurations can induce excessive vertical mixing. As the MOM6 version used in this study employs a decay scale associated with stronger mixing, we suggest that the inadequate representation of the YBCWM primarily results from excessive vertical mixing rather than from the choice of vertical discretization.

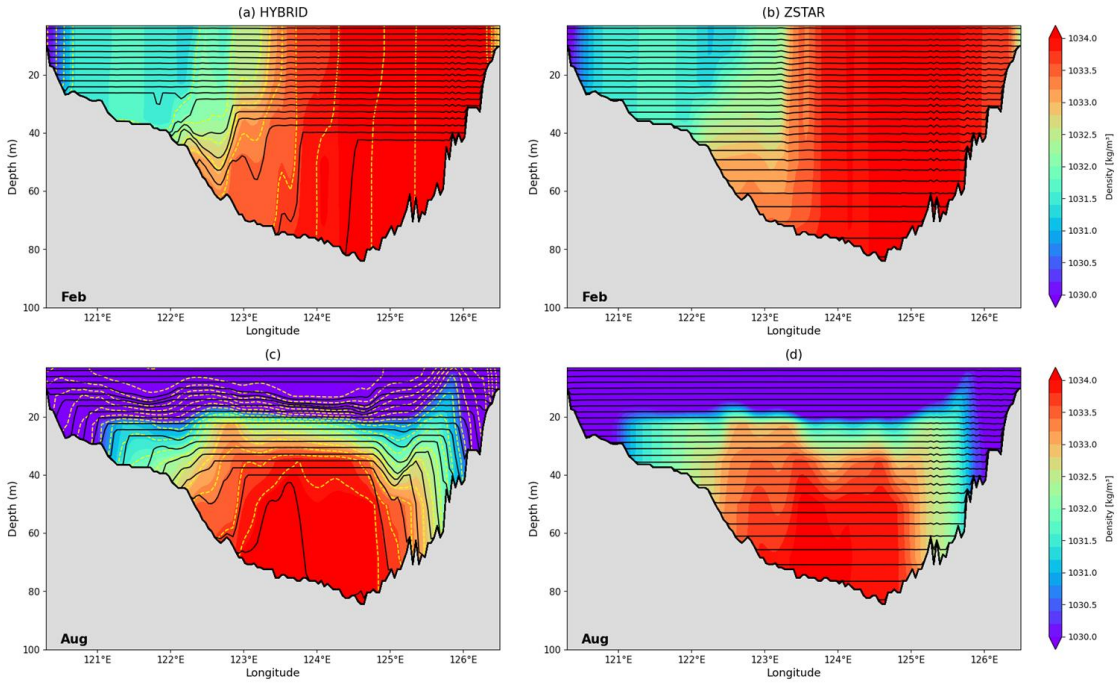

Figure 2 Zonal sections of model interfaces and density along 36°N in the Yellow Sea for HYBRID and ZSTAR configurations on 8 February (a–b) and 8 August (c–d). The background color contours represent potential density referenced to 2000 dbar. Black lines denote model layer interfaces, and yellow dashed lines indicate target density surfaces used in the HYBRID configuration.

Fig. 11: Are the discontinuities in the HYBRID profiles seen in, e.g., panel (b) at around 800m or panel (c) around 400m, due to the transition from z* to isopycnal levels?

➔ We thank the reviewer for this helpful observation. The small discontinuities visible in the HYBRID profiles (e.g., around 800 m in panel b and 400 m in panel c) are not related to the z*–isopycnal transition depth. They appeared in the earlier configuration when the number of active layers was relatively small, which led to segmented-looking profiles. After applying the regional target density array, the number of active layers in the thermocline and intermediate depths increased, yielding smoother and more continuous vertical structures. As a result, these discontinuities were largely mitigated in the updated configuration.

L620-622: "Overall, the HYBRID configuration tended to overestimate transport, particularly through the Tokara and Tsugaru Straits, while underestimating it in the Soya Strait. In contrast, ZSTAR generally underestimated transport, as observed in the Korea/Tsushima Strait and Soya Straits."Could the authors try to explain possible reasons for this? Could it be due to the fact that both configurations use the same formulation and coefficients for the bottom friction, but the ZSTAR configuration has some additional drag from the lateral boundary conditions (assuming ZSTAR uses a noslip LBC, please clarify)?

- ➔ We thank the reviewer for this insightful comment. Both configurations used the same quadratic bottom drag formulation and coefficients, and identical free-slip lateral boundary conditions were applied. Therefore, the transport differences are not related to additional drag from lateral or bottom friction effects.

- ➔ To better understand the source of the discrepancies, we examined the Tsugaru Strait as a representative narrow passage where HYBRID overestimated transport relative to ZSTAR. Fig. 3 and 4 in this letter presents meridional sections of potential density (σ_2) and along-strait velocity (U), respectively. The HYBRID configuration exhibits steeper isopycnal slopes and stronger stratification between 41.2° N – 41.4° N and 30–100 m depth, which result in a more pronounced along-strait velocity core compared to ZSTAR. These differences indicate that the enhanced transport in HYBRID arises from stronger baroclinic pressure-gradient forcing associated with sharper density gradients, rather than differences in frictional or boundary formulations.

- ➔ Mechanistically, the HYBRID vertical coordinate system aligns model layers with isopycnal surfaces derived from temperature and salinity. In narrow straits where the bathymetry changes abruptly and water masses on each side have distinct density structures, isopycnal surfaces can steepen significantly. Under such conditions, HYBRID tends to closely follow these tilted isopycnals, thereby amplifying the local horizontal density gradient ($\partial\rho/\partial x$) and associated pressure-gradient force. Consequently, the along-strait flow becomes stronger, leading to a slight overestimation of transport relative to ZSTAR.

- ➔ In contrast, ZSTAR maintains a smoother vertical discretization that damps sharp density gradients and reduces the baroclinic pressure-gradient term, which can lead to underestimated transports. Therefore, the differences between HYBRID and ZSTAR primarily stem from how each coordinate system represents stratification and baroclinic structure, not from drag or lateral boundary effects. (line 758-764)

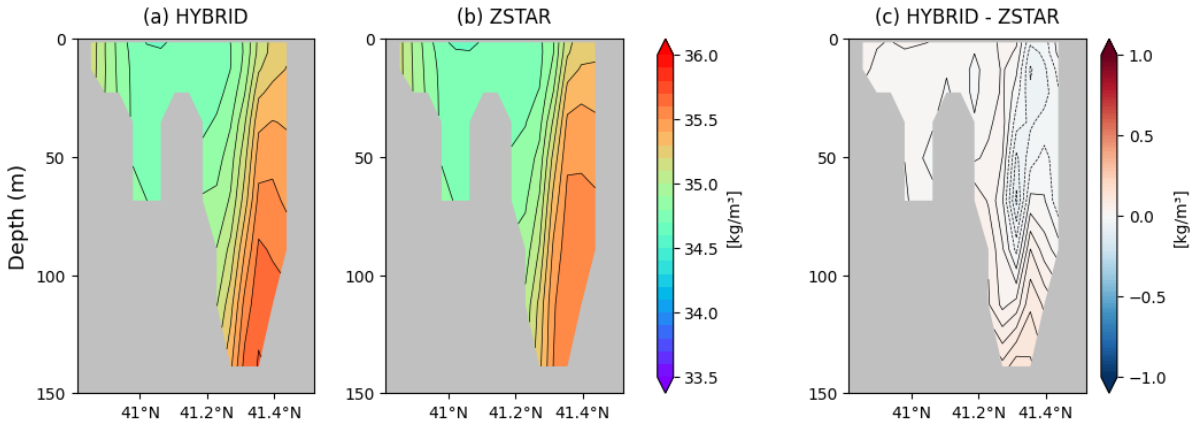

Figure 3 Meridional section of potential density (σ_2, referenced to 2000 m) across the Tsugaru Strait, averaged over 2012. (a) ZSTAR, (b) HYBRID, and (c) HYBRID–ZSTAR difference.

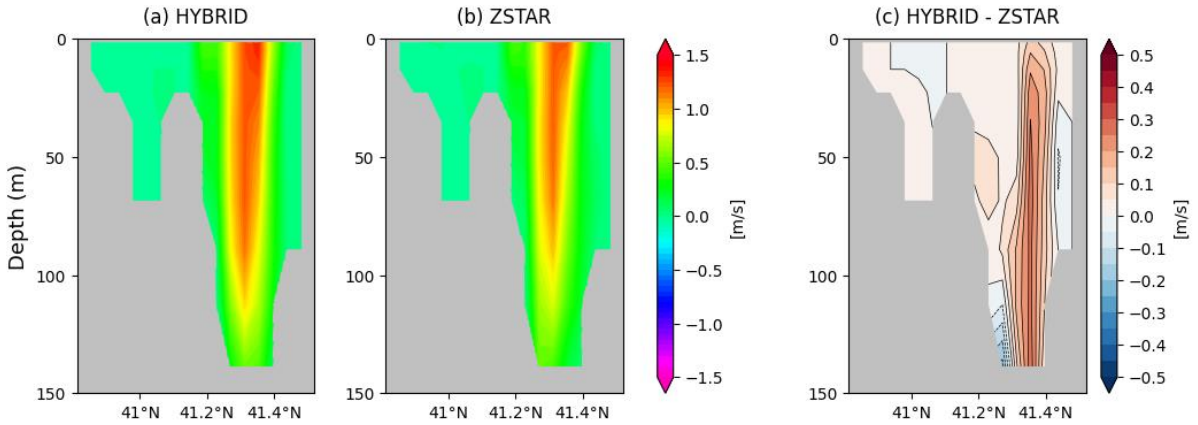

Figure 4 Meridional section of along-strait velocity (U) across the Tsugaru Strait, averaged over 2012. (a) ZSTAR, (b) HYBRID, and (c) HYBRID–ZSTAR difference.

L652-655: This seems to be in agreement with Wise et al. 2022, that shows that better resolving the bottom topography (terrain following and multi-envelope vertical coordinates versus z*-levels with partial steps) allows for a more accurate representation of the tides. Also, Graham et al. 2018 and Bruciaferri et al. 2022 showed the detrimental impact of the 10m minimum depth approximation on the tidal propagation, especially in shallow areas. This could explain the consistent underestimation of tidal amplitude in both configurations in the Yellow Sea. Please consider discussing here how the two configurations differ in the representation of the terrain and how this could explain the better performance of HYBRID.

➔ We appreciate this insightful comment. To better understand why tidal performance differs between the two vertical coordinate systems, we conducted additional analyses, and the detailed results will be presented in a separate manuscript. In this study, we focused on

evaluating the HYBRID and ZSTAR configurations against regional observations and found that HYBRID consistently achieved better tidal simulations. The improved performance of HYBRID appears to arise from its more realistic representation of stratification, particularly in shallow and estuarine regions such as the Yellow Sea and the Yangtze River estuary. The HYBRID coordinate preserves vertical density structure more effectively by reducing spurious diapycnal mixing, which helps maintain realistic vertical density gradients that are essential for accurate tidal propagation. In contrast, ZSTAR tends to smooth stratification due to stronger cross-isopycnal mixing, leading to weaker vertical density gradients and an underestimation of tidal amplitude. We have briefly mentioned this point in the revised manuscript and will present the detailed analysis in a dedicated paper.

L659: "computational efficiency"-> can the authors quantify this for this domain?

➔ We thank the reviewer for this valuable suggestion. In our Northwest Pacific configuration, the computational efficiency gain in MOM6 can be attributed to its improved numerical stability, which allows for longer stable timesteps compared to MOM5. Specifically, the maximum baroclinic timestep increased from 150 s in MOM5 to 300 s in MOM6, and the tracer timestep increased from 300 s to 900 s. These increases substantially reduced the total number of integration steps required for a given simulation period, directly translating into improved computational efficiency at the same spatial resolution. We have added a clarification of this point in the revised manuscript. (line 661-674)

L683: "lower salinity biases" -> but the temperature biases seem to me much larger (Fig 12e) – please clarify.

➔ We thank the reviewer for this valuable comment. As noted, the temperature biases in Fig. 12e were indeed more pronounced when the HYBRID configuration employed the global target density array originally designed for the OM4.0 global model. This global setup tended to produce fewer active layers in the upper ocean, particularly in stratified regions, limiting vertical resolution and leading to excessive warming near the surface. Following the reviewer's suggestion, we tested a regional target density configuration optimized for the Northwest Pacific domain. The regional target densities increased the number of active layers in the thermocline and upper ocean, thereby improving the vertical representation of temperature and mitigating the positive temperature biases previously observed in the HYBRID.

L694-695: "While such processes facilitate surface-to-interior interactions, they likely contributed to the observed temperature and salinity biases (Figs. 12 and 13)." -> could the authors please clarify a possible mechanism for this?

➔ We thank the reviewer for this helpful comment. In the initial experiments using the global target density array from OM4.0, temperature and salinity biases were evident within the Subtropical Mode Water (STMW) region, primarily due to the insufficient number of active layers. These conditions facilitated overly strong surface-to-interior exchange, which we originally described in the cited sentence. After applying the regional target density array optimized for the Northwest Pacific, the number of active layers in the upper thermocline increased substantially, leading to a much improved representation of STMW and a reduction in both temperature and salinity biases. Since this improvement effectively mitigated the previously noted issue, we have removed the corresponding sentence ("While such processes facilitate surface-to-interior interactions, they likely contributed to the observed temperature and salinity biases") from the revised manuscript. We sincerely appreciate the reviewer's suggestion, which guided us to perform this refinement and ultimately improve the model's vertical structure and bias representation.

L701-702: "This reduction in active layers likely contributed to the increased temperature and salinity biases observed in HYBRID, underscoring the challenges of using isopycnal coordinates in high-latitude environments." -> I think Fig S4 shows that HYBRID has fewer active layers not just at high latitudes, but everywhere …. As I mentioned before, are we sure these are intrinsic difficulties of the hybrid z*-isopycnal vertical coordinate and not due to the not-optimal configuration of the HYBRID vertical grid?

➔ We thank the reviewer for this thoughtful comment. We agree that the reduced number of active layers shown in Fig. S4 is not an intrinsic limitation of the HYBRID coordinate itself. In our follow-up experiments, the application of a regional target density array increased the number of active layers, especially in the upper and thermocline layers. However, even with this improvement, temperature and salinity biases persisted or became slightly larger in some regions. This suggests that the remaining biases are not solely due to the number of active layers but may instead reflect regional mismatches between the prescribed target densities and the actual density structure of the Northwest Pacific. In other words, although the vertical resolution was enhanced, the target density distribution still requires further regional tuning to better represent local water masses. It may therefore be necessary to

consider applying spatially varying (three-dimensional) target density fields that can better adapt to regional hydrographic conditions and further improve the fidelity of the HYBRID configuration.

L703-704: "modifications to the target density profile could enhance vertical resolution and better capture stratification" -> could the authors clarify why they chose to use a global setup in a regional model?

➔ We thank the reviewer for this constructive comment and the opportunity to clarify our initial choice. The global target density profile from OM4.0 (Adcroft et al., 2019) was originally adopted to ensure methodological continuity and comparability with the well-validated global MOM6 configuration. This approach provided a consistent baseline for evaluating the vertical coordinate performance in our regional setup without introducing new sources of uncertainty at the initial stage. However, as the reviewer correctly pointed out, the global configuration was not fully optimized for the hydrographic conditions of the Northwest Pacific. To address this, we subsequently developed and tested a regional target density profile tailored to the local density structure. The regional configuration improved the vertical resolution and stratification representation, particularly in the upper ocean, and helped reduce temperature and salinity biases.

L725: "HYBRID's improved tidal amplitude simulation is likely linked to its enhanced representation of stratification." -> or to a better representation of flow-topography interactions in comparison to ZSTAR?

➔ We thank the reviewer for this constructive comment. While improved representation of flow–topography interactions can certainly influence tidal performance, we believe that the primary factor behind the enhanced tidal amplitude in the HYBRID configuration is its more realistic depiction of stratification. The Yellow Sea, in particular, exhibits strong seasonally varying stratification that significantly modulates tidal propagation and dissipation (Kang et al., 2002; Liu et al., 2019). In such regions, accurate representation of vertical density gradients is crucial because stratification controls internal tide generation and modifies barotropic energy conversion and dissipation pathways. The HYBRID coordinate system better preserves these vertical density structures by reducing spurious diapycnal mixing, thereby improving the vertical phase structure of tides and their surface expression.

L729-731: "further investigation is needed to clarify the mechanisms through which

different vertical coordinates influence tidal dynamics, particularly the generation, propagation, and dissipation of baroclinic tides." -> The 10m minimum depth approximation could be one possible candidate (see Graham et al. 2018 and Bruciaferri et al. 2022).

➔ We thank the reviewer for this insightful comment and for pointing out the potential influence of the 10 m minimum depth approximation. We agree that this approximation can affect tidal propagation in shallow regions, as shown by Graham et al. (2018) and Bruciaferri et al. (2022). However, in our experiments, the difference in tidal performance between the HYBRID and ZSTAR configurations appears to be primarily related to their contrasting representations of stratification rather than the minimum-depth setting. The HYBRID coordinate system better preserves vertical density gradients and reduces spurious diapycnal mixing, which leads to a more realistic stratification structure that directly affects tidal energy propagation and dissipation. In contrast, the ZSTAR configuration tends to produce smoother and weaker stratification, resulting in reduced tidal amplitudes, particularly in the Yellow Sea.

Reference

Kang, S. K., Foreman, M. G., Lie, H. J., Lee, J. H., Cherniawsky, J., & Yum, K. D. (2002). Two-layer tidal modeling of the Yellow and East China Seas with application to seasonal variability of the M2 tide. Journal of Geophysical Research: Oceans, 107(C3), 6-1. doi: 10.1029/2001JC000838

Liu, K., Sun, J., Guo, C., Yang, Y., Yu, W., & Wei, Z. (2019). Seasonal and spatial variations of the M2 internal tide in the Yellow Sea. Journal of Geophysical Research: Oceans, 124(2), 1115-1138. doi: 10.1029/2018JC014819