Response to Comments from Referee #1

We thank the referee for careful reviews and constructive comments in improving the original manuscript. Below is our point-to-point reply to these comments (the reviewer's comments are in blue, and out responses are in black).

Summary

The main result of this study is to investigate the contribution of surface wave- and internal tides-induced vertical mixing in the upper ocean of the Indian Ocean. By adding three mixing schemes (vertical diffusive terms) into ocean circulation model, namely non-breaking surface-wave-generated turbulent mixing, the mixing induced by the wave transport flux residue, and the internal-tide-generated turbulent mixing schemes, the role of three vertical mixing schemes is quantified by switching off each diffusive term. Especially, the surface wave mainly improves the vertical mixing in the sea surface while the internal tide mainly contributes to the vertical mixing in the ocean interior. Improvement of upper ocean temperature structure is observed when all three schemes are combined.

Recommendation: Major revision.

The authors have presented a clear description of three mixing schemes, model experiments, and results that shows significant improvement of upper ocean thermal structure in the Indian Ocean. The study would be of importance to local oceanography, and it will also help improving the vertical mixing parameterization scheme that is used in the low-resolution models. However, a first impression of this paper is that the topic, i.e., what scientific object the authors are intended to improve, is not very clear, which could be related to the presentation of the introduction. The results also need more explanation. I would recommend major revision this time.

According to the reviewer's suggestion, the topic has been revised as "Improved upper-ocean thermo-dynamical structure modeling with combined effects of surface waves and M_2 internal tides on vertical mixing: a case study for the Indian Ocean" which should be clearer to show the scientific object we are intended to improve in this study. In addition, more explanation has been added in the results. The Sub-section "4.4 Effects on simulation of ocean currents" has been added in the revised version to evaluate the effects on the ocean dynamic structure of the NBSWs and the ITs. Please refer to the revised manuscript for details.

Here are some specific points below:

Major point:

1. The introduction part is not well-written, especially with respect to the relationship between vertical mixing process and upper ocean dynamic and thermodynamic processes in the Indian Ocean. For example, the paragraph from Lines 65 to 75 mainly introduces the importance of surface wave and internal tide in the Indian Ocean. But, how they are related to the upper thermal structure, and most importantly, the upper ocean dynamics, haven't been well-documented in this paragraph. In 2.4, the authors have clearly stated that the three vertical mixing schemes has been added to the momentum equation, which means that the ocean dynamic process is also influenced by three mixing schemes. Therefore, the relationship between vertical mixing (due to surface wave and internal tide) and upper ocean dynamic process should be documented in the introduction.

As the reviewer suggested, the effects of the surface waves and internal tides on the ocean dynamic processes have been documented in the 'Introduction' Section. The relationship between the surface wave and internal tide-induced mixing and the dynamic processes in the Indian Ocean has been also introduced.

Generally, the turbulent mixing induced by the wave-current interaction can improve the large-scale ocean circulation modeling. For the small- and meso-scale motions, the effects of the surface waves were also significant by modifying the surface current gradient variability and the eddy transport when the Turbulent Langmuir number is small, and the effects will become larger when the model resolution increases.

The internal wave energy in the ocean interior, which generates the turbulence processes and the diapycnal diffusivity is redistributed from large- to small-scale motions by the wave-current interactions. The parameterization of the turbulent mixing induced by the internal waves was introduced into the ocean models and makes the simulated mixing coefficients and dynamic processes, including horizontal currents and meridional overturning circulation, agree better with the Large Eddy Simulation (LES) results or observations than the original schemes.

Please refer to the revised manuscript for details, of which the content is marked in red.

2. Although the authors have stated the reason for not presenting the circulation pattern in the Indian Ocean (Lines from 350 to 355), the performance of ocean dynamic process should be presented (at least discussed) in the Result Section. As mentioned in the Major point 1, the momentum equation in the ocean model of this study is also influenced by three mixing schemes, and it in turn affects the thermal dynamic process (upper ocean temperature structure). Hence, the role of those three schemes on the ocean dynamic process, e.g., general circulation (mean state), and eddy activity (anomaly), should be investigated. Especially for the latter, since it is directly related to the parameterization of turbulent mixing, and is an important factor to the tracer conservation (Jayne and Marotzke, 2002).

Reference:

Jayne, S. R., and Marotzke, J. 2002: The oceanic eddy heat transport. J. Phys. Oceanogr., 32(12), 3328–3345. doi: 10.1175/1520-0485(2002)032<3328:TOEHT>2.0.CO;2.

We agree with the reviewer's suggestion about analyzing the effects of the NBSWs and ITs on the ocean dynamic processes. We have added Sub-section "4.4 Effects on simulation of ocean currents" to discuss the effects of the NBSWs and ITs on the ocean dynamic processes. Because the WTFR-induced mixing has a little effects on the simulated results, there is little difference between the simulation with and without the WTFR-induced mixing scheme, so we only compared the results in Exp1 – Exp 3. The monthly mean Ocean Surface Current Analyses Real-time (OSCAR) data, which are able to provide accurate estimates of the surface time-mean circulation, were used in the comparison as a reference. The comparison results showed that the NBSW and the IT somewhat improve the simulated surface currents.

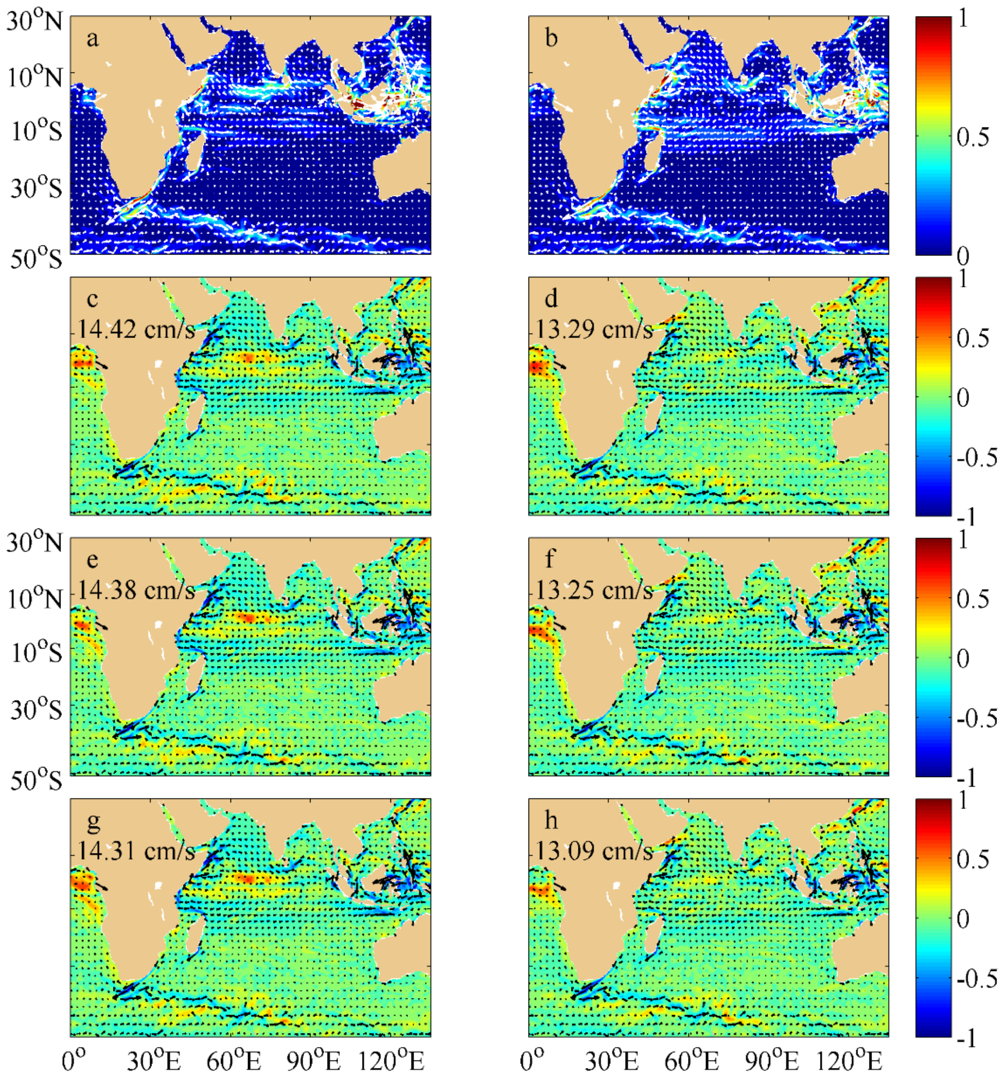

Figure: The distribution of the surface currents from the OSCAR climatologic data and the differences by subtracting the OSCAR data from the mean results from Exp 1 (c, d), Exp 2 (e, f) and Exp 3 (g, h) in January (c, e and g) and July (d, f and h). RMSEs of the surface velocities are shown on the upper left corner of the sub-figures. White arrows in Sub-figures a and b represent the surface current vectors, and black arrows in Sub-figures c – h represent the surface current difference vectors. Deep yellow areas correspond to the lands

Furthermore, we have calculated the three-dimensional vertical vorticity and the eddy kinetic energy (EKE) in Exp 1 – Exp 5 to evaluate the effects of the NBSWs and the ITs on the meso-scale eddy activity. However, the difference among the five experiments was too complicated to summarize some dynamic processes and physical mechanisms. Therefore, the analysis of the simulated eddy activity was omitted in this study. The reason should be that the climatologic modeling in this study, on one hand, may be inappropriate to analyze the meso- or small-scale processes because of the relatively coarse and smoothed surface forcing, open boundary conditions and topography; on the other hand, the induced vertical mixing may not be a key mechanism for the eddy activity, previous studies indicated that the surface waves affect the eddies through the interaction among the turbulence, the circulation and the Langmuir circulation when the Turbulent Langmuir number is small (Jayne and Marotzke, 2002; Romero et al., 2021), and the subharmonic instability may transfer the energy from the internal tides to the shear-induced turbulent diapycnal mixing (MacKinnon and Gregg, 2005; Pinkel and Sun, 2013). Additional improvements of the mixing schemes used in this article will be studied further in future. These analysis and explanation have been added in the sub-section 4.4.

Minor points:

1. Line 60. Why choose M_2 internal tides?

Many thanks for this question, which is important for clarifying further the motivation of this study. In our opinions, there should be three reasons. Firstly, as one of the main tidal constituents (M_2, S_2, N_2, O_1, and K_1), M_2 internal tides have the largest energy among the semi-diurnal tides, therefore, the turbulence generated by M_2 internal tides should be dominant and typical for studying the mixing processes. Secondly, M_2 internal tides are ubiquitous in the world oceans, and lose little energy in propagating across its critical latitudes (28.88S/N) (Zhao et al., 2016). Finally, this study is still preliminary research on the contribution of surface wave- and internal tides-induced vertical mixing in the upper ocean, we just chose one of the main tidal constituents to test the effects. Other constituents such as S_2, N_2, O_1, and K_1 will be evaluated in future. The explanation has been added in the revised manuscript.

2. Lines 155-160: A short description of the Mellor-Yamada scheme is needed for the readers to understand the difference between the experiment 1 and other experiments in the Result Section.

A short description of the M-Y 2.5 scheme has been added in the revised manuscript. The M-Y 2.5 scheme is a level-2.5 turbulence model based on the modification of the material derivative and diffusion terms. The mixing coefficients K_m and K_h can be calculated as the turbulence characteristics multiplied by a stability function associated with the Richardson number. One of the major deficiencies of the M-Y 2.5 scheme is the neglect of the surface-wave effect. Please refer to the revised version for details.

3. Line 225: Please provide the reason why you choose the 10.5°S Section.

There are two reasons for the choice of the 10.5°S Section. Firstly, the Madagascar-Mascarene regions (0° ~ 25°S in the West Indian Ocean) are considered to be a hot spot for generation of semidiurnal internal tides. Both of the surface waves and internal tides should grow fully and become large enough for the comparison of the diffusive terms. Secondly, the 10.5°S Section is typical to the different pattern among the diffusion terms obviously, which include that, the k_h calculated from the classic M-Y 2.5 scheme is relatively small, the NBSW-generated turbulent mixing is the largest in the ocean surface and decays exponentially with the depth, and the IT-generated turbulent mixing is obviously larger than other schemes in the ocean interior. The explanation has been added in the revised version.

4. Line 245: The EIO only occurs once in this manuscript. Hence it is not necessary to define this abbreviation.

We agree with the reviewer and accept the suggestion. The abbreviation "EIO" has been deleted in the revised version.

5. The thermocline structure at the equatorial region (normally defined as the depth of the 20 degree temperature, referred as Z20C) is one of the distinctive feature in the Indian Ocean. Because of the weak westerly at the equator, the Indian Ocean shows deeper and reversed slope of Z20C as compared to its counterpart in the Pacific Ocean. The mean state structure of Z20C is very important for the Indian Ocean air-sea interaction (e.g., Indian Ocean Dipole). Therefore, it would be worthwhile to find out how the Z20C responds to those three mixing schemes. I would suggest the authors to show the upper-ocean thermal structure at the Equator in Section 4.2.

Many thanks for the reviewer's constructive comments about the thermocline structure. The variation of the depths of 20 °C isothermal (Z20) have been discussed in Subsection 4.2. As another indicator of the thermal structure in the upper-100 m layers, the depths of 26 °C isothermal (Z26) are also analyzed. New figures (Figures 9 in the revised version) are plotted to show the comparison of the Z20 and Z26 depths along the equator from the WOA13 data and the model results. One can see that the Z20 and Z26 depths are both shallow in the west and deep in the east, the simulation of the thermal structure in the five experiments depict this pattern successfully. Comparisons of the RMSEs show that the NBSW- and IT-generated turbulence mixing can improve the simulated Z26 depths as two of the key factors, but have a negative effects on the Z20 depth modeling, the reason is that the Z20 isothermal simulated in the benchmark experiment (Exp 1) is generally deeper than the WOA13 data, this should be caused by inaccurate topography and open boundary conditions, more optimization and improvement of the experimental design will be implemented in future work to make the simulated results more accurate. Please refer to the revised version for details.

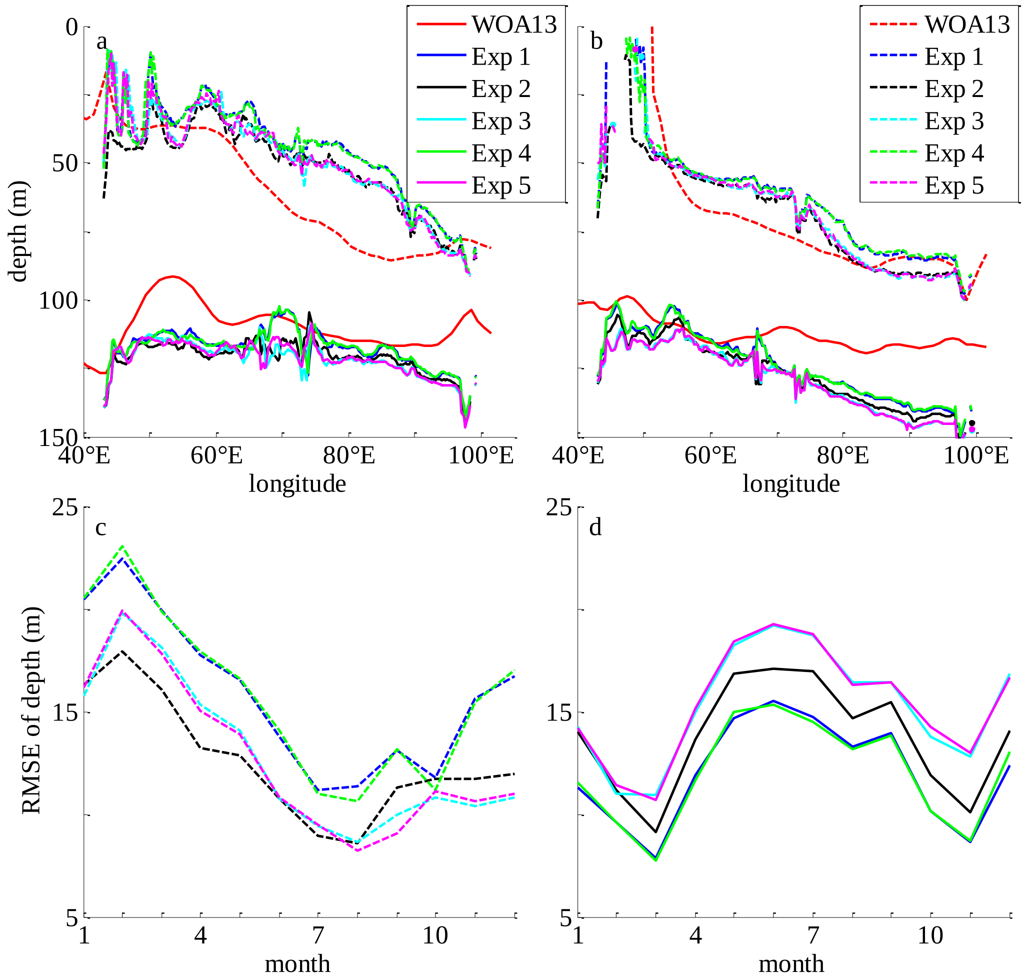

Figure: The comparison of the Z20 and Z26 depths along the equator from the WOA13 data and the model results. a and b: the Z20 (solid curves) and Z26 (dashed curves) depths from the WOA13 data and the model results (Exp 1 ~ Exp 5) in January and July, respectively. The RMSEs of the Z26 (c) and Z20 (d) depths along the equator are also plotted.

6. The fontsize of text in some figures should be made larger (e.g., Figure 8, Figure 9).

Figures 2 ~ 9 in the original manuscript have been replotted to be more clear and more readable.