Review: "Southern Ocean deep mixing band emerges from a competition between winter buoyancy loss and upper stratification strength"

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Summary

This study, using the observational monthly data and ECCO monthly outputs, explores what controls the position and narrowness of the Southern Ocean deep mixing band (DMB). The authors investigate two critical factors: the wintertime buoyancy loss and the stratification intensity. The net balance between these two factors is found to be sufficient to predict the DMB formation far from western boundary currents. Ekman buoyancy transport plays a secondary role, which can counterbalance the effect of surface buoyancy fluxes. Finally, the authors find that the spatial variations of thermal expansion coefficient (TEC) are necessary to explain the limited meridional extent of the DMB across the Southern Ocean.

The authors present some interesting results, highlighting the dominant role of surface buoyancy fluxes and the strength of the upper ocean stratification in the DMB formation. The paper is clear, well-written, and worthy of publication. However, I have some concerns on the paper's conclusions and methodology, which should be further addressed.

Major comments

(1) **Lines 305–307**: "*In this study, our goal was to determine if the position of the Southern Ocean DMB and its* ***narrowness*** *can be explained* ***only*** *by the balance between the buoyancy loss of the cooling season and the stratification intensity. We find that this balance is* ***sufficient*** *to predict the DMB away from western boundary currents.*"

(a) What is the defination of "***narrowness***" of DMB here? What is the horizontal resolution of observational data and ECCO outputs used in this study? Compared with the MLD simulated from an eddying (0.1°) ocean model (e.g., Fig. 2 in Li & Lee, 2017), the meridional extent of wintertime MLD (Fig. 1b) looks still quite broad to me. Note that the MLD from de Boyer Montégut et al. (2023) is at 1 °× 1 °spatial resolution. More discussion/clarification is needed here.

(b) The authors also need to clarify that "*this balance is* ***sufficient*** *...*" on the timescale of annual mean or 6-month-mean, which is the time period focused in this study. In fact, I am concerned on comparing the contributions of surface buoyancy fluxes and Ekman buoyancy transport on the timescale of 6-month or longer, as they both can play the dominate role of preconditioning in the deep MLD formation but during different periods. For example, the *May* net air-sea heat flux and *June* Ekman heat advection are both critical in the *August/September* MLD formation (Li & England, 2020).

(c) The first-order role of surface buoyancy fluxes is mostly considered on a large-scale or a zonal average (Fig. 5). In southeast Pacific, Ekman buoyancy transport actually dominates the deep MLD formation and Subantarctic Mode Water (SAMW) formation (Cerovečki et al., 2019; Li & England, 2020). More discussion is needed here.

(d) In the MLD budget, there are some other terms, such as vertical Ekman pumping and vertical mixing, that could be potentially important. More discussion is needed here.

(2) **Section 2.2**: I do not follow why the authors use ***a deep mixed layer threshold of 250 m*** in the estimation of stratification intensity. The wintertime MLD, that forms north of the Subantarctic Front (SAF), can be much deep over 500 m. The summertime MLD at southern high-latitudes can be less than 100 m. Thus, it is unjustified to apply this threshold across the entire Southern Ocean. I suggest to use the actual MLD in the calculations (Eq. 11). Then, this equation can be written as follows:

$$B_{\mathrm{MLD}} = \frac{g}{\Delta t}\left(\int_{-\mathrm{MLD}}^{0} \alpha(z)\frac{\partial \theta}{\partial z} z dz - \int_{-\mathrm{MLD}}^{0} \beta(z)\frac{\partial S}{\partial z} z dz\right)$$

Minor comments

- Figure 8: The authors examine three different transects in the Atlantic, Indian, and Pacific sectors of the Southern Ocean. However, these transects cover a large domain, in which many different processes may mix together. I recommend changing each domain to that more localized in the deep MLD formation region. For example, the SAMW formation regions analyzed in Li et al. (2021) and Cerovečki et al. (2013).

- Equation (3): Define the τ^x and τ^y.

- Equation (4)–(7): Define the θ and S.

- Equation (8): Define the Z and z right after this equation.

- Figure 6: Add "annual" to the figure caption.

- Line 331: Change Fig. 3 (f) to Fig. 4 (f).

- There are too many acronyms in the paper, and I suggest to reduce the use of them if possible. For example, I may suggest to spell out the "Southern Ocean (SO)", "cooling season (CS)", "warming season (WS)", etc.

References

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