Manuscript Number: egusphere-2024-2749

Dissipation ratio and eddy diffusivity of turbulent and salt finger mixing derived from microstructure measurements

Note: The reviewers' original comments are in black, and our responses are in blue.

Responses to Reviewer #2

Dissipation and related diffusion and mixing in the ocean are important for ocean dynamics (even global circulation) and for the transport of oceanic constituents. However, the causative processes are on very small scales (down to millimetres or less) as well as patchy and intermittent. Hence they are difficult to measure and quite impractical to model explicitly. As a result, empirical relationships and parameterizations are much used and evidence to improve these is valuable. This manuscript especially concerns the much used factor $\Gamma^T = 0.2$ in the Osborn relation for turbulent density diffusivity = Γ^T (dissipation)/(buoyancy frequency^2). Much evidence is cited that Γ^T varies a lot in space and time. Moreover, turbulence is not the only agent of mixing; for salt finger mixing the equivalent Γ^F may be negative. The manuscript provides separate evidence and discussion of the effective diffusivities for temperature and salinity associated with salt fingering.

Response: We sincerely thank the reviewer for the valuable comment, which helps a lot to improve the quality of our manuscript. We hope the revised manuscript meet the reviewer's requirements, and we expect this work make a positive contribution to better interpret microstructure observations and favour the improvements of mixing parameterizations.

Data for the study are from the western equatorial Pacific the subtropical NE Atlantic and tropical SW Atlantic. This is a varied set but I am left uncertain as to how comprehensive or representative it may be of all the possible data that might have been used. It is certainly sufficient to make the case that there can be improvement by moving to Γ^T other than 0.2 with some suggestion of how to derive improved values.

Response: We understand the reviewer's concern. The data used in this study is from the "Microstructure Database" (MacKinnon et al., 2017), which is publicly shared and constantly updated, and consists of most known microstructure observation projects. We chose all projects that meet the analysis requirement for this study. Before this study, we examined the dissipation ratio based on microstructure data obtained from the South China Sea (Li et al., 2023), which suggests similar relations between Γ^T and R_{OT} and Re_b, indicating the Γ^T formula in this study could be representative. This discussion has been mentioned in the revised manuscript.

Reference:

MacKinnon, J. A., and Coauthors, 2017: Climate Process Team on Internal Wave–Driven Ocean Mixing. Bulletin of the American Meteorological Society, 98, 2429–2454, https://doi.org/10.1175/BAMS-D-16-0030.1.

Li, J., Yang, Q., Sun, H., Zhang, S., Xie, L., Wang, Q., Zhao, W., and Tian, J., 2023: On the Variation of Dissipation Flux Coefficient in the Upper South China Sea, J. Phys. Oceanogr., 53, 551–571, https://doi.org/10.1175/JPO-D-22-0127.1.

I found section 2.3 lacking in logical development and am unsure as to its value to the rest of the manuscript (it is rarely referred to). Might it be replaced by a few literature references?

Response: we thank the reviewer for this valuable suggestion. In the section 2.3, we intended to give a detail introduction of the derivation of Γ and eddy diffusivities for both turbulent mixing and

salt finger mixing. However, as suggested by the reviewer, we realized that this part is lacking in logical development and is rarely referred to in the whole manuscript as the reviewer pointed out. Therefore, we simplified and reworked it as:

"Dissipation ratio Γ is defined as

$$\Gamma = \frac{\chi_\theta N^2}{2\varepsilon\theta_z^2} \tag{1}$$

for turbulent mixing and salt-finger mixing (Oakey, 1985). Based on the production-dissipation balances for TKE and thermal variance (Osborn and Cox, 1972; Osborn,1980), and introducing R_ρ and the density flux ratio $r=\alpha K_\theta\theta_z/\beta K_S S_z=K_\theta/K_S\cdot R_\rho$, we get

$$\Gamma = \frac{\chi_T N^2}{2\varepsilon\theta_z^2} = \left(\frac{R_f}{1-R_f}\right)\frac{K_\theta}{K_\rho} = \left(\frac{R_f}{1-R_f}\right)\left(\frac{R_\rho-1}{R_\rho}\right)\left(\frac{r}{r-1}\right), \tag{2}$$

which is applicable to both turbulent mixing and salt finger mixing (St. Laurent and Schmitt, 1999). For turbulent mixing only, $K_S = K_\theta = K_\rho$. Then, Eq. (2) leads to

$$\Gamma^{\mathrm{T}} = \frac{\chi_T N^2}{2\varepsilon\theta_z^2} = \frac{R_f}{1-R_f}, \tag{3}$$

and

$$K_\theta^{\mathrm{T}} = K_S^{\mathrm{T}} = K_\rho^{\mathrm{T}} = \Gamma^{\mathrm{T}}\frac{\varepsilon}{N^2}, \tag{4}$$

where superscript "T" indicates turbulent mixing.

However, for salt finger mixing only, with $\lim_{P\to 0}\frac{R_f}{1-R_f} = -1$ (St. Laurent and Schmitt, 1999), Eq. (2) yields

$$\Gamma^{\mathrm{F}} = \frac{\chi_T N^2}{2\varepsilon\theta_z^2} = -\frac{K_\theta}{K_\rho} = -\left(\frac{R_\rho-1}{R_\rho}\right)\left(\frac{r}{r-1}\right), \tag{5}$$

which cannot be used directly to estimate the salt finger induced eddy diffusivities. And they are estimated separately by introducing R_ρ and $r^{\mathrm{F}} = R_\rho\Gamma^{\mathrm{F}}/\left(R_\rho\Gamma^{\mathrm{F}} + R_\rho - 1\right)$ (St. Laurent and Schmitt, 1999; Schmitt et al., 2005; Inoue et al., 2007),

$$K_\theta^{\mathrm{F}} = \left(\frac{R_\rho-1}{R_\rho}\right)\left(\frac{r}{1-r}\right)\frac{\varepsilon}{N^2} = \Gamma_\theta^{\mathrm{F}}\frac{\varepsilon}{N^2}, K_S^{\mathrm{F}} = \frac{R_\rho-1}{1-r}\frac{\varepsilon}{N^2} = \Gamma_S^{\mathrm{F}}\frac{\varepsilon}{N^2}. \tag{6}$$

Note that all these equations are written into forms analogical to the Osborn relation for turbulent mixing. $\Gamma_\theta{}^{\mathrm{F}}$ and $\Gamma_S{}^{\mathrm{F}}$ are two artificial "mixing efficiencies", which are actually $\left(\frac{R_\rho-1}{R_\rho}\right)\left(\frac{r}{1-r}\right)$ and $\frac{R_\rho-1}{1-r}$ before "ε/N^2" for $K_\theta{}^{\mathrm{F}}$ and $K_S{}^{\mathrm{F}}$ estimation. $\Gamma_\theta{}^{\mathrm{F}}$ is the same as Γ^{F}, while $\Gamma_S{}^{\mathrm{F}}$ are further derived based on R_ρ and r^{F}, $\Gamma_S{}^{\mathrm{F}}=\Gamma^{\mathrm{F}}\cdot R_\rho/r^{\mathrm{F}}$. Investigating the statistic features of $\Gamma_\theta{}^{\mathrm{F}}$ and $\Gamma_S{}^{\mathrm{F}}$ can be practically useful when estimating $K_\theta{}^{\mathrm{F}}$ and $K_S{}^{\mathrm{F}}$ solely based on ε and N^2."

We hope the reviewer find this revision more readable.

References:

Inoue, R., H. Yamazaki, F. Wolk, T. Kono, and J. Yoshida, 2007: An Estimation of Buoyancy Flux for a Mixture of Turbulence and Double Diffusion. Journal of Physical Oceanography, 37, 611–624, https://doi.org/10.1175/JPO2996.1.

Oakey, N. S., 1985: Statistics of Mixing Parameters in the Upper Ocean During JASIN Phase 2. Journal of Physical Oceanography, 15, 1662–1675, https://doi.org/10.1175/1520-0485(1985)015<1662:SOMPIT>2.0.CO;2.

Osborn, T. R., 1980: Estimates of the Local Rate of Vertical Diffusion from Dissipation Measurements. Journal of Physical Oceanography, 10, 83–89, https://doi.org/10.1175/1520-0485(1980)010<0083:EOTLRO>2.0.CO;2.

Osborn, T. R., and C. S. Cox, 1972: Oceanic fine structure. Geophysical Fluid Dynamics, 3, 321–345, https://doi.org/10.1080/03091927208236085.

Schmitt, R. W., J. R. Ledwell, E. T. Montgomery, K. L. Polzin, and J. M. Toole, 2005: Enhanced Diapycnal Mixing by Salt Fingers in the Thermocline of the Tropical Atlantic. Science, 308, 685–688, https://doi.org/10.1126/science.1108678.

St. Laurent, L., and R. W. Schmitt, 1999: The contribution of salt fingers to vertical mixing in the North Atlantic Tracer Release Experiment. Journal of Physical Oceanography, 29, 1404–1424, https://doi.org/10.1175/1520-0485(1999)029<1404:tcosft>2.0.co;2.

The English is generally understandable but there is some curious usage that should be corrected by the publisher's copy-editing of a final manuscript. The authors unfortunately follow the current "fashion" of misleadingly using "increasing trend" when they mean "positive trend" or simply "increase". "Misleading" because the expression implies a change of trend. [Many but probably not all examples are included in the following "Detailed comments".]

Response: We thank the reviewer for point out this misleading usage. We tried our best to polish the language in the whole revised manuscript. All changes are marked in the revised manuscript one by one, especially for the misleadingly usage of "trend". We have thoroughly checked and revised all "trend" used in the manuscript.

Detailed comments

Line 104. "we chose five projects that . ." Did other projects provide χ_θ and you chose not to use them, or did you use all the projects providing χ_θ? If the latter, better "we chose all five projects that . ." to show that you did the best possible.

Response: We apologize for this unclear expression. The data used in this study should meet two criteria. First, χ_θ is available to estimate Γ. Secondly, variables should be sampled and provided in the form of vertical profile, since vertical gradients of some variables (like θ and S) are needed. We have chosen all five projects meeting these two criteria. This phrase is revised now as "Since the calculation of dissipation ratio requires the dissipation rate of thermal variance (χ_θ), and the vertical gradients of temperature θ and salinity S are needed, we chose all five projects that provide χ_θ and are in the form of vertical profiles."

Table 1. According to figure 1 NATRE is in the North Atlantic. ("S" –> "N").

Response: We are sorry for this error. It has been corrected.

"Profile Number" –> "Number of Profiles".

Response: This phrase has been corrected.

Equations (3). The sequence from left to right is not logical if Γ is already defined as in line 149. Moreover from (1) and (2) the second and last terms of (3) are directly equal irrespective of the first and third terms. Please clarify what is definition, what is derivation, and where the form of the third term comes from (there seems to be an analogy with the right-hand side of (4) for which a reference is cited).

Response: We apologize for this illogical presentation. As aforementioned, due to the confusing expression and the weak connection to the following text, the section 2.3 has been reorganized and reworked.

Lines 212-213. Better ". . divide the number of energetic turbulence patches in each depth bin by the total number of energetic turbulence patches in the whole project; . ." and Line 214 ". . by the total number of patches within the same depth bin . ."?

Response: Thanks for this wording correction. The corresponding text has been revised.

Section 4.1 is very long and I think would benefit from some sub-headings.

Response: We thank the reviewer for this nice suggestion. Section 4.1 now consists of two subsections, namely "4.1.1 Vertical variation" and "4.1.2 Relation between Γ^T, Re_b and R_{OT}".

Lines 243-244. Why are there two NATRE median values of Γ^T for each of energetic turbulence and weak turbulence?

Response: We apologize for this wording issue. It has been corrected as "the median Γ^T values are 0.33 and 0.50 for energetic turbulence and weak turbulence, respectively."

Line 257. Why "alternately"? "slightly increasing trend" –> "slight increase with depth"? (unless you mean the trend/rate increases)

Response: We are sorry for this wrong usage of "trend". It has been revised.

Lines 268, 270, 451, 498, 510. "vertical increase" (or decrease") is unclear until upwards or downwards is specified. Also (lines 268, 270, 451) I think you mean "increase" not "increasing trend" (c.f. line 257; does the trend/rate increase?).

Response: We apologize for these improper wordings. "Vertical increase" is actually "increase downwards". These errors have been revised.

Line 272. I think you mean ". . disagree about whether Γ^T is larger for energetic turbulence or weak turbulence."

Response: We are sorry for this confusing expression. It has been revised.

Lines 284, 369, 390, 451, 500. "increasing trend" –> "increase" (indeed, in line 390 referring to figure 11, the trend is positive but actually decreases for $R_\rho > 3$).

Response: We apologize for these errors. they have been corrected together.

Lines 285, 290, 397. "decreasing trend" –> "decrease"

Response: It has been corrected.

Line 286. "BBTRES" -> "BBTREs"

Response: It has been corrected.

Figure 8. In the figure legend, the red line should be ascribed to $Re_b > 160$. The grey dashed line is rather indistinct.

Response: We are sorry for these mistakes. Fig. 8 has been revised as suggested, presented here as Fig. R1 for your information.

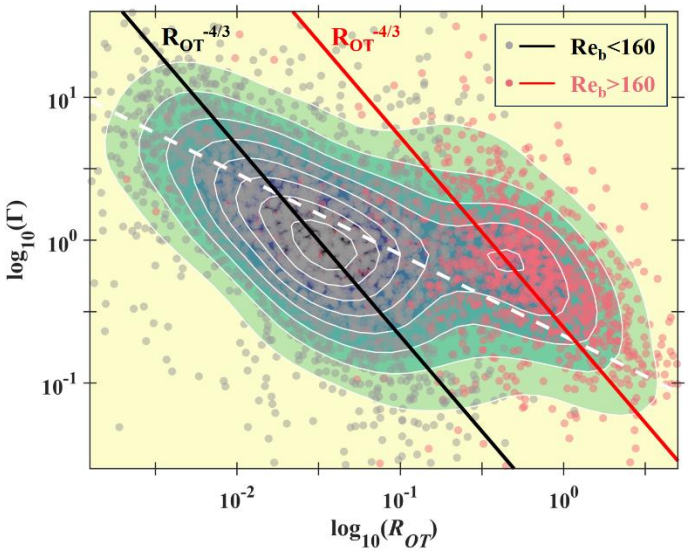

Fig. R1. Relation between overturn-based Γ^T and R_{OT}, overturns from the five projects are considered. The shading describes the distribution of probability density, with yellow indicating minimum probability density and blue representing maximum one. The overturns are correspondingly divided into two clusters: the gray dots have Re_b<160, and the pink ones, Re_b>160. The black and red lines represent $\Gamma^T \propto R_{OT}^{-4/3}$, crossing the centers of the two clusters. The white dashed line is the general relation between Γ^T and R_{OT} of the whole data collection.

Figure 9. Please explain (in the caption or against the colour bar) that the colour bar refers to median Γ^T.

Response: We apologize for this information gap. We added explains about the color bar in the caption.

Line 372. The "ref"erence needs to be included.

Response: We are sorry for this mistake. This reference has been referred to correctly.

Line 376. "Note that . . ." I think this sentence should refer to a labelled formula in section 2.3.

Response: We thank the reviewer for this suggestion. This sentence now refers to equation (6) in the revised manuscript.

Line 403. "decreasing rate" –> "rate of decrease".

Response: Sorry for this wording issue. It has been corrected.

Lines 419-420. "increasing rates" –> "increases"?

Response: It has been revised.

Line 422. "vertical decreasing trend and magnitude" –> "decrease downwards"?

Response: This phrase has been corrected as suggested.

Line 423. "increasing trend" –> "increases".

Response: It has been corrected.

Line 492. “Vertically, Γ^T in the western equatorial Pacific presents a weak decreasing trend” –> “Γ^T in the western equatorial Pacific presents a weak decrease downwards”.

Response: We thank the reviewer very much for helping us polishing language. This sentence has been reworked.