"Squeeze dispersion and the effective diapycnal diffusivity of oceanic tracers": Point-by-point response to reviewers

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1 Reviewer 1

We thank the reviewer for their comments. We address their comments and concerns point-by-point below.

1.1 "Error 1: The main message that the paper sells is wrong"

In this comment, the reviewer argues that strain does not affect 'diapycnal mixing'. The reviewer uses an Eulerian average of the vertical diffusive flux to argue this point. The reviewer also includes a discussion of the parameterization of diapycnal mixing in z-coordinate models and layered models.

The primary flaw in the reviewer's Eulerian-averaged analysis is that it neglects the advective vertical tracer flux wc, which is part of the squeeze-induced tracer flux in the presence of squeeze dispersion. Our analyses do not include the advective flux because we work in coordinate systems, such as buoyancy coordinates, that follow the vertical motion of the fluid, thereby eliminating that complication.

We note also that fluctuating strain can act to increase the Eulerian-averaged tracer gradient, $\bar{c}_z$; so that the effects of strain on $\kappa \bar{c}_z$ — only part of the total Eulerian diffusive tracer flux in squeeze dispersion — are evident in an Eulerian-averaged framework. Yet even if the Eulerian-average flux and effective diffusivity are calculated correctly, care must be taken in comparing Eulerian-average quantities with our Lagrangian or thickness-weighted-average squeeze diffusivity. There is no guarantee that either the tracer fluxes, tracer gradients, or effective diffusivities defined for different averaging procedures will agree with one another. We now discuss the caveats of using Eulerian-averages to diagnose squeeze dispersion in the fifth paragraph of the introduction and second paragraph of the conclusion.

We believe we demonstrate unequivocally that strain affects tracer dispersion associated with a molecular or local turbulent diffusivity using a coarse-grained scenario in the introduction, numerical results and an approximate analytical solution in section 2, and a thickness-weighted average theory in section 3. We believe this paper is primarily about that *process*, rather than about averaging frameworks that quantify the effect of squeeze dispersion.

Finally, we do not intend to make specific, actionable recommendations to modelers regarding the parameterization of diapycnal fluxes. We note only that because strain affects diffusive tracer flux, 'missing' strain will produce a misprediction of tracer dispersion due to diffusion, in general.

1.2 "Error 2: Section 2 is 100% wrong"

Here the reviewer remarks that the numerical experiment in section 2 quantifies the spreading of tracer due to 'adiabatic advection', rather than tracer dispersion to due irreversible diffusive mixing.

However, in section 2, a tracer patch is advected and strained through exactly one cycle of a periodic flow: the streamline configuration at the point of our analysis, at the end of one cycle of periodic squeezing, is identical to the streamline configuration in the tracer's initial state. As a result, an 'isopycnal' or streamline-coordinate analysis is identical to a z-coodinate analysis after one cycle of squeezing. The example in section 2 was constructed in precisely this manner to eliminate the complications that would be associated with an isopycnal analysis. Our analysis thus does not mistake adiabatic advection for irreversible tracer dispersion.

This point is reinforced by the analytical solution presented in section 2 and derived in appendix B, whose prediction for tracer dispersion and effective diffusivity agrees almost exactly with the numerical results. The analytical solution relies on a transformation of the tracer equation into streamline coordinates, and the adiabatic component of tracer dispersion is explicitly accounted for. The analytical solution also demonstrates that the squeeze dispersion effective diffusivity is *proportional* to the prescribed 'molecular' diffusivity, and thus vanishes for a purely adiabatic process.

We note that one motivation for using a thickness-weighted average in section 3, and an average following material surfaces in the introduction — rather than the Eulerian average advocated by the review in their first comment — is to eliminate dispersion associated with adaibatic advection.

1.3 "Error 3: The GM90 scheme is not a parameterization of the bolus velocity"

We concede this point and have modified our discussion of the GM90 scheme at the end of section 3 accordingly.

1.4 "An extra point that could be made"

The reviewer makes the point that squeezing reduced the Richardson number, thereby providing a plausible physical mechanism for correlations between strain and turbulent mixing associated with shear instability at low Richardson number. We commented on this possibility in the first paragraph of our conclusion in the original manuscript, and retain this comment in the revised submission.

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We thank the reviewer for their comments. We have expanded on our comment in the conclusion about the differences between shear dispersion and squeeze dispersion. Perhaps the clearest difference is that squeeze dispersion requires velocity gradients *parallel* to the direction of and dispersion and flow (strain), while shear dispersion requires velocity gradients *perpendicular* to the direction of dispersion and flow (shear).