Ocean Sci. Discuss.,
https://doi.org/10.5194/os-2019-97-AC1, 2019

Interactive comment on "Tracking the spread of a passive tracer through Southern Ocean water masses" *by* Jan D. Zika et al.

Jan D. Zika et al.

j.zika@unsw.edu.au

Received and published: 10 December 2019

Anonymous Referee 1

In 2009, as part of the Diapycnal and Isopycnal Mixing Experiment in the Southern Ocean (DIMES), a passive tracer was released near 1500 m depth upstream of Drake Passage. Subsequent cruises measured tracer concentrations across the Antarctic Circumpolar Current to document the gradual tracer spreading due to mixing and advection. The tracer data has been analyzed in density space and geographical space to derive integral constraints on levels of irreversible mixing and lateral stirring (Watson et al. 2013, Tulloch et al. 2014). Here, the authors use an original approach: they analyze tracer spreading along isopycnals but across isohalines. The use of salinity as the

lateral coordinate yields new insights about Southern Ocean stirring and mixing processes. The analysis is carefully exposed and the results well presented. Nonetheless, the manuscript could improve with a more pedagogical explanation of the rationale and of the hypotheses discussed. I detail this concern below.

> We thank the reviewer for these encouraging comments.

Main comments: 1. The important distinction between reversible (lateral) stirring and irreversible (isotropic) mixing is not clearly explained and is only discussed in two sentences in the discussion (lines 284-286). I think this point deserves more space throughout the manuscript. Few readers will be as familiar as the authors with this distinction. You make the point in the introduction that spreading across isohalines implies irreversible mixing. Then you move on to analyze tracer spreading in isopycnal salinity coordinates in terms of lateral diffusivities, leaving out isotropic (small-scale) diffusivities (until lines 284-286). By focusing on lateral diffusivities, you make the implicit assumption that they play the most important role in shaping the ultimate irreversible mixing. Yet irreversible mixing depends on the interaction of lateral stirring (which produces gradients) with isotropic mixing (which consumes gradients); it is not obvious which of the two processes should be the dominant cause of variations in spreading rate.

> Indeed. We have added an important paragraph to the introduction on lines 29-39 with regard to the above points.

Actually, to me, the 20-fold increase in isotropic mixing from west to east of Drake Passage (Watson et al. 2013) would be the most natural 'default' hypothesis for the inferred increase in spreading rate in your isopycnal salinity coordinate system. Could you discuss why you expect along-stream changes in lateral stirring rate to be more important?

> We have further clarified why we have given more weight to the Garrett 1983 model on lines 293-294. The main point here is that even in the absence of changes in stirring

or small scale mixing, we would expect an uptick in the rate of irreversible mixing simple due to the expected time evolution of the tracer patch.

More generally, could you make clear upfront that isopycnal stirring alone cannot mix the tracer across isohalines? Is it possible to place constraints on both reversible stirring and irreversible mixing via your analysis? Could the difference between the isopycnal diffusivities you infer and previous estimates (Tulloch et al. 2014, LaCasce et al. 2013) relate to the influence of isotropic diffusivities on spreading within your framework?

> We have added this statement on lines 58-59. We are unable to delve much further into the differences in reversible verses irreversible stirring, mostly because, as Garrett argued, the rate of stirring and the rate of irreversible mixing will converge over a year or two.

2. Lines 123-125 you state that the reference salinity varies from section to section "to account for the migration of the peak due to gradual along-isopycnal transport". This explanation is unclear to me. Do you mean that the peak slowly erodes due to small-scale isotropic mixing? Could meaningful information about isotropic mixing be hidden in this variation of the peak salinity? Should the reference salinity also vary with density within each section?

> We have reworded those two paragraphs (lines 131-139) which we hope clarifies the matter. Unfortunately the signal isn't sufficiently clear to discern anything robust.

3. It would really help to have Figure 7a at the beginning of the manuscript. The salinity ridge is key to the overall analysis.

> We agree and have included this panel in Figure 1 instead.

4. Why do you choose salinity rather than temperature as your cross-stream variable?

> We now point out on lines 56-58 that they are in fact both equivalent.

5. Does isopycnal mixing in the longitudinal direction matter for your analysis?

> It could. We have added a caveat regarding this to the discussion on lines 303-307.

Specific comments:

Line 39: "a water parcel in the interior"

> Changed

Figure 3: Mention changes in vertical scale between panels in legend.

> Done

Line 149: delete "the" at end of line.

> Deleted

Lines 173: "if it did not mix irreversibly", it would not undergo the decrease in salinity observed along $y_0(x)$.

> Some observations of salinities between the range 34.645 g kg^{-1} and 34.65 g kg^{-1} are observed all the way along the path.

Legend of figure 7: last sentence does not seem to be correct.

> Thank you. Yes, we had that back to front.

Legend of figure 8: "between those latitudes": I think you mean "between those longitudes".

> Thank you again.

Lines 244-246: I don't understand this point: please clarify.

> We have deleted this sentence as ultimately it was not relevant.

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