Review responses to OS preprint egusphere-2025-3112

We thank the reviewer for the time and effort dedicated to evaluating our manuscript. We have carefully addressed all comments and incorporated the requested changes into the revised manuscript. Detailed responses to each comment are provided below, with reviewer comments in **bold** and our replies in regular text.

1. I do not understand why the vertical velocities cannot be estimated using the 2D omega equation. As you know, the observations in this study are the same as those in Siegelman et al. (2020). The authors cannot worry about uncertainties in the estimations.

We agree that vertical velocities can, in principle, be estimated using the two-dimensional Omega equation, as in Siegelman et al. (2020). We have calculated the vertical velocities and included a description of the method and corresponding results in the Supplementary Material.

"Supplementary material: Rossby number and vertical velocity calculations

Rossby number calculation

The Rossby number (Ro) was calculated as the ratio between the relative vorticity (ζ) and the Coriolis parameter (f):

$Ro = \zeta / f,$ *(S1)*

where the relative vorticity was estimated along the glider track as the horizontal gradient of the geostrophic velocity:

$\zeta = \partial ug/\partial x,$ *(S2)*

with ug the geostrophic velocity component perpendicular to the track.

Vertical velocity calculation

Vertical velocities were estimated using the Q-vector version of the Omega equation:

$$N^2 w_{xx} + f^2 w_{zz} = -2(u_x b_x)_x, \quad \text{(S3)}$$

where the subscripts indicate the derivatives, N^2 is the Brunt–Väisälä frequency, w is the vertical velocity, f is the Coriolis parameter, u_x is the gradient of geostrophic velocity along the glider track, and b_x the horizontal buoyancy gradient. The equation was solved using a differential equation solver with boundary conditions w = 0 at the surface and bottom, and ∂w/∂x = 0 at the minimum and maximum distances along the glider's track.

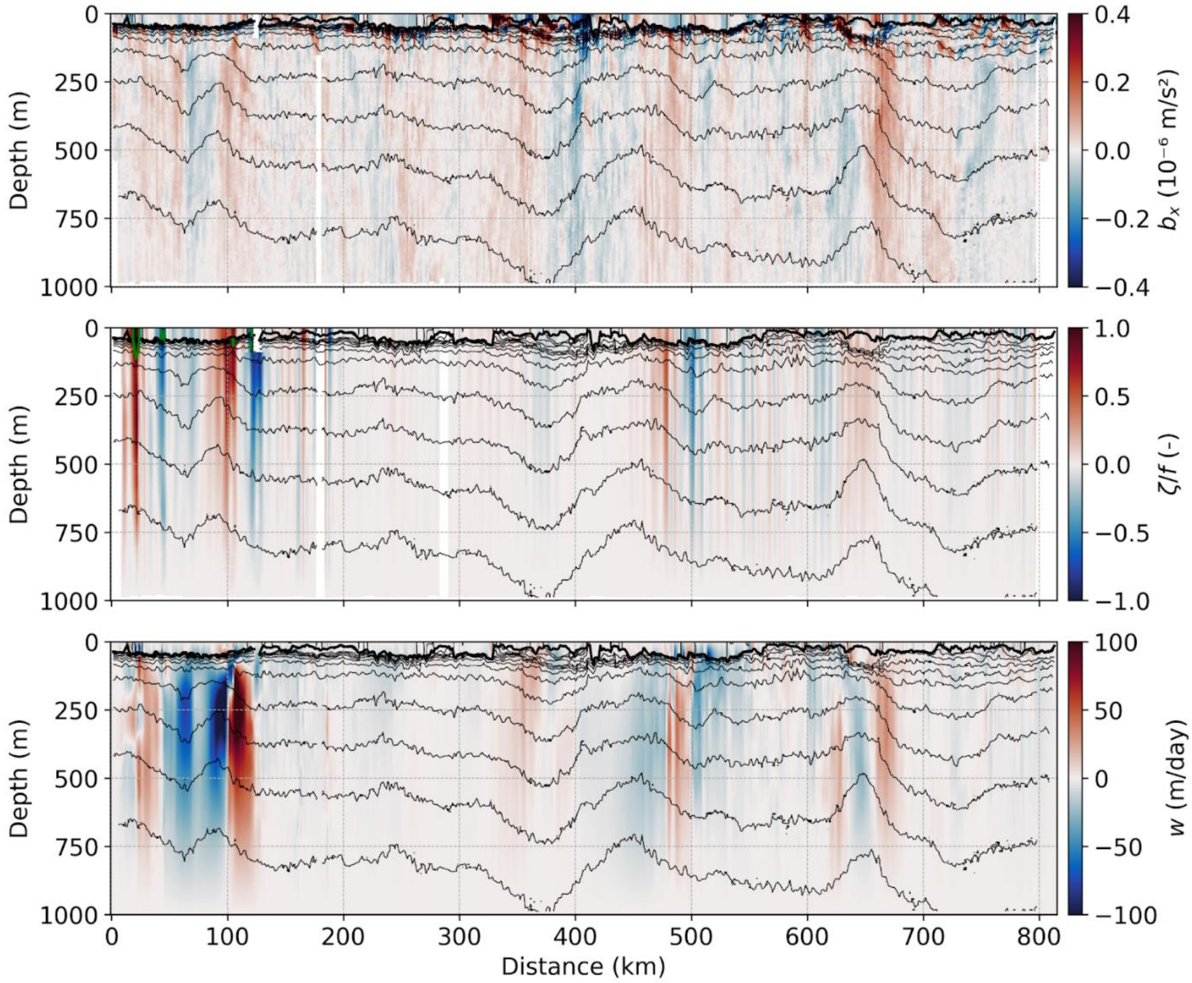

Figure S1. Glider sections showing (a) horizontal buoyancy gradient, (b) normalized relative vorticity, with green contours showing Ro ~ 1, and (c) vertical velocity. Isopycnals are overlaid using thin black contours and the MLD is depicted with the thick black line.

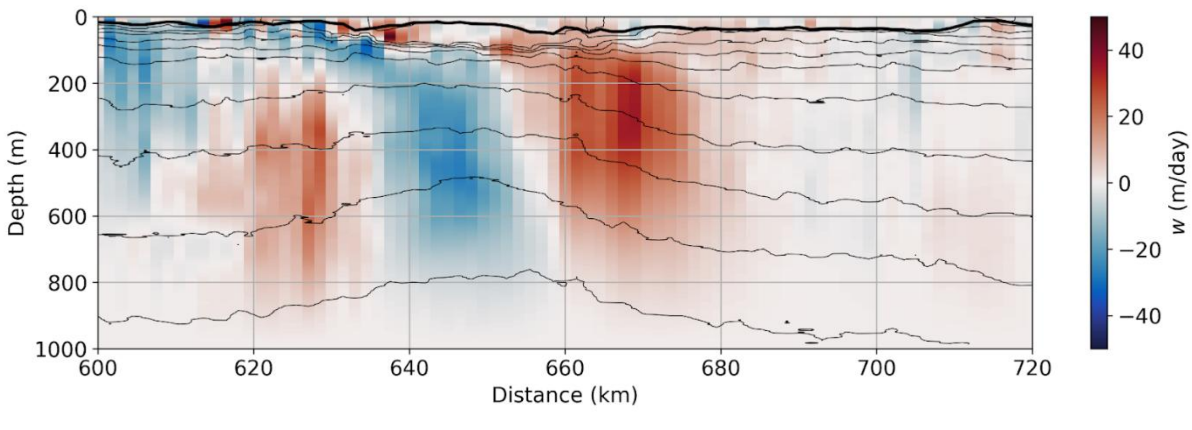

Figure S2. Glider section showing the vertical velocity. Isopycnals are overlaid using thin black contours and the MLD is depicted with the thick black line."

Two additional paragraphs summarizing this analysis and its application to the results are added to the main text at line 255 and line 268.

 # 255 "Vertical velocities were derived from the Omega equation (Siegelman et al., 2020), using boundary conditions following (Leif N and Terrence M, 2010). Methods and results are provided in the Supplementary information. Strong vertical velocities are generally found in regions with elevated horizontal buoyancy gradients and high Rossby numbers, suggesting the role of submesoscale eddies in tracer subduction (Fig. S1). These enhanced vertical velocities often coincide with elevated FSLE and low AOU at depths, however this alignment is not consistent throughout the glider section. The glider observations were often orientated along-front rather than cross-front, limiting the accuracy of derivatives such as $\partial u_g / \partial x$ and $\partial b / \partial x$. Consequently, the calculated vertical velocities are subject to large uncertainties, and the available estimates should be considered indicative rather than quantitative."

#268 "The vertical velocities in Fig. S2, show an alternating pattern indicative of a secondary circulation driven by frontogenesis, with the strongest downwelling roughly aligned with a strong POC subduction event near 650 km in distance along the glider's track (Fig. 4)."

We note, however, that the vertical velocity estimates rely on several assumptions, including quasi-geostrophy and cross-frontal sampling, leading to large uncertainties. In our case, the glider did not always cross the fronts perpendicular, leading to underestimated horizontal gradients and vertical velocities that are not spatially representative. Vertical velocities derived from along-track glider measurements represent only a section of the full three-dimensional flow field, meaning they cannot capture all lateral variations in the vertical velocities derived from the Omega equation. Furthermore, there are different formulations of the Omega equation, with varying boundary conditions, and different methods of computing the horizontal gradient u_x, that produce substantially different results, further highlighting the sensitivity of this method for calculating vertical velocities (Cutolo et al., 2022; Leif & Joyce, 2010; Ruiz et al., 2019; Siegelman et al., 2020).

To simplify the manuscript and to maintain focus on the key processes driving ventilation, we present the vertical velocity analysis in the supplement and instead use tracer-derived subduction events as a qualitative indicator of ventilation in the main text.

2. The authors cannot quantify the difference between diapycnal and isopycnal transport (mixing) in the study. The along-isopycnal transport of the AOU in Fig. 6a is not significant compared with the along-isopycnal transport of the POC in Fig. 6b. I am still confused.

Thank you for your comment. We acknowledge that the along-isopycnal transport of AOU is smaller than that of POC in Fig. 6. This is because surface production of POC that sinks below the pycnocline (80 m depth) is being decomposed, with this active remineralization of sinking POC leading to oxygen consumption, as described in lines #295 to #305 in the main text.

"The cross-isopycnal mixing enhances exchange between the surface boundary layer and the ocean interior between 630 km and 660 km along the glider's path, providing a pathway for particles to move from the surface towards 400 m depth. Elevated AOU values observed below the pycnocline at 80 m depth indicate active remineralization of sinking POC, as microbial decomposition depletes oxygen in subducted waters (Omand et al., 2015). Upward doming isopycnals between 630 - 660 km indicate upwelling, which could potentially bring nutrients to the surface layer, stimulating photosynthesis and biological activity. However, elevated

chlorophyll levels were not observed at the surface, nor was chlorophyll detected at depths below 80 meters. At the same time, POC concentrations remain elevated at depth but are lower in the mixed layer compared to surrounding regions (Fig. 6b), suggesting an enhanced export of POC."

The process of microbial decomposition depletes oxygen in the subducted waters, this results in elevated AOU values at depth where high POC values are found (Omand et al., 2015), and a relatively larger along-isopycnal flux of POC compared to AOU. In other words, POC exhibits strong surface production, with active along-isopycnal transport by subduction and eddy activity, while AOU, as a cumulative respiration signal, is more diffused along isopycnals, showing less significant along-isopycnal transport.

3. Along the glider track (Fig. 7a), can the normalized relative vorticities ζ/f reach 1 (submesoscale motions)? Perhaps the authors could make a crude estimate using the formula ζ=∂v/∂x, where x is the direction along the glider track in Fig. 7a, and v is the velocity perpendicular to the glider track.

We thank the reviewer for the suggestion. We have added the calculation of the Rossby number to the *Supplementary Material* for completeness.The Rossby number was computed as the ratio between the relative vorticity (*ζ*) and the Coriolis parameter (*f*),

$Ro=\zeta/f$,

where the relative vorticity was estimated as the horizontal gradient of the geostrophic velocity along the glider track,

$\zeta=\partial v_g/\partial x$,

While it is possible to estimate normalized relative vorticities along the glider track using geostrophic velocities $\zeta=\partial v_g/\partial x$, we do not fully capture the ageostrophic submesoscale motions. Therefore we would not always expect Ro ~ 1, even in regions where submesoscale vorticities are present. Indeed, we only find Ro > 1 in limited regions (green contour in Fig S2.b), however those are likely a result of amplifications in the derivative of the geostrophic velocity, rather than actual submesoscale dynamics. These estimates should therefore be interpreted qualitatively, providing an indication of regions where submesoscale activity may be enhanced, rather than as precise measurements of local vorticity. Notably, the regions of elevated *Ro* roughly align with areas of stronger vertical velocities, supporting their role as indicators of enhanced subduction. For this reason, we present the Rossby number analysis solely in the Supplementary Material and along with the vertical velocity estimates.

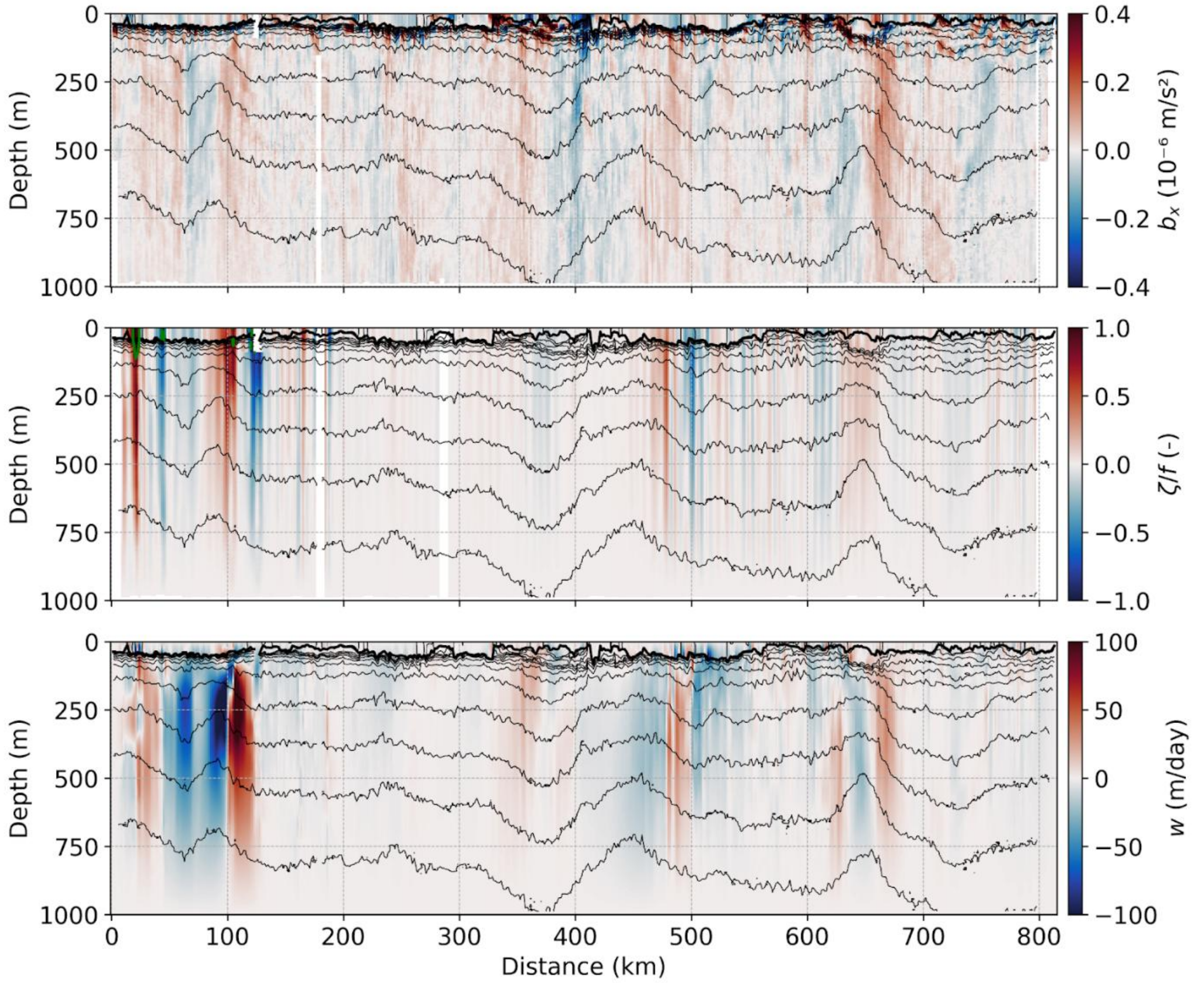

Figure S1. Glider sections showing (a) horizontal buoyancy gradient, (b) normalized relative vorticity, with green contours showing Ro ~ 1, and (c) vertical velocity. Isopycnals are overlaid using thin black contours and the MLD is depicted with the thick black line.

Bibliography:

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