

Salinas-Matus et al. investigated the influence of anticyclonic and cyclonic eddies, periphery and “background” in modulating air-sea CO₂ fluxes. For this, three different regions with differing characteristics in the Southern Ocean were picked, namely the Agulhas Region, the Brazil-Malvinas Confluence Region and the region south of Tasmania. The aim of their study is to investigate the physical and biogeochemical drivers of the air-sea fluxes at daily to decadal timescales.

Mesoscale eddies in the Southern Ocean play a key role in shaping air-sea CO₂ fluxes and carbon uptake. Using a 27-year, global eddy-rich (nominal resolution 8.4-10 km) ocean biogeochemical simulation (ICON-O with HAMOCC), eddies were identified via the Okubo–Weiss parameter and analyzed across their cores, peripheries, and surrounding waters (“background”). Since the eddies were not tracked, the lifetime of the eddies was not considered in their study.

The study highlights that the influence of eddies on CO₂ fluxes is strongly region-dependent, with controlling mechanisms largely consistent with those in background waters. Variations in air-sea CO₂ exchange are primarily driven by changes in the ocean–atmosphere pCO₂ disequilibrium ($\Delta p\text{CO}_2$), itself dominated by dissolved inorganic carbon (DIC) dynamics.

Anticyclonic eddies consistently show the strongest ingassing per unit area, which they attribute to eddy-pumping processes that transfer carbon to deeper layers, thereby enhancing long-term uptake capacity. Importantly, eddy peripheries emerge as a major contributor to regional CO₂ fluxes: while their uptake efficiency is intermediate between eddy cores and background waters, their much larger spatial coverage makes them an integral component of the Southern Ocean carbon budget which requires further analysis.

On decadal timescales, mesoscale eddies emerge as a net carbon sink, contributing roughly 10% of the Southern Ocean’s total carbon uptake if integrated over the area that the eddies cover. On shorter timescales, however, flux anomalies are more variable and reflect contrasting behaviors of cyclones and anticyclones.

We would like to thank the reviewer for the thorough evaluation of our manuscript and for the insightful and constructive comments provided. We appreciate the time and effort invested in reading our work and offering valuable suggestions that have helped us to improve the quality and clarity of the paper. The reviewer’s comments are shown in bold font, and our responses are provided in normal font below.

General comments:

The article reads very smoothly and is easily understandable. The Abstract and Introduction highlight the relevance of the research interest which is also justified by profound literature references. General information about the model and the experiment design which is crucial in order to evaluate the results is given. The presentation of the results is in a logical order, easy to follow with the presented Figures and sufficiently substantiated with observational literature. The summary rounds up the paper in a very nice way, clearing all questions presented in the introduction and pointing out the main findings. Overall, Salinas-Matus et al. is an enjoyably written paper with interesting new insights on the driving mechanisms of eddies on CO₂ fluxes that may need some clarification in some methodological details as well as a more detailed discussion about the overall impact of eddies on the Southern Ocean CO₂ fluxes (see comments below) .

We sincerely appreciate the reviewer's comments regarding the clarity, logical flow, and relevance of our study. We would like to acknowledge that we initially overlooked citing a relevant study. To address this, we have now incorporated a reference to *Smith et al. (2023)* and revised the introduction to include this work, thereby providing better context for our study. The updated paragraph now reads as follows:

“ ... From a modeling perspective, Guo and Timmermans (2024) used an eddy-resolving global biogeochemical simulation to isolate the effect of mesoscale activity. Their findings indicate that mesoscale dynamics account for over 30 % of the total variance of the air-sea CO₂ fluxes in energetic regions and can act either as sources or sinks depending on the region, showing the importance of mesoscale dynamics from a global perspective. Smith et al. (2023) analyzed the heat and carbon characteristics of mesoscale eddies in the South-East Atlantic Ocean using a regional model configuration, revealing distinct thermodynamic and biogeochemical signatures between cyclonic and anticyclonic eddies. However, no modeling study to date has investigated the contrasting impacts of cyclonic and anticyclonic eddies on air-sea CO₂ fluxes across the entire Southern Ocean, while also considering regional differences.”

Specific comments:

- **L115ff: Is there literature based on which the threshold values were defined? (Common definition e.g. $0.2 \times \text{stdev(OW)}$ as Schütte et al. 2016)**

We have incorporated some references and clarified the literature basis for the definition of the threshold. In the revised manuscript, we have added the following explanation:

“...The "background" regime is defined using a threshold equal to 0.3 of the temporal mean of the spatial standard deviation of the OW (σ_{OW}) corresponding to $\pm 0.5 \times 10^{-10} \text{ s}^{-2}$, encompassing all OW values within this range. The most common approach in the literature is to define the threshold as $0.2\sigma_{\text{OW}}$ (Schütte et al., 2016a; Vu et al., 2018), with some studies adopting more relaxed values around $0.1\sigma_{\text{OW}}$ (Beech et al., 2025). However, in this study we chose to apply a slightly stricter criterion in order to isolate more robust and well-defined eddy and mesoscale structures, while still retaining the main mesoscale (see supplementary figure S1).”

Okubo-Weiss parameter [s^{-2}]
2014-06-03

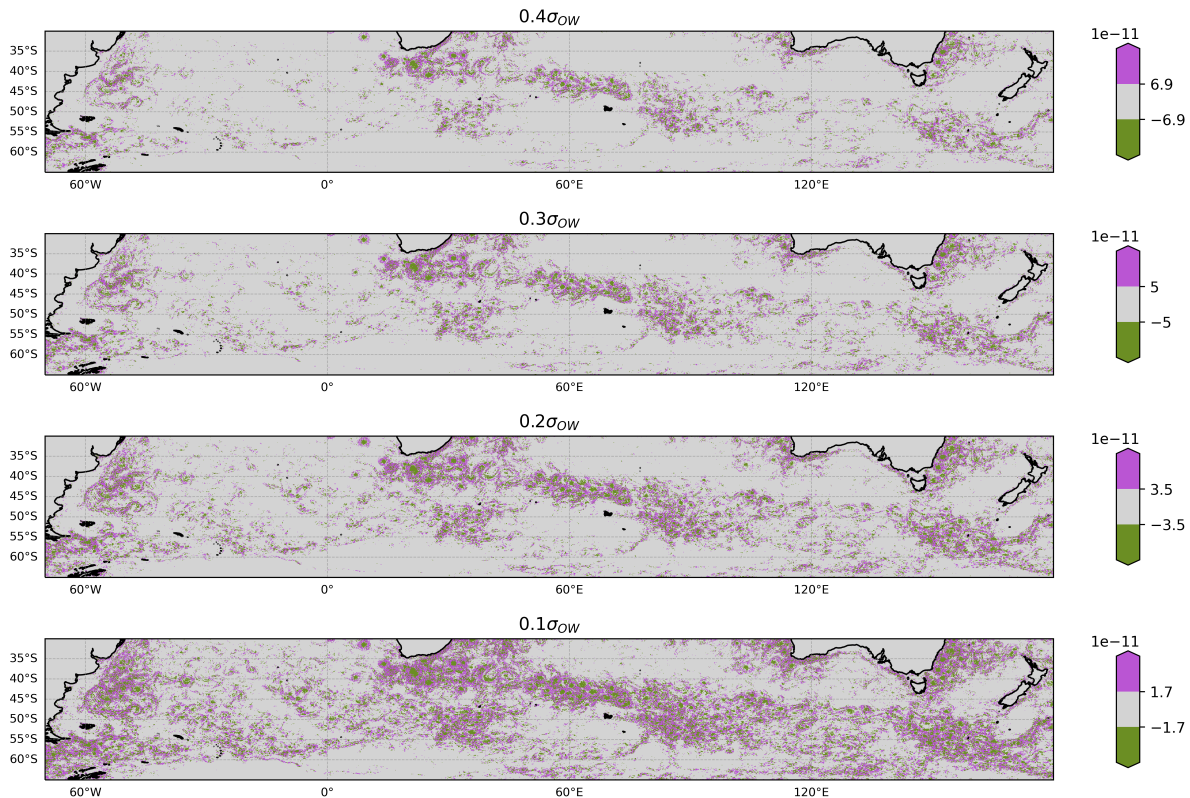


Figure S1. Sensitivity of mesoscale structure detection to different Okubo–Weiss (OW) threshold values. The panels show four threshold selections used to define mesoscale regimes. The threshold of $0.3\sigma_{OW}$ was used in this study, as it provides a balance between capturing well-defined eddy structures and preserving the main mesoscale variability.

- **Fig.2.: Some eddies look very deformed and unusually large → did the authors check for several local maxima/minima?**

We did not explicitly check for multiple local maxima/minima within each identified eddy because the Okubo–Weiss parameter defines eddy boundaries based on the balance between relative vorticity and strain, rather than on local extrema. With this methodology, you're right, in some cases, especially where two cyclonic or two anticyclonic structures are located very close to each other, the methodology may capture them as a single, elongated contour. Additionally, eddies near strong shear zones can also appear deformed due to the local flow field. However, in our composite analyses, the results are based on the total area encompassed by the detected eddy structures. Therefore, merging two nearby eddies into a single contour would not affect the aggregated statistics or the fluxes reported. We acknowledge, nevertheless, that this represents a methodological limitation inherent to the Okubo–Weiss–based eddy detection approach.

- **L126: could you elaborate on how you preprocess the data prior carrying out the Fourier analysis? The eddies are at different locations and several for each timestep. Is the average of “eddy composites” (defined as OW below the chosen threshold) taken for each time step (daily) and then the Fourier analysis on the such obtained time series applied? If this is the case, maybe a different term than “composite” should be used or at least defined.**

Thank you for the opportunity to clarify the methodology. The Fourier analysis was not applied to the eddy composites. Instead, the spectral decomposition was performed first

on the full spatial variable fields. Specifically, we applied a band-pass Fourier filtering to the complete dataset, obtaining five filtered fields corresponding to the defined frequency bands. Subsequently, eddy composites were computed from each of these filtered fields, using the same thresholding procedure described earlier. This sequence is methodologically appropriate, as it preserves the full spatial and temporal coherence prior to compositing. In the revised manuscript, we have added the following:

"The net CO₂ flux is influenced by processes operating across different timescales (Gu et al., 2023). To determine the frequency range at which mesoscale eddies have the greatest impact on CO₂ flux, we first applied a Fourier analysis to the full spatial variable fields to decompose it into distinct frequency bands. This approach ensures that the spatial and temporal coherence of the field is preserved before the identification of eddies. The analysis yielded five filtered fields corresponding to (1) intra-annual variations above 16 months and up to 27 years (M16), (2) annual variations between 8 and 16 months (M8-M16), (3) intra-annual variations between 4 and 8 months (M4-M8), (4) intra-annual variations between 1 and 4 months (M1-M4), and (5) submonthly variations shorter than 1 month, down to daily changes (M1). Subsequently, eddy composites were computed for each filtered field using the criterion described above."

- **E.g., Fig. 2: How are anomalies defined? Also, tell how is the sign of the flux defined wrt ingassing/outgassing?**

The anomalies were calculated by subtracting the long-term mean from each variable at every grid point, i.e., $\text{anomaly} = \text{variable} - \text{long-term mean}(\text{variable})$.

The air-sea CO₂ flux is positive for outgassing and negative for uptake; therefore a positive flux anomaly corresponds to an increase in outgassing relative to the mean while a negative anomaly corresponds to an increase in uptake relative to the mean. In the revised manuscript, we have added the following in the figure description:

"Figure 2. Snapshot of the identified mesoscale dynamics and tracer or tracer flux anomalies in the Agulhas Retroflection region (defined in Fig. 1b) on 03 June 2014. (a) Okubo-Weiss parameter, delineating three flow regimes: vorticity-dominated (green), deformation-dominated (violet), and "background" (grey). (b) Sea Surface Temperature (SST) anomaly, (c) air-sea CO₂ flux anomaly, and (d) Surface DIC anomaly. Anomalies represent deviations from the climatological state, computed as the difference between the instantaneous value and the long-term mean at each grid point. The air-sea CO₂ flux is defined as positive for outgassing (flux from the ocean to the atmosphere) and negative for uptake (flux from the atmosphere to the ocean). Therefore, a positive flux anomaly indicates increased outgassing relative to the mean, while a negative anomaly indicates increased uptake relative to the mean. In all panels, contours outline anticyclonic and cyclonic eddies."

- **Eddy contribution to the Southern Ocean carbon sink: the authors provide % numbers for the contribution of eddies given as flux integrated over the "eddy" (= OW below threshold) area. How much bigger is this flux than if one assumed "background flux conditions" over the same area (in %)?**

We agree with the reviewer that reporting the anomalous contribution is indeed informative. Accordingly, we have added a new table to present the anomalous eddy contribution, expressed as the percentage difference relative to the flux that would be expected under background conditions over the same area. As a result, the overall

percentage contribution of eddies and periphery to the total Southern Ocean carbon sink

Table 3. Same as table 2, but the anomalous contributions relative to the background associated with mesoscale regime flows. In other words, this table quantifies how much additional (or reduced, when negative) carbon uptake occurs due to mesoscale activity, representing the difference in carbon uptake that would be observed if only background conditions were considered.

Region	Carbon uptake [Pg C yr^{-1}]			
	Mesoscale flow regimes	Disentangling Mesoscale flow regimes		
		Anticyclones	Cyclones	Periphery
Agulhas Retroflection	0.01150 ± 0.009 (10$\pm$0.08%)	0.00428 ± 0.00030 (37 $\pm$ 2%)	0.00056 ± 0.00134 (5 $\pm$ 12%)	0.00614 ± 0.00507 (53 $\pm$ 44%)
Brazil-Malvinas Confluence	0.00348 ± 0.006 (4$\pm$0.06%)	0.00091 ± 0.00138 (26 $\pm$ 39%)	0.00017 ± 0.00080 (5 $\pm$ 23%)	0.00240 ± 0.00388 (69 $\pm$ 111%)
South Tasmania	-0.00298 ± 0.002 (-17$\pm$11%)	-0.000591 ± 0.00053 (-20 $\pm$ 18%)	-0.00074 ± 0.00061 (-25 $\pm$ 20%)	-0.00165 ± 0.00110 (-55 $\pm$ 36%)
Entire SO	0.00946 ± 0.027 (1$\pm$2.5%)	0.00313 ± 0.00531 (33 $\pm$ 56%)	-0.00136 ± 0.00414 (-14 $\pm$ 43%)	0.00769 ± 0.0180 (81 $\pm$ 190%)

decreases substantially. Here the new table in the revised manuscript: Nevertheless, we also kept the original table, since the two perspectives provide complementary information. While the anomalous contribution helps to quantify the relative enhancement or reduction induced by mesoscale activity, the total flux over the eddy-covered area remains relevant for assessing the integrated role of eddies. Moreover, it is important to note that the “what-if” scenario, assuming background flux conditions in the absence of eddies, represents a purely theoretical construct. In reality, the background state itself would likely be modified by the absence of mesoscale structures, as eddies strongly influence the mean circulation, stratification, and nutrient distributions. Therefore, the anomalous flux values should be interpreted as an idealized sensitivity test rather than a physically realizable alternative state.

- **Along similar lines, the per square meter fluxes (Fig. 4c), how different are they compared to the background fluxes (in %)?**

We have addressed the reviewer’s point. In the revised version of Figure 4c, we have added the mean background CO_2 flux value as a reference line, which allows direct visual comparison of how much stronger or weaker the eddy-associated fluxes are relative to background conditions.

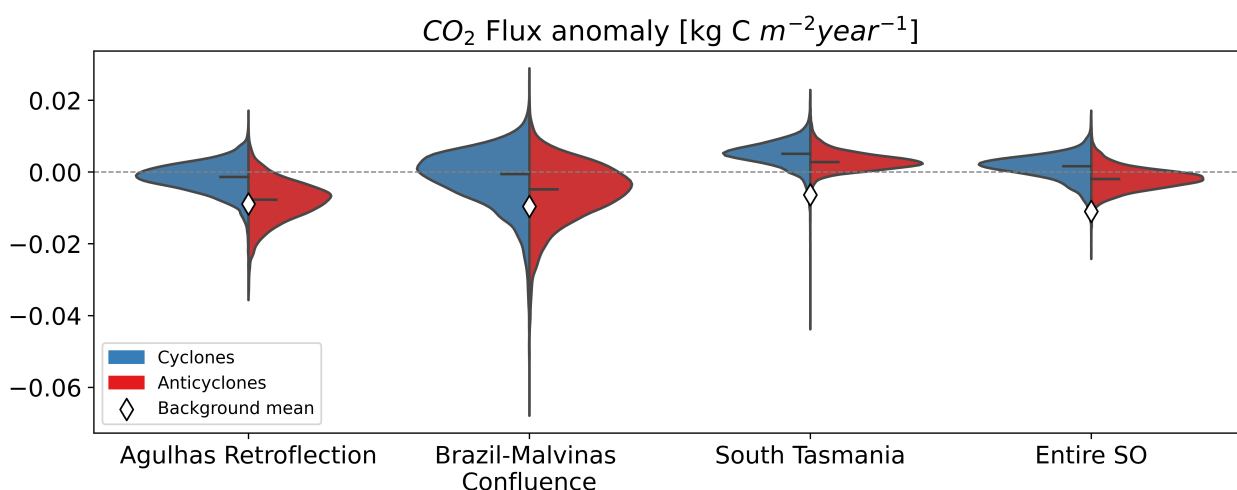


Figure 4. ... (c) Composite anomalies of total CO₂ flux relative to the “background” for anticyclonic and cyclonic eddies, including the mean background value...

- **I am asking as such a statement (of 10-20% contribution by eddies to the Southern Ocean carbon sink) makes the eddy contribution sound very important. The anomalous contribution (i.e., “what if” the area covered by eddies was not covered by eddies) is more interesting. There is a lot of compensation between anticyclones, cyclones, and perhaps seasonality, as the authors point out themselves. E.g., they cite Song et al., 2016, in the introduction (polarity dependence of fluxes), but do not get back to it in the discussion. How do the authors’ findings compare?**

The first part of this question regarding the anomalous contribution of eddies has already been addressed in above responses. The partial compensation between positive and negative CO₂ flux anomalies is now explicitly discussed in both the Results and mentioned in the Conclusions sections:

“Despite regional heterogeneity, anticyclonic eddies take up more or outgas less carbon than the background, while cyclonic eddies exhibit the opposite pattern (Fig. 4c). This is consistent with studies using observation-based datasets (Keppler et al., 2024; Li et al., 2025). This contrasting behavior may be attributed to eddy-pumping. In anticyclonic eddies, this mechanism facilitates the transfer of carbon to deeper ocean layers, enhancing the ocean’s capacity for carbon uptake over time. In contrast, cyclonic eddies may act to reduce carbon uptake by limiting this downward transport. While this opposition can lead to a partial compensation between positive and negative flux anomalies over the entire Southern Ocean, such compensation is not observed at the regional scale (Table 3).”

Regarding seasonality, we agree that interesting patterns likely exist. However, in this study we chose not to focus on seasonal variations, as this is currently the subject of ongoing work in which we aim to provide a detailed analysis of the mechanisms driving seasonal CO₂ flux changes associated with mesoscale eddies.

- **Given the above two points, I do not feel that comfortable with a strong statement that eddies are very important for the Southern Ocean carbon sink (because of the local air-sea flux anomalies they cause, which is the focus of the paper); are the authors? I would be more comfortable if they discussed the above aspects in their manuscript more clearly/transparently.**

We agree with the reviewer that the previous wording in the conclusion section may have overstated the overall importance of eddies in the Southern Ocean carbon sink. In the revised manuscript, the percentages have been updated to reflect the anomalous contributions of eddies and periphery, which are notably smaller than the originally reported total fluxes. Accordingly, the concluding statement has been rephrased to show the role of mesoscale eddies as modulators of CO₂ fluxes rather than as dominant contributors, which could have been implied by the previous version.

- **L86 or L252ff: mention somewhere, that, given that this is an ocean-only model (no coupling to the atmosphere) there is no eddy feedback on winds, i.e., a bit of the effect eddies might have on air-sea CO₂ fluxes is missing?**

The Reviewer is correct. Since this is an ocean-only model, eddy-induced feedbacks on surface winds are not represented. We have added a sentence in the Experiment Design section to clarify this:

“...As this is an ocean-only configuration without coupling to the atmosphere, eddy-induced feedbacks on surface winds are not represented.”

- **L103: the authors discuss the drift of the coarser resolution model, can they also briefly comment on the (likely) drift of the 10 km model (which was run for a much shorter time period)**

The drift mentioned refers to the 10 km high-resolution model (control simulation). We have clarified this in the revised manuscript:

“... Furthermore, all model drifts in the 10 km resolution control run remain sufficiently small in accordance with the CMIP6 protocol (Jones et al., 2016).”

- **L151: Can the authors elaborate on how/why they expect the eddy intensity to relate to air-sea CO₂ fluxes?**

We added this to the sentence to be clear why eddy intensity could be related to the air-sea CO₂ fluxes:

“... For instance, the eddy intensity differs between regions and is expected to modulate air-sea CO₂ fluxes, as stronger eddies enhance both lateral and vertical transport of water properties, including temperature and DIC.”

- **L189 “mesoscale flow regimes (anticyclones, cyclones, and periphery) have a greater capacity for carbon uptake compared to the "background" (Fig. 4a)”: not true for all regions, and not for all of the SO?**

The Reviewer is right, this statement does not apply uniformly across all regions of the Southern Ocean. We have modified the text to reflect that mesoscale regimes generally show higher efficiency than the background, but with regional exceptions. In the revised manuscript, we have added:

“The integrated CO₂ flux over the 27 analyzed years indicates that, in most regions, mesoscale flow regimes (anticyclones, cyclones, and periphery) exhibit a greater efficiency in carbon uptake compared to the background, although this pattern is not consistent across the entire Southern Ocean (Fig. 4a)”

- **L192 “Among these regimes, anticyclonic eddies show an enhanced ability to take up CO₂ (Fig. 4a).”: see comment above, how large is the enhanced ability, in absolute numbers and relative to the background flux?**

We agree with the reviewer that specifying the relative magnitude of the enhanced CO₂ uptake provides valuable context, and we have already modified this point as mentioned in the previous responses. In this case, the comparison can be directly inferred from Figure 4a, where the bars representing each flow regime are shown side by side. For the Agulhas Retroflexion region, which this sentence refers to, the CO₂ uptake in anticyclonic eddies is approximately twice that of the background flux. This relative difference can be readily appreciated in the figure, as the bar corresponding to anticyclones is roughly double the height of that for the background.

- **L197 “and the stronger vertical gradient in those two regions (Fig. 3b).”: do one clearly see this from the Figure?**

Yes, the stronger vertical gradients in the Brazil–Malvinas Confluence and Agulhas regions can be inferred from Fig. 3b. Comparing for example the surface values with those at 300 m depth, the difference is clearly larger in these two regions than in the Tasmania region,

indicating stronger vertical gradients. We added in the revised version:

“... and the stronger vertical gradient in those two regions, as indicated by the temperature and DIC profiles (Fig. 3b)”

- **L202 “a pattern influenced by sporadic but intense carbon uptake events (Fig. 3).”: can you elaborate on how one can conclude this from Fig. 3?**

It is based on the distribution shown in the violin plots in Fig. 3c for the South of Tasmania region. The mean flux is positive (outgassing) or close to zero in the background regime, but the distributions show a wide tail toward negative values (strong carbon uptake). When the fluxes are integrated over time, these less frequent but intense uptake events dominate, resulting in a net negative (into the ocean) flux.

- **L220 “it is worth mentioning that both anticyclonic and cyclonic eddies do exhibit episodes of CO₂ outgassing (Fig. 3c).”: can we see this in Fig. 3c? If so, how, can you elaborate?**

Yes, this can be seen in the distribution of CO₂ fluxes shown in the violin plots in Fig. 3c for the Brazil-Malvinas Confluence region. While the mean and most eddy fluxes are negative (uptake), the distributions also include some positive values, indicating episodes of outgassing. Similar outgassing events are also present in the background and periphery regimes.

- **L292ff importance of eddy type: mention that there is compensation of negative and positive flux anomalies?**

Yes (that is a very good point), it became clearer with your suggestion to report the anomalous contributions. We have now added the following clarification to the paragraph you mentioned:

“... Anticyclones typically enhance carbon uptake or suppress outgassing, whereas cyclones more often reduce uptake or promote outgassing. This opposing behavior leads to a partial compensation between positive and negative flux anomalies, particularly at the basin scale, where enhanced CO₂ uptake by anticyclonic eddies tends to be offset by reduced uptake within cyclonic structures. Such compensation dampens the net short-term contribution of mesoscale activity to the overall Southern Ocean carbon sink, despite strong local contrasts.”

- **L295 “despite the smaller region they occupy”: could you provide the number here (area coverage in %, you should have the numbers in your analysis), see comment above, to get a sense of to which extent the eddies enhance the flux.**

Although the area covered by the mesoscale regimes is shown in Table 1, we did not include the values for the total Southern Ocean. Thank you for noting this omission. In the revised version, we have added the total area coverage (%) for the entire Southern Ocean, and this information is now explicitly mentioned in the Summary.

- **Given that the simulation is a historical simulation (i.e., natural fluxes, with the anthropogenic perturbation of increasing atmospheric CO₂ on top): curiosity: do you have a hypothesis if the flux change (reduced outgassing) is more due to enhanced anthropogenic carbon uptake, or suppression of outgassing of carbon rich subsurface waters? If not, could you discuss these aspects in the discussion?**

It is indeed a very insightful question. However, our analysis focused primarily on characterizing the mesoscale influence on CO₂ fluxes rather than on assessing long-term changes due to the anthropogenic signal. Therefore, we are not able to directly address this aspect within the scope of the present study.

Technical comments:

- **L27. the role of cyclonic and anticyclonic eddies** Done
- **L93: mention specifically that it is eddy-rich** Done
- **L236f: repetitive with lines 208-210** Corrected
- **larger Figure labels, some not readable in when printed** We increased the font size
- **add sign convention to Figure description: negative values outgassing, positive ingassing** Done
- **Fig.2 b) take care of colorblind-friendlier choice of colormap and add whether AE or CE are blue or red** Done
- **AE are presented in blue colour, CE in red colours. This is a bit confusing, the other way around would be way more intuitively** Done
- **Fig. 1a: standard deviation vorticity** Corrected
- **Fig. 4f: Frequency** Corrected
- **L323: I suggest to add units to the variables.** Units were added.
- **L338f: pCO₂ocean** Corrected

Thank you, all technical comments have been addressed in the revised version of the manuscript.

References

Schütte, F., Brandt, P., and Karstensen, J.: Occurrence and characteristics of mesoscale eddies in the tropical northeastern Atlantic Ocean, Ocean Sci., 12, 663–685, <https://doi.org/10.5194/os-12-663-2016>, 2016.

References

Smith, T. G., Nicholson, S. A., Engelbrecht, F. A., Chang, N., Mongwe, N. P., and Monteiro, P. M.: The Heat and Carbon Characteristics of Modeled Mesoscale Eddies in the South-East Atlantic Ocean, Journal of Geophysical Research: Oceans, 128, <https://doi.org/10.1029/2023JC020337>, 2023.