Anonymous Referee #2, 01 Nov 2024

Review of Ortiz et al. "Evolution of biogeochemical Properties Inside Poleward Undercurrent Eddies in the Southeast Pacific Ocean"
The paper by Ortiz et al. aims to characterize the biogeochemical evolution of poleward undercurrent eddies (PUDDIES) generated in the Southeast Pacific OMZ. To do so, the authors use 9 years (2000-2008) of output of a physical-biogeochemical coupled model (ROMS+BioEBUS) run on mesoscale resolving grid (1/12 degree resolution ~8km) and saved as 3-day means. The authors distinguish between the evolution of PUDDIES characterized by initial hypoxic conditions and those with initial suboxic conditions, contrast the evolution of water mass properties inside and outside of the eddies and focus on a few case studies to determine changes in the eddy properties along their trajectories. The authors use Reynolds decomposition and eddy tracking methods to study the impact of the PUDDIES on the oxygen and nutrient fields.

General comment
The topic and idea of the paper are interesting, but I'm not convinced by many of the choices made by the authors and I find the paper difficult to read and its results difficult to interpret. I have decided not to go into the details of the results for this reason, but to comment on the methods at this stage. I think this manuscript and its related research needs major revisions before being published. I'll be happy to provide a more detailed review on the results once the methods are better justified.

We thank the reviewer for his/her constructive feedback. Below, we provide point-by-point responses to each comment.

Many of the choices in the methods need to be clarified. The domains in which the region of study is split (8 domains) seem odd and not well justified in the methods (especially the latitudinal boundary, which seems arbitrary). Some of these domains are very narrow and coastal (H) where the authors state the algorithm has trouble identifying eddies (lines 299-307), some mix coastal and offshore zones (G,F), some are very wide (E). All have irregular shape and mix zones at a variety distances from the coast (where eddies are generated). This makes for a statistical and geographical nightmare in understanding and interpreting the data. This is a major problem for me, because all the results are presented in terms of averages across these oddly shaped and dishomogeneous regions.

Following the reviewer's recommendation we have clarified the method for selecting the domains. It should be first recalled that selected regions have an irregular shape because they depend on mean conditions that somehow depend on the horizontal distribution of the oxygen minimum zone delimited by the dominance of ESSW. That said, for clarity, we have reduced the number of biogeochemical zones or study areas and the method has been expanded (see section 2.2). The new figure 1a displays the limits of the new domains and we present in the new figure 2 the biogeochemical contribution of the different water masses in each area. The new areas were defined to encompass a range of similar biogeochemical characteristics. Given the importance of the ESSW, as it is the water mass primarily enclosed in the Puddies, the isopycnal surface associated with the ESSW and the OMZ core (isopycnal layer 26.6 kg m⁻³) was used as a reference, similar to the approach used by Pizarro-Koch et al. (2019) for this model.

The authors interpolate 37 vertical layers of model output to a regular grid of 160 vertical layers generating a lot of “fake data” for their analysis.

Section 2.2 and Figure S1 clarify the number of sigma levels contained in the first 1000 m. The vertical resolution of 5 meters to infer tracers on a regular vertical grid through linear interpolation is commonly used (e.g. Illig et al. (2018)), but it was checked that the results are little sensitive to the interpolation method (spline versus linear) or number of z-levels retained (linear interpolation each 5 m, 10 m and 20 m to 160 z-levels was tested). For consistency with previous studies, we used a vertical resolution of 5 meters.

SENSITIVITY ANALYSIS USING VERTICAL INTERPOLATION WITH DZ=5M, 10M, AND 20M

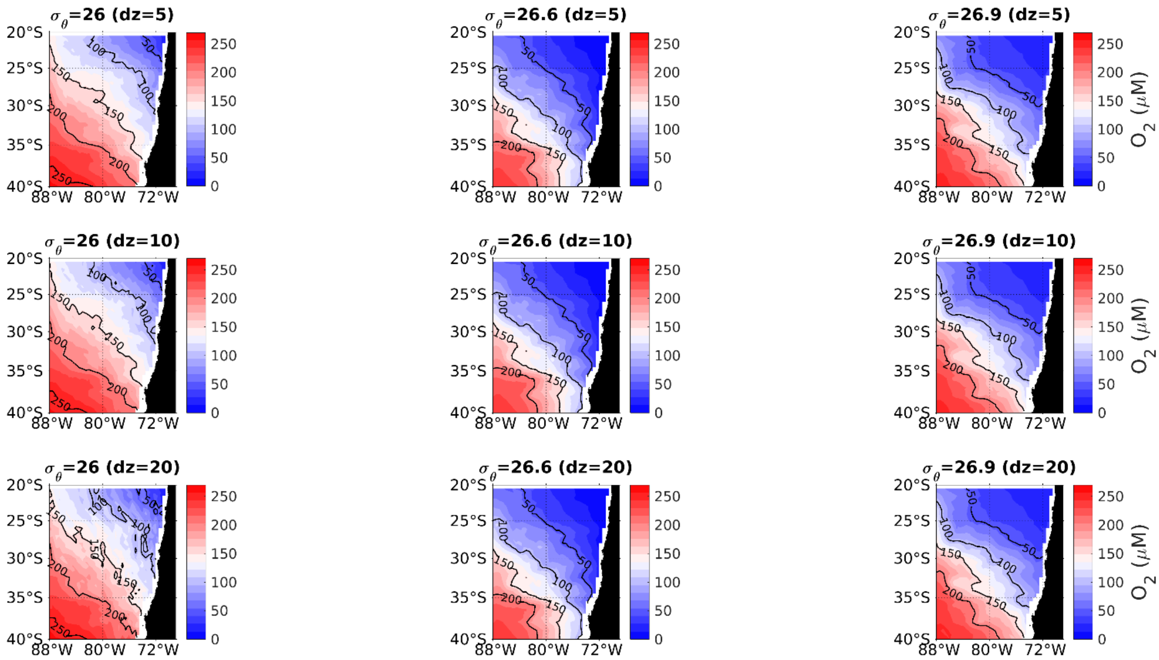

Figure 1. Comparison of isopycnals 26, 26.6, and 26.9 kg/m³ using different vertical interpolations (dz: 5 m, 10 m, and 20 m) for the modeled average oxygen (9 years). The contours (black lines) represent oxygen concentrations of 50, 100, 150, 200, and 250 μM.

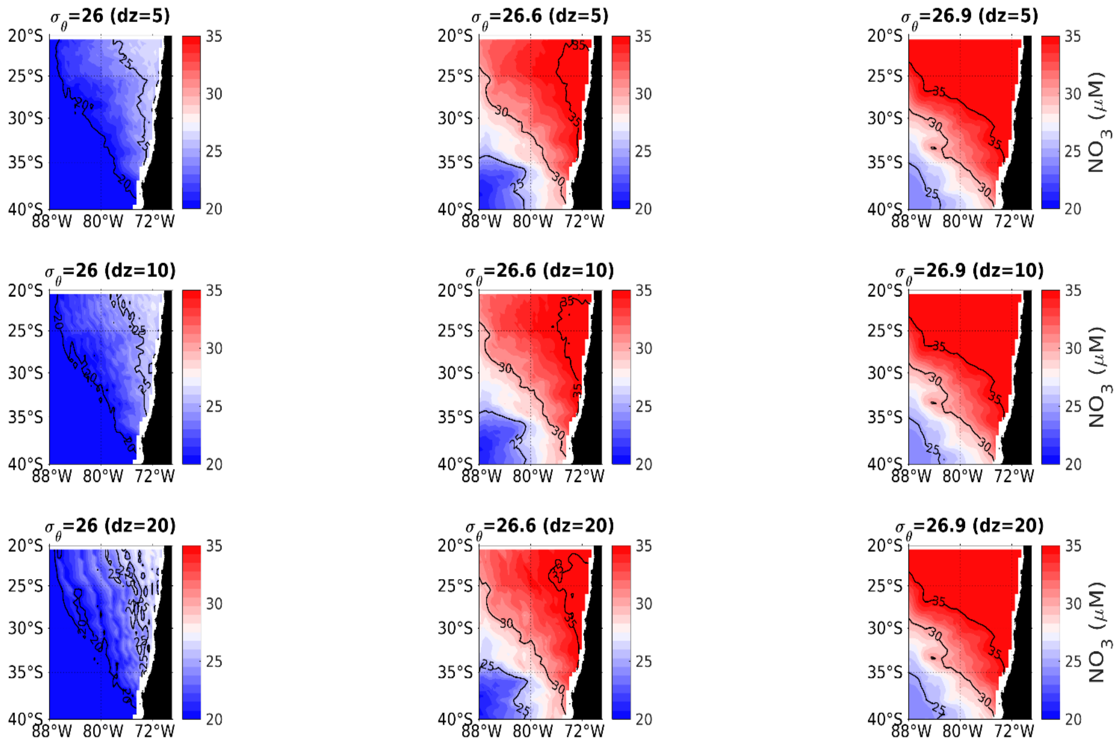

Figure 2. Comparison of isopycnals 26, 26.6, and 26.9 kg/m³ using different vertical interpolations (dz: 5 m, 10 m, and 20 m) for the modeled average nitrate (9 years). The contours (black lines) represent nitrate concentrations of 25, 30, 35 µM.

Vertical interpolation with dz=5 m allows us to reduce the variability of the isopycnals surface, particularly for the isopycnal S_{upper}=26.0 kg/m³. Since this study focuses on analyzing mesoscale processes, it is important for the identification and analysis of 3D eddies to minimize smaller-scale variability, such as that observed with coarser interpolations (dz = 10 m and dz = 20 m).

The choice of “reference average” for the Reynolds decomposition is unclear.

The sentence was modified in the text for clarity: “where $< NO_3 >_{9-year}(x, y, z)$ is the “mean state” of NO_3^- calculated as an overall mean across 9 years simulated between the period 2000-2008. Fluctuations of this “mean state” considered the seasonal variability and denote as $NO_3'(x, y, z, t)$.”

The authors say that they use a circular eddy mask to extract the eddy properties, when the Faghmous algorithm provides the actual shape of the eddy contous, which provides a more accurate definition of the eddy core properties. A lot of these choices need to be better justified and a few probably should be revised.

A sensitivity analysis was conducted to determine the optimal parameterization of the Puddies in 3D, comparing a regular circular edge to the irregular edge generated by the Faghmous algorithm (Figure S3). The results indicated that the irregular edge provided by the Faghmous algorithm was more effective. Consequently, we recalculated the sections involving 3D Puddies using this criterion. The methodology is detailed in Section 2.6.2.

The authors also use 9 years of model output at 3-day mean resolution, but then only use two eddy tracks (among likely tens or maybe hundreds found by the employed algorithm) as "case studies". There is no proof that the two tracks are representative of the eddy populations. Why not building an average of the eddies in time along their tracks so that eddies of the same age are averaged together? This was successfully done in previous studies (https://doi.org/10.5194/os-15-1111-2019) and it would allow to use a statistical approach that really takes advantage of the large amount of information provided by the model data. The model data available for the study is so abundant that the current approach seems reductive.

Following the reviewer's recommendation, we conducted a more robust analysis by considering all Puddies identified at each time step (t = 3 days) over a 9-year period across the three selected latitudes. This approach enhances the statistical significance of the results, providing deeper insights into how the internal properties of the eddies evolve as they move away from the coast and the extent to which these perturbations influence the mean state. Additionally, this analysis allowed for a clearer characterization of the differences between the selected latitudes. The methodology is detailed in Section 2.6.2, and the results are presented in Section 3.4 (Subsurface water band changes caused by Puddies). Figures 8–11 and Table 4 summarize the findings.

I have brought up many of these concerns also in the detailed comments.
The paper is also difficult to read due to the Methods section being poorly organised and missing important detail and the figures not having appropriate labelling, so the reader has to note what the figures represent by hand (impossible to do if reading the paper online). The Supplement is currently unreadable, see more comment below.

We appreciate your detailed comments and constructive feedback. We understand your concerns regarding the organization of the Methods section and the lack of clarity in figure labeling, as well as the readability issues with the Supplement.

To address these points:

Methods Section: We have restructured the Methods section to improve its clarity and organization. Additional details have been included to ensure that the methodology is thoroughly explained and easier to follow.

Figures: All figures have been revised to include appropriate and detailed labeling, making them fully self-contained and accessible for readers. Figure captions have also been expanded to ensure clarity.

Supplementary Material: We have reviewed and reformatted the Supplementary Material to ensure it is clear and readable. Specific changes include [briefly mention any significant changes made, e.g., reorganizing content, adding labels, or improving formatting].

We hope these revisions adequately address your concerns and improve the overall readability and quality of the manuscript. We are grateful for your valuable input, which has been instrumental in refining the paper.

Detailed comments

1. Line 49: “Under these conditions, heterotrophic metabolic processes prevail” - what conditions? Prevalence of heterotrophic processes is mostly due to being at depth and hence below the sun-lit layer.

For more clarity, the lines 49-52 were modify as follows: Under these conditions of low oxygen in the subsurface (i.e. O_2 falls below 20 μM), heterotrophic metabolic processes are important, dominated by activity of bacteria and archaea, resulting in significant shifts in biogeochemical cycles (Lam et al., 2009; Paulmier & Ruiz-Pino, 2009; Wright et al., 2012).

2. Line 60: “where anoxic conditions can even be observed” - this piece of sentence need revising, it doesn’t read correctly in English

The text was changed to: “where even anoxic conditions can be observed”

3. Line 67: “through the global warming” - please remove “the”
Done

4. Line 72: “turbulent dynamics” - I’d be careful here using the word “turbulent” since turbulence is a very broad term that in physical oceanography describes a large variety of scales of physical processes down to sub-meter scales. I would rather use “meso- and submesoscale” instead, which is more in line with the topic of the paper. Some processes such as “turbulent mixing” are most likely parameterised in models, but this isn’t what the authors refer to.

Thank you for this comment. The text was changed to ”sub to mesoscale dynamics”

5. Lines 72-55: I would add some support to the claim of the importance of mesoscales in the OMZ representation in models, currently unsupported in the paper. Literature suggestion: https://doi.org/10.1029/2022MS003158

Following the reviewer’s recommendations, we have added relevant references to highlight the importance of sub to mesoscale dynamics in accurately representing OMZs in models. The added text is as follows: “There is evidence highlighting the importance of mesoscale dynamics, such as mesoscale eddies and zonal jets, in expanding and ventilating oceanic zones with oxygen deficits. To better understand these mechanisms in the ocean, it has been necessary to implement models that resolve mesoscale processes, improving the representation and variability of OMZs (Bettencourt et al., 2015; Auger et al., 2021; Calil, 2023)".

6. Lines 117-118: Unclear sentence

The sentence was modified as follows: "We analyze the physical and biogeochemical factors influencing the variability in the lifespan of elements trapped within the Puddies, with a particular focus on those related to the nitrogen cycle, as they travel from the OMZ to better-ventilated oceanic waters."

7. Line 196: What about zooplankton respiration?

Zooplankton respiration was considered together with the excretion in this parametrization.

8. Line 203: The authors interpolate the model output to a regular grid of 5m of vertical spacing between 0-800 m depth. This means interpolating to 160 vertical levels! The model output has only 37 vertical levels, of which 13 are found "in the deep ocean", hence possibly only 24 model grid levels are in the range of interest. Why generating so much artificial data?

As previously mentioned, this approach is commonly used with model outputs on a sigma-level grid to determine the specific depths of isopycnals or isotherms. Estimating the error associated with the choice of the number of z-layers or interpolation methods is challenging, as it would require a thorough investigation into the model's sensitivity to vertical resolution. Such an analysis, however, falls beyond the scope of the present study.

9. Line 204: "In the deep ocean (~4000 m depth) typically 13 of the 37 vertical levels fall within this depth range." - You need to indicate the specific depth range, ~4000 m is not a range.

Of the 37 vertical levels, 28 are distributed within the upper ~1000 m of the water column, while the remaining 9 levels are allocated to depths greater than 1000 m. (See new Figure S1).

10. Lines 207-212: I don't understand the need to split the domain at 30°S. Is there a reason why this exact latitude is significant?

This was specify in the text as follows: "The latitudinal division was based on the influence of the characteristic water masses in the region, primarily the Subantarctic Water (SAAW; 11.5°C, 33.8) south of 30°S, where the OMZ is predominantly hypoxic (O_2 < 45 μM; as described by Naqvi et al., 2010, and Pizarro-Koch et al., 2019) and significantly narrower. The biogeochemistry of SAAW differs notably from that of Subtropical Water (STW; 20°C, 35.2) north of 30°S, which features a zonally broader OMZ characterized by suboxic conditions (O_2 < 20 μM, Figure 2; following Wright et al., 2012), particularly in oxygen, ammonium, and nitrite" (Section 2.2).

11. Line 211: “Pudies” - Puddies? Also, the choice of acronym must be homogenized across the manuscript: all capital (PUDDIES) as in the abstract, or capital P only (Puddies) as here?

We have homogenized the text using Puddies.

12. Lines 213-214 and Figure 1c: If the first 100 km are such a relevant range for the formation of Puddies, why not looking at zones that have boundaries at equal distance from the coast, so that the 0-100 km zone is the formation zone across the whole system and then more offshore zones can be defined?

Puddies are indeed formed in the coastal domain along the coast of central Chile, but the subregions are defined based on mean conditions over the whole domain (coast and open-ocean). The criteria used for the division of the subregions are now better explained (Section 2.2).

13. Lines 217-228: What is your definition of mean state? This must be made explicit here. Is it an overall mean across your 9 years of simulation? In this case, seasonal variability will contribute to the “fluctuations” as it will be part of the residual field. Or else, is it something like interpolated seasonal or monthly climatological means? Please specify.

We computed an overall average over the 9 years of simulation to define the "mean state." Certainly, seasonal variability can contribute to fluctuations, potentially increasing the biogeochemical variability in the cores of the Puddies (Figure 4). However, this does not significantly affect the results, as comparisons were made with other reference points, such as different percentiles (Figure 5). A more explicit definition of the mean state was provided in Section 2.3.

The sentence was modified as follows: “where $< NO_3 >_{9-year}(x, y, z)$ is the “mean state” of NO_3^- calculated as an overall mean across 9 years simulated between the period 2000-2008. Fluctuations of this “mean state” considered the seasonal variability and denote as $NO_3'(x, y, z, t)$.”

14. Line 261: Did the algorithm identify eddies larger than 300 km of diameter, and if so how many? This seems very large and surprising to be identified as eddy for the Faghmous et al. 2015 algorithm run on an 8km grid.

Puddies with a diameter >300 km were not always identified, but in the snapshots where one was identified, it reached a maximum of 3 that were removed from the analyzed sample. It is important to consider that the Faghmous algorithm defines the eddy boundary based on a single maximum (for anticyclones), closing the boundary when another maximum (or minimum) is found (Section 2.5). This causes the boundary to change in shape and size at each time step. Therefore, it is possible that at time *t*, a Puddy may have a diameter greater than 300 km, and at *t+1*, it no longer does, meaning that it would be included in our statistics.

15. Line 262: “every three days” - does this simply refer to the fact that the model output was saved as 3-day means? If so, please rephrase, since a 3-day mean is different from “every three days” output, which might mean a simple snapshot of the model every three days

Thank you for pointing out this inconsistency. The text was clarified. Eddy identification was performed using 3-day mean outputs across the entire period.

16. Lines 247-264: How many eddies were identified in total by the algorithm over the model output? How many independent tracks did they correspond to? This is important information to be included here.

On average, around 14 Puddies were identified at each time step (it ranged from 11 to 20 eddies), this was mentioned in Section 3.1. For this study, it was not necessary to track the trajectory of each Puddy.

17. Lines 265-271: I’m puzzled by this choice of only analyzing the tracks of only 2 Puddies when the authors have 9 years of model output available at three days mean output resolution, which most likely allows the authors to analyze tens or maybe hundreds of eddy tracks. Is there any reason why these two tracks should be particularly relevant or representative of the mean eddy for the northern and southern subregions?

Following the reviewer’s recommendation, we conducted a more robust analysis by considering all Puddies identified at each time step (t = 3 days) over a 9-year period across the three selected latitudes (Section 2.6.2 and 3.4). Figures 8–11 and Table 4 summarize the findings.

18. Lines 286-290: Why do you apply a circular mask that will surely miss part of the eddy shape and likely include part of non-eddy waters (eddies are rarely perfect circles), when the Faghmous et al. 2015 algorithm already provides the identified eddy perimeter mask?

For clarity the text was modified as follows: " For these Puddies, we estimated characteristics within the entire eddy volume as follows: i) for each δh_{max} (Puddy center), a mask of the entire volume was created; ii) the area mask was calculated to identify the edge using the Faghmous algorithm as the most accurate approach (Figure S3; see sensitivity analysis in the Supplementary Material); iii) this mask was applied across all depths (at 5-meter intervals), creating an irregular cylinder between S_{upper} and S_{lower}; iv) from the total volume enclosed by the cylinder, an average vertical profile was obtained at each time step for each variable (see an example of vertical Puddy characterization in Figures S2b, S2c, S2d, S2e)”. Details in Section 2.6.2

19. Line 300 – how do you define a “puddy profile”?

A brief definition is now provided: The added text is as follows “To understand the typical conditions within Puddies identified in the formation zone and each subregion, average profiles were constructed as follows: i) all eddy centers (i.e., δh_{max} positions) were classified in 1°x1° grid cells along the coast and also within the regions defined in Figure 1, ii) for each eddy center, vertical profiles were extracted between the density surfaces S_{upper} and S_{lower} for all variables in each corresponding region, iii) then, these profiles were time-averaged to obtain typical profiles for each variable. For the regions,the values associated with the S_{core} were shown (Section 3.2) to emphasize the changes in the ESSW core. "

20. Lines 304-307: This seems like an important caveat and it needs better clarification. What does "slightly overestimated" mean in numbers? Please provide a number of how many identified Puddies are actually not Puddies but coastal trapped waves or other structures. In other studies, coastal eddies in the first life stages have been excluded from the analysis just because the Faghmous et al. 2015 algorithm was having difficulty identifying them.

Original statement: "It should be noted that the number of eddies in the coastal region may be slightly overestimated by our adopted algorithm due to difficulties in distinguishing between perturbations of the density surfaces generated by eddies, coastal upwelling events, coastally trapped waves or meanders of the coastal currents."

We have revised our statement, as it was previously unclear and partially inaccurate. Coastal waves and upwelling events, in fact, exhibit larger spatial scales than Puddies and would not be misclassified as such based on our criteria. Specifically, only closed-contour structures with a minimum horizontal area of 30 grid points (A_{min} ~1.95 × 10^9 m², corresponding to a radius of ~25 km) were retained. This threshold ensures that the identified structures are distinct from coastal-trapped Kelvin waves or upwelling events. In order to provide an error estimate on the number of Puddies, we have applied the Faghmous et al. (2015)'s algorithm varying the criteria on the number of grid points to detect the closed-contour structure. When selecting an area with 25 grid points, the eddies were not properly identified (reducing the total of selected Puddies by 30%). Additionally, eddies with a radius >150 km (~32 pixels in diameter) were also not well detected, with at most three closed-contour structures per snapshot being discarded.

This is now indicated in the main text which was revised as follows: "Only eddies that reached a minimum horizontal area of 30 grid points (A_{min} ~1.95 × 10^9 m², equivalent to a radius of ~25 km) were considered, as eddies below this threshold are not well identified (reducing the total of selected Puddies by 30%). Additionally, only eddies with a radius not exceeding 150 km (~32 pixels in diameter) were included, as larger eddies are also not well detected, with at most three closed-contour structures per snapshot being discarded." Methodology was adjusted in Section 2.5 and the original statement was removed in Section 3.1

21. Figure 2: Please add labels to this figure, what does each line represent? It's not enough to have it in the caption, it makes the figure really difficult to understand.

Following the reviewer's recommendation the presentation of figure 2 (now new figure 3) was improved.

22. Table 1: Number of pixels? What does it mean?

Table 1 was modified. The number of pixels was referring to the area which is now expressed in km2 for clarity.

23. Tables (in general), Results and Methods: I'm really not convinced by having these 8 different regions. It makes the results overly complicated to understand. I think the authors should rethink this analysis almost entirely and use more regular domains, for example defined by offshore distance bands.

The use of regular domains is not appropriate because of our definition of Puddies based on the thickness between two selected mean isopycnals where the core of the Puddies is expected to be found. We have clarified the text in the method section and have retained only 6 subregions (instead of 8 initially).

24. Tables (in general): These tables are heavy to read. They need to be summarized into figures, bar plots, or something that makes it possible to the reader to grasp the results.

Following the reviewer's recommendation, the presentation of the tables was improved and their number was reduced to 4 (instead of 6). To summarize the results of two tables, we now have the new figure 5 (the tables are now presented in the Supplementary material).

The supplement is currently unreadable. It's impossible to revise a document where figures and captions are provided separately in different PDFs. I had to copy by hand the text onto a word document and then screenshot the figures and stich them on top of the correct captions in the word document, to be able to understand what I was looking at. The quality of the supplement should be at least checked by the journal upon submission. The supplement should be revised entirely to make it clear to the reader. There are also typos in the supplement's captions and figure axes miss titles and key information.

We apologize for the inconvenience. We have improved the presentation of the Figures and caption text of the Supplementary material. Proof reading was also performed to avoid typos and errors.