Response to Reviewer #3

We sincerely thank Eric Machu for his thoughtful and constructive feedback, as well as for the positive and encouraging overall assessment of our work. We are especially grateful for the recognition of the challenges involved in observing and analyzing high-baroclinic-mode vortices (HBVs), and for acknowledging the value of combining long-term in situ observations with high-resolution modeling. Eric Machu's detailed comments have helped us clarify several aspects of the manuscript and improve its overall quality. We have carefully addressed all suggestions and concerns raised, and we believe that the revised version of the manuscript is significantly improved as a result. Below, we respond point-by-point to each of the reviewer's comments. Reviewer comments are shown in **black**, followed by our responses in **green**. Changes to the manuscript are highlighted in *italics* and described where appropriate.

Referee #3: Eric Machu

Note: The reviewer comments are in **black**, our responses are in **green**

General Comments

This study convincingly presents the presence of high baroclinic mode vortices (HBVs) in the low latitudes (4°-12°N) of the North Atlantic and their effect on the presence of oxygen-depleted "islands" in its eastern to central part. The study describes the characteristics, origin and temporal evolution of eddies marked by low oxygen concentrations. The study is based on numerous observations acquired in this region over the last 15 years from sea campaigns and 3 moorings. The understanding of the evolution of these structures is completed by the exploitation of a coupled physical-biogeochemical modeling experiment.

The manuscript is very well written, organized and illustrated with relevant, high-quality figures. The work as a whole is of good quality and the results deserve to be published, as they shed light on the presence of small-scale dynamic structures, which are very poorly documented and difficult to observe (and to some extent modeled), with consequences for the biogeochemical characteristics of this oceanic region.

Thank you very much for the kind words and for placing this work in a scientific context.

A coupled model is used in this work to present the mechanisms by which an HBV is maintained and evolves over several months from the upwelling zone across the Atlantic basin. Given that the model represents oxygen minima much further west than observations show, and that the mean state of the oxygen variable presents a number of biases (notably the absence of shallow OMZ in the east), I would tend to think that the biogeochemical model is partially inadequate, and I wouldn't necessarily have put so much confidence in the respiration rates derived from it. Given the duration of the simulation, I would also have expected to see occurrence statistics for the eddies described in this study from the simulation.

We thank the reviewer for the comment. We fully acknowledge that the coupled model used here is not perfect and exhibits biases, as is the case for any ocean-biogeochemistry model. In particular, the model tends to slightly underestimate potential vorticity and the associated oxygen anomalies, leading to somewhat weaker eddy coherence compared to observations.

At the same time, due to reduced dissipation in the circulation model, the lifespan of the eddies is slightly prolonged. Additionally, the MiniBLING model does not fully account for remineralization processes in the mesopelagic zone, likely leading to an underestimation of oxygen consumption. Taken together, this implies that HBVs in the model appear with weaker anomalies but with an artificially prolonged lifespan, which we explicitly consider in our interpretation of the results now.

New Line 770: *The model tends to slightly underestimate PV and the associated O_2 anomalies, indicating somewhat weaker eddy coherence compared to observations. At the same time, due to reduced dissipation in the circulation model, we expect lifespans of the eddies to be slightly prolonged. Additionally, the MiniBLING model does not fully account for remineralization processes in the mesopelagic zone associated with HBVs, which likely leads to an underestimation of oxygen consumption. Taken together, this implies that HBVs in the model appear with weaker anomalies but with an artificially prolonged lifespan.*

Despite these limitations, our intention within the manuscript was to use the model as a complementary tool to the observational dataset, providing further insight into the origin and evolution of the eddies. In the revised manuscript, we strengthened the observational support for HBVs by including nitrate as an additional tracer: the new Figure 8b shows observed oxygen concentrations, the depth of the oxygen minimum, and the corresponding nitrate profiles from CTD casts taken inside and outside of low-oxygen events. These data reveal substantially lower oxygen concentrations between 80-250 m, accompanied by elevated nitrate levels inside HBVs, consistent with ongoing biological remineralization and thus "older" water. This supports the interpretation that HBVs represent persistent, isolated water masses rather than short-lived anomalies. We believe this addition strengthens the observational evidence and nicely complements the model-based findings, as discussed at the end of Section 4.5 *Source water of high-barocline vortices* as follows:

New Line 711 and following: *"To further support the persistence and longevity of HBVs, we analyzed CTD observations of oxygen and nitrate inside and outside of low-oxygen events. Fig. 8b shows the median oxygen profiles for CTD casts with a minimum in the upper 200 m of the water column below 60 µmol/kg (blue curve) and those above 60 µmol/kg (orange curves). Mixed layer oxygen concentrations for both cases indicate increased near-surface biological productivity of HBVs compared to outside of HBVs. The red stars indicate the depths of the observed oxygen minima clustering between 80 to 120m depth. Corresponding nitrate profiles are shown in turquoise (<60 µmol/kg oxygen) and yellow (>60 µmol/kg oxygen). The results reveal substantially lower oxygen concentrations between 80 - 250 m inside HBVs, accompanied by elevated nitrate levels, consistent with enhanced accumulated biological remineralization due to enhanced productivity and/or "older" water. This observational evidence indicates that HBVs consist of persistent, isolated water masses rather than short-lived anomalies."*

In addition, regarding the model itself, we now provide a more detailed description of its resolution and capabilities with regard to the observed eddies:

New Lines 393 and the following: "*With a nominal ocean resolution of 0.1°, CM2.6 is mesoscale eddy-resolving and submesoscale-permitting at low latitudes, capturing only the larger submesoscale vortices. The local Rossby radius of deformation (60-150 km; Fig. 1) in* *the area is resolved, but smaller eddies are near the lower limit of resolvable scales. However, the model has been shown to simulate low-oxygen mesoscale eddies at latitudes poleward of about 12° (Frenger et al., 2018) and provides a useful framework in this study to complement the observational analysis.*"

Finally, we would like to emphasize again that in this study, with regard to the model, we focus on case studies of modeled submesoscale eddies to demonstrate plausible dynamics and mechanisms rather than to derive quantitative estimates of respiration rates or oxygen concentrations. We leave quantitative statistics for future dedicated studies, that perhaps could be carried out using GLORYS 1/12° reanalysis. The model results here are used as illustrative examples to contextualize our observational data and facilitate their interpretation and mechanistic insight. All quantitative conclusions regarding HBV occurrence, longevity, and impact rely on observational evidence. We hope that these clarifications and additions in the revised manuscript now better convey our reasoning and the role of the model in supporting, but not replacing, the observational evidence.

Finally, the study could have been strengthened, particularly the occurrence statistics for this type of vortex, by integrating data from the ARGO profilers. The association of events with vortices could not have been complete, given that currents are not measured, but the study of these numerous profiles (including the depth of isopycnes) could have reinforced the information on the frequency of low-oxygen events in the subsurface waters and hence on their role in the biogeochemistry of this oceanic region.

We have conducted similar analyses using ARGO floats for eddies north of 12°N, around the Cape Verde region and the Mauritanian/Senegal upwelling zone (Schütte et al., 2016a). We attempted to perform similar analyses in the near-equatorial region; however, we encountered several obstacles that ultimately prevented us from integrating these datasets into the manuscript. First, there is almost no supporting satellite signal (contrasting to the regions further north), as the eddies in the near-equatorial region appear to have little or very weak surface expression, hindering co-location. As you noted, we also lack velocity measurements and oxygen observations (only few ARGO floats provide oxygen), which prevents direct attribution to low-oxygen eddies. In contrast, for the CTD-based assignments, we were able to use direct oxygen measurements and shipboard velocities, which we consider much more reliable and unambiguous. One could, as you suggested, attempt to use ARGO-derived isopycnal displacements; we did explore this, but this approach is prone to noise and confounding processes (other factors displacing the isopycnals), we could not reliably link such displacements to low-oxygen events, and were not satisfied with the results. For these reasons, we ultimately decided not to include ARGO-based analyses at this point, and we believe that doing so would not change the conclusions of our study (as we have a substantial amount of CTD Data, and in addition, long-term mooring datasets for statements about the frequency of low-oxygen events.

<u>Specific comments</u>

Various places in the manuscript mention the link between HBVs/oxygen depletion and biogeochemistry, biodiversity or pelagic fish:

L. 71-72: "*Such eddies have a severe impact on biogeochemical processes and organisms*"

L. 123-124: "*HBVs can play a crucial role in biogeochemical cycles and marine ecosystems*"

L. 952-953: "*which may impact on pelagic fish, biodiversity and biogeochemical cycles*"

These structures contribute to the definition of the mean state of the oxygen variable, but it seems difficult to say more, given that the study does not focus on statistics or trends associated with these HBVs. We are talking here about a few events per year, biogeochemical processes and a specific response from planktonic communities are probably associated with them, but to speak of severe impact on organisms sounds rather alarmist and it's hard to imagine a determining role for the presence of these structures for higher organisms over their entire life cycle.

We thank the reviewer for this helpful comment. We agree that the wording in the manuscript was too strong and may have overstated the broader ecological significance of HBVs. While these vortices can indeed have a regional and short-term impact on biogeochemical conditions and local plankton communities due to their transport and oxygen-depleting effects, our study does not provide direct evidence for long-term or large-scale impacts on higher trophic levels. We have therefore softened the statements in the abstract and discussion to better reflect the scope of our findings. The revised text now emphasizes that HBVs *may locally modulate* biogeochemical processes and ecosystem conditions, rather than exerting a severe or determining influence.

Line 71-72: "*Such eddies can locally modulate biogeochemical processes and influence marine organisms.*"

Line 123-124: "*HBVs may play a role in shaping local biogeochemical conditions and ecosystem variability*."

Line 952-953: "*which may have localized effects on pelagic habitats, biodiversity, and biogeochemical cycling*."

L. 66-67: Could you indicate values or a reference for ambient conditions / respiration rates?

The ambient respiration rates in the tropical North Atlantic, outside of eddy cores (in median depths of around 80 m), are reported in Schütte et al. (2016b) and amount to approximately 0.04-0.06 µmol kg^{-1} d^{-1} at similar depths. We have added this information to the manuscript to clarify the comparison with enhanced respiration rates inside the eddies.

Line 66-70: "*Respiration rates in the eddy's interior (at around 80m depth) were found to be substantially increased, with up to 3 to 5 times the values of ambient conditions for the tropical North Atlantic (approximately 0.04-0.06 µmol kg^{-1} d^{-1}), e.g. subsurface intensified anticyclonic eddies (subsurface ACEs): 0.19 ± 0.08 µmol kg^{-1} d^{-1} and surface intensified cyclonic eddies (CEs): 0.10 ± 0.12 µmol kg^{-1} d^{-1} (Schütte et al. 2016b)*."

L262-263: It would be interesting to mention the main reasons put forward to explain these biases.

We thank the reviewer for this comment. Indeed, the shallow OMZ in the tropical Atlantic (above 200 m) is not well reproduced by the model, which instead simulates a single OMZ spanning roughly 100 - 600 m. This bias is commonly found in coupled ocean-biogeochemistry models (e.g., Duteil et al., 2014) and is attributed to several factors: insufficient vertical resolution in the upper ocean, which smooths out rapid oxygen depletion; simplified or parameterized remineralization and biological processes that fail to reproduce fast upper-ocean oxygen consumption; and limited representation of physical transport processes such as submesoscale eddies and coastal upwelling, which locally enhance oxygen minima. Additionally, models often overmix oxygen from deeper layers into the upper ocean, further weakening the shallow OMZ signal. This underscores the importance of observational studies such as ours, which provide insights into the shallow oxygen minimum, its connection to low-oxygen events, and the role of high-baroclinic vortices. We have added a brief discussion of these points in the Introduction to further motivate why studies based on direct observations remain essential.

New Line 292: "*This bias is also present in other coupled ocean circulation biogeochemistry models (e.g. Duteil et al., 2014) and can be attributed, among other factors, to the limited representation of physical transport processes such as submesoscale eddies, which locally enhance oxygen minima. Additionally, simplified or parameterized remineralization and biological processes fail to reproduce rapid upper-ocean oxygen consumption. These discrepancies highlight the importance of direct observational studies, such as ours, which provide detailed insights into the shallow oxygen minimum and its connection to low-oxygen events and high-baroclinic vortices, thereby motivating the focus of this study.*"

L. 696-697: "*we identified a HBV with a low-DO core in the near-equatorial open ocean as exemplarily shown at the position 28°W, 10°N.*"

Why haven't you compiled statistics on the occurrence of this type of vortex throughout the simulation?

As discussed in previous responses, we consider the model useful primarily to illustrate plausible HBV dynamics and mechanisms. Given known biases - such as underestimated eddy intensity, weaker oxygen anomalies, and imperfect representation of shallow OMZs - we refrain from deriving quantitative statistics from it; such statistics would be better obtained from higher-resolution products or future dedicated studies. All quantitative conclusions regarding the occurrence, longevity, and impact of HBVs are therefore based solely on observational data, including CTD sections and PIRATA mooring time series.

L.765-766: "*DO continuously decreases from 97 µmol/kg to 54 µmol/kg over 300 days which yields an average DO consumption of 0.14 µmol/kg/d*"

L. 894-895: "*DO decrease from 92 to 46 µmol/kg over a period of 260 days, yielding a DO consumption of 0.18 µmol/kg/d*"

Why calculate two different respiration rates? As mentioned in the general comments, I'm not sure that the model used is relevant for estimating respiration levels, since it does not reproduce depleted structures in the right longitude bands and, on average, fails to reproduce a shallow OMZ signal (and the spatial extent of the OMZ). Observations show the occurrence of low O2 events far to the west of the basin, but in the absence of

statistics on the presence of these events in the model, we question the representativeness of the example of HBV studied from the simulation.

First, we agree that reporting two different respiration rates for slightly different time spans of the modeled HBV is not particularly helpful and can be confusing. Second, we also agree that such specific numerical values derived from the model are particularly questionable. We have therefore removed these two examples from the manuscript and replaced them with a general, qualitative statement.

Line 896: "*Oxygen in the HBVs decreased from roughly 95 µmol kg^{-1} to 50 µmol kg^{-1} over several months, corresponding to an average consumption rate of about 0.16 µmol kg^{-1} d^{-1}. This apparent decline should be regarded as a lower limit, as ventilation and mixing processes would partly offset oxygen loss*."

Line 917: "*The magnitude and timescale of this decrease are broadly consistent with observed low-oxygen events in the region, though specific rates from the model should be interpreted cautiously.*"

Line 1046: "*During the lifetime of the simulated anticyclonic HBVs, enhanced respiration within the eddy core contributes to a noticeable decrease in DO over several months. While this trend is qualitatively consistent with observations of low-oxygen events, the model-derived values should be considered indicative rather than quantitatively precise.*"

<u>Technical corrections</u>

L. 83 : correcting « dominace » into « dominance »

Thank you. Done

L. 146-147, 167, 170: Homogenize the writing of the different mooring locations (coordinate pairs) for in situ moored, shipboard observations + ocean-biogeochemistry model

We thank the reviewer for pointing this out. We have now homogenized the writing of all mooring and observation locations throughout the manuscript, including in situ moorings, shipboard observations, and model grid points. All coordinates are now consistently presented in the format °N/°W throughout the text, figures, and tables.

L. 482: correcting « asciated » into « associated"

Thank you. Done

L. 616: correcting "isopyncal" into isopycnal"

Thank you. Done

L. 856: correcting "verticies" into "vorticies"

Thank you. Done