Dear Reviewers,

We sincerely thank both reviewers for their thorough evaluation and constructive feedback on our manuscript. We appreciate the time and effort invested in reviewing our work, and we value the perspectives and suggestions provided.

Based on these reviews, we propose the following changes to improve our manuscript:

1. Clarifying in the Abstract, Introduction and Conclusions the scope of our work—analysing mesopelagic POC turnover processes through comparison between the PISCES model and available observations— in response to Reviewer 1's concern.
2. Expanding model evaluation with additional observational datasets, addressing concerns raised by both reviewers. Depending on the magnitude of the implemented changes, we might consider moving the whole model evaluation section from the Methods to the Results. This change, accompanied by an improved discussion of modelled vs. observed patterns, will link model-derived insights and the real world more explicitly. Regarding model evaluation, we specifically propose to:
    a. Move to the main text figure S7, which compares our simulation results to vertical POC flux measurements from sediment traps. Additionally, we will enhance that figure by adding the Th^{-234} export flux data from Le Moigne et al. (2013);
    b. Add an evaluation of simulated mesozooplankton biomass against recent observational datasets (see response to Reviewer 2); we will also add a comparison to satellite-derived biomass of small phytoplankton and diatoms.
    c. We will consider reorganising the content of figures 2 and 3 to better convey model evaluation results, including the additional datasets mentioned above.
    d. Add a summary table comparing our results with the budget values from Giering et al., (2014), which remains, to our knowledge, the most comprehensive study of mesopelagic POC budgets (including food web POC transformations) in the North Atlantic.
    e. Add an evaluation of simulated POC degradation rates against empirical estimates of mesopelagic POC remineralisation rates, e.g., from Table 3 of Lemaitre et al., (2018) or other suitable datasets (see response to Reviewer 2 for further details).
3. Expanding the "study limitations" section to better explain uncertainties and highlight missing components in PISCES, in order to address Reviewer 1's suggestion to avoid treating our model study as a direct representation of the real world, and Reviewer 2's recommendation to discuss important organisms that are not represented in the model.
4. Improving the Abstract and, perhaps, changing the title to better convey the goals and findings of our study. A potential new title could be "Dissecting particulate organic carbon budgets in the mesopelagic North Atlantic Ocean: An integrated assessment using the PISCESv2_RC model and observations".

We sincerely believe these changes will significantly improve the manuscript while maintaining its core focus on the **mechanistic understanding of mesopelagic POC dynamics**, which is the knowledge gap we are contributing to fill. We also want to note that this paper is a necessary step that sets the stage for other articles (in preparation), where we analyse the response of POC budgets to various sources of uncertainty (e.g., model parameters, biases in sea-surface phytoplankton types). Below we provide point-by-point responses, highlighting reviewers' comments in blue and red.

Response to reviewer 1

Reviewer: The objective of this study is to analyze simulated POC dynamics in the mesopelagic layer (defined here as below the euphotic zone and above 1,000 m) in the North Atlantic from a NEMO-PISCES simulation, compare the model results to observations, and derive a budget. The model has a relatively complicated treatment of mesopelagic particle dynamics. My hope, after reading the abstract, was that this study would drive forward ongoing efforts to better constrain the mesopelagic POC dynamics in numerical models, since these are poorly constrained by observations and prone to big uncertainties. However, the comparison to observations presented in this manuscript is cursory (in Figures 2 and 3 in section 2) and doesn't add any new insight. Presented instead (in section 3) is a detailed analysis of the output from the somewhat complicated model for different subregions. I fail to see how this adds any valuable insight. Then, in section 4, the authors seem to jump from the model analysis to drawing conclusions about the real world (line 617: "This study provides a comprehensive analysis of POC dynamics in the top 1000 m of the North Atlantic, linking POC distribution and seasonality with transport and transformation processes.") even though we know that the model is prone to big uncertainties. The obvious flaw that the model results do not equal the real world is not even mentioned. In section 5, the authors claim to have "obtained mechanistic insights into POC distribution, export patterns, and biological carbon pump efficiency across three North Atlantic regions" (line 832-834). No insights about the real world were obtained. In my view, the basic approach to this manuscript is flawed. I do not recommend publication.

Perhaps more of a side note: The authors give an inaccurate definition of the biological carbon pump that is, unfortunately, common but should not be perpetuated further. When stating "The ensemble of the biology-mediated processes that transfer POC, PIC, and DOC to the deep ocean is known as the biological C pump (Volk & Hoffert, 1985; Legendre, 2024)" (line 74-76) the authors neglect to mention that biologically derived inorganic carbon is moved from the deep ocean to the sea surface through ocean circulation. That the biological pump is the balance of the organic carbon that is moved downward (in different forms and via different mechanisms) and the resulting inorganic carbon that is moved back to the sea surface and outgasses. See Frenger et al. (2024).

Frenger, I., Landolfi, A., Kvale, K., Somes, C. J., Oschlies, A., Yao, W., et al. (2024). Misconceptions of the marine biological carbon pump in a changing climate: thinking outside the "export" box. Glob. Chang. Biol. 30:e17124. doi: 10.1111/gcb.17124

We sincerely thank Reviewer 1 for their feedback on our manuscript. We understand that some aspects of our framing may have created expectations beyond our intended scope, and we appreciate the opportunity to clarify our objectives. Our manuscript is explicitly focused on analysing simulated POC dynamics using the NEMO-PISCES model in the North Atlantic mesopelagic zone. As indicated in our original title: "Budgets of particulate organic carbon in the mesopelagic layer across contrasting North Atlantic ocean biomes: **a model study with PISCESv2_RC**", our primary aim was to provide the modelling community with a mechanistic understanding of how this specific model—which includes improved representation of mesopelagic processes compared to previous versions—represents POC flux attenuation across different biomes, rather than to validate it exhaustively or draw definitive conclusions about the real ocean.

We acknowledge that model outputs are not perfect representations of reality and contain uncertainties—this is inherent to all modelling studies. However, we believe our work provides valuable insights into the relative importance of different processes (ocean mixing, phytoplankton community composition, bacterial remineralisation, zooplankton feeding) in controlling POC dynamics across different latitudinal regimes. These process-level insights are difficult to obtain from observations alone (see for example the response to Reviewer 2) due to the logistical and technical challenges of measuring all components simultaneously in the mesopelagic zone. **Such an integrative analysis is lacking, and our study aims to contribute to filling this gap.**

1. Regarding the comparison with observations (Figures 2-3): Figure 2 was not intended as a model evaluation figure, as it did not use any observational estimates. Rather, it was meant to provide a general overview of how the model represents key stocks and fluxes, showing: the spatial distribution of NPP, export at 100 m, and POC stock integrated over the productive and mesopelagic layers, as well as the seasonal variability of export at 100 m and 1000 m and primary productivity integrated over the productive layer.

   In contrast, Figure 3 constituted a model evaluation, though not an exhaustive one, as this was not within the initial scope of our paper—the model had already been evaluated elsewhere (e.g.: Aumont et al., 2017; Galí et al., 2022). The purpose of this figure was to show how, within the seasonal cycle, our model simulations reflect the observed changes and fall within the range of observational estimates of sPOC stock. We used this product due to the availability of the reconstructed bpp dataset (Sauzède et al., 2016), which provides a proxy for small particle concentrations (since the large-particle signal —spikes— has been removed). This is the only 3D POC dataset we are aware of, and we considered it appropriate for comparison with our simulations.

   To address the reviewer's comments, we may turn both figures 2 and 3 into model evaluation figures. The new Fig. 2 would display annual maps (NPP, phytoplankton and zooplankton size class biomasses, integrated POC stocks, export fluxes), whereas Fig. 3 would display the regional mean seasonal cycles of those variables (including those currently shown in Fig. 2 bottom panels). In both figures, we would display observational estimates when available or, if adding observational data made the figures too large (especially Fig. 2), we would report evaluation metrics on each plot panel. As done for other variables, we might show model-observations bias maps in the supplementary materials. Note also that the analysis of spatial horizontal patterns (Fig. 2) and seasonal patterns (Fig. 3) is complemented by the vertical patterns shown in Fig. 4, resulting in a rather logical arrangement of information.

2. Regarding the comment: "Perhaps more of a side note: The authors give an inaccurate definition of the biological carbon pump that is, unfortunately, common but should not be perpetuated further. When stating 'The ensemble of the biology-mediated processes that transfer POC, PIC, and DOC to the deep ocean is known as the biological C pump (Volk & Hoffert, 1985; Legendre, 2024)' (line 74–76) the authors neglect to mention that biologically derived inorganic carbon is moved from the deep ocean to the sea surface through ocean circulation. That the biological pump is the balance of the organic carbon that is moved downward (in different forms and via different mechanisms) and the resulting inorganic carbon that is moved back to the sea surface and outgasses. See Frenger et al. (2024)."

   We thank the reviewer for this helpful comment and for pointing us to Frenger et al., (2024). We agree that our original sentence places the emphasis only on the downward transport of biologically mediated carbon (POC, PIC, DOC) and does not explicitly state that, in a strict sense, the biological carbon pump is defined by the balance between (i) the downward transport and remineralization of biologically produced carbon and (ii) the return of remineralised dissolved inorganic carbon (DIC) to the surface via ocean circulation and its eventual outgassing. Note, however, that lines 78–75 of our manuscript mentioned the balance between net organic C supply and DIC reemergence, though perhaps not explicitly enough.

Our focus on POC fluxes and their attenuation is intentional and does not aim to diminish the importance of DIC fluxes in the complete biological carbon pump. In this study, we do not attempt to quantify the full biological carbon pump or its direct impact on atmospheric CO_2. Our analysis is explicitly restricted to the budgets of POC in the upper 1000 m and to the "biological carbon pump strength" defined as the product of export efficiency and transfer efficiency of POC. These are widely used metrics and therefore their adoption in our study enables an explicit link to observational studies, which we will try to better exploit in the revised version. The DIC_{remin} metric adopted by Frenger et al. (2024) and previous studies (see below), while obviously relevant, is not pertinent to our study because it reflects terminal organic carbon remineralisation to CO_2, which we did not intend to assess.

The conversion of POC to DOC and ultimately to DIC is explicitly represented in PISCES (as detailed in the Methods section), so that the production of DIC of biological origin is included in the model. Nevertheless, we do not examine either the subsequent recirculation of this DIC to the surface or the air–sea CO_2 fluxes, which we consider beyond the scope of our study. Thus, our analysis deliberately focuses on the different biogeochemical and physical processes that affect the attenuation of POC fluxes within the mesopelagic layer, such as particle transformation and the interconversion between slow- and fast-sinking detritus, POC degradation and vertical mixing, which are also highlighted as essential for understanding the biological carbon pump in Frenger et al. (2024).

Following the reviewer's suggestion, we will revise the introductory definition to provide readers with a more complete context. We will clarify throughout the manuscript that, in the general sense, the biological carbon pump includes both the downward transport and remineralisation of biologically produced carbon and the circulation-driven return of remineralised DIC to the surface and possible outgassing (e.g. Volk & Hoffert, 1985; Marinov et al., 2008; Legendre, 2024; Frenger et al., 2024; Bernardello et al., 2014), and we will state explicitly that the present work focuses on the particulate component and on its mesopelagic expression as captured by export and transfer efficiencies. We hope this addresses the reviewer's concern while keeping the scope of the manuscript clear.

Response to Reviewer 2:

Reviewer:

General appreciation:

The manuscript deals with Carbon budget in the mesopelagic layers at three latitudes in the Northern Atlantic. It is a 3D modeling study using a recent version of PISCES model that include more realism in the mesopelagic layers. The study aims to understand the main drivers of flux attenuation in the mesopelagic trying to understand which component of the pelagic ecosystem is more important: ocean mixing, surface community composition of phytoplankton and initial ballasting, temperature controlled bacterial remineralisation, zooplankton feeding. Main results is that latitude affects all of them in a way that all processes are locally important.

Overall this is a very good and complete study which many questions of the control of the flux in a rigorous manner, providing the mechanistic insights that model can. The question is if the model include all important players and processes. This aspect is discussed in section "study limitation" but could be improved (see below). Hence the manuscript deserves publication with minor changes.

We are grateful for Reviewer 2's positive and constructive evaluation of our work and appreciate the specific suggestions for improvement.

Improvement could be made in the section:

- "model evaluation" by using more up to date data sourcing from imaging systems that become available in the recent years: zooplankton biomass (Drago et al., 2022), rhizarians respiration (Laget et al., 2024), and marine particle size distribution (Kiko et al., 2022) and zooplankton size distribution (Dugenne et al., 2023), and vertical export flux (Clement et al., 2023). It would be nice to see how the model is able to fit to these datasets.

We agree that incorporating more recent observational data for zooplankton would strengthen our manuscript. Therefore, we explored additional datasets whose inclusion would make the model evaluation section more comprehensive. These datasets will complement the evaluation of small POC concentration that is already included in the manuscript, which encompasses four model tracers: small and large phytoplankton, microzooplankton and small detritus.

Following Reviewer 2's suggestion, we carefully considered various mesozooplankton datasets, taking into account the size range, trophic level and feeding strategies of the organisms they include. Note that mesozooplankton in PISCESv2 nominally comprises organisms in the 0.2–2 mm size range.

- Drago et al., (2022): Machine learning reconstruction based on a global dataset of UVP5 images of 19 zooplankton taxonomic groups. Size range: 1–50 mm.
- Liu et al., (2024): Machine learning reconstruction based on a global dataset of zooplankton net tows, capturing mostly organisms in the 0.2–20 mm size range. Provides specific estimates for copepod biomass.
- Laget et al., (2024): Machine learning reconstruction based on a global UVP5 dataset of large Rhizaria. Size range: 0.6–20 mm. Machine learning reconstruction
- Clerc et al., (2024): Ensemble of machine learning reconstructions of mesozooplankton biomass (biomass distribution models) specifically targeted for comparison against a novel

PISCES version that includes mesozooplankton and higher trophic levels. It is based on the MAREDAT dataset.

Based on this analysis, we decided to prioritise the dataset of Clerc et al. (2024) because it provides the best match with simulated mesozooplankton in PISCESv2 in terms of size and trophic level. We may use Liu et al. (2024) for an additional comparison of simulated mesozooplankton and estimated copepod biomass in the epipelagic layer. Finally, we may use the dataset of Laget et al. (2024) to evaluate the model representation of flux feeders (see reply to the question below). All datasets are available online.

To further enhance the model evaluation section, we will include a comparison to satellite-derived phytoplankton carbon biomass. To this end, we will use the biomass of the pico-, nano- and microphytoplankton size classes based on the approach of Sathyendranath et al., (2019). Simulated small phytoplankton (phymisc) corresponds to pico+nanophytoplankton, whereas microphytoplankton largely corresponds to simulated diatoms. This approach has already been implemented in another study by our group (preprint: Galí et al. 2025, DOI: 10.22541/essoar.176399684.41984948/v1).

Finally, note that we are not aware of microzooplankton biomass gridded datasets that are suitable for the evaluation of our model.

- "study limitation": recent works have showed that a major player, Rhizaria (Drago et al., 2022) are important in the mesopelagic carbon budget (Stuckel et al., 2029; Laget et al., 2024) accounting for 9% of POC attenuation (globally, a little less in the Atlantic). Would the addition of this group fit within the budget. Recognizing that maybe not all players are yet known could be mention in this section.

This is an excellent point, and we acknowledge that Rhizaria represent an important player in mesopelagic carbon budgets. Although these organisms are not explicitly represented in our PISCES model version, a functional representation of flux-feeding exists in PISCES, as described in our manuscript (with detailed equations in the supplementary material). Thus, the biogeochemical impact of Rhizarians' flux-feeding lifestyle may be partially accounted for in PISCES. However, it is unknown to what extent the mesozooplankton flux feeders in PISCES can be compared to mesopelagic —heterotrophic— Rhizaria in terms of biomass and distribution, considering that the current flux feeding parameterization in PISCES is based on pteropods (line 246 of our manuscript and citations therein).

Back-of-the-envelope calculations suggest that flux-feeding in PISCES includes a wider range of organisms and has a larger biogeochemical impact than Rhizaria alone. This is in keeping with extant knowledge on the taxonomic and functional diversity of detritivorous mesozooplankton (Stukel et al., 2019; Mayor et al., 2020). For example, figure 3 of Laget et al. (2024) suggests that Rhizarian biomass in the mesopelagic is of order 10–100 µg C m^{-3}, roughly 0.001–0.01 mmol C m^{-3}. Mesopelagic mesozooplankton biomass in PISCES is usually of order 0.1 mmol C m^{-3}, 60–85% of which typically are flux feeders (line 691). Thus, Rhizaria biomass estimates correspond to <10% of simulated total mesozooplankton and a similarly low proportion of simulated flux feeders. In terms of POC fluxes, Laget et al. suggest Rhizaria contribute 1–5% of vertical POC flux attenuation across tropical to North Atlantic biomes, whereas PISCES estimates that zooplankton intercept ~50% of the POC sinking flux through the mesopelagic (line 678, Fig. 8). Yet, our study further suggests that a substantial part of the intercepted POC flux returns to the sinking detritus pool via zooplankton mortality and large aggregate fragmentation (Fig. 8). These simple calculations provide a clear example of the mechanistic insights a model can yield, which can both complement observations and motivate further in situ studies.

To address Reviewers 2's concern, we will consider adding a comparison between the model and Laget et al.'s estimates. Whether this is done using a display item (likely a table) or in the text will be decided depending on the relevance this comparison has in the context of our manuscript. We will also expand the "study limitations" section to discuss this gap and cite the relevant work — (Stukel et al., 2019; Lampitt et al., 2023, Laget et al., 2024), adding a broader statement to acknowledge that not all important players may be known or represented.

- Fragmentation by zooplankton

The fact that fragmentation was mediated by zooplankton was proposed earlier. The flow field associated with swimming or feeding zooplankton has been observed to fragment aggregates several millimeters long by Dilling and Alldredge (2000). They suggested that aggregate breakup by vertically migrating euphausiids was responsible for their observed day–night variation in marine snow size distribution in the upper 100m depth. This type of fragmentation was then shown to have less impact than the fragmentation by zooplankton feeding in the upper mesopelagic which release small particles during flux feeding on large particle (Stemmann et al., 2004b). This particle fragmentation during flux feeding was important to slow down the sinking of particles which could then be consume by bacteria. An important parameter in Stemmann et al., 2004b was the size of feeding area.

We thank the reviewer for highlighting this important process. In our model, the fragmentation by zooplankton is performed by flux-feeders, and they are represented as a percentage of mesozooplankton. Therefore, there is no separate tracer that can be directly compared with the euphausiid data from Dilling and Alldredge (2000), since the type of fragmentation they report is driven by turbulence, a process that is not included in PISCESv2. Additionally, the size of these organisms is considerably larger than what is represented in our model framework.

Coinciding with what was noted in Stemmann et al., (2004b) we observed that in PISCES, flux feeding plays a critical role in controlling the flux of particulate organic matter out of the euphotic zone. It influences the size distribution and composition of particles that reach the deep ocean. Also, flux feeding can lead to fragmentation of particles, affecting particle sinking rates and the efficiency of carbon export. In fact, in the upper mesopelagic layer, the model simulates the most efficient attenuation of POC flux by flux feeding just below the euphotic zone, where sinking particles are the primary food source for zooplankton. Flux feeding is distinguished from prey concentration-based grazing, which occurs predominantly within or near the surface.

Answering the question of Reviewer 2: *"Where does this value comes from. Has some sensitivity analysis been carried on this term in the study?"*

Flux feeding, as described in the PISCES model (Aumont et al., 2015), is a process whereby zooplankton, particularly mesozooplankton, feed on sinking particles of detritus and other particulate matter as they descend through the water column. This mechanism depends on the sinking flux of particles, unlike phagotrophic grazing (where the rate depends on prey concentration).

The grazing rate on detrital particles (sdetoc and ldetoc) is proportional to the product of their sinking flux, the flux feeding parameter, and the biomass of flux feeders. The product of flux feeder biomass and the flux feeding parameter gives the particle interception cross-section. A complete description of this parameterisation is given in SM section S1.

A sensitivity analysis of this parameter will be provided in a forthcoming study, alongside the parametric uncertainties of remineralisation and gravitational sinking (Orihuela-García et al., in prep). Large sensitivity to flux feeding was already demonstrated by Gehlen et al., (2006), albeit using a previous version of PISCES that had a different representation of flux feeding and fragmentation. Falls et al., (2021) suggested a large but hard-to-constrain sensitivity of POC stocks to the flux feeding parameter.

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