We would like to sincerely thank both the reviewers for their positive comments about the paper and for their valuable suggestions on how to further improve it. These suggestions are addressed below.

The reviewer comment is always in blue, our response in black and the cited change in green and italic. Please note that the changed sections are also marked in blue font in the submitted track-changes version of the manuscript.

Reviewer 1:

The review mentioned and discussed collaboration in the UK and its national perspective. Then the review, I think, has useful information to oceanographic community in other countries. I recommend the publication of the review after the following very minor revision.

Minor Comments:

2.1 End-user applications: I think recent environmental DNA (eDNA) observation is very important for understanding of biodiversity. If we try to analyze space-time distribution of eDNA with the MDA information, it would be very progressive. Then please try to discuss/add a paragraph about the MDA application to eDNA analyses such as:

• Marine ecosystem and biodiversity. The use of environmental DNA (eDNA) is recently used for studying the ecosystem and variability of life in the sea as a biodiversity observation network. The space-time distribution of eDNA is relatively new but growing rapidly. The distribution would be greatly useful with ocean physical and biogeochemical information by MDA.

We thank the reviewer for this suggestion. We have indeed added the biodiversity (and eDNA) application to section 2.2 (rather than 2.1 as we believe this is a scientific application). Please see the last point on the page 9, lines 210-215:

"- reanalysis data can be used for interpreting drivers of change seen in biodiversity datasets, such as from the Continuous Plankton Recorder, e.g. see the work of Holland et al., (2024). Looking more into the future, reanalyses have also the potential to assist with interpreting newer, rapidly growing datasets including those based on environmental DNA (eDNA)."

LL566-589 paragraph: An example of the use of AUV is discussed. I agree with the use of high-spatial model resolution. I think the model would/should be "a relocatable model?" And I would have expected the paper to mention an "on-spot DA" around AUV very local position? Or very many AUVs observation data would be assimilated?

Again, we thank the reviewer for this suggestion. The AUV assimilation considers data from both a single, or multiple, AUVs, depending on the observational set-up. The data are usually suitably spatially and temporally thinned, with the model data mapped into the corresponding AUV positions via observational operators. The discrepancy in spatial and temporal scale between the AUVs and the model is partly addressed through the thinning, but to a degree remains a challenge to be addressed in the future. These points are discussed in the referenced literature (e.g. Skakala et al, 2021, Ford et al, 2022). The model can be covering a larger area (e.g. the whole NWES as in Partridge et al, 2025) in its application, but could be in the future also made relocatable for higher resolution. We have added some sentences on this, please see the page 27, line 605-610:

"The biogeochemistry high-resolution models could cover large areas, such as the whole NWES (as Partridge et al, 2025, in prep), or could cover only smaller areas in the coastal zone. In such case they could be made relocatable, e.g. following techniques developed by Shapiro et al (2022, 2023)."

Reviewer 2:

I found this review to be insightful and highly informative. It offers a clear overview of the current landscape of marine data assimilation (MDA) and outlines a compelling vision for future developments, particularly in the areas of coupled systems, digital twins, and the application of machine learning.

One section that may benefit from clarification is the discussion of weakly coupled air-sea systems. In particular, the phrase "ocean ensemble developments (p.19)" is somewhat vague; it is not immediately clear whether this refers to ensemble-based data assimilation, ensemble forecasting, or both. In addition, it would help to clarify what variables these developments aim to control—presumably the initial state of the ocean (e.g., temperature, salinity), but this is not made explicit.

We thank the reviewer for this comment, we have now hopefully made these points clearer through the updated text in the section 3.3, please see the page 20, line 405:

"*Weakly coupled air-sea systems are part of ECMWF (de Rosnay et al, 2022) and Met Office (Lea et al, 2015, Guiavarc'h et al., 2019) operational short-range weather forecasts. The ocean part of the Met Office coupled NWP ensemble system is currently being developed to include improved ensemble forecast generation methods and the use of hybrid-3DEnVar (Lea et al., 2022; 2023). This will allow improved uncertainty propagation from the ocean to the atmosphere through the forecast, leading to improved forecast uncertainties in both ocean and atmosphere, and should also enable improvements in the accuracy of the ocean physical variables.*"

The definition of the digital twin is included (p.26), but it is somewhat embedded within the narrative. I suggest presenting it more prominently—perhaps as a standalone sentence early in the relevant section—and briefly connecting it to the practical examples (e.g., AUV navigation). For non-expert readers, a short plain-language summary of the loop (e.g., "the model tells the AUV where to go next, and the AUV's new observations help update the model") could also be helpful. A simple schematic illustrating this feedback loop would greatly enhance clarity.

We thank the reviewer for this great suggestion, we have now made this much more prominent by including a new Figure 5 (see the page 17) showing schematic representation of the digital twin system used in Ford et al (2022), and also in Partridge et al (2025). The Figure caption provides a simple explanation of how the digital twin works, along the lines suggested by the reviewer:

*"**Fig.5.** A schematic illustration of a digital twin system navigating fully autonomous gliders to areas of observational interest. The Figure is reproduced from Ford et al (2022), with a similar scheme also being applied in Partridge et al (2025), in prep. The digital twin system is based on information flowing in all directions: (i) glider observations are being assimilated into the pre-operational forecasting model (i.e. the model is updated by the glider). (ii) The operational model subsequently produces forecasts for a stochastic/ML model, with additional inputs into the stochastic model provided by the glider directly, (iii) The stochastic model then provides the system with a fully autonomous path-planning capacity close to the glider's spatial scale of operations, navigating the glider into the expected areas of observational interest (i.e. the model tells glider "where to go"). This exchange of information then cycles throughout the glider mission. "*

More broadly, the discussion of strongly coupled data assimilation (SCDA) might benefit from briefly touching on the role of time-ordered information flow across components. While the paper rightly highlights the challenge of different temporal scales between ocean and atmosphere, an even richer perspective might come from recent mathematical tools—such as path signatures (Lyons, 1998) and signature kernels (Chevyrev & Oberhauser, 2016)—which are designed to extract time-ordered moments from multivariate path data. These representations preserve the temporal structure and non-commutative properties of the path, and may offer future opportunities to improve the modeling of cross-component covariances and adjoint sensitivities in SCDA.

We thank the reviewer for mentioning these approaches, we have now added a sentence (along the lines suggested by the reviewer) to the section 4.1.3 on the coupled DA vision mentioning them (and the relevant references). Please see the line 545, page 25:

"The community should in future be open to new methods to advance strongly coupled DA, such as those based on path signatures (Lyons, 2014) and signature kernels (Chevyrev & Oberhauser, 2018), which are designed to extract time-ordered moments from multivariate path data."

Finally, I appreciate that this manuscript uses "digital twin" in a relatively narrow and rigorous sense—that is, referring to real-time coupled systems with feedback into observation strategy. Given the broader and often ambiguous usage of this term across domains, it might be helpful to briefly acknowledge this and clarify that the review is focused on a specific, operationally meaningful subset of digital twin applications. This would help avoid conceptual drift and assist readers in understanding the scope of the discussion.

We acknowledge that our use of the digital twin concept is rather more specific than in some of the literature. To clarify this for the reader we will propose a footnote in the Introduction (line 85, page 3), with the following:

“Digital twins are understood here in a quite specific sense, as systems where the digital twin interacts two-way (exchanging information both-ways) with the twinned physical object, whilst operating as a real time decision-making tool. The fully autonomous observing systems described here fullfil this operational definition of digital twin.”

These suggestions are offered with appreciation for an already excellent review. I believe that with minor clarifications, the manuscript will serve as a very useful and timely resource for the MDA community and beyond.

We would like to thank both reviewers for their valuable input. We hope that the paper is now ready to be accepted for publication in OS.

Best wishes,
Jozef Skakala and the co-authors