Responses to the Reviewers' Comments

Answers to reviewers' comments are reported point by point. The questions and comments of the reviewers are in blue, the answers in black, and the modifications that we made in the revised manuscript in red.

Responses to the comments of the anonymous Reviewer 1

First, we would like to warmly thank Reviewer 1 for their relevant and constructive comments, which helped to improve the manuscript.

In their manuscript, Habib et al. present a new and well-executed analysis of the mechanisms controlling dissolved oxygen dynamics in the Levantine Sea using a high-resolution coupled physical-biogeochemical model. The manuscript is generally well written, supported by observational validation, and provides valuable insights into the seasonal and interannual variability of dissolved oxygen budget, as well as the key physical-biogeochemical processes involved. I have a few minor comments, outlined below:

It would be useful to include a brief discussion on potential sources of uncertainties in the oxygen-heat budget terms (e.g., on gas transfer velocity; L138-140).

Reply: Following the suggestion of reviewer 1, we have added a brief paragraph in the discussion addressing the main sources of uncertainty affecting the oxygen-heat budget terms. We now discuss uncertainties related to the parameterization of the air–sea gas transfer velocity, which depends on wind speed and choice of formulation, as well as uncertainties associated with surface heat fluxes, vertical mixing, and model resolution. We emphasize that these uncertainties do not alter the main conclusions of oxygen variability in the Levantine Basin.

Discussion:

As a matter of comparison, the 7-year averaged oxygen uptake estimated here for the whole Levantine Basin, characterized by relatively low solubility compared to the rest of the Mediterranean (Mavropoulou et al., 2020, Di Biagio et al., 2022), represents 64% of the oxygen uptake by the NW Mediterranean deep convection estimated for the cold year 2012-13 with the same coupled model (Ulses et al., 2021). These estimates are nevertheless subject to methodological uncertainties. In particular, air–sea oxygen fluxes depend on the parameterization of the gas transfer velocity, whose sensitivity to wind speed and formulation can induce uncertainties of the order of 12-16%, as quantified by *Ulses et al.* (2021). Additional uncertainties arise from surface heat flux estimates and the representation of vertical mixing, but these are not expected to modify the relative importance or seasonal phasing of the dominant budget terms (Josey et al., 2013; Large et al., 1994).

References:

Ulses, C., Estournel, C., Fourrier, M., Coppola, L., Kessouri, F., Lefèvre, D., and Marsaleix, P.: Oxygen budget of the north-western Mediterranean deep-convection region, *Biogeosciences*, 18, 937–960, https://doi.org/10.5194/bg-18-937-2021, 2021.

Josey, S. A., Gulev, S., and Yu, L.: Exchanges through the ocean surface, in: *Ocean Circulation and Climate*, 2nd edn., edited by: Siedler, G., Griffies, S. M., Gould, J., and Church, J. A., Academic Press, 115–140, https://doi.org/10.1016/B978-0-12-391851-2.00005-2, 2013.

Large, W. G., McWilliams, J. C., and Doney, S. C.: Oceanic vertical mixing: A review and a model with a nonlocal boundary layer parameterization, *Rev. Geophys.*, 32, 363–403, https://doi.org/10.1029/94RG01872, 1994.

Since the modelling framework and methods closely follow those used in a previous study by Ulses et al. (2021), I suggest adding a short discussion (and/or in the Introduction) clarifying how the present analysis differs from and builds upon that earlier work. Highlighting the new scientific contributions that emerge from focusing on the Levantine basin will help underline the novelty of the manuscript.

Reply: Following the suggestion of reviewer 1, we have added a short paragraph in the Introduction to clarify how the present study builds upon the framework of Ulses et al. (2021) while addressing distinct scientific questions. While Ulses et al. (2021) focused on basin-scale oxygen dynamics in the western Mediterranean, the present work applies the same modeling framework to the Levantine Basin, a markedly different hydrographic and biogeochemical regime. In particular, this study provides the first basin-wide quantification of the dissolved oxygen budget in the Levantine Basin, with explicit separation of atmospheric, lateral, vertical, and biogeochemical contributions, and highlights the dominant role of the Rhodes Gyre in oxygen uptake and ventilation. This regional focus allows us to document mechanisms specific to the ultra-oligotrophic eastern Mediterranean and to assess how circulation features unique to the Levantine Basin shape oxygen variability.

Introduction:

The objective of the present work is to quantify the seasonal and interannual variations in the oxygen inventory of the Levantine surface and intermediate water masses over 7 years, detailing the contribution of air-sea oxygen fluxes, biological and physical processes. This analysis is based on 3D coupled hydrodynamic-biogeochemical model outputs covering a period of 7 years, from 2013 to 2020. Based on the budget approach developed by Ulses et al. (2021) for the north-western Mediterranean Sea, we investigate the ultra-oligotrophic Levantine Basin and provide a basin-scale quantification of its dissolved oxygen budget, highlighting the role of transport processes and permanent circulation features such as the Rhodes Gyre.

Consider linking the results to broader implications for regional biogeochemical research and/or Earth system modelling.

Reply: We agree that placing our results in a broader context strengthens the manuscript. We have therefore expanded the Discussion to highlight the relevance of our findings for regional biogeochemical research and Earth system modelling. Specifically, the quantified oxygen budget and the role of intermediate waters in the Levantine Basin provide insight into how oxygen ventilation and transport in semi-enclosed basins respond to circulation and atmospheric forcing at seasonal to interannual timescales. Because Levantine Intermediate Water is the primary source of Mediterranean Overflow Water, changes in its oxygen content may propagate beyond the Mediterranean and influence the oxygen and biogeochemical properties of intermediate waters in the Northeast Atlantic. Accurately representing these processes is essential for regional biogeochemical models and Earth system models aiming to capture Mediterranean–Atlantic exchanges and their contribution to large-scale oxygen budgets. We have also added a few lines in the conclusion.

Discussion:

Beyond the Levantine Basin, the processes identified here have broader implications for regional biogeochemical dynamics and Earth system modelling. The quantified oxygen budget of LIW highlights the sensitivity of intermediate-water ventilation to circulation and atmospheric forcing at seasonal to interannual timescales in semi-enclosed basins (e.g. Tanhua et al., 2013; Schneider et al., 2014). Because LIW constitutes the main precursor of MOW, variability in its oxygen content may propagate beyond the Mediterranean and influence the oxygen and biogeochemical properties of intermediate waters in the Northeast Atlantic (Aldama-Campino & Döös, 2020; Stendardo and Gruber, 2012). Accurately representing these processes is therefore essential for regional biogeochemical models and Earth system models aiming to capture Mediterranean–Atlantic exchanges and their contribution to large-scale oxygen budgets.

Conclusion:

This work represents a first step in our modeling of the dissolved oxygen dynamics in the Levantine Basin. The quasi-permanent Rhodes Gyre dominates the basin-scale oxygen budget, but transient cyclonic and anticyclonic mesoscale structures are expected to contribute to the oxygen variability outside the gyre at shorter time scales, further investigations on the role of the various cyclonic and anticyclonic eddies will be conducted in the future. While the 7-year study period provides high-resolution insights into oxygen dynamics, it does not cover long-term climate shifts such as the EMT. Several studies suggest a decadal variability of dissolved oxygen across the whole water column linked to the dense water formations in the south Adriatic and Aegean seas and to the general eastern Mediterranean circulation, notably the reversal of the North Ionian Gyre (Ozer et al., 2020, 2022). A time-extended simulation of the coupled model, in addition to the implementation of a finer vertical resolution at key depths, could contribute to examining this longer variability in the Levantine Basin and the connections between the sub-basins of the eastern Mediterranean. Improving the representation of intermediate-water oxygen dynamics in the Mediterranean is also a necessary step toward better quantifying Mediterranean–Atlantic biogeochemical coupling and its sensitivity to future climate-driven changes in ventilation and circulation.

References:

- Aldama-Campino, A., & Döös, K. (2020). Mediterranean overflow water in the North Atlantic and its multidecadal variability. Tellus A: Dynamic Meteorology and Oceanography, 72(1), 1–10. https://doi.org/10.1080/16000870.2018.1565027
- Stendardo, I., & Gruber, N. (2012). Oxygen trends over five decades in the North Atlantic. Journal of Geophysical Research: Oceans, 117, C11004. https://doi.org/10.1029/2012JC007909

L90-91: Please add a reference.

Reply: Thank you for this suggestion. A reference has been added at lines 90–91.

L149-150: specify which product is used.

Reply: The product we used is the Atmospheric Model high resolution forecast (HRES), this was added to the text. *"We used the wind speed and solar radiation from the HRES (Atmospheric Model high resolution forecast) product of ECMWF for the hydrodynamic simulation."*

L451: Correct the dots in the parentheses.

Reply: Thank you for pointing this out. The punctuation in the parentheses at line 451 has been corrected.

L483-495: The sentences "This aligns ... distribution of chlorophyll" seem tangential and could be shortened for clarity.

Reply: We thank the reviewer for this suggestion. The paragraph at lines 483–495 has been shortened to improve clarity.

The new sentences are as follows:

"This is consistent with previous studies reporting strong temporal and spatial heterogeneity in the trophic status of the oligotrophic Levantine Basin (Christaki et al., 2011; Siokou-Frangou et al., 2010). The planktonic ecosystem is largely regulated by heterotrophic processes, with higher heterotrophic/autotrophic biomass ratios typically observed in the most oligotrophic regions and during stratified periods (Christaki et al., 2002; Siokou-Frangou et al., 2002). Despite this general heterotrophic character, mesoscale physical structures promoting vertical mixing and nutrient upwelling play a key role in shaping the basin's trophic gradients, particularly within cyclonic systems (Legendre and Rassoulzadegan, 1995; Salihoğlu et al., 1990)."

Fig. 11: add a note clarifying the sign convention (i.e., positive/negative = upward/downward fluxes).

Reply: We thank the reviewer for this suggestion. The figure caption has been revised to specify that positive values correspond to a net flux of oxygen into the ocean (uptake), while negative values indicate a net flux from the ocean to the atmosphere. For net community production, positive (negative) values indicate net biological oxygen production (consumption).

"Figure 11: Modeled annual air-sea oxygen flux and net community production (mol O_2 m^{-2} yr^{-1}) in the surface layer (0-150 m) for the period from December 2013 to December 2020. The black line delimits the Rhodes gyre. Positive values for the air-sea oxygen flux indicate a net flux of oxygen into the ocean (uptake), while negative values indicate a net flux from the ocean to the atmosphere. Positive NCP values correspond to net biological oxygen production and negative values to consumption."