Oxygen budget for the North-Western Mediterranean deep convection region

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Responses to the comments of the anonymous Reviewer 1

First we would like to warmly thank Reviewer 1 for his relevant and constructive comments which will help to improve the manuscript.

Answers to reviewers' comments are reported point by point. The questions and comments of the anonymous Reviewer 1 are in *blue*, the answers in black and the modifications that we propose for the revised manuscript in *black*.

Review of Manuscript "Oxygen budget for the north-western Mediterranean deep convection region" by Ulses et al. General comment to the Authors and the Editor: The ms presents an analysis, based on in situ data and model results, of the dissolved oxygen inventory of the dense water formation area in the NW-Mediterranean during one of the most active years in terms of dense water formation. They assess the inventory on a seasonal and an annual scale, describe the role of deep convection in ventilating the intermediate and deep layers of the basin, and make inferences on primary production in the euphotic layer. The ms is rigorous, very well organized, clearly written, with well-announced objectives and a logical structure that guides the reader through the author's reasoning. I recommend publication of the ms after minor revision.

Reply: We appreciate the positive assessment of Reviewer 1.

Everywhere in the paper it should be written "Gulf of Lion", not "Lions".

Reply: This will be corrected as suggested in the revised manuscript.

Title: I would suggest "of" or "in the north-western" instead of "for"

Reply: We will replace "for" by "of" as suggested in the title in the revised manuscript.

L35 also increased salinity reduces the solubility

Reply: Observational and modelling studies over the past decades show a spatial heterogeneity and a time evolution in the sign of salinity changes and trends at the global scale, with in general increases in salinity in subtropical gyres in the oceans dominated by evaporation and a freshening in regions dominated by precipitation, modulated by impacts of circulation (Durack and Wijffels, 2010). Therefore to take into account this comment we will modify the sentence as follows: *"[...] to be one of the primary factors, along with the slowdown of the overturning circulation,* ***warming-induced decrease in solubility modulated by salinity changes,*** *and changes in C:N utilization ratios, [...]"*

L40 "of marine ecosystems"

Reply: This will be corrected as suggested in the revised manuscript.

L41 "implications for"

Reply: This will be corrected as suggested in the revised manuscript.

L48 "subsequent density increase of surface waters"

Reply: This will be corrected as suggested in the revised manuscript.

L49 "induces convective missing of surface"

Reply: In the revision, we will replace "results" by "induces" as suggested.

L56 is convection mainly responsible for this higher nutrient supply or the preconditioning given by the cyclonic circulation?

Reply: Previous studies showed that in the north-western Mediterranean open-sea the nutrient replenishment of the surface layer essentially takes place during the deep mixing period. Using in situ profiles of nutrient at the DYFAMED station in the Ligurian Sea over the period 1995-2007, Marty and Chiavérini (2010) showed that the amount of nutrients in the surface layer is maximum during the deep convection period and that on an pluriannual scale it increased with the intensity and depth of the winter mixing (Figure 1 corresponding to Fig.9 from Marty and

Chiavérni, 2010). Also based on nutrient data at the DYFAMED station but over an extended period (1991-2011), Pasqueron de Fommervault et al. (2015) found a moderate increase of the monthly median nutrient concentrations in autumn during the preconditioning phase, from October to December (from 0.19 to 1.20 mmol m^{-3} for nitrate and 0.03 to 0.05 mmol m^{-3} for phosphate), and a strong increase in winter (between 2.60 and 2.70 mmol m^{-3} for nitrate and 0.11 to 0.14 mmol m^{-3} for phosphate). However, the observations of nutrient profiles alone do not allow deducing the vertical fluxes of nutrients, which can be more rapidly consumed by phytoplankton in autumn than during deep convection.

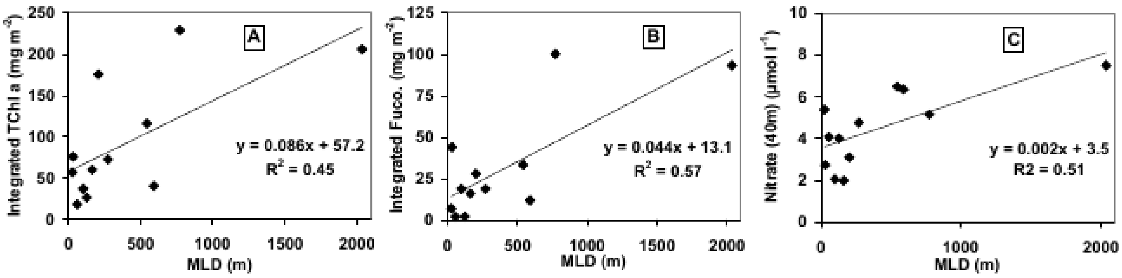

Figure 1. Fig. 9 extracted from Marty and Chiavérini (2010): (A) Correlation between maximum winter MLD and annual integrated chlorophyll a; (B) Correlation between maximum winter MLD and annual integrated fucoxanthin. (C) Correlation between maximum winter MLD and maximum nitrate concentration at 40 m depth in early spring.

Using a 3D physical-biogeochemical model, Ulses et al. (2016) simulated the evolution of the injection of nutrients into the surface layer due to vertical advection and mixing over the 5-year period 2004-2008 in this region. Their results showed that the nutrient vertical import was significantly correlated with the depth of the mixed layer ($R=0.8$, p-value <0.01). Kessouri et al. (2017) studied the nitrogen and phosphorus cycle in the convective zone over the same period (September 2012-September 2013) and based on the same coupled physical-biogeochemical model as in our study, they found that nutrient upward input to the surface layer remained relatively low during the preconditioning period and clearly increased during the convective period (their Figure 10A shown in this response as Figure 2).

To complete their nutrient budget and answer more precisely this question, we have calculated the vertical transport of nutrient into the surface layer during both periods using the outputs of our model: we have found that a nitrate and phosphate upward transport of 13 and 11%, respectively, of the annual upward input occurred during the preconditioning period (1 September to 15 December as defined by Testor et al., (2018)) vs 67 and 68%, respectively, during the deep convection period.

Thus it appears that a higher nutrient supply of the surface layer occurred during the convective phase than during the preconditioning phase. Obviously, the destruction of the stratification of the water column initiated during the preconditioning influences the extension and intensity of the winter mixing and consequently those of the nutrient inputs during deep mixing as shown by Volpe et al. (2012) who studied the interannual variability of the Mediterranean ecosystem using an EOF analysis.

To take into account this comment and a comment of Reviewer 2, we will modify the sentence as follows:

"At the Mediterranean basin scale, the NW deep convection is one of the major processes responsible for an enrichment of the euphotic layer with nutrients, comparing to Atlantic influx as well as terrestrial and atmospheric inputs (Severin et al., 2014; Ulses et al., 2016; Kessouri et al., 2017). The replenishment of the surface layer with nutrients during the deep convection is followed by an intense bloom in spring when vertical mixing weakens (Bernadello et al., 2012; Lavigne et al., 2013; Auger et al., 2014; Ulses et al., 2016; Kessouri et al., 2018)."

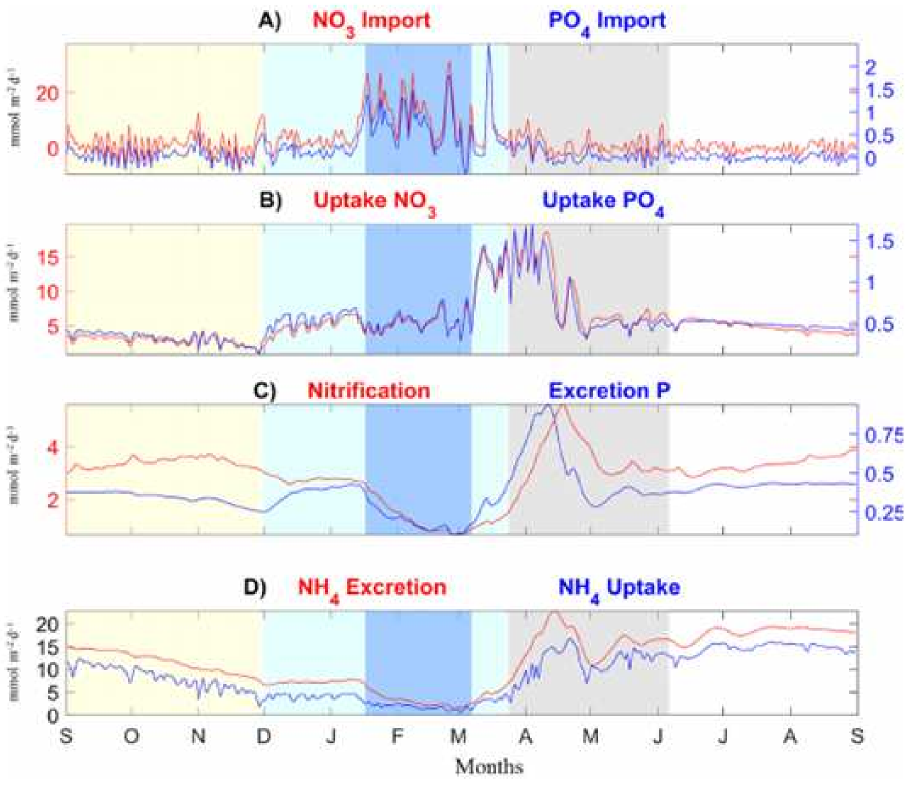

Figure 2. Fig. 10 extracted from Kessouri et al. (2017) : Time series of physical and biogeochemical fluxes that impact the stock of the inorganic nitrogen and phosphorus in the surface layer (0–130 m) from September 2012 to September 2013. These fluxes are inferred from the model and averaged over the open deep convection area. (a) Net import due to vertical advection and turbulent mixing of nitrate (red) and of phosphate (blue) into the surface layer, (b) uptake of nitrate (red) and phosphate (blue), (c)

nitrification (red) and inorganic phosphorus excretion rates (blue), and (d) ammonia excretion (red) and uptake (blue). Units: mmol m^{-2} d^{-1} .

In the Introduction it should be mentioned that concerning the OMZ, the Mediterranean Sea is far from what we observe in the ocean, maybe giving some numbers to exemplify

Reply: We agree that it should be mentioned that the OMZ in the Mediterranean is much less pronounced than in the oceans where oxygen concentration is usually lower than 20 µmol kg^{-1}. The Mediterranean is characterized by the presence of an OML (Oxygen Minimum Layer) with oxygen concentration ranging from 170 to 180 µmol kg^{-1} in the western basin (Coppola et al., 2018). Therefore we will follow the recommendation of Reviewer 1 and will add the following sentences in this Introduction:

"The oxygenation induced by recurrent deep convection together with a relatively low primary production, make the Mediterranean Sea a well oxygenated basin (Tanhua et al., 2013). In the western Mediterranean open sea, the oxygen minimum layer (OML) is located in the LIW and shows minimum oxygen concentration ranging from 170 to 180 µmol kg^{-1}, above ~70% of the saturation levels (Tanhua et al., 2013; Coppola et al., 2018). Thus the OML in this region is clearly less pronounced than in the open oceans or deep basins of other seas, such as the adjacent Black Sea, where hypoxic and even anoxic conditions (oxygen concentration <2 ml O_2 l^{-1} or <61 µmol O_2 kg^{-1}, Diaz and Rosenberg, 2008; Breitburg et al., 2018) are encountered. However the semi-enclosed Mediterranean Sea with a fast warming was identified as one of the most vulnerable marine regions to climate change (Giorgi, 2006). Recently, regional ocean models of the Mediterranean Sea converged to predict a weakening of NW deep convection intensity under climate change scenarios by the end of the 21st century (Soto-Navarro et al., 2020). Yet, Coppola et al. (2018), by analyzing the evolution of observed oxygen profiles in the Ligurian Sea over a 20-year period, suggested that hypoxic conditions may be reached in water masses at intermediate depths after a period of 25 years without deep convection events (presuming bacterial respiration remains the same)."

L170 "Study Area"

Reply: This will be corrected as suggested in the revised manuscript.

L194 instead of "Group", use "initiative" or "programme"

Reply: This will be corrected as suggested in the revised manuscript.

L250 use the acronym LIW

Reply: This will be corrected as suggested in the revised manuscript.

L252 move "respectively at the surface. . ..transect" at the end of the sentence

Reply: This will be corrected as suggested in the revised manuscript.

L254 "During the spring cruise period"

Reply: This will be corrected as suggested in the revised manuscript.

Figure 5: I could not find the explanation on why you integrate down to 1800 m and then down to 1000 m.

Reply: We apologize for the lack of explanation on this point. For float 6901487 the data do not allow the calculation of the integrated quantity of oxygen over 1800 m due to the poor quality of the salinity data below 1000 m (Coppola et al. 2018). We therefore calculated it over 1000 m, for which we have 111/118 profiles. As we are interested in deep convection in this study, we chose to integrate the quantity of oxygen over a maximum depth, 1800 m, for the two other floats. An explanation will be added in Section 2.2.2:

"We calculated the oxygen inventory from 1800 m to the surface for floats 6901467 and 6001470 and only from 1000 m to the surface for float 6901487 due to poor quality salinity data below this depth."

L639 "the surface layer of the deep convection area" is the source for the intermediate and deep layer, not the convection area itself, which comprises the whole water column.

Reply: We agree with Reviewer 1. In the revised manuscript, this sentence will be modified to take into account this comment and a comment of Reviewer 3 on the role of the deep convection area of conveyor, from the surface layer to the deep layer of the western Mediterranean, of atmospheric oxygen as well as oxygen produced locally and in the surrounding areas.

Finally, we would also like to point out that we have found an error regarding the trajectory and the name of the float for which the temporal evolution of the oxygen content is shown in Figure 5b. We apologize for this error that will be corrected in the revised manuscript.

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