Author responses to Reviewer#1 comments for the manuscript: "Acidification, deoxygenation, nutrient and biomasses decline in a warming Mediterranean Sea"

February, 18th 2022

The authors projected the climate change-related impacts in the marine ecosystems of the Mediterranean Sea in the middle and at the end of the 21st century using an offline coupling model combining the physical model MFS16 and the transport-reaction model OGSTM-BFM, under emission scenarios RCP4.5 and RCP8.5, focusing on the middle and the end of 21st century. Projected changes are presented for temperature, salinity, dissolved nutrients and oxygen, net primary production, respiration, organic matter, plankton and bacterial biomass, particulate organic matter, and biogeochemical parameters (DIC, pH).

The paper provides interesting projections in a changing Mediterranean Sea that is already under multiple pressures.

We thank the Reviewer #1 for their positive feedback and for providing detailed comments and suggestions, which will be considered to improve the manuscript. Reviewer's comments are in bold, authors' responses are in normal font, italicized where they quote the proposed changes to the manuscript.

Major comments:

1) P3, L75: No, not "all" the modelling studies focused on high emissions scenarios. For example, there is Benedetti et al. (2018) who used A2, A1B and B1, and Goyet et al. (2016) who used B1 and A1F1.

- **Benedetti, F., Guilhaumon, F., Adloff, F. and Ayata, S.-D. (2018), Investigating uncertainties in zooplankton composition shifts under climate change scenarios in the Mediterranean Sea. Ecography, 41: 345-360. https://doi.org/10.1111/ecog.02434**
- **Goyet, C., Hassoun, A., Gemayel, E., Touratier, F., Abboud-Abi Saab, M. and Guglielmi, V., 2016. Thermodynamic forecasts of the mediterranean sea acidification. Mediterranean Marine Science, 17(2), pp.508-518. Thermodynamic Forecasts of the Mediterranean Sea Acidification | GOYET | Mediterranean Marine Science (ekt.gr).**

Goyet et al. (2016) is the only modelling study that it is projecting carbonate system parameters in the Mediterranean Sea so far, and the one used in MedECC (2020; cited by the authors to tackle OA projections in the Mediterranean). Yet, it is not mentioned at all in this work. Please check this study out and try to compare your results with theirs.

We thank the Reviewer for pointing out this error in the sentence. We propose to include and discuss the suggested references in the manuscript. In the introduction we will state:

"An assessment of the effects of climate change on the biogeochemistry and marine ecosystem dynamics of the Mediterranean Sea has been considered in a certain number of studies based on different emission scenarios".

"Benedetti et al. (2018), using environmental niche models and considering six physical simulations based on different emission scenarios (A2, A2-F, A2-RF, A2-ARF, A1B-ARF, B1-ARF; Adloff et al., 2015), projected, in response to climate change, a loss of copepods diversity throughout most of the surface of the Mediterranean Sea."

Goyet et al. (2016) will be discussed in the Discussions and Conclusions section where it will be stated that:

"*The overall accumulation of CO_2 in the basin resulted in an acidification of the Mediterranean water with a decrease in pH of approximately 0.23 units, which is slightly lower than the 0.3 projected on a global scale (Kwiatkowski et al., 2020) and lower than the value provided in Goyet et al. (2016), who projected, using thermodynamic equations of the CO_2/carbonate system chemical equilibrium in seawater, a variation of 0.45 pH units in the basin under the worst SRES case scenario (0.25 pH units in the most optimistic SRES scenario). However, this last estimate probably tends to overestimate the future acidification of the basin, as it does not consider the decrease in the exchanges and the penetration of CO_2 across the ocean-atmosphere interface due to the warming of the water column (MedECC, 2020)."*

2) P3, L78-79: The authors mentioned that Moullec et al. (2019), under RCP8.5 emission scenario, found an increase in both phytoplankton biomass and net primary production by the end of the 21st century. However, this pattern is not homogenous in the Mediterranean since Moullec et al. (2019) have also highlighted a difference between the Eastern and Western basins with an increase in the first and a decrease in the second. Please edit accordingly.

Agreed. The paragraph will be reformulated as follows:

"On the other hand, Moullec et al. (2019), under RCP8.5 emission scenario, found an increase/decrease in both phytoplankton biomass and net primary production by the end of the 21st century in the Eastern/Western Mediterranean Sea."

P4, L111-113: In addition to the BOUM mesoscale experiments working on relating eddies with biogeochemical changes (BG - Influence of anticyclonic eddies on the Biogeochemistry from the Oligotrophic to the Ultraoligotrophic Mediterranean (BOUM cruise) (copernicus.org)), there are actually many modelling studies, for example:

- **Ramirez-Romero E, Jordà G, Amores A, Kay S, Segura-Noguera M, Macias DM, Maynou F, Sabatés A and Catalán IA (2020) Assessment of the Skill of Coupled Physical–Biogeochemical Models in the NW Mediterranean. Front. Mar. Sci. 7:497. doi: 10.3389/fmars.2020.00497**
- **Guyennon, A., Baklouti, M., Diaz, F., Palmieri, J., Beuvier, J., Lebaupin-Brossier, C., Arsouze, T., Béranger, K., Dutay, J.-C., and Moutin, T.: New insights into the organic carbon export in the Mediterranean Sea from 3-D modeling, Biogeosciences, 12, 7025–7046, https://doi.org/10.5194/bg-12-7025-2015, 2015.**

- **Herrmann, M., Somot, S., Sevault, F., Estournel, C., and Déqué, M. (2008), Modeling the deep convection in the northwestern Mediterranean Sea using an eddy-permitting and an eddy-resolving model: Case study of winter 1986–1987, J. Geophys. Res., 113, C04011, doi:10.1029/2006JC003991.**

Therefore, I would suggest to re-write this paragraph.

We agree with the Reviewer that, before our work, there have already been other observational/modeling efforts to resolve the eddies dynamics in the Mediterranean Sea and its impacts on the biogeochemistry. However, our work has two specific differences with respect to the available literature: i) the works listed by the Reviewer, although being eddy-resolving, focus either on limited areas of the Mediterranean Sea or on a single variable/physical process; (ii) they are hindcasts and do not provide projections for the biogeochemical variables under different emission scenarios. In order to address the Reviewer's comment, we propose to reformulate the paragraph as follows:

"*These considerations emphasize the importance of providing eddy-resolving future projections of the Mediterranean Sea biogeochemistry that further extends the analysis of the climate change-related impacts in the marine ecosystems of the basin under different emission scenarios. In fact, although in the recent period observational and modeling studies have been carried out to further highlight the importance of the mesoscale dynamics in the physical and biogeochemical state of specific areas of the Mediterranean Sea (e.g. Hermann et al., 2008; Moutin and Prieur, 2012; Guyennon et al., 2015; Ramirez-Romero et al., 2020), long-term eddy-resolving biogeochemical projections under different emission scenarios, to the best of the authors' knowledge, have not been analyzed so far in the region. Such projections might be used in future studies specifically focused on the analysis of climate change impact on specific organisms, habitats and/or local areas."*

P8, L263-266: To characterize the spatial distribution and the variability of anomalies, the authors considered their horizontally averages in each sub-basin in the Western Mediterranean (WMED=(ALB+SWM+NWM+TYR)/4) and in only two sub-basins of the Eastern Mediterranean (EMED=(ION+LEV)/2). Why did you exclude the Adriatic and the Aegean Sub-basins here?

We thank the Reviewer for pointing this issue, because we realized that this explanation was missing in the manuscript. Here we followed the approach already adopted in the other works (for example Lazzari et al., 2012; 2016; Di Biagio et al., 2019; Reale et al., 2020 a,b) where the characteristics of both Adriatic and Aegean Sea (for example the paramount importance of riverine inputs or Dardanelles straits in the biogeochemical dynamics of both basins) are considered such peculiar to make both basins separate with respect to the Eastern Mediterranean. For this reason, they are not included in our averages.

In order to address the Reviewer's comment, we will modify the sentence as follows:

"Horizontally spatial averages are computed considering the sub-basins defined in Fig. 1, the whole Mediterranean basin and two macro-areas: Western Mediterranean (WMED which includes ALB, SWM, NWM, TYR) and the Eastern Mediterranean (EMED which includes ION and LEV). The Adriatic and Ionian Sea are not usually considered part of the Eastern Mediterranean due to the importance of local forcing, such as riverine load, in shaping the variability of the biogeochemical dynamics in two sub-basins. Because of that, following the approach already adopted in previous works

(Lazzari et al., 2012; 2016; Di Biagio et al., 2019; Reale et al., 2020 a,b) they are not considered in the spatial averages related to WMED and EMED."

P9-10, L306-315 & Fig. 2: The authors mentioned that mean simulated values in the first 0-200 m are quite realistic in all the variables, and that biases started to show at 600 m depth. However, the vertical profiles show such discrepancies between CTRL average profiles and observational data (EMODnet) even in shallower depths, i.e. less than 50 m for phosphate in the WMed., surface waters for nitrate in the WMed., greater than 200 m for oxygen, and so much general biases in pH. Could you please elaborate more on this?

We thank the Reviewer for raising this point and pointing out this lack in the manuscript. We agree with the Reviewer that the model clearly shows some underestimation/overestimation in some of the simulated biogeochemical variables that have not been thoroughly discussed. On the other hand, our validation shows that the main biogeochemical characteristics of the basin such as presence and features of the Deep Chlorophyll Maximum (DCM), nutricline deepening between Western and Eastern basin, low nutrient concentration at the surface, vertical profiles of DIC, spatial distribution of total alkalinity and pH are well simulated. Thus, without presuming to oversell our results, we believe that our modeling tool is fairly good to be used for scenario simulations, also considering the levels of validation of other scenario simulations published in literature (see for example Richon et al., 2019 and Solidoro et al., 2022).

We propose to further elaborate the paragraph by listing the major biases in variables and layers. More specifically we will rewrite the paragraph as follows:

"Figure 2 also shows the average vertical profiles, computed for the entire, Western and Eastern Mediterranean basin, of Chl-a (c), PO_4 (d), NO_3 (e), dissolved oxygen (f), DIC (g), pH (h) and total alkalinity (i) in the CTRL compared with the recent CMEMS reanalysis (only for Chl-a and pH, Teruzzi et al., 2021) and EMODnet datasets (European Marine Observation and Data Network; Buga et al., 2018). The model captures the DCM location, the west-east trophic gradient in the basin, the nutricline depth deepening between Western and Eastern basin and the low nutrient surface concentrations. Mean simulated values in the first 0-200 m are fairly realistic for almost all the variables, with correlation coefficients between observations and model larger than 0.93. At the same time, between 100 and 300 m the CTRL overestimates (underestimates) the PO_4 concentration (pH) of about 50% (1%), and below 200 m it overestimates (underestimates) the dissolved oxygen (NO_3) of about 15% (20%).

In general, these biases in the initial conditions come from the spin-up simulation, that allows the largest part of the model drift to be removed. Biases are still present in both the CTRL and scenario simulations while the eventually still-present drifts in the CTRL are by far lower than the climate signal.

To summarize, although the model shows some deficiencies in simulating the vertical distribution of some biogeochemical variables, the main biogeochemical features of the basin are very well simulated and thus, MFS16-OGSTM-BFM can be used to investigate the evolution of the Mediterranean biogeochemistry under different emission scenarios."

P11, L326: Could you explain in the text the depth classification adopted in this study: 0-100 m and 200-600 m?

Agreed. The sentence will be modified as follows:

"Mean temperature and salinity evolution between 0-100 m and 200-600 m in the 2005-2099 period under the RCP4.5 and RCP8.5 scenarios in the whole Mediterranean Sea and in the Western and Eastern basins, are shown in Fig. 3. As for the biogeochemical variables, these depths have been chosen as they represent the location of MAW and LIW, respectively".

P12, L342-358: Is it possible to check if those differences are significant or not?

Following also the Reviewer#2's suggestion we propose to extensively redraw the figures including also an assessment of the statistical significance of the observed difference using the Mann-Whitney test with $p<0.05$. Just as an example here we report the proposed "new" Figure 5 with the relative caption.

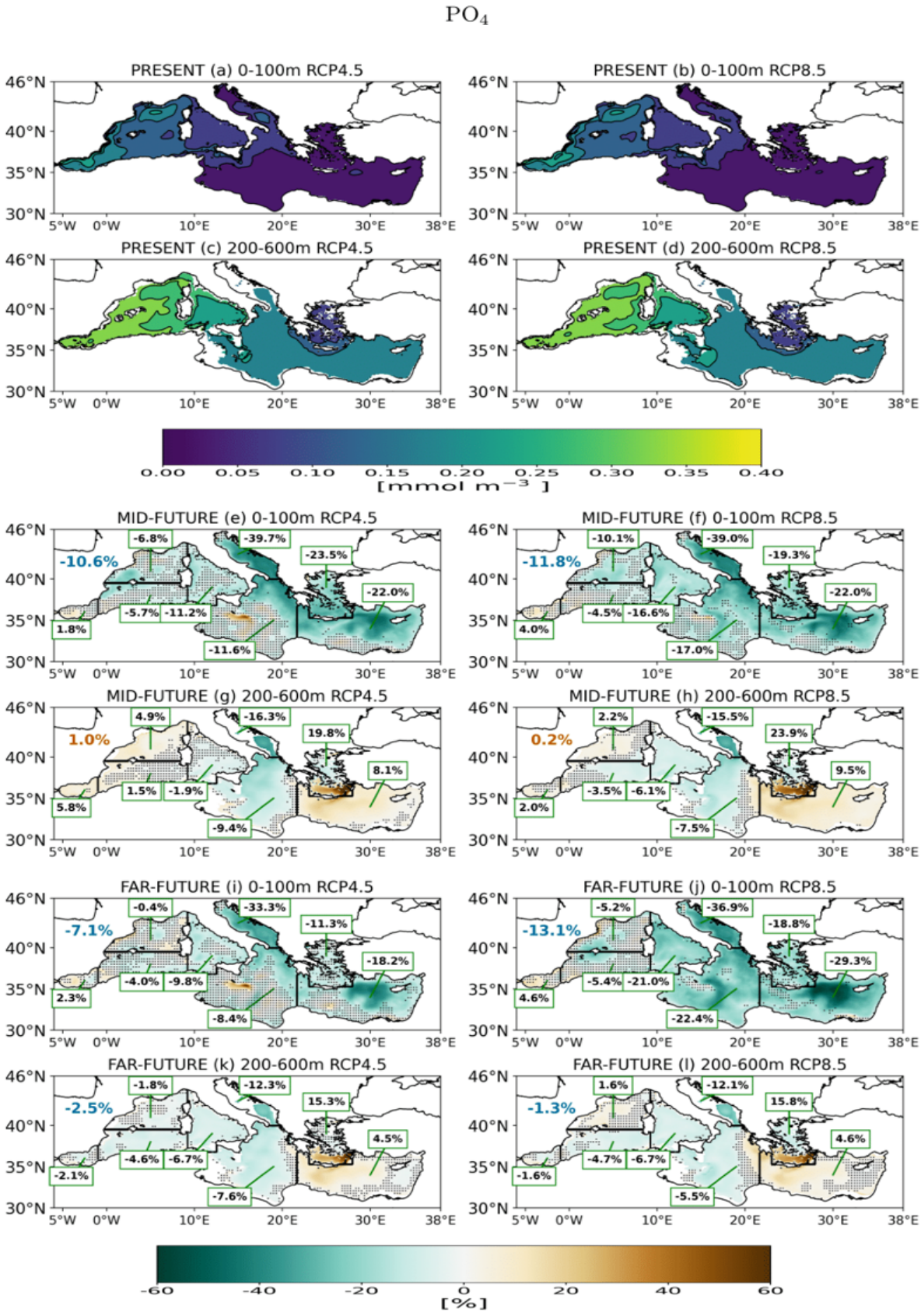

Fig. 5 - Phosphate concentration (in mmol m^{-3}) in the layers 0-100m and 200-600m in the PRESENT (2005-2020, a,b,c and d), and relative climate change signal (with respect to the PRESENT) in the MID-FUTURE (2040-2059, e,f,g and h) and FAR-FUTURE (2080-2099, i,j,k and l) in the RCP4.5 (left column) and RCP8.5 (right column) emission scenario. The Mediterranean average relative

climate change signal in each period (with respect to the PRESENT) is displayed by the top-left colored value (blue or dark orange when negative or positive). Values in the green boxes are the average relative climate change in each period and in each sub-basin shown in Figure 1. Domain grid points where the relative climate change signals are not statistically significant according to a Mann-Whitney test with $p<0.05$ are marked by a dot.

P20, L476: Please explain briefly the role of "damping effect" in controlling oxygen values at the Gibraltar Strait?

We thank the Reviewer for raising this point. Here, with damping effect we refer to the fact that the inflow of biogeochemical properties at the Gibraltar Strait plays a fundamental role in driving the biogeochemical dynamics of the sub-basins near the Strait such as the Alboran Sea, partially limiting, in the case of the oxygen, the reduction in the solubility at the surface in response to the warming of the water column. To better address the Reviewer's comment we propose to write:

"The projected decreases in both scenarios are usually lower in the Alboran Sea and Southern Western Mediterranean with respect to the rest of the basin, as a consequence of the damping effect driven by the oxygen values imposed at the Atlantic boundary. In fact, the advection of dissolved oxygen associated with AW partially limits the reduction in the oxygen solubility at the surface as a consequence of the warming of the water column in the sub-basins near the Strait of Gibraltar such as the Alboran Sea."

P24, L565-566: I guess you are talking here about the "projected" change not the "observed" change. In any case, I would suggest to better re-write this sentence.

Agreed. The sentence will be reformulated as follows:

"In the RCP4.5 simulation, a recovery at the end of the century is simulated for all these biogeochemical variables while the projected change is approximately 50% with respect to the RCP8.5 scenario".

P29, Fig.16: Captions on the plots should be corrected to distinguish between its different components (a-f), as well as between the locations (Med., WMed., EMed.).

We thank the Reviewer for spotting the error in the figure. The figure will be modified accordingly.

In section 2, authors refer to alkalinity (ALK) in the text (i.e. L188). Do you mean by this term, the number of moles of hydrogen ions equivalent to the excess of proton acceptors (bases formed by weak acids) over proton donors (acids) in a kilogram of sample? Mostly yes, and this term should be labeled total alkalinity (DOE, 1994): TA = [HCO3-] + 2[CO32-] + [B(OH)4-] + [OH-] – [H+]. Moreover, except for figure 2 for the period 2005-2020, there is no results about ALK in the following sections. Why?

Yes, the carbonate chemistry of BFM follows the OCMIP protocols, thus considering the alkalinity as "Total". The manuscript has been modified, including the adjective "total" every time we refer to alkalinity. We included "total" alkalinity in Figure 2 to show that the MFS16-OGSTM-BFM reproduces fairly well the prognostic variables of the carbonate system (DIC and total alkalinity), while, to limit the size of the manuscript we preferred to focus our attention

on DIC and pH for the carbon budget, as they have already been discussed in other manuscripts (such as Solidoro et al., 2022), and to leave a deeper discussion of the carbon budget, including total alkalinity, to a future dedicated study.

The term "tracers" is usually used for conservative elements that can be traced in function of time. It is not the appropriate term for the carbonate system parameters, such as TA, DIC or pH. Please refer to them as biogeochemical parameters/features/properties but not tracers.

We agree with the Reviewer that some of the variables considered such as pH or pCO_2 cannot be considered tracers. However, the dynamics of other variables such as DIC and total alkalinity are described with conservative equations within the BFM and thus they can be considered like tracers. In order to accommodate with Reviewer's comment in the manuscript we will talk about *"biogeochemical tracers and properties"*

Minor comments:

Please write the E and W in Eastern and Western in capital letters, and unify this in the text.

The text will be modified accordingly.

While I would suggest to add "sub-basin" to any sub-entity in the Mediterranean (i.e. Alboran Sub-basin, Levantine Sub-basin, etc.), it is OK to use "sea" instead like many other publications (i.e. Adriatic Sea, Aegean Sea). However, I would recommend the authors to unify the terms adopted throughout the manuscript since they use "Adriatic Sea and Levantine basin", why? Also, sometimes you refer to the Gulf of Lion as Gulf of Lions (i.e. L445). Please rectify and unify this in the ms.

We thank the Reviewer for the suggestion. We will extensively check the text and fix the typo related to the Gulf of Lion. Moreover, we would prefer, if not explicitly required by the Reviewer, to maintain the original name of each sub-basin in the text. The reason for that is that, essentially, all these sub-basins (for example the Alboran Sea) are reported in the scientific literature of the Mediterranean Sea with the original name (see Lazzari et al., 2012 or Cossarini et al., 2021), not often followed by the term "sub-basin", although it is well known that they are sub-basins of the Mediterranean Sea. The only exception is the Levantine which is often followed by the term "basin". Because of that we adopt this approach in our manuscript.

Please make italic the "a" in Chl.a throughout the text.

The text will be modified accordingly.

Please write "time-series" instead of "timeseries" throughout the entire manuscript (as you have already done it in L502).

The text will be modified accordingly.

Abstract:

P1, L16-18: Please write it as follows "The analysis shows significant changes in the dissolved nutrient content of the euphotic and intermediate layers of the basin, of the net primary production, phytoplankton respiration and carbon stock (including phytoplankton, zooplankton, bacterial biomass and particulate organic matter)."

Agreed. The text will be modified accordingly.

P1, L20: Please avoid using personal pronouns. The sentence can be written as follows "Moreover, an acidification trend (signal) was observed in the upper water column…".

Agreed. The text in the manuscript will be modified following the Reviewer's suggestion.

P1, L22-23: Please write it as follows "The projected changes are stronger in the Eastern Mediterranean due to the limited influence of the exchanges in the Strait of Gibraltar in that part of the basin."

Agreed. The text will be modified accordingly.

Introduction:

P1, L31: These are some key references (Lascaratos, 1993; Nittis and Lascaratos, 1998) but they are old. I would suggest to also add newer ones, i.e.

- **Fedele, G., Mauri, E., Notarstefano, G., and Poulain, P. M.: Characterization of the Atlantic Water and Levantine Intermediate Water in the Mediterranean Sea using Argo Float Data, Ocean Sci. Discuss. [preprint], https://doi.org/10.5194/os-2021-68, in review, 2021**
- **Fach, B. A., Orek, H., Yilmaz, E., Tezcan, D., Salihoglu, I., Salihoglu, B., & Latif, M. A. (2021). Water mass variability and Levantine Intermediate Water formation in the Eastern Mediterranean between 2015 and 2017. Journal of Geophysical Research: Oceans, 126, e2020JC016472. https://doi.org/10.1029/2020JC016472**
- **Velaoras, D., Papadopoulos, V.P., Kontoyiannis, H., Cardin, V. and Civitarese, G., 2019. Water masses and hydrography during April and June 2016 in the cretan sea and cretan passage (Eastern Mediterranean Sea). Deep Sea Research Part II: Topical Studies in Oceanography, 164, pp.25-40.**

Agreed. The references will be included.

P1-2, L41-42: These are some key references but they are old. I would suggest to also add newer ones, i.e.

- **For Marine heatwaves: Ibrahim, Omneya, Bayoumy Mohamed, and Hazem Nagy. 2021. "Spatial Variability and Trends of Marine Heat Waves in the Eastern Mediterranean Sea over 39 Years" Journal of Marine Science and Engineering 9, no. 6: 643. https://doi.org/10.3390/jmse9060643**
- **For Med. droughts: Mathbout, Shifa, Joan A. Lopez-Bustins, Dominic Royé, and Javier Martin-Vide. 2021. "Mediterranean-Scale Drought: Regional Datasets for Exceptional Meteorological Drought Events during 1975–2019" Atmosphere 12, no. 8: 941. https://doi.org/10.3390/atmos12080941**

Agreed. The references will be included.

P3, L75: Please remove "thus far".

The text will be modified accordingly.

P3, L97: I would suggest to replace "provide" by "sustain".

The text will be modified accordingly.

P3, L74-97: There are some missing articles in this section. For example, Howes et al. (2015) also derived the same conclusions using the RCPs 4.5 and 8.5. There is also Macias et al. (2018) who used two different global circulation models (GCMs; equivalent to RCP4.5 and RCP8.5), and other studies.

- **Herrmann, M., Estournel, C., Adloff, F., and Diaz, F. (2014), Impact of climate change on the northwestern Mediterranean Sea pelagic planktonic ecosystem and associated carbon cycle, J. Geophys. Res. Oceans, 119, 5815– 5836, doi:10.1002/2014JC010016.**
- **Howes EL, Stemmann L, Assailly C, Irisson JO, Dima M, Bijma J, Gattuso JP (2015) Pteropod time series from the North Western Mediterranean (1967-2003): impacts of pH and climate variability. Mar Ecol Prog Ser 531:193-206. https://doi.org/10.3354/meps11322**
- **Macias, D., Garcia-Gorriz, E. and Stips, A. (2018), Major fertilization sources and mechanisms for Mediterranean Sea coastal ecosystems. Limnol. Oceanogr., 63: 897-914. https://doi.org/10.1002/lno.10677**

We thank the Reviewer for the suggestion. We will include and discuss Hermann et al., (2014) because we would prefer to focus the introduction on the scientific literature discussing the projections under different emission scenarios, being Howes et al., (2015) focused on the period 1967-2003 and Macias et al., (2018) on the period 1959-2013. We propose to modify the text as follows:

"Hermann et al. (2014) assessed the response of the pelagic planktonic ecosystem of the North-Western Mediterranean to different emission scenarios and showed that, at end of the 21st century, the biogeochemical processes and marine ecosystem components should be very similar to those observed for the end of the 20th century, although quantitative differences might be observed such as an increase in the bacteria growth, gross primary production and biomass of small-size phytoplankton group."

P3, L99: Please write "All the above-mentioned works…" instead of "All of these previous works…".

The text will be modified accordingly.

P4, L112: Please write "non-living" instead of "nonliving".

The text will be modified accordingly.

Data and methods:

P6, L184: Please write "non-living" instead of "nonliving". And edit it through the entire text.

The text will be modified accordingly.

P6, L187: Please write "physico-chemical" instead of "physical-chemical".

The text will be modified accordingly.

P6, L191-192: Please pay attention to the subscripts throughout the manuscript, i.e. $CaCO_3$

The text will be modified accordingly.

P7-8, section 2.4: The subscripts are sometimes too small to read. Please rectify it.

The text will be modified accordingly.

Results:

P8, L284: It would be helpful to add the ranges, SDs, maybe in a table. What are the precisions of T and S derived from this model?

We revised the sentence by clearly stating that the comparison of the physical quantities simulated by MFS16 against different ocean reanalyses was thoroughly addressed in previous works (Lovato et al., 2013; Galli et al., 2017). In particular, Lovato et al. (2013) reported the comparison of the MFS16 simulations against a reanalysis product (Adani et al., 2010) focusing on the temporal evolution of temperature, salinity, and water fluxes, while Galli et al. (2017) provided an extensive comparison against CMEMS reanalyses (Simoncelli et al., 2019) of marine heatwave events and temperature data at different depth levels (see their supplementary material 3).

The revise sentence will read as follows:

"MFS16 modelling system performances under present climate conditions were previously analyzed (Lovato et al., 2013; Galli et al., 2017), showing that the main spatial-temporal characteristics of the Mediterranean Sea physical properties reliably compared against ocean reanalysis datasets."

Here, we propose to merge this request with those of the Editor by providing a new table in the supplementary material that summarizes the mean values of the key physical and biogeochemical variables under the two scenarios (including the three time-windows considered in our analysis) for the Western and Eastern Mediterranean sub-basins at the two considered layers. Please refers for more details to the replies to the Editor's comments.

Adani, M., Dobricic, S., Pinardi, N., 2010: Quality assessment of a 1985–2007 Mediterranean Sea reanalysis. Journal of Atmospheric and Oceanic Technology 28, 569-589.

Simoncelli, S., Fratianni, C., Pinardi, N., Grandi, A., Drudi, M., Oddo, P., & Dobricic, S. (2019). Mediterranean Sea Physical Reanalysis (CMEMS MED-Physics) (Version 1) [Data set]. Copernicus Monitoring Environment Marine Service (CMEMS). https://doi.org/10.25423/MEDSEA_REANALYSIS_PHYS_006_004

P10-11, L317-322, Fig. 2:

- **I would recommend to add the Chl-a unit on the next to the bar dedicated for a & b.**

The figure will be modified accordingly.

- **Also add the unit of the depth, on the profiles or the caption.**

For sake of consistency, we will add the unit of depth in the caption

- **You need to add in the caption that the vertical profiles are shown for the Mediterranean scale, Western Mediterranean, and Eastern Mediterranean. This was not mentioned in the corresponding text as well**

Agreed. The caption will be modified as follows:

"Fig.2 Average Chl-a in the first 10m in CTRL (a) for the period 2005-2020 and CMEMS-SAT (b) together with CTRL average vertical profiles (blue lines) for the period 2005-2020 of Chl-a (c,mg m^{-3}), PO_4 (d, mmol m^{-3}), NO_3 (e, mmol m^{-3}), Dissolved oxygen (f, mmol m^{-3}), DIC (g, µmol kg^{-1}), pH(h) and total alkalinity (i, µmol kg^{-1}). The averaged profiles are computed for the entire (MED), Western (WMED) and Eastern (EMED) Mediterranean Sea. The light blue areas represent the spatial standard deviation of the monthly model data. The model data are compared with CMEMS reanalysis (Chl-a and pH; Colella et al., 2016: Teruzzi et al., 2021) and observations provided by EMODnet (PO_4, NO_3, Dissolved oxygen, DIC, total alkalinity; Buga et al., 2018): annual mean (black squares) and related standard deviations (black bars). Depth is measured in meters."

Please write the unit appropriately for "µmol kg^{-1}" in the caption as well as throughout the ms.

The text will be modified accordingly.

P11, L338: Please add "such as…" instead of "as…".

The text will be modified accordingly.

P12, L354-355: Please make it clearer, i.e. General freshening of the upper layers and saltening of the intermediate layers are observed over the entire basin during the MID-FUTURE period (Fig. S3 in the supplementary materials).

Agreed. The sentence will be reformulated as suggested by the Reviewer.

P13, L382: Please edit: "Only for the Aegean Sea, the changes in the winter mixed layer maximum depth are less marked, …".

The text will be modified accordingly.

P14, Fig. 4: Please correct the presentation of scenarios in the plots: RCP 4.5 and 8.5 instead of RCP 45 and 85.

The plots will be modified accordingly.

P14, L404: Please delete both "the" in "the nutrients at the river mouths."

The text will be modified accordingly.

P16-17, Fig. 5-6: Please add the unit on both color bars. Please correct the presentation of scenarios: RCP 4.5 and 8.5 instead of RCP 45 and 85.

The figure will be modified accordingly.

P18, L445-449: Please try to make this sentence clearer, i.e. Between 2055 and 2075, the peak in both nutrients' concentration, for RCP4.5, timely corresponds to a peak in the inflow of nutrients at the Gibraltar strait (Fig. S7). Additionally, in both scenarios the intermediate layer of the Western basin, after 2035, experiences a negative tendency in the nutrient concentration which is greater than 0.01 mmol m^{-3} for PO_4 and 0.1 mmol m^{-3} NO_3, this is related to a reduced westward transport of nutrients associated with LIW (Fig.S5).

Agreed. We will reformulate the sentence as follows:

"Under RCP4.5, the peak in both nutrients' concentration, between 2055 and 2075, timely corresponds to a peak in the inflow of nutrients into the Alboran Sea (Fig. S7). Moreover, in both scenarios after 2035, the intermediate layer of the Western basin experiences a negative tendency in the nutrients concentration (greater than 0.01 mmol m^{-3} for PO_4 and 0.1 mmol m^{-3} NO_3) related to a reduced westward transport of nutrients associated with LIW (Fig. S5)".

P20, L479-80: Please add references here.

Agreed. The following references will be included in the manuscript:

Keeling, R. F., A. Kortzinger and N. Gruber Ocean Deoxygenation in a Warming World Annual Review of Marine Science 2: 199-229, (2010)

Shepherd, J. G., Brewer, P. G., Oschlies, A., & Watson, A. J.: Ocean ventilation and deoxygenation in a warming world: introduction and overview. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences,375(2102), 20170240, 2017

P20, L484: Please correct "in vertical processes' intensity".

The text will be modified accordingly.

P21, L489: Do you mean "in both basins"? Please correct.

Agreed. We will explicitly state that we are talking about**:**

"in both Western and Eastern Mediterranean"

P21, Fig. 9: Please correct the presentation of scenarios: RCP 4.5 and 8.5 instead of RCP 45 and 85.

The figure will be modified accordingly.

P21, L498: Please remove "the" from "both the scenarios".

The text will be modified accordingly.

P21, L499: Please add a "," after scenario.

The text will be modified accordingly.

P22, L508: Please add a "," after scenarios.

The text will be modified accordingly.

P22, L514: Please add a "," after scenario.

The text will be modified accordingly.

P22, L519: Please add a "," after scenarios.

The text will be modified accordingly.

P23, L526, Fig.11: Please add the unit on both color bars. Please correct the presentation of scenarios: RCP 4.5 and 8.5 instead of RCP 45 and 85. Please unify the term "Mid-FUTURE" in the captions and the plots.

We thank the Reviewer for spotting the errors in the figures and captions that will be modified accordingly.

P23, L535: Please write it "parts of the Levantine basin".

The text will be modified accordingly.

P23, L538: Please add a "," after FUTURE.

The text will be modified accordingly.

P24, L562: Please keep either "of approximately" or "of about".

The text will be corrected with "*of approximately*"

P26, L580: Please add a "," after FUTURE.

The text will be modified accordingly.

P27, Fig. 14: Why did you choose the abbreviation BACTC to bacterial biomass? It is not conventional. I would suggest to make it "BACT".

Agreed. The abbreviation will be changed to BACT

P27, L592: Please remove the "," after also, and add it before "the decline".

The text will be modified accordingly.

P28, L616-617: The influence of the air-sea CO2 exchanges on DIC concentrations in the Mediterranean were already highlighted in multiple studies, i.e.

from models

- **D'Ortenzio, F., Antoine, D. and Marullo, S., 2008. Satellite-driven modeling of the upper ocean mixed layer and air–sea CO2 flux in the Mediterranean Sea. Deep Sea Research Part I: Oceanographic Research Papers, 55(4), pp.405-434.**

for observations

- **Wimart-Rousseau, C., Lajaunie-Salla, K., Marrec, P., Wagener, T., Raimbault, P., Lagadec, V., Lafont, M., Garcia, N., Diaz, F., Pinazo, C. and Yohia, C., 2020. Temporal variability of the carbonate system and air-sea CO2 exchanges in a Mediterranean human-impacted coastal site. Estuarine, Coastal and Shelf Science, 236, p.106641.**
- **Hassoun, A.E.R., Fakhri, M., Abboud-Abi Saab, M., Gemayel, E. and De Carlo, E.H., 2019. The carbonate system of the Eastern-most Mediterranean Sea, Levantine Sub-basin: Variations and drivers. Deep Sea Research Part II: Topical Studies in Oceanography, 164, pp.54-73.**
- **De Carlo, E.H., Mousseau, L., Passafiume, O., Drupp, P.S. and Gattuso, J.P., 2013. Carbonate chemistry and air–sea CO 2 flux in a NW Mediterranean bay over a four-year period: 2007–2011. Aquatic geochemistry, 19(5), pp.399-442.**

We thank the Reviewer for the suggested references that will be included in the text.

P28, L620: Please replace "fairly" by "equal".

The text will be modified accordingly.

P28, L621: Please replace "consistently".

The text will be modified accordingly.

P28, L625: Please remove "than in".

The text will be modified accordingly.

P30, L649: Please remove the "s" from "produces".

The text will be modified accordingly.

P30, L651: Please correct the subscript in "pCO_2".

The text will be modified accordingly.

P30, L654-655: Please re-write, i.e. "consistent with the estimates of Solidoro et al. (2021)."

The text will be modified accordingly.

P30, L657-658: Do you mean "by the end of the 21st century for RCP8.5?". Please rectify.

We thank the Reviewer for spotting the error in the sentence. We will reformulate the sentence as:

"However, the fate of the absorbed carbon is quite different: the Western basin during the 21st century (RCP8.5 scenario) accumulates only 0.85 PgC , while 1.7 PgC are retained in the water column of the Eastern basin".

P31, Fig.17: Please write the unit appropriately for "µmol kg^{-1}" in the caption. Please correct the presentation of scenarios: RCP 4.5 and 8.5 instead of RCP 45 and 85.

The caption and figures will be modified accordingly.

P31, L673-674: I would recommend to also check Goyet et al. (2016), as the pattern of your results are somehow in harmony.

Agreed. We will reformulate the paragraph as follows:

"Consequently, to the CO_2 invasion and DIC increase, the change in the carbonic acid equilibrium causes a generalized decrease in pH, as also shown in Solidoro et al. (2022) in the case of the A2 scenario. The change in pH, which is very well correlated in time and space with the DIC change and almost similar in both Western and Eastern Mediterranean (as already projected by Goyet et al., 2016), is approximately 0.23 units by the end of the century in the RCP8.5 scenario (Fig. 18)"

P31, L675: I would suggest to mention "by the end of the 21st century for RCP8.5" or "by the end of the century for RCP8.5".

We will reformulate the sentence as:

"by the end of the century in the RCP8.5 scenario"

P3, L682-684: Please unify the term "Mid-FUTURE" in the captions and the plots.

The text and plots will be modified accordingly.

Discussions and conclusions:

P33, L689: Please add a "," after "In this study".

The text will be modified accordingly.

P33, L693: Please add a "," after "To the best of the authors' knowledge".

The text will be modified accordingly.

P33, L693-696: Please re-write this sentence taking into consideration the major comments above.

We thank the Reviewer for the comment that we have already addressed above. Following the suggestion we proposed to reformulate the sentence as follows:

"To the best of the authors' knowledge, this work is the first one which analyzes long-term eddy-resolving projections of the biogeochemical dynamics of the Mediterranean Sea under two different emission scenarios. In fact, the horizontal and vertical resolution (1/16° and 70 vertical levels) of the long-term projections here analyzed is higher than that of previous works available in the scientific literature that focuses on the area (e.g Lazzari et al., 2014; Macias et al., 2015; Richon et al., 2019; Pagès et al., 2020; Solidoro et al., 2022)

The use of eddy-resolving higher horizontal and vertical resolutions allows a more detailed representation of the vertical mixing and ocean convection processes, which play a fundamental role in the ventilation of the water column and in the nutrient supply into the euphotic layer of the basin (Kwiatkowski et al., 2020). Moreover, the use of a higher resolution for the projections has allowed to identify and characterize, for the first time, spatial gradients, existing in the same sub-basin (such as in the Adriatic Sea) or between coastal and open ocean areas (such as in the North-Western Mediterranean) that involve the signs and statistical significance of the projected changes for certain biogeochemical tracers and properties. This represents a clear advantage for the future assessment of climate change impacts on specific organisms, habitats or target areas."

P33, L718: Please remove the "s" at the end of "shows".

The text will be modified accordingly.

P35, L768-769: This sentence is important for coastal ecosystems, and needs thus better elaboration, and references too.

Agreed. We propose to reformulate the sentence as follows:

"On the other hand, the greatest threat considering the oxygen water content might be linked to the combination of surface warming and faster respiration processes in the coastal areas of the basin, which could result in hypoxia conditions and alteration of the local marine ecosystem functioning and structures (Bindoff et al., 2019)".

We propose to include the following reference corresponding to the IPCC report chapter dedicated to the ocean and cryosphere which provides an extensive review of the local effects of the deoxygenation on the marine ecosystems:

Bindoff, N. L., Cheung, W. W., Kairo, J. G., Arístegui, J., Guinder, V. A., Hallberg, R., ... & Williamson, P. : Changing ocean, marine ecosystems, and dependent communities. IPCC special report on the ocean and cryosphere in a changing climate, 477-587, 2019.

P35, L771-772: The exchanges via the Strait of Gibraltar are surely crucial, but there are other factors that should be taken into consideration such as the difference in the ventilation period between both basins, among other factors (i.e. Pujo-Pay et al., 2011; Álvarez et al., 2014; Stöven and Tanhua, 2014; Cardin et al., 2015; Hassoun et al., 2015; Goyet et al., 2016; etc.).

- **Álvarez, M., Sanleón-Bartolomé, H., Tanhua, T., Mintrop, L., Luchetta, A., Cantoni, C., Schroeder, K., and Civitarese, G.: The CO2 system in the Mediterranean Sea: a basin wide perspective, Ocean Sci., 10, 69–92, https://doi.org/10.5194/os-10-69-2014, 2014.**
- **Cardin, V., Civitarese, G., Hainbucher, D., Bensi, M., and Rubino, A.: Thermohaline properties in the Eastern Mediterranean in the last three decades: is the basin returning to the pre-EMT situation?, Ocean Sci., 11, 53–66, https://doi.org/10.5194/os-11-53-2015, 2015.**
- **Goyet, C., Hassoun, A., Gemayel, E., Touratier, F., Abboud-Abi Saab, M. and Guglielmi, V., 2016. Thermodynamic forecasts of the mediterranean sea acidification. Mediterranean Marine Science, 17(2), pp.508-518.**
- **Hassoun, A.E.R., Gemayel, E., Krasakopoulou, E., Goyet, C., Abboud-Abi Saab, M., Guglielmi, V., Touratier, F. and Falco, C., 2015. Acidification of the Mediterranean Sea from anthropogenic carbon penetration. Deep Sea Research Part I: Oceanographic Research Papers, 102, pp.1-15.**
- **Pujo-Pay, M., Conan, P., Oriol, L., Cornet-Barthaux, V., Falco, C., Ghiglione, J.F., Goyet, C., Moutin, T. and Prieur, L., 2011. Integrated survey of elemental stoichiometry (C, N, P) from the western to eastern Mediterranean Sea. Biogeosciences, 8(4), pp.883-899.**
- **Stöven, T. and Tanhua, T.: Ventilation of the Mediterranean Sea constrained by multiple transient tracer measurements, Ocean Sci., 10, 439–457, https://doi.org/10.5194/os-10-439-2014, 2014.**

We thank the Reviewer for the suggestion. The sentence refers to the particular case of DIC. It was worth noting how the two basins react differently to the same driver (i.e., the spatially uniform increase of atmospheric pCO2). Indeed, as suggested by the Reviewer, differences in resident times of water masses, which are in turn influenced by the different ventilation, circulation and influence of the exchanges with the Atlantic waters, can be indicated as the major cause of the different rate of carbon absorption and accumulation in the two basins. The sentence will be reformulated as follows:

"*This difference in the response to climate change between the Western and Eastern basins has been also observed for the dissolved inorganic carbon accumulation and reflects indeed different factors such as the different ventilation and residence time of water masses in the two basins as well as the exchanges in the Gibraltar Strait (e.g. Alvarez et al., 2014; Stöven and Tanhua, 2014; Cardin et al., 2015; Hassoun et al., 2019)."*

P35, L778: Please also compare it with Mediterranean projections (i.e. Goyet et al., 2016).

We thank the Reviewer for the suggestion. The sentence will be modified as follows:

"*The overall accumulation of CO_2 in the basin resulted in an acidification of the Mediterranean water with a decrease in pH of approximately 0.23 units, which is slightly lower than the 0.3 projected on a global scale (Kwiatkowski et al., 2020) and lower than the value in Goyet et al. (2016), who projected, using thermodynamic equations of the CO_2/carbonate system chemical equilibrium in seawater, a variation of 0.45 pH units in the basin under the worst SRES case scenario (0.25 pH units in the most optimistic SRES scenario). However, this last estimate probably tends to overestimate the future acidification of the basin, as it does not consider the decrease in the exchanges and the penetration of CO_2 across the ocean-atmosphere interface due to the warming of the water column (MedECC, 2020).*"

P35, L790-792: Is it possible to estimate these uncertainties? It would be great to mention the level of overestimation derived from the model compared to the present conditions.

We thank the Reviewer for the suggestion. The overestimation between model and observations will be discussed in section 3.1. However, we want to stress here that we do not expect these biases to significantly impact the conclusions of our work. This for two reasons: (i) the CTRL simulation is always removed from scenarios (and thus also the biases observed in the CTRL simulation are removed from scenarios), (ii) in the Discussions and Conclusions, we focused our attention mainly on the future trends in the biogeochemical variables rather than on the absolute values of the projected changes. In the case of two variables (oxygen and pH) the absolute values of the projected changes can be higher than the biases discussed in sect 3.1 (at least at the surface). In any case, the signs of the projected changes are robust in the sense that they are a consequence of simulated mechanisms (*e.g. temperature and respiration increase, weakening of the thermohaline circulation, increase in the stratification and so on)* that are extensively discussed in the manuscript but their absolute values could be affected by uncertainty because of these biases. Because of that we do not focus our attention on the absolute values at the end of the work but rather on the signs of the projected changes (as already done in previous scientific works such as Richon et al., 2019). In order to accommodate the Reviewer's comment we propose to write in the discussion and conclusions:

"Additional sources of uncertainties in the modelling framework can be traced back to the BFM biogeochemical model. For instance, in the present-day period the model tends to overestimate the chlorophyll-a at the surface and, even more, the oxygen concentration below 200 m (section 3.1). These overestimations can be propagated into the future projections. However, the conclusions of the present work should not be significantly affected by that because, at the same time, the CTRL simulation is also removed from both the scenario simulations. Moreover, the signs of the projected changes (not their absolute values) result from different physical and biogeochemical processes (e.g., temperature and respiration increase, weakening of the thermohaline circulation, increase in the stratification and so on) which are independent from the biases discussed in section 3.1."

P35, L794-801: A recent study by Gazeau et al. (2021) is a good fit in this section as well, as it highlights the potential impact of aerosol deposition (dust in this case) both in present and future climate conditions in the Mediterranean.

- **Gazeau, F., Ridame, C., Van Wambeke, F., Alliouane, S., Stolpe, C., Irisson, J.-O., Marro, S., Grisoni, J.-M., De Liège, G., Nunige, S., Djaoudi, K., Pulido-Villena, E., Dinasquet, J., Obernosterer, I., Catala, P., and Guieu, C.: Impact of dust addition on Mediterranean plankton communities under present and future conditions of pH and temperature: an experimental overview, Biogeosciences, 18, 5011–5034, https://doi.org/10.5194/bg-18-5011-2021, 2021.**

Agreed. We will reformulate the paragraph as follows:

"Atmospheric deposition is an important source of nutrients for the basin and it has been shown that the biogeochemical dynamics of the Mediterranean Sea is influenced by aerosol deposition (e.g. Richon et al., 2018, 2019). The projected decrease in the nutrient supply from intermediate and deep waters caused by climate-driven increase in the stratification, could increase the importance of the atmospheric deposition as a source of nutrients for the euphotic layer (Gazeau et al., 2021). Thus, possible future changes in the deposition of aerosols could influence the biogeochemistry of the basin and the nutrients concentration at the surface projected for the 21st century and depicted in Section 3.3. However, in both RCP4.5 and RCP8.5 simulations, a present-day phosphate and nitrogen deposition is used. Potential improvements will be achieved, indeed, by the inclusion of more accurate deposition information derived from CMIP6 global estimates for the 21st century (O'Neill et al., 2016)"

P36, L826: Please write it "such as".

The text will be modified accordingly.

Supplementary document:

Fig. S2: Please add the temperature unit on both color bars (°C). Please correct the presentation of scenarios: RCP 4.5 and 8.5 instead of RCP 45 and 85. Please correct "blue" instead of "blu".

The figure will be modified accordingly.

Fig. S3: Please correct the presentation of scenarios: RCP 4.5 and 8.5 instead of RCP 45 and 85.

The figure will be modified accordingly.

Fig. S4: Please correct the presentation of scenarios: RCP 4.5 and 8.5 instead of RCP 45 and 85. Please correct "blue line" instead of "blu line".

The figure will be modified accordingly.

Fig. S8: Please add the unit on both color bars. Please correct the presentation of scenarios: RCP 4.5 and 8.5 instead of RCP 45 and 85.

The figure will be modified accordingly.

Fig. S9-14: Please add the unit on both color bars. Please correct the presentation of scenarios: RCP 4.5 and 8.5 instead of RCP 45 and 85.

The figure will be modified accordingly.

Fig. S14: Why are you mentioning the DIC unit in ug kg^{-1} here while it is in µmol kg^{-1} in the text? Please adopt the second one.

The figure will be modified accordingly.