Reply to Reviewer #1

We thank reviewer #1 for the detailed comments in a very friendly manner. We addressed all points with our answer given in Italics following the original comment.

Comments

Line 23: I would say "was characterized"…then "is characterized"

done

Line 29: "Fresher" then "Less saline"

Changed to fresher

Line 32: Probably I missed the point in the sentence and thus I'm asking for some additional clarification. As far as I remember the formation of LIW is driven by the salinity. The Authors states that in response to the reduction of the inflow at Gibraltar there is an increase in the salinity in the east Med.. thus I would expect an increase in the LIW formation not a reduction..Could you please explain better this point?

The short-term effect of a local salinity increase would be an increased formation of LIW. But on longer terms the whole water column and, thus, the stability of the water adjusts to the higher surface salinity. See further discussion under your comment ***Paragraph 4.1 and 4.2***

Line 79: I would say "coupled" than "combined"

done

Line 93 onwards: How many biogeochemical tracers considers HAMOCC? How do you represent the phytoplankton in your model? As functional group? Please explain better and provide more information about

We extended the description of HAMOCC. It now reads:

HAMOCC includes a description of the full carbon chemistry, the cycling of nutrients (phosphate, nitrate, silicate, iron) and oxygen, and an extended NPZD-type plankton dynamic with 5 tracers (2 types of phytoplankton, i.e. bulk and nitrogen fixers, one zooplankton type, dissolved and particulate organic matter, the latter called detritus in the following). Phytoplankton growth depends on incoming light at the corresponding depth level, the availability of nutrients and temperature (Paulsen et al, 2017). HAMOCC includes detritus settling and remineralization of dissolved organic matter and detritus (aerobic and anaerobic) as well as production, gravitational sinking, and dissolution of opal and calcite shells (Ilyina et al., 2013, Mauritsen et al., 2019). Shell production is linked to plankton concentration changes with a preference to opal production as long as silicate is available (Ilyina, et al., 2013). Organic matter from primary production is composed of carbon, phosphorus, nitrogen, and oxygen according to a constant stoichiometry ($C:N:P:O_2$=122:16:1:-172, Takahashi, et al., 1985) and iron (Fe:P=366 10^{-6}, Johnson et al., 1997).

Line 128: How do you consider the period of 1000 year as suitable for the spin up? Did you check the kinetic energy? What about drifts in the tracers?

From our point of view, a 1000-year spin-up is sufficient for all simulated tracers in the water column. In Figure 1 below, we show the spin-up and the 1000 years of the experiment for the LGM state of GLAC-1D. The transient forcing from the parent simulation shows some variability, but not large trends over the years 22-20 kyrs BP (see Kapsch etal, 2022, doi.org/10.1029/2021GL096767, their Fig. 1b). Physical tracers (T,S) in medHAMOCC are quasi-stationary in the last 250 years of the spin-up phase with little variability induced by the transient forcing. Phosphate shows a higher variability, but no clear trend for the last 400 years of the spin-up. The transient forcing of the 1000 years following the spin-up induces much stronger variability .

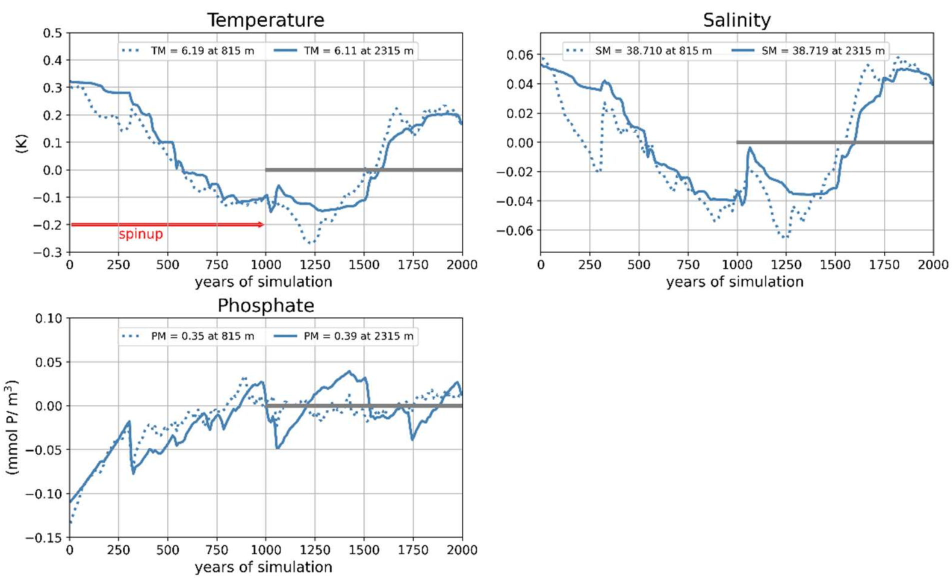

Fig 1: Variations of decadal means of temperature (upper left), salinity (upper right), and phosphate (lower left) at one location in the Levantine at two depth levels: 815 m (dotted line) and 2315 m (solid line). Shown are the deviations from the means of the years 1001-2000 (grey lines; the absolute mean values are given for each depth level in plots). The spin-up period is indicated by the red arrow in the temperature plot.

Line 133: what about the zenith and albedo?

We use monthly mean incoming downward short-wave radiation provided by the atmospheric parent model of the MPI-ESM. This includes direct and diffuse components of the downward short-wave radiation and diurnal zenith angle variations. Orbital parameter changes between LGM and PI are also considered in the MPI-ESM simulations. The albedo is set to a constant value in time and space in the physical component of our MedSed model. For the biogeochemistry, we calculate the light availability from the incoming downward short-wave radiation and light absorption due to clear water and due to the simulated phytoplankton concentrations converted to chlorophyll concentration (see Paulsen et al 2017).

Line 145 onwards: The Authors use an open boundary at Gibraltar Strait but they do not impose any speed. Could you please why? Is you E-P+R balance over the Mediterranean sea equal to zero or did you apply any correction to preserve the total volume of the domain? Please explain

The open boundary is not directly at the Strait of Gibraltar. We include part of the North Atlantic to 10°W (see Fig. 1) to allow for a more or less free development of the dynamics at the entrance of the MedSea. At the western boundary, we include an approx. 80 km wide sponge zone where water properties are relaxed to prescribed values. By setting sea level to zero at the western boundary we guarantee a nearly constant water volume in the model domain and a consistent water flux at the Strait of Gibraltar.

Line 185: "precipitation"

Corrected

Figure 2: As far as I remember Medar medatlas also provides the uncertainties for each variable and for each depth. I would include them in the figure as error bars to see if they overlap the values simulated by the model. Did you have an explanation for the difference in the oxygen vertical profiles with depth? Respiration processes?

We included the standard deviation of the Medar medatlas in Fig. 2. Basin averages are calculated from the mean values and their provided standard deviations.

Wrt to the difference in oxygen profiles: Oxygen profiles below the euphotic zone are shaped by an interplay between biological processes such as respiration and physical processes such as vertical mixing, the effectiveness of which depends on the water column stability. In view of the impact of biological drivers on oxygen, we see a complementary feature in the nutrient profile with less PO4 in the deep layers of the eastern basin than found in the Medatlas. Both profiles, oxygen and phosphate, point towards a too low export of organic matter and potentially too low primary production. The latter could be a result of a too low nutrient supply via the rivers. However, we base our simulation on literature values of river load (Ludwig etal. 2009) and did not do additional tuning. On the other hand, the Medar climatology may already include an anthropogenic signal from the riverine nutrient supply, which is omitted in our simulation. Wrt the physical drivers: the same figure shows that the temperature profile in the Levantine matches quite well the observations, while the salinity is too low compared to the climatology. This might indicate that we simulate a less stabile water column and thereby overestimate the potential of vertical mixing which, in turn, may lead to a too well-ventilated ocean.

Line 203 onwards: There are some recent results related to the Med ZOC simulated and discussed in Reale et al., 2022. I would include them here. Reale, M., Cossarini, G., Lazzari, P., Lovato, T., Bolzon, G., Masina, S., Solidoro, C., and Salon, S.: Acidification, deoxygenation, and nutrient and biomass declines in a warming Mediterranean Sea, Biogeosciences, 19, 4035–4065, https://doi.org/10.5194/bg-19-4035-2022, 2022.

Reference included

Line 204: All the listed areas are characterized by deep water formation processes. The Rhodes gyre is the area for the intermediate waters. Please correct

Our statement refers to the model state. However, even in the real world, intermediate and deep water are formed in the south of the region that we define as Aegean basin (Fig. 1), i.e. the Cretan Sea with the Cretan Intermediate Waters (CIW) and the Cretan Deep Waters (CDW) and in the Rhodes Gyre for the Levantine Intermediate Waters (LIW) and the Levantine Deep Waters (LDW) according to Simoncelli and Pinardi (3.4. Water mass *formation processes in the Mediterranean Sea over the past 30 years, in Schuckmann et al.,2018, Copernicus Marine Service Ocean State Report, Journal of Operational Oceanography, https://doi.org/10.1080/1755876X.2018.1489208). We did not change the sentence.*

Line 209 onwards: I would provide more quantitative information here about the differences between simulated and observed values. The Authors could use for example for the NPP the table 4 in Reale et al., 2020 Reale, M., Giorgi, F., Solidoro, C., Di Biagio, V., Di Sante, F., & Mariotti, L., et al. (2020). The regional Earth system Model RegCM-ES: Evaluation of the Mediterranean climate and marine biogeochemistry.

We added a table in Appendix A which provides the annual mean net primary production of GLAC-1D and ICE-6G for the PI and a selection of literature values. We added in the main text: "Compared to satellite derived estimates from Uitz et al (2012), our simulated NPP is rather on the low side, but fits well within the range of other modelling studies (Table A1). However, the absolute value of the NPP is not so relevant for our study. The amount of exported nutrient from the surface layers below the euphotic zone is more important, as it shapes the nutrient profile."

Line 220 onwards: 10-20 % is not slightly higher. Please correct

We agree and deleted the word "slightly".

Figure 7 and Paragraph 4 The authors talk about anomalies and biases. As far as I see they are differences. I would call them like that. I would test if these differences are statistically significant and I would mark the map with a dot where this happens.

The word "anomaly" is the common nomenclature to refer to the difference between temporal mean tracer distributions e.g. the LGM and the PI (see e.g. Kageyama et al., The PMIP4 Last Glacial Maximum experiments: preliminary results and comparison with the PMIP3 simulations, Clim. Past, 17, 1065–1089, https://doi.org/10.5194/cp-17-1065-2021, 2021).

Regarding the term "bias":

1) *We use the term in connection of the comparison of model results with observations or reanalysis data (e.g. the description of the bias correction in line 147). All models exhibit spatial deviations from "reality" which result, among other things, from the temporal and spatial resolution or the parameterization of the processes.*
2) *Biases are also mentioned when describing paleoceanographic tools, such as the alkenone unsaturation ratio to estimate the annual mean sea surface temperature. We follow here the nomenclature of the authors (e.g. Conte et al., 2006, Global temperature calibration of the alkenone unsaturation index (U37 K03) in surface waters and comparison with surface sediments, Geochem. Geophys. Geosyst., 7, Q02005, doi:10.1029/2005GC001054)*

There is no use for carrying out a statistical analysis. We averaged our data over 1000 years and the obtained LGM and PI mean states are very different. Changes are everywhere much larger than e.g. the temporal variability of the PI state. We expect insignificant signals only in the few areas where is anomaly is close to zero.

Line 262-264: Could you explain better this point since it is not very clear

To understand the pronounced increase in SSS that is found in the Ionian Sea, we have to look at circulation changes in more detail. We added here only a note on the later discussion on pycnocline changes.

Paragraph 4.1 and 4.2 as far as I understand from the results the SST gets colder and thus I would expect a decrease in the vertical stability and increase in deep water formation processes. Could you please explain better why happens the opposite?

*As stated above (see our answer to your comment on **line32**), a short-term change in sea surface properties, either a colder SST or increased SSS, will, of course, lead to enhanced deep-water formation. But if we run the model persistently with colder SST and higher SSS as provided by the LGM conditions, starting e.g. from PI conditions for T and S in the water column, the enhanced deep-water formation fills up the entire deep basins and increases the water column stability. It will take a long time for the surface signal to change the entire MedSea conditions so that dense enough water can form again to overcome the stratification.*

However, the dominant effect is related to the reduction and shallowing of the inflow at the Strait of Gibraltar which alone causes a shallowing of the pycnocline depth (Rohling, 1991). Rohling also demonstrates that the reduced inflow invokes an increase in the salinity contrast between the upper und the deeper layers. The pycnocline depth change due to a reduced inflow is shown by our sensitivity study PI-Straits (Fig. 10b in the paper). Figure 2 shows the changes of the surface salinity in PI-Straits due to the reduced exchange at the Straits of Gibraltar and the corresponding maximum mixed layer depth (MLD) over 2000 years of one location in the eastern basin. As mentioned in the paper, the slow-down of the ZOC increases the residence time of the water in the eastern basin and leads to the SSS increase. This SSS increase invokes deep MLDs in the first 400 years during the spin-up. After this time of circulation adjustment, MLDs in PI-Straits are lower than in the PI experiment which indicates the increased stratification.

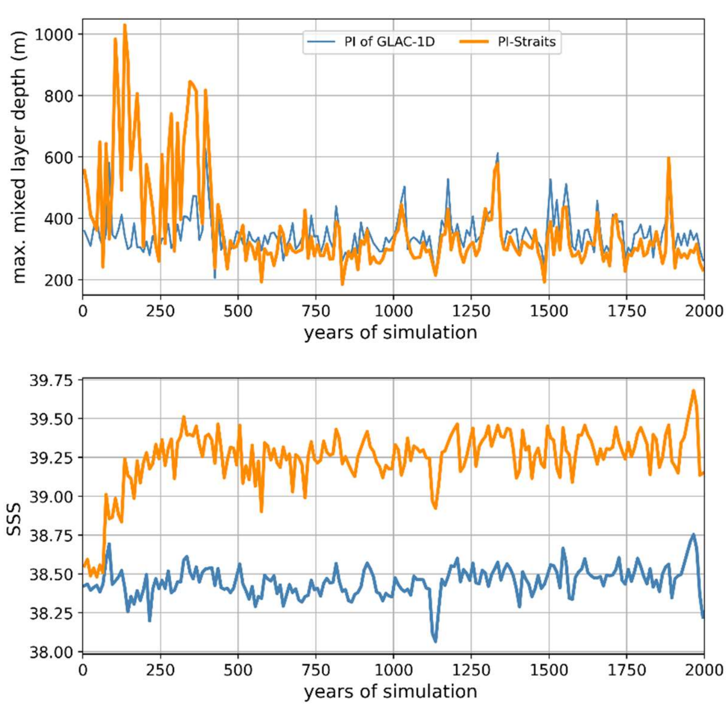

Fig 2: Time series of maximal annual mixed layer depth (upper panel) and sea surface salinity (lower panel) for a point south of the Peloponnese for PI of GLAC-1D (blue) and PI-Straits (orange) over the 1000 years spin-up and 1000 years used for analysis. Salinity data are 10yr averages, mixed layer depths are the seasonal maximum of decadal data.