Response to reviewer 1

General comment on "Climate change signal in the ocean circulation of the Tyrrhenian Sea" by Alba de la Vara et al.

Thank you for your positive evaluation on our manuscript. We believe that the raised comments have helped us to attain a more complete and robust version of the manuscript.

The manuscript addresses future changes that could take place in the Tyrrhenian Sea (TS) circulation by the end of the current century under the "business–as-usual" high-emission RCP8.5 scenario. Authors use the regionally-coupled climate model ROM (from REMO-OASIS-MPIOM) to conclude that surface mesoscale patterns in the basin are slightly modified, which authors asc,ribe to changes in water transport across Sardinia Strait and mechanical energy transfer from wind field to the ocean in the vicinity of Bonifacio Strait. More interesting is the conclusion that the flow from the TS into the Liguro-Provençal basin will weaken and the advected waters will be more stratified, speculating about the possibly hampering of winter deep water formation in the Gulf of Lions by the end of the century. While the objective of the manuscript is of interest, a question that arises is why authors made up their mind to select the TS instead of the critical areas of intermediate and deep water formation, focusing on these important processes. Such a study would provide a deeper insight on the future evolution of the Mediterranean Sea circulation. I would like to have read a sentence explaining the reasons and the pros of their selection against the other alternatives.

Thank you for the comment. The main reasons to choose the Tyrrhenian Sea are the following. First, it features distinct winter and summer surface circulation patterns with an enriched in dynamical mesoscale-size structures in summer. Thus, from a modeling perspective it is a challenging area and the study of the future evolution of these patterns is of interest. Second, because the Tyrrhenian Sea is connected to the Liguro-Provençal basin and the waters that reach this area from the Tyrrhenian play an important role in the preconditioning for deep water formation in the Gulf of Lions. Therefore, changes in the water properties within the Tyrrhenian Sea inherent to climate change may have an impact on deep winter convection in the Gulf of Lions, which is important for the hydrographic properties of the Mediterranean Sea water, its thermohaline circulation and thus sea-bottom ventilation. Third because, to our knowledge, there are no studies devoted to the study of changes in the Tyrrhenian surface circulation in future climate. This insight will be added to the Introduction, to make it clear our choice to focus on the Tyrrhenian Sea. This being said, we agree that critical areas of intermediate and deep water formation have to be analyzed. However, given the complexity of these water formation processes, they merit a separate in-depth study.

In its present form, there are some points that should be considered and revised or completed. My objections refer to the model set-up, mainly the (boundary?) condition at Gibraltar, and to the validation. The review only addresses these two aspects and it does not include specific comments, technical corrections or typing errors.

Thank you for your consideration. The ROM coupled system does not use any boundary conditions at Gibraltar. Actually, the oceanic component of our coupled model is global and the boundaries of the atmospheric component are located far from Gibraltar. As previously exposed in Parras-Berrocal et al. 2020: "ROM introduces the novel approach of implementing a global ocean model with high horizontal resolution at regional scales. This allows us to obtain information of the global ocean maintaining the high spatial resolution in the coupling area. The model simulates explicitly the exchange of water through the Strait of Gibraltar and the Dardanelles, taking into account the signals from the neighboring basins (i.e. Atlantic Ocean), which are essential to include the large-scale feedbacks in the climate signal of the Mediterranean."

In response to this comment, this will be more clearly explained in the model setup in the revised version of the manuscript.

MODEL SET-UP

One of the ms main conclusions is the future enhanced stratification in the TS, which is the joint result of the expected SST increase in a warming ocean and the freshening of the surface water. Whereas the SST increase is an undisputed fact, the freshening is not. Obviously, it must be the result of a fresher Atlantic inflow through the Strait of Gibraltar, which has consequences on the whole Mediterranean Sea, not only in the TS.

Indeed, the freshening of Atlantic inflow has consequences in the Mediterranean Sea, more evident in the Western Mediterranean. As shown in Parras-Berrocal et al. (2020) the SSS in the Western Mediterranean under the RCP8.5 is expected to slightly reduce (from −0.5 to −1.0 psu; see Figure 1R). The authors point out that this freshening is a direct consequence of the North Atlantic Ocean, accounted through the ROM global ocean component. Moreover, as shown in Soto-Navarro et al. (2020), the freshening of the surface waters in the Western Mediterranean is a robust feature in the coupled regional simulations analyzed in that paper. In response to this comment, the robustness of the results regarding the future signal of the SSS in the Mediterranean Sea will be mentioned in the revised manuscript in Section 3.3.

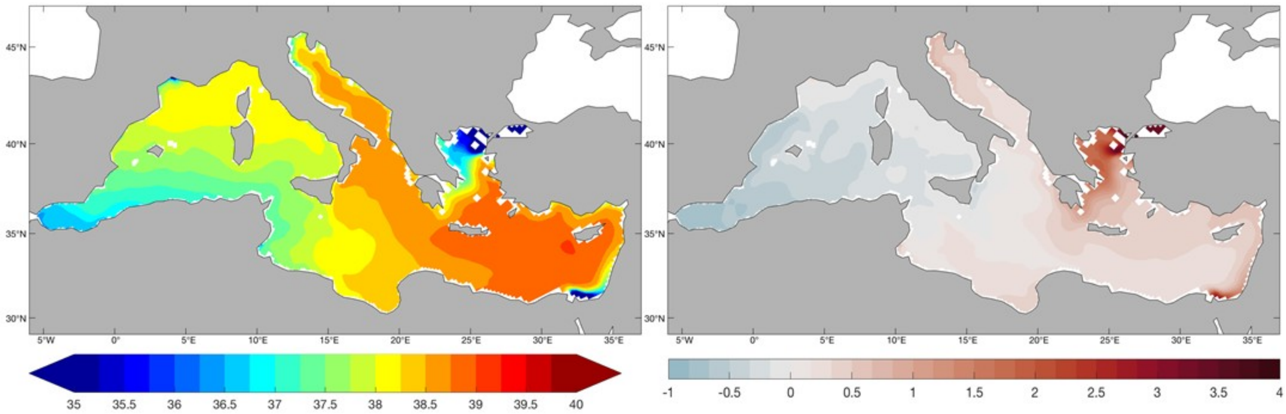

Figure 1R. Mean SSS (left, in psu), averaged over the 1976–2005 period (ROM). Differences between mean SSS (right, in psu) in RCP8.5 projection (2070–2099) and present climate (1976–2005). Taken from Parras-Berrocal et al. (2020).

This surface freshening together with the expected warming of the whole water column will strengthen the stratification in the Tyrrhenian Sea in the future. As a result, higher values of stratification index (SI) express higher stratification of the water column. In our simulations (Figure 2R), there is a general increase of the vertical stratification in the Tyrrhenian Sea at the end of the 21st century, especially in summer.

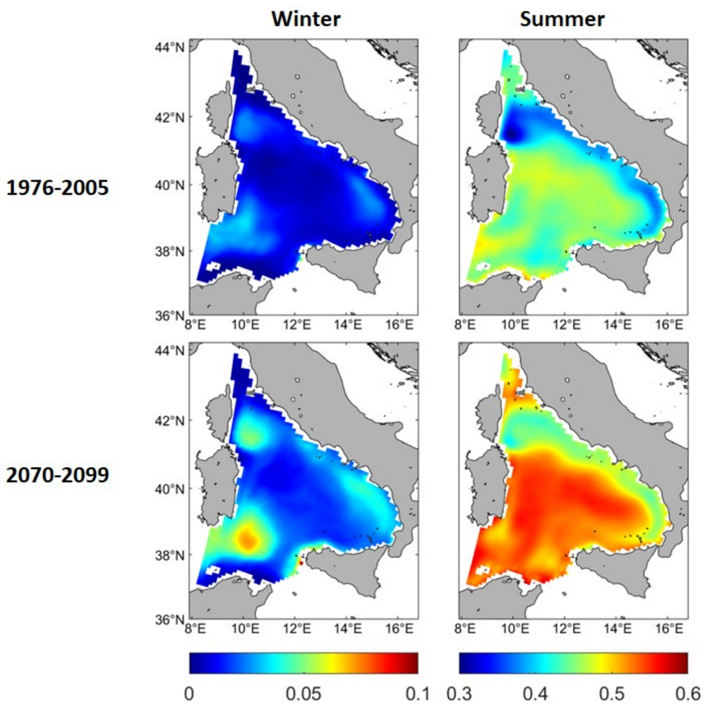

Figure 2R. Stratification Index map (in m^2/s^2) averaged for the periods (i) 1976-2005 and (ii) 2070-2099 computed from the surface to 51 m depth.

And obviously again, all the results of the modelling (not in the TS uniquely) rely critically on the validity of this boundary condition. Except for a vague sentence on lines 104-105 ("the water exchange at Gibraltar and Dardanelles in ROM is not parameterized and Atlantic water properties are not relaxed towards climatological values in the areas adjacent to the straits"), nothing else is said about this critical point, as if the future freshening of the Atlantic inflow were a proven result or another indisputable fact. Does this result come from MPIOM global model? Authors must be much more explicit about this point, discuss its validity and assess how sensitive their conclusions are against small changes of Atlantic inflow salinity.

This comment has already been addressed in the previous response. As pointed out by the Reviewer, the freshening of Atlantic inflow comes from the global oceanic component of ROM (MPIOM). Soto-Navarro et al. (2020) also found a freshening of the Western Mediterranean under RCP8.5 scenario in several Regional Climate Models and their explanation for the SSS reduction in the Western Mediterranean is related to the Atlantic conditions. Furthermore, they also pointed that “different models advect the fresher waters from the Arctic following different paths, and in some cases they may arrive close to the Iberian Peninsula and thus affect the waters entering into the Mediterranean, as seen by Gomis et al. (2016)”. In response to this comment, we will expand this issue further in the revised manuscript.

Similar considerations can be extended to the strength and size of the exchanged flows through the Strait of Gibraltar, which should be notably increased if the density contrast between inflow (warmer and fresher) and outflow increases. Could authors show the ROM forecast for these variables in the “Model setup” section and extend the section by addressing the conditions that hold at the western boundary of the Mediterranean. It is necessary in order to support adequately the conclusions of the paper and to discuss how robust they are against changes of those conditions.

Thank you for the comment. As we explained above, ROM does not use boundary conditions for the Mediterranean Sea, and the exchange flows at the Strait of Gibraltar are explicitly simulated, obviously accounting for changes in surface and internal pressure gradients originating from changes in SSH and water masses characteristics, with a resulting net water flow that must compensate the net evaporation (Evaporation - Precipitation -River Runoff) over the whole Mediterranean. Indeed, as pointed out by the Reviewer, the density contrast between inflow and outflow increases by 0.2 kgm^{-3} (nearly 10% of the density contrast) from the 2006-2040 (1026.8 kgm^{-3} for inflow and 1028.7 kgm^{-3} for outflow) to the 2070-2099 (1026.3 kgm^{-3} for inflow and 1028.4 kgm^{-3} for outflow) period. As a result, there is a slight reduction in both water inflow and outflow, but with a noticeable increase in the net water flow (from 0.037 Sv in 2006-2040 to 0.056 Sv in 2070-2099) in order to compensate for the increased net evaporation (E-P+R) over the Mediterranean basin in the 2070-2099 period. This point will be clarified in the revised manuscript, where it will be stressed that no boundary conditions are applied at the Strait of Gibraltar.

VALIDATION is addressed in a very light way in Section 3 (RESULTS), where it appears in different places along with the interpretation of the model outputs. AVISO geostrophic currents is the reference for validation, which is carried out by comparing the thirty-year period 1976-2005 averaged circulation from ROM with the thirteen-year (1993-2005) period of AVISO.

Many aspects of the simulations analyzed here have been validated in Parras-Berrocal et al (2020). However, for the sake of completeness, the validation of present time results will be expanded in the revised version of the manuscript, both the parts regarding the Mediterranean and the Tyrrhenian geostrophic circulation.

The reason why the time periods considered for the validation are not exactly the same is because AVISO data are only available since 1993. In order to address the reviewers' concerns, we have plotted some of the validation figures for the suggested time period. The geostrophic circulation of the Mediterranean Sea and the Tyrrhenian Sea computed from ROM and AVISO considering the 1993-2005 time period is represented in Figures 3R and 4R. As it can be observed, differences between the results obtained with ROM considering the 1993-2005 or the 1976-2005 time period are small and do not influence qualitatively our findings. Thus, for simplicity and consistency with figures shown in the Results, which have to be necessarily created with data from the 30 years 1976-2005 period, as recommended in the World Meteorological Organization Guide nº100, we will keep the latter period for the validation of the present-day Mediterranean and Tyrrhenian Sea, respectively. In response to this comment, we will mention the reasons why the AVISO and ROM data time periods are not exactly the same, and the consequences of our choice in terms of the results will be stated in the figure captions of Figures 2 and 3 of the manuscript.

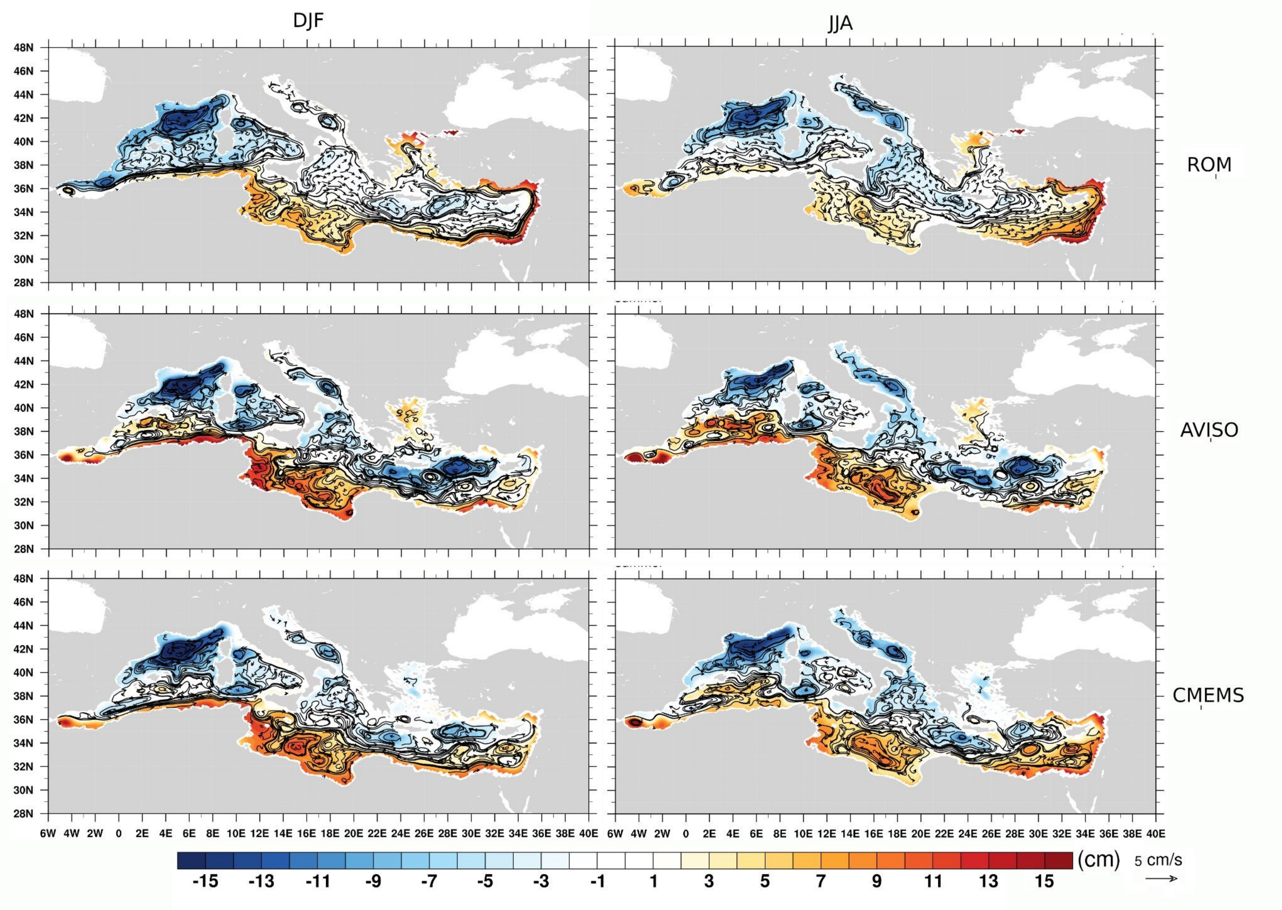

Figure 3R. Winter (left column) and summer (right column) averages of present-day Mediterranean geostrophic circulation (vectors, cm/s) and sea-surface height (SSH, colors, cm) from ROM (first row), AVISO (second row) and a CMEMS* reanalysis (third row). Results are computed with data from the 1993-2005 time period. Only one out of four vectors is plotted.

**The CMEMS reanalysis used for the revision is MEDSEA_MULTIYEAR_PHY_006_004, with a horizontal resolution of 4-5km (see https://resources.marine.copernicus.eu/?option=com_csw&view=details&product_id=MEDSEA_MULTIYEAR_PHY_006_004).*

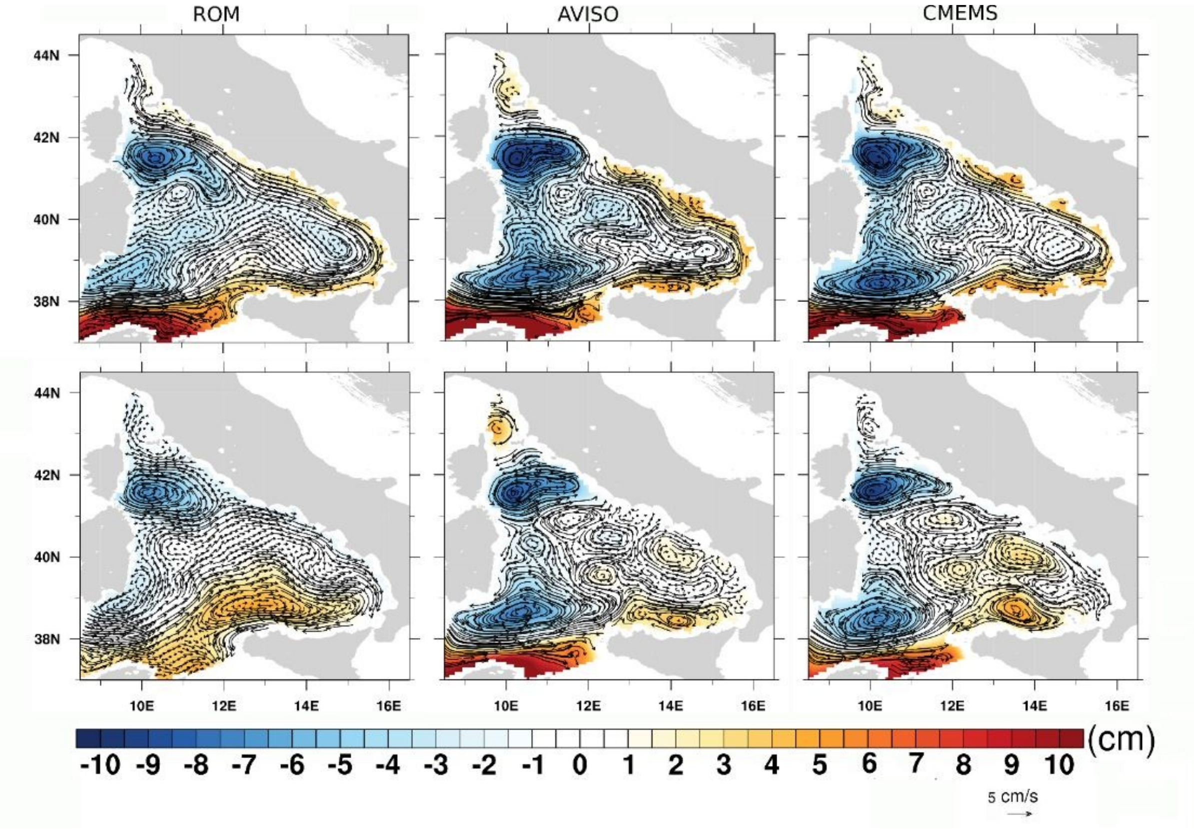

Figure 4R. Winter (upper row) and summer (lower row) averages of present-day Tyrrhenian geostrophic circulation (vectors, cm/s) and sea-surface height (SSH, colors, cm) from ROM (first column), AVISO (second column) and and a CMEMS reanalysis (third column). Results are computed with data from the 1993-2005 time period. Only one out of four vectors is plotted.

From Figure 2, it is difficult to conclude that both patterns agree satisfactorily, partially because of the poor resolution of the figure. Rather, the agreement seems to be only moderate if not arguable. But, even if it was satisfactory, the question that arises is why different time periods are used to average both data when ROM can use exactly the same period as AVISO. Why this mismatch of periods? Considering that the longer the averaging period the smoother the resulting pattern, the, for instance, disagreement between the mesoscale-rich circulation summer pattern in the TS from AVISO (Figure 3D) and ROM (Figure 3E) could be partially explained. In any case, the right way of comparing results is to make use of identical periods if possible.

As mentioned in above responses, the text regarding the validation of the Mediterranean and Tyrrhenian geostrophic circulation will be expanded. Also, the point regarding the different time periods considered for the evaluation and the changes that will be introduced in the manuscript were tackled in the previous response.

Reasons provided in lines 136-140 to focus on the surface geostrophic circulation for validation purposes are strange. Actually, using surface geostrophic circulation and/or sea surface height (SSH) from AVISO is out of necessity: they are the only available variables.

Thank you for your comment. We are not sure we understand your point but, for the sake of clarity, we prefer to keep the text as it was in the originally-submitted version of the manuscript, but stating that we use the Mediterranean version of the AVISO dataset.

The mention to the in-preparation paper by Parras-Berrocal et al. in order to justify the realistic representation of the main features of the surface circulation (lines 156-157) should be removed. If ROM is successful in doing this, the results should be either shown in this paper or referred to an already published paper, not to an in-preparation work.

Thank you for your recommendation. We will replace Parras-Berrocal et al. (in preparation) by Parras-Berrocal et al. (2020). There, the authors validate the ability of ROM to reproduce the Mediterranean sea-surface height for the 1980-2012 using AVISO. It is shown that ROM is able to successfully reproduce the main circulation structures in the Western Mediterranean (see Figures 11 and 12 of Parras-Berrocal et al. 2020).

Reference list

Gomis, D., Alvarez-Fanjul, E., Jordà, G., Marcos, M., Martínez-Asensio, A., Llasses, J. and Sotillo, M. G.: Regional marine climate scenarios in the NE Atlantic sector close to the Spanish shores. Sci Mar., 80:215–234, doi: 10.3989/scimar.04328.07A, 2016.

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