Response to reviewer 2

Review of the manuscript "Climate change signal in the ocean circulation of the Tyrrhenian Sea", by Alba de la Vara et al.

Thank you for your positive evaluation of our manuscript. The posted comments have helped us to achieve a more complete and robust version of the manuscript.

This work is devoted to the analysis of the future evolution of the circulation in the Tyrrhenian Sea (TS) under the pessimistic RCP 8.5 emission scenario. Using the outputs of the regional atmospheric-ocean coupled model ROM, the authors study the projected changes in the seasonal circulation patterns and the exchange through the main straits connecting the TS with the rest of the Western Mediterranean: the Sardinia Strait (SS) and the Corsica Channel (CS). The results show a weakening of the TS main cyclonic circulation and an enhancement of the mesoscale structures of this sub-basin. Authors attribute this changes to a reduced inflow of Modified Atlantic Waters across the SS and to an increase of the kinetic energy transferred by the wind. In addition, the results also show an increase of the water column stratification and a reduction in the water transport to the Liguro-Provençal basin across the CS, which may impact the deep water formation process at the Gulf of Lions.

For my review, I'll take advantage of the journal's format that allows me to read the comments of my fellow reviewer. I agree with him/her in the interest of this work, but I'm also surprised that the authors have chosen the TS as area of study. Given the potential of the model to reproduce complex dynamics processes in the whole Mediterranean, I coincide with reviewer #1's (R1) opinion that extending the region analyzed to, at least, include key processes like the deep water formation would have substantially increased the impact of the paper. Clarifying the reasons of this choice is important in my view.

Thank you for this comment. As exposed in the response to Reviewer 1, 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 given the potential of the model 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.

Nonetheless, the results obtained are relevant and well presented, and the conclusions are well-argued. However, I have some concerns about both formal and content aspects of the current MS.

Formal aspects:

My main recommendation here is that the differences between the future and present climates would be much easier to understand if they are directly represented in the figures. Instead of only plotting the average for the present and future, if you include a panel with their differences with a positive-negative color bar the reader will be able to rapidly identify the regions where the different magnitudes increase/decrease. I understand that this is tricky for the velocity vectors, but for the scalar magnitudes it would be of great help.

In response to this comment, Figures 4-11 have been updated to additionally include the differences between the future and present climate situation of the corresponding fields. The corresponding figure captions have also been accordingly modified.

Contents:

Model set-up: In general, I agree with R1 that the description of the model should be extended, more considering that one of the key results strongly depends on the modification of the MAW properties. It is important to understand how the Atlantic Waters are imported through the Strait of Gibraltar and which are the conditioning factors for their lower salinity. For instance, is the salinity of the GCM used as boundary condition for ROM, MPI-ESM-MR, driving the properties of the inflowing waters?

The oceanic component of ROM, MPIOM, is global and the use of any boundary conditions is not necessary. Therefore, the exchange flows through Gibraltar are explicitly simulated by our regionally coupled model. As the atmospheric domain is large and encompasses most of the North Atlantic, MPIESM influences the oceanic properties through the large-scale forcing on the atmospheric component of ROM. This aspect will be extended in the Model Setup of the revised version of the manuscript.

Validation: Following my previous comment, Parras-Berrocal et al. (2020) show that for a hindcast of ROM forced by ERA-Interim in the present climate the average SSS in the Mediterranean is between 1 and 2 psu higher than MPI-ESM. This result should be commented here or in the previous section to contextualize the results. It means that, for the present climate, the GCM could be underestimating the salinity. This doesn't necessarily mean that the projected freshening of the surface layer is wrong, but it is an important information in order to interpret the results. Comparing with the SSS projected by other regional models of the Mediterranean, particularly if they are forced by different GCMs, would also give more context to the results.

Regarding the differences in SSS between ROM and MPIESM, in Figures 4R and 5R, in response to a later comment, we compare in detail the SSS simulated by ROM with a high-resolution reanalysis from CMEMS and MPIESM in both the Mediterranean and the Tyrrhenian Sea. In the Mediterranean Sea, the global oceanic component of ROM (MPIOM) improves the SSS simulated by MPIESM relative to the high-resolution reanalysis.

The salinity simulated by ROM when forced by MPIESM has been validated individually in Parras-Berrocal et al. (2020) and in a multimodel study by Soto-Navarro et al. (2020). In Soto-Navarro et al. (2020) it is shown that in the present-time evaluation period (1987-2005) the ROM performance is similar to that of the other state-of-the-art regional coupled models participating in the MEDCORDEX project. Although the amplitude of the SSS seasonal cycle in ROM was lower than in the datasets used for evaluation, the amplitude of the seasonal cycle in the upper layer (0-150 m) as well as the standard deviation of SSS and the whole water column salinity in

ROM is close to the range of the datasets. In Section 3.3 of the revised manuscript we will add the following text: “We would like to emphasize that a detailed validation of ROM’s capability to simulate the present-time salinity and temperature over the Mediterranean Sea has been extensively studied (we refer the reader to Darmaraki et al. (2019); Parras-Berrocal et al. (2020) and Soto-Navarro et al. (2020) for details). In particular, ROM improves a strong negative bias in SSS present in MPI-ESM.”

In the validation of the geostrophic currents using AVISO altimetry data, I also agree with R1 that the results shown in figure 2 are not as conclusive as the authors claim, and that the comparison should be made using the same periods for the average.

As stated in the response to Reviewer 1, 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. We took 1976-2005 because 30-year time periods are recommended by the World Meteorological Organization for validation and 1976-2005 is the standard for the historical run validation in CMIP5. Nevertheless, we computed the geostrophic circulation of the Mediterranean Sea and the Tyrrhenian Sea for ROM, a CMEMS* reanalysis and AVISO considering the 1993-2005 time period (Figures 1R and 2R). 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 change qualitatively our findings. Thus, for the sake of simplicity and consistency with figures shown in the Results, which have to be necessarily created with data from the 1976-2005 period, 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. Also, the consequences of our choice in terms of the results will be stated.

** 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).*

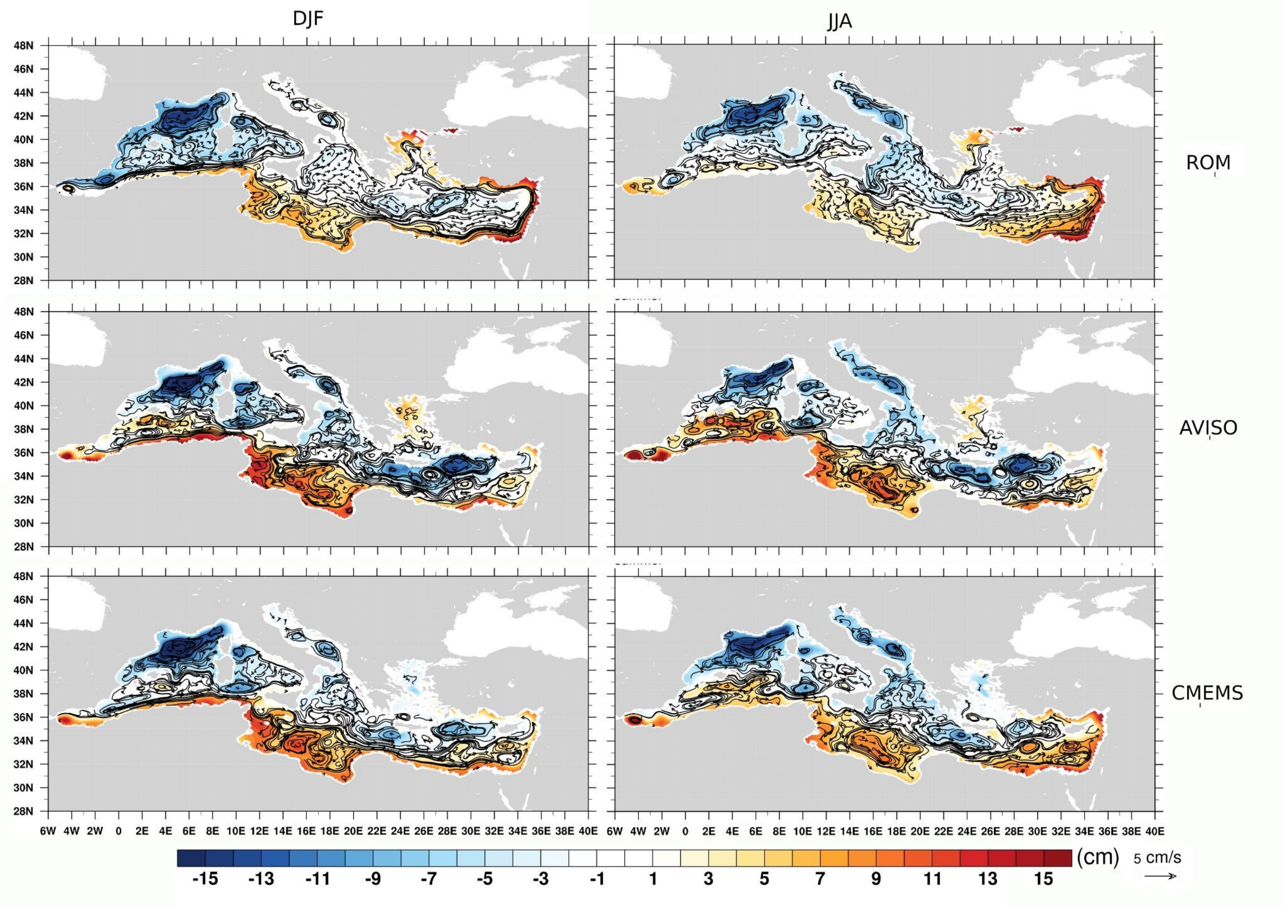

Figure 1R. Winter (left column) and summer (right column) averages of present-day Mediterranean geostrophic circulation (vectors, cm/s) and sea-surface height (SSH, colors, cm) from ROM (first row), AVISO (second row) and the CMEMS* reanalysis (third row). Results are computed with data from the 1993-2005 time period. Only one out of four vectors is plotted.

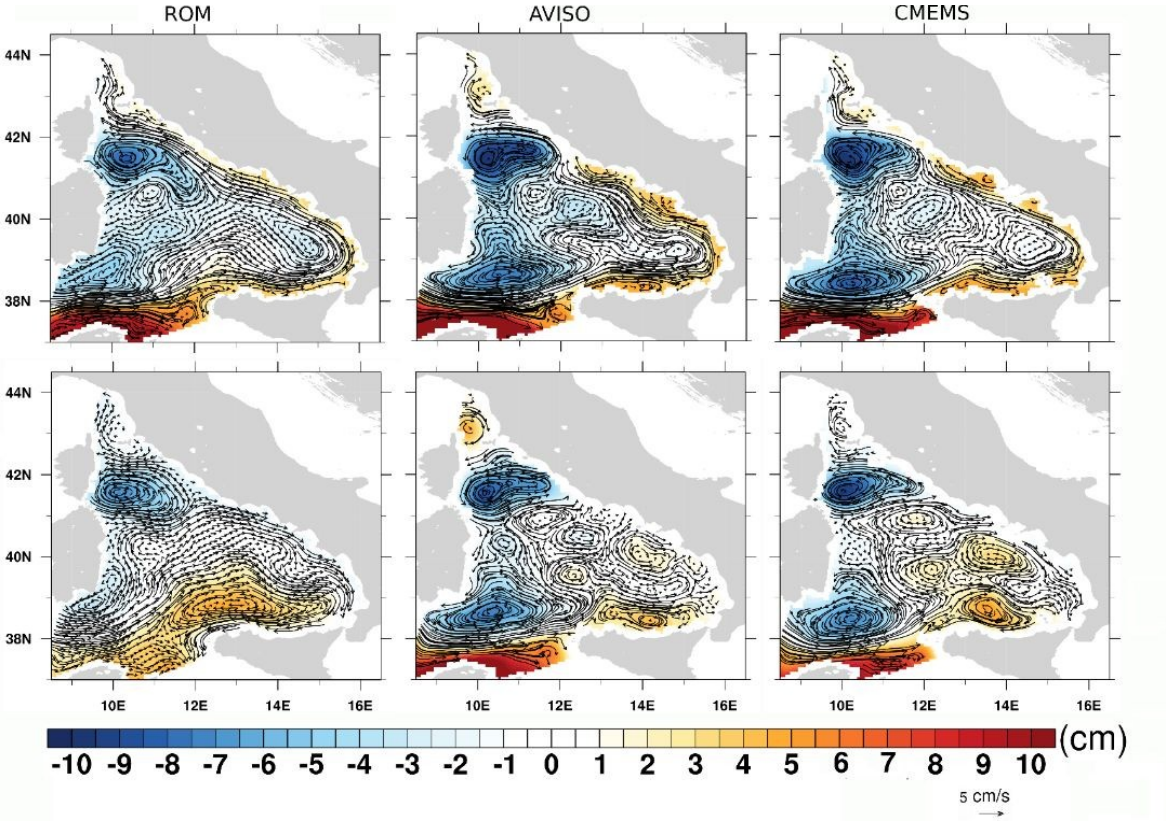

Figure 2R. Winter (upper row) and summer (lower row) averages of present-day Tyrrhenian geostrophic circulation (vectors, cm/s) and sea-surface height (SSH, colors, cm) from ROM (first column), AVISO (second column) and the CMEMS reanalysis (third column). Results are computed with data from the 1993-2005 time period. Only one out of four vectors is plotted.

Here a plot showing the difference between model and altimetry data would also be of great help to identify similarities/differences. A quantitative analysis, perhaps computing the spatial correlation in the area of study, would also help.

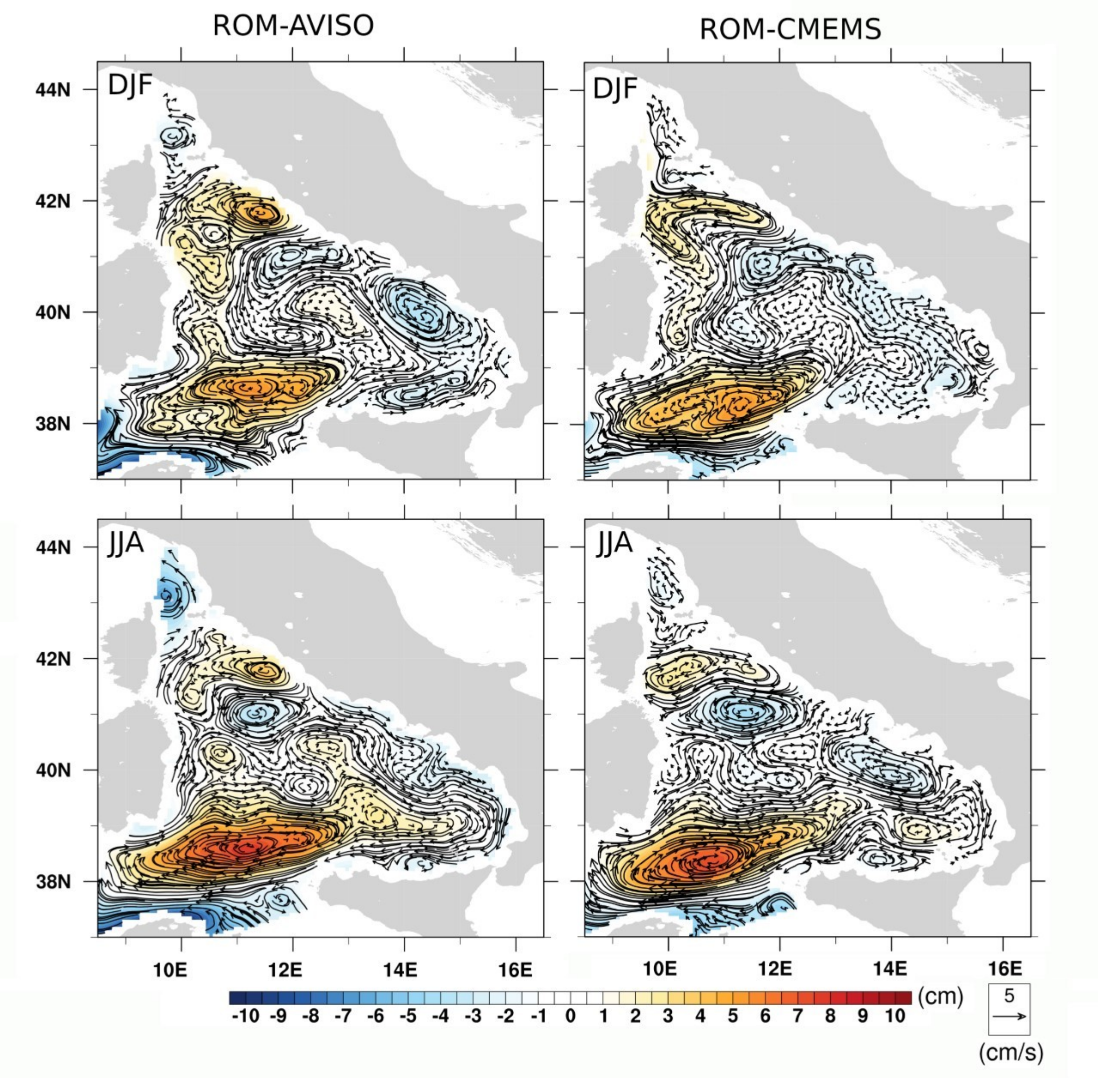

Figure 3R. Winter (first row) and summer (second row) differences of Tyrrhenian sea-surface height (SSH; cm) in colors and geostrophic circulation (cm/s) in arrows between ROM and AVISO (first column) and ROM and the CMEMS reanalysis (second column). Differences are computed for the 1993-2005 period. Positive values indicate that ROM simulates a greater SSH than the corresponding product and negative values the opposite.

In Figure 3R, the differences between ROM and AVISO, as well as between ROM and CMEMS for the present time period for winter and summer are shown. We note that regardless of the season the most important differences between ROM and the products occur to the south, near the recirculation cyclonic structure next to Sardinia, which is slightly weaker in the model. A likely major cause for these differences is probably the lower resolution of ROM's oceanic component relative to AVISO and the CMEMS reanalysis chosen. Nevertheless, the SSH is well correlated in both seasons: in winter, a correlation of 0.90 is found between ROM and AVISO SSH and 0.91 between ROM and the CMEMS reanalysis. In summer, the corresponding values are 0.64 and 0.73, respectively. In response to this comment, we will mention in the validation section of the revised manuscript that a good correlation is found between ROM and AVISO in both seasons.

Another point to be considered is extending the validation to include the seasonal cycle and the interannual variability, not only mean state for winter and summer, and including the SSS (as carried out by Parras-Berrocal et al. (2020) for the SST in the whole Mediterranean). This way if there is a bias in the SSS variability of the simulation in the present it could be identified and considered for the discussion of the results.

Thank you for your comment. However, in our view, this is out of the scope of the paper, the aim of which is to focus on the climate change signal on the circulation of the Tyrrhenian Sea. In this study, we provide a generic validation of the Mediterranean Sea circulation as a first step before focusing on the Tyrrhenian. A more exhaustive and complete validation of the Mediterranean Sea thermohaline properties is already done in Parras-Berrocal et al. (2020). As stated above, the text regarding the validation of the Mediterranean and Tyrrhenian geostrophic circulation will be expanded in the revised version of the manuscript. References to previous works will also be included where relevant.

Just for the review we include Figures 4R-6R, which show ROM's SSS biases for the Mediterranean and Tyrrhenian Sea, as well as ROM's SSS time series relative to other products. In Figure 4R we note that regardless of the season the SSS biases from ROM are smaller with the high-resolution reanalysis from CMEMS, being the magnitude of the biases much smaller than 0.5 psu, with prevailingly negative values in the Eastern Mediterranean. Regarding MPI-ESM, ROM presents positive differences of a magnitude close to 1 psu all over the Mediterraean basin. This fact reflects a negative bias in MPI-ESM with respect to CMEMS, which is partly corrected in our downscaling.

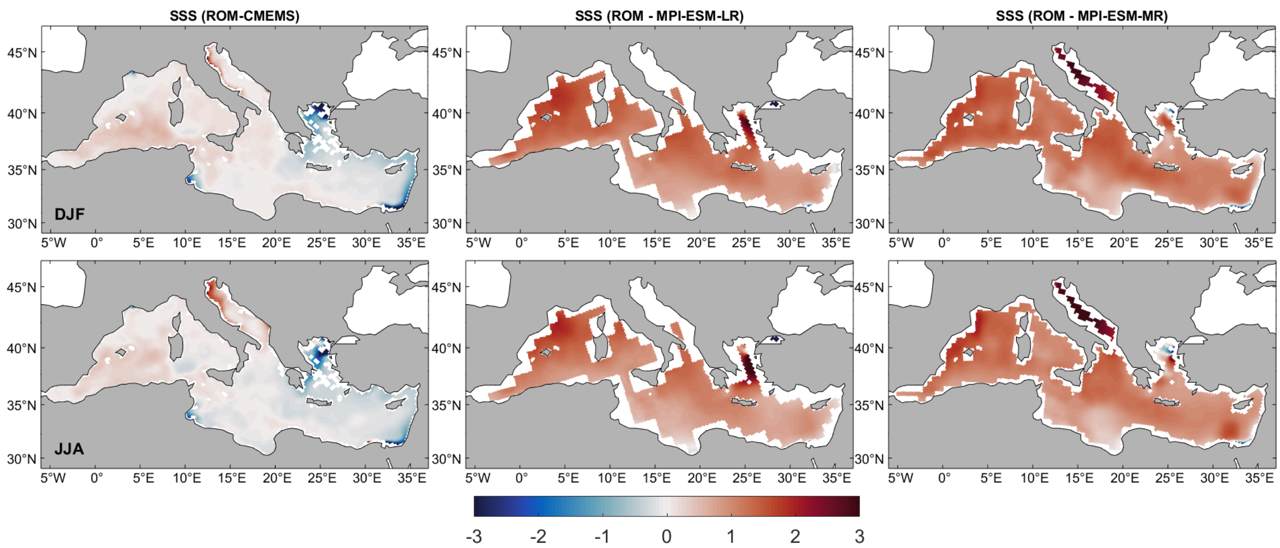

Figure 4R. Winter (first row) and summer (second row) differences of Mediterranean sea-surface salinity (SSS; psu) between ROM and the CMEMS reanalysis (first column), MPI-ESM-LR (second column) and MPI-ESM-MR (third column), respectively. Differences are computed for the present-time period (1993-2005). Positive values indicate that ROM simulates a greater salinity than the corresponding product and negative values the opposite.

In the Tyrrhenian Sea, as for the Mediterranean Sea, in both seasons the SSS biases from ROM are smaller with the high-resolution reanalysis from CMEMS, being the magnitude of the biases much smaller than 0.5 psu, with prevailingly negative values to the south of the basin (Figure 5R). With MPI-ESM, ROM presents positive biases of a magnitude close to 1 psu. Again, as for the whole Mediterranean basin, MPI-ESM shows a negative bias with respect to CMEMS, which is partly corrected in our downscaling.

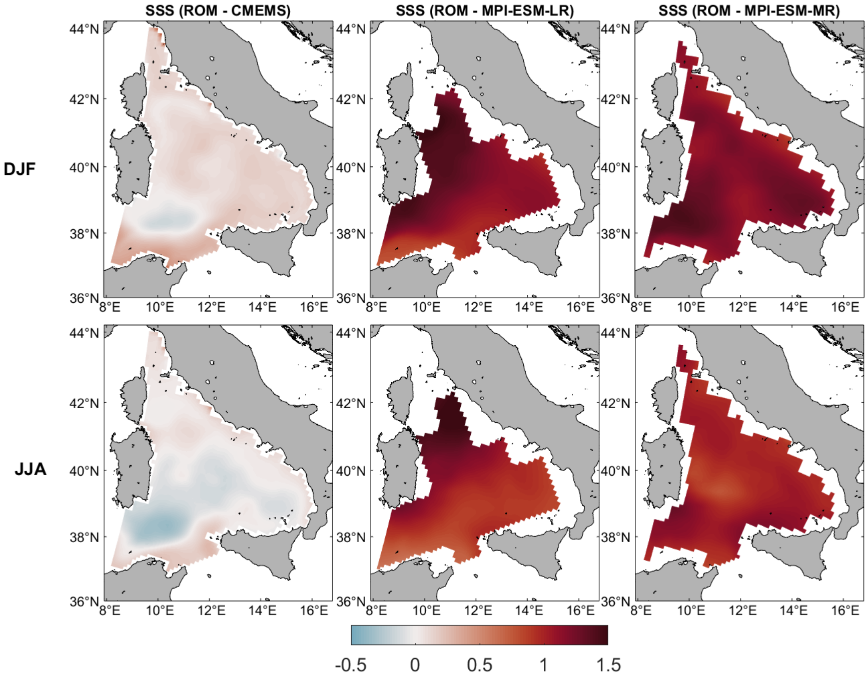

Figure 5R. Winter (first row) and summer (second row) differences of Tyrrhenian sea-surface salinity (SSS; psu) between ROM and the CMEMS reanalysis (first column), MPI-ESM-LR (second column) and MPI-ESM-MR (third column), respectively. Differences are computed for the present-time period (1993-2005). Positive values indicate that ROM simulates a greater salinity than the corresponding product and negative values the opposite.

In Figure 6R we observe that in the Mediterranean, the SSS is lower with ROM than with the CMEMS reanalysis. However, the interannual variability is relatively well represented, although with a small lag (upper panel). In the Tyrrhenian Sea, contrary to what happens in the Mediterranean, the SSS from ROM is generally slightly higher than that from the CMEMS reanalysis, and again the interannual variability is captured.

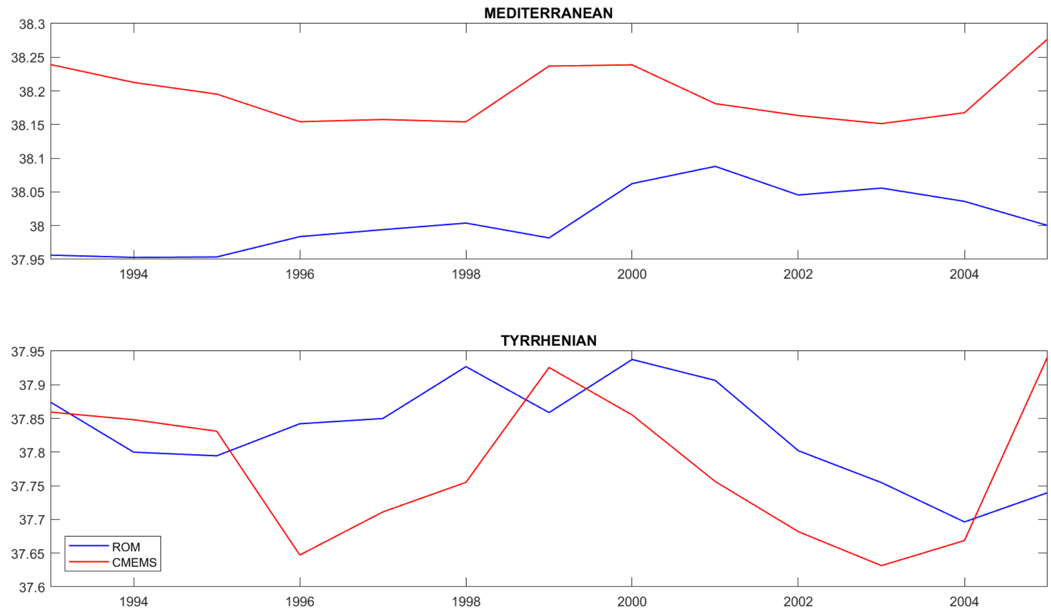

Figure 6R. Annual time series of sea-surface salinity (SSS), in psu, for the Mediterranean Sea (upper panel) and the Tyrrhenian Sea (lower panel). The blue lines highlight the results obtained with ROM and the red lines those for CMEMS.

At this point we would like to remark that the freshening of the Atlantic surface waters, and thus Atlantic inflow, has not only been found here and in Parras-Berrocal et al. (2020), but also in other simulations such those analyzed in Soto-Navarro et al. (2020), in which the SSS reduction appears to be a robust signal coming from the North Atlantic. This insight will be added to the revised manuscript.

Finally, the AVISO interpolated products in the Mediterranean have strong limitations representing mesoscale structures (see Amores et al. 2018, JGR https://doi.org/10.1029/2018JC014140). I would suggest complementing the validation using a reanalysis dataset.

In order to address this comment, here we show a comparison of our results to the chosen CMEMS reanalysis. In particular, Figures 1R and 2R the Mediterranean and Tyrrhenian geostrophic circulation from ROM, AVISO and the CMEMS reanalysis is presented. As it can be observed, differences between the results obtained from the comparison to AVISO and CMEMS, respectively, are small. Thus, in order not to make the figure much bigger in size, we prefer not to add the CMEMS results to the manuscript, but to stick to those obtained from AVISO given, again, the small differences between them.

Results, discussion and conclusions: In my view these sections are complete. Results are clearly explained and argued. My only suggestion is to include some of the referenced results, particularly those related to

the previous work of Parral-Berrocal et al. (2020) and to the reduction of the deep water formation in the Gulf of Lions (I agree with R1 that a work in preparation shouldn't be references).

Thank you for your comment. In this respect, we would like to add that the reduction of the deep water formation in the Gulf of Lions is not something that has been exclusively found in the aforementioned work, but also in former papers such as that from Soto-Navarro et al. (2020), in which this is seen as a robust feature of the regional coupled climate models of the ensemble used in the study. This work will be mentioned in the revised version of the paper.

Also, in the discussion section, I miss a comparison of the results for the future evolution of the different variables with previous work for the region. Are they consistent with other modelling studies?

As stated above, to our knowledge, there are no studies devoted to the study of the Tyrrhenian Sea in future climate. However, an effort will be made to provide more context, making use of available literature dealing with the study of the whole Mediterranean Sea in the future e.g., Ser-Giacomi et al. (2020).

Reference list

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