Response to Reviewer #2

We thank the Reviewer #2 for the effort in reviewing the manuscript and for her/his positive evaluation. The posted comments have helped us to improve the manuscript and make it more robust and complete.

Reviewer #2 (Comments to Author (shown to authors):

The authors investigated the variations of dense water formation (DWF) in the Eastern Mediterranean (EMed) through the twenty-first century under the RCP8.5 emission scenario for understanding the impacts of climate changes on the Mediterranean overturning circulation. Their results indicated that the dominant source of Eastern Mediterranean Deep Water (EMDM) shifts from the Adriatic Sea to the Aegean Sea during the 2005-2040 period. By the end of the century, DWF for the Adriatic Sea, the Aegean Sean, and the Levantine Sea all perform a pronounced decrease by 75%, 84%, and 83%, respectively, which is a result of hydrographic changes of surface and intermediate water and the associated strengthening water column stratification under the RCP8.5 emission scenario. The results shown are impressive and, as was pointed out in the manuscript, also fill in the gap of the DWF study in the EMed providing a more quantitative assessment than previous studies. The manuscript was also well-written and easy to follow. But some improvements may be needed before the publication.

1) The coverages of the Adriatic Sea, the Aegean, and the Levantine Sea should be specified and shown in a figure as results and discussions of this study focus on the DWF from these regions. Thus, it is important to provide the spatial extent of these basins, which can also help readers to understand the studied area better. In addition, as it was stated that the horizontal resolution of the model varies from 7 km to 25 km (which is a big difference, I think), it is better to show the computational grid as well.

Response: Thank you for the comment. In order to represent the spatial extent of each sub-basin and the oceanic computational grid, we have modified Figure 1 as follows:

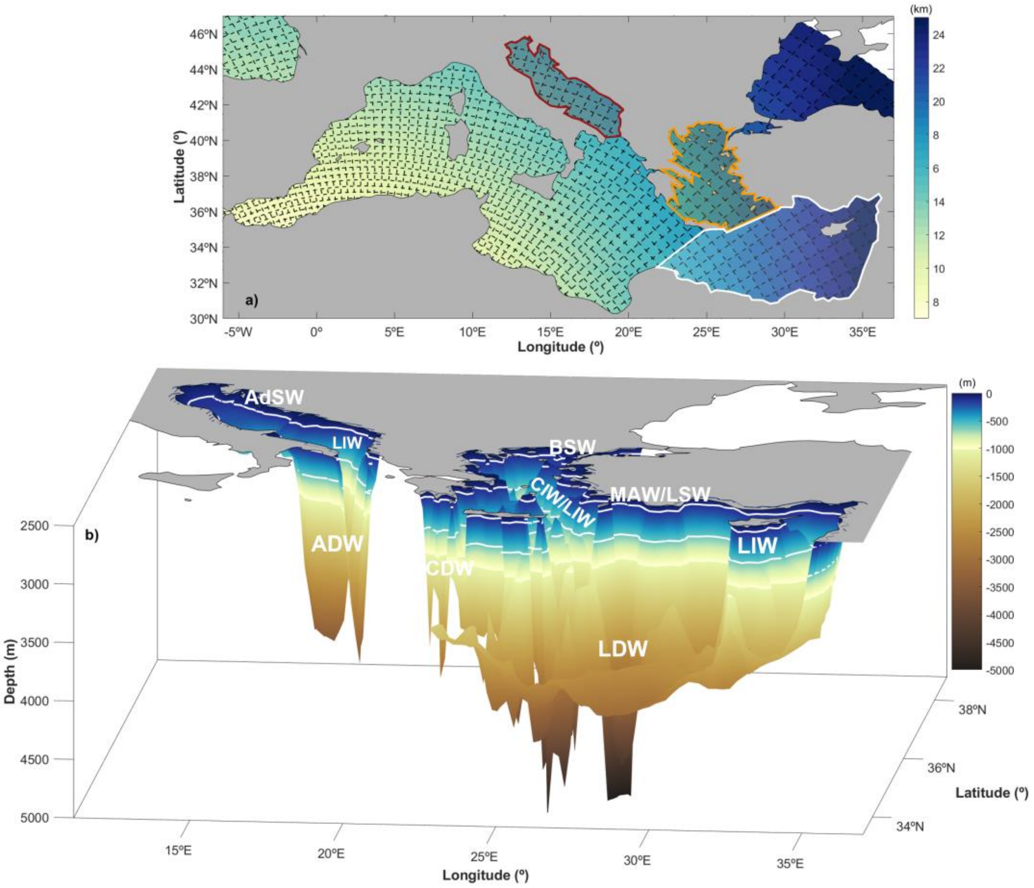

Figure 1. a) Oceanic computational grid and resulution adopted in ROM (in km, only one out of four lines are drawn). The domain used for the calculations in each sub-basin are souounded by color lines: Adriatic (red), Aegean (orange)

and Levantine (grey). b) Bathymetry of the main spots for dense water formation in the EMed: Adriatic Sea, Aegean Sea and Levantine Sea. The main water masses of each spot sorted by depth range are also shown: [0-100 m] Adriatic Surface Water (AdSW), Black Sea Water (BSW), Levantine Surface Water (LSW); [100-650 m] Levantine Intermediate Water (LIW), Cretan Intermediate Water (CIW); [650-1000 m] Adriatic Deep Water (ADW), Cretan Deep Water (CDW) and Levantine Deep Water (LDW).

2) Statistics analysis and parameters are needed. Firstly, the authors may need to provide p values for every correlation coefficient as they are important to illustrate the significance. Secondly, the 2040s was regarded as a time point around which sharp changes in SI and DWF (Figure 3) were observed. However, the author may need to provide a more convincing way to address this time point not just by the naked eye but using some statistical tools, like the non-parametric change-point Pettitt test (Pettitt, A.N. A non-parametric approach to the change-point problem. Appl. Stat. 1979, 28, 126–135).

Response: We agree with the reviewer. Therefore, we have tested every correlation coefficients at the 95% confidence level and the p-values obtained have been included in the revised manuscript. Now reads:

Line 111f: "The interannual DWF rate in the Adriatic Sea (Figure 2a) agrees well (r=0.70 at 95% of confidence level, p-value=0.001) with estimates based on the Princeton Ocean Model (POM) of Mantziafou and Lascaratos (2008)."

Line 116f: "On the other hand, the interannual DWF rate in the Aegean Sea (Figure 2b) is also well correlated (r=0.75, p-value=0.002) with the POM results reported by Nittis et al. (2003)."

Line 171f: "Our results indicates that the intensity of DWF rate is mostly determined by the SI (Pearson correlation coefficient (r) > 0.7 and p-values=0 in all regions), as low or high amount of water produced can be found with similar BL values (r < 0.1 and p-values > 0.05) (Figure 3)."

P-values for DWF rate vs. BL: Adriatic Sea (0.55), Aegean Sea (0.13) and Levantine Sea (0.78).

Following the indications of the reviewer, we have applied the non-parametric change-point Pettitt test in order to provide convincing result of abrupt shifts in SI and DWF rates.

Adriatic Sea: DWF rate (year = 2054, K= 2.937, p-value=0) | SI (year = 2039, K= 3.104, p-value=0)

Aegean Sea: DWF rate (year = 2040, K= 2.457, p-value=0) | SI (year = 2040, K= 3.639, p-value=0)

Levantine Sea: DWF rate (year = 2054, K= 2.918, p-value=0) | SI (year = 2041, K= 3.764, p-value=0)

Abrupt changes in DWF rates are projected to occur by 2054 in Adriatic and Levantine Seas while in the Aegean the shift happens by 2040. The expected SI changes in all regions take place around 2040. We will include these results in the revised manuscript.

3) Could you double-check the unit "Sv yr" which first appears on Line 113? If my understanding of the unit "Sv" is correct, Line 113 should be rewritten as:

During 1981-1999, ROM_P0 produces a total of 5.45 Sv of newly waters denser than 29.0 kg/m3 corresponding to an annual formation rate of 0.29 Sv…

Response: We are sorry for the confusion. We use "Sv yr" because we do not consider the DWF rate but the total volume of dense water formed, following Nittis et al. (2003).

4) Lines 202-211. Although the authors provided descriptions of SI for different periods, I am still not quite sure how the authors calculated the percentage contributions of different water bodies to the temporal changes in SI. Could you please provide some descriptions or equations to further address the calculation?

Response: We calculate the relative contributions of different water masses using the SI number of Figures S2, S3 and S4, as previously carried out in Parras-Berrocal et al. (2022).

We use data from Aegean Sea as example (see Table 1 of the manuscript):

The total SI change (Proj. – Hist.: 2.13-1.40 = 0.73 m^2s^{-2}) and the BSL/LSW layer accounts for (2.13-1.54= 0.59 m^2s^{-2}) whereas the CIW/LIW layer accounts for (2.13-1.99= 0.14 m^2s^{-2}).

Then, we applied a simple rule of three:

BSL/LSW: (((0.73-0.59)*100)/0.73) = 19.2 %

CIW/LIW: (((0.73-0.14)*100)/0.73) = 80.8 %

Thanks to the Referee comment we have detected an error/typo. We apologize for the error in lines 209-211, where the percentages of each contribution were mistakenly interchanged. We have changed it in the revised manuscript and now reads:

“In the Aegean Sea, the alteration in BSW/LSW properties leads the 19.2% of the total SI future change while the change in CIW/LIW is 80.8%. Finally, in the Levantine Sea changes in the MAW/LSW properties contributes in a 40% whereas LIW in a 60%.”

5) Lines 268-270. It may be a jump to conclude that the increasing potential density is caused by the increasing salinity over the upper 100 m, as the authors only compared the salinity changes and density changes (Figure S7) but ignored the contributions of temperature changes. As shown in Figure 4 subsurface (0-100 m) temperature seemly performs an increase in the ADR (Figure 4a) from the period of 2006-2020 to the period of 2020-2040 but fluctuates in the AEG (Figure 4c) and LEV (Figure 4e). Thus, the author may need to quantify both contributions of the changes in temperature and salinity to the changes in density.

Response: Thank you for the remark. In order to address this comment, we have evaluated the spatially and temporally averaged vertical profiles (0-100 m depth) of temperature, salinity, and density for the 2006-2020 (solid lines) and 2020-2040 (dashed lines) periods in the Adriatic, Aegean, and Levantine Seas (Figure R1). In the bottom row, we also show two synthetic density profiles: (red line) displays the density profile keeping the salinity fixed (2006-2020) whereas the temperature is evolving (2020-2040) and (blue line) the opposite.

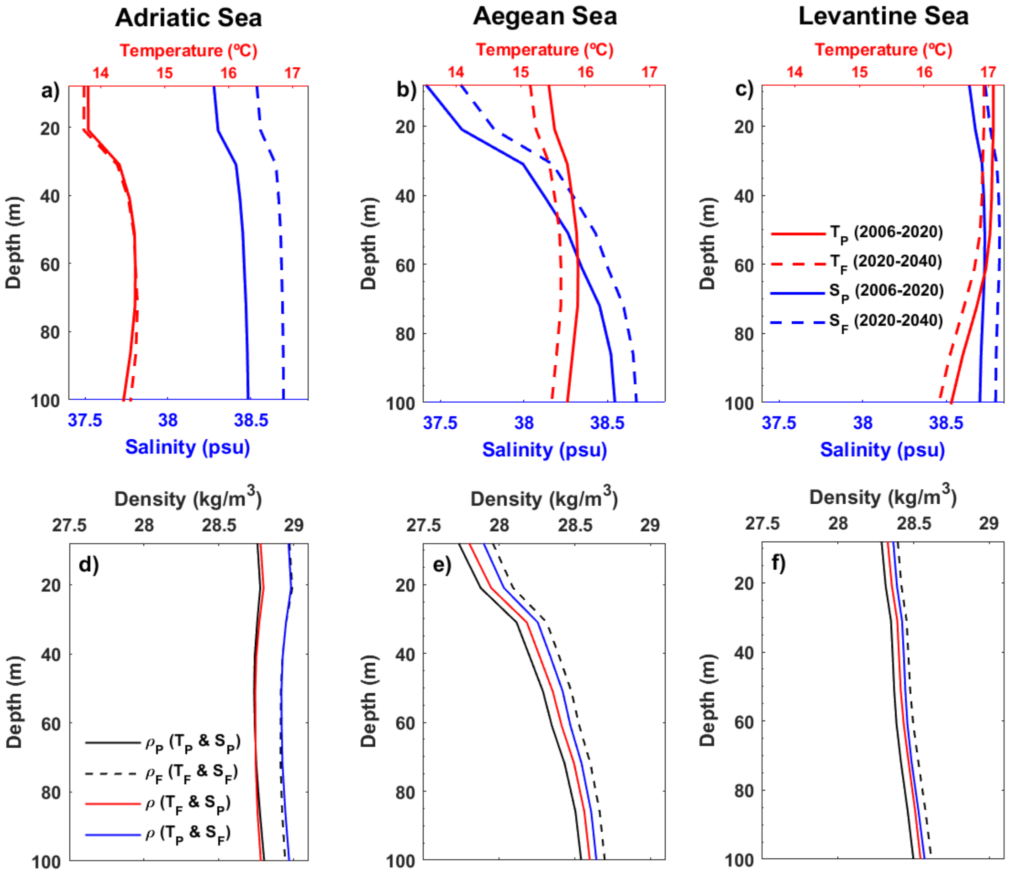

Figure R1. Spatially and temporally averaged vertical profiles (0-100 m depth) of temperature, salinity, and density for the 2006-2020 (present ($_{P}$), solid lines) and 2020-2040 (future ($_{F}$), dashed lines) periods in the Adriatic, Aegean, and Levantine Seas. (d, e, f) It is shown two synthetic density profiles: (red line) display the density profile keeping the salinity fixed (2006-2020) whereas the temperature is evolving (2020-2040) and (blue line) the opposite.

Table R1. Quantification of the relative contributions of temperature and salinity to changes in density calculate from vertical profiles presented in Figure R1.

	Adriatic Sea		**Aegean Sea**		**Levantine Sea**	
	ρ (kg/m^3)	**% of each contribution**	**ρ (kg/m^3)**	**% of each contribution**	**ρ (kg/m^3)**	**% of each contribution**
T_p-S_p (2006-2020)	28.76	-	28.23	-	28.38	-
T_f-S_f (2020-2040)	28.94	-	28.42	-	28.49	-
T_f-S_p	28.76	0%	28.29	31.6%	28.42	36.4%
T_p-S_f	28.94	100%	28.36	68.4%	28.45	63.6%

In the Adriatic Sea, changes in salinity are responsible of nearly the total density change expected in the 2020-2040 period (Table R1). In the Aegean and Levantine Sea, changes in salinity contribution to density changes (2020-2040) are 68.4% and 63.6%, respectively (Table R1). These results suggest that salinity changes are the only cause of those density changes in the Adriatic Sea and a primary factor in the Aegean and Levantine Seas. We will address this point in the revised manuscript.

6) Lines 270-271. The authors may need to provide more evidence in addressing the causes of the changes in the upper ocean circulation, like correlations between changes in salinity or temperature and changes in circulation patterns. Or to provide some mechanistic explanations on how the changes in salinity or temperature would lead to changes in circulation. Or to provide results of previous studies here that may have such discussions.

Response: Thank you for your comment. We agree with the reviewer. In lines 270-271, we advanced a suggestion that “the increase of the salt content in the 0-100 m layer could be the result of a change in the upper ocean circulation that alters the AW path”, which is clearly a hypothesis that needs further in-depth work and it is not properly placed. We understand that this further analysis is out of the scope of this work therefore we have decided to remove Lines 270f and the Figure S7 from the revised manuscript.

However, in order to provide an extended response to this comment we explored some of the possibilities indicated by the Reviewer, and we found in previous works (Gasparini et al., 2005; Incarbona et al., 2016) that in periods of intensified EMed DWF, for example during the EMT, there is a decrease in the salinity in the AW in the Sicily channel, which seems to be provoked by an enhancement in the MTHC which implies an increase in the energy inflow at the Strait of Gibraltar. Such more energetic inflow results in the AW more directly conveyed to the Sicily Channel, therefore less mixed with the surrounding resident water, resulting in a decrease of salt transport to the EMed in the upper layer through the Sicily Channel.

In fact in our results, a significant part of the period 2020-2040 (period with the higher DWF rates, Figure 3 of the manuscript) we found a negative upper layer salt transport anomaly through the Sicily Channel towards the Eastern basin. We have calculated the anomalies of salt transport through the Sicily Channel (Figure R3) by using a moving mean filter to reduce the noise signal, and then subtracting the trend of the time series. We detected that there is a certain significant negative correlation (r=-0.38, p-value=0) between the upper salt transport through the Sicily Channel and the 0-100 m salinity of EMed (Figure R3b). While very interesting, the results are not conclusive in our opinion, and demand complimentary work.

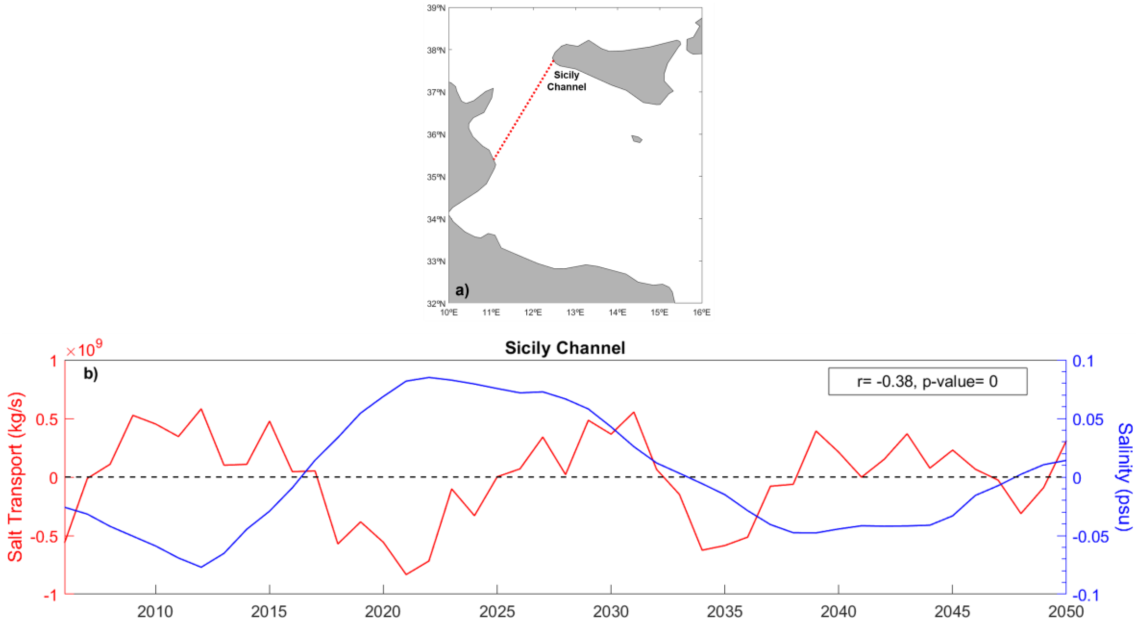

Figure R2. a) Transect in with the transport across the Sicily Channel is calculated. b) Time series (2006–2050) of ROM_P2 simulation of yearly [red] salt transport anomaly through the Sicily Channel integrated for the 0-100 m depth and [blue] salinity anomaly (psu) averaged for the layers 0–100 m in the EMed.

As we stated above, we are very grateful for her/his critical remark. This is an interesting issue, but it requires a targeted and more in-depth analysis, which could be addressed in forthcoming studies.

References:

Gasparini, G.P., Ortona, A., Budillon, G., Astraldi, M., and Sansone, E. (2005). The effect of the Eastern Mediterranean Transient on the hydrographic characteristics in the Strait of Sicily and in the Tyrrhenian Sea. Deep-Sea Res. I, 53, 915-935, doi: 10:1016/j.dsr.2005.01.001

Incarbona, A., Martrat, B., Mortyn, P.G., Sprovieri, M., Ziveri, P., Gogou, A., Jordà, G., Xoplaki, E., Luterbacher, J., Langone, L., Marino, G., Rodríguez-Sanz, L., Triantaphyllou, M., Di Stefano, E., Grimalt, J-O., Tranchida, G., Sprovieri, R., and Mazzola, S.: Mediterranean circulation perturbations over the last five centuries: Relevance to past Eastern Mediterranean transient-type events, Sci. Rep-UK, 6, 1-10, doi:10.1038/srep29623, 2016.