Response to Reviewer #1

We thank the Reviewer #1 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 #1 (Comments to Author (shown to authors):

Review of the article "Dense water formation in the Eastern Mediterranean under global warming scenario" by Parras-Berrocal et al.

In this paper the authors study the evolution of the dense water formation in the Eastern Mediterranean (EMED) along the 21st century, under RCP 8.5 greenhouse gases emission scenario, using the ROM Regional Climate Model (RCM). This RCM have been previously validated and used in several climate studies for the Mediterranean basin and sub-basins. They find a significant reduction of the deep water formation (DWF), between 75% and 85%, in the three regions were deep and intermediate convection take place (Adriatic, Aegean and Levantine basin) by the end of the century. The authors identify the increase in the water column stratification, due to the projected warming and salinization caused by the global warming, as the main factor driving this DWF reduction. They also predict a shift in the main Eastern Mediterranean Deep Water (EMDW) formation region, from the Adriatic to the Aegean Sea, similar to what occurred in the mid-90s with the so called Eastern Mediterranean Transient (EMT).

I find the paper very interesting. As the authors mention, this topic has not been studied in depth and it is very important to understand the expected changes in the Mediterranean thermohaline circulation as a consequence of the climate change. Although the use of a single model limits the robustness of the results, as the authors themselves point out, the results presented and the analysis of the mechanisms behind them are very relevant to the climate modeling community of the Mediterranean region. The manuscript is well written and organized, all the ideas are concisely and clearly stated, and well referenced. There are only a couple aspects that, in my opinion, need to be clarified before its publication in OS.

The first and more important one is the selection of the density of reference used to estimate the DWF rate in the model. As the authors themselves explain, the potential density they use in the model for the newly formed deep water in the Adriatic, Aegean and Levantine basins is slightly lower than the observed and reported in the literature. This is due to the lower salinity, and hence density, of the model respect to the observations in these regions (figure S1). Adjusting the reference density to the 'model reality' is a sound methodology, so this shouldn't be a problem. It would be interesting, though, to identify these references (both for observations and model) in the profiles of figure S1. The selected reference corresponds with approximately 650 m depth in the historical period. However, the authors maintain the same reference densities in the future to compute the DWF rate evolution, which could have led to an underestimation. The profiles for the projections seem to show a general reduction of the density in the whole water column for the Adriatic and the Aegean regions (figures S2,3). This mean that the density of reference would correspond with a deeper layer, and that future deep water might be lighter than the present one. It is difficult to identify these differences in the figures, and very likely there will be no significant variations in the results, but in my opinion the authors should clarify this point in in the results or discussion sections. Would the DWF rate increase if a different density of reference is used for the future? Maybe including a third set of panels with the evolution of the density in figure 4 would be also of help.

Response: Thank you for the remark. We have identified the density of reference in the profiles of ROM and WOA18 (Figure S1):

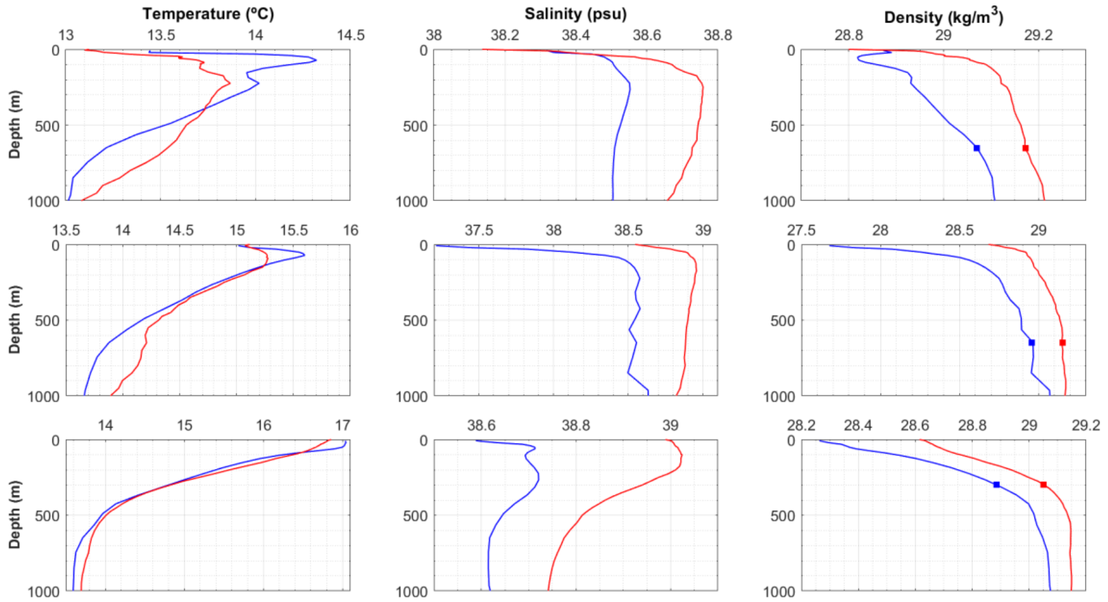

Figure S1. Winter spatially and temporally averaged vertical profiles of (a, d, g) temperature, (b, e, h) salinity (psu) and (c, f, i) density (kg/m^3) in the Adriatic Sea (top), Aegean Sea (middle), and Levantine Sea (bottom) for the 1980-2012 period. ROM_P0 (blue) and WOA18 (red). Note different ranges in horizontal axes.

We estimate the future reduction of dense water formation by using hydrographic properties of the present climate (ROM_P0) as a reference. However, we acknowledge the concerns raised by Reviewer regarding this approach. Indeed addressing that concern is a challenge, as the density vertical structure is changing differently in different sub-basins, so the "present" deep water density thresholds might not be applicable to sub-basins with strong changes in density vertical structure in the future. On the other hand, the water formation rate above a certain density threshold is a model output, which allows a direct comparison between "present" and "future", but as the Reviewer points out the issue of a future lighter sea must be taken with care and properly addressed in the discussion. Our projections indicate that changes in the hydrographic properties of the water column are likely to lead to a reduction in density, which may affect our estimates. In order to address this comment, we have computed the water column density anomalies over the Adriatic, Aegean, and Levantine Seas (as shown in Figure 1). These anomalies were defined as the difference between the averaged vertical profile of density for the ROM_P2 period (2070-2099) and the present climate period (ROM_P1, 1976-2005). By comparing these density anomalies, we were able to identify changes in the hydrographic properties of the water column over time and across different geographic regions.

By the end of the century, the Adriatic Sea experienced a decrease in density of 0.1 kg/m^3 at a depth of 650 m, while the average decrease over the entire water column was 0.2 kg/m^3 (Figure 1d). In contrast, in the Aegean Sea we found no changes in density at the 650 m depth, and the averaged over the entire water column decrease was 0.08 kg/m^3 (Figure 1e). In the Levantine Sea, we observed a reduction in density of 0.15 kg/m^3 at both 300 m depth and throughout the entire water column (Figure 1f).

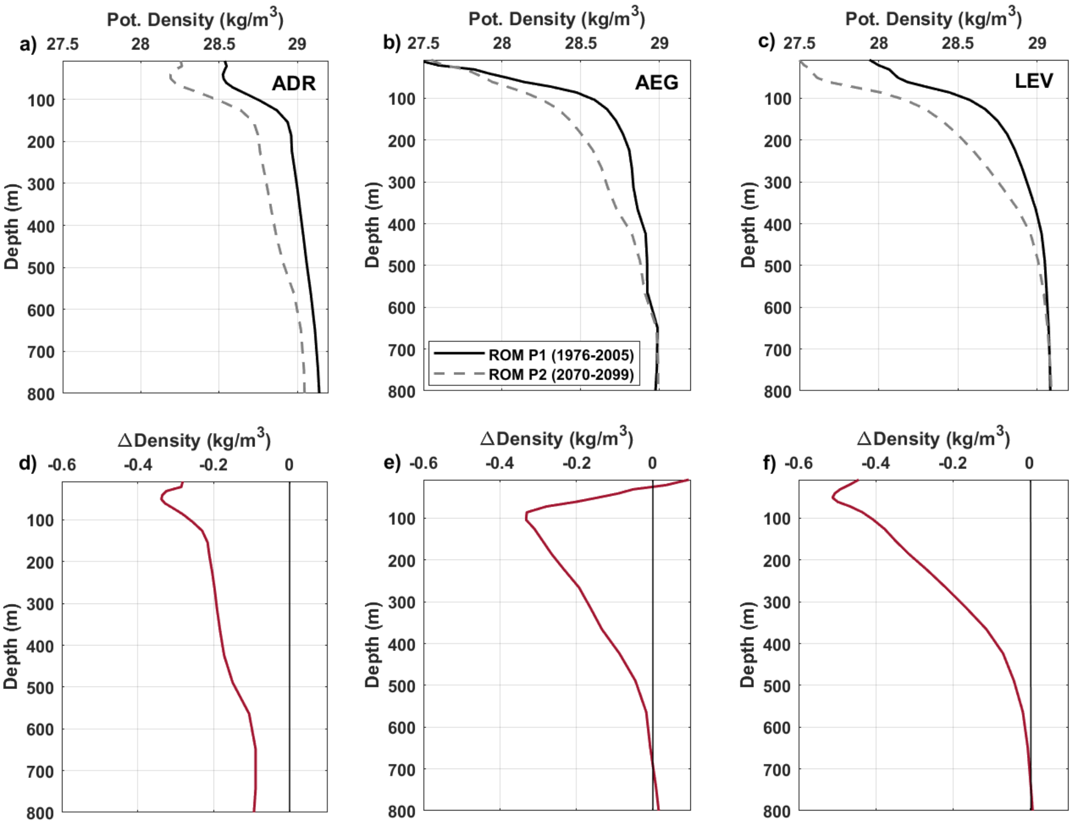

Figure 1. Spatially and temporally averaged vertical profiles of density in the (a) Adriatic, (b) Aegean, and (c) Levantine Seas values corresponding to the historical period (1976-2005), future projection (2070-2099). (d, e, f) The difference between future and historical averaged vertical profiles are also shown.

Based on the observed density reductions (Figure 1), we calculated the potential changes in dense water formation rates in the Adriatic, Aegean, and Levantine Seas (Figure 2). In the Adriatic Sea, using a density reference of 29 kg/m^3, we projected a 75% reduction in DWF rate. Using lower density references of 28.9 kg/m^3 and 28.8 kg/m^3 resulted in smaller reductions of 58% and 39%, respectively. In the Aegean Sea, where the density is expected to remain relatively stable, the differences in the calculated changes in DWF rate are negligible, with a projected decrease that varies from 84% (using a density of 28.95 kg/m^3) to 80% (using 29.9 kg/m^3). In the Levantine Sea, the reduction of the projected decrease in DWF rate is more substantial, with a drop from 83% (using a density of 28.7 kg/m^3) to 56% (using 29.55 kg/m^3).

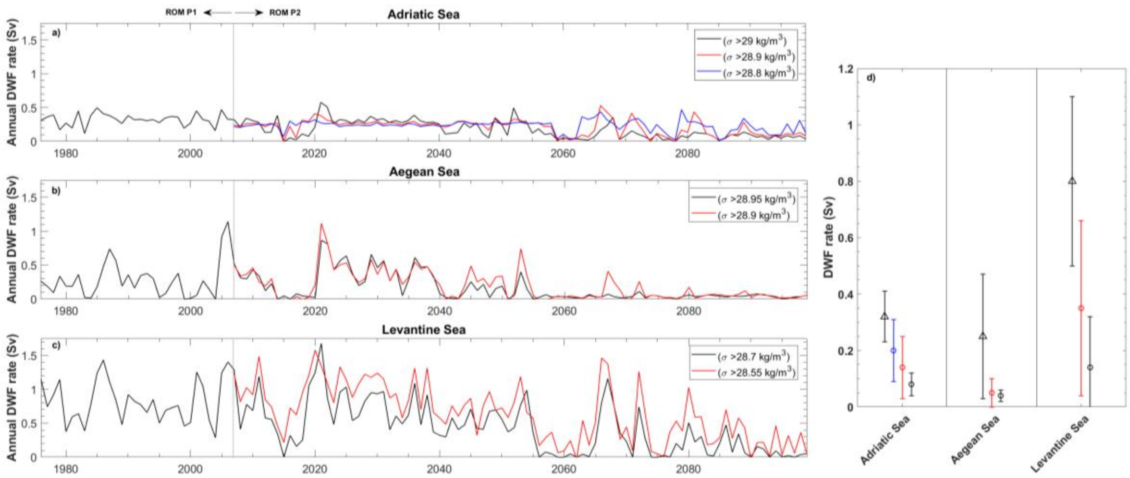

Figure 2. Time series (1976–2099) of ROM_P1 and ROM_P2 simulations of yearly DWF rate (Sv) averaged over (a) Adriatic Sea, (b) Aegean Sea and (c) Levantine Sea. d) Averaged DWF rates for 1976-2005 (triangle) and 2070-2099 (circle) periods.

Overall, the use of a lower isopycnal threshold leads to the same conclusions: a collapse of DWF in the Aegean Sea (Figure 2b) and a notable reduction (of more than 50%) in the Levantine basin (Figure 2c).

However, in the Adriatic Sea this is not the case: when using the lowest isopycnal density threshold (28.8 kg/m^3, blue line in Figure 2a) there are events with notable DWF rates during the last third of the century.

After conducting a deeper analysis, as suggested by the reviewer, we noted different DWF rate responses to changes in density threshold for each sub-basin. In the Adriatic Sea, the future changes on DWF strongly depends on the density change in the water column and therefore on the choice of the density threshold, with denser isopycnals corresponding to stronger DWF rate reductions, with no remarkable DWF change for the less dense threshold (Figure 2d). In the Aegean Sea, a collapse of DWF is expected regardless of the density reference used. Finally, in the Levantine Sea, the changes in DWF rate appear to have a limited dependence on the choice of the density threshold. The reduction in the DWF rate is 83% for 28.7 kg/m^3 and 56% for 28.55 kg/m^3, so the reduction is noticeable in both cases, although sensitive to the choice of the density threshold. We will address this point in the discussion of the revised manuscript.

We have included a third set of panels with the evolution of the density in Figure 4 of the manuscript:

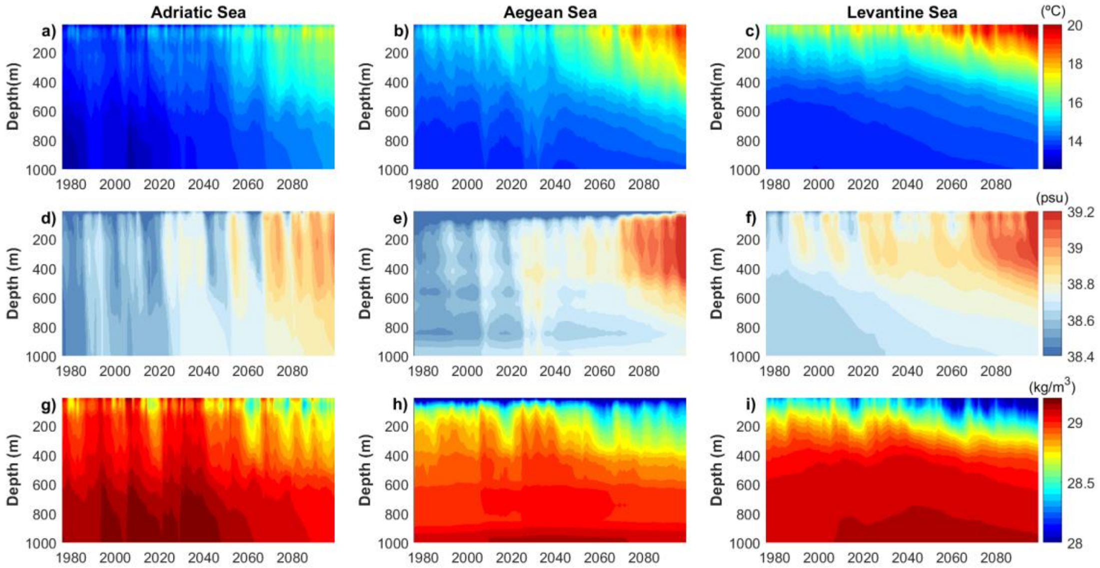

Figure 3. ROM RCP8.5 time series (1976-2099) of 0-1000 m (a, b, c) potential temperature (ºC), (d, e, f) salinity (psu) and (g, h, i) potential density (kg/m^3). All-time series correspond to winter months (December-January-February-March) in the Adriatic (upper row), Aegean (middle row) and Levantine (bottom row) Seas.

My second concern is that the authors did not describe the limits of the regions of each sub-basin used to estimate the average profiles shown in the figures and the DWF rates. As they point out in the introduction, the areas of the Aegean and Adriatic where the deep convection take place are very specific. Are the profiles and DWF rates estimated in these specific areas or in the whole sub-basins? When computing the volume of deep water formed every year, do they account for all the volume of water with densities higher than the reference in a specific region, in the whole sub-basin or in the whole EMED (maybe considering the possible spread)? The region selected could also modify the results, so I think this should also be clarified in the MS. Maybe you could include the basins limits in figure 1 (the color scale is also missing).

Response: Thank you for the comment. We have estimated the DWF rates and profiles considering the whole sub-basins (Adriatic, Aegean and Levantine).

We computed the volume of the deep water formed every year in the whole sub-basins, so we could take into account the non-negligible amount of deep water formed on the continental shelf and subsequently spread in the sub-basin (Lascaratos et al., 1999, Nittis et al., 2003) and to make our model estimates comparable to other estimates existing in the literature (Nittis et al., 2003; Mantziafou and Lascaratos 2008). ROM_P0 has shown a good representation of the deep water volume formed during present climate. In order to clearly show the limits that define each sub-basin we have modified Figure 1 as follows:

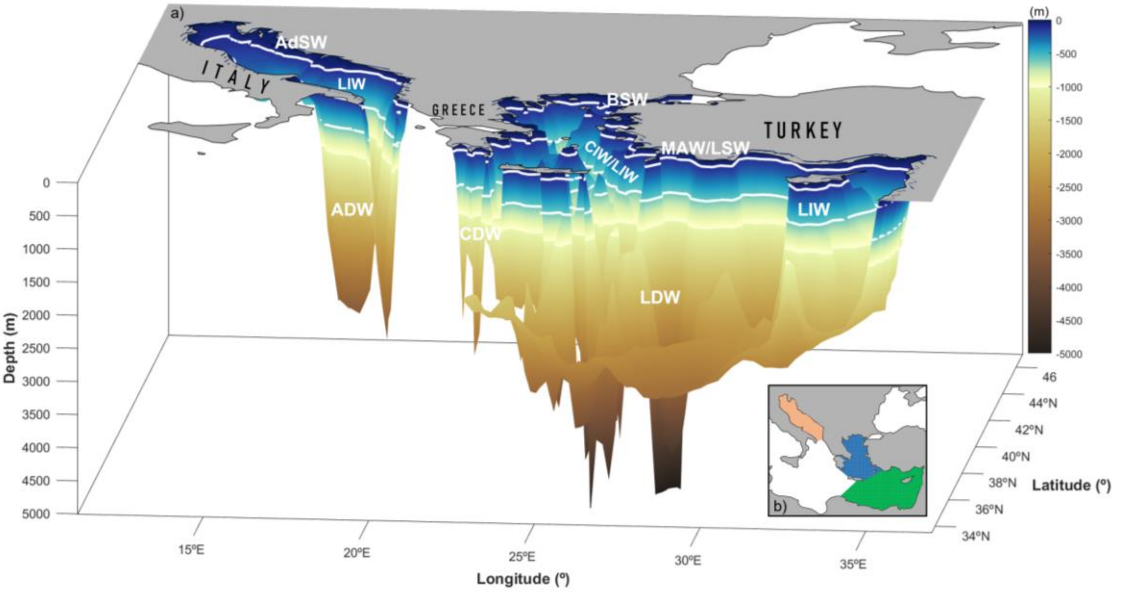

Figure 1. a) Bathymetry of the main spots for dense water formation in the EMed: Adriatic Sea, Aegean Sea and Levantine Sea. The main water masses of each spot sorted by depth range are also shown: [0-100 m] Adriatic Surface Water (AdSW), Black Sea Water (BSW), Levantine Surface Water (LSW); [100-650 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). b) The domain used for the calculations in each sub-basin are colored: orange-Adriatic, blue-Aegean and green-Levantine.