Response to reviewer comments

In the following sections we respond to the comments from the reviewers and indicate where changes have been made to the manuscript. The reviewer's comments are given in italic font, our responses in normal font. Page and line numbers mentioned in this document refer to page and line numbers in the CPD manuscript.

Reviewer #1

(1) *The authors change the depth of the sill at Gibraltar, but don't modify ocean depths elsewhere. I think this needs more justification. Especially for places like the Straits of Sicily and Otranto, which might be significantly impacted if the depth change assumed for Gibraltar is related to large scale sea level changes. Which might significantly impact exchanges between the different sub-basins within the Mediterranean, salt exchange, deep water formation, etc. Therefore I think that the authors have to be careful with their conclusions based on changes only at Gibraltar given one would expect more broad scale depth changes.*

As stated in the introduction, the purpose of this study is to examine how the sill depth of the Atlantic-Mediterranean connection affects circulation and water characteristics in the Mediterranean. By just changing the sill depth in the Strait of Gibraltar we isolate the changes caused by the different sill depths. The sill depth changes considered are not assumed to be related to large scale sea level changes but to tectonics in and/or near the Gibraltar Arc. The range of sill depths examined in this study can hardly be considered a reasonable range if we would be interested solely in the response to large scale sea level changes. Tectonically-driven sill depth changes are thought to be responsible for the restriction of the Late Miocene Atlantic-Mediterranean connection(s), the setting discussed extensively in both the introduction and discussion.

To stress that Late Miocene gateway restriction is related to tectonics, we have added 'tectonically-driven' in lines 13 and 16 of page 2982. At page 2983, we have added 'influenced by long-term tectonics' to line 17 where we describe the purpose of the study.

(2) *I understand why the authors use annual forcing, although including a seasonal cycle with a perpetual year should not have been difficult. But is it certain that a basin with continuous water formation will behave the same as one with episodic winter formation? I don't think it is obvious, especially as the stratification might be quite different. I think, at the very least, more discussion is needed on this topic. I'm also concerned that the mixed layers in the western basin are way too shallow to represent Western Mediterranean Deep Water. Also, the model doesn't seem to have any Levantine Intermediate Water formation, and given the importance of that watermass, without it, can one believe issues of salinity change and exchange between the eastern and western basins?*

The objective of our work is to understand the effect of the ocean gateway on behaviour of the Mediterranean basin going back millions of years in time. Because the atmospheric forcing at those times is not known in detail, we seek a model setup with as simple a forcing as possible, introducing a minimum number of uncertainties. So, leaving aside whether it is difficult or not, it was a deliberate choice not to include a seasonal cycle.

The obvious first question then is, to what extent does the idealised model still reproduce the features of the circulation? This question is answered by running a reference model with the present-day basin and gateway geometry (it was addressed before with a different model but similar setup by Meijer and Dijkstra, 2009). We find that, perhaps surprisingly, the major aspects of the basin-scale overturning are fairly well reproduced, if not quantitatively then at least qualitatively. Based on this we argue that the model setup forms a meaningful starting point for an analysis of the past. The model should give significant insight into trends and changes in circulation in response to gateway depth, even when absolute values of deep and intermediate water formation are slightly off in the control run (discussed in more detail below). It is indeed not "certain that a basin with continuous water formation will behave the same as one with episodic" formation, but knowing how a model with continuous formation responds to sill depth is certainly a significant first step.

Having said this, we agree with the Referee that we ought to have paid attention to the question whether and how we expect mismatches in the reference experiment to affect our conclusions. This has been added to the revised manuscript in the form of a new first sub-section of the Discussion. In this we summarize the consequences of the constant forcing already mentioned throughout the earlier sections and briefly discuss what would change if a seasonal cycle would be used.

The following two sections describe why the mixed layer depth appeared to be too shallow, and intermediate and deep water formation didn't seem to occur at all in Figure 6 of the manuscript. More importantly, the revised version of Figure 6 is introduced.

Mixed layer depth The overview of the mixed layer depth (Figure 6 of the CPD manuscript) indeed shows, as remarked by the reviewer, a very shallow mixed layer depth in the Levantine basin and the northern part of the western basin. The mixed layer depth doesn't seem to fit with the modelled temperature, salinity, and velocity patterns. The mixed layer depth for the CPD manuscript was derived from a time-average of the vertical mixing parameter (*km*) of the last 10 years of the model run. Taking a time-average of the vertical mixing parameter before determining its minimum, i.e. the mixed layer depth, leads to a severe underestimation of the mixed layer depth. The mixed layer depth varies significantly spatially and through time, a variation that was lost in the time-averaged vertical mixing parameter calculation.

Figure 6 has been updated for the revision (reproduced here as Figure 1). It now contains 3 plots: the average and maximum mixed layer depth of the last 50 years of the model run, and the average bottom velocity. The average mixed layer depth is calculated by taking the average of the mixed layers depths calculated each half year in the last 50 years of the model run. It already shows a significantly deeper mixed layer depth in the Levantine basin and the northern part of the western basin. However, a lot of the variation in time is still lost due to the time-averaging. To emphasize that deep and intermediate water is indeed formed, the maximum mixed layer depth is also shown.

Intermediate/deep water formation

In the average mixed layer depth plot four zones of deep mixing, i.e. intermediate/deep water

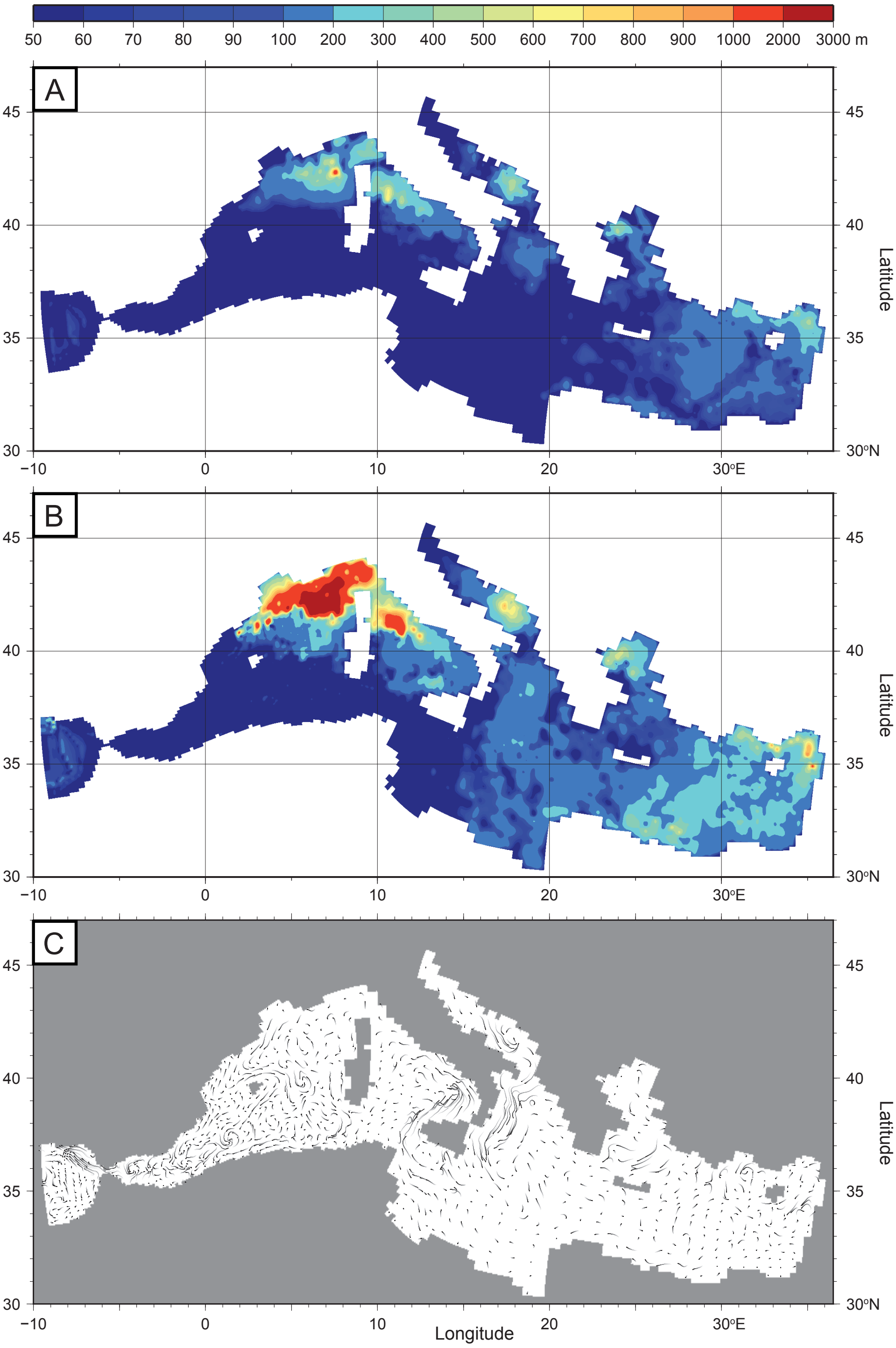

Figure 1: The average **(a)** and maximum **(b)** mixed layer depth, calculated from the last 50 years of integration, and bottom currents **(c)** in the reference experiment. The mixed layer depth is defined as the depth, measured from the surface, of the minimum vertical mixing parameter. Bottom currents are visualized by tracking water particles for 30 days in the average velocity field of the last 10 years of integration. Trajectories start at light grey and proceed to black at the 30th day.

formation, can be recognized: the northern part of the western Mediterranean, the Adriatic Sea, the Aegean Sea, and the central and northeastern part of the Levantine basin.

In the western basin the average mixed layer is up to 1400 meters deep, large parts show mixing up to 200 - 500 meters. Due to temporal changes in the location of the deepest mixing, WMDW formation doesn't stand out. However, from the maximum mixed layer depth plot we can see that mixing actually reaches depths up to 3 km in a large parts of the Provencal and Ligurian basins.

Mixed layer depths in the Adriatic and Aegean Seas are not severely suppressed in the average mixed layer depth plot due to their limited depths and limited spatial variability. However, maximum depths once again show a larger spread and depth.

Mixed layer depths in the central and northwestern Levantine basin are on average 100 - 300 meters, fairly low for LIW formation. But, as in the western basin, the mixed layer depth shows a strong temporal and spatial variability that is lost in the time-averaged plot. The maximum mixed layer depth plot shows mixing of 200 - 500 meters in a large part of the eastern basin with peaks north of Cyprus.

Based on our new overview of the mixed layer depth, the overview of salinity, temperature, and velocity patterns, and the overturning circulation, we conclude that intermediate and deep water formation are actually fairly well represented in our model.

The last paragraph of page 2991 has been extended with a few lines that explain the new figure and the difference in average and maximum mixed layer depths.

(3) *Might the results be a function of both sill depth, and net Evaporation? I.e. With different climate conditions and sea levels, might net E also change, with such changes having feedbacks on the behavior just do to the change in sill depth?*

Different climatic conditions and global sea level do undoubtedly affect the Mediterranean circulation and water characteristics; the Mediterranean response to climate change has already been examined with a similar model as used in this studies in Meijer and Dijkstra (2009). However, as stated in the introduction and already in response to a comment above, our focus is just on the sill depth of the Atlantic-Mediterranean connection. An examination of the response to different climates and global sea levels is well beyond the scope of this study, but would certainly be of interest to a large number of researchers and a good topic to further examine in future studies.

(4) *It seems like a large number of additional sensitivity experiments were performed, but not discussed, other than vague statements like "in a series of sensitivity experiments". This is not good enough for the reader. Either remove these comments if they aren't key to the paper. Or add more detail on them.*

Only two series of sensitivity experiments are mentioned in the manuscript: (1) a series to determine the appropriate model parameters, mentioned in Table 1, and degree of bathymetric smoothing (referred to at page 2986, line 9 - 11, and page 2994, lines 8 - 14), and (2) a series to examine the driving force of deep water formation in our model (referred to at page 2993, lines 20 - 28). We think it is relevant to mention that a series of sensitivity experiments (1) has been performed to assess the influence of various model parameters. In the results section it is useful to know how the strength of the overturning circulation is affected by the degree of bathymetric smoothing (1). Further details on the second series (2) are in our view not necessary and the key findings are mentioned. We agree with the reviewer that more detail on the sensitivity experiments would be interesting, but it would lengthen the manuscript and distract from the main message of the manuscript.

(5) *I think the terms shallower/deeper would be better for referring to sill depth changes than lower/higher. One could think of lower as deeper (as the sill is lower in the water column) but also as shallower (lower depths), which can confuse the reader.*

We agree with the reviewer on this point, using both shallower/deeper and lower/higher may be confusing. All references to sill depth changes now use shallower/deeper.

(6) *In the title, the word parallel is not needed. Many ocean models are run in parallel now. In any case, this is just a technical detail about the computing (and the time needed to run it) and has nothing to do with the underlying science and results.*

"parallel" has been removed from the title as suggested.

(7) *How many sigma levels does the model have? Are there enough such that the thermocline can be resolved in deeper water within the basin interior?*

As already mentioned at line 2 on page 2987 of the manuscript, the model has 40 sigma layers. At the deepest point in the Mediterranean, 4000 m in the Ionian basin, the first 100 m is still represented with 5 layers. This is sufficient for a reasonable representation of the thermocline. A higher resolution at the surface in the basin interior can only be achieved by sacrificing resolution at other water depths or increasing the number of sigma layers. The former is definitely undesirable, the latter would increase the computational cost of the model which conflicts with our aim to run a relatively high resolution model for several centuries.

(8) *How many grid points does the model have in the Strait of Gibraltar? Thus, how sensitive are the results to potential cross-strait variability?*

Even with the highest resolution near the Strait of Gibraltar, it is represented with just one grid cell of 12.9 km in the j-direction. Therefore there is no cross-strait variability.

(9) *For the Atlantic relaxation being applied in the first 18 columns of the grid, how does that relate to the location of Gibraltar? I.e. Does any relaxation extend into the strait?*

The Strait of Gibraltar starts at the 22$^{\text{nd}}$ column of the grid. Due to it's position outside the relaxation area and the weak relaxation in the eastern part of the relaxation area, flow through the gateway is not affected by it. In the revised manuscript the location of the Strait of Gibraltar with respect to the relaxation area is now mentioned.

Reviewer #2: Mike Rogerson

[...] I do have one strong worry about the results; the heat budget at Gibraltar is wrong. The Mediterranean today is a heat sink for the Atlantic, and because of the high altitude of its northern margin it probably was in the past also. In the model presented, it is a heat source for the Atlantic.

We thank the referee for his positive comments preceding the statement here copied but have to correct him on this point underlying also his subsequent comments: the heat budget in our models is not of the wrong sign. What is not right perhaps is that we did not provide details about the heat budget in our experiments. This would have prevented misunderstanding.

The revised manuscript contains a new table (Table 2), here reproduced as Table 1, which gives an overview of the heat flow through the Strait of Gibraltar. Furthermore, two paragraphs have been added in section 3.2.1 that describe the heat flow results and explains why the Mediterranean warms when the sill gets shallower.

This has some important consequences

1) The Western Mediterranean Deep Water does not seem to form properly (today this is fresher and colder than eastern sourced waters, and the missing heat sink is essential to its formation).

2) Levantine Intermediate Water seems to be to weak, probably also because it is being formed too warm. As about 2/3 of the water leaving Gibraltar is LIW, this matters.

Comments 1 and 2 have been answered in detail in response to the second comment of the other reviewer.

3) As the sill level drops, the Mediterranean warms. It should cool - at least on average.

Although this may intuitively seem to be the case, the actual behaviour is more complex than this. A lot of factors affect the heat budget of the Mediterranean. In short, the temperature of the Atlantic inflow goes up when the sill is shallower. The surface heat loss is not affected by the warmer inflow. Hence, the Mediterranean warms up in order to preserve a zero heat budget.

A more extensive explanation has been added to section 3.2.1, as already mentioned above.

4) As the sign of the heat budget is wrong, the simulations may be wholly specific missing thermal convection processes in shallow sill scenarios driven by strong cooling in parts of the western Mediterranean. I fear that the lack of this thermal convection means "real life" sill-depth scenarios will certainly be different to those presented, which limits their usefulness.

Unfortunately there is no basis to this comment.

Table 1: Overview of heat transport through the Strait of Gibraltar. ENSHL = Equivalent net surface heat loss

Sill depth (m)	Inflow (TW)	Outflow (TW)	Net flow (TW)	ENSHL (W/m^2)
500	73.604	74.108	-0.504	-0.212
400	63.121	62.326	0.795	0.334
300	52.984	50.583	2.401	1.010
200	39.231	36.028	3.204	1.348
100	21.241	18.142	3.099	1.304
50	10.542	7.563	2.980	1.253
20	3.487	0.607	2.880	1.212
10	3.035	0.000	3.035	1.277

References

Meijer, P.Th.., Dijkstra, H.A., 2009. The response of Mediterranean thermohaline circulation to climate change: a minimal model. Climate of the Past 5, 713–720.