Response to reviewer comments

We would like to thank Mario Krapp and the anonymous referee for their constructive comments. Below we respond to the remarks and suggestions, following the order in which they were presented to us.

General comments

The study is motivated by the role closure plays for the global circulation but this is to large parts barotropic; closure is related to flow reversal in other model studies but these flows are generally barotropic (p.4388/ll.12), e.g., von der Heydt and Dijkstra (2006).

While this comment appears to be incomplete it is clear that the reviewer refers to our model's inability to capture the barotropic component of gateway transport. This issue is addressed in p.4391/l.20-24, p.4400/l.21-28 and p.4401/l.1-3. In these paragraphs it is explained that the use of sponges does not allow to simulate scenarios in which a net inflow from one gateway is compensated by outflow from the other and we discuss how this may affect the interpretation of our model results.

It is important to realize that this limitation must be considered the price one has to pay for the greater resolution and shorter computation time (allowing for many different model experiments) offered by a regional-scale model. Moreover, the limitation is not particular for regional models in which sponges are implemented. Also in the models that use open boundaries some choices have to been made to arrange the external and internal mode of the open boundary conditions (i.e., inflow condition, elevation condition, radiation etc.). In this context, only global climate models are able to capture more realistically the barotropic component. However, their coarse resolution can also affect the results, especially when we study narrow or shallow gateways.

In the paper by von der Heydt and Dijkstra (2006) a reversal of flow through the Panama Seaway is captured between the Oligocene and Miocene. According to these authors, this flow reversal is induced by the closure of the Indian Gateway and the widening of the Southern Ocean marine passages and has an important barotropic component. However, the use of a flat-bottom ocean with a constant depth of 5000 m probably enhances the importance of the barotropic component. More recent global studies addressing the closure of the Indian Gateway that use a more complex topography and also simulate intermediate stages of closure (e.g., Hamon et al., 2013) find a substantially different circulation pattern, which is more similar to the one that we get in our study.

For better evaluation of results a present-day boundary conditions setup is essential (not only mention in the discussion that results are comparable to a more comprehensive model). A comparison to the Miocene results would make the paper even more valuable.

A present-day setup of our model was the topic of Meijer and Dijkstra (2009). In this paper it was shown that, the idealized setup notwithstanding, it was still possible to reproduce, for example, a realistic overturning circulation. The statement in the discussion that the referee points to is related to an aspect particular for the Miocene setup: the fact that bathymetry is not known as well as it is for the present. To assess the role played by that uncertainty we repeated the present-day model with bathymetry simplified into only two levels, just as we do for the Miocene.

Deep water formation in the Mediterranean takes place mainly during winter. Therefore, the seasonal cycle is important for present-day. What is the role of the seasonal cycle in this study. If there is none, is it not important?

Meijer and Dijkstra (2009) found that the 100-year average circulation and water properties of the Mediterranean Sea could be reproduced with idealized forcing, ignoring the seasonal cycle. In this case, a perpetual cooling of the sea surface in the northernmost parts of the sea drives a deep-water formation that results in a realistic overturning circulation (both by comparison to our image based on observation and by comparison to the result of more realistic models that do include the seasonal cycle). Since it is (changes in) this long-term average circulation that we are interested in, and we aim to achieve this with as simple a model setup as possible, the use of a constant sea surface temperature to force our model appears justified.

The structure of Sect. 3 has some flaws and the separation between overturning and velocity/salinity does not work well in my opinion. The authors should put the focus on the individual stages of gateway closure as they did in the subsections of 3.2.

In retrospect we agree. It would be more natural to merge section 3.1. and section 3.2. We could combine the description of the zonal overturning streamfunction with the effect of closure on the salinity and velocity field for each of the stages of closure.

How is the Atlantic affected by the exchange? Today Mediterranean outflow water is one important source of North Atlantic Deep water which drives the Atlantic meridional overturning circulation.

As shown in Table 1, the water exchange with the Atlantic varies very little as a consequence of the shoaling and closure of the Indian Gateway. Our results suggest that this event mainly affected the Indian Ocean. We can include a brief statement including this in section 4.2. or section 4.4. and also in the conclusions.

In the introduction, proxies records showing that closure affects temperature and salinity have been mentioned. Why not incorporating (these numbers) in the discussion of the results?

We realize that the corresponding statement in the introduction (p. 4388, l. 10) needs rephrasing because it does not do justice to the complexity. Also, in a revised version, we will discuss the possibilities and limitations in more detail.

The study of the C and O isotope compositions of benthic and planktonic foraminifera as well as isotopic compositions of marine sediments and faunal studies are useful tools to reconstruct marine palaeonvironments (i.e., Bicchi et al., 2003; Bosellini and Perrin, 2008; Kocsis et al., 2008). Although a direct comparison of our model results to these studies would be of interest, this proves not so straightforward for several reasons: i) there are just few studies focusing on the eastern sub-basin where, according to our results, changes in response to closure are greatest (i.e., Kocsis et al., 2008; Mourik et al., 2011); ii) most of the studies report environmental changes for a specific time interval and our model-derived insights depend on the bathymetry of the Indian Gateway. Unless a Mediterranean palaeogeography is provided in these studies a comparison is not possible; iii) it is difficult to locate precisely the study sites in our palaeogeography, which results essential due to the spatial variability of the basin response to closure.

Thus, as we also state in the Introduction (p. 4389, l. 3-6), the main purpose of our analysis is to provide a framework for the collection and interpretation of new data. For example, our results suggest that the optimal location to study the effects of the closure of the Indian Gateway is the easternmost Mediterranean where, as stated in the text, we observe a temperature decrease to the north and an increase to the south (Figure A included below). If future studies focusing on these regions do not find differences in the temperature trend of sections in the northeastern and southeastern Mediterranean, then we would have a strong basis to say that other factors are prevailing over the gateway signal.

Specific comments

Introduction:

p.4389/l.6 new observational evidence: what kind of evidence would that be?

We refer to proxies such as benthic and planktonic foraminifera or isotope data which can provide an observational estimate of the temperature or salinity variation as a result of closure of the Indian Gateway.

l.8: What are sedimentary basins?

Sedimentary basins are regions subject to long-term subsidence which creates accommodation space for sediments to accumulate.

Model description:

Sponge boundary conditions are important part of the study and have to be mentioned earlier than in Sect. 2.3, i.e., in the abstract (to let the reader know what kind of experiments to be expected).

We could talk about the sponge boundary conditions earlier in the text. We would argue that in the introduction (in the paragraph extending from p.4388/l.20-29 and p.4389/l.1-9) it would suit better than in the abstract, where no details about the model settings are given.

Missing reference for Levitus data, p.4392/l.5

The Levitus Atlas is a very well-known source and for that reason it is commonly not included in the references. However, we can add it to make it clearer to the reader. The correct reference is: Levitus, S. and Boyer, T.P.: World Ocean Atlas 1994 Volume 4: Temperature, number 4, 1994.

Atmospheric forcing is constant in time: present-day deep-water formation during winter in Gulf of Lion (see above)

This has already been addressed in the third bullet of the general comments.

Evaporation is set to 0.5m/yr. The present-day seasonal cycle is large— precipitation has an amplitude of 700mm/yr and evaporation 1000mm/yr—and there is a significant east–west gradient (Mariotta et al., 2002). Why is a constant evaporation still justified?

This value, which is within the range estimated for the present-day Mediterranean region (see Topper and Meijer, 2013) was shown by Meijer and Dijkstra (2009) to reproduce realistically the large-scale circulation of the Mediterranean Sea.

Results:

p.4394/ll.9-11: I cannot see this from the overturning circulation in Fig.4

In Figure 4 it can be appreciated that the Mediterranean waters extend until the 50ºE, where they sink until approximately 500 meters depth to return back to the Atlantic Ocean. To check if water sinks in the Mediterranean or the Indian Gateway, the easternmost Mediterranean (32-36ºN/45-53ºE) was masked. Results obtained confirmed that it occurred in the easternmost Mediterranean and not in the Indian Gateway. In our manuscript we could simple add "not shown".

p.4396/ll.4-5 and p.4397/ll.4-7: I don't get that from the figures. Maybe add a "not shown"?

To do show this we would have to include in Figure 5 and Figure 8 not only the salinity and horizontal velocity at 10 meters, but also at different depths. We consider that this is not a first-order importance aspect and it would imply the introduction of new plots that would make the paper denser. As you suggest, we can simply mention that it is not shown in the figures.

p.4398/ll.16: The homogeneous salinity pattern with non-uniform evaporation may result from a too large decrease in evaporation. What would happen if the basin-wide average evaporation is kept the same, i.e., evaporation over the Mediterranean increases on the expense of a lower evaporation over the Paratethys.

The experiment you propose would probably result in relatively low salinities in the Paratethys and higher values in the Mediterranean. However, the main aim of the extra experiment we performed was to avoid the high salinities found in the Paratethys with a constant net evaporation rate related to its enclosed nature. For this reason the net evaporation was reduced to the half over the Paratethys. With these new settings the Paratethyan salinities were around 35, which is closer to the value accepted for the Early Miocene in this realm. What is relevant is that even with a different atmospheric forcing, the first-order response of the basin (i.e., overturning streamfunction) is very similar to that obtained with the present-day forcing, as long as the same Indian Gateway depth is considered.

p.4398/ll.13: The effect is also comparable to the intermediate IG (Fig. 4b).

Not really. In Figure 4b both oceans (Indian and Atlantic) control the Mediterranean general circulation and that is not the case in Figure 7a. In other words, with an intermediate-depth Indian Gateway the Mediterranean Sea accommodates anti-estuarine exchange to the Atlantic and the Indian oceans. In Figure 7a there is no effective water exchange with the Indian Ocean and the "blue cell", which indicates deep water formation, is not related to the Indian Ocean.

Discussion:

p.4400/ll.2: Isn't that obvious? How would imposing a slightly different evaporation rate or temperature profile change the large-scale circulation with respect to the closure of an ocean gateway?

Exactly because our atmospheric forcing is idealized we think it is important to assess its role. We start by using present-day values and then we impose different atmospheric conditions to check how sensitive the system is to the choices we made for the atmospheric forcing. With the different sets of atmospheric forcing we tried, the basin response was very similar to that with the present-day data set as long as the same Indian Gateway bathymetry is compared.

p.4400/l.8: What is the two-level bathymetry?

This is explained in some detail on p.4390 /l.25. The geological data used to construct the paleogeographical map which we take as a starting point only allow to distinguish between “shallow basin” and “deep basin”, hence the two levels.

p.4400/l.10 What does "very similar" mean?

This means consisting of cells of similar extent, sign and strength.

I have difficulties to understand what the second paragraph of 4.1. is about. The aspect of a net barotropic transport needs clarification. For example, a net trans- port from the Indian Ocean into the Atlantic can reverse the freshwater transport across the Strait of Gibraltar (see Fig. 12e/f in Krapp and Jungclaus, 2011)

This paragraph refers to the anti-estuarine circulation pattern that we observe in our results. We understand that we need to rephrase the text to make it clearer. The aspect of (the lack of) a barotropic component has been addressed in the first general comment. Krapp and Jungclaus (2011) would indeed serve as an example of work in which the role of the barotropic component is demonstrated (but note that here the Gibraltar Strait is deeper than in our work). We will mention it as such in the revised version.

Provide a definition of "anti-estuarine" earlier in the text

We can give a definition of anti-estuarine exchange the first time we refer to it in the results section.

In 4.3 the authors discuss local temperature changes in response to gateway closure but this has not been shown in the results. (Also relevant for conclusion point 4).

In the figure below we show the temperature changes between a deep and a closed Indian Gateway at a depth of 220 m. This illustrates our point that temperature variations due to closure, just like salinity changes (which can be learned from Figure 5), are not uniform throughout the basin. While we are aware that it is not straightforward to reconstruct temperatures at this specific depth from faunal or isotope data, the same non-uniform changes also occur at shallower depths, albeit at lower amplitude because at the surface the same forcing field is applied in both experiments.

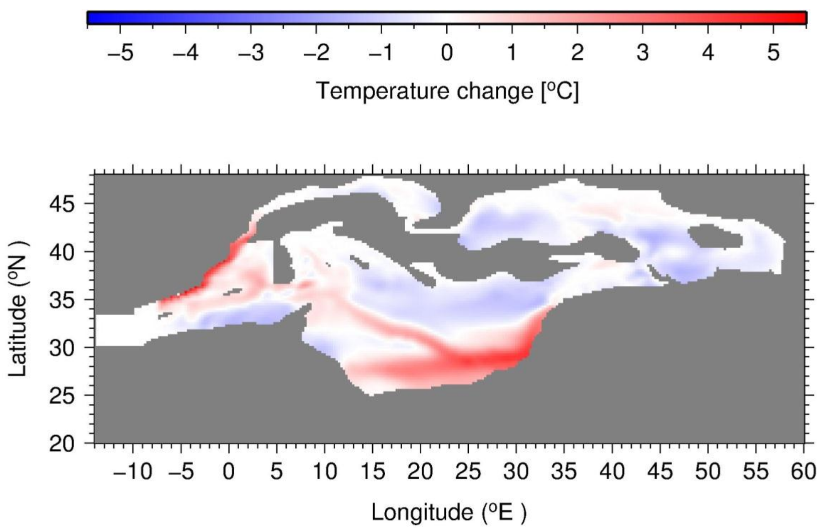

Figure A. Temperature change due to closure of the Indian Gateway at a depth of 220 m.

p.4406/ll.5: Isn't it trivial that outflow from a basin with imposed evaporation is saltier than the inflow? (Also relevant for statement 3 of the conclusions)

A saltier outflow is indeed expected since we consider a negative water budget for the Mediterranean. However, it is something we have to point out to the reader.

Conclusions:

point 6: That Indian Gateway closure affects Indian Ocean water and, hence, the development of the East Antarctic Ice Sheet cannot be concluded from the results shown here. This point is more of a conjecture.

In a revised version we will mention in the conclusions and abstract that closure interrupted a source of relatively warm and salty waters to the Indian Ocean, but we will only speculate about its connection with the East Antarctic Ice Sheet in the discussion.

Tables:

Choose one significant digit in Table 2 and 3 to facilitate readability.

Agreed. We will reduce the numbers to one decimal and, in the second part of Table 3, change the order of magnitude of the values to improve clarity.

Regarding the numbers from the tables: What about variability in temperature, salinity, and stream function, for example, in terms of standard deviation (+/-)?

We consider it is clearer if we include the values instead of the standard deviation because the reader would have a general idea of the temperatures, salinities, water transport through the different gateways, etc., at a glance.

The interpretation of Table 1 is difficult and more connections within the text are appreciated.

Good point. We will refer to the table more often, especially in the results section. In addition, as we proposed previously, we should also refer to the reader to this table to address the changes in water transport through the Atlantic Gateway as a result of closure.

Figures:

Dashed lines in Fig. 4 are hard to read.

We will change the color and thickness of the dashed lines to make them more visible.

I've had a hard time reading the velocities from Fig. 5. I suggest to plot velocity vector field separately with absolute values as colors.

We consider that this way of plotting the salinities and horizontal velocities is very visual and we would certainly like to retain it. Another option to make the arrows more readable is to enlarge the panels and put the plots one on top of the other instead of side by side. If it does not improve the readability of the arrows, then we would look for another way of plotting our results.

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