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Climate of the Past Discussions

Interactive comment on "The response of Mediterranean thermohaline circulation to climate change: a minimal model" *by* P. Th. Meijer and H. A. Dijkstra

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Response to Reviewer Comments "The response of Mediterranean thermohaline circulation to climate change: A minimal model"

We wish to start by thanking both reviewers, Bernd Haupt (Referee #1) and the anonymous referee (Referee #2) for being appreciative of our overall objective and approach and for providing two constructive reviews. Below I will try to offer a clear response to the comments, following the order in which they were presented to us.

Please note that the new figures mentioned below are also available as a separate supplement (without down-scaling applied).

Paul Meijer, on behalf also of Henk Dijkstra September 2009

Response to comments of Referee #1

1. This comment indicates to me that we have not been altogether clear about the history of the ocean model we use. The point is that the Mediterranean implementation of MOMA on which we base ourselves has been extensively researched and documented using non-idealised setups, in particular where it concerns the present-day circulation of the Mediterranean Sea but also regarding the (recent) past. The first relevant study dates back to 1995 when Roussenov et al. presented a model analysis of the present-day Mediterranean circulation using the predecessor of MOMA, MOM. Subsequently, a series of publications by Keith Haines and colleagues (Edinburgh University) presented significant advances made using MOMA. This work formed the basis for investigations of the Mediterranean paleocirculation by Paul Myers and co-workers, again extensively documented. In addition, two of our own earlier papers (Meijer et al., 2004; Meijer and Tuenter, 2007) also present model results obtained with realistic atmospheric forcing.

Given this large body of published work on realistic setups of "our" model we think it justified to directly present the results obtained with the idealised setup. What should certainly be stressed, however, is that the idealised model, although less realistic in setup, does not perform worse than some of the more advanced implementations. On the contrary, in Meijer et al. (2004) and Meijer and Tuenter (2007), notwithstanding the complex forcing scheme adopted, the model proved unable to capture deep-water formation.

The last point concerning the need for an experiment including winds was elaborated upon under 4 and will be responded to below.

2. Global coupled AOGCM's would, in principle, indeed be able to provide the required information. Still, this is our point exactly: when dealing with the geological past one has to turn either to model-derived atmospheric fields or insight based on the proxy record, both inherently much less certain (and, for the moment at least, less detailed)

than what one has available for the present day.

3. See under 2.

4. In order to gain insight into the effect of (the neglect of) wind stresses, pointed to by the Refereee, we had already repeated our reference experiment, adding a constant wind-stress field obtained by annually averaging the ECMWF climatology (as used in Meijer et al., 2004). Figure R1 (attached below) presents the time series for kinetic energy measure and basin-averaged temperature and salinity and should be compared to Figure 2 of our original paper. As expected, kinetic energy stabilizes at a slightly higher level in the presence of winds. In contrast, basin mean temperature and salinity are hardly affected. As shown by Figure R2 (cf. Figure 3), winds have a strengthening effect on the overturning in the eastern Mediterranean, for the upper cell as well as for the deep cell. Adding wind stress does not seem to affect the overturning in the western basin: the model does still not capture the deep-water formation known to occur there in reality. Finally, in Figure R3b we illustrate the response of the deep cell to a sudden reduction of the net evaporation to 0.25 m/yr, now for the case of wind stress added (both before and after the reduction in evaporation). Figure R3b should be compared to original Figure 4b, here repeated as Figure R3a. As found for the case without winds the effect of a reduction in net evaporation is a strong decrease in the strength of the deep cell. Following this initial drop in intensity, with passing time, the deep cell picks up strength again; this recovery appears to go slower in the presence of winds than without wind stress added.

Because the addition of wind stress does not alter the first-order aspects of basin circulation we choose to neglect winds in our reference experiment, consistent with our aim to arrive at a truly minimal model.

We have not also experimented with the addition of wind fields obtained by interpolation of coarse resolution global coupled climate models as suggested by the Referee. The reference experiment presented in our original paper and the additional experiment

presented here are likely to represent the end-members as regards to the role of wind stress.

5. The alternative value for the initial temperature of the basin of 10°C was not chosen arbitrarily but because of the fact that this is the temperature of the deep water in the “Atlantic box”. Our objective was to explore what would happen starting in a situation of Atlantic-like properties throughout. It is this what we meant to convey with the phrase in parentheses on line 21-22 of page 1735, not that we judge the results looking at the “Atlantic cell” as mentioned by the Referee. In any case, to illustrate our point, Figure R4 shows the time series for basin-averaged temperature and salinity (i.e., excluding the Atlantic box) for the two alternative values of initial Mediterranean temperature. The solid lines for temperature start at values that lie 6°C apart but are seen to coincide after a little more than 200 years. In addition, Figure R5 depicts the zonal overturning streamfunction (average of years 901-1000). This is nearly identical to that obtained for the reference experiment (cf. Figure 3).

6. Please see our response under 1.

7. The reason for chosing a reference value of net evaporation from the low end of the estimates for the present-day is that we find that the idealised model tends to overestimate the strength of the overturning cells (page 1736, line 23). This overestimation is most likely due to the absence of seasonality in our forcing: atmospheric conditions conducive to deep-water formation are present continuously. Since we also found that overturning strength generally increases with increasing net evaporation we took the low estimate of 0.5 m/yr as our reference.

8 and 9. The novelty of these findings lies perhaps mostly in the fact that this mechanism has, to our knowledge, not yet been found or described in the context of models for the Mediterranean Sea.

10. Figure R6 shows the equivalent of Figure 2 for a 2000 year long integration (i.e., twice as long as before). The kinetic energy shows a reduced variability between,

roughly, years 800 and 1000 but its average level is essentially constant from about year 800. The latter also holds true for average salinity and temperature. The strength of the deep cell for the reference case was already shown for 1500 years in Figure 4.

11. As to intermediate-water formation in the eastern Mediterranean the model in idealised setup matches the observed present-day situation in that it captures an eastward surface transport and a return flow at intermediate depth. The model reproduces the basin-scale surface/intermediate depth circulation but most likely not the exact site of formation, nor the properties, of the water mass known as Levantine Intermediate Water.

The minor comments listed by the Referee will be accomodated in a revised manuscript.

Response to comments of Referee #2

The first 4 comments, relating to page 1733, will be taken to heart in the preparation of a revised manuscript.

Page 1734, lines 15-16. Our choice to adopt mixed boundary conditions (a relaxation condition for temperature in combination with an imposed flux for salinity) was based firstly on the fact that this type of conditions has been succesfully applied before for global-scale idealised models. In particular the analysis by Rahmstorf (1995) served as a source of inspiration. Secondly, however, given what we know, or rather, not know, about the past (atmospheric) conditions of the Mediterranean this particular choice really appeared to be the only possibility. Whether the steady-state solutions we obtain would be different for a different type of boundary conditions is an interesting question but it is not clear how to define any alternative atmospheric forcing.

Page 1734, lines 20-25. This remark is very true, of course. What we should have stressed is that an important reason why we set out to explore the possibilities of an idealised model is that we wish to arrive at a model setup suitable also for configura-

tions of the Mediterranean basin in the geological past, i.e. millions of years back in time when geography and orography were significantly different from that at present.

Page 1734, lines 24-25. Our simple forcing scheme does not involve bulk formula. The role of the lack of winds was discussed above as part of the response to the comments of Referee #1.

Figure 2. The spike in kinetic energy coincides with a change in the variability of the basin-mean temperature and occurs at the time that the basin-mean salinity is stabilising. We are most likely seeing a sudden increase in deep convection giving way to the steady-state overturning pattern depicted in Figure 3.

Page 1735, lines 15-20. The range for "net evaporation" mentioned in the text of 0.5-1.3 m/yr refers to evaporation minus precipitation and river runoff. Rivers are thus accounted for. We will clarify what we mean by net evaporation in a revised manuscript.

Page 1736, paragraph 1. Indeed, models with a much more sophisticated forcing scheme also prove unable to reproduce deep-water formation in the western basin. Apart from failure of the models to capture the short-lived and localised cooling at the sea surface which is known to be instrumental at the present day, the difficulty is perhaps also caused by the fact that in particular deep-water formation west of Sicily strait is the last step in a long chain of processes. To get the western deep waters right, all previous steps would need to be captured correctly first.

Page 1736, lines 20-21. We observe the Adriatic to be well-mixed throughout the water column and to produce an inflow into the Ionian basin that sinks to great depth.

Page 1737. The role of pre-conditioning will be mentioned in a revised manuscript.

Page 1738, line 19. With time the deep layers loose salt by upward mixing: whereas immediately upon the addition of freshwater to the surface the density structure is stable, it becomes unstable again over time because the deep layers also experience a reduction in density.

Page 1740, lines 14-16. Will be accomodated.

Please also note the Supplement to this comment.

Interactive comment on Clim. Past Discuss., 5, 1731, 2009.

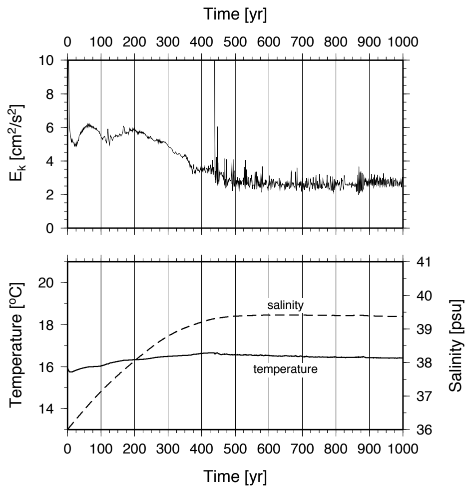

Figure R1. Wind stress added.

Fig. 1.

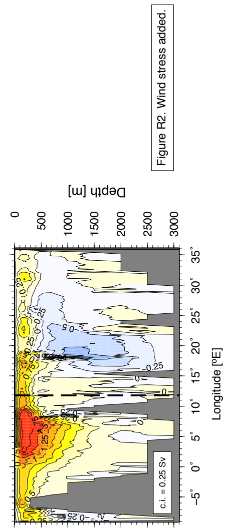
Figure R2. Wind stress added.
Depth [m]
Longitude [°E]
c.i. = 0.25 Sv

Fig. 2.

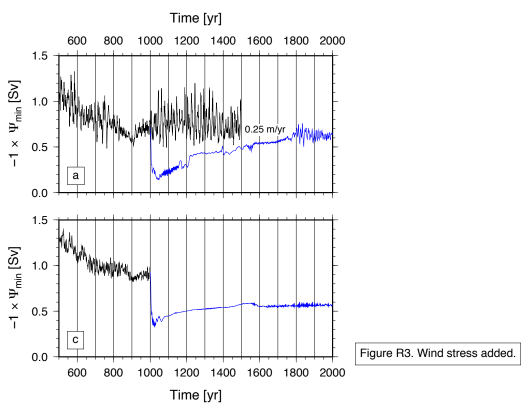
Time [yr]
−1 × Ψmin [Sv]
0.25 m/yr
a
c
Figure R3. Wind stress added.

Fig. 3.

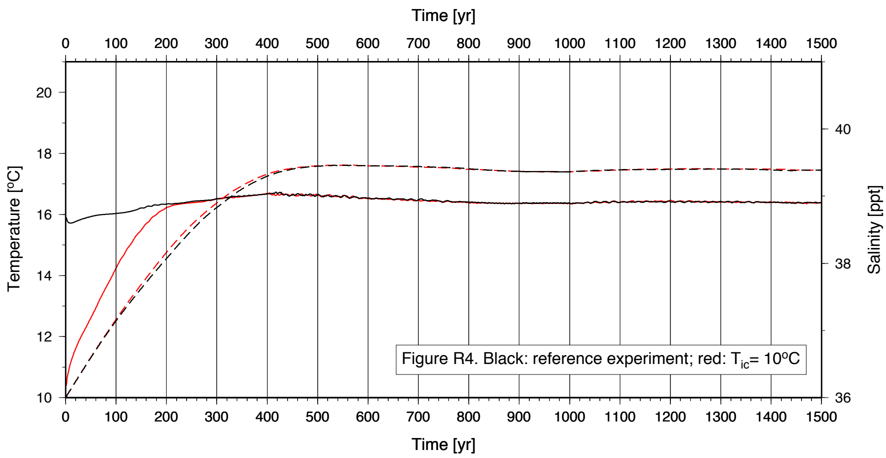
Time [yr]
0 100 200 300 400 500 600 700 800 900 1000 1100 1200 1300 1400 1500
Temperature [ºC]
10 12 14 16 18 20
Salinity [ppt]
36 38 40
Figure R4. Black: reference experiment; red: T_{ic}= 10ºC

Fig. 4.

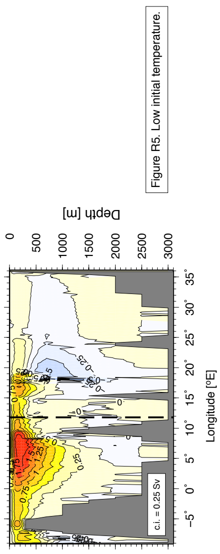
Figure R5. Low initial temperature.
Depth [m]
0 500 1000 1500 2000 2500 3000
Longitude [ºE]
c.i. = 0.25 Sv

Fig. 5.

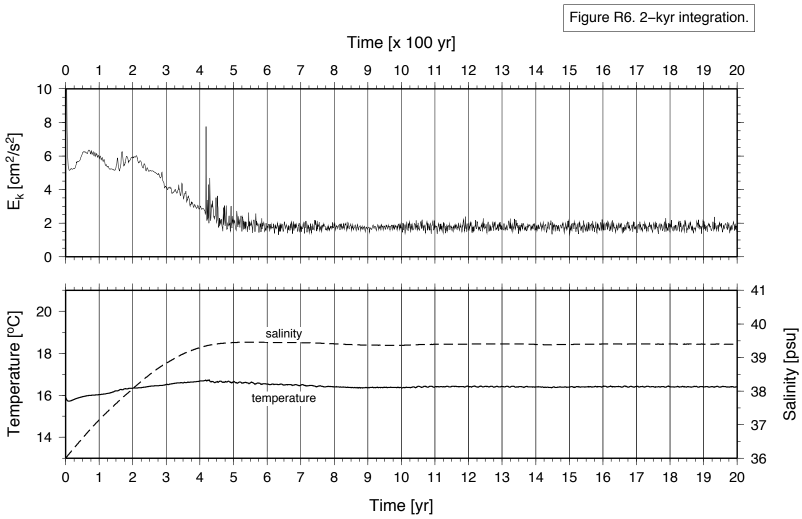
Figure R6. 2–kyr integration.
Time [x 100 yr]
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
E_k [cm^2/s^2]
10
8
6
4
2
0
20
18
16
14
Temperature [ºC]
salinity
temperature
41
40
39
38
37
36
Salinity [psu]
Time [yr]

Fig. 6.