Role of marine gateways in the paleoceanography of the Miocene Mediterranean Sea; A model study

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1. Introduction

During the Miocene, due to the convergence of the African plate and the Eurasian plate, the Mediterranean region was subject to palaeogeographic changes. The evolving coastline and bathymetry of the Mediterranean Sea and the opening and closure of the marine connections between the Mediterranean and the outside oceans, triggered important changes in Mediterranean circulation.

Figure 1. Schematic palaeogeographic maps of the circum-Mediterranean region modified from Harzhauser and Piller (2007) at different points in time. "C. P." and "E. P." refer to Central and Eastern Paratethys, respectively. "BeC" corresponds to the Betic corridor and "RiC" to the Rifian corridor.

Series/Epoch		Age/Stage	Age (Ma)
			2.58
Pliocene		Piacenzian	3.600
Pliocene		Zanclean	5.333
Miocene	Late	Messinian	7.246
Miocene	Late	Tortonian	11.63
Miocene	Middle	Serravallian	13.82
Miocene	Middle	Langhian	15.97
Miocene	Early	Burdigalian	20.44
Miocene	Early	Aquitanian	23.03
Oligocene		Chattian	28.1
Oligocene		Rupelian	33.9

Figure 2. Oligocene to Pliocene geologic time scale based on the International Chronostratigraphic Chart of 2015/01 (Cohen et al., 2013; updated).

2. Objective

Using the ocean general circulation model sbPOM (Jordi and Wang, 2012) we aim to achieve physics-based insight into the role of marine gateways in the palaeoceanography of the Miocene Mediterranean Sea. We address:

a) The Early to Middle Miocene closure of the Indian Gateway, which used to connect the proto-Mediterranean Sea to the Indo-Pacific Ocean.

b) The interplay of the Betic and Rifian corridors that connected the Mediterranean and the Atlantic during the Late Miocene, before the Messinian Salinity Crisis.

Comparing model results to available data we discard previously proposed scenarios and formulate new ones

This work is based on:

de la Vara, A., and P. Th. Meijer. Response of Mediterranean circulation to Miocene shoaling and closure of the Indian Gateway; A model study. Palaeogeography, Palaeoclimatology, Palaeoecology (in press).

de la Vara, A., R. P. M. Topper, P. Th. Meijer, and T. J. Kouwenhoven (2015), Water exchange through the Betic and Rifian corridors prior to the Messinian Salinity Crisis: A model study, Paleoceanography 30(5), pp. 548–557, doi: 10.1002/2014PA002719.

Acknowledgements

This work is funded by NWO/ALW and computational resources were provided by the Netherlands Research Center for Integrated Solid Earth Science (ISES 3.2.5. High End Scientific Computational Resources).

References

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- Cohen, K. M., S. C. Finney, P. L. Gibbard, and J. -X. Fan (2013; updated), The ICS International Chronostratigraphic Chart, Episodes 36, pp.199-204.
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3. Response of Mediterranean circulation to shoaling and closure of the Indian Gateway

3.1. Model setup

- From an early Burdigalian palaeogeography multiple gateway geometries are constructed (Figure 3 and Figure 4).
- We start with atmospheric conditions based on the present and explore alternative atmospheric conditions.
- The Atlantic Gateway has a depth of 500 or 900 m, depending on the experiment.
- We impose net westward flows through the gateways.

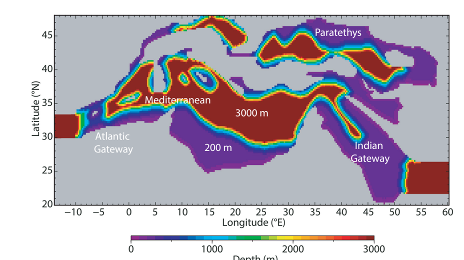

Figure 3. Reference bathymetry based on the early Burdigalian palaeogeographic map of the Peri-Tethys Atlas.

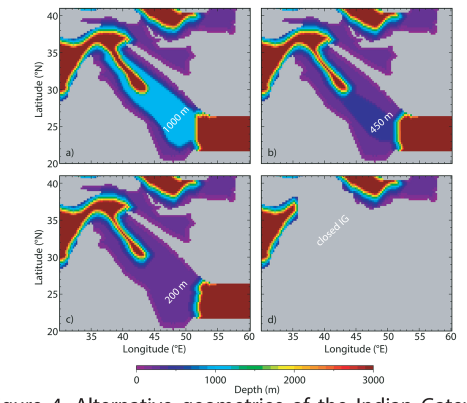

Figure 4. Alternative geometries of the Indian Gateway which allow us to examine the process of closure.

3.2. Results

Reference experiments

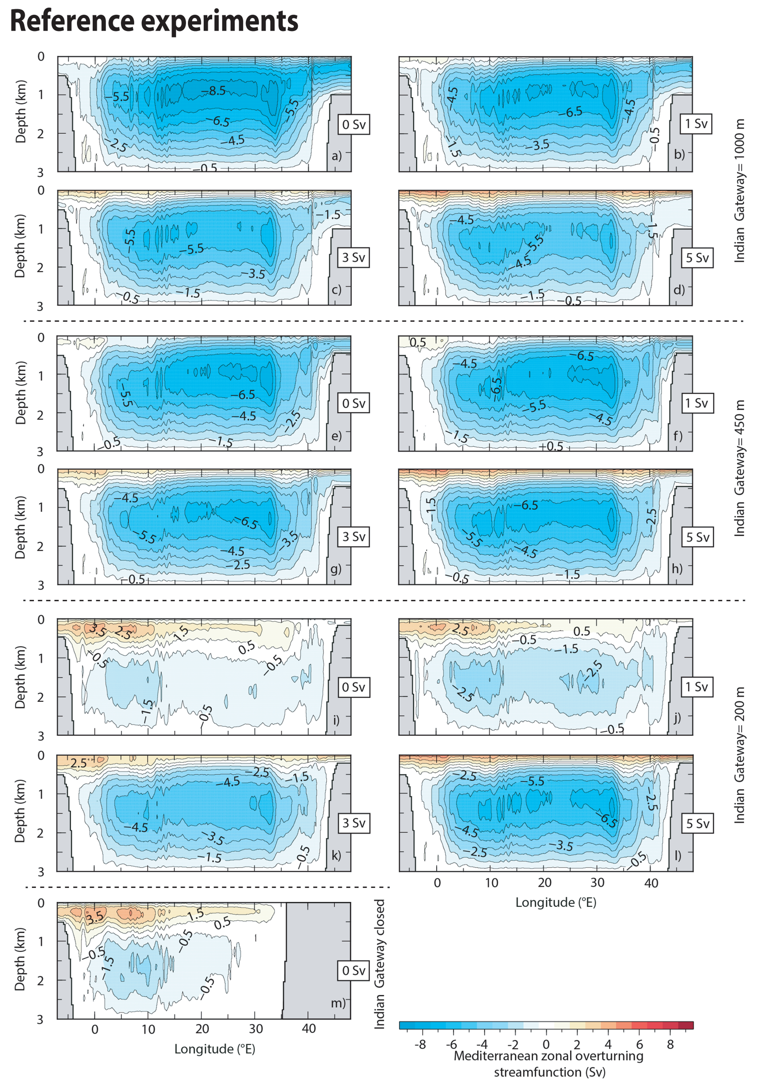

Figure 5

Figure 5. Mediterranean zonal overturning streamfunction for several Indian Gateway depths and different amounts of net westward flow. The Indian Gateway is set to 1000 m (a-d), 450 (e-h), 200 m (i-l), and it is closed in (m). As indicated in the figure, in the first panel of each block of four no net flow is imposed and, in the following ones, 1, 3, and 5 Sv are prescribed, respectively. Reference atmospheric forcing based on the present day is used.

Figure 6. Mediterranean zonal overturning streamfunction for a deep Atlantic Gateway when alternative atmospheric forcings (Alt.) are considered. In panels (a) and (b) the net evaporation is reduced over the Paratethys (RNE) and in panels (c) and (d) the Middle Miocene sea-surface temperature is prescribed (MM SST). In panels (a) and (c) the gateways do not accommodate net flow and, in (b) and (d), 3 Sv are imposed.

Figure 7. Mediterranean zonal overturning streamfunction for a deep Atlantic Gateway and a deep (a-b), shallow (c-d) and closed (e-f) Indian Gateway. In panels (a) to (d) reference atmospheric forcing is used (i.e., Ref) and, in (b) and (d) a net flow of 3 Sv is superimposed. In panel (e) reference atmospheric conditions are used again and, in (f), alternative atmospheric forcing (i.e., Alt) consisting of the Middle Miocene sea-surface temperature is prescribed (MM SST).

Alternative experiments

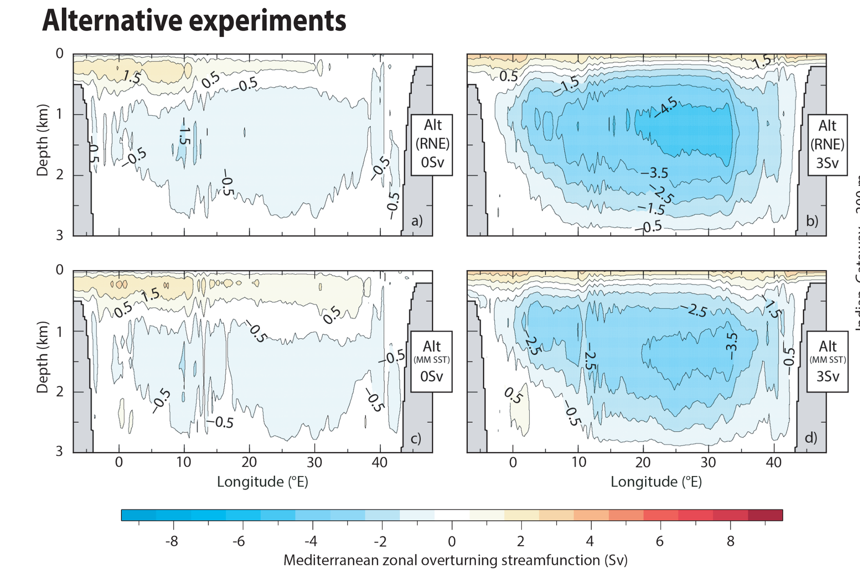

Figure 6

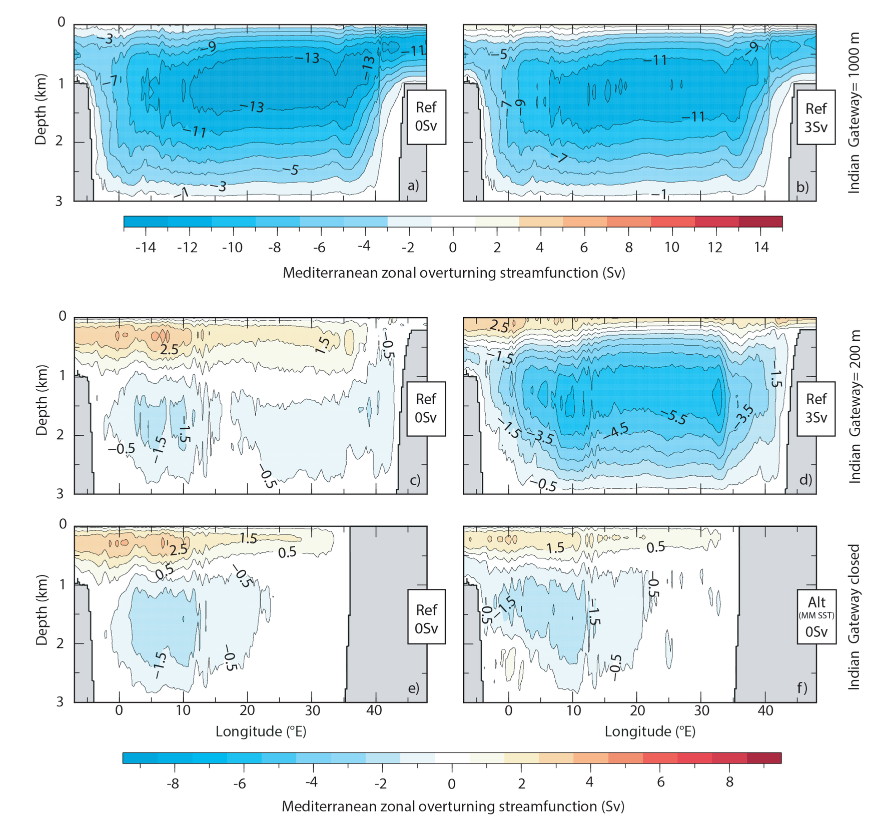

Figure 7

3.3. Conclusions

- Antiestuarine exchange with the Indian Ocean occurs unless the Indian Gateway is 200 m and the gateways accommodate net flow.

- The exchange with the Atlantic is estuarine if the Indian Gateway is deep. If it is shallow or closed, there are several possible Mediterranean-Atlantic exchange patterns.

- A comparison between the model results and proxy data from the Langhian suggests estuarine exchange or three-layer flow between the Mediterranean and the Atlantic when the Indian Gateway was shallow (Figure 8).

- After closure antiestuarine exchange with the Atlantic develops unless the Atlantic Gateway is deep and alternative conditions are applied. Then, three-layer flow develops (Figure 8).

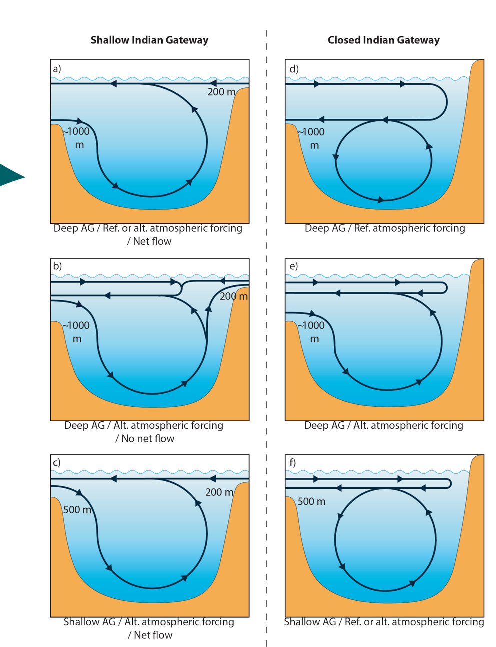

Figure 8. Panels (a), (b), and (c): modelled Mediterranean-Atlantic exchange patterns consistent with data from the Langhian for a shallow Indian Gateway. Panels (d), (e), and (f): all possible exchange patterns found after closure. The conditions under which these flows arise are also indicated. "AG" refers to the Atlantic Gateway; "Ref" and "Alt" to reference and alternative atmospheric conditions, respectively.

4. Water exchange through the Betic and Rifian corridors prior to the Messinian Salinity Crisis

4.1. Model setup

- From a late Tortonian palaeogeography multiple gateway geometries are constructed (Figure 9).
- We start with atmospheric conditions based on the present and explore alternative atmospheric forcings.

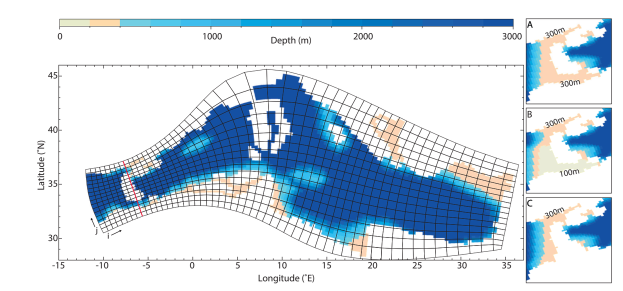

Figure 9. Reference bathymetry based on the late Tortonian palaeogeographic map from the Peri-Tethys Atlas and the orthogonal curvilinear grid (only one out of three gridlines is drawn). Right-hand side panels illustrate in detail the gateway area to exemplify the alternative bathymetries. The BeC is set to 300 m, and the RiC is (a) 300, (b) 100 and (c) 0 m. The red line shows the transect where horizontal velocities are illustrated (Figures 11 and 12).

4.2. Results

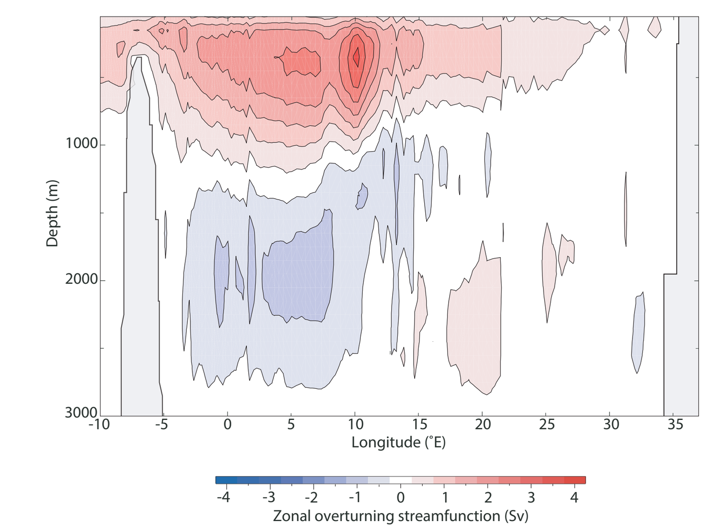

Figure 10. Zonal overturning streamfunction for a double-gateway scenario where both corridors have a depth of 300 m. Red colours indicate clockwise sense of flow in this projection and blue colours counterclockwise.

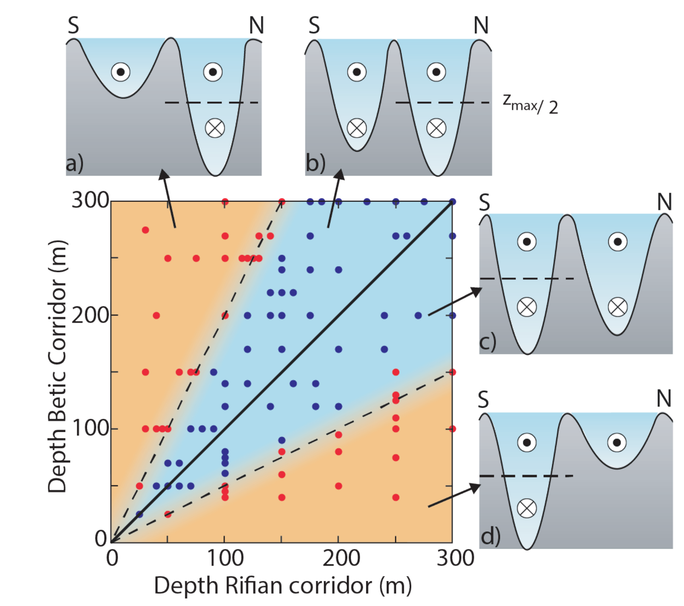

Figure 11. Exchange patterns through the corridors. The blue dots indicate that we find two-way flow in both gateways. The red dots represent two-layer flow in the deep corridor and only Atlantic inflow in the shallower one. The continuous line designates that both gateways have the same depth, and the dashed lines that one corridor is twice the depth of the other. Panels (a-d) show various gateway configurations as seen from the Mediterranean. The discontinuous line indicates the mid-depth of the deep corridor.

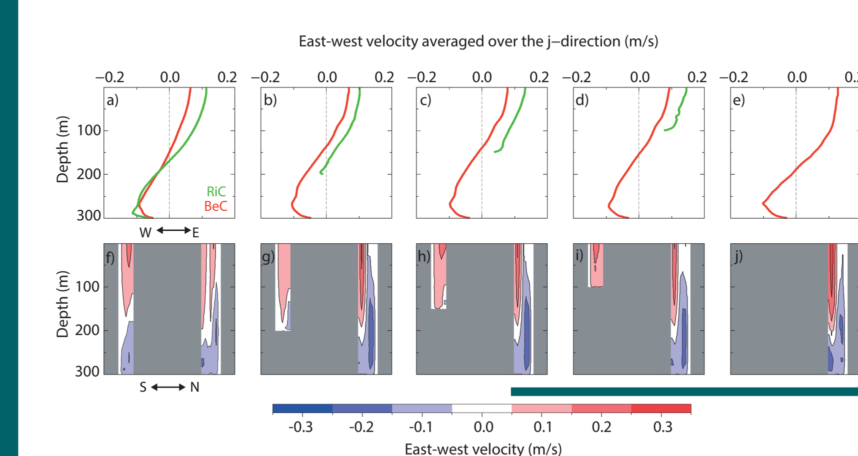

Figure 12. Profiles of latitudinally-averaged east-west velocity (a-e) and east-west velocity (f-j) both calculated at the same transect (i=25). The BeC has a constant depth of 300 m and the RiC is set to 300, 200, 150, 100 and 0 m from (a) to (e) and from (f) to (j).

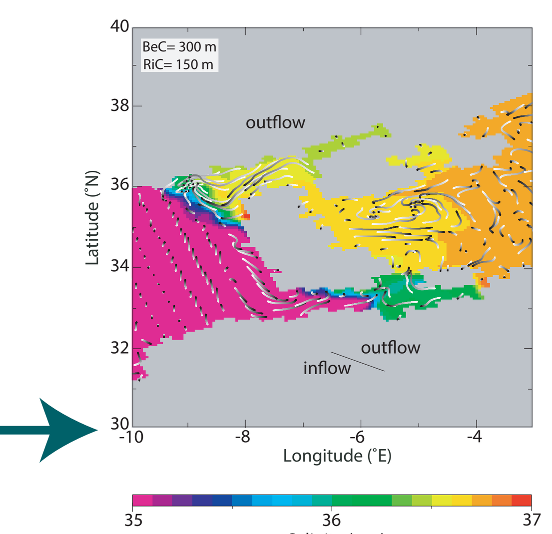

Figure 13. Salinity (psu) and flow trajectories just above the seafloor in the gateway area (shown is the deepest sigma layer). Trajectories show the paths water would travel in 30 days, on the basis of the velocity field at steady state. The BeC is set to 300 m and the RiC to 150 m.

4.3. Conclusions

- The water exchange through these corridors depends predominantly on the depth of a corridor relative to the other and it does not depend on the atmospheric conditions prescribed.

- Both corridors present two-way flow (i.e., antiestuarine exchange) unless the shallow gateway is shallower than about the mid-depth of the deeper corridor.

- Outflow evidence in a corridor automatically relates to two-way flow.

- Evidence for inflow could be the result of one-way flow or a rotational two-layer flow; in this case evidence from a location further north would clarify if this corresponded to one- or two-layer flow.

- One-way flow in a corridor indicates that this corridor was shallower than half the depth of the deeper gateway.

- Outflow disappearance in a corridor does not necessarily indicate its closure.

- The siphon scenario (Benson et al., 1991) involving inflow of Atlantic waters through the RiC and only outflow trough the BeC prior to the Messinian Salinity Crisis is unlikely.