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# Model study of the circulation of the Miocene Mediterranean Sea and Paratethys: closure of the Indian Gateway

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## Abstract

The early Mediterranean Sea and the Paratethys were both connected to the Indian Ocean until the Early/Middle Miocene, when the convergence of the Eurasian and African-Arabian plates caused the constriction and final closure of the Indian Gateway.

5 Although little is certain concerning the timing of the closure and the consequences that it entailed, it is broadly accepted that it had a large effect on water properties and ocean dynamics on the regional and global scales and, in that way, may have also played a role in the evolution of climate.

The purpose of this work is to investigate the palaeocirculation of the Mediterranean Sea and the Paratethys during different stages of closure and the impact of this event on the water exchange between the Mediterranean and the adjacent Indian and Atlantic oceans. To this extent we use a regional ocean model and an Early Miocene palaeogeographic map. In addition to varying the depth of the Indian Gateway, different sets of values for the atmospheric forcing have been applied in order to check the robustness of our results and to understand the role of the temperature and net evaporation on the marine circulation and the strait dynamics.

The series of experiments performed shows that, with an Indian Gateway ranging from 1000 to 460 m deep, the Mediterranean accommodates anti-estuarine exchange to the Indian and Atlantic oceans. The shoaling of the Indian Gateway results in a progressive decrease in the water exchanged between the Indian Ocean and the Mediterranean basin, and increases the spatial extension of the Atlantic inflow. When the gateway is as shallow as 220 m, there is no effective water exchange between the Indian Ocean and the Mediterranean basin, suggesting that the gateway may have been closed in an oceanographical sense, even while a water passage was still in existence. On a basinal scale, closure results in a rearrangement of the circulation pattern which leads to changes in salinity and temperature in both the Paratethys and the Mediterranean Sea. On the global scale, closure implies the disappearance of a source of dense outflow into the Indian Ocean which could have played a role in the

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Stream and entailed Northern Hemisphere glaciations (e.g., Haug and Tiedemann, 1998; Bartoli et al., 2005).

In the Mediterranean region, the constriction of the Betic and Rifian corridors between Spain and Morocco resulted in the desiccation of the Mediterranean Sea during the well-known Messinian Salinity Crisis (Hsü et al., 1973). Earlier in the Miocene, the closure of the Indian Gateway is thought to have entailed important local and global effects. On a regional scale, closure favored a near landlocked physiography, resulting in a decrease of the basin's buffering capacity, increasing its sensitivity to climate change (Gladstone et al., 2007) and leading to the present-day net evaporative loss. Palaeoceanographic records show that closure affected the temperature, salinity and the sedimentary environment of the Mediterranean Sea and Paratethys (Mutti et al., 1999; Kocsis et al., 2008, 2009). On a global scale, closure played a role in the reversal of flow in the Panama Seaway (von der Heydt and Dijkstra, 2006) and has also been linked to the development of the East Antarctic Ice Sheet and an abrupt Middle Miocene climate change (e.g., Woodruff and Savin, 1989). Many studies have focused on unraveling the timing of collision of the African/Arabian plates (e.g., Hessami et al., 2001; Mouthereau et al., 2006; Hassanzadeh et al., 2008; Horton et al., 2008). However, the complexity of this process as well as the lack of properly dateable sediments makes the reconstruction of closure of the Indian Gateway difficult (e.g., Mourik, 2010).

Our objective is to gain physics-based insight into the functioning of the proto Mediterranean Sea-Paratethys system, communicating as it was with an ocean to both sides, and into the response to be expected from closure, both for the basin and for the adjacent oceans. To be able to reach sufficient amount of detail we use a regional-scale ocean general circulation model. Our code of choice is MOMA (e.g., Webb, 1996) and the calculations are centered on a Burdigalian palaeogeography (about 20 Ma) taken from the Peri-Tethys Atlas (Dercourt et al., 2000). In the interest of gaining insight into the first-order response of the basin to gateway evolution, a set of idealized experiments was carried out, ranging from a deep Indian Gateway to a completely closed one. In addition, to test the sensitivity of the model results to the assumed atmospheric

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circulation (e.g., Wu and Haines, 1998), but has also been used to study the palaeoceanography of the Mediterranean Sea (e.g., Myers et al., 1998; Meijer and Dijkstra, 2009; Karami, 2011). Our setup largely follows Meijer and Dijkstra (2009) to which we refer for more details.

In our experiments the model was run for an average of 700 computational years. Generally, after 500–600 yr, the basin-average salinity, temperature and kinetic energy were found to be in equilibrium. Temperature, salinity and velocity fields are averaged over the last 100 yr of each run. The results of each experiment thus represent the steady state conditions associated with a certain stage of the closure process. This “time slice” approach is justified because the change in palaeogeography is much slower than the adjustment of circulation.

## 2.2 Set of bathymetries

Combining a Burdigalian palaeogeographic map from the Peri-Tethys Atlas (Dercourt et al., 2000) with the absolute position of the main units reconstructed on the basis of a recent compilation of rotation poles (Müller et al., 2008), a simplified palaeobathymetry was built. As the palaeogeographic map used as a reference only distinguishes between shallow and deep areas, the palaeobathymetry was simplified into these two levels. The shallow domains were set to 220 m, the model level approximating the average depth of the continental shelves. The deep levels, which correspond to oceanic crust, were set to 3000 m. To avoid computational instabilities related to the sharp depth differences between the two levels, it was found to be necessary to introduce a continental slope (Fig. 1). This slope was created taking as a reference the continental slope proposed by Tessarolo et al. (2008) for the present-day Calabrian region, which is very steep and does not introduce major variations in the two-level bathymetry, but proves smooth enough to prevent model instabilities. Using the map thus created as a reference, alternative geometries were constructed varying only the bathymetry in the region of the Indian Gateway in order to be able to isolate the effect of the depth of this gateway. The Indian Gateway is set to the effective depths of 1000,

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460 and 220 m, and is completely closed in a fourth geometry (Fig. 2). Unless specified otherwise, the Atlantic Gateway will always be 460 m deep. This value, somewhat higher than the depth of the present-day Strait of Gibraltar (about 300 m), is chosen because the marine connections between the Mediterranean and the Atlantic Ocean were not severely restricted until the Late Miocene (Meulenkamp and Sissingh, 2003). The role of variations in the depth of the Atlantic connection and in the two Mediterranean-Paratethys connections (kept at a constant 220 m) is mostly beyond the scope of this paper but will be addressed where relevant.

### 2.3 Open-ocean boundaries

In the west and in the east the model domain extends beyond the gateway a little distance into the open ocean creating small “boxes” in which temperature and salinity are gradually restored to prescribed oceanic values. These “sponge” boundary conditions represent the open ocean in the sense that they control the properties of water flowing into the basin and set the oceanic side of any along-gateway gradients in temperature, salinity and thus density. Sponges were part of original MOMA setup for present Mediterranean and have been successfully applied in previous palaeo-modelling studies (e.g., Meijer and Dijkstra, 2009; Topper et al., 2011). While sponges are relatively easy to implement and allow for fast computation, they are no true open boundaries: volume is conserved and transports into and from the boxes are thus constrained to be the same. The disadvantage of this for our particular application is that we cannot consider scenarios in which a net inflow into the basin occurs from one side, which is compensated by a net outflow to the ocean on the other side. In other words, we will capture any baroclinic flow but cannot allow for a barotropic component of flow through the gateways.

In the sponges, the time scale of restoration for cells adjacent to the basin is smaller. This favors a smooth gradient in water properties, allowing a more natural water exchange between the box and the adjacent waters. While, inside both boxes, salinity is set to a constant value of 35 psu from the surface to the bottom, temperature settings

are more complex. To ensure a match to the prescribed surface forcing and to avoid unrealistic temperature contrasts across the box limits, temperature was set in the form of an exponential curve decreasing from the sea surface temperature value until a minimum of 5 °C at depth. For this we use present-day Atlantic and Indian vertical potential temperature profiles taken from the Levitus Atlas as a reference.

## 2.4 Atmospheric forcing

The heat exchange between the atmosphere and the ocean is defined by means of relaxation of the surface layer to the prescribed present-day sea surface temperature shown in Fig. 3, which varies only with latitude and is constant in time. The temperature-latitude curve approximates the present-day zonally-averaged annual-mean sea surface temperature proposed on the basis of satellite data by Steppuhn et al. (2006). In all the experiments performed, the relaxation time scale is two hours. Evaporation is represented by means of an equivalent salt flux and is idealized to a uniform and constant value of  $0.5 \text{ myr}^{-1}$  (e.g., Topper et al., 2011; Meijer, 2012). This flux represents the net effect of evaporation, precipitation and river runoff. Whereas the salinity over the Mediterranean, the Paratethys and the Indian Gateway is initialized to a uniform value of 35 psu, initial temperature is made depth dependent to prevent steep temperature gradients between the waters inside and those outside the boxes, which would cause undesirable high velocities in the initial stages.

We decided not to use winds for several reasons. On the one hand there is much uncertainty regarding the Early Miocene winds and, on the other hand, forcing the model with the present-day wind pattern does not seem to be appropriate since it is strongly influenced by the continental geometry, which is substantially different from that in the present-day. Most importantly, previous model studies have been able to reproduce the main features of the current Mediterranean Sea thermohaline circulation also without winds (Meijer and Dijkstra, 2009).

### 3 Results and analysis

In this section we start studying the main features of the general circulation induced by the shoaling of the Indian Gateway by analyzing the zonal overturning streamfunction (see Fig. 4). While “blue cells” correspond to west directed surface flow and eastward deep flow, “red cells” represent the opposite tendency. Here and elsewhere in this work, the sense of the overturning is described as seen from the south.

#### 3.1 Effect of closure on overturning circulation

As shown in Fig. 4a, with a deep connection between the Indian Ocean and the Mediterranean basin, the circulation is characterized by the presence of two cells, an anticlockwise circulation and a clockwise cell associated with the Indian and Atlantic oceans, respectively. The anticlockwise cell extends over the Indian Gateway and a great part of the Mediterranean. According to the streamlines, Indian waters flow into the gateway and Mediterranean basin from the surface until an intermediate depth of 200–300 m. At longitudes 4° E and 9° E water sinks to great depth and then returns to the Indian Ocean in the depth interval between 200–300 and 1000 m. If we observe the upper red cell located in the westernmost Mediterranean, we realize that water transport through the Atlantic Gateway follows a similar pattern compared to that in the Indian Gateway: oceanic inflow occurs at the surface and water returns back to the box from an intermediate depth. Note that, as the two gateways are set to different depths, the interface between the inflow and outflow is not located at the same depth in the two connections. The great extension of the blue cell, as well as its strong intensity, indicates that the circulation within the Mediterranean basin is dominated by the Indian Ocean. Mediterranean water properties are thus influenced more by the Indian than by the Atlantic Ocean.

When the Indian Gateway is made shallower, reaching an intermediate depth of 460 m (Fig. 4b), not only are the cells described previously still present, but also deep water formation occurs at the same spots. However, the magnitude and extension of the

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cells associated with the Indian and Atlantic oceans change substantially. Whereas the Indian inflow does not extend spatially as much as before and has a lower magnitude compared to the previous situation, the opposite occurs to the cell linked to the Atlantic Ocean. This reflects that, as the Indian Gateway shoals, the relative importance of the Indian with respect to the Atlantic decreases. This tendency is clearly appreciated when the Indian Gateway is set to 220 m (Fig. 4c). In this simulation the blue cell related to the Indian Ocean disappears for the first time and the basin circulation is now dominated by the Atlantic Ocean. The inflow coming from the Atlantic Ocean can be traced to the easternmost Mediterranean and extends into the Indian Gateway. In the north-easternmost Mediterranean water sinks and joins a return flow at an intermediate depth back to the Atlantic. Deep water formation takes place at the same locations again, but it forms below the upper anti-estuarine cell associated with the Atlantic inflow.

Finally, when the Indian Gateway is completely closed, the water exchange across the Atlantic Gateway (Table 1) and the general features of the zonal overturning function are almost identical to the shallow pre-closure case (Fig. 4d). This suggests that, in terms of general basin circulation, at the depth of 220 m, the gateway can be considered effectively closed.

### 3.2 Effect of closure on the salinity and velocity field

After this general overview, we present a more detailed analysis of the changes in the Mediterranean basin, the Paratethys and within the Indian Gateway itself.

#### 3.2.1 Deep Indian Gateway

As can be appreciated in Fig. 5a (salinity and horizontal velocity field at 10 m deep), when the Indian Gateway is 1000 m deep, the Mediterranean basin is influenced by both oceans. Nevertheless, the amount of water exchanged through the Indian Gateway is much greater. There is a clear correspondence between the horizontal velocity field at the surface and the zonal overturning streamfunction. The Indian inflow extends

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through the gateway and the Mediterranean basin until 12° E. The Atlantic inflow, which is spatially more limited, splits into two branches, a northern and a southern one. While the branch flowing towards the north is stronger and reaches into the northwestern corner of the western Mediterranean basin, the southern one is more localized.

5 There is water exchange between the Mediterranean and the Paratethys through two narrow and shallow connections (dimensions are listed in Table 1). Inflow into the Paratethys occurs through the eastern Mediterranean-Paratethys connection and outflow takes place along the western one. Flow directions are uniform across the entire depth of the straits. The Indian inflow has a strong impact on the Indian Gateway water properties and also has a clear effect within the Mediterranean basin and the Paratethys. As a result, relatively fresh waters are found in the Indian Gateway. Salinity differences between this gateway, the Mediterranean basin and the Paratethys realm are very small (Table 2). As shown in Fig. 5a, in the eastern Mediterranean basin the lowest salinities are found from 30° N northward, where the Indian inflow still has an influence. Further south, the highest salinities of the whole domain occur. Crucial to this is the combination of two factors: (i) this area is not affected directly by any source of ocean water, and (ii) it is a shallow region, which means that it is more sensitive to evaporation.

### 3.2.2 Intermediate-depth Indian Gateway

20 In this experiment, the constriction of the northern domain of the gateway to the shallower depth of 460 m limits the exchange to this intermediate depth (Fig. 4b). It can be appreciated that both oceans have a significant influence on water properties. The water transport across the Atlantic Gateway is very similar to that with the previous bathymetry. Although the Indian Gateway is still more effective in exchanging water than the Atlantic one, water transport through it decreases by about 1.8 Sv compared to the deep Indian Gateway configuration (Table 1). The Indian inflow is only able to reach northwestern areas around the Indian Gateway. Similarly, Indian waters reach the Paratethys, but the inflow through the eastern Mediterranean-Paratethys connection

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is smaller than with the deep Indian Gateway. At shallow levels, the Paratethys waters cannot reach the Mediterranean basin through the western Mediterranean-Paratethys connection. The strong, northern branch flowing in from the Atlantic Ocean blocks the southward flow from the Paratethys. Paratethys inflow into the Mediterranean does occur from an intermediate depth downwards.

The new flow pattern leads to a subtle salinity increase, which is sharper over the Paratethys and eastern Mediterranean (Table 2). In the eastern Mediterranean basin, especially towards the north, waters get saltier because of the reduction in the amount of Indian inflow. Maximum salinity values are located over the Paratethys, where salinity tends to go up westward, as the distance from the main entrance of relatively fresh water increases. Locally, there is a maximum at the easternmost Paratethys coinciding with an area hidden from the general inflow.

### 3.2.3 Shallow Indian Gateway

Results show that, for the first time, water exchange through the Indian Gateway has not only been reduced, but it is smaller than that through the Atlantic Gateway (Table 1). In other words, the relative importance of the Indian Ocean decreases substantially when the gateway is set to 220 m (the reference geometry based directly on the Peritethys Atlas). Despite having water exchange with the Indian Ocean the flow does not appear in the zonal overturning streamfunction plot because the horizontal velocity field at the surface shows north–south oriented flow (see Fig. 5c). It does show up clearly in the meridional overturning streamfunction depicted in Fig. 6. When the Indian Gateway is deep, there is a strong and continuous red cell, while when it is shallow there are two independent and weaker red cells, one for the Mediterranean Sea and another one for the Indian Gateway. These plots confirm that, with a shallow Indian Gateway, the gateway and the basin behave as separate systems.

The water transport through the Mediterranean-Paratethys connections is less than with the previous geometry and this results in a sharp salinity increase over the Paratethys, which is 2.65 psu saltier (Table 2). This value corresponds to the highest

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salinity found in all the experiments until now. Moreover, the way in which the Mediterranean and Paratethys exchange waters is different from the previous case as well. Before, the water inflow into the Paratethys occurred through the eastern Mediterranean-Paratethys connection throughout the whole water column. Now, the eastern connection shows inflow into the Paratethys at the surface and outflow at depth. Similarly to the previous experiment, Paratethys inflow into the Mediterranean occurs through the western Mediterranean-Paratethys connection, but only below a certain depth. Associated with the new circulation pattern, salinity experiences significant changes. While values on the western Mediterranean do not differ from the previous experiments, they increase substantially in the rest of the Mediterranean basin and Indian Gateway. Despite that it is over the Paratethys where the maximum differences occur, we also notice a large increase over the central Indian Gateway (30–35° N). This is related to two factors: (i) the bathymetry: the strait itself is shallow and (ii) the distance from the ocean. The influence of the warm and relatively fresh Indian inflow, which obviously decreases with distance, is not as great as before since the cross-sectional area available for exchange is smaller.

### 3.2.4 Closed Indian Gateway

With a closed Indian Gateway, water transport across the Atlantic Gateway has the same magnitude as with a shallow eastern connection (Table 1). The circulation pattern in the two experiments is identical and water transport through the Mediterranean-Paratethys connections does not show significant differences in magnitude or type of exchange. Finally, differences found in salinity and temperature between the last two experiments, are negligible (Table 2). As stated before, a 220 m Indian Gateway can be considered closed from a palaeoceanographic point of view.

### 3.3 Additional experiments: sensitivity to atmospheric forcing

Two extra experiments to test the sensitivity of results to atmospheric forcing are also presented. In both experiments, the reference bathymetry taken directly from the Peritethys Atlas is used: the Indian Gateway is set at 220 m.

#### 3.3.1 Reduced net evaporation over the Paratethys

Until this point, we applied the same net evaporation rate over the whole domain to keep the model as simple as possible. These settings caused the highest salinities to be found in the Paratethys (Fig. 5), reflecting its enclosed nature. Since we know that normal oceanic salinity values existed in the Paratethys during the Early Miocene (Grunert et al., 2010), we try a new experiment in which the net evaporation is reduced the half over the Paratethys. A cosine function is used to create a smooth transition between the Mediterranean and the Paratethys.

The zonal overtuning now obtained (Fig. 7a) displays the same pattern as with a uniform evaporation (Fig. 4c). Nevertheless, the amount of water transport through both gateways and deep water formed decrease. As expected, salinity falls significantly, especially over the Paratethys (Fig. 8a). This results in a more homogeneous salinity (and density) field over the whole model domain. Water transport across the Mediterranean-Paratethys connections is also different. There is mainly inflow into the Paratethys through the eastern connection from top to bottom and inflow into the Mediterranean only occurs from an intermediate depth downwards through the western one. In the equivalent run with a uniform net evaporation, the differences between the Mediterranean and Paratethys average salinity were larger than 3psu. Now, the average salinity in the Paratethys is only 0.2psu higher compared to the Mediterranean Sea. Moreover, salinity within the Indian Gateway is identical to that in the Mediterranean basin (Table 2). Although results obtained with a non-uniform net evaporation and a deep, intermediate-depth and closed Indian Gateway configurations are not shown,

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the response of thermohaline circulation to decrease in gateway depth is found to be essentially unchanged.

### 3.3.2 Middle Miocene sea surface temperature

To investigate the role of the imposed sea surface temperature, several experiments were repeated with an estimate of the Middle Miocene temperature profile (Fig. 3). An idealized curve was built using the sea surface temperature reconstruction based on oxygen stable isotopes of You et al. (2009). While, in the south of the domain, temperatures are similar to the current ones, values do not decrease as much with latitude, resulting in a reduced north–south temperature gradient. Results show that the average temperature over the Paratethys, as one could expect, increases more than in the Indian Gateway or Mediterranean basin compared to the equivalent experiment with the initial settings (Table 2). Once again, the overall circulation pattern over the Mediterranean basin does not show remarkable changes (Fig. 7b). However, the amount of deep water formed is even smaller than with a non-uniform net evaporation rate. Since water exchange to the outside oceans decreases, salinities tend to go up all over the domain, especially over the Paratethys because of its enclosed geometry (Fig. 8b). We register inflow into the Paratethys at the surface in both Mediterranean-Paratethys connections and outflow from an intermediate depth for the first time. The response to shoaling of the Indian Gateway proves not to change appreciably when the new temperature profile is used (results not shown). The two sets of additional experiments confirm that with a shallow Indian Gateway there is no effective water exchange between the Mediterranean and the Indian.

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## 4 Discussion

### 4.1 Robustness of model results

The response to changes in depth of the Indian Gateway was found to be independent of the atmospheric forcing (Sect. 3.3). To assess the limitations that the simplification of the bathymetry into two levels could entail, the same procedure described in Sect. 2.2 was followed to create a bathymetric model for the present-day Mediterranean Sea. Results obtained with this bathymetry were compared to those found with a realistic present-day model. The two-level bathymetry proves able to capture the major features of the current Mediterranean thermohaline circulation. The circulation pattern is very similar to that found by Meijer and Dijkstra (2009) for the present-day Mediterranean Sea. It would thus seem that uncertainties derived from the simplification of the bathymetry are minimal.

Regarding the ocean boxes, to make the interpretation of the results easier, we tried to simplify the conditions inside the boxes as much as possible. However, we do not expect that to be a limitation since what really determines the anti-estuarine circulation that we find is that the Mediterranean is saltier than the Indian and Atlantic oceans. Our model correctly captures this type of exchange. In a similar sensitivity analysis carried out by Karami (2011), the type of exchange to the Indian and Atlantic is anti-estuarine as well, even though in this work the Indian Ocean was warmer and fresher than the Atlantic. Gateway exchange is driven by gradients in density and, in combination with the pattern of sea surface elevation, in pressure. Our results may be thought of as capturing that component of gateway transport that has its cause on the Mediterranean side of the connection. In our experiments the basin is, for example, never subjected to a flow coming from the adjacent ocean driven by processes within that ocean. Barotropic inflow through the Indian Gateway was found in the global model studies of von der Heydt and Dijkstra (2006) but here the gateway was both wide and deep due to the limited resolution. Generally speaking it is conceivable that in reality the flows through the Indian Gateway consisted of a superposition of net barotropic

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flow and the baroclinic exchange found in our experiments. As to the response to closure, in addition to the effects found in our analysis, closure may have witnessed the disappearance of any barotropic flow coming from the Indian Ocean.

## 4.2 The Mediterranean/Paratethys between two oceans

5 Our sensitivity analysis provides insight into the role of the configuration of the Indian Gateway on marine circulation in the Mediterranean Sea, the Paratethys and within the gateway itself. Results show that, with a deep to intermediate-depth Indian Gateway, both, this gateway and the Atlantic connection accommodate anti-estuarine exchange: at depth Mediterranean water flows out to the Atlantic Ocean and to the Indian Ocean,  
10 while water enters the Mediterranean from the adjacent oceans at the surface.

As in the current Mediterranean Sea, there is a shallow (0–500 m depth) zonal circulation cell associated with the inflow of Atlantic waters at the surface. Atlantic inflow is transformed into the equivalent of the present-day Levantine Intermediate Water in the eastern Mediterranean. Changes that occur in overall circulation when the Indian Gateway is made shallower suggest that the controlling mechanism is essentially the one  
15 which is commonly thought to operate in the present-day Mediterranean Sea: net evaporation increases the density of the surface waters of Atlantic origin, these waters sink and the relatively dense water flows out over the sill, triggering a compensating surface inflow. With a deep Indian Gateway, most exchange occurs on the Indian side of the basin, but when this connection is taken to be shallower, the exchange with the Atlantic grows in relative importance. To understand in more detail the Indian Gateway dynamics, an experiment with the initial settings and the shallow Indian Gateway geometry with a closed Atlantic Gateway, was carried out. Results show that the disappearance of the Atlantic inflow causes a dramatic salinity increase over the basin. This leads to  
20 a strong density gradient between the Indian Ocean and the Mediterranean, resulting in a considerable increase in water flowing along the Indian Gateway, reaching values as high as 6 Sv.

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Similar to the present-day Mediterranean Sea (e.g., Pinardi and Masetti, 2000), the basic and additional experiments performed show that deep water formation occurs in the northern parts of the eastern and western Mediterranean sub-basins. In all the experiments, deep water forms at 4° E and 9° E. The deep water cells are always found to have an anticlockwise sense of motion, as viewed from the south, and are connected to the cell associated with the Indian Ocean when this gateway is set to deep or intermediate levels. At shallow depths, the lowest temperatures of the Mediterranean basin occur at the spots where water sinks, strongly suggesting that density increase and subsequent deep water formation is linked to cooling. This is supported also by the fact that salinities at these locations are not higher than in the rest of the basin. Strong cooling occurs at these sites because they are located at relatively high latitude. We also propose that the cold Paratethys inflow into the Mediterranean also plays a role in this process. In an extra experiment in which the western Mediterranean-Paratethys connection was closed, deep water formation on the western Mediterranean sub-basin was found to disappear. It seems that one of the reasons why we capture deep water formation on the western Mediterranean, which is not present in most of the present-day models, is the cold and saline Paratethys inflow into this sub-basin.

In order to understand the role of the Atlantic and Indian gateways in the heat and salt budget of the Mediterranean basin, the net heat and salt transport through the gateways was quantified (Table 3). On the one hand, we find that the Mediterranean outflow into the adjacent oceans is, regardless the Indian Gateway depth used, saltier than the corresponding inflow, meaning that closure entails a general salinity increase (Table 2). On the other hand, while there is always a net heat loss through the Indian Gateway, the basin tends to gain heat from the western side. Only with a deep Indian Gateway the heat lost from the eastern side exceeds that gained from the Atlantic. In this case the basin experiences a net heat input from the atmosphere. For the other Indian Gateway configurations, the heat lost to the Indian is smaller (one order of magnitude less) than that gained from the Atlantic Ocean and values of the high fluxes involved are very similar. In these cases the basin behaves similar to the present-day

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Mediterranean Sea: the heat gained from the Atlantic Ocean is lost to the atmosphere. Even though closure results in significant changes in the distribution of temperature within the basins (see next section) the Mediterranean-averaged temperature does not vary appreciably between the different stages of closure here examined (Table 2). This is most likely due to the buffering action of the relaxation boundary condition on sea surface temperature.

### 4.3 Proxies and basin response to closure

One of the strengths of this study is that it approaches the closure of the Indian Gateway from a regional perspective, which allows us to establish a guide for future data acquisition and interpretation. To this extent, we identify in our model results those areas in which major temperature and salinity changes occur in response to closure.

Our experiments indicate that the closure of the Indian Gateway, regardless of the choices made for the forcing, entailed major changes in the water properties of the Mediterranean and Paratethys. Since the circulation pattern in the western Mediterranean is determined, prior as well as after closure, by the exchange with the Atlantic Ocean (the magnitude of which does not increase substantially with closure), this area is least subject to change. This is not the case for the eastern sub-basin, where the restriction and closure of the Indian Gateway implies the transition from a circulation pattern dominated by the Indian Ocean to one which is controlled by the Atlantic Ocean.

In the eastern Mediterranean, the salinity increase due to shoaling of the gateway becomes gradually larger towards the east. At a depth of about 200 m the salinity rise is maximum, reaching values which can be greater than 1 psu, depending on the atmospheric forcing. From this depth downwards, salinity differences are smaller and more homogeneous horizontally. Temperature behaves similar to salinity in the sense that, in the eastern Mediterranean, temperature differences are more pronounced towards the east and the basin-averaged value also increases upon closure. Although one could expect temperature to go up as a result of closure since the Mediterranean does not lose heat by means of the outflow into the Atlantic, as it has been explained



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Savin, 1991; Gurlan et al., 2008), which are potentially useful since the closure marks the termination of migration of marine biota and the exchange of tropical waters between the eastern Mediterranean and the western Indo-Pacific (e.g., Harzhauser et al., 2007). While the dating of the closure is clearly essential to pin down the chain of events, we expect that our model-derived insights into the effects of closure are largely independent of the exact timing. Basin configurations proposed in the Peri-Tethys Atlas (Dercourt et al., 2000), as well as by other authors (e.g., Rögl, 1999; Jolivet et al., 2006), are very similar from the Early Oligocene to the Burdigalian situation which we used as a reference. By varying the depth of the Indian Gateway we captured the main factor of palaeogeographic change in the Oligocene-Middle Miocene period.

The closure of the Indian Gateway has been linked to different global changes in climatic conditions. Woodruff and Savin (1989) suggest that the closure of the Indian Gateway interrupted the formation of “Tethyan Indian Saline Water” during the Middle Miocene. This would have caused a decrease of the meridional heat transport to high southern latitudes through the Indian Ocean, thereby cooling the Antarctic surface waters and allowing the expansion of the East Antarctic Ice Sheet and leading to a Miocene cooling (e.g., Woodruff and Savin, 1989; Flower and Kennett, 1994). Ramsay et al. (1998) argue that the Mediterranean Sea was a source of warm and saline deep water to both the Indian and the Atlantic oceans. These authors propose that cooling and the expansion of the mid-Miocene Antarctic Ice Sheet was induced by changes in the deep circulation of the Atlantic Ocean and only to a lesser extent by the closure of the Indian Gateway and the disappearance of a warm inflow into the Indian Ocean. Even while some aspects of these ideas are being disputed on other grounds (e.g., Huber et al., 2004; Hüsing et al., 2009), our experiments confirm that prior to closure the Mediterranean was a source of dense outflow waters (at depth in the gateways) for both, the Atlantic and Indian/Pacific oceans. While Ramsay et al. (1998) suggest that changes in salinity and temperature of the outflow to both oceans would be related to climatic events within the Mediterranean, we propose that changes in depth of the Indian Gateway could have had similar effects. In a general way we can say that a deep

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Indian Gateway promotes a colder and fresher outflow to both oceans compared to the other gateway configurations. This is the result of two factors: (i) the amount of water exchanged between the Indian Ocean and the Mediterranean increases, resulting in a less saline outflow and (ii) water flows into the Indian Ocean at greater depth, causing a decrease in the outflow temperature (Table 3). According to our results, outflow waters to both oceans are always saltier than the corresponding inflow. In addition, while on the western side the Atlantic inflow is warmer than the Mediterranean outflow, the opposite is found in the Indian Gateway. Results shown in Table 3 indicate that, with a deep Indian Gateway, heat transport through both gateways is of the same order of magnitude as through the current Strait of Gibraltar ( $10^{13}$  W) but values are slightly higher, especially in the Indian Gateway. This implies that closure interrupted an important source of relatively warm and salty waters to the Indian Ocean.

Our experiments show that no remarkable differences in water properties or general circulation exist between a shallow (220 m depth) and closed Indian Gateway, confirming earlier findings by Karami (2011). The implication is that the gateway may have been effectively closed in an oceanographical sense even while a water passage was still in existence. Oceanographic closure seems to have preceded “geographic” closure. Where in this sequence “tectonic closure” must be placed will depend on the type of observations being used. While the first tectonic expressions of collision can be imagined to occur well before the oceanic connection is disrupted, the shedding of sediments from one continent onto the other would imply the seaway to have disappeared.

## 5 Conclusions

This study offers physics-based insight into the implications of the shoaling and closure of the Indian Gateway on the circulation and water properties of the Mediterranean basin and the Paratethys, as well as on the exchange to the surrounding oceans. The main findings from this work can be summarized as follows:

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1. With a deep to intermediate-depth Indian Gateway (ranging from 1000 to 460 m deep), the Mediterranean Sea accommodates anti-estuarine exchange to both adjacent oceans. The basin is dominated by the Indian Ocean with westward flow at the surface and eastward flow at depth.
2. When the Indian Gateway is shallow at 220 m, the basin circulation is controlled by the Atlantic and there is no effective water exchange between the Mediterranean and the Indian Ocean: a shallow Indian Gateway can be considered closed from an ocean-circulation perspective.
3. The Mediterranean outflow is always found to be saltier than the water flowing into the Mediterranean from the adjacent oceans. This means that the Mediterranean tends to lose salt through the Atlantic and Indian gateways. In contrast, while inflow through the Atlantic Gateway is always warmer than the corresponding outflow, the opposite behavior is found in the Indian Gateway. This implies that the basin loses heat through the Indian Gateway but gains heat from the Atlantic Ocean.
4. On a regional scale the effects of closure become more detectable towards the east of the eastern sub-basin, close to a depth of 200 m. While closure implies a general salinity increase, Mediterranean-averaged temperature is unaffected. Changes in the amount of heat lost to the Indian are compensated by the exchange with the Atlantic Ocean and the atmosphere. However, the temperature response to closure is spatially heterogeneous due to the rearrangement of the circulation pattern. It follows that, results obtained from proxies in a specific area or from a certain depth range will not readily apply to the basin as a whole.
5. The relatively small volume and enclosed configuration of the Paratethys favor a salinity increase in response to closure. Although Paratethys-averaged temperature, prior and after closure, does not change substantially, on a local scale we observe variations in temperature. More specifically, the eastern Paratethys tends

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to get slightly colder after closure. In addition, changes in the magnitude and the way in which the Paratethys and Mediterranean exchange water as the Indian Gateway shoals are also found.

6. On a global scale, the closure of the Indian Gateway interrupted a source of relatively salty and warm waters to the Indian Ocean which could have played a role in the development of the East Antarctic Ice Sheet.

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**Table 1.** Magnitude and type of exchange flow through the main gateways and the Mediterranean/Paratethys corridors for the different experiments. The two first rows of each triplet of values show the flow into the basin/ocean indicated and the last one corresponds to the net flow through the gateway/corridor there specified. Values are in Sverdrup ( $1 \text{ Sv} = 10^6 \text{ m}^3 \text{ s}^{-1}$ ); Key: IG = Indian Gateway; NUNE = non-uniform net evaporation (see Sect. 3.3.1); MMSST = model forced with the idealized Middle Miocene sea surface temperature shown in Fig. 3 (see Sect. 3.3.2).

Length of the sections where water transport is measured: Atlantic Gateway: 445 km; Indian Gateway: 778 km; western Med/Parat: 83 km and eastern Med/Parat: 119 km.

		Deep IG	Intermediate-depth IG	Shallow IG	Closed IG	Shallow NUNE	Shallow IG MMSST
Atlantic Gateway	Into Medit.	4.5	5.0	5.1	5.1	2.0	3.2
	Into Ind.	4.5	5.0	5.1	5.1	2.0	3.2
	Net flow	0.0	0.0	0.0	0.0	0.0	0.0
Indian Gateway	Into Medit.	14.8	13.0	2.0	0.0	1.7	1.6
	Into Ind.	14.8	13.0	2.0	0.0	1.7	1.6
	Net flow	0.0	0.0	0.0	0.0	0.0	0.0
Eastern Med/Par	Into Parat.	1.9	1.1	0.9	1.4	0.7	1.5
	Into Med.	0.0	0.0	0.4	1.0	0.1	1.2
	Net into Par.	1.9	1.1	0.5	0.4	0.6	0.3
Western Med/Par	Into Parat.	0.0	0.0	0.1	0.2	0.0	0.4
	Into Med.	1.9	1.1	0.6	0.6	0.6	0.7
	Net into Med.	1.9	1.1	0.5	0.4	0.6	0.3

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**Table 2.** Volume-averaged salinity (psu) and temperature (°C) of the Mediterranean basin, the Paratethys and the Indian Gateway for the different experiments. Key: IG = Indian Gateway; NUNE = non-uniform net evaporation (see Sect. 3.3.1); MMSST = model forced with the idealized Middle Miocene sea surface temperature shown in Fig. 3 (see Sect. 3.3.2).

	Deep IG	Intermediate-depth IG	Shallow IG	Closed IG	Shallow NUNE	Shallow IG MMSST
Med. average salinity (psu)	35.60	35.95	36.20	36.15	35.20	36.70
IG average salinity (psu)	35.25	35.30	36.40	–	35.20	36.80
Par. average salinity (psu)	35.85	36.70	39.35	39.20	35.40	40.40
Med. average temperature (°C)	14.25	14.30	14.40	14.40	14.00	19.80
IG average temperature (°C)	15.60	16.15	18.85	–	18.00	22.65
Par. average temperature (°C)	11.10	10.80	10.90	10.90	11.00	17.55

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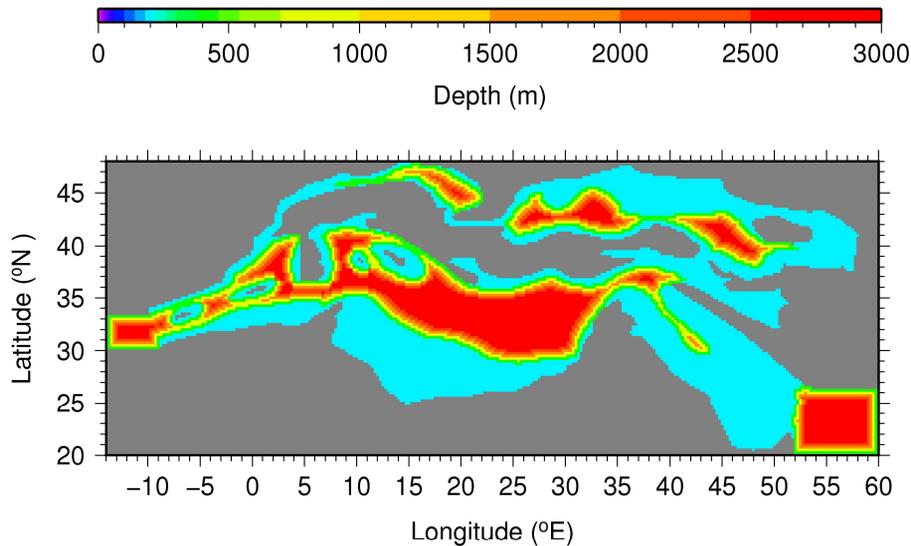
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**Fig. 1.** Palaeobathymetry of the Mediterranean region used as a reference in our experiments based on the Burdigalian sheet of the Peri-Tethys Atlas (Dercourt et al., 2000) and absolute rotation poles due to Müller et al. (2008).

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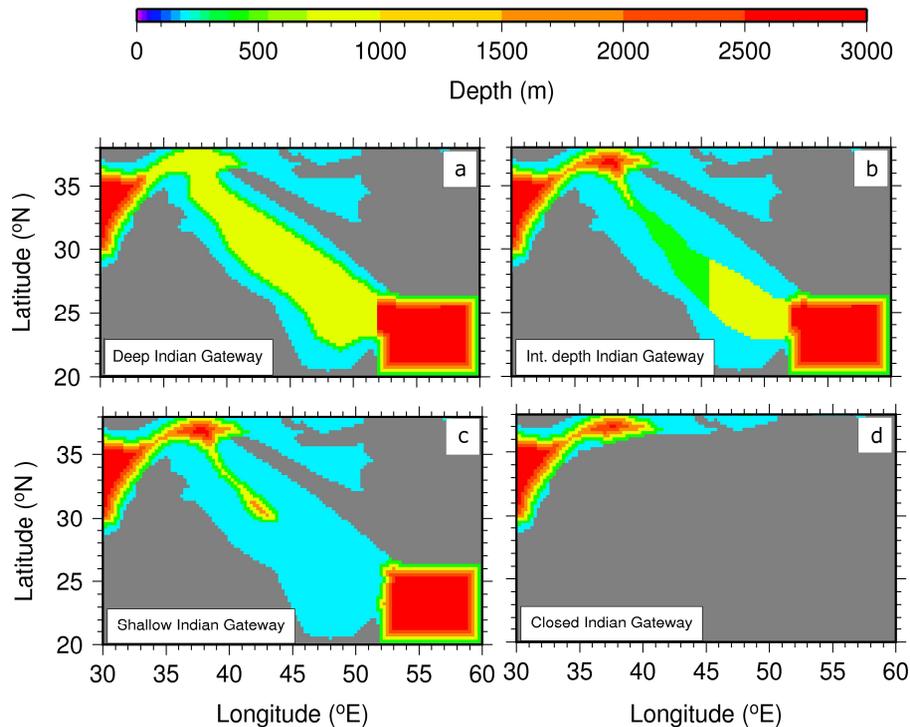
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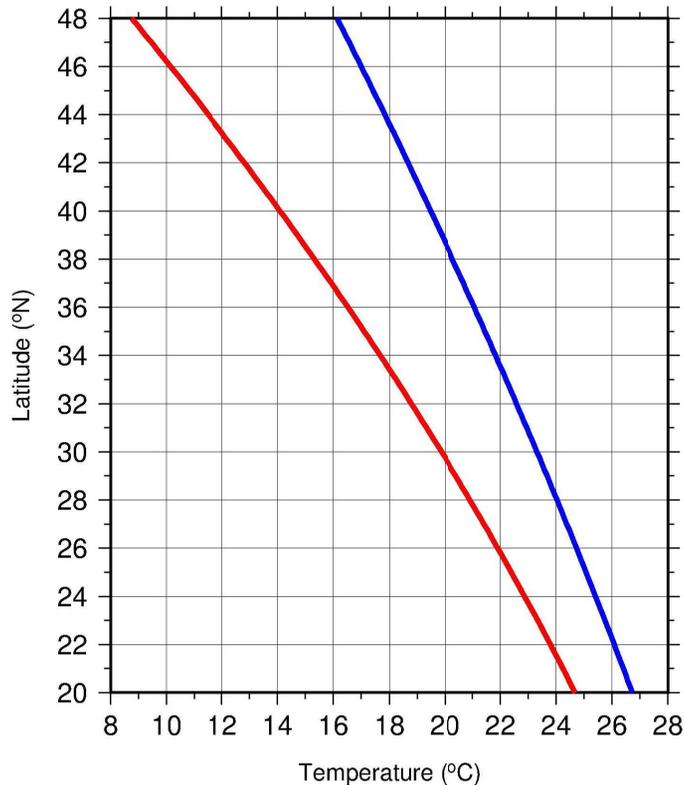
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**Fig. 2.** The four idealized configurations considered in our experiments for the region of the Indian Gateway.

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**Fig. 3.** Zonally-averaged sea surface temperature used as a surface boundary condition. The red line approximates the present-day sea surface temperature constructed from satellite data by Steppuhn et al. (2006). The blue line is built taking as a reference the Gaussian best-fit for a medium equator-to-pole gradient Middle Miocene sea surface temperature profile proposed by You et al. (2009) on the basis of oxygen stable isotopes.

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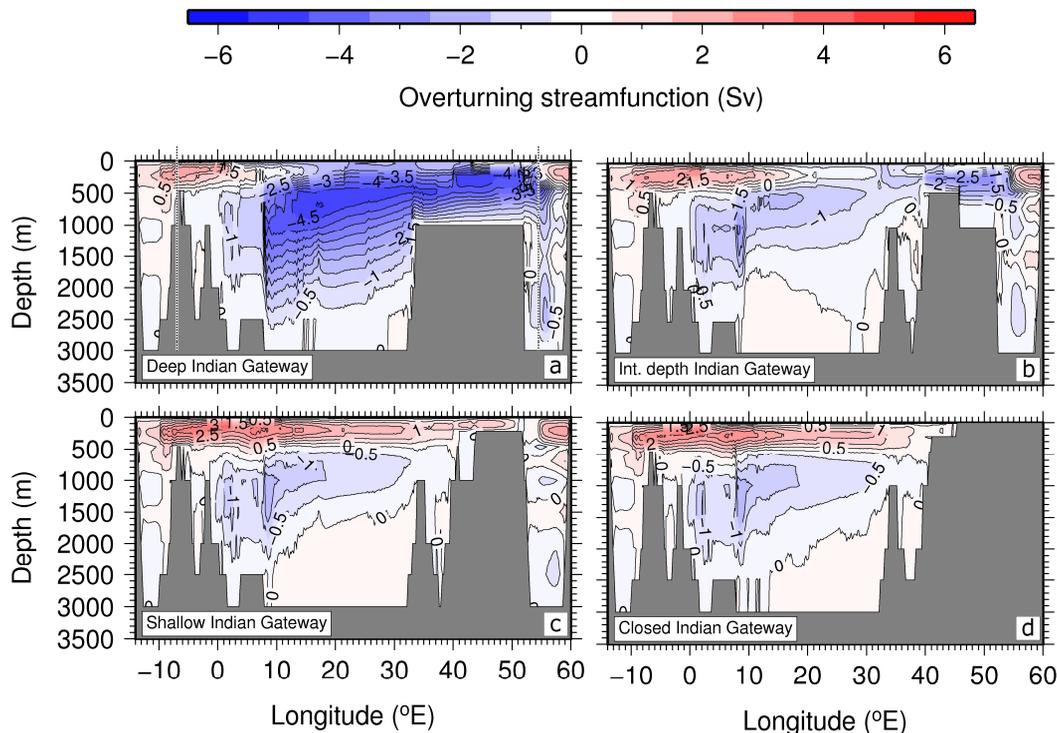
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**Fig. 4.** Computed zonal overturning streamfunction for the different Indian Gateway configurations shown in Fig. 2. Based on the last 100 yr of each model run, the zonal streamfunction illustrates the integrated water transport in the east-west and vertical direction. Contour interval is 0.5 Sv ( $1 \text{ Sv} = 10^6 \text{ m}^3 \text{ s}^{-1}$ ). Seafloor is depicted at the deepest point encountered at each longitude. Note that the Paratethys basin has been excluded from the calculation. The start of the Atlantic and Indian box is indicated by a dashed line in 4a.

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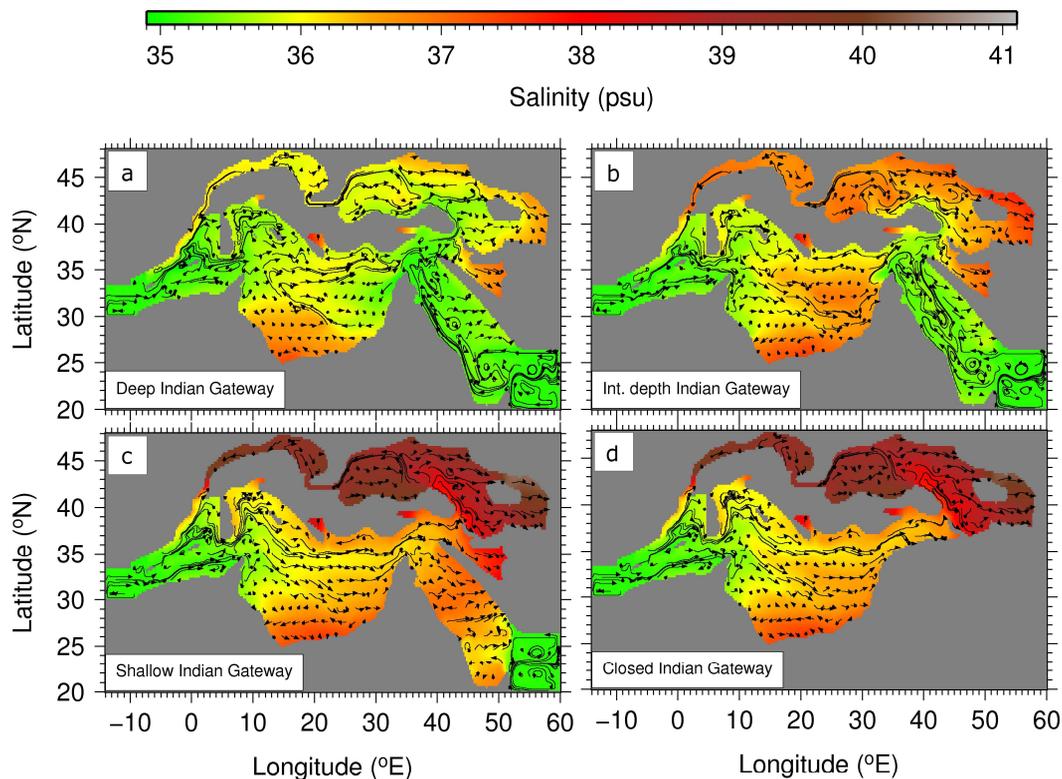
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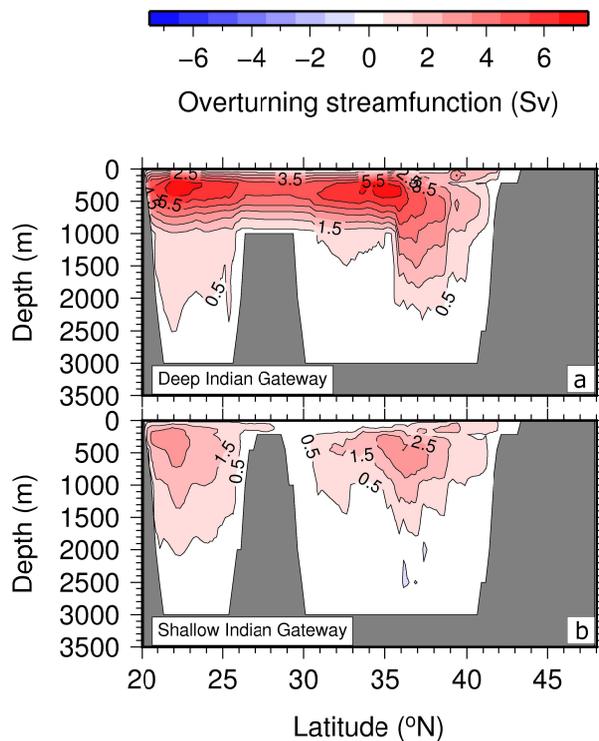


**Fig. 5.** Salinity field (psu) and trajectories of horizontal flow at 10m depth for the different Indian Gateway configurations. Shown are the paths particles would travel in 80 days keeping the annual-mean velocity field constant.

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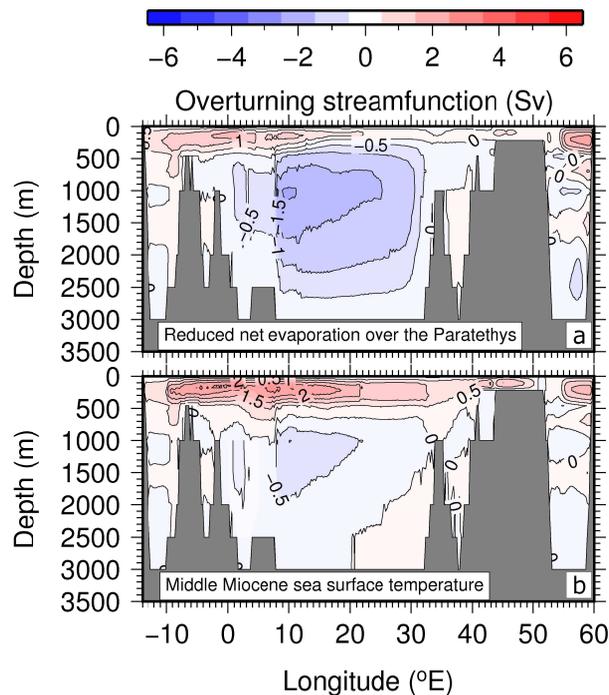


**Fig. 6.** Computed meridional overturning streamfunction for two different depths of the Indian Gateway. This illustrates the integrated water transport in the north–south and vertical direction. Red cells (positive values) indicate northward motion at the surface and southward at depth. Contour interval is 1 Sv.

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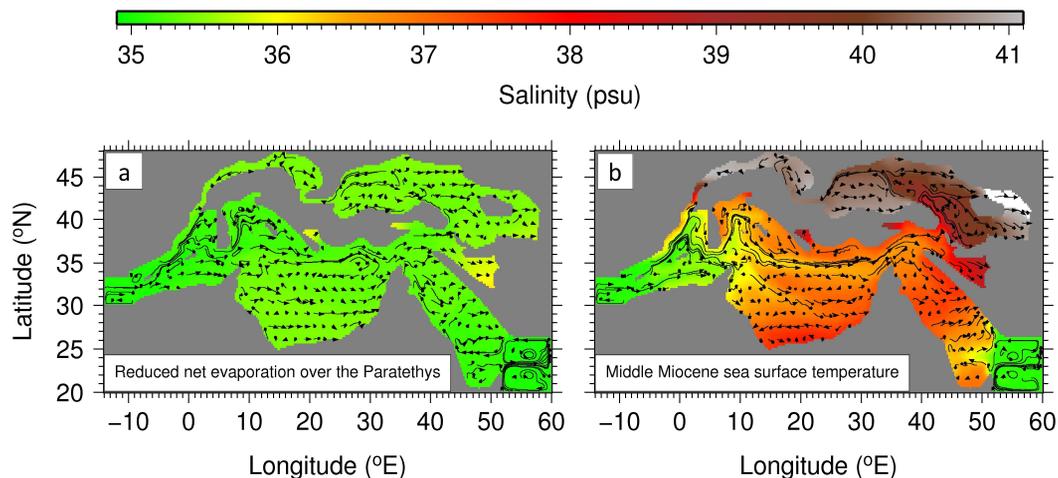


**Fig. 7.** Zonal overturning streamfunction for a shallow Indian Gateway forced with a non-uniform net evaporation rate (top panel) and a Middle Miocene sea surface temperature (bottom panel). Contour interval is 0.5 Sv.

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**Fig. 8.** Salinity field (psu) and horizontal velocity at 10 m depth for a shallow Indian Gateway forced with a non-uniform net evaporation rate (left panel) and a Middle Miocene sea surface temperature (right panel). White values correspond with salinities higher than 41 psu. Velocity traces are calculated as in Fig. 5.

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