



RESEARCH ARTICLE

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Key Points:

- First model study to provide physics-based insight in double-gateway behavior
- Combining model and observations new scenarios for 7.2 Ma are achieved
- The “siphon theory” is shown incompatible with the laws of water exchange

Correspondence to:

A. de la Vara,
delavarafernandez@uu.nl

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Water exchange through the Betic and Rifian corridors prior to the Messinian Salinity Crisis: A model study

Alba de la Vara¹, Robin P. M. Topper^{1,2}, Paul Th. Meijer¹, and Tanja J. Kouwenhoven¹
¹Department of Earth Sciences, Faculty of Geosciences, Utrecht University, CD, Utrecht, Netherlands, ²MARUM—Center for Marine Environmental Sciences, University of Bremen, Bremen, Germany

Abstract Although the present-day Mediterranean-Atlantic water exchange has been extensively studied, little is known about the dynamics of the Betic and Rifian corridors that existed before the Messinian Salinity Crisis. Due to the difficulties in studying the paleogeographic evolution of these corridors, physics-based knowledge of their behavior is essential to interpret observational evidence and to relate flow structures to gateway geometries. Here we present the first systematic model study of the water exchange through these gateways. We use the parallel version of the Princeton Ocean Model (sbPOM) and a set of idealized bathymetries based on a late Tortonian paleogeography. This analysis represents a major step forward in the understanding of the behavior of the double-gateway system constituted by the Late Miocene Betic and Rifian corridors. We demonstrate that the “siphon” scenario, involving inflow of cold upwelled Atlantic water through the Rifian corridor and outflow of Mediterranean water only via the Betic corridor, is unlikely from a physics perspective. It is shown that two exchange patterns are possible depending solely on the relative depth of the corridors. The implication of this is that geological evidence for the behavior of one corridor provides information about the dimensions of the other. We show that disappearance of outflow in one corridor does not necessarily imply its closure and we establish a guideline to determine how geological evidence can be interpreted as indicating one- or two-layer flow. Based on the model results, we propose new physics-based scenarios for the time interval defined for the siphon.

1. Introduction

During the Late Miocene, the Mediterranean and the Atlantic were connected by at least two marine gateways: the Betic and Rifian corridors through southern Spain and northern Morocco, respectively [e.g., *Santisteban and Taberner*, 1983; *Benson et al.*, 1991] (see Figure 1). Tectonic restriction, in combination with glacioeustatic sea-level fluctuations, led to the Messinian Salinity Crisis during which evaporites were deposited throughout the Mediterranean basin [e.g., *Roveri et al.*, 2014]. Knowledge about the paleogeographic evolution of these two gateways is essential to reconstruct the sequence of events resulting in the salinity crisis. However, it is difficult to identify the gateways because of the local nature of the strait deposits and the erosion inherent to regression and uplift [e.g., *Martín et al.*, 2009]. For this reason, most of the information about gateway dimensions and evolution derives from the study of the past exchange. For this, indirect methods such as faunal [e.g., *Pérez-Asensio et al.*, 2012] or isotope [e.g., *Ivanovic et al.*, 2013] studies are used. However, the lack of insight regarding the functioning of a double gateway limits the interpretation of results. It is generally assumed that each gateway either behaves in the same way as a single gateway or that the two corridors acted together as in the “siphon” scenario proposed by *Benson et al.* [1991]. The siphon theory entails that in a double-gateway scenario prior to the Messinian Salinity Crisis, the Rifian corridor (RiC) accommodated only upwelled inflow from the Atlantic while the Betic corridor (BeC) was the sole conduit for Mediterranean outflow.

The purpose of our study is to gain physics-based insight into the interplay of the two gateways prior to the salinity crisis in order to (i) establish a solid framework that provides information relevant to data acquisition and (or) interpretation and (ii) test the validity of the “siphon theory.” For this we use a regional-scale ocean general circulation model. The experiments include multiple gateway geometries created from a reference bathymetry based on a late Tortonian paleogeography from which only the depths of the gateways are modified. Our model study allows us to assess the significance of observational evidence for patterns of exchange and provides a basis for relating observed flow configurations to the associated gateway geometries. To the extent that our work provides insight regarding the behavior of the Mediterranean



Figure 1. Earliest Messinian paleogeography modified from *Martín et al.* [2001] showing the location of the Taza-Guercif basin, Bou Regreg valley, and the Guadalhorce corridor. The black line corresponds to the present-day coastline. Note that this map is a snapshot in the evolving paleogeography and our model geometry (Figure 2) is more generic.

outflow in a double gateway it is relevant also for ongoing efforts to reconstruct the pathway of outflow water from contourites (e.g., ODP Leg-339) [see *Hernández-Molina et al.*, 2014].

2. Model Setup

We use a parallel version of the Princeton Ocean Model [Blumberg and Mellor, 1987] called sbPOM [Jordi and Wang, 2012]. This is a three-dimensional, sigma-grid coordinate, free-surface, hydrostatic, primitive equation numerical model. The use of sigma coordinates gives the same amount of vertical levels regardless of the water depth, which is optimal for the study of shallow (strait) areas. The horizontal grid is curvilinear and has a resolution between 12 and 63 km in the i direction and between 11 and 70 km in the j direction of the grid (Figure 2). For brevity, we will refer to the i direction as

“east-west” and j direction as “north-south.” Starting with *Zavatarelli and Mellor* [1995], POM has been widely applied to investigate the oceanography of the Mediterranean Sea. Recently, sbPOM has been successfully used to study the Mediterranean circulation [Topper and Meijer, 2015].

A series of idealized bathymetries based on the late Tortonian map of the Peri-Tethys Atlas [Dercourt et al., 2000] is considered. The Paratethys is not included because we focus on the functioning of the Betic and Rifian corridors and the presence of the Paratethys is not necessary to reproduce the basin-scale circulation of the Mediterranean. To construct the reference bathymetry, the deep and shallow levels distinguished on the atlas are set to 3000 and 220 m, respectively. Between these two levels, a continental slope is introduced to create a smooth transition (Figure 2). In the alternative geometries, we only change the depth of the gateway areas, which are set before the continental slope is implemented (Figures 2a–2c). The coastline is not modified so as to enable the isolation of the effect of the straits. Although the Atlantic region is always 3000 m deep, the smoothing introduces a continental slope that extends toward the west over different distances depending on strait depth. The maximum gateway depth we consider is that of the present Strait of Gibraltar (300 m) arguing that in a double-gateway scenario just prior to the Messinian crisis—during which the corridors were severely restricted [e.g., *Roveri et al.*, 2014]—these gateways were most likely shallower than that. We do not include geometries where both corridors are shallower than 25 m because these configurations lead to very high salinities, which are not expected before the crisis.

We use idealized atmospheric forcing which has been shown to be able to capture the first-order features of the thermohaline circulation [e.g., *Meijer and Dijkstra*, 2009] and allows us to isolate the basin’s response to bathymetric changes in the gateways. Because the Late Miocene climate is uncertain [e.g., *Roveri et al.*, 2014], atmospheric values based on the present day are used. The freshwater flux (evaporation minus precipitation and river discharge) is set to a uniform and constant value of 0.5 m/yr. This is close to the value for the present day and also appropriate for the Mediterranean region during the Late Miocene [Gladstone et al., 2007; see discussion in *Topper et al.*, 2011]. To simulate heat exchange with the atmosphere, the upper layer of the model is relaxed to the modern latitudinal profile of zonal and annual mean sea-surface temperature of *Steppuhn et al.* [2006]. To test sensitivity of the model results to changes in climate we ran several experiments with alternative atmospheric conditions (this aspect will be addressed in the discussion). Because former sensitivity studies conclude that main effect of the addition of winds is the enhancement of the circulation in the uppermost water column [e.g., *Meijer and Dijkstra*, 2009], winds are neglected.

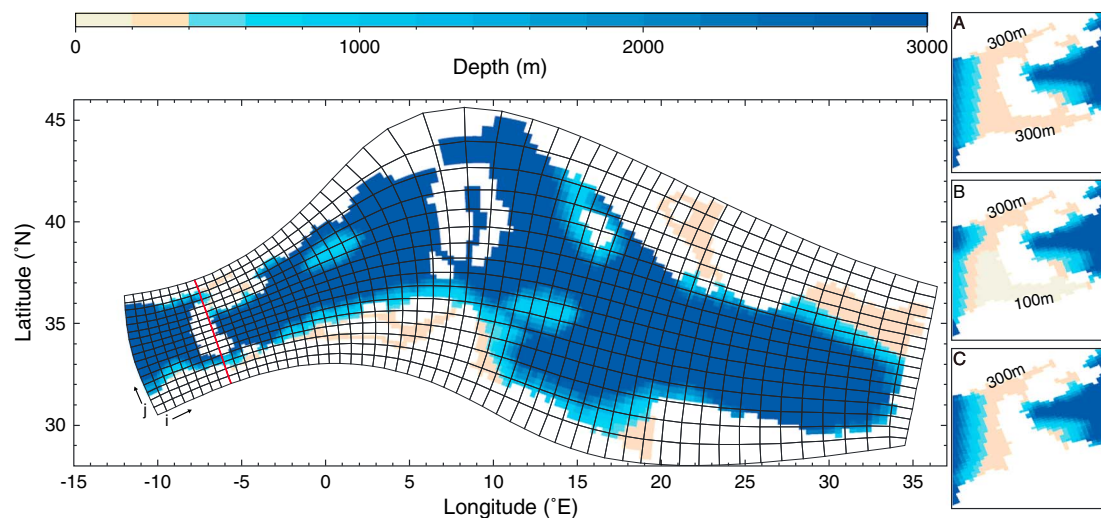


Figure 2. Reference bathymetry based on the late Tortonian paleogeographic map from the Peri-Tethys Atlas and the orthogonal curvilinear grid (only one out of three gridlines is drawn). Right-hand side panels illustrate in detail the gateway area to exemplify the alternative bathymetries. The BeC is 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 4–6).

In the Atlantic, west of the gateways, our model features an open boundary that represents the communication with the Atlantic Ocean and through which an amount of water flows that exactly compensates for the evaporative loss in the Mediterranean. Atlantic water flowing into the Mediterranean is given a salinity of 35 psu independent of latitude and depth. The temperature of the top layer of the model is set equal to that used for the atmospheric forcing. The vertical distribution of temperature is an exponential curve approximating the vertical distribution of potential temperature in the Atlantic Ocean [10°W, 35°N] from the Levitus' World Ocean Atlas [Locarnini *et al.*, 2013]. The Mediterranean basin and the Atlantic are initialized with a salinity of 35 psu, and temperature decreases with depth from the sea-surface value. To ensure a progressive transition from the open boundary to the Mediterranean, water properties are gradually relaxed toward conditions equal to the initial values over the first 18 grid columns as in *Topper and Meijer* [2015]. Each experiment is run until steady state, and all results shown are averages over 100 years of equilibrium. This snapshot approach is warranted because paleogeographic changes are slower than the establishment of the new circulation pattern. The implications of the model parameters here used have been tested in *Topper and Meijer* [2015].

3. Analysis and Results

3.1. Exchange Pattern

In Figure 3 the zonal (i.e., east-west) overturning streamfunction illustrates the basin circulation for a double-gateway scenario where both corridors have a depth of 300 m. The overturning streamfunction may be thought of as all water transport projected on a vertical east-west section through the basin. Although variations in the depth of the gateways affect the strength of the overturning cells, the basin-scale circulation remains unchanged in the experiments. The model simulates well the overall behavior of the present-day Mediterranean, where the thermohaline circulation is characterized by shallow and deep cells. The shallow cell extends to an intermediate depth and shows antiestuarine exchange with the Atlantic: oceanic inflow occurs at the surface, extends to the eastern Mediterranean where it sinks due to net evaporation, and returns back to the Atlantic. The underlying deep circulation cell is fed by deep-water formation. Detailed analysis shows that deep water forms in the northern parts of the basin where temperature is low and salinity is high [see also *Topper and Meijer*, 2015].

To gain insight into the Mediterranean-Atlantic exchange, we study profiles of east-west velocities averaged over the j direction of the grid at the transect shown in red in Figure 2 for a range of gateway-depth configurations. This location is chosen because it coincides with the shallowest region of the gateways and, consequently, determines the particular type of exchange within the corridors. The modeled exchange

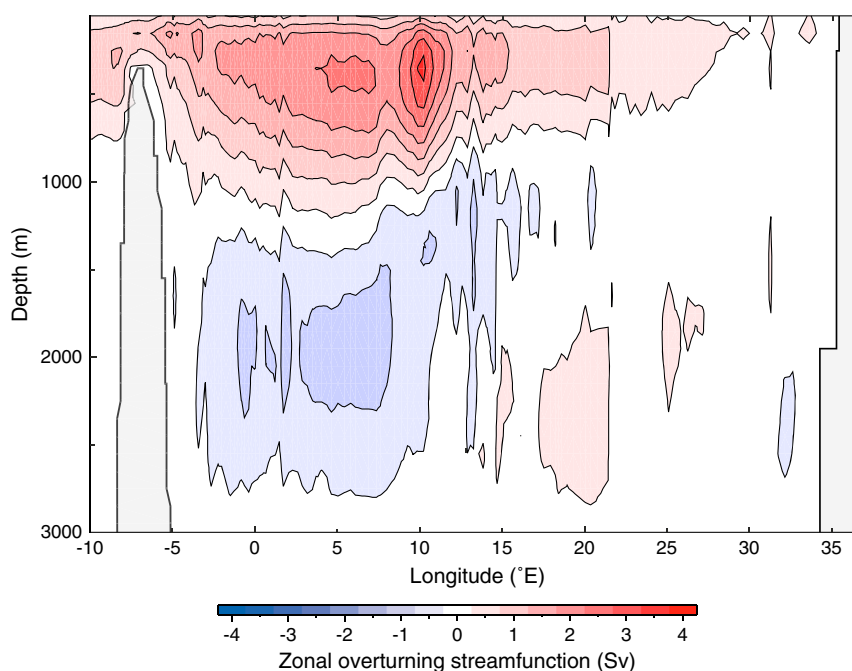


Figure 3. Zonal overturning streamfunction for a double-gateway scenario where both corridors have 300 m. Red colors indicate a clockwise sense of flow in this projection and blue colors counterclockwise. The seafloor is depicted at the maximum depth that occurs at each longitude and the contour interval is 0.5 Sv.

patterns are summarized in Figure 4 in the form of colored dots. The blue dots indicate that we find two-way flow consisting of Atlantic inflow at the surface and Mediterranean outflow at depth through both corridors, and the red dots correspond to two-way flow in the deep corridor and only Atlantic inflow in the shallower one. The overall behavior that emerges from the large set of runs we carried out is that the pattern of exchange depends on the relative depth of the two corridors. Specifically, two-way flow in both corridors occurs when the shallow corridor is deeper than about half the depth of the deep corridor; one-way flow develops when the shallow corridor is shallower than this. Small deviations from a completely regular pattern occur near the lines that limit the segment with two-way flow in both corridors, especially when the corridors are deep. On the one hand, the Mediterranean basin is less sensitive to bathymetric changes in the gateways when these are deep. This causes the shift from one circulation pattern to the other to occur slightly further away from the halfway position. On the other hand, the transition from one- to two-layer flow is gradual and we only classify a gateway as presenting outflow when the latitudinally averaged velocity at depth is oceanward.

3.2. Velocity Profiles

Figure 4 demonstrates that the exchange in a gateway depends on the depth of one corridor relative to the other. Profiles of east-west velocity averaged by latitude (j direction) are shown in Figure 5 for the following gateway configurations: the RiC has a constant depth of 100 m, and the BeC is set to 250, 120, 75, and 40 m in Figures 5a–5d. In Figures 5b and 5c, the shallow corridor is deeper than half the depth of the other corridor and both gateways have two-way flow. In contrast, in Figures 5a and 5d, where the shallow corridor is shallower than this halfway position, it only accommodates Atlantic inflow.

Next, we illustrate in detail the flow structure when the shallow corridor approaches the mid-depth of the deeper one. Figure 6 shows velocity profiles for several depth combinations where the BeC has a constant depth of 300 m and the RiC is 300, 200, 150, 100, and 0 m in panels a to e, respectively. In Figure 6a both gateways have the same depth and present eastward velocities at the surface and westward flow at depth. When the RiC is set to a depth slightly shallower than the BeC, the outflow occurs only at the bottom of the corridor and its velocity decreases (Figure 6b). If the shallow gateway is half the depth of the deep corridor or shallower outflow disappears in the RiC (Figures 6c and 6d). In Figures 6b–6d the BeC

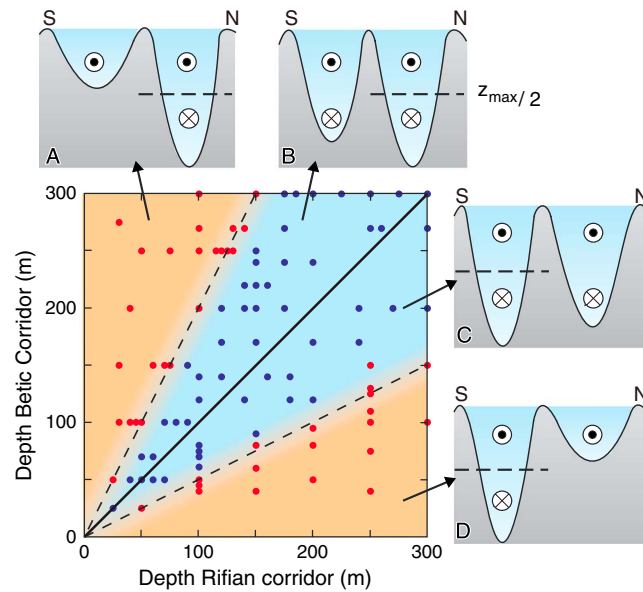


Figure 4. Exchange patterns through the corridors. The blue dots indicate that we find two-way flow in both gateways. The red dots represent two-layer flow in the deep corridor and only Atlantic inflow in the shallower one. The continuous line designates that both gateways have the same depth, and the 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.

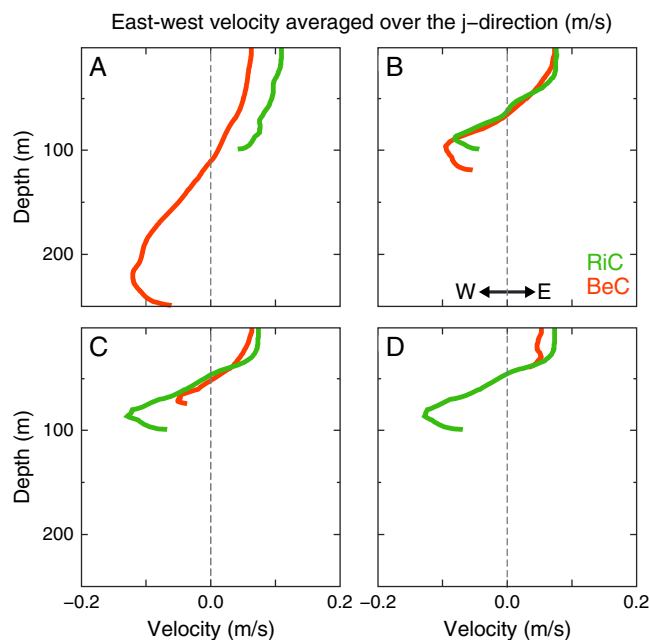


Figure 5. Profiles of east-west velocities averaged over the north-south direction, measured at $i=25$ (red line in Figure 2) for the Betic and Rifian corridors. The RiC (green) is set to 100 m, and the BeC (red) is (a) 250, (b) 120, (c) 75, and (d) 40 m. Positive velocities indicate eastward flow.

is always deeper than the RiC and it accommodates two-way flow. In the last configuration, where the RiC is closed, the positive velocities in the BeC increase compared with a double-gateway scenario (Figure 6e).

3.3. Interface Between Inflow and Outflow

Figures 6a–6e also serve to examine the average depth of the interface, i.e., the level at which velocities are zero. When both gateways have the same depth, the interfaces are close to the middle of the water column but not exactly at the same position probably due to the complex gateway geometry (Figure 6a). In Figure 6b, the interface is shallower in the BeC than in the RiC. Moreover, with two gateways, the interface in the deep corridor is always located at its mid-depth or shallower levels (Figures 6b–6d). Finally, with a closed RiC, the interface in the BeC deepens (Figure 6e).

To investigate the interface configuration in more detail, we study east-west velocities through the same transect again (Figures 6f–6j). The gateway geometries are the same as before and presented in the same order. When the two corridors are 300 m deep, both interfaces are tilted down to the south (Figure 6f). This indicates that at the location of the profiles the flows are affected by Coriolis force, which causes water accumulation to the right of the flow direction. Note that at locations where the gateways are narrower, Coriolis force does not play a role and the interface is flat. When the RiC is shallower than the BeC, but still deeper than half the depth of the latter, the interface configuration in the RiC is substantially different (Figure 6g). In this corridor the outflow is restricted to a small triangle at the bottom in the northernmost part of the gateway. In Figure 6h, where the RiC is half the depth of the BeC, the interfaces look similar to Figure 6g but the outflow in the RiC is closer to the bottom due to the smaller water depth. When the RiC is shallower than half the depth of the

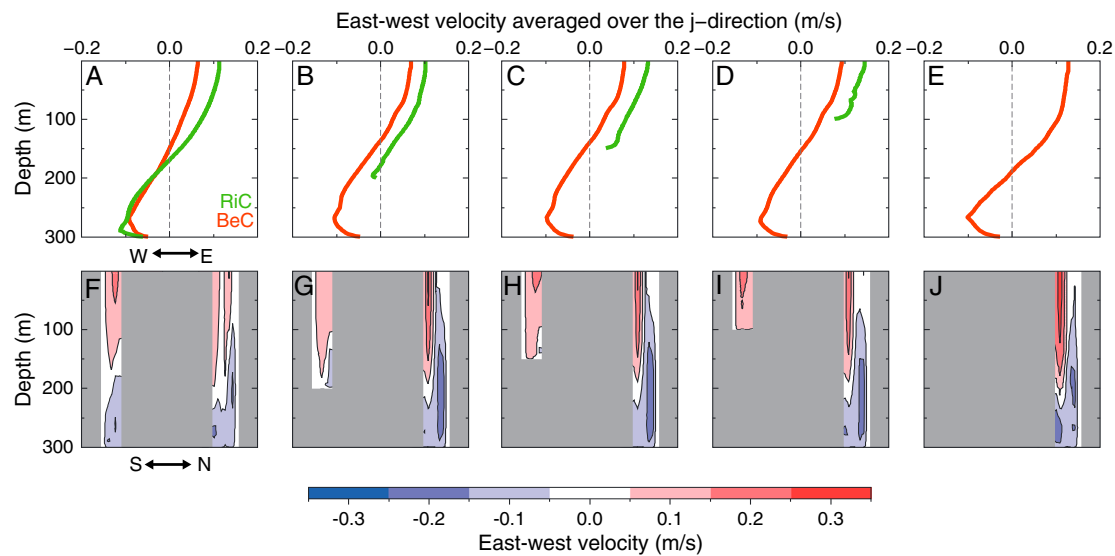


Figure 6. Profiles of latitudinally averaged east-west velocity (a–e) and east-west velocity (f–j) both calculated at the same transect ($i = 25$). The BeC has a constant depth of 300 m, and the RiC is set to 300, 200, 150, 100, and 0 m from Figures 6a to 6e and from Figures 6f to 6j. The contour interval is 0.1 m/s.

BeC (Figure 6i) we find that while the RiC presents Atlantic inflow only, the BeC still accommodates two-way flow and has a similar interface to Figures 6g and 6h. With a closed RiC the interface in the BeC resembles the previous configuration but positive (eastward) velocities increase (Figure 6j).

In the shallow corridor of a double gateway, rotational effects cause the interface, located relatively close to its bottom, to reach the floor of the corridor (Figures 6g and 6h). However, in the deeper corridor or in a single-gateway setting, where the interface is at about the mid-depth of the corridor, the interface is tilted but it does not reach the seafloor (Figures 6f to 6j). An interface located at an intermediate depth in a corridor would only reach the bottom when the effect of rotation increases (i.e., in a wider gateway, see Timmermans and Pratt [2005]).

Figure 7 shows the salinity and trajectory of the flow at the bottom in the gateway area. The BeC is set to 300 m and the RiC to 150 m (same geometry as in Figures 6c and 6h). The purpose of this figure, in which salinity is used as a tracer to distinguish between the low salinity Atlantic waters and the saltier Mediterranean outflow, is to illustrate how the exchange pattern would be recorded in the sediments of the corridor. Although in this specific case both corridors accommodate two-layer flow, only in the shallower RiC, rotational effects allow the upper inflowing layer to reach the bottom on the southern side of the gateway.

4. Discussion

4.1. Causal Mechanism

The finding that the behavior of the shallower corridor depends on its depth relative to the mid-depth level of the deep corridor indicates that the deeper corridor controls the behavior of the double gateway. The antiestuarine exchange in the deep corridor is the same as in the present-day Strait of Gibraltar and for the same reason: evaporation leads to a salinity and, thus, density, increase in the Mediterranean basin. The resulting pressure gradient between basin water and lower density Atlantic waters drives outflow over the sill. This outflow causes the Mediterranean Sea surface to drop, which drives a compensating inflow at the surface. The deep corridor apparently always has the interface positioned near its mid-depth (it is never exactly halfway and the reasons for this are discussed shortly) and imposes this position of the interface on the shallower corridor. If the bottom of the shallow corridor is above the interface level, this corridor does not accommodate outflow. Because the gateways are geographically close to each other, the sea-surface gradient is similar in both, and both therefore accommodate surface inflow.

In the deeper corridor the interface is near mid-depth most likely because for a given density (pressure) gradient along the strait, an intermediate position of the interface is associated with the greatest inflow

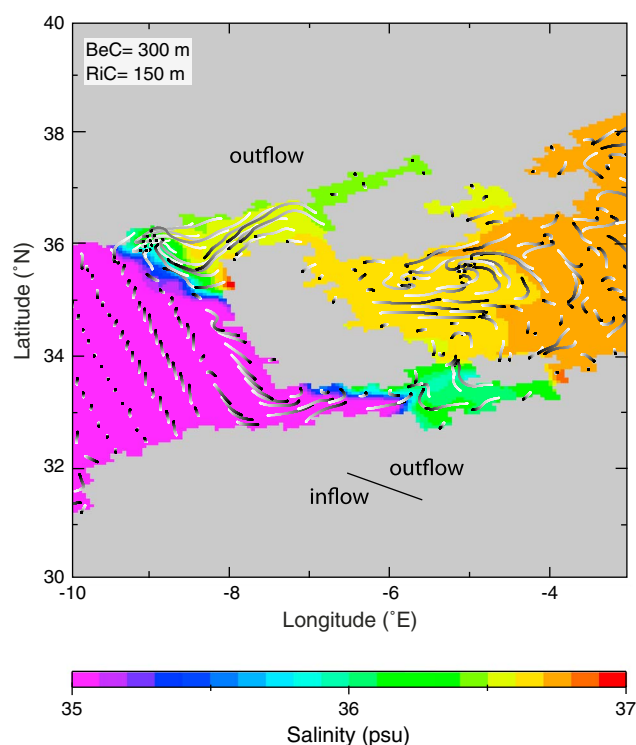


Figure 7. Salinity (psu) and flow trajectories just above the seafloor in the gateway area (shown is the deepest sigma layer). Trajectories show the paths water would travel in 30 days, on the basis of the velocity field at steady state. Tails are white and heads are black. The BeC is set to 300 m and the RiC to 150 m.

and outflow [e.g., Bryden and Stommel, 1984; see also Meijer, 2012]. In their turn, these flows are driven toward a maximum by the intrinsic tendency of the Mediterranean to be well mixed, subject as it is to net evaporation and buoyancy loss of its surface water [e.g., Bryden and Stommel, 1984]. A well-mixed basin implies a small difference between density of inflow and outflow and this—from budget considerations—is associated with relatively large exchange flows. Note that we neither wish nor need to argue that our modeled gateways and basin are in the rather precisely defined states of maximal exchange and overmixing, respectively.

Viewed in more detail, we find that in the deep corridor of a two-gateway system, the interface is shallower than it would be in a single gateway of the same depth (Figures 6b–6e). The shallow gateway acts as an extra source of Atlantic inflow into the basin; hence, less inflow needs to be accommodated in the deep corridor, causing the interface to shoal there (Figures 6b–6d). Finally, when both

corridors accommodate two-way flow, the interface is always deeper in the shallow corridor than in the deeper corridor (Figure 6b). As the shallow corridor shoals, the space available for the outflow gets smaller. Friction from the overlying layer and the bottom increases in importance and this reduces the outflow—deepens the interface—even more.

4.2. Sensitivity of the Mediterranean Circulation to Climate

To investigate how sensitive the Mediterranean large-scale circulation and Mediterranean-Atlantic exchange patterns are to changes in climate, we ran a large set of experiments with alternative atmospheric conditions. In particular, we considered a warmer than present-day temperature profile based on the Middle Miocene latitudinal profile of zonal and annual mean sea-surface temperature proposed by You *et al.* [2009]. This profile was used instead of a Late Miocene one because this is warmer and thus represents a more extreme case to test. In addition to this, in another collection of experiments, we set the freshwater flux to 1 m/yr (instead of 0.5 m/yr).

Overall, these experiments show that the main features of the Mediterranean large-scale circulation remain unchanged. Similar to when present-day atmospheric conditions are prescribed, the zonal overturning streamfunction presents deep and shallow cells (see Figure 3) and only variations of the magnitude of these cells occur depending on the specific atmospheric forcing applied. This implies that although changes in the properties and amount of outflow produced in response to climate are expected, outflow is always present in—at least—one of the two corridors. This is consistent with faunal and isotope studies that report the existence of Mediterranean outflow in the Betic [e.g., Pérez-Asensio *et al.*, 2012] and Rifian [e.g., Ivanovic *et al.*, 2013] corridors prior to the Messinian Salinity Crisis. Regarding the exchange in the corridors, we find, again, that the shift from one- to two-way flow occurs when the shallow corridor is deeper than about the mid-depth of the deeper corridor. This confirms that our results are robust and that the exchange pattern is not sensitive to the atmospheric conditions imposed.

4.3. Reassessment of the “Siphon Event”

Compositional changes in marine microfossil assemblages at the Tortonian-Messinian boundary led *Benson et al.* [1991] to propose the “siphon event.” An influx of deep-water Atlantic ostracods to the western end of the Rifian corridor (Salé core in Bou Regreg valley; see Figure 1), coincident with a transition from tropical-epipelagic to temperate-mesopelagic planktic foraminifera, was interpreted as evidence for inflow of upwelled Atlantic waters. *Benson et al.* [1991] suggested that this inflow occupied the whole RiC while the BeC accommodated only outflow. The event is thought to have started about 7.2 Ma [*Hodell et al.*, 1994] and may have ended 6.58 Ma on the basis of the presumed siphon expression in the Melilla basin (near the eastern end of the RiC) [*van Assen et al.*, 2006].

None of our modeled exchange patterns matches the organization of flows proposed for the siphon event. This suggests that the siphon hypothesis is incompatible with the physics of water exchange. However, combining model results with our knowledge of gateway evolution, it is possible to sketch an alternative scenario that is consistent with certain elements of the siphon scenario. In the gateways at 7.2 Ma, two important events occur: (1) rapid shoaling of Taza-Guercif basin in the central RiC from about 500 m to less than 100 m [*Krijgsman et al.*, 1999] and (2) opening of the Guadalhorce corridor of the BeC with a depth between 50 and 120 m [*Martín et al.*, 2001] (see locations in Figure 1). Although the existence of a second Betic connection prior to the crisis is still under debate [e.g., *Soria et al.*, 1999; *Hüsing et al.*, 2010], for simplicity we assume a single Betic corridor. In this context, immediately before 7.2 Ma, the RiC may have been the only Mediterranean-Atlantic connection, and therefore, two-way flow is expected. At 7.2 Ma, the shoaling of Taza-Guercif basin together with the opening of the Guadalhorce corridor may well have led to the northern corridor being deeper than the southern one. In this situation model calculations suggest that the BeC would have accommodated two-way flow while the RiC experienced only inflow (i.e., as in Figure 6i) or mostly inflow with minor outflow (see Figure 6g), depending on its exact depth compared to the BeC. Both possibilities entail an increase in the relative importance of Atlantic-derived waters in the RiC at 7.2 Ma. In the first case (with RiC shallower than half the depth of BeC), the sole presence of Atlantic inflow would be consistent with the siphon hypothesis in the RiC. A possibility that cannot be ruled out based on the depth estimates is that the RiC was still the deeper corridor. In this case both corridors may have seen two-way flow. The possibility that the RiC was more than twice as deep as the BeC can be discarded because then, the BeC would be subject only to inflow and this is inconsistent with the presence of sedimentary structures in the Guadalhorce corridor indicating oceanward flow [*Martín et al.*, 2001].

Does other observational evidence allow further constraint on the evolution of the Mediterranean-Atlantic exchange through the gateways? As yet, the available data are not conclusive. *Ivanovic et al.* [2013] present a first bottom-water record of the exchange through the RiC based on neodymium isotopes. Although the overall picture emerging is far from straightforward, the data do indicate that before the restriction of the RiC at 7.2 Ma, bottom waters in the Taza-Guercif basin are of Mediterranean origin. This is consistent with the presence of two-way flow in the RiC before the opening of the Guadalhorce corridor. It is important to note that for this same period, the Bou Regreg valley sections (situated somewhat south of the middle in the wide western end of the RiC, see Figure 1) only present Atlantic bottom waters [*Ivanovic et al.*, 2013]. Apparently, the Mediterranean outflow passing through the central RiC is not recorded at this location on the Atlantic side. In a wide section of a single gateway, the interface tilted southward by rotation may reach the bottom. Whereas within the central corridor (i.e., Taza-Guercif basin) only outflow would be recorded at the bottom, in the much wider Atlantic end of the RiC, inflow and outflow could be side by side on the gateway floor. Consequently, Mediterranean outflow may have passed to the north of the location of the Bou Regreg sections. The implication would be that we should not expect major changes at this site in response to variations in the depth of the RiC. The Bou Regreg neodymium signal is puzzling by all means; it indicates more Mediterranean-like water after 7.2 Ma and even after the RiC has closed, possibly due to reworking [*Ivanovic et al.*, 2013].

A new, detailed analysis of benthic foraminiferal assemblages from the Salé Briqueterie core in the Bou Regreg valley shows only minor compositional changes for the time interval proposed for the siphon and fails to show the “influx” of *Uvigerina peregrina* and *U. pygmaea* used as evidence for influx of deeper-water Atlantic taxa by *Benson et al.* [1991; A. Cutler, A reexamination of the Miocene Morocco siphon event

hypothesis using benthic foraminifera, unpublished MSc thesis, University of Birmingham, 2013]. This casts doubt on the validity of the siphon hypothesis and thus supports the conclusions derived from our model results. The fact that faunal changes are only minor may again be an expression of the location of the section in the wide western portion of the gateway (see Figure 7).

Seemingly in favor of the siphon hypothesis, several studies reported a cooling of waters of the RiC at the start of the siphon [e.g., *Hodell et al.*, 1994; *Cunningham and Collins*, 2002]. The flow configurations that we propose for the time interval corresponding to the siphon event actually entail a warming in the RiC, although our results prove to be not fully conclusive in this respect. The great shoaling of this corridor implies that the Atlantic inflow and the Mediterranean outflow (if present) come from shallower depths and carry higher temperature. If deep-water Atlantic organisms were able to reach the RiC at 7.2 Ma when this corridor was as shallow as 100 m, then this may have been due to upwelling in the Atlantic Ocean not captured by our model.

4.4. Further Implications

The systematic behavior of these gateways in terms of exchange patterns is useful to determine the depth of a corridor relative to the other. For instance, evidence for outflow in both gateways would not only automatically relate to two-way flow through both but also indicate that the shallow corridor was deeper than the mid-depth of the other gateway (Figures 4b and 4c). When evidence for inflow is found in a corridor, it is important to note that this could be an expression of rotational two-layer flow. In this case, as explained above, evidence from another location to the north of where evidence for inflow was found is required to determine if the corridor accommodated one- or two-layer flow. If one-layer flow occurred, this may be taken to indicate that the corridor was shallower than half the depth of the other one (Figures 4a and 4d). Our results also entail an important consequence regarding the reconstructions of the time of gateway closure. In a double-gateway configuration, the disappearance of evidence for outflow from the sedimentary record does not necessarily indicate that the gateway was closed. According to our results, estimates of the age of closure of the Guadalhorce corridor based on this criterion [*Pérez-Asensio et al.*, 2012] are too old.

5. Conclusions

This model analysis offers, for the first time, physics-based insight into the functioning of the Late Miocene Betic and Rifian corridors that connected the Mediterranean and the Atlantic prior to the Messinian Salinity Crisis. Our results show that the water exchange through these two corridors depends predominantly on the depth of a corridor relative to the other. More specifically, 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. We show that the configuration of the flows postulated in the “siphon theory” by *Benson et al.* [1991] is unlikely from a physics perspective. Combining our model results with the information available regarding the evolution of the corridors, we propose new, model-based flow patterns for the time interval defined for the “siphon event.”

The finding that the exchange pattern varies systematically depending only on the depth ratio of the corridors allows, even from limited geological evidence, to gain valuable insight regarding the double-gateway geometry: (i) outflow evidence in a corridor automatically relates to two-way flow; (ii) 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; (iii) one-way flow in a corridor indicates that this corridor was shallower than half the depth of the deeper gateway; (iv) outflow disappearance in a corridor does not necessarily indicate its closure; and (v) two-way flow in the two gateways indicates that the shallower corridor was deeper than the mid-depth of the other.

References

- Benson, R. H., K. Rakic-El Bied, and G. Bonaduce (1991), An important current reversal (influx) in the Rifian Corridor (Morocco) at the Tortonian-Messinian boundary: The end of the Tethys ocean, *Paleocyanography*, 6(1), 165–192, doi:10.1029/90PA00756.
- Blumberg, A. F., and G. L. Mellor (1987), A description of a three-dimensional coastal ocean circulation model, *Coastal Estuarine Sci.*, 4, 1–16, doi:10.1029/CO004p0001.
- Bryden, H. L., and H. M. Stommel (1984), Limiting processes that determine basic features of the circulation in the Mediterranean Sea, *Ocean Acta*, 7(3), 289–296.

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- Cunningham, K. J., and L. S. Collins (2002), Controls on facies and sequence stratigraphy of an upper Miocene carbonate ramp and platform, Melilla basin, NE Morocco, *Sediment. Geol.*, **146**(3), 285–304, doi:10.1016/S0037-0738(01)00131-2.
- Dercourt, J., M. Gaetani, B. Vriekynck, E. Barrier, B. Biju-Duval, M. F. Brunet, J. P. Cadet, S. Crasquin, and M. Sandulescu (Eds.) (2000), *Atlas Peri-Tethys, Palaeogeographical Maps*, CCGM/CGMW, Paris.
- Gladstone, R., R. Flecker, P. Valdes, D. Lunt, and P. Markwick (2007), The Mediterranean hydrologic budget from a Late Miocene global climate simulation, *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **251**(2), 254–267, doi:10.1016/j.palaeo.2007.03.050.
- Hernández-Molina, F. J., et al. (2014), Onset of Mediterranean outflow into the North Atlantic, *Science*, **344**(6189), 1244–1250, doi:10.1126/science.1251306.
- Hodell, D. A., R. H. Benson, D. V. Kent, A. Boersma, and K. Rakic-El Bied (1994), Magnetostratigraphic, biostratigraphic, and stable isotope stratigraphy of an Upper Miocene drill core from the Salé Briqueterie (northwestern Morocco): A high-resolution chronology for the Messinian stage, *Paleoceanography*, **9**(6), 835–855, doi:10.1029/94PA01838.
- Hüsing, S. K., O. Oms, J. Agustí, M. Garcés, T. J. Kouwenhoven, W. Krijgsman, and W.-J. Zachariasse (2010), On the late Miocene closure of the Mediterranean-Atlantic gateway through the Guadix basin (southern Spain), *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **291**(3), 167–179, doi:10.1016/j.palaeo.2010.02.005.
- Ivanovic, R. F., R. Flecker, M. Gutjahr, and P. J. Valdes (2013), First Nd isotope record of Mediterranean-Atlantic water exchange through the Moroccan Rifian Corridor during the Messinian Salinity Crisis, *Earth Planet. Sci. Lett.*, **368**, 163–174, doi:10.1016/j.epsl.2013.03.010.
- Jordi, A., and D.-P. Wang (2012), sbPOM: A parallel implementation of Princeton Ocean Model, *Environ. Modell. Softw.*, **38**, 59–61, doi:10.1016/j.envsoft.2012.05.013.
- Krijgsman, W., C. G. Langereis, W.-J. Zachariasse, M. Boccaletti, G. Moratti, R. Gelati, S. Iaccarino, G. Papani, and G. Villa (1999), Late Neogene evolution of the Taza-Guercif Basin (Rifian Corridor, Morocco) and implications for the Messinian salinity crisis, *Mar. Geol.*, **153**(1), 147–160, doi:10.1111/j.1365-3121.2004.00564.x.
- Locarnini, R. A., et al. (2013), World Ocean Atlas 2013, Volume 1: Temperature, in *NOAA Atlas NESDIS 73*, edited by S. Levitus and A. Mishonov, p. 40, Silver Spring, Md.
- Martin, J. M., J. C. Braga, and C. Betzler (2001), The Messinian Guadalquivir corridor: The last northern, Atlantic-Mediterranean gateway, *Terra Nova*, **13**(6), 418–424, doi:10.1046/j.1365-3121.2001.00376.x.
- Martin, J. M., J. C. Braga, J. Aguirre, and A. Puga-Bernabéu (2009), History and evolution of the North-Betic Strait (Prebetic Zone, Betic Cordillera): A narrow, early Tortonian, tidal-dominated, Atlantic-Mediterranean marine passage, *Sediment. Geol.*, **216**(3), 80–90, doi:10.1016/j.sedgeo.2009.01.005.
- Meijer, P. T. (2012), Hydraulic theory of sea straits applied to the onset of the Messinian Salinity Crisis, *Mar. Geol.*, **326**, 131–139, doi:10.1016/j.margeo.2012.09.001.
- Meijer, P. T., and H. A. Dijkstra (2009), The response of Mediterranean thermohaline circulation to climate change: A minimal model, *Clim. Past*, **5**(4), 713–720, doi:10.5194/cp-5-713-2009.
- Pérez-Asensio, J. N., J. Aguirre, G. Schmiedl, and J. Civis (2012), Impact of the restriction of the Atlantic-Mediterranean gateway on the Mediterranean Outflow Water and eastern Atlantic circulation during the Messinian, *Paleoceanography*, **27**, PA3222, doi:10.1029/2012PA002309.
- Roveri, M., et al. (2014), The Messinian Salinity Crisis: Past and future of a great challenge for marine sciences, *Mar. Geol.*, **352**, 25–58, doi:10.1016/j.margeo.2014.02.002.
- Santisteban, C., and C. Taberner (1983), Shallow marine and continental conglomerates derived from coral reef complexes after desiccation of a deep marine basin: The Tortonian-Messinian deposits of the Fortuna Basin, SE Spain, *J. Geol. Soc.*, **140**(3), 401–411, doi:10.1144/gsjgs.140.3.0401.
- Soria, J. M., J. Fernández, and C. Viseras (1999), Late Miocene stratigraphy and paleogeographic evolution of the intramontane Guadix Basin (Central Betic Cordillera, Spain): Implications for an Atlantic-Mediterranean connection, *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **151**(4), 255–266, doi:10.1016/S0031-0182(99)00019-X.
- Steppuhn, A., A. Micheels, G. Geiger, and V. Mosbrugger (2006), Reconstructing the Late Miocene climate and oceanic flux using the AGCM ECHAM4 coupled to a mixed-layer ocean model with adjusted flux correction, *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **238**(1), 399–423, doi:10.1016/j.palaeo.2006.03.037.
- Timmermans, M.-L. E., and L. J. Pratt (2005), Two-layer rotating exchange flow between two deep basins: Theory and application to the Strait of Gibraltar, *J. Phys. Oceanogr.*, **35**(9), 1568–1592, doi:10.1175/JPO2775.1.
- Topper, R. P. M., and P. Th. Meijer (2015), Changes in Mediterranean circulation and water characteristics due to restriction of the Atlantic connection: A high-resolution ocean model, *Clim. Past*, **11**(2), 233–251, doi:10.5194/cp-11-233-2015.
- Topper, R. P. M., R. Flecker, P. T. Meijer, and M. J. R. Wortel (2011), A box model of the Late Miocene Mediterranean Sea: Implications for combined $^{87}\text{Sr}/^{86}\text{Sr}$ and salinity data, *Paleoceanography*, **26**, PA3223, doi:10.1029/2010PA002063.
- van Assen, E., K. F. Kuiper, N. Barhoun, W. Krijgsman, and F. J. Sierro (2006), Messinian astrochronology of the Melilla Basin: Stepwise restriction of the Mediterranean-Atlantic connection through Morocco, *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **238**(1), 15–31, doi:10.1016/j.palaeo.2006.03.014.
- You, Y., M. Huber, R. D. Müller, C. J. Poulsen, and J. Ribbe (2009), Simulation of the Middle Miocene Climate Optimum, *Geophys. Res. Lett.*, **36**, L04702, doi:10.1029/2008GL036571.
- Zavatarelli, M., and G. L. Mellor (1995), A numerical study of the Mediterranean Sea Circulation, *J. Phys. Oceanogr.*, **25**(6), 1384–1414, doi:10.1175/1520-0485(1995)025<1384:ANSOTM>2.0.CO;2.