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A quantitative analysis of the desiccation and re-filling of the Mediterranean during the Messinian Salinity Crisis

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Abstract

Notwithstanding the great deal of attention that the Messinian evaporites of the Mediterranean region have received from an observational point of view, there is, to date, no consensus as to their mechanism of formation. We aim to contribute to the investigation through a quantitative analysis of the processes of desiccation and re-filling. These processes are thought to have played a role in particular during the deposition of the upper part of the evaporite sequence. We calculate the evolution of sea level and average salinity based on both the present-day geometry and a paleogeographic reconstruction and assess the sensitivity to variations in the freshwater budget. Our results support previous inferences that desiccation and re-filling are fast; desiccation occurs on a time scale of 3–8 kyr, re-filling probably even faster. Equilibrium sea levels imply that most water has gone from the western basin while a significant water column remains in the eastern basin. Whether or not the eastern basin reaches the level of halite saturation depends critically on, in particular, the freshwater budget. The fast rate of desiccation and re-filling imply that temporal differences in the onset of salt precipitation between western and eastern basin and between marginal basins and basin centres are below the resolution of (astronomical) dating. Also, when Atlantic sea level periodically varied from below to above the level of the intervening sill, the Mediterranean basin will have responded with repeated desiccation and re-filling. Fast re-filling is found to require only a small connection to the Atlantic Ocean. This, in combination with the previous results, suggests the Mediterranean is unlikely to attain stable intermediate water levels.

Keywords: Mediterranean Sea; Messinian; modelling; evaporite

1. Introduction

The classic cyclically bedded open-marine sedimentary successions of the Mediterranean Neogene are disrupted by a large body of evaporites in the Messinian Stage [1,2]. These evaporites were produced by the so-called Messinian Salinity Crisis (MSC), a period during which the Mediterranean was largely isolated from the Atlantic Ocean. The Messinian evaporite successions comprise a total volume of about 10^6 km^3, and reach thicknesses of up to 1500 m and 3500 m in the western and eastern Mediterranean deep basins, respectively, while thinner evaporite successions were deposited in the marginal basins (e.g., [3–5]). The interpretation of the MSC event generated a long period of controversial debate and resulted in the development of fundamentally different stratigraphic scenarios (e.g., [6–9]).

Cyclostratigraphic correlations with the open-ocean record show that the onset of the "Lower Evaporite" formation had a dominantly tectonic (and/or astronomic)

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origin, and that glacio-eustatic sea level fluctuations have only been of minor importance [10,11]. Furthermore, most studies agree that the lowermost water levels were reached during the latest phase of the MSC when the "Upper Evaporites" were suggested to have been deposited in shallow brine pools more than a thousand meters below the world sea level [2,5]. Evidence for the exceptional water level lowering comes in part from numerous seismic studies showing that the Mediterranean margins underwent intense processes of subaerial erosion [12–14]. The environmental conditions that prevailed during deposition of the Upper Evaporites have been highly discussed. Geochemical and paleontological data seem to indicate that influxes of marine (oceanic) waters continued to enter the Mediterranean, but that freshwater dilution increased significantly upward in the evaporite succession, resulting episodically in Mediterranean-wide brackish water conditions of the so-called Lago Mare (Lake Sea) facies [2,4]. Based on sedimentary observations, it was recently concluded that, instead of one major drawdown event, the Mediterranean water level might have been significantly fluctuating (several hundreds of meters) during this latest Messinian period [15]. It is generally admitted that normal marine conditions were restored at the beginning of the Pliocene by an abrupt re-flooding of the Mediterranean during the "Zanclean deluge" (e.g., [16]).

It is the objective of this paper to contribute to our quantitative understanding of in particular the Upper Evaporites by modelling the processes of partial desiccation and re-filling. Without a compensating net inflow from the Atlantic Ocean, the excess of evaporation over precipitation and river input will result in a lowering of the surface level of the Mediterranean Sea. The first question to address is: how fast is this drawdown or, in other words, what is the associated time scale? Also, a lower sea level entails a reduced surface area of the sea and, consequently, the total volume of water that evaporates per unit of time will decrease. Taking river input as more or less constant, we may thus expect that at some point, i.e., at a given sea level and associated water surface area, inflow and outflow will attain a balance. This leads to a second question: after how much time and at what depth is this balance achieved and how large is the associated increase in salinity? Finally, a third question to address is how does sea level evolve after connection with the Atlantic is re-established; in particular: how fast does the basin fill again?

This study is not the first to address the Messinian Salinity Crisis from a quantitative point of view. For example, Hsü et al. [2] and Benson et al. [17] already present a back-of-the-envelope estimate of the duration and extent of desiccation and re-filling. Actual modelling of the budgets of water and salt was pioneered by Blanc [18,19]. Blanc [18] finds that, following closure of the connection to the Atlantic, it takes about 6 kyr to reach equilibrium at a level that is roughly 1500–1600 m below normal. Our analysis differs from all previous studies in that we consider a realistic (reconstructed) bathymetry. Like Blanc [18], we improve on Hsü et al. [2] and Benson et al. [17] by assessing also the role of uncertainty in the water budget. Furthermore, compared to Blanc [18,19], we take a different approach to the filling stage. Rather than aiming to produce a scenario that explains the entire Messinian record such as Blanc [18], our objective is to examine in detail two of the processes involved: that of desiccation and re-filling. Our analysis provides significant additional insight that is less dependent on an adopted evolutionary model.

2. Method

In the absence of an obvious alternative and aiming to establish the first-order features of the evolution of sea level, we apply the present-day value of evaporation minus precipitation ($E-P$, i.e., the net air–sea flux of water) to the Messinian. Estimates of present-day $E-P$ vary considerably. In our analysis, we start with a convenient reference value of 1 m/yr uniform over the entire basin. This, in combination with our estimate of river discharge (R; see below), corresponds to a net water loss ($E-P-R$) of 0.8 m/yr. This value is well within the range reported in the literature. For example, Hopkins [20] mentions a range of 0.5–1.3 m/yr, Bethoux and Gentili [21] give 0.8–1.0 m/yr, Castellari et al. [22] find 0.6–0.7 m/yr while values of 0.9–1.0 m/yr are adopted by Hopkins [20], Zavatarelli and Mellor [23] and Blanc [18]. Most importantly, we will also examine the consequences of a variation of 25% in our starting value. The results of this will give insight into the effect of even greater deviations.

The value for $E-P$ can be read either as the basin-wide lowering of sea level caused by the net air–sea flux in 1 yr or the volume of water that, on average in 1 yr, disappears into the atmosphere through each unit of surface area ($m^3/m^2/yr$). River discharge is also implemented using present-day values. Discharging into the western sub-basin are, Ebro: 550 m^3/s and Rhône: 1700 m^3/s, and serving the eastern sub-basin are, Po: 1550 m^3/s and the net inflow from the Black Sea: 6000 m^3/s [23]. For the Nile we use a value of 2854 m^3/s which is an estimate of the discharge that existed prior to damming and extraction of water for irrigation [24,25]. Following Zavatarelli and Mellor [23], an unspecified discharge of 6000 m^3/s is distributed evenly over the basin. As for net evaporation, river discharge will also be varied by 25%. Again to first approximation, we assume river discharge to be constant with time.

To calculate the evolution of sea level we proceed through time in discrete steps. At each time step the net air–sea flux is combined with river discharge spread out over surface area present at that time. The resulting rate of sea level variation is then used to compute the position of sea level after the increment of time has elapsed and the associated change in volume. Assuming an initially uniform salinity of 35 g/l (i.e., approximately 35 psu; the average value for seawater in general) the calculated changes in volume are used to compute the variation in basin-averaged salinity. When sea level has dropped below the level of the sill separating the western from the eastern sub-basin, the calculation is done for each sub-basin separately. At greater depth, no further separation into sub-basins is considered to take place; a simplification that can be shown not to affect our conclusions (see below). When dealing with the filling stage, the fluxes are supplemented with a specified inflow of (Atlantic) water and the calculation proceeds as before.

3. Hypsometry

The surface area of the (sub-)basin as it corresponds to a given sea level is specified for 1-m increments by hypsometric curves that are constructed based on (1) a present-day bathymetric grid at 5×5 min resolution ("TerrainBase95") and (2) a first-order paleobathymetric reconstruction for the late Miocene [26]. Prior to calculation of the hypsometric curve the present-day grid is brought down in resolution to $0.25^\circ \times 0.25^\circ$ — which is also the resolution of the paleo-grid (Fig. 1). The bathymetric reconstruction was prepared for ocean circulation modelling; it consists of 19 horizontal levels between which we here interpolate linearly. In both cases, the sill separating the western and eastern sub-basin is considered to be situated at the present-day depth of 300 m.

Fig. 2a shows the hypsometric curves of the two sub-basins and the entire Mediterranean Sea for both the present-day and the late Miocene. Due to the later counter-clockwise rotation of the Apennines the reconstruction features, compared to the present situation, a smaller western sub-basin and a larger eastern sub-basin. Strictly speaking, the reconstructed geometry

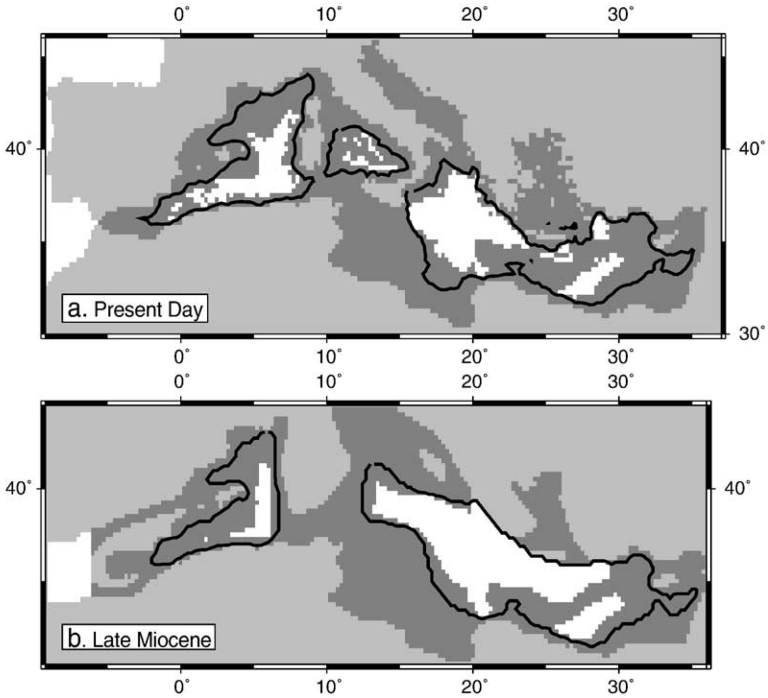

Fig. 1. (a) Present-day coastline of the Mediterranean Sea (land area in light shading) and extent of water-covered part after desiccation down to equilibrium level in western and eastern sub-basin (water area shown in white). Dark shading indicates where seafloor has fallen dry. Solid line denotes coastline at the time that mean salinity reaches the level at which gypsum precipitation starts (130 g/l). Isolated patches of water within one of the three principal basins (western Mediterranean proper, Tyrrhenian, and eastern Mediterranean) are considered interconnected in our calculation. (b) As previous for the case of a reconstruction of the late Miocene bathymetry (from [26]).

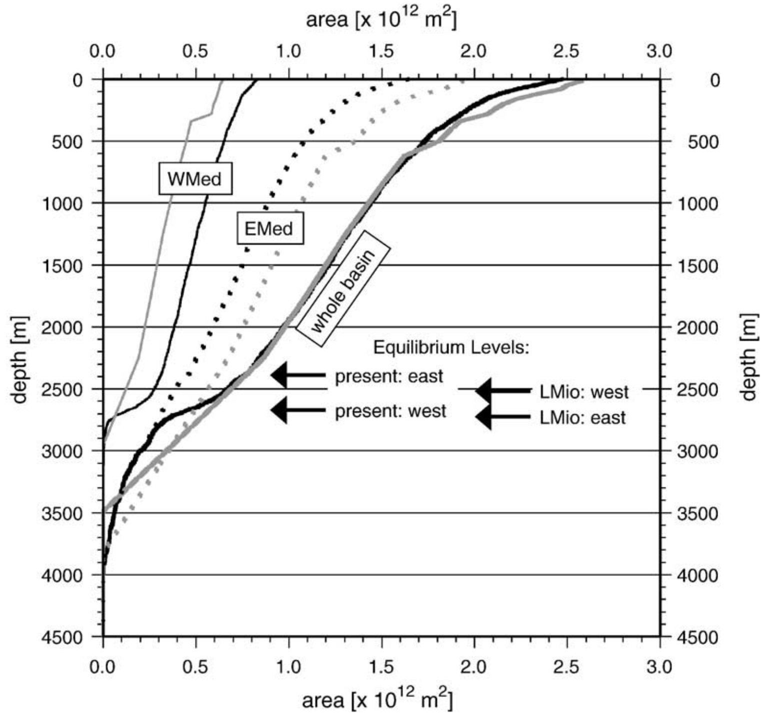

Fig. 2. Hypsometric curves for present-day Mediterranean Sea (black lines) and the reconstruction of the late Miocene (grey lines). Shown are curves for the entire basin (thick solid lines), the western sub-basin (thin solid lines), and the eastern sub-basin (dotted lines). Model-derived equilibrium sea levels have also been indicated; see Fig. 3 for details.

refers to Tortonian time when the Tyrrhenian Sea had not yet opened [26]. It follows that during the Messinian the hypsometry most likely occupied a position intermediate between that for the present day and the reconstruction used here.

Overall, the curves for present day and late Miocene have a similar shape. Curves relating to the entire basin are even largely the same for both times. The interval of rapid change in the area at about 300 m in the reconstructed western sub-basin appears anomalous and may well be unrealistic. The reconstructed geometry is known to be less realistic at great depth (below 2500 m; see also [26]). It is because of these uncertainties/simplifications inherent to the reconstruction that we consider the present-day geometry as well.

At almost all levels above about 2500 m the eastern basin displays a faster decrease in area with depth than the western basin. For the top few 100 m this difference is obvious from the greater extent of shallow shelf areas in the eastern basin. In the present-day situation a large part of the deepest portion of the western basin has a uniform depth of around 2550–2700 m; this explains the sudden decrease near the lower end of the corresponding hypsometric curve.

4. Results: desiccation

As shown in Fig. 3a, without a connection to the Atlantic Ocean, the sea level of the Mediterranean basin drops fast. The western basin displays an almost linear decrease until attaining equilibrium after about 4 kyr in the case of the present-day geometry or 5 kyr for the reconstruction. The eastern basin takes about 3–4 kyr longer to reach equilibrium. This is explained by the fact that the eastern basin receives more river input which, although spread over a larger area than in the west, results in a slower sea level drop. The eastern basin also clearly shows a decrease in the rate of sea level lowering with time. The levels at which equilibrium is attained in the sub-basins are similar for the present-day geometry and the reconstruction. The equilibrium level is somewhat less deep in the east than in the west for the present day, and vice versa for the late Miocene. In view of what was said in the previous section, Messinian equilibrium levels in the two sub-basins are expected to be very similar indeed.

Comparison of the equilibrium levels with the hypsometric curves (see Fig. 2) indicates that, at equilibrium, most water has gone from the western sub-basin while the eastern basin still retains a significant depth of

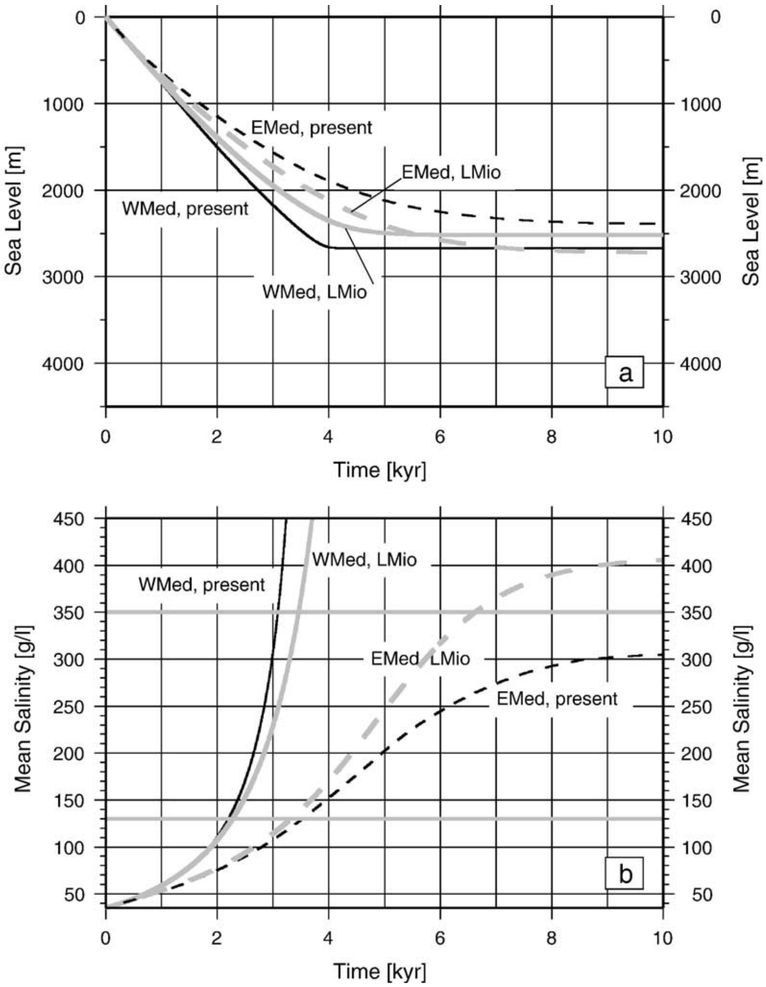

Fig. 3. (a) Modelled evolution of sea level for present-day Mediterranean Sea (black lines) and the reconstruction of the late Miocene (grey lines). Shown are curves for the western sub-basin (solid lines) and the eastern sub-basin (dashed lines). (b) Evolution of (sub-)basin-averaged salinity. Lines as in panel (a). The level of gypsum precipitation (130 g/l) and the minimum level at which halite precipitation starts (350 g/l) are also indicated.

water. This is expressed also in Fig. 1 which shows the areas below the levels of equilibrium. In the present-day case, should sea level drop below the level of the sill south of Sardinia (1463 m in our bathymetric grid), the Tyrrhenian basin becomes disconnected from the remainder of the western sub-basin. Although discharge from the Ebro and Rhône rivers will then no longer reach the Tyrrhenian, this basin still receives its share of the "unspecified discharge". Consequently, the effect of including a separate Tyrrhenian basin on the equilibrium sea level and salinity is small. Fig. 1 is produced with a separate Tyrrhenian; however, for clarity, all other results are without differentiation of the western basin.

The relatively fast and near-complete sea level drop in the western basin results in a strong increase in basin-average salinity (Fig. 3b). The eastern basin shows a more gradual rise and attains a maximum of about 300 g/l with the present-day geometry and about 400 g/l with the reconstruction. This difference in the maximum salinity attained is due to the increase in surface area of the eastern basin when reconstructed: discharge is spread over a larger area, sea level drops deeper (Fig. 3a) and salt concentration proceeds further. In about 3.5 kyr, both basins have passed the concentration at which gypsum precipitation is expected to start (130 g/l); only in the case of the reconstruction does the eastern basin also reach the salinity at which halite deposition starts (>350 g/l) but it does not pass this value by much (saturation concentrations are from [27]). Gypsum precipitation is expected to occur slightly earlier in the western basin. Fig. 1 also indicates the extent of the water surface at the time that gypsum saturation is reached (solid line). In the east this area is only slightly larger than the part of the basin that is still water-covered at the time when sea level becomes stable.

Under the simplifying assumption that all salt in excess of 130 g/l is precipitated, it is possible to calculate expected evaporite thicknesses. Thickness is expressed in terms of the average value across the wet surface area at the time of gypsum saturation. Values obtained are in the range 33–47 m for the western basin and 24–41 m for the eastern basin (the exact value depending on the geometry considered and the assumed evaporite density — here taken to lie in the range 2200–2900 kg/m^3). The order of magnitude of a few tens of meters is only a fraction of the estimated average thickness of the entire Messinian evaporites in the deepest Mediterranean basins (1–3 km). Consequently, the MSC either comprised many cycles of desiccation and re-filling or, more likely, a significant portion of the salts was formed in a configuration of continuous inflow from the Atlantic in combination with blocked return flow (e.g., [3,9]).

4.1. Sensitivity to net air–sea flux and discharge

To assess the effect of the uncertainty in the estimates of evaporation minus precipitation and river discharge, as well as to gain some insight into the role of possible temporal change of these parameters (i.e., climate change), a variation of 25% in the value of the water fluxes was examined. Results in terms of sea level drop and salinity increase are shown in Figs. 4 and 5 for

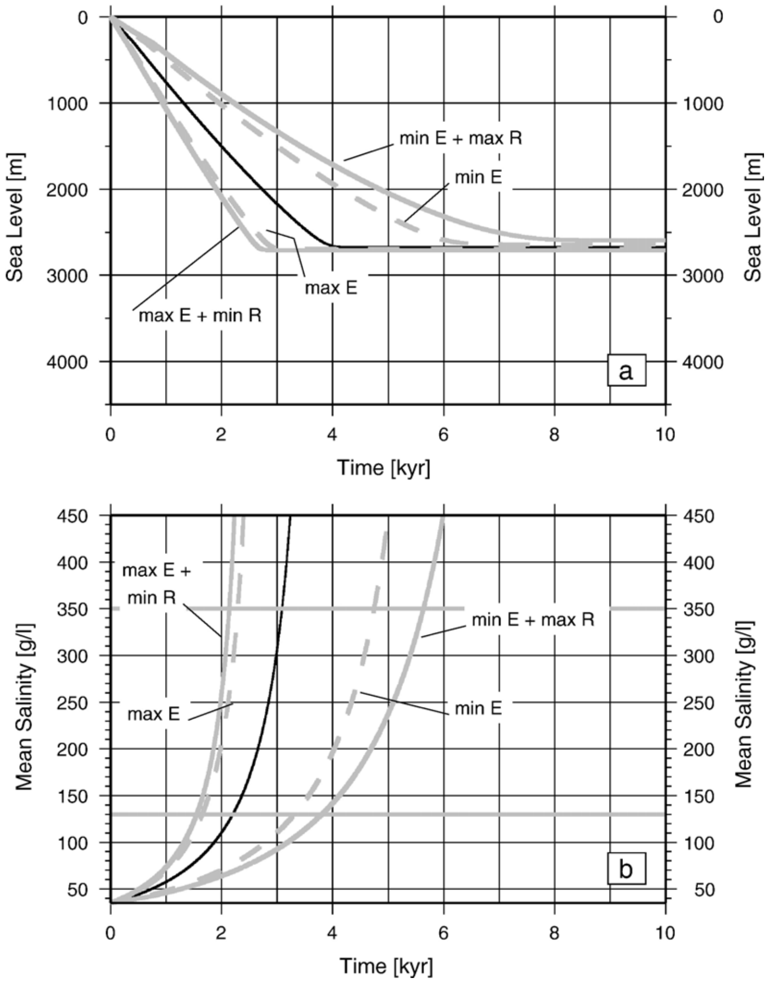

Fig. 4. Sensitivity of (a) sea level variation and (b) (sub-)basin-averaged salinity to a 25% increase or decrease in net evaporation and river discharge. Curves relate to the present-day western sub-basin. Black lines refer to the "mean" case and are the same as in Fig. 3. Dashed grey lines give the effect of only a 25% change in net evaporation. Solid grey lines give the extremes obtained either by combining increased net evaporation with reduced discharge or by combining reduced net evaporation with increased discharge.

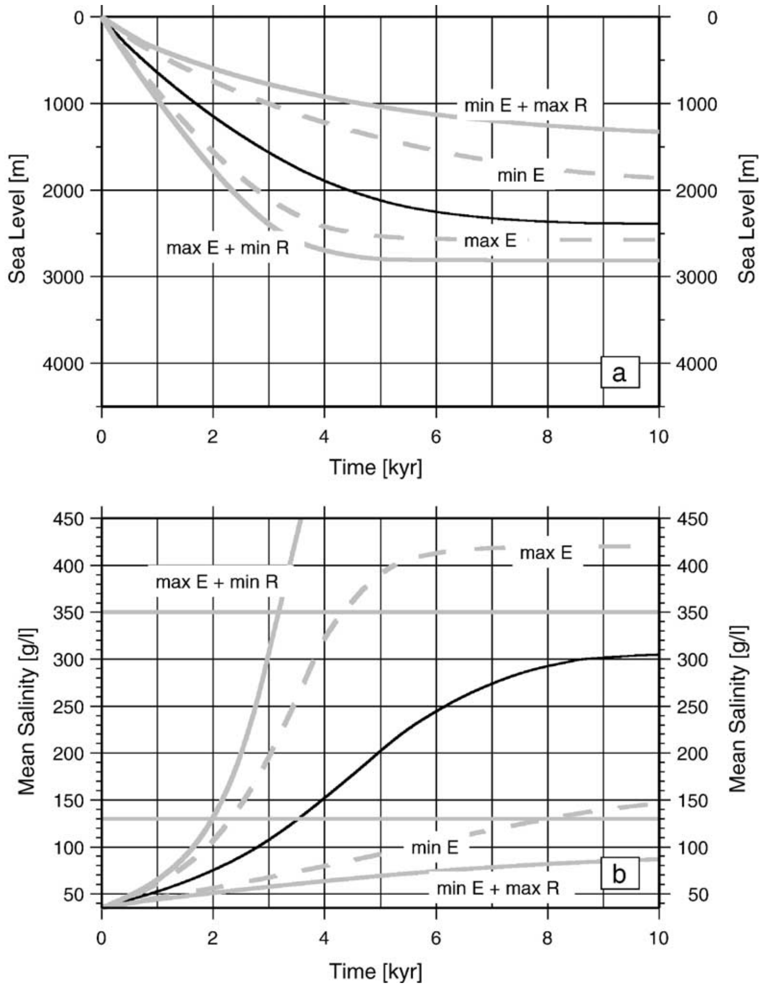

Fig. 5. As in Fig. 4 for the present-day eastern sub-basin.

the western and eastern sub-basin respectively. The sensitivity analysis is done only for the present-day geometry. This is warranted in view of one of the main results of this sensitivity analysis namely that the effect of changes in geometry are small compared to that of variation in the water fluxes (compare the spread in curves in Figs. 4 and 5 to that in Fig. 3).

Generally speaking, a 25% change in $E-P$ is found to have a stronger effect than a 25% change in discharge. This is explained by the greater absolute size of the net air–sea flux. Also, as anticipated, sea level drop is slowest and salinity increase smallest for minimum values of $E-P$ and maximum values for discharge. The sensitivity is largest for the eastern sub-basin. For low values of $E-P$ and high values of discharge the eastern basin hardly passes the saturation concentration of gypsum: no significant evaporites would be expected at all in this case.

5. Results: re-filling

The difficulty with quantifying what happens when the connection with the Atlantic ocean is re-established is that we need to know the associated volume flux. This flux depends on the geometry of the connecting strait and the elevation of Atlantic sea level above the sill, both of which are uncertain. We approach the matter from a different angle and show in Fig. 6 how sea level evolves in case of a constant inflow of the same size as the present-day net inflow at Gibraltar. To be precise, the inflow equals the $E-P$ of 1 m/yr acting over the present-day surface area of the sea, minus river discharge. This amounts to 65.897 m^3/s (i.e., about 0.07 Sv) which is equal to about 3.5 times the total river discharge. The Atlantic inflow is “switched on” at the arbitrary moment of 8 kyr after the start of the computation. Differences between the two geometries prove

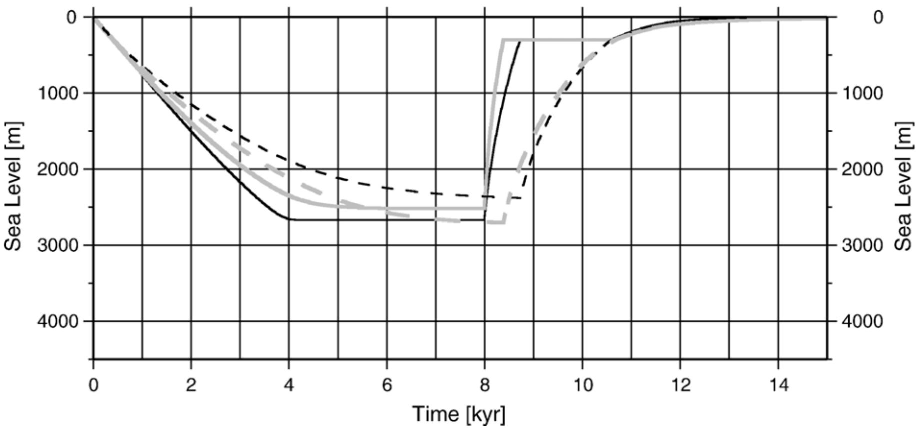

Fig. 6. Modelled sea level variation for the filling stage. Inflow from the Atlantic is “switched on” at 8 kyr after the start of desiccation. Lines as in Fig. 3.

very small. The western basin first receives all water and rapidly fills up to the 300 m depth of the sill separating it from the eastern basin. The sill is reached in less than 1 kyr and, for the following approximately 2 kyr, water spills over into the eastern basin. When the eastern basin has also filled up to sill depth, sea level rises in both sub-basins simultaneously until, about 4–5 kyr after the start of refilling, the Mediterranean basin has regained its present-day level.

Fig. 6 shows that the rate of sea level rise in the eastern basin is generally lower than in the western basin. This can be understood as a direct effect of basin shape (Fig. 2). With decreasing depth the areal extent of the eastern basin increases faster than that of the western basin and the Atlantic inflow spreads out over an ever greater area, reducing the rise rate. The western basin is more cylindrical and its water surface rises relatively fast.

At this point it remains to be determined how realistic the assumed rate of inflow actually is. One way to address this is to calculate which combinations of strait width and depth are minimally needed to accommodate an inflow of this size. The result is shown by the curve in Fig. 7. The calculation assumes one-way critical flow in a channel of rectangular cross-section and ignores the possible role (again, geometry-dependent) of friction and Coriolis force. As expected, a wider strait needs to be less deep and vice versa. Most relevant, however, are the values along the axes: for straits wider than a few kilometers, required water depths are very small, in

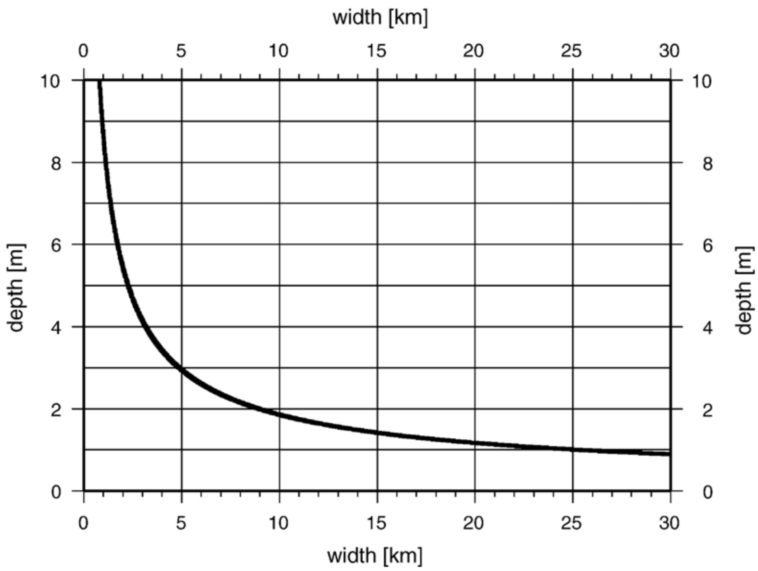

Fig. 7. Combinations of strait width and depth that are minimally required to accommodate the inflow considered in the calculation of Fig. 6.

the order of a few meters (for reference: the present Strait of Gibraltar has a width of about 13 km). This suggests that, if anything, the rate of inflow is likely to have been larger than assumed in the above and the time span associated with re-filling even shorter.

6. Discussion

6.1. Uncertainties

Although as yet beyond the reach of quantification, it is pertinent to point out some sources of uncertainty in the parameters included in our analysis. For example, it would appear that both $E-P$ and river discharge may in fact change as a consequence of the drawdown of sea level. The sea-level drop will most likely result in a rise of the temperature just above the water surface which will increase evaporation. In its turn, increased evaporation may result in more precipitation over the continents bordering the Mediterranean Sea [28], which might augment river discharge into the basin — compensating at least partly for the higher evaporation. Also, during the later stages of drawdown, the effectiveness of evaporation will be limited by its inherent salinity dependence (e.g., [29]).

Perhaps the most uncertain aspect of the river discharge is the contribution from the Black Sea. Whether or not and, if so, how much, Black Sea water reached the eastern sub-basin during desiccation depends in particular on the level of the Black Sea relative to the floor of the intervening strait(s). It may be inferred from Fig. 5b that reduction of R will cause the eastern basin to pass beyond the level of halite saturation (for reference: in our budget the net Black Sea outflow amounts to 32% of R, i.e. even larger than the variation applied in Fig. 5b). Can we now take an observed occurrence of halite in the eastern basin to indicate that less Black Sea water reached the Mediterranean during desiccation than at present? Alas, it seems we would need to know the exact range of $E-P$ during the Messinian to answer this decisively: an increase in salinity could equally well be achieved by an increase in $E-P$ (Fig. 5b). In this respect it is also important to note that $E-P$ over the eastern basin is always expected to be somewhat larger than the basin-averaged value.

By examining two different basin geometries we have most likely bracketed the bathymetric configuration of the Messinian. Nevertheless, the first part of the drawdown and the later part of the re-filling, in detail, will depend on the depth of the sill near Sicily that separates the two sub-basins. This strait may have been deeper than the (present-day) value of 300 m adopted here. The area was involved in the opening of the Tyrrhenian Sea and the eastward translation of Calabria (e.g., [30]).

In our calculation of the stage of re-filling we assume a constant volume flux of oceanic waters. In general it is uncertain whether, during a filling stage, the rate of inflow of Atlantic water is constant or not. In fact, during the last part of filling the inflow is likely to be non-constant. As soon as the water level of the Mediterranean rises above the level of the sill, we may expect a transient state intermediate between the situation of inflow only and the present-day two-way transport.

6.2. Implications

Besides several specific aspects mentioned in the above, the following implications stand out. Our model confirms earlier calculations (e.g., [2,7,18,19]) that sea level drawdown and basin re-fill happen fast in the Mediterranean configuration. In fact, our results show that complete desiccation (up to equilibrium) and re-filling can easily occur within one precession cycle (about 21 kyr). To the extent that desiccation and re-filling were the acting processes, such a fast rate is in agreement with: (1) astronomical dating results on the Messinian sequences, indicating that the onset and end of evaporite precipitation are synchronous Mediterranean-wide events; and (2) geological field observations, showing that the number of precession-related sedimentary cycles in both Lower and Upper Evaporites are approximately the same in all Mediterranean sub-basins (e.g., [9,31,32]). The time lag between the onset of gypsum precipitation in the sub-basins of about 1–2 kyr is too small to be measured by astronomical means. Likewise, salt deposition in any silled marginal basins left perched during the sea level drop will not be strictly synchronous to salt precipitation in the basin centres, but will nevertheless be "time-equivalent" given the resolution of our dating techniques (cf. [6]). The fast rate of re-fill also explains the razor-sharp sedimentary contact at the Mio-Pliocene boundary in the Mediterranean where deep marine marls of the Trubi Formation are found conformably on top of shallow brackish water deposits of the Upper Evaporite/Lago Mare facies.

During deposition of the Lower Evaporites, global sea level is inferred to have fluctuated by up to 30 m [33,34]. There is no reason to assume that these relative fluctuations were different during Upper Evaporite times, although oxygen isotope records indicate a slightly warmer climate in that period [10]. The geological data for the Upper Evaporites suggest shallow water levels in a deep basin with major erosion at the margins, but also indicate intervals of inflow of Atlantic water. Such a scenario is possible when global sea level variations straddle the depth of the Gibraltar sill. If the Atlantic water level indeed periodically fluctuated with 10–30 m about the level of the sill, our results indicate that the Mediterranean sea level will have significantly fluctuated during this period, as suggested by Fortuin and Krijgsman [15]. Canyon cutting, vigorous erosion and continental sedimentation may take place at the marginal areas during Mediterranean low stands, while fast re-filling may episodically result in the formation of a large interconnected Lake Sea, as indicated by strontium isotope studies [27,35]. Despite the potential importance of global sea level changes, regional climate fluctuations must certainly not be underestimated during these processes since the sedimentary cyclicity observed in all MSC units appears to be dominantly related to precession-controlled variations in local climate (e.g. [32]).

Our calculations suggest that the fast re-filling of the Mediterranean requires only a limited connection to the Atlantic. It follows that, for a true partial desiccation to have occurred, disconnection from the Atlantic must have been near complete. To be more specific, with a strait that is 13 km wide as the present-day Strait of Gibraltar, our simplified calculations suggest that the water level above the sill must have been lower than about 2 m to allow drawdown of the Mediterranean Sea. Also, any excess over 2 m would quickly fill the entire basin. It would thus appear unlikely that the Mediterranean water level ever stayed stable at a value intermediate between “desiccated” and “full” over a time span of thousands of years. This is particularly so given that, as stated above, global eustatic sea level most likely changed periodically over several tens of meters on astronomical time scales. A period of stable intermediate sea level in the western Mediterranean is assumed in the two-step scenario for the MSC as proposed by Clauzon et al. [7] and adopted in modelling by Blanc [18]. Here, however, the western Mediterranean Sea level drop is considered eustatic, i.e., in concert with a global sea-level lowering.

7. Conclusions

Based on our quantitative analysis we can formulate the following main conclusions and implications.

1. Desiccation and re-filling happen fast and could take place within one precession cycle. Consequently, temporal differences in the onset of salt precipitation between western and eastern basin and between marginal basins and basin centres are below the resolution of (astronomical) dating. Also, when Atlantic sea level periodically varied from below to above the level of the intervening sill, the Mediterranean basin will have responded with repeated desiccation and re-filling.
2. Desiccation is near complete in the western basin while a significant water column remains in much of the eastern basin.
3. Uncertainty regarding the freshwater budget is more significant to the evolution of desiccation than uncertainty in paleogeography and affects the eastern basin more than the western basin. Whether or not the eastern basin reaches the level of halite saturation depends critically on the freshwater budget (including the absence or presence of water input from the Black Sea).
4. The fast re-filling of the basins requires only a very limited connection to the Atlantic. It would seem to require exceptional conditions for the Mediterranean water level to stay stable at values intermediate between “desiccated” and “full”.

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