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Estimating past changes in the Eastern Mediterranean freshwater budget, using reconstructions of sea level and hydrography

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ABSTRACT

We present a method for estimating the order of magnitude of past changes in the (eastern) Mediterranean freshwater budget, that relies on knowledge of past sea level and pycnocline depth, as reconstructed from fossil evidence. First we discuss the influences of sea level change on the exchange transport through the Strait of Gibraltar, and on the Atlantic-Mediterranean salinity contrast. These variations are studied with a recently developed hydraulic control model for that strait. The exchange transport appears to decrease quasilinearly, whereas the salinity contrast shows a distinctly nonlinear increase with falling sea level. Even when we assume that Mediterranean excess evaporation remained constant at its modern value, the 120 m sea level lowering during the Last Glacial Maximum (18 000 BP) would have caused a strong decrease in the volume of Mediterranean outflow, as well as a very substantial increase in its density. Thus, the Mediterranean outflow would have settled in the Atlantic at much greater depths than at present, which in turn may have influenced the process of salty North Atlantic Deep Water formation in the Norwegian Sea. Subsequently, the hydraulic control model is combined with a two-layer model for the eastern Mediterranean, resulting in a description of how sea level fluctuations and depth variations of the eastern Mediterranean pycnocline may be used to quantify variations in the eastern Mediterranean freshwater budget. Next, we discuss the sensitivity of the resulting model to the necessary assumptions and to the input parameters that need to be constrained using the geological record, and define a confidence-interval for the model solutions. To give an example of how the model presented in this paper may be used to infer past changes in the freshwater budget relative to the present, we apply it to assess the eastern Mediterranean conditions at the Pleistocene-Holocene transition (9 600 BP), when sea level stood 50 m below the present. The model suggests: 1) that excess evaporation was in the order of 20% higher than today; 2) that the Atlantic-Mediterranean salinity contrast and the salinity contrast across the eastern Mediterranean pycnocline were both in the order of 50% higher than today; and 3) that the volume of surface water flowing into the eastern Mediterranean through the Strait of Sicily was reduced by about 15% from its present value.

INTRODUCTION

General introduction

In the past eight decades, a great number of theoretical studies has been performed on the processes that govern the exchange of water masses through sea straits (among others Nielsen, 1912; Stommel and Farmer, 1953; Whitehead et al., 1974; Gill, 1977; Bryden and Stommel, 1984; Armi and Farmer, 1986; Farmer and Armi, 1986; Dalziel, 1991; Bormans and Garrett, 1989; Bryden and Kinder, 1991). The present-day exchange of water masses through the Strait of Gibraltar, which separates the Mediterranean Sea from the Atlantic Ocean, was used as the principal test-case for the models presented in most of these studies, or even formed the major impetus.

In more recent years, another notable effort concerned the modeling of climate related changes in (especially eastern) Mediterranean hydrography on geological time-scales (among others Béthoux, 1979, 1984; Mangini and Schlosser, 1986; Thunell et al., 1987; Sarmiento et al., 1988; Rohling, 1991a, 1991b). This work was triggered by the accumulation of fossil evidence of hydrographic changes in the Mediterranean, which were found to be closely related to Milankovitch cycles of orbital climatic forcing, either in a global (ice ages) or in a regional (variable aridity) context. Much of this modeling effort focused on the influences exerted on hydrography by either sea level fluctuations, or changes in the (eastern) Mediterranean freshwater budget. Very little of the effort dealt with the possible interactions between these processes.

A combination of the two types of model discussed above, in particular those of Bryden and Kinder (1991) and Rohling (1991a, 1991b), should yield a method for estimating (at least the order of magnitude of) past variations in the freshwater budget, relative to the present, given the input of reconstructed sea level and hydrography. Sea level is an input parameter, since detailed reconstructions of global sea level are possible from the geological record, especially for the past 18000 years (Fairbanks, 1989). Although existing reconstructions of past hydrography (for instance Rohling and Gieskes, 1989) are less commonly accepted than those of sea level, we expect them to be improved considerably in the near future (see also Castradori, 1993; McIntyre et al., 1989). Studies of lake level records, stable isotope records, and pollen and spore records, which reveal past trends of increasing or decreasing aridity rather than quantitative estimates of the freshwater budget, may be useful for evaluation of the model results.

Background and outline of the present contribution

The hydraulic control model for exchange through the Strait of Gibraltar described by Bryden and Kinder (1991) assumes that the exchange is maximal with respect to the hydraulic control imposed by the sill and narrows in that strait. For given strait configuration, the model calculates the exchange transport and the outflow-inflow salinity contrast (ΔS_{gib}) as functions of the Mediterranean excess of evaporation over freshwater input (X_{med}). We use this model to evaluate the influences of glacial-interglacial sea level fluctuations via changes in strait geometry. We assume, during that exercise, that X_{med} was constant at its present value. Thus, we determine relations between glacial to interglacial variations in sea level (-120 to $+10$ m) and changes in ΔS_{gib} and exchange transport, for constant X_{med}. We show that the influences on ΔS_{gib} and exchange transport are quite substantial, and argue that the observed changes in these parameters may be potentially important for the Atlantic thermohaline circulation.

Next, we evaluate the importance of superimposed changes in excess evaporation. The fossil record has convincingly demonstrated that the Mediterranean freshwater budget has varied substantially through geologic time (among others Rognon and Williams, 1977; Sarmhein, 1978; Street and Grove, 1979; Rossignol-Strick et al., 1982; Rossignol-Strick, 1985; Guiot, 1987; Magaritz and Goodfriend, 1987; Prell and Kutzbach, 1987; Wijmstra et al., 1990; Hilgen, 1991; Rohling and Hilgen, 1991). Using these studies for the general trends in the changes of the freshwater budget, we think that it should be possible to quantify variations in X_{med} through geologic time. We present a first step in that direction, namely a method to determine the order of magnitude of eastern Mediterranean excess evaporation (X). This is done by combining the Bryden and Kinder (1991) model with variable sea level with the eastern Mediterranean pycnocline depth model of Rohling (1991a, 1991b). After constraining the paleodepth of the pycnocline (we give an example using the planktonic foraminiferal record), the resultant model may be used to estimate eastern Mediterranean excess evaporation (X).

It should be stressed, that the pycnocline depth model of Rohling is intended for reconstructing long-term average conditions in the eastern Mediterranean through the recent geological history (Quaternary) and is, therefore, kept very simple. This is done to reduce the influence of parameters that cannot be accurately estimated for the geological past, and which might introduce uncontrollable errors (such as fluctuations in absolute temperature, windstress, incoming radiation, etc.). As a result, the model is rather primitive in comparison with detailed models of the mixed-layer, or numerical models of the large-scale ocean circulation. Nevertheless, we believe that the simple model provides a sufficient account of variations in long-term average pycnocline depth to warrant its application with the hydraulic control model to estimate long-term changes in the eastern Mediterranean freshwater budget. We feel supported by the capacity of the model to accommodate the modern average conditions in the eastern Mediterranean.

Sea level change and exchange transports at the Strait of Gibraltar and Strait of Sicily

Before being able to study how sea level fluctuations and estimates of the paleodepth of the eastern Mediterranean pycnocline may be used to constrain variations in the eastern Mediterranean freshwater budget, we first need to discuss how glacial-interglacial sea level fluctuations influence changes in the volume of surface water flowing into the eastern Mediterranean. In other words, we need to evaluate the importance of the geometry of the Strait of Gibraltar and the Strait of Sicily in limiting the exchange of water-masses between the Atlantic Ocean and the entire Mediterranean, and between the eastern and western sub-basins, respectively. Modern property distributions show a greater contrast between Atlantic and western Mediterranean waters than between western and eastern Mediterranean waters (Wüst, 1961; Miller et al., 1970; Bryden and Stommel, 1984). This suggests that the Strait of Gibraltar, being much narrower and also shallower than the Strait of Sicily, is much more effective in limiting the exchange transports.

In the Bryden and Kinder (1991) model, the geometry of the Strait of Gibraltar was represented by a shallowest (sill) section in its western part, and a narrowest (narrows) section positioned some 20 km further eastwards. Furthermore, width versus depth plots showed that the profiles of both the sill-section and the narrows-section are essentially V-shaped. Then, Bryden and Kinder argued that the upper (inflowing) layer essentially achieves critical Froude number at the narrows, while the lower (outflowing) layer does so at the sill. In other words, the exchange transport through the Strait of Gibraltar is assumed to be maximal with respect to the hydraulic control imposed by the sill and narrows. The above considerations suggest that sea level changes would, through alteration of the strait's geometry, exert a strong influence on the amount of exchange transport through the Strait of Gibraltar. We study that the influence using the Bryden and Kinder model with sea level variations between −120 and +10 m, relative to the present.

The exchange through the Strait of Sicily seems to be much less limited by the strait's geometry, as indicated by a more effective smoothing of differences between the property distributions on either side. Since the width of the channel deeper than 200 m is about 35 km (Bryden and Stommel, 1984), the Strait of Sicily should be sufficiently wide to allow for important rotational effects in the exchange, as confirmed by the observations of Garzoli and Maillard (1979). As yet, there are no elaborate models for the physical constraints of the exchange transport through the Strait of Sicily as there are for the Strait of Gibraltar. However, in spite of the highly irregular sea-floor topography in the Strait of Sicily (Garzoli and Maillard, 1979), we think that the strait cross-section is sufficiently wide and deep to ensure substantial surface water flow from the western into the eastern basin, even with a sea level lowering of 120 m relative to the present.

Summarizing, we determine changes in the exchange transport through the Strait of Gibraltar related to sea level fluctuations, using the Bryden ad Kinder (1991) model for hydraulic control in the Strait of Gibraltar. Furthermore, we assume, according to the above considerations, that the influence of the Strait of Sicily on the surface water flow from the western into the eastern Mediterranean does not change markedly as a result of sea level fluctuations between −120 and +10 m. As a consequence of this assumption, the sea level related variations of surface water inflow into the eastern Mediterranean, which we use in the eastern Mediterranean pycnocline depth model, are fully determined by sea level related changes in the exchange transport through the Strait of Gibraltar.

Effects of sea level change in the Strait of Gibraltar

The hydraulic control model for the Strait of Gibraltar in its present-day configuration, in combination with mass and salt conservation statements, allows for calculation of the exchange transport through the Strait of Gibraltar and the Atlantic-Mediterranean salinity difference (ΔS_{gib}), as functions of the Mediterranean excess evaporation (Bryden and Kinder, 1991), according to

$$(1) \qquad Q_{\text{net}} = C\,\frac{W_{\text{s}}\,D_{\text{s}}}{2}\sqrt{\frac{g\,\beta\,\Delta S\,D_{\text{s}}}{\rho_{\text{med}}}} = \frac{2S_{\text{atl}} + \Delta S_{\text{gib}}}{\Delta S_{\text{gib}}}\,X_{\text{med}}$$

where W_{s} and D_{s} are the width and depth of the sill-section, respectively. C is a constant depending on strait geometry, S_{atl} is the salinity of surface inflow from the Atlantic, X_{med} is excess of evaporation over freshwater input for the entire Mediterranean, $g = 9.81\,\text{m}\,\text{s}^{-2}$ is the gravitational acceleration, and $\beta = 0.77 \times 10^{-3}\,\text{g}\,\text{cm}^{-3}\,\text{ppt}^{-1}$ is a coefficient used by Bryden and Kinder to convert $\Delta\rho_{\text{gib}}$ to ΔS_{gib}. Q_{net} determines the net exchange across the sill, $Q_{\text{atl}} - Q_{\text{med}}$, where Q_{atl} is the eastward Atlantic water inflow, $-Q_{\text{med}}$ the westward Mediterranean water outflow, and $Q_{\text{atl}} + Q_{\text{med}} = X_{\text{med}}$. Thus, relation (1) yields the maximal exchange and minimal salinity difference, for given values of excess evaporation.

Using the Bryden and Kinder model with sea level variations between -120 and $+10$ m, relative to the present, we obtained the results presented in table 1. During this procedure, the Mediterranean excess evaporation has been kept constant at the value of $56\,\text{cm}\,\text{yr}^{-1}$. With that value, the results of the present-day model were in reasonable agreement with observations (Bryden and Kinder, 1991). The magnitude of excess evaporation does influence the absolute value of inflow volume, but since it is kept constant this influence disappears in the ratio Φ between sea level related inflow V_{atl} and the present-day inflow $V_{\text{atl}}^{\text{p}}$ ($\Phi = V_{\text{atl}}/V_{\text{atl}}^{\text{p}}$; the symbol Q of Bryden and Kinder is replaced by V for compatibility with the model of Rohling discussed in the following sections). The same applies for the ratio ψ between the sea level related value ΔS_{gib} and the present-day value $\Delta S_{\text{gib}}^{\text{p}}$ ($\psi = \Delta S_{\text{gib}}/\Delta S_{\text{gib}}^{\text{p}}$).

Figure 1 shows the plots of ψ, Φ, and $H_{1\text{N}}$ versus sea level. It is obvious that Φ changes quasi-linearly with sea level variation, by about $4.4 \times 10^{-3}\,\text{m}^{-1}$. Rohling's (1991a) value of $\Phi_{18000} = 0.60$ for sea level at -100 m, derived from a study of Béthoux (1984), seems to agree fairly well with our value of $\Phi_{18000} = 0.56$. The relation between ψ and sea level is evidently non-linear. In fig. 2, we plotted our calculated values of Φ, ψ, and $H_{1\text{N}}$ in relation to the detailed sea level curve for the past 18000 years as described by Fairbanks (1989).

Discussion of the results from the hydraulic control model with variable sea level

In spite of being obtained under the assumption of invariable Mediterranean

Table 1. The effects of sea level change in the model of Bryden and Kinder (1991). Inflow and Outflow are given in Sverdrups (1 Sv = 10^6 m^3 s^{-1}). Φ is the ratio between sea level related inflow and present-day inflow. ΔS_{gib} is the Atlantic-Mediterranean salinity contrast, and ψ is the ratio between sea level related ΔS_{gib} and present-day ΔS_{gib}. H_{1N} stands for the depth of the inflow-outflow interface in the eastern end of the Strait of Gibraltar (at the narrows), $H_1 S$ for the depth of the interface in the western end of the strait (at the sill).

Sea lev. (m)	Inflow (Sv)	Outflow (Sv)	ΔS_{gib} (ppt)	H_{1N} (m)	H_{1S} (m)	Φ	ψ
+10	0.95	0.90	1.79	71.9	140.0	1.05	0.95
+5	0.92	0.88	1.84	70.4	137.2	1.02	0.98
0	0.90	0.86	1.88	69.0	134.4	1.00	1.00
−5	0.88	0.84	1.93	67.6	131.6	0.98	1.03
−10	0.86	0.81	1.98	66.1	128.8	0.95	1.05
−15	0.84	0.79	2.04	64.7	126.1	0.93	1.08
−20	0.82	0.77	2.09	63.3	123.3	0.91	1.11
−25	0.80	0.75	2.15	61.9	120.5	0.88	1.14
−30	0.78	0.73	2.21	60.5	117.7	0.86	1.17
−35	0.76	0.71	2.27	59.1	115.0	0.84	1.21
−40	0.74	0.69	2.34	57.7	112.2	0.81	1.24
−45	0.71	0.67	2.41	56.3	109.5	0.79	1.28
−50	0.70	0.65	2.48	54.9	106.7	0.77	1.32
−55	0.68	0.63	2.56	53.6	104.0	0.75	1.36
−60	0.66	0.61	2.64	52.1	101.2	0.73	1.40
−65	0.64	0.59	2.73	50.8	98.5	0.71	1.45
−70	0.62	0.57	2.82	49.4	95.7	0.68	1.50
−75	0.60	0.55	2.92	48.0	93.0	0.66	1.55
−80	0.58	0.54	3.02	46.7	90.3	0.64	1.60
−85	0.56	0.52	3.13	45.3	87.5	0.62	1.66
−90	0.54	0.50	3.24	44.0	84.8	0.60	1.72
−95	0.53	0.48	3.36	42.7	82.1	0.58	1.79
−100	0.51	0.46	3.49	41.3	79.3	0.56	1.85
−105	0.49	0.45	3.63	40.0	76.6	0.54	1.93
−110	0.47	0.43	3.78	38.7	73.9	0.52	2.00
−115	0.46	0.41	3.93	37.4	71.1	0.51	2.09
−120	0.44	0.39	4.10	36.1	68.3	0.49	2.18

excess evaporation (X_{med}) the results shown in table 1 and fig. 2 show some effects of sea level lowering that deserve to be emphasized.

The salinity contrast between inflow and outflow through the Strait of Gibraltar during the Last Glacial Maximum (LGM; 18 000 BP) appears to have been more than doubled, relative to the present. It is interesting to speculate about the importance of a glacial Mediterranean outflow with considerably increased salinity and, therefore, density. Such outflow water should have settled at much greater depths in the Atlantic than it does at present. This should have influenced the process of North Atlantic Deep Water (NADW) formation, following Reid's (1979) theory that the formation of relatively salty NADW is strongly linked to penetration of high salinity Mediterranean outflow water into the Norwegian Sea. Settling of glacial Mediterranean outflow in the deep-sea, in contrast with the intermediate levels at which it settles today, would make its

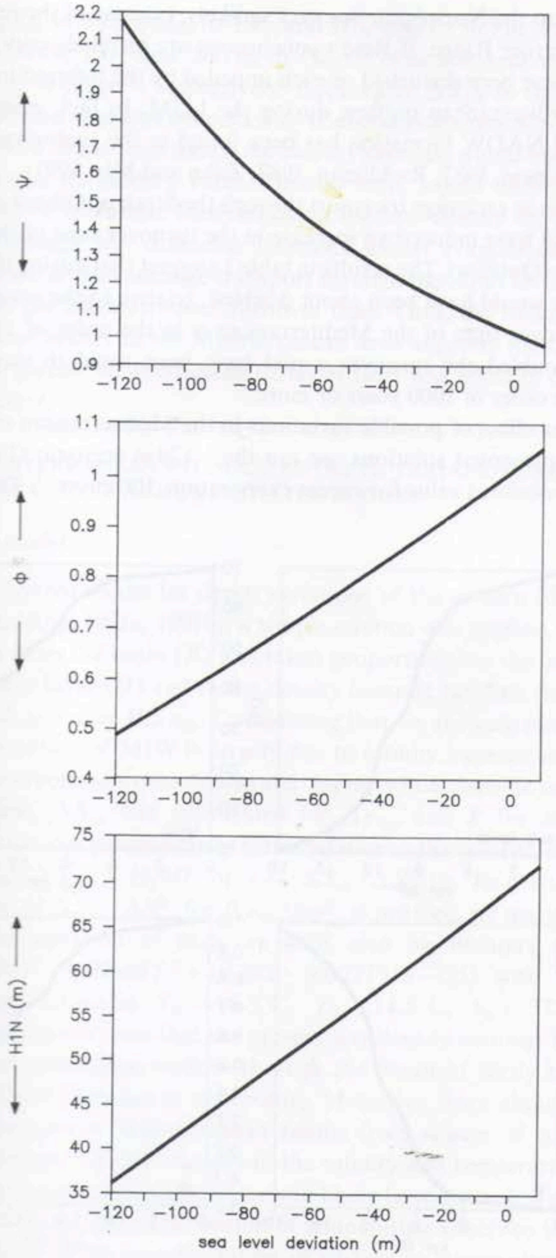

Fig. 1. Plots of ψ (non-dimensional coefficient, $= \Delta S_{gib} / \Delta S_{gib}^{p}$), Φ (non-dimensional coefficient, $= V_{atl} / V_{atl}^{p}$), and H_{1N} (in meters), versus deviation of sea level from the present (in meters), as determined with the model of Bryden and Kinder (1991), with a constant excess evaporation. Plots according to values listed in table 1.

penetration into the Norwegian Sea very unlikely, because of the relatively shallow Iceland-Faroer Ridge. If Reid's conclusions are justified, salty NADW formation may have been disturbed or even impeded by the inferred increase in the density of Mediterranean outflow during the LGM. In fact, evidence for disturbed glacial NADW formation has been found in the geological record (a.o. Boyle and Keigwin, 1987; Ruddiman, 1987; Zahn and Mix, 1991).

The decrease in exchange transport through the Strait of Gibraltar with falling sea level would have induced an increase in the turnover time of the Mediterranean (Volume/Outflow). The results in table 1 suggest that during the LGM, this turnover time would have been about doubled, relative to the present. The present-day turnover time of the Mediterranean is in the order of 100 years, and even when doubled the turnover would have been rapid in view of oceanic periods in the order of 1000 years or more.

To study the effect of possible variations in the Mediterranean excess evaporation on the presented solutions, we ran the -120 m scenario (18 000 BP) also with a nearly doubled value for excess evaporation, 100 cm yr^{-1}. This resulted in

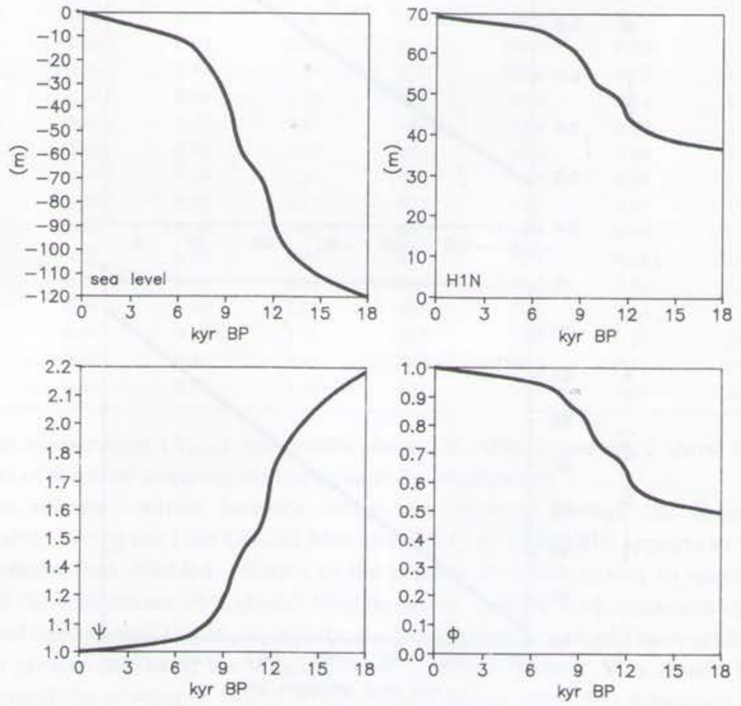

Fig. 2. The changes in Φ (non-dimensional coeffcient, $= V_{atl}/V^{p}_{atl}$), ψ (non-dimensional coefficient, $= \Delta S_{gib}/\Delta S^{p}_{gib}$), and H_{1N} (in meters), related to sea level change (in meters) during the past 18000 years (Fairbanks, 1989), as determined with the hydraulic control model for the Strait of Gibraltar of Bryden and Kinder (1991), assuming that Mediterranean excess evaporation remained constant through time.

changes of Φ_{18000} to 0.63, ψ_{18000} to 3.45, and $H_{1N\ 18000}$ to 36.9 m, as compared to the values of 0.49, 2.18, and 36.1 m in the −120 m scenario with an excess evaporation of 56 cm yr^{-1}, respectively. Apparently ΔS_{gib} is very sensitive to changes in the rate of excess evaporation. If excess evaporation at glacial times was substantially larger than today, the salinity contrast would have been much larger than twice its modern value. This, in turn, would have enhanced the potential effect of increased Mediterranean outflow density on salty NADW formation. Although less dramatic, increased excess evaporation would also cause an increase in the exchange transport through the Strait of Gibraltar. This would shorten the Mediterranean turnover time. Thus, the fossil evidence for increased glacial aridity in the Mediterranean area suggests that it is not very likely that the glacial Mediterranean turnover time was actually doubled, relative to the present.

EASTERN MEDITERRANEAN PYCNOCLINE DEPTH VARIATIONS RELATED TO CHANGES IN SEA LEVEL AND FRESHWATER BUDGET

Outline of the model

In the two-layered model for depth variations of the eastern Mediterranean pycnocline (Rohling, 1991a, 1991b), a simple relation was applied, in which net buoyancy loss from the basin (B) was taken proportional to the average thickness of the upper layer (H) and to the density contrast between the deeper and upper layers ($\Delta\rho_{\mathrm{sic}}$): $B \propto H\Delta\rho_{\mathrm{sic}}$. Considering that, on the long term and basin-wide scale, formation of MIW is largely due to salinity increase resulting from an excess of evaporation over freshwater input, while there is only little net temperature loss, ΔS_{sic} was substituted for $\Delta\rho_{\mathrm{sic}}$, and X for B. Expressing changes in the various parameters as ratios relative to the present, it follows that $X/X^{\mathrm{p}} = (\Delta S_{\mathrm{sic}}/\Delta S^{\mathrm{p}}_{\mathrm{sic}}) \times H/H^{\mathrm{p}}$, or $\gamma = (\Delta S_{\mathrm{sic}}/\Delta S^{\mathrm{p}}_{\mathrm{sic}})\,\alpha$. To evaluate whether the substitution of $\Delta S_{\mathrm{sic}}/\Delta S^{\mathrm{p}}_{\mathrm{sic}}$ for $\Delta\rho_{\mathrm{sic}}/\Delta\rho^{\mathrm{p}}_{\mathrm{sic}}$ is justified, we use the simplified version of the equation of state as used also by Béthoux (1979), $\sigma_t = 28.152 - 0.0735T - 0.00469T^2 + (0.802 - 0.002T)(\mathrm{S} - 35)$ with the modern annual average estimates $T_{\mathrm{u}} = 16.5\,^{\circ}\mathrm{C}$, $T_{\mathrm{d}} = 14.5\,^{\circ}\mathrm{C}$, $S_{\mathrm{u}} = 37.2$ ppt, $S_{\mathrm{d}} = 38.75$ ppt. This demonstrates that the present-day density contrast between surface inflow and subsurface outflow through the Strait of Sicily is only for a maximum of about 30% due to net cooling. Moreover, since about 90% of the heat loss in the eastern Mediterranean results from release of latent heat by evaporation (Béthoux, 1979), changes in the salinity and temperature contrasts between surface and intermediate water will likely be more or less proportional to one another. Hence, the contribution of temperature effects to the net buoyancy loss involved in the transformation of surface to intermediate water will remain relatively similar to the present (maximum 30%). Therefore, we estimate that, when substituting $\Delta S_{\mathrm{sic}}/\Delta S^{\mathrm{p}}_{\mathrm{sic}}$ for $\Delta\rho_{\mathrm{sic}}/\Delta\rho^{\mathrm{p}}_{\mathrm{sic}}$, the ignoring of temperature effects may introduce an error of only about ±5%. The influence of this error in the final model equation may be considered using non-dimensional coefficient δ, so that $(\Delta\rho_{\mathrm{sic}}/\Delta\rho^{\mathrm{p}}_{\mathrm{sic}}) = \delta(\Delta S_{\mathrm{sic}}/\Delta S^{\mathrm{p}}_{\mathrm{sic}})$, with $0.95 < \delta < 1.05$.

Furthermore, it was assumed that the mass and salt budgets in the basin are maintained by the exchange through the Strait of Sicily. In the previous section, we argued that sea level imposed changes of inflow through the Strait of Sicily were proportional to those through the Strait of Gibraltar, which we quantified with coefficient Φ. Thus, the combined effects of sea level fluctuations and changes in the excess of evaporation over freshwater input (X) relative to the present (X^p), affect the volume of inflow (V_u) relative to the present (V_u^p), so that $X/X^p = \gamma$ and $V_u/V_u^p = \Phi\,\Omega$ (where $\gamma \approx \Omega^2$, see Rohling (1991b)). Then, it is possible to describe how the salinity contrast between inflow and outflow at the Strait of Sicily (ΔS_{sic}) changes with variations in sea level and excess evaporation, according to

$$(2) \qquad \Delta S_{sic} = \frac{S_u}{\left(\frac{V_u^p}{X^p}\,\frac{\Phi\,\Omega}{\gamma}\right) - 1}$$

where S_u stands for salinity of the upper layer inflow through the Strait of Sicily.

The combined studies of Rohling (1991a, 1991b) give a solution in α, the non-dimensional coefficient for pycnocline depth variation (αH^p gives paleodepth of the pycnocline; H^p being the modern average depth of about 150 m). The equation consists entirely of ratios relative to the present, which eliminates the problem that only proportionalities could be determined between some of the input parameters (such as B, H, X, and $\Delta\rho_{sic}$), instead of strict equalities. With respect to the specific purpose we need the model for in this paper, we rearranged the final model equation to solve for Ω ($\approx \sqrt{\gamma}$), giving

$$(3) \qquad \Omega = \frac{\left(\frac{V_u^p}{X^p}\,\Phi\right) - \sqrt{\left(\frac{V_u^p}{X^p}\,\Phi\right)^2 - 4\,\frac{\alpha\left(\frac{V_u^p}{X^p} - 1\right)}{\delta\left(\frac{S_u^p}{S_u}\right)}}}{2}$$

Note that from fig. 3 and eq. (3), sea level lowering relative to the present (reduction of Φ) would facilitate a rise of the eastern Mediterranean pycnocline to the base of the euphotic layer in response to decreases in excess evaporation. Should Φ be reduced sufficiently, the pycnocline would reside within the euphotic layer ($\alpha < 0.8$, see below) even if excess evaporation was equal to, or somewhat larger than the present value. Such a relationship helps to explain the inferred shallow position of the glacial pycnocline (Rohling and Gieskes, 1989), despite strong excess evaporation at that time.

Confidence-intervals

In the previous section, we argued that substitution of $\Delta S_{sic}/\Delta S_{sic}^p$ for $\Delta\rho_{sic}/\Delta\rho_{sic}^p$ introduced an uncertainty factor $\delta = 1 \pm 0.05$. An additional error is involved in determining the paleosalinity S_u. In practice, oxygen isotope records will prove to be the most promising tool for paleosalinity determination, but that method requires some basic information about regional temperatures, and the

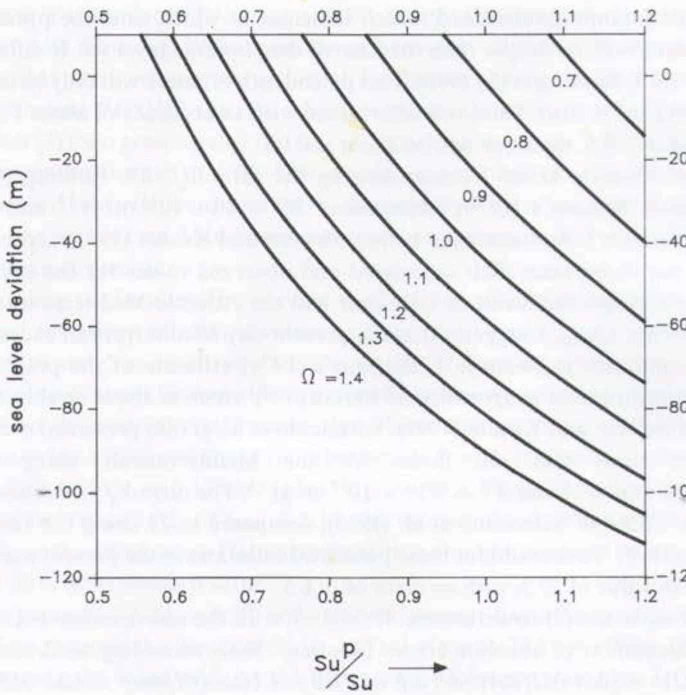

Fig. 3. The relation between the deviation of sea level from the present (in meters) and the ratio S_u^p/S_u for several values of Ω (the non-dimensional coefficient of inflow variation due to changes in the freshwater budget), as described by eq. (3) and plotted for $\alpha = 0.8$, which implies a pycnocline position at the base of the euphotic layer. For the ratio V_u^p/X^p, a value of 23.5 is used, as explained in the text. The non-dimensional coefficient of changes in the freshwater budget (γ) can be derived directly from Ω, using $\gamma = \Omega^2$.

derived paleosalinity should be checked against as many other values for that parameter as possible. In cases of intervals studied in high detail, and in numerous cores from the study region, we estimate that a paleosalinity value with an accuracy of ± 0.5 ppt should be possible. A major problem with inferring paleosalinity from δ^{18}O records concerns the common practice of extrapolating the modern S : δ^{18}O relation back into geologic time, without accounting for changes in the importance of the various terms in the freshwater budget relative to one another. Although that method provides some estimate of paleosalinity, it is prone to uncontrollable errors, since the S : δ^{18}O relation will display significant deviations from the present when changes occur in the relative importance of the various freshwater terms. These deviations originate in the contrast between an equal salinity value (0 ppt), and substantial differences in the respective δ^{18}O values, for the various terms (Van Os and Rohling, submitted).

A third significant error results from estimating α, which equals the ratio between average paleodepth of the pycnocline and its modern average depth (about 150 m). In this paper, we constrain pycnocline paleodepth using the planktonic foraminiferal record, which indicates at which time the pycnocline resided shallower, or deeper than the base of the euphotic layer (cf. Rohling and Gieskes, 1989; Rohling et al., 1993). This paleodepth estimate will only be reliable within limits of ± 10 m. Thus, α is determined with an accuracy of about 7%. For a mean of $\alpha = 0.8$, the error will be about ± 0.06.

Finally, an error arises from estimating the ratio V_u^p/X^p. Rohling (1991a, 1991b) used Béthoux's (1979) estimates of $V_u^p = 40 \times 10^{12}\,\mathrm{m^3\,yr^{-1}}$ and $X^p = 1.8 \times 10^{12}\,\mathrm{m^3\,yr^{-1}}$. As mentioned before, Bryden and Kinder (1991) argued that the best match between their calculated and observed values for the exchange transport through the Strait of Gibraltar and the Atlantic-Mediterranean salinity difference (ΔS_{gib}) suggests that the present-day Mediterranean excess evaporation amounts to 56 cm $\mathrm{yr^{-1}}$. Béthoux's (1979) estimate of the present-day Mediterranean excess evaporation is 100 cm $\mathrm{yr^{-1}}$, which is about double the estimate of Bryden and Kinder (1991). Sarmiento et al. (1988) presented a compilation of mass and salt fluxes for the Mediterranean, using $V_u^p = 22.86 \times 10^{12}\,\mathrm{m^3\,yr^{-1}}$ and $X^p = 9.15 \times 10^{11}\,\mathrm{m^3\,yr^{-1}}$. The ratio V_u^p/X^p is about 25 using the values of Sarmiento et al. (1988), compared to 22 using the values of Béthoux (1979). To account for these published estimates in the present paper, we use a mean value of 23.5, with an error of ± 1.5.

Use of equation (3) to determine Ω (and γ), with the above estimated errors, allows calculation of absolute errors (Squires, 1988), according to $\Delta\gamma \approx 2\Delta\Omega$ and $(\Delta\Omega)^2 = (\Delta A\,\partial\Omega/\partial A)^2 + (\Delta B\,\partial\Omega/\partial B)^2 + (\Delta\alpha\,\partial\Omega/\partial\alpha)^2 + (\Delta\delta\,\partial\Omega/\partial\delta)^2$, where $A = V_u^p/X^p$, and $B = S_u^p/S_u$.

APPLICATION: ESTIMATING CONDITIONS AT THE PLEISTOCENE-HOLOCENE TRANSITION

Using eq. (2) and (3) in combination with the variation of Φ with sea level fluctuation as determined with the Bryden and Kinder model (see table 1), and a value of 23.5 for V_u^p/X^p, we will now assess the conditions at the Pleistocene-Holocene transition, to show an example of how the method presented in this paper may be applied. At the Pleistocene-Holocene transition, dated accurately with the AMS ^{14}C method at 9 600 BP (Jorissen et al., 1993), the planktonic foraminiferal genus *Neogloboquadrina* disappeared abruptly from the eastern Mediterranean. According to the interpretation of Rohling and Gieskes (1989), in which the abundance of *Neogloboquadrina* was linked to a position of the pycnocline within the euphotic layer and consequent development of a Deep Chlorophyll Maximum layer, this disappearance should be attributed to deepening of the pycnocline, crossing the base of the euphotic layer around 9 600 BP. Furthermore, this interpretation implies that the pycnocline should generally have resided below the euphotic layer after 9 600 BP, as it actually does at present. Support for the above scenario has come from a study of changes in the entire planktonic foraminiferal assemblage (Rohling et al., 1993). In the present model, using today's average depths of the pycnocline (about 150 m) and base of the euphotic layer (about 120 m), the above scenario translates into the condition $\alpha = 0.8$ at the Pleistocene-Holocene transition (9 600 BP).

We use a value for $(S_u^p/S_u)_{9600} = 0.97$, simply the mean of the pleniglacial value of 0.94 (Rohling, 1991a) and the present-day value of 1.00. According to the detailed sea level reconstruction of Fairbanks (1989), sea level stood near -50 m around 9 600 BP (fig. 2), which corresponds to $\Phi_{9600} = 0.77$ (table 1). Equation (3) then gives a value of $\Omega_{9600} = 1.10$, so that $\gamma_{9600} = 1.20$, compared to the present-day values of 1.00. This would suggest that the conditions at the Pleistocene-Holocene transition were characterized by a sea level position of -50 m and an eastern Mediterranean excess evaporation that was about 20% higher than at present.

According to the above mentioned method for calculating confidence-intervals, and the above calculated values of $\Omega_{9600} = 1.10$ and $\gamma_{9600} = 1.20$, we find $\Delta\Omega = 0.10$ and $\Delta\gamma = 0.20$ (or: $\Omega \pm 9\%$; $\gamma \pm 17\%$). Because subtle changes in the temperature contrast between the upper and deeper layers through geologic time cannot be determined, we assume that these changes were proportional to changes in the salinity contrast (in other words $\delta = 1$). In that scenario, we find $\Delta\Omega = 0.08$ and $\Delta\gamma = 0.17$ (or: $\Omega \pm 7\%$; $\gamma \pm 14\%$). Then, according to $\Phi_{9600} = 0.77$ and the range $1.02 < \Omega_{9600} < 1.18$, the volume of inflow through the Strait of Sicily at the Pleistocene-Holocene transition would have been between about 80 and 90% of its modern value.

Since we used $S_u^p/S_u = 0.97$, and since the present-day salinity of surface water inflow through the Strait of Sicily (S_u^p) is close to 37.2 ppt (Wüst, 1961), we can estimate the value of S_u at the Pleistocene-Holocene transition at 38.4 ppt. Using that value, in combination with $\Phi = 0.77$, = 1.20, and $\Omega = 1.10$, the MIW to surface water salinity contrast in the eastern Mediterranean at the Pleistocene-Holocene transition can be calculated according to eq. (2), giving $\Delta S_{\mathrm{sic}\ 9600} = 2.46$ ppt. The involved errors determine a confidence interval of $\pm 10\%$ for ΔS_{sic}, so that $2.21 < \Delta S_{\mathrm{sic}\ 9600} < 2.71$ ppt. With the model of Bryden and Kinder (1991), the Atlantic-Mediterranean salinity contrast for the described conditions can be calculated, yielding $\Delta S_{\mathrm{gib}\ 9600} = 2.80$ ppt. Both the calculated value for $\Delta S_{\mathrm{sic}\ 9600}$, and that for $\Delta S_{\mathrm{gib}\ 9600}$ are in the order of 50% higher than today. In the Bryden and Kinder model, the increase in excess evaporation does not induce any significant change in the depth (H_{1N}) of the inflow-outflow interface in the eastern end of the Strait of Gibraltar (at the narrows), which therefore remains at a depth of about 55 m for a sea level lowering of 50 m (table 1).

SUMMARY AND CONCLUSIONS

The relation between sea level changes and variations in surface water inflow is studied using the hydraulic control model for the Strait of Gibraltar (Bryden and Kinder, 1991), with sea level varying between -120 and $+10$ m relative to the present. The additional influence which the Strait of Sicily may exert on the volume of surface flow into the eastern Mediterranean is assumed to have remained equal to the present. We demonstrate that the ratio between sea level related inflow and present-day inflow changes quasi-linearly by $4.4 \times 10^{-3}\,\mathrm{m}^{-1}$ (fig. 1;

table 1). The Atlantic-Mediterranean salinity contrast displays a distinctly non-linear increase with falling sea level (fig. 1; table 1). Using the detailed sea level curve for the past 18 000 years presented by Fairbanks (1989), we calculate the changes in inflow, the Atlantic-Mediterranean salinity contrast, and the depth of the interface at the narrows, during the interval of time (fig. 2). The inflow-outflow salinity contrast during the Last Glacial Maximum appears to have been more than twice its modern value, indicating that the Mediterranean outflow into the Atlantic had a much higher density and, consequently, should have settled at much greater depths. This may have influenced the formation of salty NADW in the Norwegian Sea, according to Reid's (1979) hypothesis. The above mentioned results were based on the assumption that Mediterranean excess evaporation remained constant through time. We also demonstrate that the higher glacial Mediterranean excess evaporation inferred from fossil evidence would have caused an even more pronounced salinity contrast.

Combining the Bryden and Kinder (1991) model with variable sea level with the pycnocline depth model of Rohling (1991a, 1991b), gives a method to relate changes in sea level and eastern Mediterranean pycnocline depth to changes in the eastern Mediterranean freshwater budget (eq. (3), fig. 3). As an example, we apply the combined model to assess the conditions in the eastern Mediterranean at the Pleistocene-Holocene transition (9 600 PB), when sea level stood about 50 m lower than today (Fairbanks, 1989) and the eastern Mediterranean pycnocline crossed the base of the euphotic layer (as deduced from the foraminiferal record). The model calculates that the eastern Mediterranean excess evaporation around 9 600 BP was in the order of 20% higher than at present. In addition, the model shows that the Atlantic-Mediterranean salinity contrast and the salinity contrast across the eastern Mediterranean pycnocline were both in the order of 50% higher than today, and that the inflow-outflow interface in the eastern end of the Strait of Gibraltar (at the narrows) resided at an approximate depth of 55 m, compared to 69 m at present.

Note that a number of assumptions and estimates are necessary to apply the model for calculation of excess evaporation rates in the geologic past, and that the involved errors generate an interval of possible excess evaporation values ranging from equal to, to about 40% higher than present. Therefore, the values calculated with our model should be regarded as first estimates, which need to be refined by reducing the assumptions and estimates, as well as by comparison with other methods for reconstruction of past excess evaporation values. We emphasize that, besides foraminifera-based interpretations of hydrographic changes, also other proxy records of paleohydrography may be used, in combination with sea level data, to estimate past excess evaporation rates in the (eastern) Mediterranean with the method presented in this paper. Examples of such other records are, for instance, time-series of stable isotope measurements on tests of deeper and shallower living organisms to reveal depth variations of the pycnocline, or dinoflagellate and calcareous nanofossil time-series to discern at which time the pycnocline resided within the eupotic layer with resultant development of a Deep Chlorophyll Maximum.

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