PALEOCEANOGRAPHY, VOL. 6, NO. 4, PAGES 537-541, AUGUST 1991

A SIMPLE TWO-LAYERED MODEL FOR SHOALING OF THE EASTERN MEDITERRANEAN PYCNOCLINE DUE TO GLACIO-EUSTATIC SEA LEVEL LOWERING

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Abstract. A simple two-layered model is developed to assess the depth of the permanent pycnocline in the eastern Mediterranean during glacial times. Shoaling of this pycnocline, from its present depth below the euphotic layer to a depth within that layer at glacial times, has been inferred from the planktonic foraminiferal record (Rohling and Gieskes, 1989). In this paper, a two-layered model is applied to study the origin of the glacial shoaling of the permanent pycnocline. The model suggests that shoaling is due to glacial sea level lowering. Using literature-based glacial salinity and inflow reduction values, the model yields an estimated depth of about 80 m for the glacial pycnocline. This estimate represents an upper depth limit, since the model discards possible differences in the basin's heat loss between glacial and interglacial times.

INTRODUCTION

In the present-day eastern Mediterranean, the upper part of the permanent pycnocline resides at an average depth of about 150 m [Wüst, 1961; Miller et al., 1970]. This permanent pycnocline essentially is a halocline between the surface water and the Mediterranean Intermediate Water (MIW). Rohling and Gieskes [1989] discussed high abundances of the planktonic foraminiferal genus *Neogloboquadrina* in pleniglacial sediments of the eastern Mediterranean. They argued that these high abundances indicate that the permanent pycnocline had shoaled to a depth within the euphotic layer, which at present may extend as deep as 120 m. Rohling and Gieskes [1989], however, were not able to formulate a satisfactory explanation for the shoaling of the permanent pycnocline at glacial times.

In the present paper, a simple two-layered model is described for the eastern Mediterranean. This model is applied to estimate the pycnocline depth under glacial conditions. First, a scenario is evaluated in which the eastern Mediterranean freshwater budget is assumed to have remained equal to the present. Subsequently, an extremely arid glacial scenario is discussed in order to evaluate the effect of reduced glacial precipitation and runoff on pycnocline depth estimates. Finally, possible changes in the presented solutions, which may result from differences in the basin's thermal balance between glacial and interglacial times, are briefly evaluated.

BASIS OF THE MODEL

The eastern Mediterranean is considered very simplified as a two-layered system. The upper layer

Paper number 91PA01328.
0883-8305/91/91PA01328$10.00

has temperature T_u, salinity S_u, and density ρ_u. The deeper layer has temperature T_d, salinity S_d, and density ρ_d. H represents the thickness of the upper layer, which is the approximate thickness of the surface layer above the top of the permanent pycnocline.

The buoyancy loss per unit area (B) necessary to transform a column of upper layer water of thickness H into deeper layer water can then be described [cf. Bryden and Stommel, 1984] as

$$B = (\rho_d - \rho_u) H g \qquad (1)$$

in which $g = 9.81 \text{ m s}^{-2}$ is the acceleration due to gravity.

In the simple two-layered model, the upper layer in the basin results from inflow across the Sicilian sill, and the deeper layer constitutes the outflow. The buoyancy loss (B), due to a net water deficit and heat loss, drives localized transformation of water with surface layer characteristics toward water with deep layer characteristics. As a result, a uniform density difference between the surface and deep layers prevails throughout the rest of the basin. Therefore, in the presented model, the density difference between the surface layer and the deep layer is the same as that between the inflowing and outflowing waters in the Strait of Sicily. As a consequence,

$$\rho_u V_u S_u = \rho_d V_d S_d$$

in which the ratio between the two densities is very close to 1, and the densities may therefore be omitted. V_u and V_d, respectively, indicate the volumes of inflow and outflow through the Strait of Sicily. These volumes are related to the basin's freshwater budget according to

$$V_d = V_u - F$$

in which F stands for the freshwater budget (E - P), i.e., evaporation minus total freshwater input (precipitation and runoff). Now, the difference between the deep layer salinity and the upper layer salinity is defined as dS (= S_d -S_u), so that

$$dS = \frac{S_u}{\frac{V_u}{F} - 1} \qquad (2)$$

EFFECTS OF SEA LEVEL LOWERING, USING THE PRESENT-DAY FRESHWATER BUDGET

At present, V_u is about 40 x 10^{12} $\text{m}^3 \text{ yr}^{-1}$, and F about 1.8 x 10^{12} $\text{m}^3 \text{ yr}^{-1}$ [Béthoux, 1979]. Hence, the present-day value of V_u/F is about 22. In this section, F is considered constant through time, but V_u is considered variable. Béthoux [1984] argued that a 100 m sea level lowering probably reduced the inflow across the Gibraltar sill to 60% of its present magnitude, and similar effects are to be expected at the Sicilian sill. If we apply an inflow reduction factor (ϕ), which is the ratio between inflow at times of a sea level low-stand and inflow at present, equation (2) changes to

$$dS = \frac{S_u}{22\phi - 1} \qquad (3)$$

Equation (3) demonstrates that a reduction of inflow due to sea level lowering ($\phi < 1$) would invoke an increase in the salinity contrast between the upper and deeper layers.

The buoyancy loss (B) depends on the freshwater budget (F) of the basin, which is the difference between evaporation (E) and the total freshwater input (P). B also depends on the thermal balance of the basin. Béthoux [1979] emphasized that only about 10% of the heat loss is due to conduction, whereas about 90% results from a release of latent heat by evaporation. Therefore variations of evaporation and the thermal balance are closely related. Since evaporation (E) was assumed constant through time, I will also assume that the thermal balance of the basin remained constant. In a later section, the possible modifications of the solution, related to variations in the thermal balance, will be evaluated.

Due to the assumption, in this section, that both the freshwater budget and the heat loss at glacial times were equal to those at present, the buoyancy loss (B) may be treated as a constant. Then, if the glacial depth of the interface equals α times its present value (H^P), the glacial value of (ρ_d - ρ_u) should equal $1/\alpha$ times the present-day value (see equation (1)).

As a result of the assumption that heat loss remained equal to the present, variations in $d\rho$ (= ρ_d - ρ_u) are linearly related to variations in dS (= S_d - S_u) [Béthoux, 1979; Bryden and Kinder, 1991]. Furthermore, equation (1) indicates that the glacial $d\rho$ was $1/\alpha$ times the present-day $d\rho$, when the thickness of the surface layer at glacial times was α times that at present (H^p). As a consequence,

$$dS = \left(\frac{1}{\alpha}\right) dS^p \tag{4}$$

in which the superscript p indicates the present-day value. Combining equations (3) and (4) gives

$$\alpha = \frac{22\phi - 1}{21} \frac{S_u^p}{S_u^g} \tag{5}$$

in which the superscripts g and p indicate the glacial and present-day values, respectively.

Figure 1 shows the relations between α and S_u^p/S_u^g for several values of ϕ, as described by equation (5). Since αH^p yields the corresponding depth of the interface between the two layers, it is now possible to calculate the interface depth for any estimate of ϕ and S_u^p/S_u^g, using $H^p = 150$ m. The reconstructed interface depth may then be compared to the depth of the base of the euphotic layer (about 120 m), which corresponds to $\alpha = 0.8$.

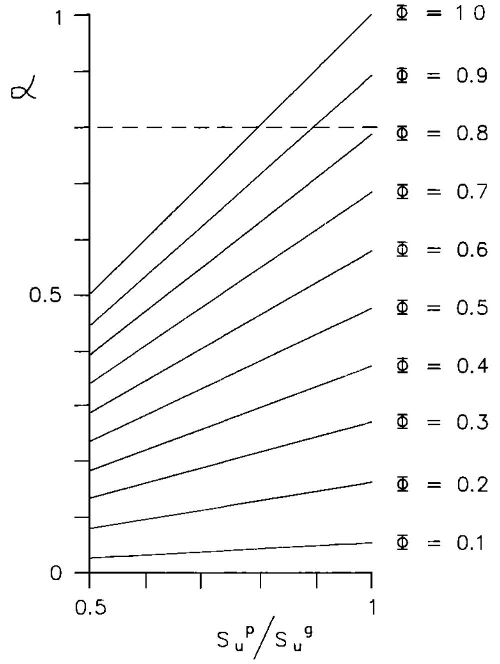

Fig. 1. The relations between α and S_u^p/S_u^g for several values of the inflow reduction factor ϕ. The dashed line indicates the depth of the base of the euphotic layer (about 120 m), which corresponds to $\alpha = 0.8$, using H = 150 m.

APPLICATION OF LITERATURE-BASED GLACIAL CONDITIONS

Possible glacial values for ϕ, S_u^p, and S_u^g, as suggested in the literature, can be inserted in equation (5). If Béthoux's [1984] proposed reduction of inflow through the Strait of Gibraltar to 60% of its present-day value at times of 100 m sea level lowering may be transposed to the Strait of Sicily, then $\phi = 0.6$, and

$$\alpha = 0.57 \frac{S_u^p}{S_u^g}$$

Using the salinity values which Thunell et al. [1987] calculated using the Bryden and Stommel [1984] overmixing model ($S_u^p = 38.2$ and $S_u^g = 40.5$ ppt), a glacial estimate of $\alpha = 0.54$ is found.

At present, the top of the eastern Mediterranean permanent pycnocline resides at an average depth of about 150 m. In terms of the two-layered model, the present-day thickness of the surface layer $H^p = 150$ m. The above calculated $\alpha = 0.54$ at glacial times would then imply that the pycnocline resided at 0.54 x 150 = 81 m, which is well within the euphotic layer.

This result suggests that the shallow position of the permanent pycnocline at glacial times, which Rohling and Gieskes [1989] inferred from the planktonic foraminiferal record, was primarily due to the effects of sea level lowering.

TOTAL GLACIAL ARIDITY (P = 0) SCENARIO

In the two previous sections, the freshwater budget at glacial times was assumed to have been equal to that at present. However, glacial periods are characterized by increased aridity in most circum-Mediterranean countries. In this section, I will discuss to what extent the solution in equation (5) might change due to the incorporation of increased glacial aridity. Therefore I will assume that total aridity prevailed, which implies that P = 0 and, consequently, that F = E. The magnitude of E has been derived from Béthoux [1979] as 2.7×10^{12} m^3 yr^{-1}.

In the total aridity scenario, the relation between the variations of $d\rho$ and the depth of the interface (equation (1)) is somewhat different from that in the constant F scenario described above. This is due to the fact that the buoyancy loss (B) depends on the freshwater budget (F). I will proceed with B increasing proportionally to F. In the total aridity scenario, F is 2.7/1.8 = 1.5 times larger than at present. Therefore a similar change in B, to 1.5 times its present value, is used. Then, with the glacial depth of the interface being α times its present value (H^p), the value of $d\rho = (\rho_d - \rho_u)$ should be $1.5/\alpha$ times the present-day value (see equation (1)).

Using $F = E = 2.7 \times 10^{12}$ m^3 yr^{-1} and the initial $V_u = 40 \times 10^{12}$ m^3 yr^{-1}, equation (2) gives

$$dS = \frac{S_u}{15\phi - 1} \tag{6}$$

From equation (1), using $H = \alpha H^p$, $B = 1.5B^p$, and a linear relationship between $d\rho$ and dS, it follows that

$$dS = \left(\frac{1.5}{\alpha}\right) dS^p \tag{7}$$

The present-day difference between the salinity of the deeper layer and the salinity of the upper layer $dS^p = S_u^p/21$ (equation (3) with $\phi = 1$). In combination with equations (6) and (7), this gives

$$\alpha = \frac{15\phi - 1}{21} \, \frac{S_u^p}{S_u^g} \, 1.5 \tag{8}$$

This relation is very similar to the one decribed by equation (5), which indicates that the incorporation of increases in F does not substantially alter the solution obtained from the constant F scenario.

INFLUENCE OF CHANGES IN THE THERMAL BALANCE

In the previous calculations, possible differences in the basin's thermal balance between glacial and present-day times have been neglected. Changes in the thermal balance would induce changes in the buoyancy loss (B). If the net heat loss were greater, the buoyancy loss would be increased.

The minimal value of buoyancy loss increase necessary to "deepen" the interface down to the base of the euphotic layer, can be calculated using the total glacial aridity scenario. Using the aforementioned values of $S_u^p/S_u^g = 0.94$ and $\phi = 0.6$ in that scenario, a 2.25-fold increase of the buoyancy loss (B) would be necessary to "deepen" the interface position down to the base of the euphotic layer. This implies that the net heat loss from the basin should be increased, imposing a 1.5-fold increase on B superimposed on the 1.5-fold increase in B which resulted already from the change in the freshwater budget (F).

Note, however, that the extreme situation of total glacial aridity is purely hypothetical. If a more realistic increase in F would be applied, the possible change in the basin's thermal balance should impose an increase well over 1.5 times to "push" the interface down to the base of the euphotic layer.

It is obvious that detailed reconstructions of glacial freshwater and thermal balances are required to determine the interface position more exactly. Nevertheless, our model strongly suggests that reduction of inflow through the Strait of Sicily invoked by glacio-eustatic sea level lowering would account for a shallow position of the interface, at a depth well within the euphotic layer.

CONCLUDING REMARKS

On the basis of their faunal analyses, Rohling and Gieskes [1989] argued that, in the eastern Mediterranean, the upper part of the permanent pycnocline resided within the euphotic layer at glacial times. In order to determine which process(es) caused the glacial pycnocline to reside within the euphotic layer, a simple two-layered model was applied to estimate the surface layer thickness under glacial conditions.

The glacial pycnocline depth estimate from this simple model, discarding probable changes in the basin's thermal balance, ranges well within the euphotic layer. Using literature-based glacial salinity and inflow reduction values, a depth of approximately 80 m was determined for the permanent pycnocline in the pleniglacial eastern Mediterranean. This glacial estimate should be compared with the present-day average permanent pycnocline depth of about 150 m and a euphotic layer thickness of about 120 m. Presumably, incorporation of a realistic increase in heat loss at glacial times, relative to the present, will not result in a deepening of the pycnocline to a depth below the base of the euphotic layer. Such an incorporation would, however, lead to a calculated pycnocline position at a somewhat greater depth than the 80 m mentioned above. Therefore the latter figure should be considered as an "upper depth limit".

The presented model suggests that the shallow permanent pycnocline position in the glacial eastern

Mediterranean, as envisaged by Rohling and Gieskes [1989], resulted from a reduction of surface water inflow through the Strait of Sicily. Béthoux [1984] demonstrated that the low pleniglacial sea level could have invoked an important reduction of water exchange through the Strait of Gibraltar and the Strait of Sicily. The shallow permanent pycnocline position at pleniglacial times in the eastern Mediterranean seems therefore to have resulted essentially from glacio-eustatic sea level lowering.

Acknowledgements. Thanks are due to T. H. Kinder (U.S. Naval Academy, Annapolis, Maryland) and H. L. Bryden (Woods Hole Oceanographic Institution) for valuable suggestions which helped to improve this work, and to E. C. Kosters and W. J. Zachariasse (Earth Sciences, University of Utrecht) for critical reviewing.

REFERENCES

Béthoux, J. P., Budgets of the Mediterranean Sea. Their dependance on the local climate and on characteristics of the Atlantic waters, *Oceanol. Acta, 2*, 157-163, 1979.

Béthoux, J. P., Paléo-hydrologie de la Méditerranée au cours des derniers 20 000 ans, *Oceanol. Acta, 7*, 43-48, 1984.

Bryden, H. L., and T. H. Kinder, Steady two-layer exchange through the Strait of Gibraltar, *Deep Sea Res.*, in press, 1991.

Bryden, H. L., and H. M. Stommel, Limiting processes that determine basic features of the circulation in the Mediterranean Sea, *Oceanol. Acta, 7*, 289-296, 1984.

Miller, A. R., P. Tchernia, H. Charnock, and D. A. McGill, *Mediterranean Sea Atlas of Temperature, Salinity, Oxygen: Profiles and Data from cruises of R.V. Atlantis and R.V. Chain. With distribution of Nutrient Chemical Properties*, edited by A. E. Maxwell et al., 190 pp., Alpine, Braintree, Mass., 1970.

Rohling, E. J., and W. W. C. Gieskes, Late Quaternary changes in Mediterranean Intermediate Water density and formation rate, *Paleoceanography, 5*, 531-545, 1989.

Thunell, R. C., D. F. Williams, and M. Howell, Atlantic-Mediterranean water exchange during the Late Neogene, *Paleoceanography, 2*, 661-678, 1987.

Wüst, G., On the vertical circulation of the Mediterranean Sea, *J. Geophys. Res., 66*, 3261-3271, 1961.

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(Received January 3, 1991;
revised May 7, 1991;
accepted May 8, 1991.)