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SHOALING OF THE EASTERN MEDITERRANEAN PYCNOCLINE DUE TO REDUCTION OF EXCESS EVAPORATION: IMPLICATIONS FOR SAPROPEL FORMATION

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Abstract. A simple two-layered model is applied to assess the relation between variations in the depth of the permanent pycnocline and changes in the excess of evaporation over freshwater input, in the eastern Mediterranean. This study is performed to estimate the magnitude of the excess evaporation at times of sapropel formation in the eastern Mediterranean. Pycnocline shoaling, from a depth below the euphotic layer to a depth within that layer at times of sapropel formation, has been inferred from the planktonic foraminiferal record by Rohling and Gieskes (1989). The model suggests that a decrease in the eastern Mediterranean excess evaporation, defined as evaporation minus total freshwater input, by about 8.5 x 10^{11} m^3 yr^{-1} would suffice to invoke shoaling of the pycnocline to a depth within the euphotic layer. A consideration of the effects exerted by concomitant changes in the thermal balance suggests that the necessary decrease of excess evaporation may even be smaller than the above estimate.

INTRODUCTION

Since the discovery of eastern Mediterranean sapropels in cores collected during the 1947–1948 Swedish Deep-Sea Expedition [Kullenberg, 1952], much effort has been devoted to unravel the oceanographic processes that led to the formation of these anoxic sediments. Olausson [1961] was the first to link sapropel formation to deepwater stagnation induced by lowering of the surface water salinities. This hypothesis is supported by the excess lowering of the oxygen isotopic signal at times of sapropel formation [for example Cita et al., 1977; Vergnaud-Grazzini et al., 1977; Williams et al., 1978; Jenkins and Williams, 1984; Thunell and Williams, 1989]. Increased freshwater fluxes from various sources, coeval with sapropel formation, have been positively identified [Rossignol-Strick et al., 1982; Shaw and Evans, 1984; Rossignol-Strick, 1985; Cramp et al., 1988]. De Lange and Ten Haven [1983] suggested that enhanced primary production exerted a major influence on the formation of eastern Mediterranean sapropels.

A new model for sapropel formation, combining increased productivity with decreased deep water formation and a more detailed assessment of the eastern Mediterranean's vertical density structure, has been proposed by Rohling and Gieskes [1989]. Their model was primarily based on the high abundances of the planktonic foraminiferal genus Neogloboquadrina in sapropelic sediments. In the model of Rohling and Gieskes [1989], increased freshwater input into the basin resulted in shoaling of the density gradient (pycnocline) between the Mediterranean Intermediate Water (MIW) and the surface water, to a depth within the euphotic layer, which may extend as deep as 120 m.

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At present, the upper part of the permanent pycnocline (essentially a halocline) resides at an average depth of about 150 m. Shoaling of the pycnocline to a depth within the euphotic layer would have invoked increased nutrient availability to the euphotic layer, enabling the development of a deep chlorophyll maximum (DCM) and a concomitant increase in the downward flux of organic matter from the euphotic layer (export production). In addition to an increase in export production, Rohling and Gieskes [1989] argued that the formation rate of Eastern Mediterranean Deep Water (EMDW) would have decreased. This decrease would have resulted from reduction of the MIW to surface water salinity contrast which, in turn, resulted from increased freshwater input into the basin. Rohling and Gieskes [1989] envisaged that the combination of increased export production and decreased oxygen advection to deep waters resulted in the development of severely dysoxic to anoxic conditons in the bottom waters, enabling the formation of sapropels.

High abundances of Neogloboquadrina in pleniglacial intervals were also attributed to shoaling of the pycnocline to a depth within the euphotic layer [Rohling and Gieskes, 1989]. Rohling [1991a] designed a simple two-layered model for the eastern Mediterranean. This model demonstrated that pycnocline shoaling at glacial times resulted from glacio-eustatic sea level lowering. Also, the model demonstrated that the MIW to surface water salinity contrast was increased at glacial times, compared to the present.

In the present paper, the two-layered model of Rohling [1991a] is modified and applied to calculate the magnitude of decreases in the excess of evaporation over freshwater input, which may have invoked pycnocline shoaling at times of sapropel formation in the eastern Mediterranean. Initially, the thermal balance of the basin is assumed to have remained equal to the present. Subsequently, I will discuss how incorporation of changes in the thermal balance would affect the presented estimates. In the discussion, the importance of the results for the development of a comprehensive model for sapropel formation is briefly evaluated.

BASIS OF THE MODEL

The basis of the model has been outlined by Rohling [1991a]. In the present paper, the term "freshwater budget" (F), which Rohling [1991a] used to describe the difference between evaporation and total freshwater input, has been replaced by a more correct term, namely, "excess evaporation" (X). Furthermore, the variable P, which Rohling [1991a] used to describe the total freshwater input into the basin, in the form of both precipitation and runoff, has been replaced by the variable I, since the use of P for total freshwater input might be confusing in that it is usually applied to indicate precipitation only.

In Rohling's [1991a] model, the eastern Mediterranean is considered very simplified as a two-layered system. The upper layer has temperature T_u, salinity S_u, and density ρ_d. 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 pycnocline. V_u and V_d respectively indicate the volumes of inflow and outflow across the Sicilian sill. X stands for excess evaporation, defined as evaporation (E) minus total freshwater input (I); $X = E - I$. Thus, the basis of the model consists of the following equations:

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

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

$$V_d = V_u - X$$

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

Equation (1) describes the buoyancy loss per unit area (B) necessary to transform a column of upper layer water of thickness H to deeper layer water [cf., Bryden and Stommel, 1984], where $g = 9.81$ m s^{-2} is the acceleration due to gravity. In equation (2), dS indicates the difference between the deep layer salinity and the upper layer salinity; $dS = S_d - S_u$.

EFFECTS OF DECREASES IN EXCESS EVAPORATION

The two-layered model will now be applied to study changes in pycnocline depth due to decreases in the eastern Mediterranean excess evaporation, a situation that prevailed at times of sapropel formation. In this section, I will assume that the thermal balance remained constant. Therefore buoyancy loss (B) decreases proportionally to X.

The depth of the interface at times of sapropel formation is defined as α times its present value (H^p). The excess evaporation at times of sapropel formation is characterized as γ times its present value (X^p). Since we consider the variation in buoyancy loss (B) to be proportional to that in X, the buoyancy loss at times of sapropel formation is also defined as γ times its present value (B^p). Equation (1) then indicates that the density difference between the upper layer and the deeper layer, at times of sapropel formation, should equal γ/α times its present-day value $d\rho^p = (\rho_d - \rho_u)^p$. Summarized,

$$H = \alpha H^p$$

$$X = \gamma X^p$$

$$B = \gamma B^p$$

$$d\rho = \left(\frac{\gamma}{\alpha}\right) d\rho^p$$

in which the superscript p indicates present-day values. As argued before, sapropel formation coincided with decreased values of X, and therefore $0 \leq \gamma \leq 1$. Furthermore, since the basin's excess evaporation influences the surface water inflow (V_u) through the Strait of Sicily, a decrease in X, relative to the present, will invoke a reduction of inflow. This reduction of inflow, imposed by variation of γ, is expressed by a coefficient Ω. As with γ, also $0 \leq \Omega \leq 1$. Hence

$$X = \gamma X^p$$

$$V_u = \Omega V_u^p$$

At present, V_u is about 40 x 10^{12} m^3 yr^{-1} and X about 1.8 x 10^{12} m^3 yr^{-1} [Béthoux, 1979]. Therefore the value of V_u^p/X^p is about 22, and

$$\frac{V_u}{X} = 22 \left(\frac{\Omega}{\gamma}\right)$$

This relation may be used in combination with equation (2), so that the difference between salinities S_d and S_u can be expressed as

$$dS = \frac{S_u}{22\left(\frac{\Omega}{\gamma}\right) - 1} \tag{3}$$

Since heat loss was assumed constant, variations in $d\rho$ are linearly related to variations in dS [Béthoux, 1979; Bryden and Kinder, 1991]. Therefore

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

Combining equations (3) and (4) gives

$$\alpha = \frac{22\,\Omega - \gamma}{21} \frac{S_u^p}{S_u} \tag{5}$$

To solve (5), the relation between γ and Ω should be defined, expressing how changes in the eastern Mediterranean excess evaporation affect the volume of surface water flowing into the basin across the Sicilian sill. I will apply the result obtained by Bryden and Kinder [1991], which portrays the relation between the excess evaporation of the entire Mediterranean and inflow through the Straits of Gibraltar. This study suggested that, approximately, $\gamma = \Omega^2$.

Figure 1 shows the relations between α and S_u^p/S_u for several values of Ω. Since αH yields the corresponding depth of the interface between the two layers, it is now possible to calculate the interface depth for any estimate of Ω and S_u^p/S_u, using $H = 150$ 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 $\alpha = 0.8$.

APPLICATION OF LITERATURE-BASED CONDITIONS AT TIMES OF SAPROPEL FORMATION

Rohling and Gieskes [1989] argued that the top of the eastern Mediterranean permanent pycnocline resided within the euphotic layer at times of sapropel formation and therefore that $\alpha < 0.8$. Also, the salinity of the eastern Mediterranean surface layer seems to have been considerably reduced at times of sapropel formation, compared to that at present. According to Thunell and Williams [1989], $S_u \approx 36$ ppt. These authors obtained this result from oxygen isotope values, calibrated to a present-day average surface layer salinity (S_u^p) of 38.8 ppt. Using these values and $\alpha < 0.8$, we find $\Omega < 0.73$ and therefore $\gamma < 0.53$.

In the eastern Mediterranean, the present-day value of X ($= E - I$) is about 1.8 x 10^{12} m^3 yr^{-1} [Béthoux, 1979]. At times of sapropel formation,

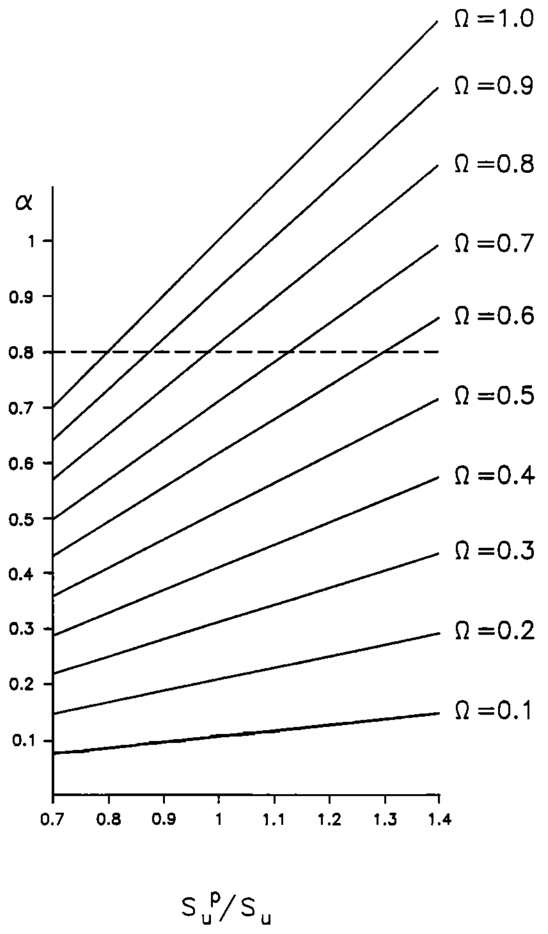

Fig. 1. The relations between α and S_u^p/S_u for several values of the inflow reduction factor Ω. The dashed line indicates the depth of the base of the euphotic layer (about 120 m), which corresponds to $\alpha = 0.8$, using $H = 150$ m. The reduction of the excess evaporation, expressed by the coefficient γ, can be derived directly from Ω, using $\gamma = \Omega^2$.

the excess evaporation should have been decreased at least to $\gamma = 0.53$ times its present value, which implies a reduction to 9.5 x 10^{11} m^3 yr^{-1}. That is, 8.5 x 10^{11} m^3 yr^{-1} less than the present-day value.

Béthoux [1984] calculated that an increase of the Nile discharge to 2.5 times its present (pre-Aswan) volume, which he derived from the work of Rossignol-Strick et al. [1982], would invoke stagnant conditions below 1000 m water depth in the eastern Mediterranean. Since the present-day (pre-Aswan) Nile discharge amounts to approximately 9 x 10^{10} m^3 yr^{-1} [Béthoux, 1984], however, a 2.5-fold increase would not suffice to account for the necessary decrease of excess evaporation by at least 8.5 x 10^{11} m^3 yr^{-1} as calculated above. In the hypothetical case that the Nile was the exclusive source for the total excess of freshwater and that the "local" eastern Mediterranean climate remained constant, the Nile's discharge should have been at least 10.4 times that at present (pre-Aswan).

If the estimate used by Béthoux [1984] is correct, which implies that the Nile's discharge was only 2.5 times greater than at present (pre-Aswan), then the Nile provided an excess freshwater input of 1.35 x 10^{11} m^3 yr^{-1}. Consequently, variations in the "local" eastern Mediterranean climate should have induced at least an additional 7.15 x 10^{11} m^3 yr^{-1} decrease in the eastern Mediterranean excess evaporation.

Note, however, that variations in the excess evaporation (X) depend on the amount of both evaporation (E) and total freshwater input (I). Evaporation is entirely related to the "local" eastern Mediterranean climate. On the contrary, freshwater input is influenced both by the "local" eastern Mediterranean climate and, via the Nile river, by the "distant" monsoonal system of the Indian Ocean. It would be easiest to proceed calculating increases of freshwater input assuming a constant evaporation (E). However, such an assumption would be erroneous if part of the freshwater input resulted from "local" Mediterranean precipitation systems. Increased activity of such systems would increase not only the freshwater input but also the amount of cloud-coverage and the moisture content of the air, which would invoke a significant reduction of evaporation (E).

Following the above arguments, variations in the Nile river's discharge are not coupled to the evaporation rate in the eastern Mediterranean. Therefore, if the decreases in excess evaporation at times of sapropel formation were entirely due to increases in the Nile's discharge, the evaporation could be considered constant. On the contrary, as soon as variations in the "local" eastern Mediterranean climate are inferred, changes in the evaporation rate must be considered.

In the following, I will consider variations in evaporation (E) and variations in the "local" part of the freshwater input ($I_{loc} = I -$ Nile discharge) as equally distributed according to their relative present-day proportions. At present, evaporation (E) amounts to 27 x 10^{11} m^3 yr^{-1} and total freshwater input (I) to 9 x 10^{11} m^3 yr^{-1} [Béthoux, 1979], while the (pre-Aswan) contribution of Nile discharge to the latter figure is 0.9 x 10^{11} m^3 yr^{-1} [Béthoux, 1984]. Hence $I_{loc} = 8.1$ x 10^{11} m^3 yr^{-1}.

The relative present-day proportions of E and I_{loc}, therefore, are 3.3 : 1.

Previously, I concluded that, if the Nile's discharge at times of sapropel formation was indeed 2.5 times that at present, variations in the "local" eastern Mediterranean climate should have accounted for a decrease of at least 7.15 x 10^{11} m^3 yr^{-1} in the excess evaporation ($X = E - I$). Using the ratio 3.3 : 1 between E and I_{loc} determined above, this decrease in the excess evaporation can be subdivided into a decrease of E amounting 5.49 x 10^{11} m^3 yr^{-1} and an increase of I_{loc} amounting 1.66 x 10^{11} m^3 yr^{-1}. These are variations of about 20%.

INFLUENCE OF CHANGES IN THE THERMAL BALANCE

In the previous sections, I have neglected changes in the thermal balance of the eastern Mediterranean, which would accompany changes in evaporation (E) since 90% of the heat loss results from release of latent heat by evaporation [Béthoux, 1979]. Hence decreases in the buoyancy loss (B) were assumed to have been proportional to decreases in the excess evaporation ($X = E - I$). However, if E was not constant but reduced, B would have decreased not proportionally to X but faster. If β is applied as a coefficient describing the additional decrease in B resulting from variation in the thermal balance, with $0 \leq \beta \leq 1$, then

$$H = \alpha H^p$$

$$B = \beta \gamma B^p$$

$$d\rho = \left(\beta \frac{\gamma}{\alpha}\right) d\rho^p$$

As a result, equation (5) changes to

$$\alpha = \beta \frac{22\Omega - \gamma}{21} \frac{S_u^p}{S_u} \qquad (6)$$

Equation (6) indicates that incorporation of the effects of decreased net heat loss allows a larger value for γ than the scenario in the previous sections, which assumed an invariable thermal balance. Therefore, using the invariable thermal balance scenario to calculate γ with $\alpha < 0.8$ results in a maximum estimate for the change of X necessary to raise the interface into the euphotic layer. Incorporation of possible changes in the thermal balance would result in a smaller estimate for the decrease of X.

These considerations obviate the need for detailed assessment of the eastern Mediterranean thermal balance, in both the present-day climatic configuration and that at times of sapropel formation.

DISCUSSION AND CONCLUSIONS

General Discussion

On the basis of their faunal analyses, Rohling and Gieskes [1989] argued that the permanent pycnocline in the eastern Mediterranean resided within the euphotic layer at times of sapropel formation. Rohling [1991a] designed a simple two-layered model to assess pycnocline depth variations in the eastern Mediterranean resulting from sea level lowering. In the present paper, this model was adapted to study the relation between pycnocline depth variations and decreases in the eastern Mediterranean excess evaporation, assuming that sea level remained equal to the present. Due to this assumption, the obtained estimates (of decreases in the excess evaporation necessary to induce pycnocline shoaling to the base of the euphotic layer) are maximum estimates, since a lower-than-present sea level at times of sapropel formation would have invoked an initial situation with a shallower pycnocline than at present [see Rohling, 1991a]. In such a case, smaller decreases in the excess evaporation would suffice to induce shoaling of the pycnocline to the base of the euphotic layer. Before attempts can be made to model the combined effects of sea level lowering and decreases in the excess evaporation, however, the relation between variations of the inflow reduction factor and variations of sea level needs to better constrained.

Initially, the thermal balance of the basin was assumed constant. Afterwards, I briefly discussed the effects of possible changes in the thermal balance, which would accompany variations of evaporation. It appeared that the invariable thermal balance scenario yields a maximum estimate for the decrease in excess evaporation necessary to induce shoaling of the pycnocline to the base of the euphotic layer. The estimates could be improved by an accurate study of variations in the thermal balance through geologic time. Unfortunately, this is not yet possible.

Using the invariable thermal balance scenario, it was calculated that the eastern Mediterranean excess evaporation ($X = E - I$) should have decreased by at least 8.5 x 10^{11} m^3 yr^{-1} to induce shoaling of the pycnocline into the euphotic layer. If this were exclusively due to an increase in the

Nile river's discharge, the calculated change in the excess evaporation would indicate that the Nile discharged at least 10.4 times its present (pre-Aswan) volume, at times of sapropel formation.

Rohling and Hilgen [1991] reviewed paleoclimatological reconstructions concerning times of sapropel formation. They concluded that, although the Nile river was important, it certainly was not the only enhanced freshwater source. The "local" eastern Mediterranean precipitation was substantially increased as well. Presumably, this increase of "local" precipitation resulted from increased activity of Mediterranean depressions, which invoke a net transport of moisture from the west towards the eastern Mediterranean [Rohling and Hilgen, 1991]. In the present paper, I emphasized that such an increased activity would, additionally, induce a decrease in the eastern Mediterranean evaporation (E), due to increases in cloud coverage and moisture content of the air. Both the increase of net moisture transport from the west and the decrease of evaporation, as consequences of increased activity of Mediterranean depressions, tend to lower the eastern Mediterranean excess evaporation ($X = E - I$).

Considering a similar increase in the Nile river discharge at times of sapropel formation as did Béthoux [1984], which is 2.5 times the present (pre-Aswan) flux, the Nile accounted for only 1.35×10^{11} m^3 yr^{-1} of excess freshwater. Since the excess evaporation (X) should have been decreased by at least 8.5×10^{11} m^3 yr^{-1} to invoke pycnocline shoaling into the euphotic layer, the "local" climate should account for a decrease in X amounting to 7.15×10^{11} m^3 yr^{-1}. I argued that this may be accomplished by coeval variations of about 20% in evaporation (E; decreased) and "local" freshwater input (I_{loc}; increased). These variations suggest a (roughly) 20% increased intensity of the westerly system of Mediterranean depressions, at times of sapropel formation.

Importance of the Results for the Development of a Comprehensive Model of Sapropel Formation

Since $\gamma \approx \Omega^2$, while $0 \leq \gamma \leq 1$, equation (3) shows that a reduction of excess evaporation to γ times its present-day value would induce a decrease in dS, which is the salinity contrast across the pycnocline. Such a decrease in the MIW to surface water salinity contrast would affect the rate of formation of Eastern Mediterranean Deep Water (EMDW) in the Adriatic Sea [cf. Mangini and Schlosser, 1986; Rohling and Gieskes, 1989]. The EMDW formation rate would be decreased, invoking a reduction of oxygen advection to deeper waters.

The calculations in the present paper indicate that the shallow pycnocline position at times of sapropel formation [Rohling and Gieskes, 1989] could be realized in an anti-estuarine circulation, with the intensity of exchange-transport across the Sicilian sill reduced to about 70% of the present. Despite the fact that the assumptions in the two-layered model make this 70% a fairly rough estimate, it does place much less severe constraints to the circulation than the solutions presented by Sarmiento et al. [1988]. These authors concluded that only an extremely weak anti-estuarine, or reversed (estuarine), circulation in the eastern Mediterranean might explain the limited flux of phosphate from the eastern into the western Mediterranean at times of sapropel formation, which they inferred from the literature.

This condition of limited phosphate flux, however, would be satisfied equally well if the reduction of subsurface outflow across the Sicilian sill (to about 70% of its present-day intensity as calculated in the present paper) were caused in large part by a decrease in the EMDW contribution to that outflow. Such a decrease would have resulted from a pronounced drop in the EMDW formation rate, invoked by reduction of the MIW to surface water salinity contrast (see above). Meanwhile, shoaling of the pycnocline into the euphotic layer would have induced an increase in export production [Rohling and Gieskes, 1989]. The combination of increased export production and poor ventilation would cause oxygen depletion and phosphate enrichment in the EMDW. However, poor ventilation of the EMDW would also prevent the phosphate-enriched EMDW from contributing significantly to the subsurface outflow towards the western Mediterranean. In such a scenario, most of the subsurface outflow across the Sicilian sill would consist of relatively well-ventilated Mediterranean Intermediate Water (MIW), thus agreeing with the suggestion that oxygen-depleted conditions were limited to below the "base" of the MIW during deposition of most sapropels [Rohling and Gieskes, 1989].

Rohling [1991b] discussed this scenario for the phosphate budget in more detail and concluded that the EMDW formation rate at times of sapropel formation may have been as much as 36 times lower than at present, invoking a proportional decrease in the EMDW contribution to subsurface outflow across the Sicilian sill. As a result, the increase in the average phosphate concentration of the subsurface outflow towards the western Mediterranean would have amounted up to only 25%.

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