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A box model for the paleoceanography of the Black Sea

M. Karaca

Eurasia Institute of Earth Sciences and Maden Fakultesi Genel Jeoloji ABD, Istanbul Technical University, Maslak, 80626 Istanbul, Turkey

A. Wirth and M. Ghil

Department of Atmospheric Sciences and Institute of Geophysics and Planetary Physics, University of California, Los Angeles, CA 90095-1565, USA

Abstract. The evolution of the Black Sea's salinity after the opening of the Bosphorus about 7500 years ago is investigated using a simple two-box model. The model consists of watermass and salt conservation equations, and allows for changes in halocline depth. The paleoceanographic box model is forced by present-day Mediterranean inflow and outflow, and atmospheric forcings. Analytic solutions for the evolution of the box volumes are given. Model salinities reach 90% of their the present-day values in both boxes about 2,500 years after the opening of the Bosphorus. The evolution of the salinities is shown to be almost independent of the evolution of the box volumes, and the results are compared with the existing paleoceanographic proxy records.

1. Introduction

The Black Sea is a semi-closed sea subject to restricted water exchange with the Mediterranean and substantial river discharge into its northwestern part. Today, it is the largest anoxic sea in the world, as there is almost no oxygen below a depth of 150–200 meters [Özsoy and Ünlüata, 1997].

The evolution of the physical processes in the Black Sea on geological time scales is controlled strongly by changes in the Mediterranean water inflow and outflow through the Bosphorus Strait. During the last glacial maximum (approximately 30,000–25,000 years B. P.), when the sea level was lower, the Mediterranean inflow ceased and the Black Sea became fully enclosed and thus almost a freshwater lake [Degens and Ross, 1974].

Recent studies by Jones and Gagnon [1994] and Ryan *et al.* [1997], using carbon dating, have indicated that the opening of the Black Sea through the Bosphorus occurred $7,540 \pm 130$ years B. P., initiating a cascade of saltwater pouring into a partly emptied Black Sea lake. The salty and thus heavier water coming from the Mediterranean sank to the bottom and created an interface that separated fresh water above from salty water below. This stable stratification led to water rich in oxygen (O_2) at the top and anoxic water rich in hydrogen sulfide (H_2S) at the bottom [Degens and Ross, 1974]. The H_2S -rich watermass has thickened up to the present, resulting in a 2000-m layer, out of the Black Sea's total depth of 2200 m.

The purpose of this study is to expand our understanding of the evolution of the Black Sea's salination from lake phase to sea phase during the Holocene, using a two-box model. Several modeling approaches have been taken to understand this process [Fonselius, 1974; Boudreau and Leblond, 1989; Mamayev, 1994].

These modeling studies have explained certain aspects of the effect that the opening of the Black Sea had on its subsequent evolution. But all of them have tuning parameters or prescribed fluxes, and lack a satisfactory representation of the entrainment of deep waters by the upper layers and of surface waters by the Bosphorus inflow.

We present here a time-dependent, self-consistent two-box model for the problem at hand. The variable size of the boxes permits one specifically to track the position of the halocline, and hence of the O_2 - H_2S interface, after the opening of the Bosphorus Strait around 7540 years B. P. At that point, we assume that the first box extends through the entire depth of the Black Sea and is filled with fresh water.¹

2. Box model

Our simple box model for the evolution of the Black Sea in the late Holocene makes the simplest possible assumptions to obtain results that are as robust as possible. We thus assume that evaporation and precipitation rates and river runoff have not changed substantially in the last 8,000 years.

Murray *et al.*'s [1991] and Özsoy and Ünlüata's [1997] observations suggest that the composition of the Black Sea can be very well modeled by two homogeneous boxes. The first box represents the less saline, ventilated surface water extending to about 150 m depth, and the second box the remaining deep water that is anoxic and more saline (see Fig. 1).

The present-day inflow and outflow are fairly well known and the only source of salinity is the Mediterranean water from the Bosphorus inflow. Mass and salinity balance for these two model boxes can thus be used to calculate residence times and input and output rates. We adopt here Fonselius' approach to compute the present-day rates of downwelling and upwelling in the Black Sea using water mass and salt conservation.

¹When completing this paper, we became aware of the just published work of Arthur and Dean [1998], who used a fixed-size two-box model. Both our model and the nature of our analysis thereof differ from theirs.

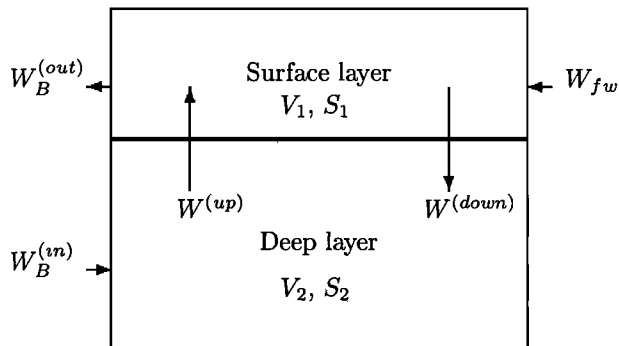


Figure 1. Schematic diagram of our variable-size two-box model for the Black Sea. Fluxes are represented by arrows.

Water mass conservation for the entire Black Sea is given by

$$W_B^{(in)} - W_B^{(out)} + W_{fw} = 0, \quad (1)$$

where $W_B^{(in)}$ and $W_B^{(out)}$ represent the present-day Bosphorus inflow and outflow, respectively. The net freshwater inflow W_{fw} is itself the sum of river inflow, precipitation and evaporation.

$W^{(down)}$ and $W^{(up)}$ represent the water-mass fluxes from the upper to the lower box and *vice-versa*. The downward transport is mainly due to entrainment, diffusion and vertical advection [Garrett, 1984]. The entrainment is caused by the inflow of heavy Mediterranean water through the Bosphorus Strait that entrains lighter surface water with it while flowing down through the upper layer into the lower one. The upward transport is due to the same phenomena as the downward transport, with the important difference that upward entrainment is due to the motion in the upper layer being more turbulent than that in the bottom layer [Ellison and Turner, 1959].

The rate of change of the volume V_1 of the upper layer is

$$\dot{V}_1(t) = W_{fw} - W_B^{(out)} + W^{(up)} - W^{(down)}. \quad (2)$$

The fluxes between the upper and the lower layer are not constant in time, as they are allowed to depend on the thickness of the upper layer (see Section 4).

The equations for the salinity in each layer, S_1 and S_2 , are based on Knudsen's relation:

$$\dot{S}_1 = [(S_2 - S_1)W^{(up)} - S_1 W_{fw}] / V_1, \quad (3)$$

$$\dot{S}_2 = [(S_1 - S_2)W^{(down)} + (S_M - S_2)W_B^{(in)}] / (V_0 - V_1); \quad (4)$$

here $V_0 = V_1 + V_2$ is the total volume of the Black Sea, $V_0 \approx 537,000 \text{ km}^3$, and S_M is the salinity of the Mediterranean water. In Eqs. (2)–(4) time increases from the past ($t < 0$) to the present ($t = 0$), to that t years B.P. = $-t$ years.

3. Present-day physical budgets

In this section we compute present-day budgets for upwelling and downwelling, as well as the Bosphorus outflow and the freshwater flux, by analyzing the model equations (1)–(4) for a steady-state case. Solving this steady-state system for the salinities yields

$$S_1 = S_M \frac{W_B^{(in)}}{W_B^{(out)}}, \quad S_2 = S_1 \left(1 + \frac{W_{fw}}{W^{(up)}}\right). \quad (5)$$

The salinity S_1 in the upper layer is thus completely independent of the transport between the two layers. This allows us to calculate the Bosphorus outflow, the net freshwater inflow and the upward and downward transport, given only the salinities and the Bosphorus inflow.

By using the salinity values $S_1 = 18.5$ ppt and $S_2 = 22.33$ ppt for the two boxes and $S_M = 35$ ppt for Mediterranean water, and the Bosphorus inflow $W_B^{(in)} = 312 \text{ km}^3 \text{ yr}^{-1}$ derived from observations by Ünlüata *et al.* [1989], the values for the upward and downward transport, the Bosphorus outflow and the net freshwater inflow are found to be:

$$\begin{aligned} W^{(up)} &= 1344 \text{ km}^3 \text{ yr}^{-1}, W^{(down)} = 1032 \text{ km}^3 \text{ yr}^{-1}, \\ W_B^{(out)} &= 590 \text{ km}^3 \text{ yr}^{-1}, W_{fw} = 278 \text{ km}^3 \text{ yr}^{-1}. \end{aligned} \quad (6)$$

The first two values agree with those found by Murray *et al.* [1991] using a different model, while the last two compare very well with the values $W_B^{(out)} = 605 \text{ km}^3 \text{ yr}^{-1}$ and $W_{fw} = 300 \text{ km}^3 \text{ yr}^{-1}$ derived from the observations of Özsoy and Ünlüata [1997].

4. Model solutions for the Holocene

We now consider the evolution of the two-box model from a state where all the water in the Black Sea is contained in the fresh “surface” layer. It is clear that the fluxes between the upper and the bottom layer are no longer constant, but are a function of the thickness of the upper layer. In addition, the entrainment of surface water by the heavier Mediterranean water is clearly an increasing function of the thickness of the upper layer. When the upper layer is thicker, the passage of the Mediterranean water through it lasts longer and more water is entrained from the upper into the lower layer. Furthermore, as turbulent motion decreases with depth [Garrett, 1989], the entrainment of deep water into the upper layer due to its higher turbulence level is a decreasing function of its thickness. The exact form of these dependences, however, is difficult to determine.

We write the fluxes as a Taylor series in the deviations of the upper-box volume V_1 from a reference value $V_1^{(0)}$ and retain only the two leading-order contributions:

$$W^{(down)} = W_{(0)}^{(down)} + \alpha(V_1 - V_1^{(0)})/V_0, \quad (7)$$

$$W^{(up)} = W_{(0)}^{(up)} - \beta(V_1 - V_1^{(0)})/V_0. \quad (8)$$

Here $V_1^{(0)}$ is the value to which $V_1(t)$ converges and it is set to today's observed value of about $84,000 \text{ km}^3$; superscript or subscript (0) all denote therewith present-day values. It is clear from the discussion above that α and β are positive constants, but their exact values can only be estimated.

We now use the highly simplified time-dependent model comprised of Eqs. (1)–(4), (7) and (8) to obtain information about the history of the Black Sea beginning from the opening of the Bosphorus at $t_0 = -7540$ years. The analytic solution to Eq. (2) — using present-day values from 6) for W_{fw} and $W_B^{(out)}$ and Eqs. (7) and (8) for $W^{(up)}$ and $W^{(down)}$ — can be written as:

$$\begin{aligned} V_1(t) &= \frac{V_0 - V_1^{(0)}}{\exp[-\frac{(\alpha+\beta)t_0}{V_0}]} \\ &\quad \exp[-\frac{\alpha+\beta}{V_0}t] + V_1^{(0)}. \end{aligned} \quad (9)$$

If we choose $\alpha + \beta = 300 \text{ km}^3 \text{ yr}^{-1}$, this simple exponential behavior simulates well the evolution of the depth of the $\text{O}_2\text{-H}_2\text{S}$ interface calculated by *Deuser* [1974], who assumed a logarithmic oxygen depletion rate to match existing radio-carbon rates for the initiation of sapropel deposition. This determines the last important parameter of our model.

We now turn our attention to the salinity evolution in the two layers; it is obtained by substituting Eqs. (7) and (8) into (3) and (4), and using the values of Eq. (6) for $W_{(0)}^{(down)}$ and $W_{(0)}^{(up)}$. The salinities depend on the two parameters α and β in two ways: directly, since α and β appear in Eqs. (3) and (4) when substituting for $W_{(0)}^{(up)}$ and $W_{(0)}^{(down)}$, and indirectly due to the dependence of V_1 on these parameters [see Eqs. (7)–(9)]. The direct dependence is negligible, as the terms containing α and β only represent a small part of the total vertical fluxes (see also Fig. 2 below). This immediately suggests that, in deriving the salinities, only the sum $\alpha + \beta$ matters, as it does for $V_1(t)$.

We investigate the sensitivity of our model results to different values of α and β . To do so, the volume $V_1(t)$ of the upper layer is obtained analytically from Eq. (9), while the salinities $S_1(t)$ and $S_2(t)$ in each layer are computed by solving Eqs. (3) and (4) numerically. The results for different α and β are shown in Fig. 2.

The results for $\alpha + \beta = 300$ are totally independent of α or β being zero in the top panel [see also Eq. (9)], and the dependence is very small to negligible in the lower and middle panel. Choosing α three times as large (dotted lines) or three times as small (dashed lines) does speed up or slow down, respectively, the convergence of $V_1(t)$ to present-day values, but it barely affects the evolution of $S_1(t)$ and $S_2(t)$. Hence today's value for the depth of the upper layer, the salinities in the two layers, and the value of $\alpha + \beta$ completely determine the evolution of model salinities. The dynamics of the salinities is, furthermore, almost independent of the halocline depth.

5. Concluding remarks

We have presented a “minimal” two-box model for the late Holocene evolution of the Black Sea, after the start of Mediterranean water inflow about 7500 years ago (Fig. 1). The model's allowing for a variable halocline depth permits a fairly realistic simulation of the salinity concentrations above and below the halocline (Fig. 2). All the model parameters are determined either directly from present-day observations (halocline depth and salinities) or from a fit to proxy records of halocline depth (entrainment parameters α and β). The evolution of the salinities is therewith quite robust to changes in the ratio α -to- β of downward-to-upward entrainment coefficients. This robustness should allow the match of the model's salinity curves to those that may be derived from proxy records of the basin's Holocene biogeochemistry [Murray *et al.* 1991; Jones and Gagnon, 1994; Ryan *et al.*, 1997].

The model's utter simplicity and relative robustness make it well suited for a study of, and comparison with proxy records on, nutrient evolution [Murray *et al.*, 1991; Fonselius, 1994; Wilkin *et al.*, 1997] and other aspects of biogeochemical cycles in this unique, highly anoxic basin. The present study's purpose was basic model formulation and validation, and so the fluxes of fresh and saline water — from river runoff and precipitations vs. Bosphorus

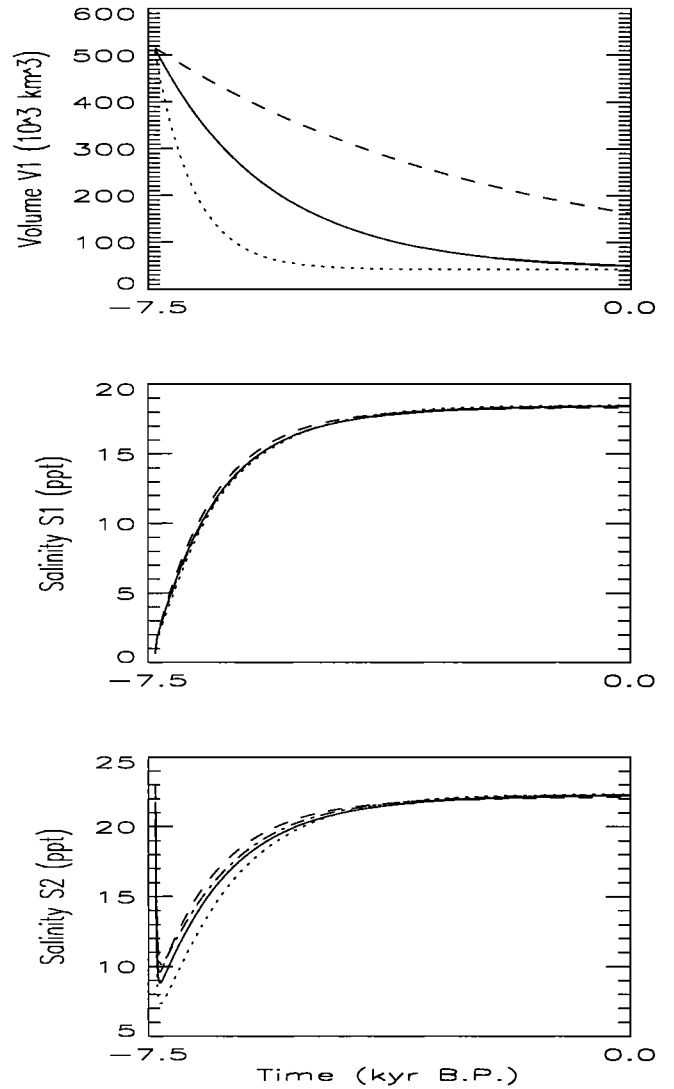


Figure 2. Model solutions for the late Holocene. From top to bottom: Volume of upper layer, salinity in upper layer, and salinity in bottom layer. Different curves correspond to different values of the two parameters: $\alpha = 300 \text{ km}^3 \text{ yr}^{-1}$ and $\beta = 0$ solid lines; $\alpha = 900 \text{ km}^3 \text{ yr}^{-1}$ and $\beta = 0 \text{ km}^3 \text{ yr}^{-1}$ dotted; $\alpha = 100 \text{ km}^3 \text{ yr}^{-1}$ and $\beta = 0$ dashed; $\alpha = 0$ and $\beta = 300 \text{ km}^3 \text{ yr}^{-1}$ dash-dotted.

Strait inflow and evaporation, respectively — have been assumed constant and equal to present-day values. It will be of interest to allow for fluxes that vary in time either in a prescribed manner, based on paleorecords from the past or global-change scenarios for the future, or as a result of changes in model variables.

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M. Karaca, Eurasia Institute of Earth Sciences and Maden Fakültesi Genel Jeoloji ABD, Istanbul Technical University, Maslak, 80626 Istanbul, Turkey

A. Wirth and M. Ghil, Department of Atmospheric Sciences and Institute of Geophysics and Planetary Physics, University of California, Los Angeles, CA 90095-1565, USA

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