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The Black Sea basin filling by the Mediterranean salt water during the Holocene

N.V. Esin [a,*], N.I. Esin [a], V. Yanko-Hombach [b,c]

[a] Southern Branch of the P.P. Shirshov Institute of Oceanology, Russian Academy of Science, Gelendzhik, Krasnodar Region, 353467, Russian Federation
[b] Odessa I.I.Mechnikov National University, 2 Dvoryanskaya Str., Odessa 65082, Ukraine
[c] Avalon Institute of Applied Science, 976 Elgin Ave., Winnipeg, MB, Canada, R3E 1B4

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A B S T R A C T

The origin of the bottom counterflow in Bosphorus Strait during the early Holocene, its temporal development and the Black Sea filling by the Mediterranean salt water is discussed in this paper. At 10 ka, the depth of the strait was 10 m, the velocity of accumulation body growth in the southern part of the strait was 3 mm/year, and the velocity of the ocean transgression was 13.5 mm/year. The freshwater balance of the Black Sea is accepted as it is now. Based on mathematical modeling the bottom counterflow breakthrough occurred when the depth of the strait was 16.5 m, at about 9400 years ago. Before this, salt water penetrated into the Black Sea in the autumn-winter seasons during short periods of time, when the Bosphorus upper stream was absent. The Navier–Stokes equations were used to describe the water circulation. Temporal dependencies of the counterflow depth, water discharge in counterflow and depth of the halocline in the Black Sea was calculated.

The halocline reached the depth of 100 m about 7200 years ago, and a situation close to present one (the lower Bosphorus flow brought salt into the Black Sea, with the upper stream returning it to the Sea of Marmara. The water discharge in the low water layer was insignificant during the time interval from 9400 to 8400 years ago. Then, it quickly rose to about 700 km^3/year.

1. Introduction

In several papers concerning the study of the Black Sea level changes (Esin et al., 2010, 2011, 2013; Esin and Esin, 2012, 2014) a method of physical (mathematical) description of the geological processes is applied. This method allows connecting geological events which happened at different times in a continuous time series, in which each subsequent event is prepared by previous geological history.

In the present paper we attempt to describe the process of the Black Sea basin filling by salt Mediterranean Sea water in condition of a sufficiently deep strait. The question about the minimum depth of the strait, when arose counterflow there, has been debated repeatedly in the literature (Lane-Serff et al., 1997). This depth depends on the freshwater balance of the Black Sea. The larger is the freshwater balance value, the greater is the strait depth, when the salt water can penetrate into the Black Sea.

* Corresponding author.
E-mail addresses: ovos_oos@mail.ru (N.V. Esin), esinnik@rambler.ru (N.I. Esin), valyan@onu.edu.ua (V. Yanko-Hombach).

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Water circulation of two-layer flow in the Bosphorus Strait is described by the equation system of Navier–Stokes. In earlier papers, the Boussinesq, Bernoulli, and Saint-Venant equations were used. They are Euler equations for ideal liquid, averaged in vertical direction. There is no friction mechanism between layers of viscous fluid. In the case of two-layer flow friction determines the position of interface between upper and near-bottom currents. Shearing stresses on the interface have equal values from above and below, but opposite direction. Such a mechanism forms the process of capturing a certain value of water from the low stream by the upper stream and its returning to the Marmara Sea. Gregg and Ozsoy (2002) used a full hydrodynamical model in the form of Navier–-Stokes equations, diffusion equations, and equation of fluid state. However, it is not expedient to use such a model for the description of geological processes as there are insufficient data about hydrodynamic conditions in the Holocene.

2. Mathematical model of two-layer flow

According to theoretical conclusions of previous investigations (Esin et al., 2010, Esin and Esin, 2014) based on geological and other studies (Ostrovsky et al., 1977; Serebrinanii, 1982; Lane-Serff et al., 1997; Izmailov, 2005), about 10000 years ago the levels of the Black and Marmara seas converged and a Bosphorus Strait with depth of about 10 m formed. Thereafter, the oceanic transgression of the Black Sea began. The Black Sea level repeated the Marmara Sea level course with an excess of a few tens of centimeters. The depth of the strait was being increased and counterflow arose. Temporal discharge in counterflow increased over time. We describe, with the use of Navier–Stokes equations, two-layer water flow in the strait with depth increasing. The flow diagram is presented in Fig. 1.

In the upper layer of Bosphorus Strait, the Black Sea water flows to the Marmara Sea, as the result of the Black sea level being higher than the Marmara sea level. Water flows due to pressure gradient, which is created by the free water surface inclination in the strait. In this case the bottom of the upper stream is the interface between flow and counterflow. On the bottom water motion velocity is equal to zero and on the free surface shearing stress is equal to zero.

Within the bottom water flows under the influence of two factors - pressure gradient, created by the inclination of the free water surface and due to the fact that the Marmara Sea water is denser than that of the surrounding Black Sea water by ~0.03 g/cm^3. Therefore heavy water flows along the bottom.

For the description of the upper stream X_{up} axis must be directed towards the Marmara Sea and Z_{up} axis is directed upwards (Fig. 1). In the case of quasi-stationary sum, when the process of a slow change of a mean value of the Black Sea freshwater balance (during several millenniums), members of Navier–Stokes equations describing viscosity are of 10^{-3}–10^{-4} m/s^2 order and members describing acceleration – 10^{-10} m/sec^2. We may neglect inertia and describe the upper stream in the Bosphorus Strait by Navier–Stokes equations as:

$$-\frac{1}{\rho}\frac{\partial P_{up}}{\partial x_{up}} + \nu\frac{\partial^2 U_{up}}{\partial z_{up}^2} = 0; \quad (1)$$

$$\frac{\partial P_{up}}{\partial z_{up}} = -\rho g; \quad (2)$$

$$\int_o^{H_{up}} U_{up} dz_{up} = Q_{up}/l. \quad (3)$$

where ρ – water density within the upper stream, P_{up} – pressure, ν – kinematic viscosity coefficient, Q_{up} – water discharge, l - width of the Strait.

Solution of (1)–(3) equations can be written as:

$$P_{up} = \rho g (H_{up} - z_{up}); \quad (4)$$

$$U_{up} = \frac{g}{2\nu}\frac{dH_{up}}{dx_{up}} z_{up}(2H_{up} - z_{up}); \quad (5)$$

$$H_{up}^4 = H_0^4 + \frac{12\nu Q_{up}}{gl}(L - x_{up}). \quad (6)$$

or:

$$H_{up}^4 = (H_{up} - \Delta H)^4 + \frac{12\nu Q_{up}(L - x_{up})}{gl}. \quad (7)$$

Here H_{up} – water surface in the strait, H_0 – depth of the upper stream near the entrance to the Marmara Sea, ΔH – difference between the levels of neighboring seas, L – length of the strait from the southern sill to the Black Sea ($L = 20000$ m).

In the low layer, water is denser (roughly 0.03 g/cm^3) than the Black Sea water. This water flows downstream along the bottom under the influence of gravity. Another factor influencing the nearbottom water is a pressure gradient, originated by the inclination of the upper stream water surface to the sea-line. This gradient is directed against the current within the nearbottom layer. When water surface in the strait is approximated as a straight line, then a pressure gradient does not depend on X and is equal to $\rho g \cdot \mathrm{tg}\varphi$, where $\mathrm{tg}\varphi$ – the average slope of water surface which is of the order from 10^{-6} to 10^{-5}. Now, Navier–Stokes equations can be written as:

$$g\frac{\Delta\rho}{\rho_s}\sin\alpha - g\mathrm{tg}\varphi + \nu\frac{\partial^2 U_{dn}}{\partial z_{dn}^2} = 0; \quad (8)$$

$$g\frac{\Delta\rho}{\rho_s}\cos\alpha - \frac{1}{\rho_s}\frac{dP}{dz_{dn}} = 0; \quad (9)$$

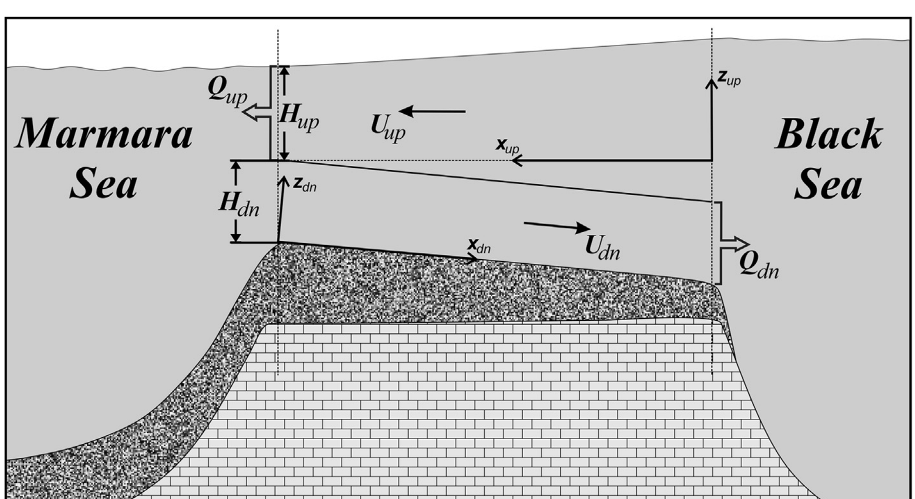

Fig. 1. The scheme of the water circulation in the Bosporus Strait.