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Abstract

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ON NEAR-BOTTOM CURRENTS AT GREAT DEPTHS IN THE BLACK SEA

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At present the importance of a detailed study of the dynamics of the near-bottom layers of seas and oceans is evident. However, experimental investigations of the velocities of near-bottom currents at great depths involve considerable difficulties. Only isolated measurements are known of the distribution of the magnitude of the velocity of near-bottom currents ([1,2]).

At the Department of Physics of the Sea and Inland Waters of the Faculty of Physics of Moscow University, methods and apparatus ([3,4]) have been developed for recording the velocities of near-bottom currents, as well as a bottom gradient installation ([5]) for autonomous and synchronous recording of the magnitude of the velocity and the direction of near-bottom currents. The starting speed of the rotors is 1.5 cm/sec. The accuracy of recording the angle of the current direction is 3°.

The expedition work was conducted from the research vessel "Moskovskii universitet," mainly in the spring–autumn period. More than 30 velocity profiles of near-bottom currents were obtained in various regions of the sea. Each profile was obtained from velocity values measured synchronously at 5 horizons. Ten deployments were carried out on the continental slopes. The remaining material pertains to the deep-water part of the eastern half of the Black Sea. Most of the obtained distributions of current velocities have a clearly expressed velocity maximum. The values on average lie within the range from 3–5 cm/sec to 12–16 cm/sec. In 5 cases velocity profiles were obtained that obeyed a logarithmic law; in 3 cases the current velocities were less than the starting speed of the rotors. Special attention should be given to the materials obtained on the section from Cape Bafra to Sochi in the autumn of 1966, when current velocities reaching 3 m/sec were recorded. At the same time, the direction of the current changed periodically.

Figure 1 shows curves of the distribution of current velocity in the near-bottom layer, obtained on a traverse off Yalta. The observational data show that the near-bottom current is directed from the shore toward the center of the eastern half of the sea. The absolute values of the current velocity decrease with distance from the slope, while the thickness of the layer encompassed by the current increases from 2.5-3 m at a distance of 10 miles from the shore (curve 1) to 5 m at a distance of 65 miles (curve 3). Similar profiles were obtained by us at different times on sections near Cape Sinop and in the region of Sochi. The obtained distribution of current velocities indicates the possibility of the existence of suspension flows, which is also confirmed by materials from other investigations (^{6,7}). The presence of suspension flows leads to the formation of a density jump in the deep-water part of the sea near the bottom.

An interesting phenomenon in the dynamics of near-bottom velocities was discovered on 6–8 IX 1966 on the section from Cape Bafra to Sochi, crossing almost diagonally the eastern half of the Black Sea. The recording of profiles of the velocities of near-bottom currents and of their directions was carried out on average every 40 miles, and in time every 6 hours (Fig. 2). The maxima

velocities were observed at 2-3 m from the bottom. The magnitude of the velocity modulus at the maximum was about 3 cm/s. The direction of the current changed to the opposite every 6 hours.

Fig. 1. Curves of the distribution of the modulus of the current velocity in the near-bottom layer, obtained on the section from Yalta toward the central part of the eastern half of the Black Sea. Profile 1—distance from the shore 10 miles, depth 500 m; 2—distance from the shore 30 miles, depth 2078 m; 3—distance from the shore 65 miles, depth 2150 m.

Analysis of mareograph observations at three coastal points (Odessa, Sevastopol, Tuapse) for the period from 1 to 15 IX 1966 showed that fluctuations of sea level agree fairly well with the change in current direction. In addition, during the period from 1 to 4 IX 1966, the sea-level records trace a disturbance moving from west to east, which caused a rise of the free sea surface reaching up to 30 cm above the mean level. This disturbance of the level, quite large for the Black Sea, may have caused the occurrence of natural oscillations of the waters and the formation of internal seiches.

Fig. 2. Profiles of near-bottom current velocities obtained on the section from Cape Bafra to Sochi. Arrows indicate current directions. a–17°27′, 6 IX 1966; b–00°19′, 7 IX 1966; c–05°58′, 7 IX 1966; d–11°49′, 7 IX 1966; e–17°37′, 7 IX 1966; f–23°56′, 7 IX 1966.

Let us consider the problem of free oscillations of a closed basin, taking geostrophic effects into account. In density terms, we shall represent the sea as consisting of three layers. The thickness of the upper layer is determined by seasonal temperature fluctuations, and that of the lower layer by the thickness of suspension flows.

Let us coincide the plane XOY with the undisturbed sea surface. We choose the positive direction of the OX axis to the south, and OY to the east. Let ρ_j, h_j, and z_j denote the density, thickness, and depth below the equilibrium position of the corresponding layer. Let H and l be the depth and length of the sea; ζ_j,

u_j, and v_j the elevations of the interfaces of layers of different density and the components of current velocity in the layers; P_a the atmospheric pressure. In the notation adopted, $j = 1, 2, 3$, respectively, for the upper, middle, and lower layers.

We shall neglect the vertical component of velocity in comparison with the horizontal one; we shall also not take into account the internal friction of the fluid against the walls and bottom of the basin. Within each layer the components of the current velocity will be assumed constant with depth. The latitude of the place will be taken as constant for the entire basin, and consequently the period of inertial oscillations will be the same for the entire sea. We denote it by T_p. We shall assume that the oscillatory motion occurs only along the Y-axis. Under the assumptions adopted, with sufficient accuracy one may regard the pressure in the layers P_j as purely hydrostatic, determined by the depth of occurrence of the corresponding layer.

The equations of continuity and motion in this case may be written in the form:

$$h_j \frac{\partial v_j}{\partial y} + \frac{\partial}{\partial t}(\zeta_j - \zeta_{j+1}) = 0, \qquad \text{where } \zeta_4 = 0; \tag{1}$$

$$\frac{\partial u_j}{\partial t} - \frac{2\pi}{T_p} v_j = 0, \qquad \frac{\partial v_j}{\partial t} + \frac{2\pi}{T_p} u_j = F_j; \tag{2}$$

$$F_j = \begin{cases} -g \dfrac{\partial \zeta_1}{\partial y}, & \text{for } j = 1, \\ -g \dfrac{\rho_1}{\rho_2} \dfrac{\partial \zeta_1}{\partial y} - g \left(1 - \dfrac{\rho}{\rho_2}\right) \dfrac{\partial \zeta_2}{\partial y}, & \text{for } j = 2, \\ -g \dfrac{\rho_1}{\rho_3} \dfrac{\partial \zeta_1}{\partial y} - g \left(\dfrac{\rho_2 - \rho_1}{\rho_3}\right) \dfrac{\partial \zeta_2}{\partial y} - g \left(1 - \dfrac{\rho_2}{\rho_3}\right) \dfrac{\partial \zeta_3}{\partial y}, & \text{for } j = 3. \end{cases}$$

The boundary conditions for the current velocities will be $u_j = v_j = 0$ at $y = 0$ and $y = l$. We shall seek the solution of the equations for v_j in the form

$$v_j = C_j \sin \frac{\pi y}{l} \sin \frac{2\pi}{T} t. \tag{3}$$

Then from (1), (2)

$$u_j = -C_j \frac{T}{T_p} \sin \frac{\pi y}{l} \cos \frac{2\pi}{T} t; \tag{4}$$

$$\zeta_j = \frac{T}{2l} \sum_{n=1}^{k} C_n h_n \cos \frac{\pi y}{l} \cos \frac{2\pi}{T} t. \tag{5}$$

In the last equation $k = 3$ for $j = 1$; $k = 2$ for $j = 2$ and $k = 1$ for $j = 3$. Expressing C_2 and C_3 through C_1, we obtain

$$C_2 = C_1 \left\{ 1 - \frac{gT_1^2 h_1}{4l^2} \left(1 - \frac{\rho_1}{\rho_2} \right) \right\}; \tag{6}$$

$$C_3 = C_1 \left\{ \frac{4l^2}{gT_1^2 h_3} + \frac{gT_1^2 h_1 h_2}{4l^2 h_3} \left(1 - \frac{\rho_1}{\rho_2} \right) - \frac{h_1 + h_2}{h_3} \right\}; \tag{7}$$

$$\frac{1}{T_1^2} = \frac{1}{T^2} - \frac{1}{T_p^2}. \tag{8}$$

From the equations of motion, taking into account the solutions for the elevations of the interfaces of the layers with different density and the current velocities in the layers, we obtain an equation for determining the oscillation period T_1

$$T_1^6 \frac{g^3 h_1 h_2 h_3}{4l^2} \left(1 - \frac{\rho_1}{\rho_2} \right) \left(1 - \frac{\rho_2}{\rho_3} \right) - T_1^4 g^2 \left\{ h_1 h_2 \left(1 - \frac{\rho_1}{\rho_2} \right) + h_1 h_3 \left(1 - \frac{\rho_1}{\rho_3} \right) + \right.$$

$$\left. + h_2 h_3 \left(1 - \frac{\rho_2}{\rho_3} \right) \right\} + T_1^2 4l^2 gH - 16l^4 = 0. \tag{9}$$

Calculation by (9), for the parameter values $h_1 = 30$ m, $h_2 = 1600$ m, $h_3 = 10$ m, $H = 1700$ m, $l = 10^6$ m, $(1 - \rho_1/\rho_2) = (1 - \rho_2/\rho_3) = 5 \cdot 10^{-3}$, $(1 - \rho_1/\rho_3) = 1 \cdot 10^{-2}$, gives $T_{1,1} = 12$ hours, $T_{1,2} = 15.5$ days, $T_{1,3} = 35$ days. From (8), knowing $T_{1,1}$ and T_p, we find $T = 10$ hours.

Having determined the constant from observational data on changes in sea level, we find the amplitude values of the current velocities in all three layers:

$$\begin{aligned} v_1 \approx v_2 &= 2.6 \cdot 10^{-2} \text{ m/sec}, & v_3 &= -3.8 \text{ m/sec}, \\ u_1 \approx u_2 &= -1.6 \cdot 10^{-2} \text{ m/sec}, & u_3 &= 2.3 \text{ m/sec}. \end{aligned} \tag{10}$$

It follows from the solutions of the system of equations that, as a result of the action of the Coriolis force, the current-velocity vector rotates with a period of about 10 hours. The opposite signs of the values of v_3 and u_3 relative to the corresponding quantities for the upper layers indicate that in the lower layer all processes occur in antiphase. This is also confirmed by experimental data when comparing the phases of oscillations of the free-surface level with the phases of currents in the near-bottom layer.

Comparison of the calculated values of the oscillation period and the calculated values of the current velocities in the near-bottom layer with the experimentally measured quantities shows fairly good agreement between them. Indeed, the calculated oscillation period is $T_{\text{calc}} = 10$ hours, the observed one $T_{\text{obs}} = 12$ hours; the calculated value of the velocity modulus for the lower layer, in accordance with (10), is $|v_{\text{calc}}| = 4.5$ m/sec, while the maximum value of the measured modulus of the current velocity is on average about 3 m/sec.

The cause of the high current velocities in the near-bottom layer of the Black Sea should be sought in density stratification. The near-bottom layer of increased density, formed by suspension flows and also because of the inflow of highly saline Mediterranean waters, creates conditions for the occurrence of internal seiches. The resulting oscillations lead to significant current velocities in the near-bottom layer, which, because of the presence of friction, inevitably lead to erosion of this layer and to its destruction, until after some interval of time the process is repeated. For a detailed study of the dynamics of near-bottom layers, comprehensive investigations are needed of the processes occurring at the ocean–bottom interface.

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Note: Figure translations are in progress. See original paper for figures.

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