THERMOHYDRODYNAMICS OF THE OCEAN

GENERATION OF SEICHES BY MOVING BARIC FRONTS IN BOUNDED BASINS

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We consider a plane problem of barotropic seiches generated by a front of atmospheric pressure moving over a bounded basin. A system of nonlinear equations of long waves is solved by the finite-difference method with regard for the bottom friction and Earth's rotation. The numerical analyses are performed for two basins with distributions of depths typical of the Black Sea. It is shown that the passage of a baric front over the basin leads to the generation of lower seiches. The oscillations of level and the corresponding currents are especially intense in the shallow-water zones of the basins. The seiches become more intense as the velocity of transfer of the atmospheric front increases and the width of the front decreases. Earth's rotation leads to the generation of longshore currents and promotes the process of weakening of residual oscillations of the fluid following the passage of the front. The influence of nonlinearity on seiches is small for the analyzed basins.

Introduction

The process of interaction with the atmosphere is one of the causes of the space variability of hydrophysical fields in the World Ocean [1]. On the synoptic scales of motion, the predominant contribution to the energy transfer from the atmosphere into the ocean is made by the wind stresses [2]. The relative contribution of the variations of atmospheric pressure to the oscillations of the sea level depends on the scales of the process. The analyses of the *in-situ* data and the results of numerical simulations reveal the predominant role of the baric field in the generation of nontidal oscillations of sea level with periods from ten hours to ten days on space scales of 200–1000 km [3, 4]. For this reason, the investigation of the response of marine media to the variations of atmospheric pressure is necessary to understand the dynamics of the World Ocean.

During a year, about 10^4 cyclones and anticyclones participate in cyclogenesis over the World Ocean [3]. The passage of intense meteorological formations can be accompanied by displacements of the sea level 3–4 times larger than the equilibrium values [3]. As follows both from the data of *in-situ* observations [5–9] and from the results of numerical simulations for the Black Sea and Sea of Azov [10, 11] the process of motion of baric formations over closed basins can lead to the generation of seiches. At the same time, the general physical regularities of the process of generation of seiches in closed basins of variable depth by moving baric fronts are now studied insufficiently well.

In what follows, we study the plane problem of generation of barotropic seiches by a front of atmospheric pressure moving over a bounded basin. We analyze the dependence of the efficiency of generation of nonlinear seiches on the velocity of motion and width of the front. Unlike our previous work [12], the analysis of the dynamics of water in the basin is performed for a moving front with regard for Earth's rotation.

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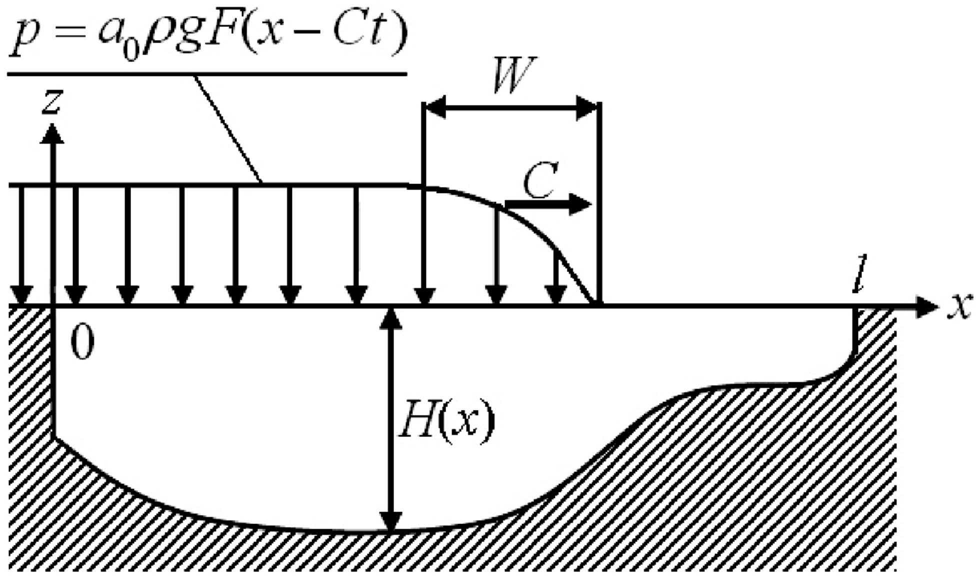

Fig. 1. Schematic diagram of the problem.

The numerical analyses of the oscillations of fluid are carried out for two basins with distributions of depths typical of the Black Sea.

Mathematical Statement of the Problem

Consider a channel of constant width l unbounded in the direction of the (horizontal) y-axis. Thus, the channel occupies the region $0 \le x \le l$, $-\infty < y < +\infty$, $-H(x) < z < 0$ (Fig. 1), where x is the horizontal coordinate across the channel, z is the coordinate measured vertically upward from the unperturbed position of the free surface of fluid $z = 0$, and $H = H(x) > 0$ is the distribution of depth in the channel for the nonperturbed state. At the initial time $t = 0$, the fluid is immobile and its free surface is horizontal.

Within the framework of the nonlinear theory of long surface waves and with regard for the square law of bottom friction and Earth's rotation, we study the motion of the fluid in a basin caused by the passage of a baric front over the basin in the positive direction of the x-axis with a constant velocity $C > 0$. The distribution of perturbations of the atmospheric pressure in the front is specified as follows:

$$p = a_0 \rho g F(\xi), \qquad \xi = x - Ct, \tag{1}$$

where a_0 is the amplitude of perturbations of the atmospheric pressure (in meters of the water column), ρ is the density of the fluid, g is the gravitational acceleration, and $F(\xi)$ is a dimensionless function such that $F(\xi) \to 0$ as $\xi \to +\infty$ and $F(\xi) \to 1$ as $\xi \to -\infty$. The characteristic width of the zone of significant variations of the atmospheric pressure is equal to W (Fig. 1) and plays the role of the width of the baric front. The hydrostatic displacement of the free surface of the fluid in the field of atmospheric pressure is given by the formula (in the inverted-barometer approximation [3])

$$z = -\frac{p}{\rho g} = -a_0 F(\xi). \tag{2}$$

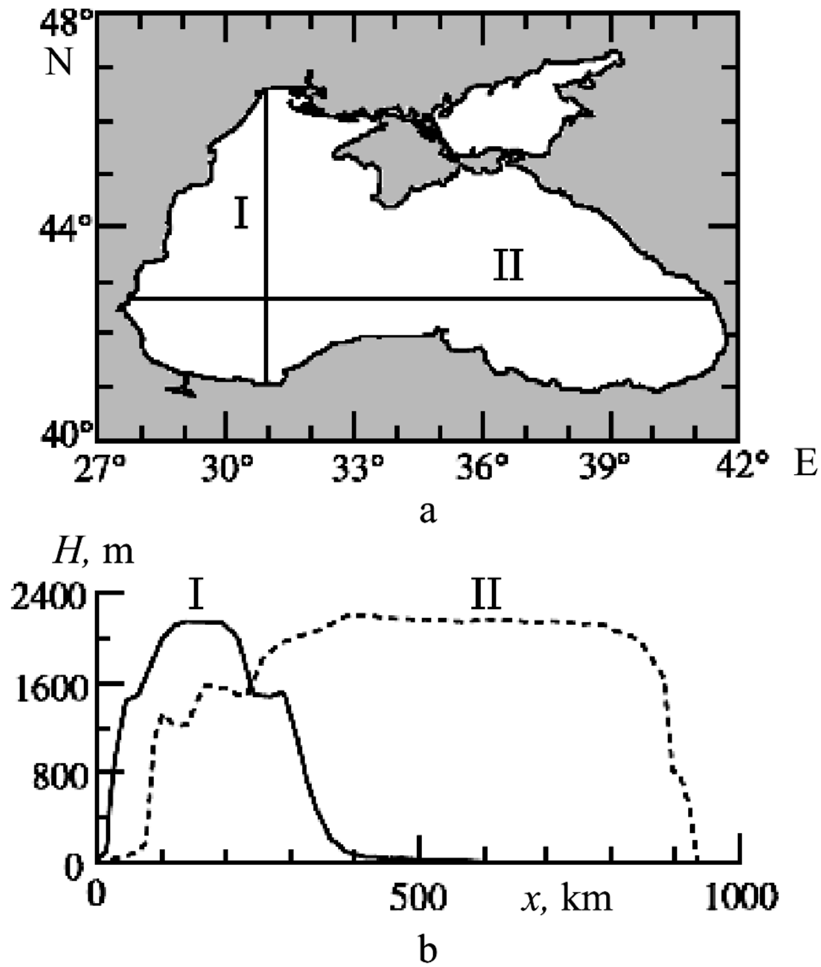

Fig. 2. Sections I (in the south–north direction) and II (in the west–east direction) made in the Black Sea (a) and the corresponding distributions of depths (b) used for the numerical simulation of the process of generation of seiches by moving fronts.

Under the above-mentioned assumptions, the motion of the fluid in the basin is two-dimensional $(\partial/\partial y \equiv 0)$ and is described [in the cross section of the channel (vertical plane Oxz)] by the following system of equations:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} - fv = -g\frac{\partial \zeta}{\partial x} - k\frac{u\sqrt{u^2+v^2}}{D} - g\frac{\partial \tilde{\zeta}}{\partial x}, \tag{3}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + fu = -k\frac{v\sqrt{u^2+v^2}}{D}, \tag{4}$$

$$\frac{\partial \zeta}{\partial t} + \frac{\partial (Du)}{\partial x} = 0, \tag{5}$$

with the initial conditions

$$u = v = \zeta = 0 \qquad (t = 0), \tag{6}$$

where $u(x, t)$ and $v(x, t)$ are the projections of the horizontal velocity of motion averaged over the depth onto the x- and y-axes, respectively, $\zeta(x, t)$ is a displacement of the free surface from the horizontal position, $D = H(x) + \zeta(x, t)$ is the total depth of the basin, $\tilde{\zeta} = a_0 F$, $k = 2.6 \cdot 10^{-3}$ is the coefficient of bottom friction, and f is the Coriolis parameter regarded as constant.

On the lateral boundaries of the basin $x = 0$ and $x = l$ regarded as vertical solid walls, we specify the conditions of impermeability of the fluid:

$$u(0, t) = 0 \quad \text{and} \quad u(l, t) = 0. \tag{7}$$

The total energy of the fluid in the basin is given by the formula

$$E_T(t) = E_K(t) + E_P(t), \tag{8}$$

where

$$E_K(t) = \int_0^l e_k \, dx \quad \text{and} \quad E_P(t) = \int_0^l e_p \, dx$$

are, respectively, the kinetic and potential energies,

$$e_k = \frac{1}{2}\rho D(x, t)\left[u^2(x, t) + v^2(x, t)\right], \quad \text{and} \quad e_p = \frac{1}{2}\rho g \zeta^2(x, t). \tag{9}$$

In what follows, we study the motion of the fluid for two basins with typical distributions of depths (Fig. 2b) corresponding to sections I and II made in the Black Sea along 31.00°E and 42.66°N, respectively (Fig. 2a).

Linear Seiches

Assume that waves are linear and free. We set $k = 0$ and $\tilde{\zeta} = 0$. As a result of linearization of Eqs. (3)–(5), we arrive at the following boundary-value problem:

$$\frac{\partial u}{\partial t} - fv + g\frac{\partial \zeta}{\partial x} = 0, \quad \frac{\partial v}{\partial t} + fu = 0, \quad \frac{\partial \zeta}{\partial t} + \frac{\partial (Hu)}{\partial x} = 0, \quad u(0, t) = 0, \quad u(l, t) = 0. \tag{10}$$

We now consider harmonic (in time) oscillations of the fluid with frequency σ:

$$u = A_1(x)\cos\sigma t, \quad v = A_2(x)\sin\sigma t, \quad \zeta = B(x)\sin\sigma t \quad (\sigma > 0), \tag{11}$$

where $A_1 = U(x)/H(x)$, and $U(x)$ is the total horizontal flow of the fluid in the section of the basin. Substituting expressions (11) in (10), we get the Sturm–Liouville boundary-value problem for the frequencies of seiches σ and the corresponding distributions $U(x)$:

Table 1. Periods T_s of the Five Lowest Seiches in Basins I and II With and Without Regard for Earth's Rotation

Basin	f, sec^{-1}	T_1, h	T_2, h	T_3, h	T_4, h	T_5, h
I	$10.07 \cdot 10^{-5}$	8.792	4.235	2.718	2.054	1.675
	0	10.202	4.367	2.752	2.068	1.683
II	$9.856 \cdot 10^{-5}$	3.973	2.801	1.768	1.386	1.144
	0	4.078	2.837	1.777	1.391	1.146

$$\frac{d^2U}{dx^2} + \frac{\sigma^2 - f^2}{gH(x)}U = 0, \qquad U(0) = U(l) = 0. \tag{12}$$

By using the properties of the spectrum of the Sturm–Liouville problem [13], we can conclude that all eigenfrequencies of oscillations of the fluid are real and form a countable set, i.e., $\sigma = \sigma_s$ $(s = 1, 2, \ldots)$, and $f < \sigma_1 < \sigma_2 < \ldots$. The horizontal distribution of the total flow of fluid $U = U_s(x)$ for the sth seiche has exactly $s - 1$ zeros in the interval $0 < x < l$.

If the functions U_s are known, then it is possible find the distributions over x of the projections of horizontal velocity u_s and v_s and the displacements of the free surface ζ_s for the sth seiche:

$$u_s = A_{1s}(x)\cos\sigma_s t, \qquad v_s = A_{2s}(x)\sin\sigma_s t, \qquad \zeta_s = B_s(x)\sin\sigma_s t, \tag{13}$$

$$A_{1s} = \frac{U_s(x)}{H(x)}, \qquad A_{2s} = -\frac{f}{\sigma_s}A_{1s}(x), \qquad B_s = -\frac{1}{\sigma_s}\frac{dU_s(x)}{dx}. \tag{14}$$

In order to find the frequencies of free oscillations of the fluid, problem (12) on a grid $x = x_i = \delta i$ $(i = 0, \ldots, N)$ with steps $\delta = l/N$ is replaced by its finite–difference analog

$$U_0 = 0, \qquad U_1 = \gamma\delta, \qquad U_{i+1} = \left[2 - \frac{\mu}{gH_i}\right]U_i - U_{i-1} \quad (i = 1, \ldots, N-1), \quad U_N = 0, \tag{15}$$

where $U_i = U(x_i)$, $H_i = H(x_i)$, $\mu = (\sigma^2 - f^2)\delta^2$, and $\gamma = dU(0)/dx$ is a constant. The difference boundary-value problem (15) is reduced to finding the roots of the equation $U_N(\mu) = 0$ and solved by the method of shooting with respect to the parameter $\mu > 0$ starting from $\mu = 0$.

The outlined algorithm of numerical analysis of linear seiches is used to find the lowest five seiches in two basins with distributions of depths presented in Fig. 2b. The periods of seiches $T_s = 2\pi/\sigma_s$ $(s = 1, \ldots, 5)$ are given in Table 1 and vary within the range 1–10 h. The periods of seiches in basin I are much larger than the periods of the corresponding seiches in basin II.

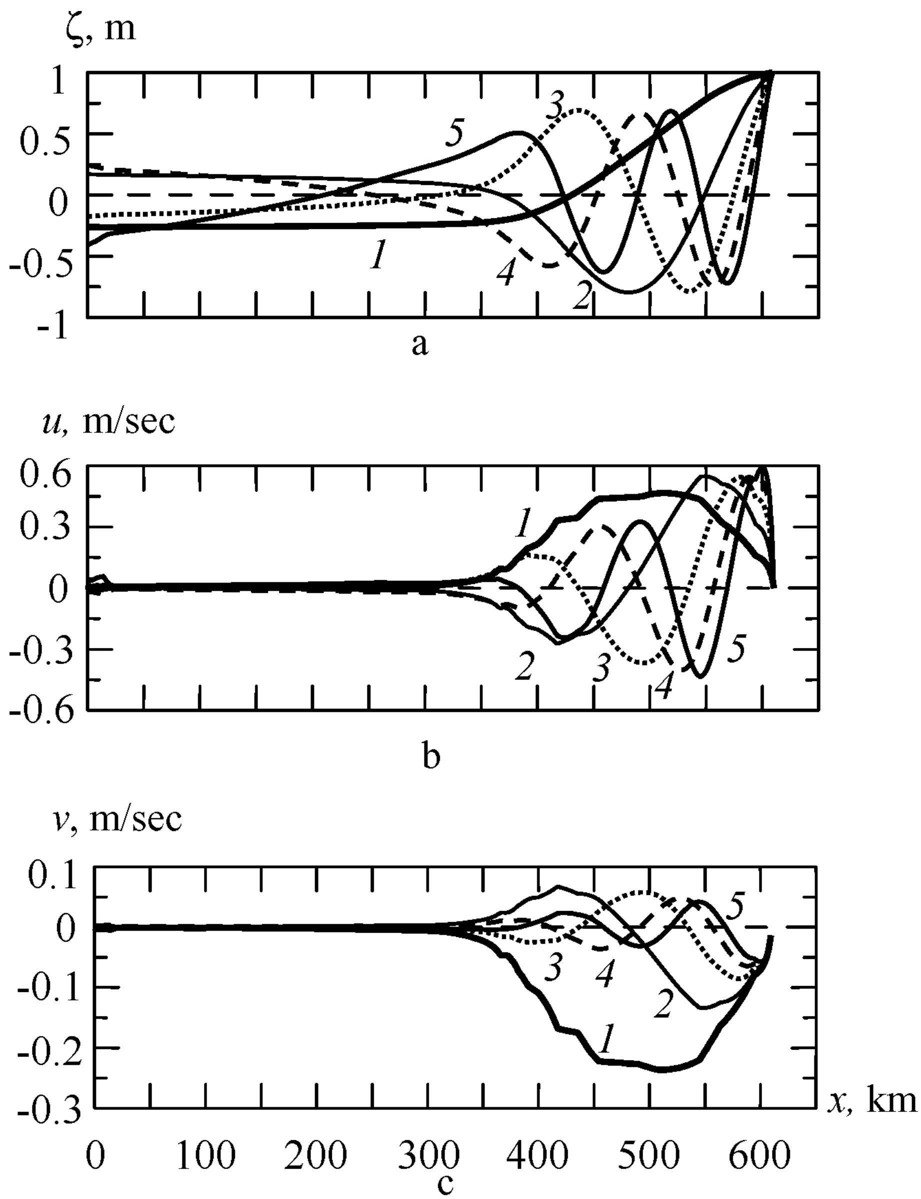

Fig. 3. Displacements of the free surface ζ (a) and the projections of the flow velocity across u (b) and along v (c) the channel for the five lowest modes in basin I.

The data presented in Table 1 also show that, for basin I, the distorting influence of Earth's rotation on the period of the single-node seiche constitutes 13.82% but does not exceed 3.02% for all other seiches. For basin II, the indicated influence on the periods of free oscillations is smaller than 2.6%.

For the five lowest seiches in basin I, the variations of u, v, and ζ along the x-axis are found by using relations (14) and depicted in Fig. 3. The displacements of the level are normalized so that $B_s(l) = 1$ m. The number of nodes in the distribution of ζ_s for a seiche is equal to its number s. The structure of seiches is correlated with the bottom topography. Indeed, the amplitude of displacements of the sea level is maximum in the shallow-water part of the basin corresponding to the extended northwest part of the Black Sea. In basin II, the smallest depths are located in its west part and, therefore, the extreme values of displacements of the free surface and projections of the flow velocity are observed in the left-hand part of the basin.

Algorithm of the Numerical Analysis of Forced Motions of the Fluid

For the numerical solution of the initial-boundary-value problem (3)–(7) in the segment $0 \le x \le l$ for $t \ge 0$, we use an explicit-implicit finite-difference scheme [14]. The field of the velocity u transverse to the channel at times $t = t_n$ $(n = 0, 1, \dots)$ is found at the nodes of a uniform grid $x = x_i$ $(i = 0, \dots, N)$, whereas the projection of the flow velocity along the channel υ and the displacements of the free surface of the fluid are determined at the middle points of the cells: $x = x_i - \delta/2$ $(i = 0, \dots, N-1)$.

We introduce the notation

$$x_i = i\delta, \quad i = 0, \dots, N, \qquad t_n = n\tau,$$

$$u_0^n = 0, \qquad u_i^n = u(x_i, t_n), \qquad u_N^n = 0,$$

$$\upsilon_i^n = \upsilon\left(x_i - \frac{\delta}{2}, t_n\right), \qquad \zeta_i^n = \zeta\left(x_i - \frac{\delta}{2}, t_n\right), \quad i = 1, \dots, N-1,$$

where τ is the time step. The depth of the basin H is specified at the nodes of the grid $H_i = H(x_i)$ and linearly interpolated between the nodes.

In the explicit form, we get the following difference analog of Eq. (3):

$$u_i^{n+1} = u_i^n - 0.5\beta u_i^n\left(u_{i+1}^n - u_{i-1}^n\right) + f\tau\upsilon_{i+1/2}^n - g\beta\left[\left(\zeta_{i+1}^n - \zeta_i^n\right) + \left(\tilde{\zeta}_{i+1}^n - \tilde{\zeta}_i^n\right)\right] - \frac{k\tau u_i^n\sqrt{\left(u_i^n\right)^2 + \left(\upsilon_{i+1/2}^n\right)^2}}{D_i^n}, \tag{16}$$

where $\upsilon_{i+1/2}^n = 0.5\left(\upsilon_{i+1}^n + \upsilon_i^n\right)$, $D_i^n = H_i + 0.5\left(\zeta_{i+1}^n + \zeta_i^n\right)$ is the total depth of the fluid at the node $x = x_i$, $\beta = \tau/\delta$, $i = 1, \dots, N-1$.

In the difference form, Eq. (4) can be rewritten as

$$\upsilon_i^{n+1} = \upsilon_i^n - 0.5\beta u_{i-1/2}^n\left(\upsilon_{i+1}^n - \upsilon_{i-1}^n\right) - f\tau u_{i-1/2}^n - \frac{k\tau\upsilon_i^n\sqrt{\left(u_{i-1/2}^n\right)^2 + \left(\upsilon_i^n\right)^2}}{D_{i-1/2}^n}, \tag{17}$$

where $u_{i-1/2}^n = 0.5\left(u_i^n + u_{i-1}^n\right)$ and $D_{i-1/2}^n = 0.5(H_i + H_{i-1}) + \zeta_i^n$ is the total depth of the fluid at the point $x = x_i - \delta/2$.

The difference analog of the equation of continuity (5) takes the form

$$\zeta_i^{n+1} = \zeta_i^n - \beta\left(u_i^{n+1}D_i^n - u_{i-1}^{n+1}D_{i-1}^n\right). \tag{18}$$

On the right-hand side of Eq. (18), we use the values of the velocity u for the time step $n+1$ and the values of displacements of the free surface of the fluid for the previous time step. According to (5), the initial conditions for the system of difference equations (16)–(18) take the form

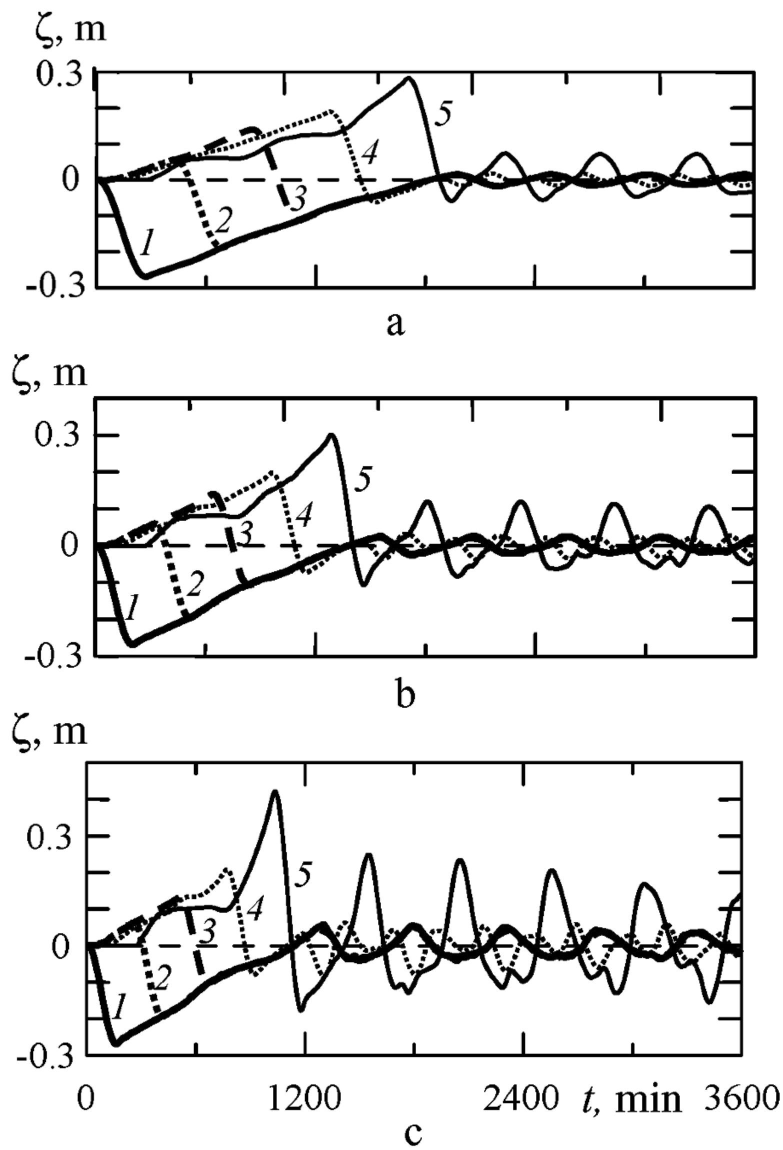

Fig. 4. Oscillations of the free surface of the fluid caused by the passage of a front of atmospheric pressure over basin I with various velocities ($a_0 = 0.3$ m, $W = 100$ km): (a) $C = 6$ m/sec, (b) $C = 8$ m/sec, (c) $C = 10$ m/sec. The curves correspond to the following points of the basin: (1) $x = 0$, (2) $x = l/4$, (3) $x = l/2$, (4) $x = 3l/4$, (5) $x = l$.

$$u_i^0 = \zeta_i^0 = 0, \quad i = 0, \dots, N. \tag{19}$$

The energy characteristics of the fluid in the basin at time t_n are given by the formulas

$$E_K = \sum_{i=1}^{N} e_k^i, \quad E_P = \sum_{i=1}^{N} e_p^i, \quad \text{and} \quad E_T = E_K + E_P \tag{20}$$

following from relations (8) and (9), where

$$e_k^i = \frac{1}{2}\rho D_{i-1/2}^n\left[\left(u_{i-1/2}^n\right)^2 + \left(v_i^n\right)^2\right]\delta \quad \text{and} \quad e_p^i = \frac{1}{2}\rho g\left(\zeta_i^n\right)^2\delta.$$

Numerical Results

The analysis of the response of the fluid in basins I and II to the motion of a baric front was performed by using relations (16)–(20) for various values of the velocity C, width W, and the intensity a_0 of atmospheric perturbations. The function $F(\xi)$ used to describe the horizontal behavior of perturbations of the atmospheric pressure (1) across the front was specified by the formula

$$F = \sin^2\frac{\pi\xi}{2W} \quad (-W < \xi < 0), \quad F = 1 \quad (\xi \le -W), \quad F = 0 \quad (\xi \ge 0).$$

In Fig. 4, we present the oscillations of the free surface at five equidistant points of basin I caused by the passage of a front of atmospheric pressure over the basin with various velocities C. As the front moves from the left lateral boundary of the basin to its right boundary, we observe the formation of a displacement of the sea level nonuniform over the water area and moving together with the atmospheric perturbation. This is, in fact, a transformed hydrostatic displacement of the water surface (2) well visible for all velocities of motion of the atmospheric perturbation. The difference from the hydrostatic deflection is significant and caused by the boundedness of the basin (this circumstance prevents the emission of waves), variations of depth, and motion of the baric front.

As soon as the meteorological front leaves the area of the basin (for $t \ge (l + W)/C$), we observe the formation of oscillations of the level in the basin with period $T \approx 8.5$ h. The oscillations of the level on the left (curves 1) and right (curves 2) boundaries of the basin run in the opposite phases, which means that the single-node barotropic seiche is predominant. The amplitude of residual oscillations of the level observed after the passage of the front in the shallow-water part of the basin increases with the velocity of motion of the baric front and can be 1.5 times higher than the hydrostatic response of the sea surface to the spatially nonuniform external pressure (Fig. 4c). This conclusion completely agrees with the simple solution of the linear problem presented in [15].

The width of basin II is much larger than the width of basin I. Moreover, the zone of small depths in basin II is located near its left boundary. As the front moves over basin II, the maximum nonequilibrium displacements of the level are detected near the right coast of the channel (Fig. 5), which is, most likely, explained by the phenomenon of squeezing of the fluid into the region ahead of the moving front. The indicated displacements of the level and the hydrostatic deflection of the free surface have the opposite signs (curves 5). As the front moves beyond the boundaries of the basin, the oscillations of the level with the maximum amplitude are formed near the left boundary of the basin for all velocities (curves 1). The depths observed in the left part of basin II significantly exceed the depths typical of the shallow-water northwest part of the Black Sea (i.e., of the right part of basin I). Therefore, the amplitudes of seiches generated in basin II are lower for the same velocities of the front (Fig. 5). According to the results of numerical experiments, the nonlinearity of waves and bottom friction weakly affect the oscillations of level in basin II.

In Fig. 6, we illustrate the dependence of the wave motion in basin I on the width of the front. The oscillations of level observed after the passage of the front are determined by the single-node seiche. As earlier, the seiches are especially intense in the shallow-water part of the basin (Fig. 6c). Note that narrow fronts (curves 1) generate seiches more efficiently. These conclusions are also true for basin II.

Consider the energy characteristics of motion of the fluid induced by the passage of the baric front [see relations (20)]. The time variations of the integral values of the potential, kinetic, and total energies in basins I and II are presented in Figs. 7 and 8.

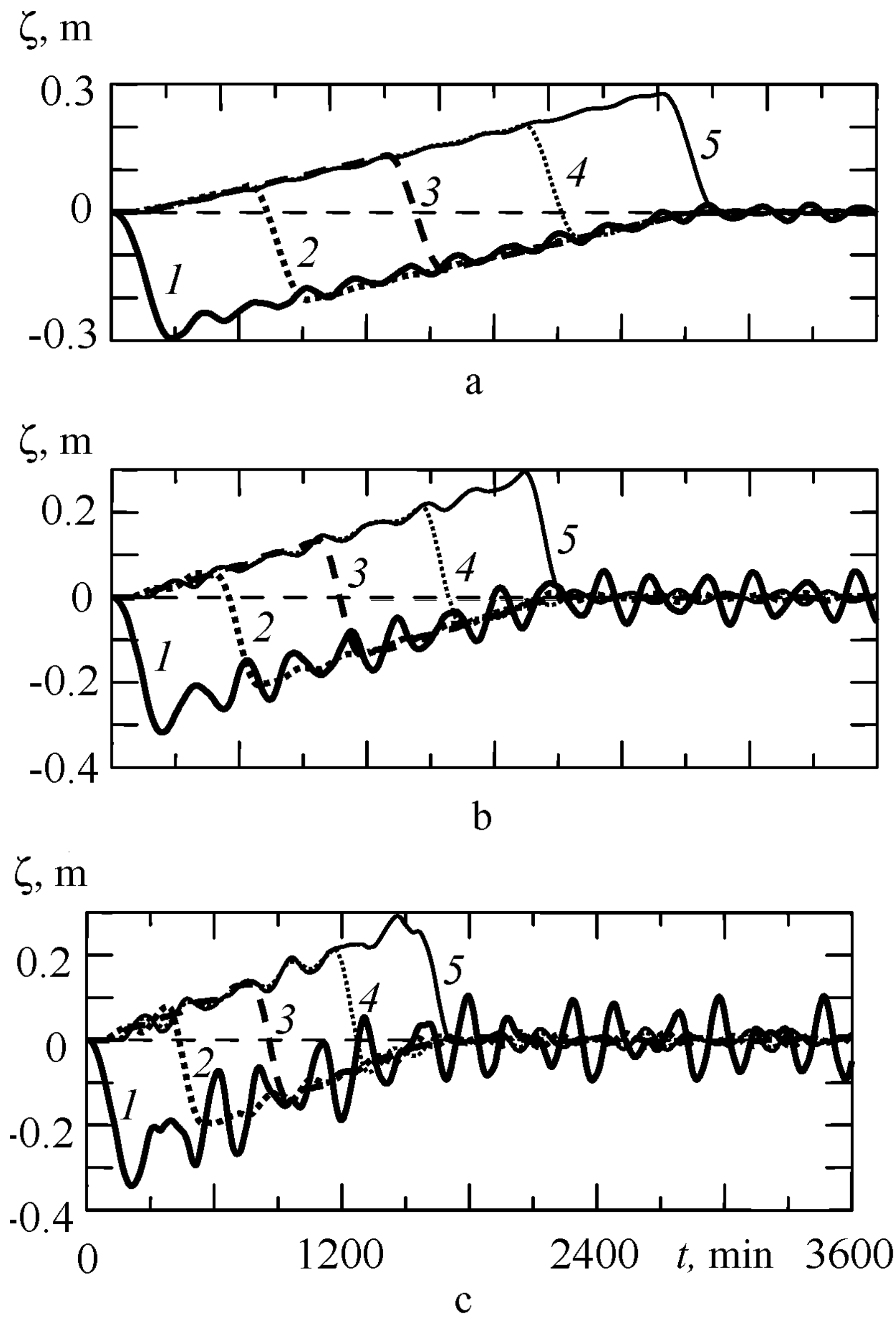

Fig. 5. The same as in Fig. 4 but for basin II.

The most significant perturbations of the free surface of the fluid and the most intense flows in the basins correspond to the location of the frontal zone directly over the basin. In all cases, the integral potential energy is much higher than the kinetic energy and determines the variations of the total energy of the fluid in the basin. The potential energy of the fluid is caused by the dynamic displacements of the level in the zone of action of the baric front. The total energy of residual motions observed in the basin after the passage of the front slowly decreases due to the energy losses for bottom friction (Fig. 7c). After the passage of the front, when the waves can be regarded as free, the potential energy transforms into the kinetic energy, and vice versa. The intensity of residual perturbations of the fluid is maximum for basin I and increases with the velocity of motion of the front.

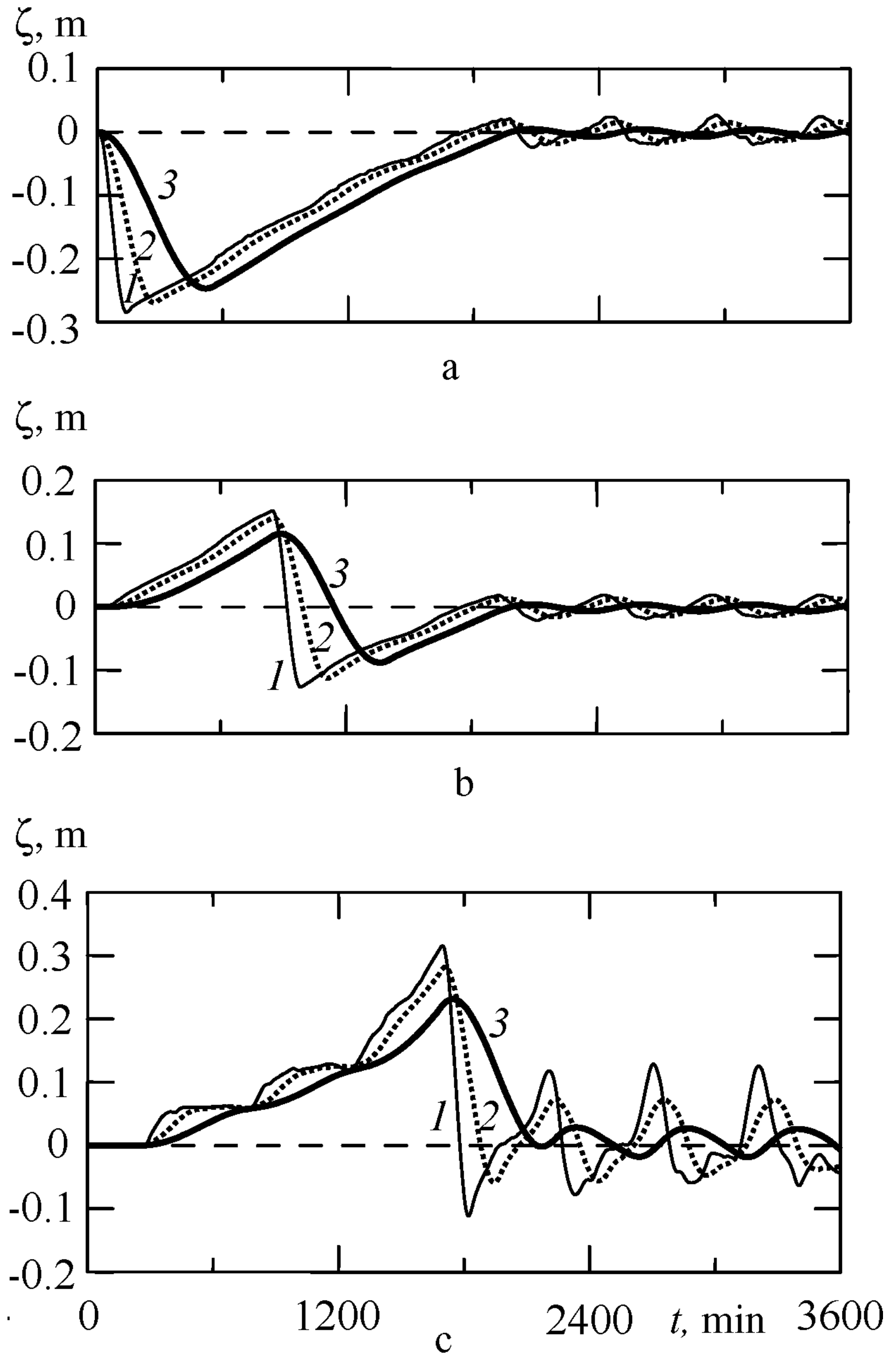

Fig. 6. Oscillations of the free surface of basin I caused by the passage of baric fronts with a velocity $C = 6$ m/sec and different widths at the following points: (a) $x = 0$, (b) $x = l/2$, (c) $x = l$ (for curves 1–3, the width of the front $W = 50$, 100, and 200km, respectively; $a_0 = 0.3$ m).

As follows from Figs. 7 and 8, the variations of the total and potential energies contain an oscillatory component, which is especially well visible in Fig. 8. These oscillations are induced by the distortions of the cup of deflection of the fluid surface (perturbations of the potential energy) caused by the generation of seiches. The faster the motion of the atmospheric front, the smaller the number of oscillations of the hydrophysical fields observed for the time of motion of the baric front directly over the basin.

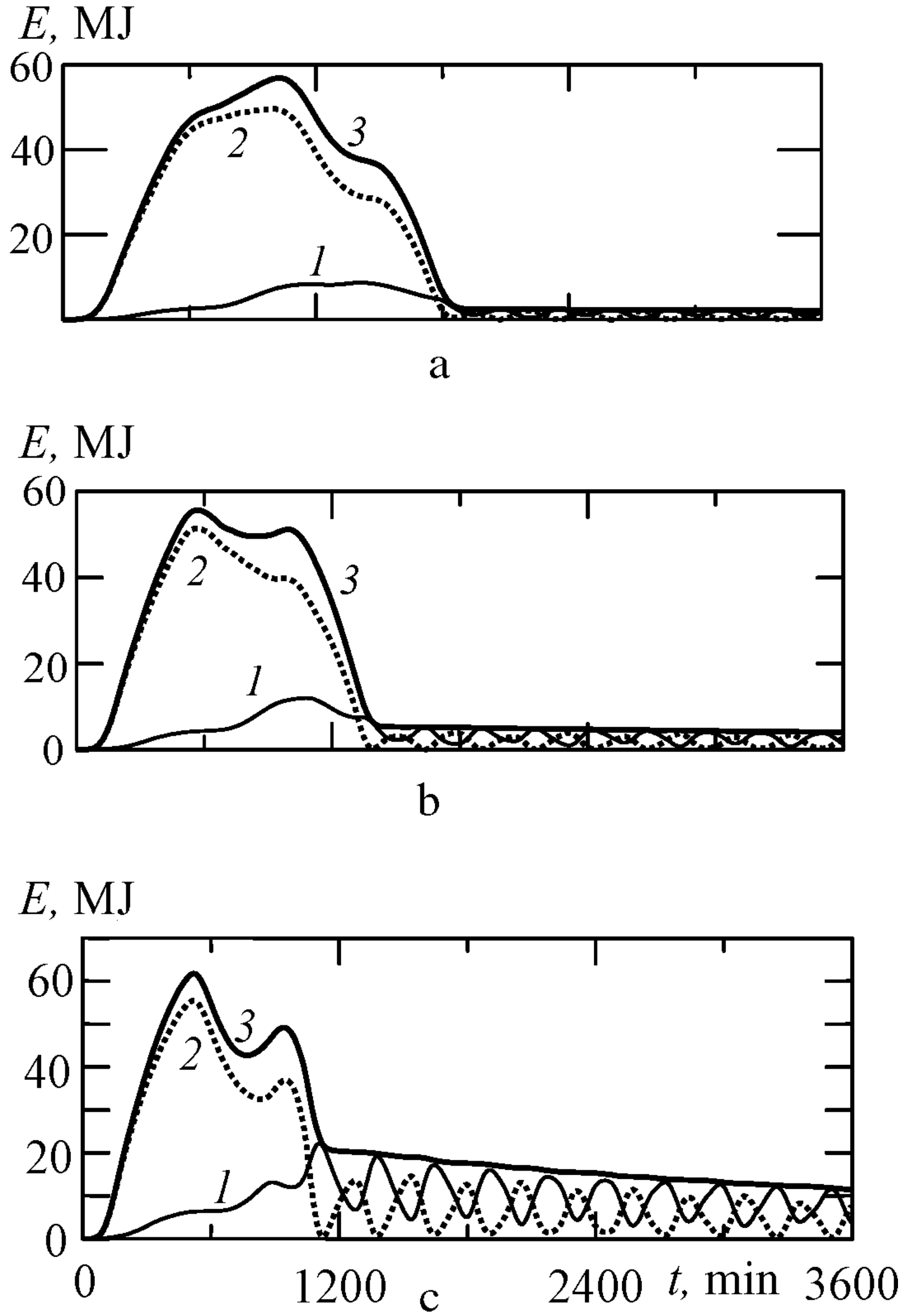

Fig. 7. Kinetic (curves 1), potential (curves 2), and total (curves 3) energies of oscillations of the fluid in basin I caused by the motion of an atmospheric front with $a_0 = 0.3$ m and $W = 100$ km: (a) $C = 6$ m/sec, (b) $C = 8$ m/sec, (c) $C = 10$ m/sec.

The general characteristic of the dependence of the intensity of residual oscillations observed in basin I when the baric front moves outside the limits of the water area on the parameters of the front is given in Fig. 9, where, in the plane of the parameters W and C, we present the isolines of the amplitudes of oscillations of the sea surface in the shallow-water part of the basin. Both the increase in the velocity of motion of the front and the decrease in its width lead to the increase in the efficiency of generation of seiches. For the analyzed ranges of the parameters W and C, the influence of Earth's rotation in the long-wave model (3)–(7) weakens the residual oscillations of the fluid in the basin.

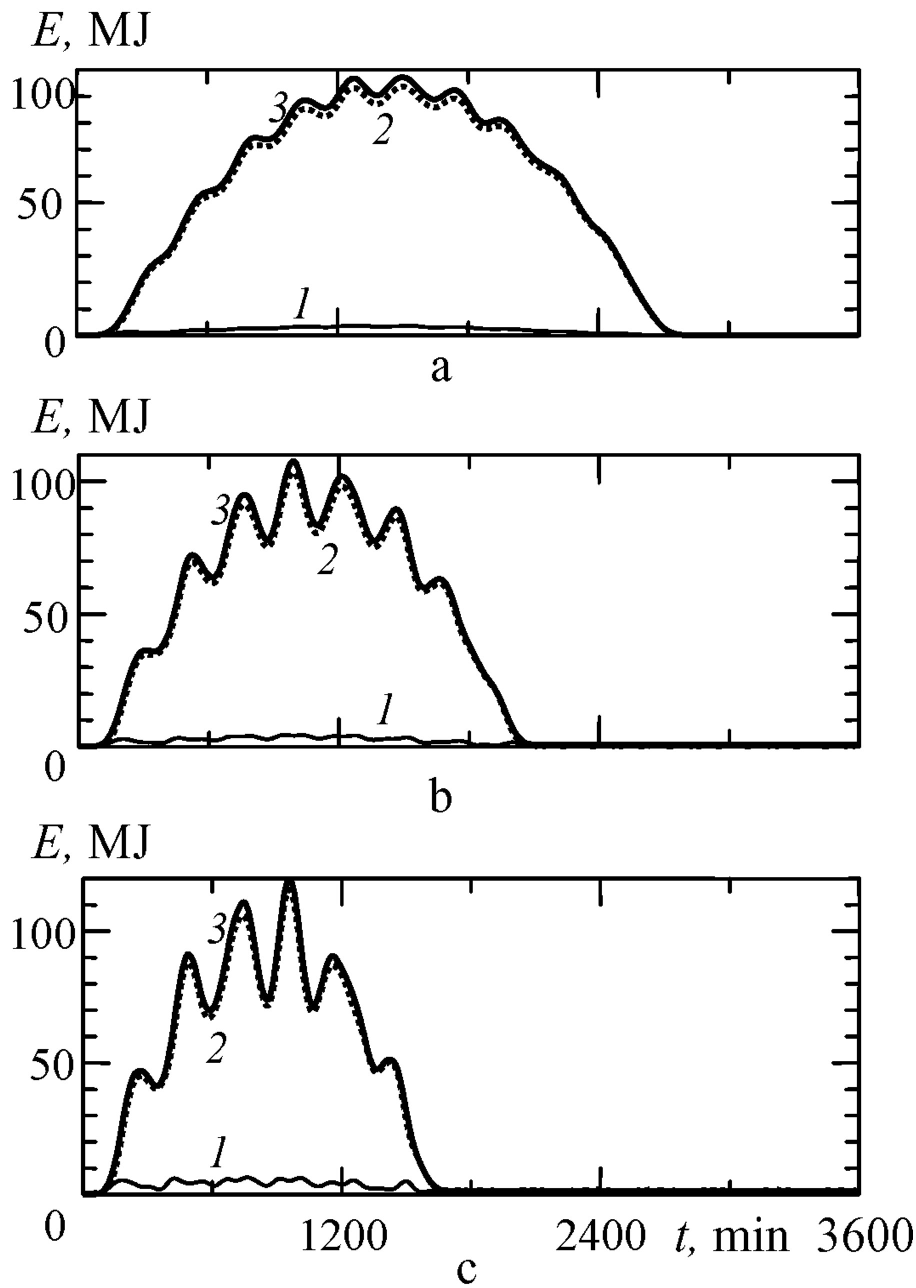

Fig. 8. The same as in Fig. 7 but for basin II.

CONCLUSIONS

Within the framework of the nonlinear theory of long waves, we study the plane problem of generation of barotropic seiches by a front of atmospheric pressure (bounded region of monotonic increase or decrease in the atmospheric pressure) over a bounded basin. We take into account both the square law of bottom friction and Earth's rotation. The problem is solved numerically by the finite-difference method. The numerical analyses are carried out for two basins of variable depth corresponding to certain meridional and zonal sections of the Black Sea. The periods and horizontal structure of the five lowest seiches are determined in the linear approximation.

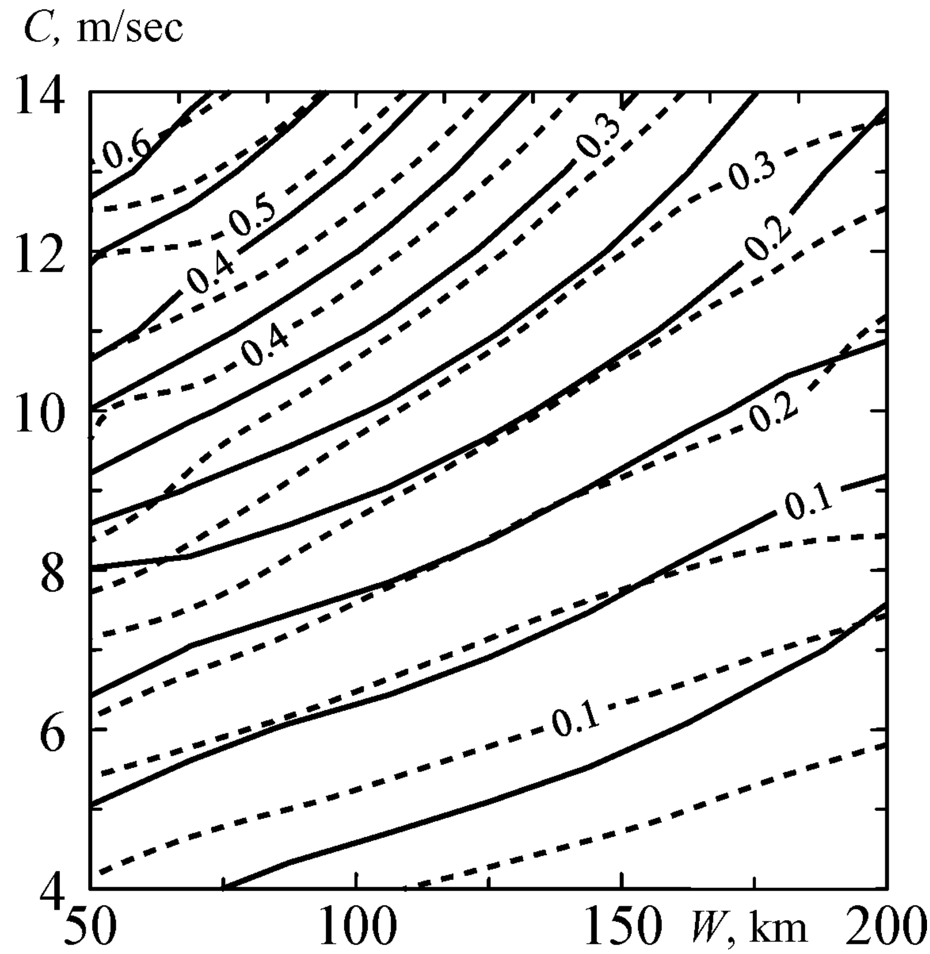

Fig. 9. Dependences of the amplitude of residual oscillations of the level at the point $x = l$ of basin I on the width of the atmospheric front W and the velocity of its motion C with (solid lines) and without (dashed lines) regard for Earth's rotation for a_0 = 0.3 m.

It is shown that the baric front moving over the basin generates the lowest barotropic seiches. The oscillations of the sea level and wave velocity of the flow are especially intense in the shallow-water zones of the basins and determined by the single-node (lowest) barotropic seiche. The amplitude of residual oscillations increases with the velocity of motion of the atmospheric front. The oscillations in the basin slowly decay in time due to the energy losses for bottom friction. The effect of Earth's rotation promotes the generation of longshore currents and a certain weakening of residual oscillations of the fluid in the basin.

The analysis of the integral energy characteristics of oscillations of the fluid in the basins shows that the most significant perturbations of the free surface of the fluid and the most intense currents correspond to the case where the moving frontal zone is located directly over the basin. In all cases, the integral potential energy is much higher than the kinetic energy and, therefore, determines the variations of the total energy of the fluid in the basin. The potential energy of the fluid is determined by the dynamic displacements of the free surface in the zone of the baric front. The intensity of residual oscillations of the fluid increases with the velocity of motion of the atmospheric perturbation.

The influence of nonlinearity and Earth's rotation on the seiches is especially pronounced in the shallow-water regions. According to the numerical results, the contribution of these factors to the dynamics and energy of oscillations of the fluid is small for the analyzed basins.

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