ISSN 0001-4370, Oceanology, 2018, Vol. 58, No. 1, pp. 19–27. © Pleiades Publishing, Inc., 2018.
Original Russian Text © L.V. Cherkesov, T.Ya. Shul'ga, 2018, published in Okeanologiya, 2018, Vol. 58, No. 1, pp. 23–33.

MARINE PHYSICS

Numerical Analysis of the Effect of Active Wind Speed and Direction on Circulation of Sea of Azov Water with and without Allowance for the Water Exchange through the Kerch Strait

L. V. Cherkesov† **and T. Ya. Shul'ga***
Marine Hydrophysical Institute, Russia Academy of Sciences, Sevastopol, 299011 Russia
**e-mail: shulgaty@mail.ru*

Received September 8, 2015; in final form, December 2, 2016

Abstract—The effect of seawater movement through the Kerch Strait for extreme deviations in the level and speed of currents in the Sea of Azov caused by the action of climate wind fields has been studied using the Princeton ocean model (POM), a general three-dimensional nonlinear model of ocean circulation. Formation of the water flow through the strait is caused by the long-term action of the same type of atmospheric processes. The features of the water dynamics under conditions of changing intensity and active wind direction have been studied. Numerical experiments were carried out for two versions of model Sea of Azov basins: closed (without the Kerch Strait) and with a fluid boundary located in the Black Sea. The simulation results have shown that allowance for the strait leads to a significant change in the velocities of steady currents and level deviations at wind speeds greater than 5 m/s. The most significant effect on the parameters of steady-state movements is exerted by the speed of the wind that generates them; allowance for water exchange through the strait is less important. Analysis of the directions of atmospheric circulation has revealed that the response generated by the movement of water through the strait is most pronounced when a southeast wind is acting.

DOI: 10.1134/S0001437018010022

1. INTRODUCTION

The Sea of Azov communicates with the Black Sea through the Kerch Strait by the movement of water. This movement arises from the difference in levels in the northwestern (Azov) and southern (Black Sea) parts, as well as under the action of wind, whose impact on the water level in the strait is on average five to six (and during storms, 10–15) times stronger than the impact of river flow [2, 13]. Currents from the Sea of Azov are observed more often during northern winds, and the current from the Black Sea is less common with southern winds. As well, the flow velocity reaches 154 cm/s in the narrows [19]. The Kerch Strait is an important shipping lane and fishing area of the Azov–Black Sea Basin. Unstable weather in the Kerch Strait, characterized by regular strong wind gusts and storms, poses a great danger for all surface structures, like how in 1944 they destroyed a 4452-m-long bridge that had only been standing for less than four months. A storm on October 11, 2007, resulted in a serious environmental disaster on the Crimean coast due to flooding of ships and oil spills. An additional anthropogenic factor affecting hydrodynamic processes was the construction (currently stopped) of a dam in October 2003, which resulted in the width of the passage between Tuzla Island and the Taman Peninsula decreasing from almost 4 km to 300 m [13].

A series of works by Yu.G. Filippov is devoted to numerical simulation of the Sea of Azov water dynamics. [14], where the main characteristics of wind currents and wind tide events for typical stationary wind fields were studied for the first time with linear two-dimensional models. The authors of [9, 10] studied the currents and free and induced fluctuations in the level of the Sea of Azov using the theory of long waves and the results of two-dimensional modeling [9, 10]. In contemporary publications devoted to simulation of currents in the Sea of Azov and the Kerch Strait, there are studies that analyze the results of the two-layer hydrodynamic model using uniform rectangular grids, which applies the shallow-water equations for the upper layer and three-dimensional equations for the motion of a viscous incompressible fluid in the lower layer [8, 11, 12]. With this mathematical model, flow patterns were obtained in [11] for various wind scenarios, and the influence of the presence or absence of a dam along the Tuzla Spit on currents in the central part of the Kerch Strait was investigated in the absence of background stationary currents. Based on this mathematical model and materials of daily hydrometeorological observations at the coastal base of the Southern Scientific Center of the Russian Acad-

---

† Deceased.

emy of Sciences, the pattern of anomalous phenomena in the Kerch Strait has been reconstructed [8]. Papers [4, 5] study wind tide events and currents in the Sea of Azov without taking into account the Kerch Strait. These studies reveal the features of the formation of sea-level fields and currents generated by various wind fields with the use of a three-dimensional nonlinear σ-coordinate model [15, 20].

The inhomogeneous depth distribution in the Sea of Azov (up to 19 m in the southern part and, at the same time, 0.5–4 m in the coastal regions of Taman and Dinsky bays) implies the need to use mathematical models with special curvilinear coordinate systems (σ-coordinates). In this paper, the simulation of water circulation in a basin with the indicated bottom topology and extensive shallow-water areas is based on the application of the Princeton Ocean Model (POM) [20] adapted to the Sea of Azov region [15].

This work studies the formation of extreme values of wind tide fluctuations in the level and currents in the Sea of Azov Basin (which is relatively small compared to the Black Sea) and their response to currents arising in the Kerch Strait. This study is performed on the basis of numerical experiments. The Kerch Strait, which occupies a boundary position in the intersection of land and sea transport routes, is involved in economic activity, which is the cause of both ecological and political problems. The importance of this study related to the description of circulation of waters in the Sea of Azov when the Kerch Strait is blocked, stems from the transport transition between the Kerch and Taman peninsulas, which is being built in this region between Tuzla Island and Tuzla Spit. It is a combination of subsoil earth structures and parallel-axis structures for rail and road traffic. The planned footings for road and railway bridges will be based on more than 5500 piles, which will narrow the waterway. Therefore, it is of practical interest to study the relationship between currents and deviations of levels in the Kerch Strait formed by acting wind directions, as well as the extreme characteristics of wind tide fluctuations and currents in the Sea of Azov.

The relevance of numerical experiments is heightened by the fact that modeling makes it possible to study not only the parameters of atmospheric impacts on water circulation, but also to test various hypotheses related to changes in the resolution or structure of the estimated area of the basin. The aim of this paper is to determine the conditions under which it is possible to use a simplified model of the Sea of Azov Basin with a solid boundary at the entrance to the strait. Obviously, in the established case, the flow of water through the Kerch Strait should be zero, otherwise the task cannot be considered established due to the increase or drop in the level in the Sea of Azov as a whole caused by water flow through the Kerch Strait. This is possible due to the difference between the average level of the Sea of Azov and a level in the vicinity of the Kerch Strait, as well as due to the depth variability of currents, or the presence of opposite barotropic currents in the strait. However, these currents cannot be large, due to the shallow water and narrowness of the Kerch Strait in the Sea of Azov region. Thus, stationary motions caused by a constant wind should be practically the same with and without the Kerch Strait, and therefore, the circulation in the Sea of Azov can be simulated without taking into account water exchange though the strait.

In the stationary problem, wind and water flow should be set as two independent external factors. However, according to [2], the flow is proportional to the projection of the wind speed (average daily) on the "axis" of the strait, and the effect of wind on the level of the strait exceeds its discharge variations. For this purpose, a comparative analysis of the simulation results was carried out according to scenarios with a computational domain consisting of the Sea of Azov and the Kerch Strait, and a region of simplified geometry (with a boundary at the entrance to the strait). We have studied the dependences of the velocities of surface and deep currents and the extrema of positive and negative surges on the direction and speed of a constant wind with and without water exchange through the strait.

2. FORMULATION OF THE PROBLEM. INFORMATION ON THE MODEL AND ITS PARAMETERS

2.1. Equations of the Model: Initial and Boundary Conditions

The mathematical model is based on the equations of motion and continuity written in a Cartesian coordinate system in which the $x0y$ plane coincides with an unperturbed fluid surface, the x axis is directed to the northeast, y is directed to the northwest, and z is directed vertically upward. The use of Cartesian coordinates in the equations of motion and continuity is valid in cases when the horizontal dimensions of the basin (360 km) are much smaller than the Earth's radius (6400 km). In this case, the relative error of numerical calculations for the Sea of Azov without taking into account the Earth's sphericity, which is calculated as the ratio of the arc length of the Earth's surface [6] connecting the extreme points of the Sea of Azov (45°12′30″–47°17′30″ N and 33°38′–39°18′ E) to the horizontal distance between them, is 0.02%. The equations of motion in the Boussinesq and hydrostatics approximation [15, 20] are as follows:

$$\begin{aligned}\frac{du}{dt} - fv + \frac{1}{\rho}\frac{\partial p}{\partial x} &= 2\frac{\partial}{\partial x}\left(A_M\frac{\partial u}{\partial x}\right)\\ &+ \frac{\partial}{\partial y}A_M\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right) + \frac{\partial}{\partial z}K_M\frac{\partial u}{\partial z},\end{aligned} \tag{1}$$

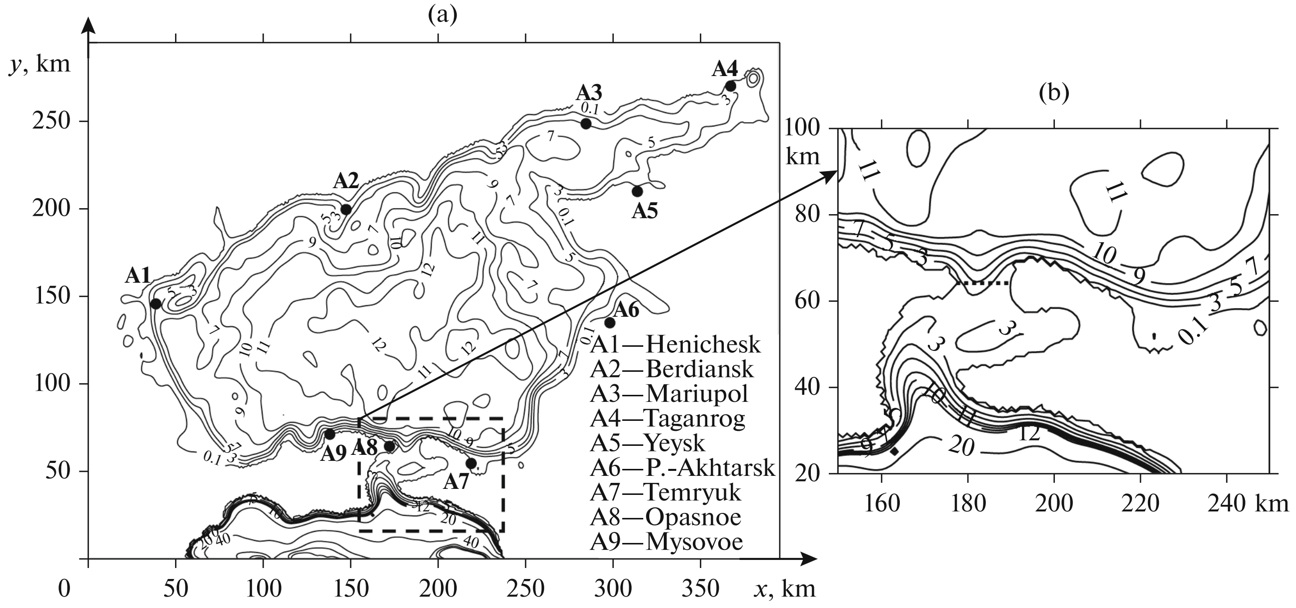

Fig. 1. (a) Position of coastal stations along Sea of Azov coast and (b) cross section through which water flow is calculated. Thin lines with numbers show isobaths. Region of strait is enclosed in rectangle delineated by dotted line.

$$\frac{dv}{dt}+fu+\frac{1}{\rho}\frac{\partial p}{\partial y}=\frac{\partial}{\partial x}A_M\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}\right)+2\frac{\partial}{\partial y}\left(A_M\frac{\partial v}{\partial y}\right)+\frac{\partial}{\partial z}K_M\frac{\partial v}{\partial z},\tag{2}$$

$$\frac{\partial p}{\partial z}+g\rho=0,\tag{3}$$

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0.\tag{4}$$

In the model equations and further, the following conventional notation is used: $u\ (x, y, z, t)$, $v\ (x, y, z, t)$, $w\ (x, y, z, t)$ are the velocity vectors of fluid flow; t is the time; $p\ (x, y, z, t)$ is the pressure; ρ is the water density; g is gravitational acceleration; f is the Coriolis parameter; $\zeta\ (x, y, t)$ is the topography of the free surface (elevation of the sea level from its unperturbed state). The coefficient of horizontal turbulent viscosity $A_M\ (x, y, z, t)$ is calculated as a function of the horizontal velocity gradients using the Smagorinsky formula [23], and the Mellor–Yamada semiempirical differential model [22] is used to parameterize the coefficient of vertical turbulent viscosity $K_M\ (x, y, z, t)$.

The boundary conditions on a free surface have the form

$$w\big|_{z=\zeta}=\frac{\partial\zeta}{\partial t}+u\frac{\partial\zeta}{\partial x}+v\frac{\partial\zeta}{\partial y},\tag{5}$$

$$\rho K_M\left(\frac{\partial u}{\partial z},\frac{\partial v}{\partial z}\right)\bigg|_{z=\zeta}=\left(\tau_{0x},\tau_{0y}\right).\tag{6}$$

Here, $\tau_{0x}=\rho_a C_a W_x\left|\mathbf{W}\right|$, $\tau_{0y}=\rho_a C_a W_y\left|\mathbf{W}\right|$ are the projections of tangential wind stresses, $\mathbf{W}$ is the wind speed vector at an altitude of 10 m above sea level, ρ_a is the air density in standard atmospheric conditions, and C_a is an empirical coefficient of surface friction as a function of the wind speed [21]:

$$C_a=k^2\left(14.56-2\ln W_0\right)^{-2},\tag{7}$$

where $k = 0.4$ is the Karman constant, and $W_0=\left|\mathbf{W}\right|/W_1$; $W_1 = 1$ m/s.

Adhesion conditions are fulfilled at the lateral boundaries. When solving the problem with allowance for the strait, we used the idealized case of specifying conditions on the fluid boundary: a free flow condition was adopted (the vanishing of the derivative of the normal velocity component to the fluid boundary $\partial\mathbf{U}_n/\partial\mathbf{n}\big|_\Gamma=0$). This method was used for the initial understanding of the significance of a steady fluid flow through the strait. The fluid boundary Γ (Fig. 1a) corresponds to the vertical profile at 44.81° N along the Black Sea ($60\le x\le 240$ km, $y = 0$), $\mathbf{n}$ is the normal tangential direction. When solving the problem without accounting for the strait, we considered a closed basin in which there is a vertical side wall along 39.33° N (dashed line in Fig. 1b).

At the bottom ($z = -H(x, y)$), the normal velocity component

$$\left(w+u\frac{\partial H}{\partial x}+v\frac{\partial H}{\partial y}\right)\bigg|_{z=-H}=0.\tag{8}$$

The near-bottom tangential stresses are related to the speed by a quadratic dependence [20]:

$$\rho K_M \left(\frac{\partial u}{\partial z}, \frac{\partial v}{\partial z} \right) \Bigg|_{z=-H} = \left(\tau_{bx}, \tau_{by} \right), \tag{9}$$

where $\tau_{1x} = c_b u_b \left| \mathbf{U}_b \right|$; $\tau_{1y} = c_b v_b \left| \mathbf{U}_b \right|$; c_b is the coefficient of bottom friction, which is logarithmic ($c_b = k^2 \left[\ln z_b / z_0 \right]^{-2}$, where z_b is the first grid point nearest the bottom, $z_0 = 3$ cm is the roughness parameter of the bottom surface); $\mathbf{U}_b = (u_b, v_b)$ is current bottom horizontal speed.

There is no fluid motion at the initial time $t = 0$, and the free surface is horizontal:

$$\begin{aligned} &u(x,y,z,0) = 0, \quad v(x,y,z,0) = 0, \\ &w(x,y,z,0) = 0, \quad \zeta(x,y,z,0) = 0. \end{aligned} \tag{10}$$

Closeness to a steady-state regime is estimated from the relative changes in the kinetic $E_K(t)$ and potential $E_P(t)$ energies averaged over the sea volume. It is believed that the steady-state regime is achieved at $\max\left(\left| \left(E_K^{n+1} - E_K^n \right) / E_K^n \right|, \left| \left(E_P^{n+1} - E_P^n \right) / E_P^n \right| \right) \le 10^{-3}$, where n is the time step [7]. Based on this, the time in which fluid motion is established is determined: $t = t_1$.

To calculate the water exchange through the Kerch Strait at each time step, the total flow of water passing through the profile at a latitude of 39.33° N is calculated (Fig. 1b). The volume of flowing water in a time $0 \le t \le t_n$ is determined by the expression

$$G(t_n) = S \sum_{i=1}^{n} \overline{\mathbf{U}(t_i)} t_i, \tag{11}$$

where $\overline{\mathbf{U}(t_i)}$ is the average velocity of currents in the cross section of the strait at the ith time step and S is the cross-sectional area.

2.2. Numerical Model

In the initial equations (1)–(4), boundary conditions (5), (6), (8), (9), and initial conditions (10), the transition from coordinate z to the dimensionless variable σ is carried out using the relations $x^* = x$, $y^* = y$, $\sigma = [z - \zeta]/[H + \zeta]$, $t^* = t$, where $\sigma \in [-1; 0]$. A modified version of the POM model [15, 20] was used for numerical calculations. The model was modified in the program unit to calculate the tangential stresses of wind friction and expanded by including additional units to calculate the extreme deviations of the level and currents. The number of calculated grid levels along the vertical was 11, and a version of the model was used that had an increased spatial resolution (the linear dimensions of the grid cell were $\Delta x = \Delta y \sim 1$ km) compared with the previous implementations [4, 5]. The equations were integrated with a step of $\Delta t = 18$ s to determine the averaged two-dimensional horizontal velocity and sea level components, and with steps of $10\Delta t = 3$ min to calculate the deviations from the found average and vertical velocity components.

The relief of the bottom of the calculated regions (Fig. 1) for the two variants of model grids is interpolated from an array of depths taken from navigation charts. The first model basin of the Sea of Azov is closed with a border at the entrance to the Kerch Strait. The second one includes the Sea of Azov and the Kerch Strait with a fluid boundary on a transect in the Black Sea. Sea level variations are analyzed on each grid for nine stations located near large settlements in accordance with their geographical coordinates.

3. RESULTS AND DISCUSSION

Study of steady-state regimes plays an important role in investigating the specific features of sea basin water dynamics. Seasonal features of the weather in the Sea of Azov region form under the influence of two large-scale synoptic processes: the Siberian and North Atlantic anticyclones. In spring and summer, the spur of the Azores maximally affects the water area of the sea, which determines the prevalence of southwest (SW) winds that coincide with the direction of the greatest extent of the sea and cause significant wind tide processes in the Sea of Azov. The latter often cause hurricane floods (e.g., in Taganrog Bay on September 24, 2014 [8]). The effect of water exchange through the Kerch Strait on sea level can be traced in strong southeast (SE) winds, which increase the influx of Black Sea water to the Sea of Azov, and in the northwest (NW) winds, which increase the flow of Azov water to the Black Sea.

Based on long-term instrumental observation data, it is known that waves with a height of 0.7–1 m predominate in the strait, the maximum velocities of the Black Sea current reach 60–80 cm/s, and the flow from the Sea of Azov reaches 40–70 cm/s, with an average annual frequency of 42 and 58% respectively [2, 3].

Numerical experiments were carried out for the acting seasonal directions (SW, NW, SE) of three wind speeds: 5, 10, and 15 m/s. The evolution of wind over the sea surface occurs in two stages. From the initial time $t = 0$, wind of a given (constant) direction starts to act on the water surface, the speed of which increases with time (3 h) according to a linear law. Then, the wind speed at each point of the water reaches a specified value, then does not change.

3.1. Comparative Analysis of Wind Tide Values at Coastal Stations of the Sea of Azov with and without Water Exchange through the Kerch Strait

The time variability of deviations in the level and currents yields the generalized characteristics of steady-state movements in the sea during integration of the model. The effect of intensity and direction of the constant wind on extreme wind tide events and the speed of the currents in the steady-state regime was studied in a series of numerical experiments. The results are compared with the calculations performed in the modeling of stationary movements in the Sea of Azov without taking into account water exchange through the Kerch Strait.

Figure 2 shows the fields of sea level at the moment of time, from which the movements are set steady ($t = t_1$). These fields were generated by a constant wind with different directions acting at a speed of 15 m/s. It can be seen that with steady motion with different wind directions, there is a decrease in the level at leeward shores (negative surge) and an increase in windward shores (positive surge). The nodal (dashed) line is oriented perpendicular to the direction of the active wind; it crosses the central part of the sea in the zonal (Figs. 2b, 2c) and meridional (Fig. 2a) directions. In the case of SW and SE winds, Taganrog Bay is the most affected by wind tide processes (up to 1.4 m) (Figs. 2a, 2b). A northwestern storm wind, on the contrary, causes strong discharge of water along the east coast (Fig. 2c).

Table 1 shows the dependences of deviation in level ($|\zeta|$) on wind direction and speed at coastal stations of the Sea of Azov in the steady state with and without water exchange through the strait. From analysis of the data, it follows that at each station, the most significant wind tide events are noted under the action of SW wind at higher speeds and when water exchange with the Black Sea is taken into account.

A comparison of the $|\zeta|$ values generated by a wind of one direction, obtained when solving the problem with and without the effect of the strait, shows that allowance for water exchange leads to a significant increase in level deviations only at wind speeds of more than 5 m/s. Thus, the greatest differences in the values of surges and drifts at a wind speed of 10 m/s are 8% (SW), 24% (SE), and 13% (NW); at a wind speed of 15 m/s, it is 10% (SW), 27% (SE), and 14% (NW). The increase in the active wind speed is more significant compared with the effect of water exchange through the strait. A constant wind of one direction (SW), but at a higher speed (10 and 15 m/s), leads to an increase in level deviations by 62%.

The amplitudes of wind tide events are also significantly affected by the direction of the acting wind. It should be noted that at the considered stations, the greatest fluctuations in level occur for a SW wind. For this wind, the largest positive surges are noted at the Taganrog (143 cm), Yeysk (127 cm), and Primorsko-Akhtarsk stations (121 cm), and the maximum negative surges, at the Genichesk station (133 cm). Winds of other directions generate smaller deviations in level. In the SE wind, the highest peaks in level occur at the Taganrog (108 cm) and Mariupol (79 cm) stations, and the maximum decrease in level, at the Temryuk (59 cm) and Cape (58 cm) stations. The NW wind causes the greatest positive surges at the Temryuk station (50 cm), and the largest negative surges, at the Taganrog (126 cm) and Mariupol (71 cm) stations.

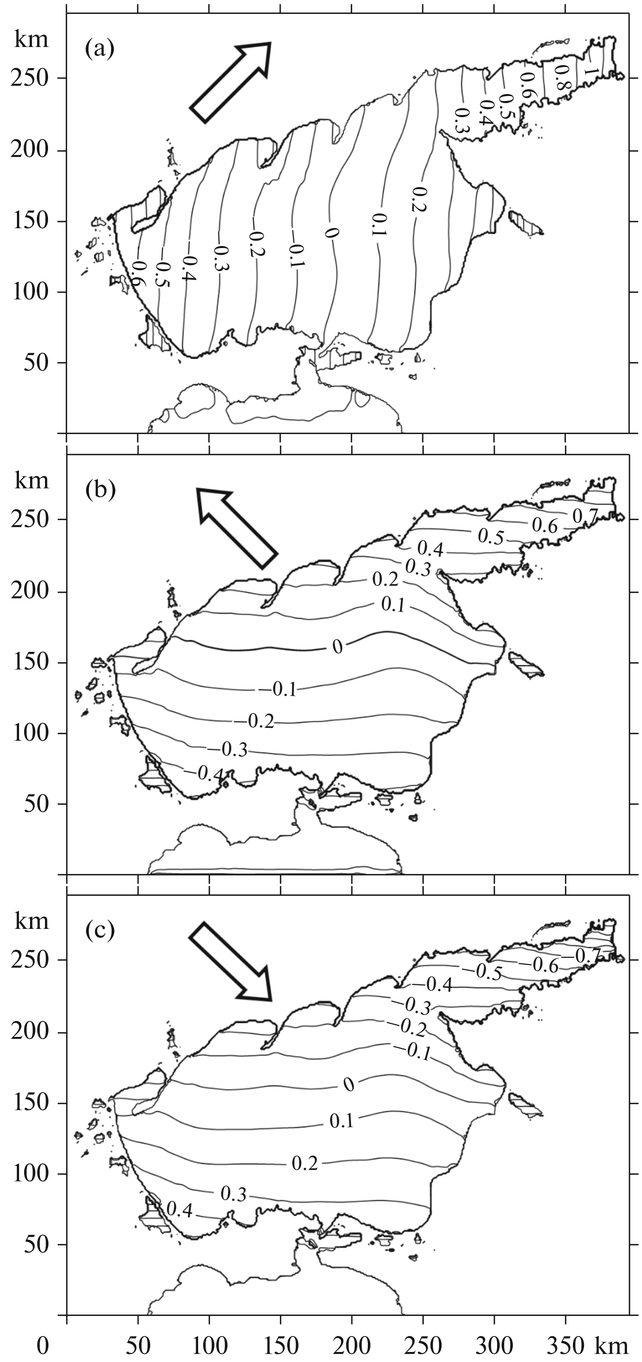

Fig. 2. Results of numerical simulation of shifts in level (m) of Sea of Azov in steady-state conditions for different wind directions indicated by arrows: (a) southwest, (b) southeast, (c) northwest.

From the analysis of the data, it follows that regardless of the wind direction, the largest positive and negative surges are formed in the Taganrog region. At the Genichesk and Berdyansk stations, the greatest negative surges also develop with the SW wind. The most

Table 1. Deviations in level (cm) in steady state, which are caused by constant wind with three speeds and directions at coastal stations of Sea of Azov (1) taking into account and (2) not taking into account the strait

Coastal stations	Acting wind																	
	5 m/s						10 m/s						15 m/s					
	SW		SE		NW		SW		SE		NW		SW		SE		NW	
	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2
Henichesk	−12	−12	0	0	0	0	−54	−52	−1	−1	1	1	−133	−120	−4	−3	3	3
Berdiansk	−4	−4	−3	−3	3	3	−19	−18	17	14	−18	−16	−49	−44	46	37	−43	−38
Mariupol	10	10	−5	−5	6	6	40	37	31	24	−32	−29	92	84	79	58	−71	−63
Taganrog	21	21	−9	−8	8	8	81	77	44	33	−48	−42	143	130	108	81	−126	−110
Yeysk	14	14	−4	−4	4	4	55	52	16	13	−16	−14	127	117	41	31	−32	−29
P.-Akhtarsk	10	10	−1	−1	1	1	46	43	−7	−6	8	7	121	110	−20	−15	12	11
Temryuk	6	6	3	3	−3	−3	29	27	−22	−17	22	20	75	68	−59	−47	50	43
Opasnoe	−4	−4	3	3	−3	−3	−17	−16	−21	−16	21	19	−43	−39	−56	−43	46	42
Mysovoe	−7	−6	3	3	−3	−3	−27	−26	−22	−17	21	19	−67	−62	−58	−42	49	44

dangerous, from the viewpoint of negative surges for the Mariupol, Taganrog, and Yeisk stations, is the NW wind, while the maximum positive surges here are caused by the SW wind. In Primorsko-Akhtarsk, negative surges occur with the SE wind, while the SW wind causes significant level rises. At the Temryuk station, positive surges develop in the SW wind, while significant negative surges develop in the SE wind. In the areas of the Opasnoe and Mysovoe stations, rises in level are observed in the NW wind; they are smaller than the negative surges that occur in the SW and SE winds.

Thus, the direction and strength of the active wind is the predominant factor affecting the magnitude of positive and negative surges. The greatest increase in the amplitudes of wind tide fluctuations associated with taking into account water exchange through the Kerch Strait is 24% (with the SE wind), whereas the effect of winds of higher speed leads to an increase in these quantities by 62%. The change in wind direction from SW to NW at Taganrog station leads to a decrease in the positive surge by 25 and 38% with and without the strait, respectively.

Let us determine the effect of wind speed and direction, as well as water exchange through the strait, on deviation in the level of the open part of the Sea of Azov in the steady-state regime. Analysis of the calculation results and comparison of the two $|\zeta|$ values obtained under different conditions in the strait and with the same wind effect shows their coincidence within 10% (at wind speeds of 5 and 10 m/s). A strong SE wind at a speed of 15 m/s causes the greatest difference between the amplitude of level fluctuations calculated with and without water exchange with the Black Sea. For the three investigated constant wind directions, it is 9, 22 and 12% (SW, SE, and NW respectively). It should be noted that the speed of the active wind exerts a more significant effect (67%) on the magnitude of steady-state fluctuations in the open sea.

3.2. Analysis of Speeds of Stationary Currents in the Sea of Azov with and without Water Exchange through the Kerch Strait

Figure 3 shows the spatial distributions of the speed and direction of currents at the 1 and 10 horizons m, at time $t = t_1$ with a constant wind of different directions, at a speed of 15 m/s. The flow fields are obtained by linear interpolation of the numerical simulation results from σ-coordinate surfaces to the plane z = const.

Analysis of the fields shows that currents in the steady-state regime are characterized by pronounced eddy formations. Their position and configuration are determined by the direction of the wind. The most intense currents occur in the deep-water part of the sea. With (Under) the SW wind in the Sea of Azov, two circulation systems appear, which are oriented in a zonal direction (Fig. 3a). At the boundary between these circulations, the direction of fluid flow is oriented opposite the actual wind. In Taganrog Bay, a pair of eddies of opposite sign are formed. For a NW wind, two circulations of opposite sign are formed in the central part of the sea (Fig. 3c). The larger circulation (cyclonic) adjoins the west bank and contains a small eddy formation. The smaller, but more powerful circulation (anticyclonic), is located in the eastern part of the sea. A narrow band of water mass transfer, which is oriented opposite the wind, is located between these two circulations. The SE wind forms currents whose fields are a mirror image of the current fields in the NW wind (the same configuration of eddy formations is traced, but they have the opposite sign) (Fig. 3b).

Currents are observed at a depth of 10 m (Fig. 3) in the central part of the water area, the direction of

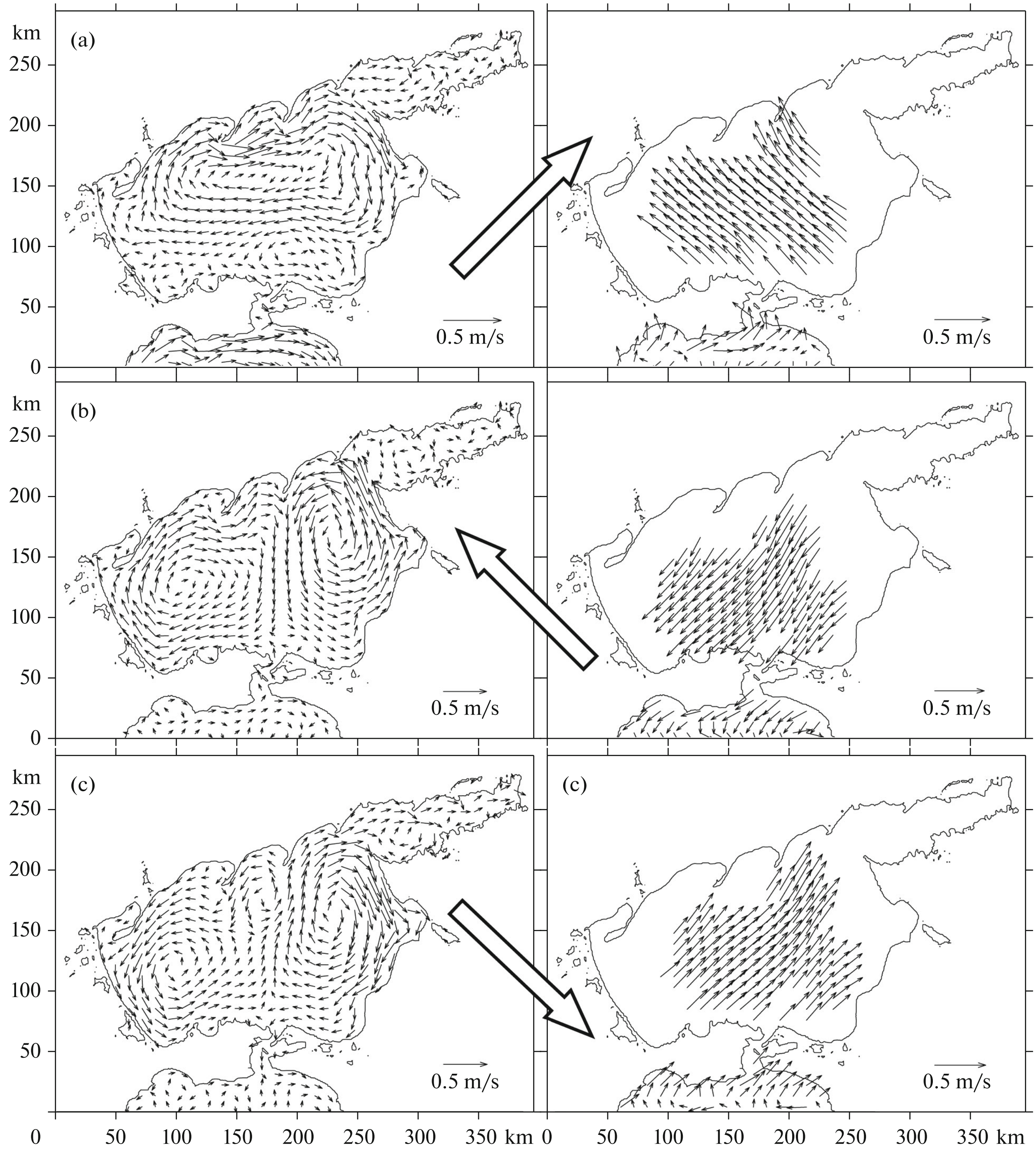

Fig. 3. Results of numerical simulation of fields of stationary currents of Sea of Azov at various horizons: 1 m (left column), 10 m (right column). Different wind directions are indicated by arrows: (a) southwest, (b) southeast, (c) northwest at wind speed of 15 m/s.

which deviates by 135° or more from the direction of the active wind. As follows from Fig. 3, the directions of currents through the strait are opposite when exposed to the same wind in the surface and near-bottom layers. In the near-bottom layer, for the SW and NW winds (Figs. 3a, 3c), flows through the Kerch Strait are directed from the Black Sea to the Sea of Azov, and in the surface layer (Figs. 3a, 3c), in the opposite direction. In the SE wind (Fig. 3b), currents at a depth of 10 m are directed from the Sea of Azov to the Black Sea, i.e., back to their direction in the surface layer.

Table 2 shows the speeds of stationary currents at different horizons, depending on the speed and direction of the wind, with and without water exchange through the strait. From analysis of these data, it fol-

Table 2. Speeds of stationary flows (cm/s) at different horizons of Sea of Azov as function of speed and direction of active wind, obtained with (1) and without (2) taking strait into account

Horizon, m	Acting wind																	
	5 m/s						10 m/s						15 m/s					
	SW		SE		NW		SW		SE		NW		SW		SE		NW	
	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2
1	14	11	16	12	14	11	44	40	46	39	42	41	87	64	122	85	99	69
3	11	9	13	10	12	9	28	23	38	28	35	28	73	52	113	68	94	57
5	9	8	11	9	10	8	20	14	35	23	31	22	62	39	98	46	79	44
10	6	5	8	6	7	6	17	13	24	16	21	16	41	29	51	35	42	27

lows that the values of the steady-state current speed found from the simulation with the effect of the strait under the action of the same wind are greater than without taking the strait it into account. In this case, allowance for water exchange at the horizons under consideration leads to a difference in the speeds of currents not exceeding 45%. The greatest current speeds caused by the wind of the same speed are seen for the SE wind; the smallest, for the NW wind. Thus, the maximum speeds of surface currents calculated with allowance for the effect of the strait at a wind speed of 15 m/s are 0.87 (SW), 1.22 (SE), and 0.99 m/s (NW). The relative difference between the largest and smallest values of these speeds is 30%. A similar relationship between the speeds of currents is also observed at other horizons under the action of a constant wind with speeds of 5 and 10 m/s. Thus, the SE wind acting along the Kerch Strait causes currents whose speeds exceed (by 12–30%) the speeds of currents caused by the SW or NW wind.

Let us establish the effect of wind direction and speed on the integral water exchange ($G(t)$) through the Kerch Strait in the steady state. In numerical experiments, the values of the function $G(t)$ are calculated according to (11) at each step in time, where the values of the vertical averaged speeds of currents in the strait are taken at five points uniformly located in the cross section (Fig. 1b). It should be noted that the maximum current speeds are reached at the center of the strait and depend on the direction of the active wind (15 m/s): 0.33 (SE), 0.29 (NW), and 0.21 m/s (SW). They are 1.5 times higher than the current speeds at the western boundary of the strait: 0.23 (SE), 0.19 (NW), 0.14 m/s (SW). The S value can be found from the real bottom relief (the average depth of the cross section of the strait is 4 m, and the width is 10 km).

From the analysis of the time dependence of the integral water flow rate (m^3) through the strait during the calculation period (200 h), it can be concluded that the largest volume of water flow occurs for the SE wind, and the smallest, for the NW wind: 53.6 (SE), 26.4 (NW), 12.7 m^3 (SW). These results agree with the observation data of the average annual influx of Black Sea waters through the Kerch Strait and the flow of Azores into the Black Sea [16].

The average long-term flow through the Kerch Strait during the periods 1927–1940 and 1948–1970 was 50.6 km^3/year for the Azov stream, 32.7 km^3/year for the Black Sea, and 17.9 km^3/year in general [3], which is consistent with the flow rate obtained from the water balance for the Sea of Azov based on current speed measurements [1]. According to these data (more than 400 determinations of water consumption were measured over the period from 1963 to 1974 in different seasons and in different synoptic situations), the average values of water flow are 77 km^3/year for the Sea of Azov currents and 51 km^3/year for the Black Sea currents, with prevalence of the Azov flow by 26 km^3/year. The average current speed of 1.7 cm/s corresponds to the magnitude of this water flow and cross-sectional area in the northern narrows of the Kerch Strait (29 400 m^2) [18]. In cases of storm winds, the flow calculated from the measured speeds of currents [1] reaches 315 km^3/year. The current speed averaged over the cross-sectional area exceeds 30 cm/s, which agrees with the found water flow and average current speed values (Table 2).

4. CONCLUSIONS

The paper presents the results of the study of wind tide phenomena and currents caused by the action of a constant wind in the Sea of Azov. It was found that the variability of water exchange through the Kerch Strait correlates well with variations in the direction and intensity of wind action, which affects stationary movements in the Sea of Azov. Numerical solutions to this problem are given in the tables of the values of surges and current speeds for various characteristics of the acting constant wind.

Let us formulate the results of studies carried out:

—Allowance for the water exchange through the Kerch Strait has a marked effect on the speed of steady currents and wind tide phenomena at wind speeds greater than 5 m/s;

—Numerical simulation of steady flows in the Sea of Azov at wind speeds of 10 and 15 m/s, which was performed taking into account water exchange through the strait, showed an increase in extreme wind tide events by no more than 25% compared to the calculation results obtained without taking into account the strait;

—The SE wind—in the presence of water exchange through the strait—generates currents whose speeds are 30% higher than the speeds of steady movements caused by the SW and NW winds;

—The speed of the active wind exerts the most significant impact on the increase in the extreme of wind tide events in the open sea, and the maximum difference in amplitudes of positive and negative surges caused by wind of one direction with speed of 10 and 15 m/s is 67%;

—Analysis of the directions of atmospheric circulation revealed that the response to movement of water through the Kerch Strait is most pronounced for an intense SE wind; the difference in the values of the positive and negative surges obtained with and without the strait in this case does not exceed 24%;

—Out of the three considered wind directions, the SW wind causes the highest values of wind tides (up to 12%) and deviations in level in the open part of the Sea of Azov (up to 29%), regardless of whether water exchange through the strait is taken into account.

REFERENCES

1. E. N. Al'tman, "The variability of water expenditure in the Kerch Strait according to field observations," Tr. Gos. Okeanogr. Inst., No. 132, 17–28 (1976).
2. E. N. Al'tman, "Water dynamics in the Kerch Strait," in *Hydrometeorology and Hydrology of the Soviet Seas*, Vol. 4: *The Black Sea* (Gidrometeoizdat, St. Petersburg, in *Hydrometeorology and Hydrology of the Soviet Seas*, Vol. 4: *The Black Sea* (Gidrometeoizdat, St. Petersburg, 1991), pp. 291–328.
3. *Hydrometeorology and Hydrochemistry of the Soviet Seas*, Vol. 5: *The Azov Sea* (Gidrometeoizdat, St. Petersburg, 1991) [in Russian].
4. V. A. Ivanov, L. V. Cherkesov, and T. Ya. Shul'ga, "Investigation of effects of spatially and temporally variable wind on currents, surges, and admixture spread in the Sea of Azov," Russ. Meteorol. Hydrol. **37**, 553–559 (2012).
5. V. A. Ivanov, L. V. Cherkesov, and T. Ya. Shul'ga, "Dynamic processes and their influence on the transformation of the passive admixture in the sea of Azov," Oceanology (Engl. Transl.) **54**, 426–434 (2014).
6. V. P. Kozhukhov and A. M. Zhukhlin, *Mathematical Basis of Navigation* (Transport, Moscow, 1987) [in Russian].
7. A. A. Kordzadze, D. I. Demetrashvili, and A. A. Surmava, "Numerical modeling of hydrophysical fields of the Black Sea under the conditions of alternation of atmospheric circulation processes," Izv., Atmos. Ocean. Phys. **44**, 213–224 (2008).
8. G. G. Matishov, "The Kerch Strait and the Don River delta: safety of communications and population," Vestn. Yuzh. Nauch. Tsentra **11** (1), 6–15 (2015).
9. G. G. Matishov and Yu. I. Inzhebeikin, "Numerical study of the Azov Sea level seiche oscillations," Oceanology (Engl. Transl.) **49**, 445–452 (2009).
10. G. G. Matishov, R. M. Savitskii, and Yu. I. Inzhebeikin, "Conditions and consequences of ship accidents in the Kerch Strait during a storm on November 11, 2007," Nauka Yuga Ross. **4** (3), 54–63 (2008).
11. G. G. Matishov and A. L. Chikin, "An approach to modeling wind currents in Kerch Strait," Dokl. Earth Sci. **445**, 920–923 (2012).
12. G. G. Matishov and A. L. Chikin, "Analysis of wind currents in the Kerch Strait using the mathematical modeling," Nauka Yuga Ross. **8** (2), 27–32 (2012).
13. D. Ya. Fashchuk, S. N. Ovsienko, and O. A. Petrenko, "Ecological problems of Cimmerian Bosporus," Chernomorsk. Vestn., No. 1, 52–58 (2007).
14. Yu. G. Filippov, "Calculation of the marine currents," Tr. Gos. Okeanogr. Inst., No. 103, 87–94 (1970).
15. V. V. Fomin, "Numerical modeling of water circulation in the Sea of Azov," Nauch. Tr. Ukr. Nauchno-Issled. Gidrometeorol. Inst., No. 249, 246–255 (2002).
16. A. P. Tsurikova and E. F. Shul'gina, *Hydrochemistry of the Sea of Azov* (Gidrometeoizdat, Moscow, 1964) [in Russian].
17. A. L. Chikin, "Mathematical model of the wind currents in the Kerch Strait," Nauka Yuga Ross. **5** (2), 58–63 (2009).
18. N. B. Shapiro, "The theory of currents in the Kerch Strait," in *Ecological Safety of the Coastal and Self Sea Regions* (Sevastopol, 2005), No. 12, pp. 320–331.
19. *Black Sea and Sea of Azov Pilot* (United Kingdom Hydrographic office, Taunton, 2003).
20. A. F. Blumberg and G. L. Mellor, "A description of a three-dimensional coastal ocean circulation model," in *Three-Dimensional Coastal Ocean Models*, Ed. by N. Heaps (American Geophysical Union, Washington, 1987), Vol. 4, pp. 1–16.
21. S. A. Hsu, "A mechanism for the increase of wind stress coefficient with wind speed over water surface: a parametric model," J. Phys. Oceanogr. **16**, 144–150 (1986).
22. G. L. Mellor and T. Yamada, "Development of a turbulence closure model for geophysical fluid problems," Rev. Geophys. Space Phys. **20** (4), 851–875 (1982).
23. J. Smagorinsky, "General circulation experiments with primitive equations. I. The basic experiment," Mon. Weather Rev. **91** (2), 99–164 (1963).

Translated by I. Ptashnik