Investigation of the Effect of the Baric Formation Parameters on Free and Forced Oscillations of the Level and Flow in the Sea of Azov

L.V. Cherkesov, T.Ya. Shul'ga

Marine Hydrophysical Institute, Russian Academy of Sciences, Sevastopol, Russian Federation
e-mail: shulgaty@mail.ru

The effect of inhomogeneous moving atmospheric pressure fields upon the flows, and free and forced oscillations of the Azov Sea level induced by constant wind is studied by the method of mathematical modeling. The hypothesis on the role of the resonance mechanism in arising of the extremely high amplitudes of the surge oscillations and seiches generated by a baric field moving at the velocity equal to that of a free long wave is tested. The equations of the applied mathematical model are described in general, transition to the curvilinear coordinates is shown, the model parameters chosen allowing for different physical factors are substantiated, and the features of the model numerical realization are explained. The information on the wind and atmospheric pressure fields used in the numerical experiments is given. The results of simulations of free oscillations in the Sea of Azov are discussed with the purpose to analyze the impact of the resonance characteristics related to the speed and time of the baric fields' motion over the sea. The sea level deviations resulted from the calculations with constant pressure and those with passing of the inhomogeneous baric front are compared. It is revealed that at one and the same wind, the baric disturbances moving over the Sea of Azov induce the forced oscillations and after their forcing is stopped – free oscillations the amplitudes of which exceed those obtained at constant atmospheric pressure by 14%. It is shown that the baric front motion, speed and time of which are chosen based on the assumption on generation of the waves with maximum amplitudes, plays an important but not decisive role in formation of the currents' structure and the level oscillations in the Sea of Azov.

Keywords: the Sea of Azov, sigma-coordinate model, free oscillations of liquid, seiches, stationary currents, storm surges, nodal lines, atmospheric front, free long wave velocity.

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Introduction. In the seas and oceans the oscillations of level and currents are formed under the influence of different internal and external forces. Diversity of influences of such forces leads to the formation of different-scale oceanographic processes with the periods from several seconds to several tens of years. Surge, seiche and seiche-like oscillations (they are the wave motions with the periods from several hours to several days [1, 2]) play an important role in formation of extreme levels and hydrologic processes in the coastal area of the Sea of Azov. The structure of dominating longitudinal self oscillations is such that their peaks fall on the areas situated close to the major population centers [3, 4]. Therefore, it is of interest to study the effect of seiche-like oscillations on the formation of level oscillation extreme amplitudes and the currents of the Sea of Azov.

Often the cause of seiche-like oscillations in realistic bottom boundary layers is a change of atmospheric pressure. A dramatic change of pressure in different parts of the basin forces the entire water mass in it into oscillatory motion. Seiches with significant amplitude occur when a resonance phenomenon takes place (when the basin self oscillation period coincides with the period of driving force). Relatively low pressure gradient at the edges of the basin and small differences of levels corresponding to them cause significant seiches at that. Moving above the water surface at the velocity which is almost equal to the one of a free long wave, baric front generates extreme surges which change into the high amplitude seiches after the termination of atmospheric perturbation effect.

The investigation of wave behavior at the atmospheric front area have recently been started and we have no enough practical experience of free and forced oscillation forecasting in these conditions yet [5 – 7]. Currently, natural marine basin water dynamics, affected by mesoscale atmospheric processes, is considered to be one of the most important investigations [8, 9]. The study of seiche-like oscillations in the Sea of Azov and the analysis of field observation data were carried out in [3]. Seiche oscillations of level and current, occurring in this sea as a result of surges with 1 m height at the open boundary, were studied in [4] within the framework of linear two dimensional mathematical model.

The given investigation is a continuation of the papers [10 – 12] on the study of the Sea of Azov level free and forced oscillations within the framework of three-dimensional nonlinear sigma-coordinate model. In the given paper the development of currents, surge and seiche-like oscillations of the Sea of Azov level in the atmospheric pressure perturbation field on the basis of the analysis of numerical modeling results is studied. A hypothesis on a resonance mechanism role in the occurrence of extremely high surge amplitudes and seiches generated by a baric field (which moves above the sea at the velocity equal to the one of a free long wave [13]) has been tested. A period of perturbing pressure is equal to one of liquid free oscillations in the basin. Spatiotemporal features of seiche-like oscillations occurring after the passage of atmospheric formations were determined. Conclusions about dependence of storm surge and seiche characteristics on atmospheric effect parameters were drawn.

Statement of the problem. Applied model and its parameters. Equations of the model. Initial and boundary conditions. The investigation of free and forced oscillations in the Sea of Azov was carried out using the mathematical modeling technique. For this purpose, three-dimensional barotropic nonlinear sigma-coordinate *POM* model [14, 15] based on a system of sea dynamics differential equations [16] has been applied. Variable depth of the basin, the Coriolis force, variable atmospheric pressure, friction at the bottom and at the free surface are taken into account by this model:

$$\frac{du}{dt} - fv + \frac{1}{\rho}\frac{\partial P}{\partial x} = 2\frac{\partial}{\partial x}\left(A_M\frac{\partial u}{\partial x}\right) + \frac{\partial}{\partial y}\left[A_M\left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}\right)\right] + \frac{\partial}{\partial z}\left(K_M\frac{\partial u}{\partial z}\right), \quad (1)$$

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

$$\frac{\partial P}{\partial z} + g\rho = 0, \quad (3)$$

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

Here the following symbols are used: x, y, z are spatial variables; x-axis is directed to the East, y-axis to the North and z-axis is directed vertically upwards; t is time; $u(x, y, z, t)$, $v(x, y, z, t)$ are the components of horizontal current velocity vector; $w(x, y, z, t)$ is a vertical component of current velocity; $P(x, y, z, t) = P_{\text{atm}} + g\rho_0(\zeta - z)$ is a pressure at z depth on the basis of integration (3) vertically, $P_{\text{atm}} = 1013.25$ is standart atmospheric pressure at 0 °C temperature at a latitude of 45°; ρ is a water density; $\rho_0 = (\zeta + H)^{-1} \int_{-H}^{\zeta} \rho dz$ is mean water density by depth; g is free fall acceleration; f is the Coriolis parameter; K_M is a coefficient of vertical turbulent viscosity (for its determination Mellor-Yamada theory is used [17]); A_M is a coefficient of horizontal turbulent viscosity calculating by Smagorinsky formula [18].

At the sea surface universal condition for w

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

and boundary conditions for horizontal velocity as a momentum flux from wind friction stress are set:

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

where $(\tau_{0x}, \tau_{0y}) = \rho_a c_a |\mathbf{U}_W|(u_W, v_W)$, $\mathbf{U}_W$ wind velocity vector at the standard height of 10 m above the sea water surface, u_W and v_W are wind velocity vector components, ρ_a is density of air at standard atmospheric conditions, c_a is a surface friction coefficient which varies depending on wind velocity:

$$10^3 \tilde{n}_a = \begin{cases} 2.5, & |\mathbf{U}_W| > 22 \ \text{m} \cdot \text{s}^{-1}, \\ 0.49 + 0.065|\mathbf{U}_W|, & 8 \le |\mathbf{U}_W| \le 22 \ \text{m} \cdot \text{s}^{-1}, \\ 1.2, & 4 \le |\mathbf{U}_W| \le 8 \ \text{m} \cdot \text{s}^{-1}, \\ 1.1, & 1 \le |\mathbf{U}_W| \le 4 \ \text{m} \cdot \text{s}^{-1}. \end{cases} \tag{7}$$

Expression (7) follows from the paper [19] when wind velocity is less than 22 m/s. In other cases c_a is a constant proposed in [20].

At the bottom impermeability conditions expressed by kinematic boundary condition (reflecting the absence of flux which is normal to the wall)

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

and bottom friction quadratic parameterization are set

$$K_M \left(\frac{\partial u}{\partial z}, \frac{\partial v}{\partial z} \right)\Bigg|_{z=-H} = (\tau_{1x,} \tau_{1y}), \tag{9}$$

where $(\tau_{1x}, \tau_{1y}) = c_b|\mathbf{U}_b|(u_b, v_b)$, u_b and v_b are current velocity horizontal components in the grid nodes near the bottoms of the basin, c_b is bottom friction coefficient determined as a maximum between the value, which is calculated κthrough the logarithmic law, and empiric constant 0.0025: $c_b = \max\{k^2(\ln(H+z_b)/z_0)^{-2}; 0{,}0025\}$. Here z_0 = 3 cm is a roughness parameter; z_b is the closest to the bottom grid node; k = 0.4 is the Karman constant.

At the side boundaries the conditions of absence of normal flux $\mathbf{U_n} = 0$ and adhesion $\mathbf{U_\tau} = 0$ (where $\mathbf{n}$ and $\boldsymbol{\tau}$ are normal and tangential directions) are set for the velocity. The conditions of absence of fluid motion and free surface horizontality prior to the beginning of atmospheric perturbation effect are set as initial ones (at $t = 0$).

Finite differential method is centered in time and space on the *C*-grid, transport operators are approximated using *TVD*-scheme (*Total Variation Diminishing*) [21]. The computations of the model take place on a $\Delta x = \Delta y = 1.4$ km rectangular grid at the horizontal coordinates and at σ-coordinate. The selection of spatial and temporal coordinate integration steps was performed in accordance with stability criterion for barotropic waves [22]. Computational domain bottom topography was interpolated at the model grid from the array of depths taken from navigation charts. The investigation of free and forced oscillations of liquid in the Sea of Azov was carried out using the results of numerical calculations by the mentioned ocean dynamics barotropic model.

Meteorological input data. According to the observations, in the sea areas which intersect or adjoin the continents the frontal zones, moving at 30 – 35 km/h (8 – 10 m/s) velocity and covering 600 – 800 km per day, occur in the transitional seasons. The width of frontal surface makes up several tens of kilometers covering the water area of the Sea of Azov. Wind and wave regimes in front of the front and behind it differ significantly. In the areas of fronts (especially of the cold ones) significant gradients of air temperature, humidity and other meteorological parameters which contribute to dramatic increase of wind velocity [23, 24] take place.

During the computational experiments the scenarios of passage of seasonal atmospheric fronts above the Sea of Azov have been reproduced (Fig. 1). Movement of pressure area boundary takes place along one of predetermined trajectories: meridional (Fig. 1, *a*), zonal (Fig. 1, *b*, *e*) or diagonal (Fig. 1, *c*). Baric gradient, frontal zone width and their values in the areas of increased and decreased pressure are taken on the basis of generalized hydro-meteorological reference data analysis [23, 24].

Velocity and baric field movement time are selected with regard to assumption on generation of maximum amplitude waves. It is possible when barometric pressure period becomes closer to the basin self-oscillation period. Baric front, moving above the Sea of Azov at the velocity close to $\sqrt{gH}$, generates high surges near the shores. These surges form high amplitude seiches then [13].

Front movement time (t_f) over the entire area is assigned to be equal to the first highest rise of the Sea of Azov level taking place during the half-period of free oscillation first harbor resonant mode. Its value is determined on the basis of observational data and the results of analytical calculations. In [3, 23, 24] seiches with 6 – 7 and 23 h periods (T_{obs}) are noted. Theoretical values of periods (T_{Merian}) are obtained by Merian formula with regard to Rayleigh correction [3]:

$$T_{\text{Ìerian}} = \frac{2L}{\sqrt{gh}}(1+\varepsilon), \quad \varepsilon = \frac{b}{\pi l}\left(\frac{3}{2} - \ln\frac{\pi b}{l} - C_{\varepsilon}\right). \tag{10}$$

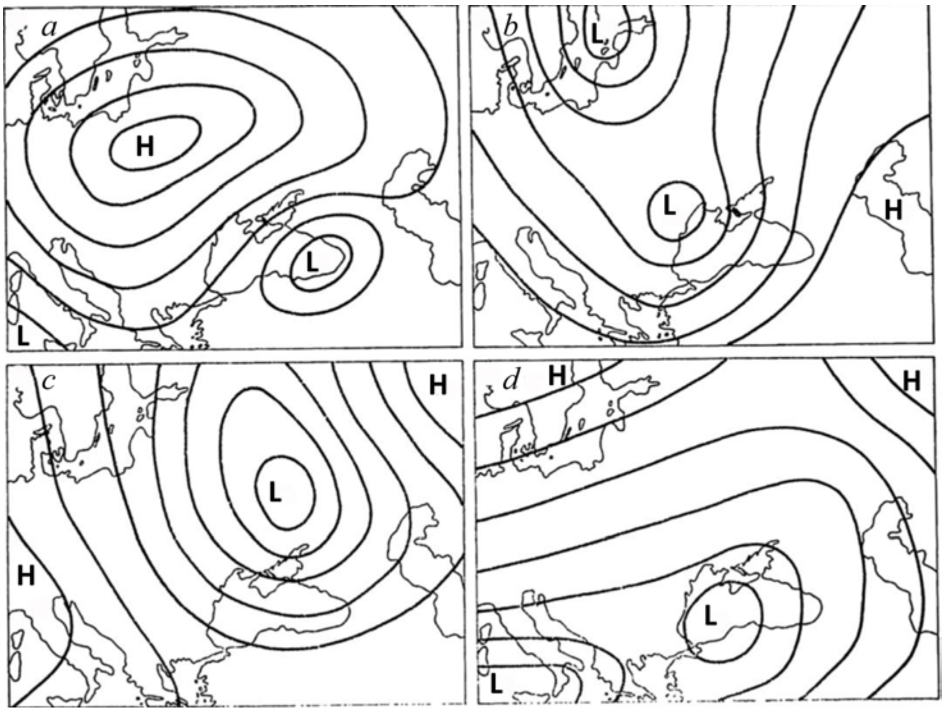

Fig. 1. Types of baric synoptic processes for the Sea of Azov area: anticyclone above the central regions of the European part of Russia (*a*), anticyclone above the Asia Minor and Kazakhstan (*b*), anticyclone above the Balkan Peninsula (*c*), Mediterranean anticyclones (*e*)

Here $C_\varepsilon = 0.5772$ is Euler constant; $L = 360$ km is the sea lengh (along Genichesk – Pereboyniy); $h = 10$ m is mean sea depth; $b = 30.6$ km is a strait width at the entrance to the Taganrog Bay; $l = 137$ km is a length of the Taganrog Bay. First mode period, calculated by the formula (10), is equal to 24.1 h.

Thus, comparing T_{obs} and T_{Merian} values we consider that dominant longitudinal self-oscillations of the Sea of Azov level first mode have the period which is close to $T = 24$ h. The structure of this mode is such that one of its peaks is located in the Taganrog Bay and the opposite one – near Genichesk. Therefore, it is of interest to study the effect of non-uniform baric fields on surge and seiche-like oscillation formation in these areas.

The study of hypothesis on extreme seiche occurrence at air pressure change in different parts of the sea was carried out on the basis of analysis of results of two series of numerical experiments. Experimental conditions differed in resonance mechanisms of the Sea of Azov surge oscillation and seiche extreme amplitude formation. In the first series of experiments the atmospheric pressure period (multiple of the basin self-oscillation period) is the characteristic of a baric front. In the second series of experiments the characteristic of a baric front is a velocity almost equal to the one of free long wave.

In each experiment the development of a front takes place in the field stationary currents and the start of its movement corresponds to stationary time ($t_{\text{st}} = 48$ h) [10]. In the Sea of Azov steady motions are generated by spatially and temporally homogeneous South-Western wind with $|\mathbf{U}_W| = 10$ m/s velocity. At this stage ($0 \le t \le t_{st}$) atmospheric pressure is constant all over the sea area and its value is equal to standard atmospheric pressure (P_{atm}).

The next stage of experiment corresponds to the passage of nonuniform atmospheric pressure field over the Sea of Azov waters. From the start of its movement (t_{st} = 48 h) the sea area is divided into the parts: the area D, above which the pressure is constant and is equal to normal atmospheric one P_{atm} , and the area $\overline{D}$ above which nonuniform baric field moves. The dimensions of D and $\overline{D}$ areas change with time and are limited by dimensions of the Sea of Azov basin computational grid ($0 \le x \le x_{max}$ = 350 km, $0 \le y \le y_{max}$ = 250 km). $P_a(x, y, t)$ function (which models the pressure in the atmospheric front) is assigned by two different analytical expressions for D и $\overline{D}$ domains:

$$P_a(x,y,t) = \begin{cases} P_{atm} = \text{const}, & (x,y) \in D, \\ P_{atm} + a(t - t_{st}), & (x,y) \in \overline{D}, \end{cases} \tag{11}$$

the function also depends on time varying in $t_{st} \le t \le t_f$ interval. The coefficient a is selected in such a way that $P_a(x, y, t)$ has the only jump with the amplitude that is equal to surface pressure gradient along the front line ($a(t_f - t_{st}) = \Delta P_f$). ΔP_f is calculated according to the wind velocity value (known in this experiment) on the basis of the formula $\left|\mathbf{U}_W\right| = 0.7\sqrt{(4.8/\sin\varphi)^2(\Delta P_f^2 + \alpha^2 \Delta t_f^2) + 64}$ proposed in [25]. Here Δt_f is an air temperature drop in the area of a front at 50 km distance; α is transition coefficient; φ is geographic latitude.

The areas of constant and variable atmospheric pressure (D and $\overline{D}$) are located on both sides of the front line γ. The position of this line depends on current coordinates (x, y) and time (t). The determination of spatial curve γ was carried out by using γ parametric expressions: $x = x(t)$, $y = y(t)$. Parametric equation type defines the front line configuration: straight lines are with a certain inclination angle and curves with a certain radius of curvature. Velocity and time of perturbing baric field movement over the Sea of Azov area is determined by $\mathbf{U}_\gamma$ velocity and time of front line moving t_f. For the mentioned series of numerical experiments these values are found in different ways.

For the first series of numerical experiment we select atmospheric perturbation period t_f to be multiple of the period of the Sea of Azov free oscillation first resonant mode T. In this case the module of front boundary movement velocity is determined using the following formula: $|\mathbf{U}_\gamma| = 2L/T$. For the second series of calculations the velocity of atmospheric pressure area boundary movement is a variable value. It is equal to the free long wave velocity which depends on the sea depth ($|\mathbf{U}_\gamma(H)| = \sqrt{gH}$). In this case the time of atmospheric perturbation effect at different movement velocity varies and it is also determined using the known relation $t_f = L/|\mathbf{U}_\gamma(H)|$.

The analysis of numerical modeling results. The calculation of extreme surges (caused by baric perturbation effect) was carried out and maximum characteristics of free oscillations in the Sea of Azov (arising after the passage of atmospheric fronts) were determined within the framework of mathematical model.

The values of level amplitudes, current velocities and seiche-like oscillation periods are analyzed in detail by the calculations obtained at shore stations and in the areas of the central part of the basin.

The Taganrog Bay, located in the north-eastern part of the Sea of Azov, is a basin of almost rectangular shape with 137 km length and 30 km maximum width. Uninodal longitudinal seiche (dominating in the Taganrog Bay) affects the formation of surge oscillations of level. This effect may be significant when self and forced oscillation periods coincide.

1. The purpose of numerical experiments is to study the response of free and forced oscillations of the Sea of Azov level to the baric field passage during the time, which is equal to the basin self-oscillation period. Air moves from high pressure area to the one with low pressure under the influence of baric gradient. When the air starts to move the Coriolis force also begins to deflect its flow to the right. With the increase of wind velocity the deflection of its direction also increases under effect of the Coriolis force. As a result, the geostrophic wind moves not from the high pressure area to the low pressure one but along the isobar line.

The trajectories of nonuniform baric field movement above the Sea of Azov (taken in numerical experiments) are represented in Fig. 2. Baric field isolines correspond to 9 h time which is counted from the beginning of reduced pressure field movement. The examples of distribution of these fields with $|\mathbf{U}_\gamma|$ = 8 m/s velocity in the direction of zonal wind blowing along Genichesk – Pereboyniy line are shown in Fig. 2, *a*, *b*. They differ in geometry of separation lines (γ): in Fig. 2, *a* it is a straight line with tilt angle of 135° to the *x*-axis. The movement of boundary section of pressure areas along the diagonal trajectory (with 90° tilt angle to the *x*-axis) is represented in Fig. 2, *b*.

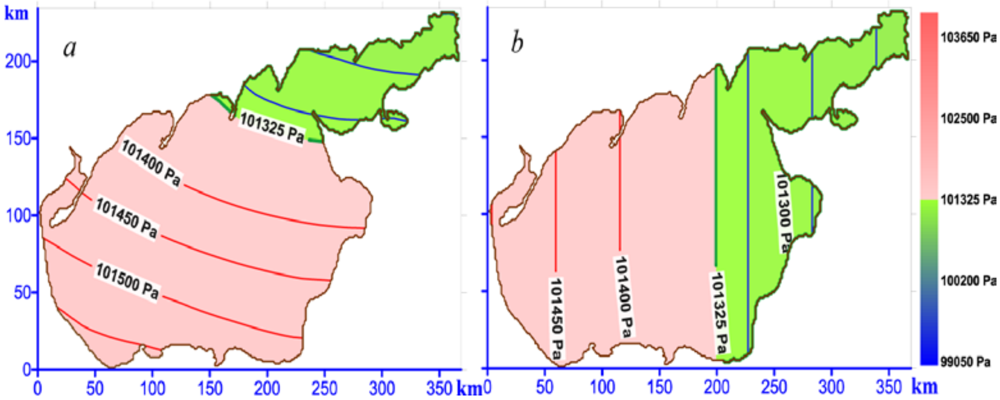

Fig. 2. Variable atmospheric pressure area movement at 8 m/s velocity in Genichesk – Pereboyniy direction at different geometry of its boundaries: *a* – a straight boundary with 135° tilte angle to the *x*-axis; b – straight boundary with 90° tilt angle to the *x*-axis

The calculation results of extreme sea level deviations (obtained at constant pressure and also during the passage of nonuniform baric front) caused by the effect of the same western stationary wind with of 10 m/s velocity are represented in Tabl. 1. Here maximum and minimum values of level deviation at the Sea of Azov shore stations at the moment of wind effect termination (ζ_{st}, ζ_{extr}) and the first consequent extrema of seiche-like oscillation amplitudes ($\zeta_{1,\,2}$) with corresponding to them ($t_{1,\,2}$) time points (which are counted from t_{st} time moment) are given. In the left part of the table modeling results at constant pressure P_{atm} are represented. In the right part the results obtained during the passage of varying pressure area $P_a(x, y, t)$ over the entire basin with 8 m/s velocity are given.

T a b l e 1

Stationary surges (ζ_{st}, m), amplitude extrema of forced (ζ_{extr}, m) and the first two seiche-like ($\zeta_{1,\,2}$, m) oscillations with the corresponding time points ($t_{1,\,2}$, h) at constant atmospheric pressure and after the baric front passage (at 8 m/s velocity) under effect of stationary wind (of 10 m/s velocity)

Station	P_{atm}					$P_a(x, y, t)$				
	ζ_{st}	ζ_1	t_1	ζ_2	t_2	ζ_{extr}	ζ_1	t_1	ζ_2	t_2
Genichesk	2.02	−0.27	9.5	0.33	16.5	2.15	−0.28	10.0	0.39	16.8
Berdyansk	0.25	−0.57	2.5	0.46	7.7	0.25	−0.60	2.8	0.48	7.7
Mariupol	−1.53	−0.01	12.3	−0.20	20.2	−1.82	−0.01	12.5	−0.21	20.6
Taganrog	−1.58	−0.89	24.3	0.30	31.5	−1.64	−0.97	24.4	0.35	31.5
Eisk	−2.44	−0.06	18.3	0.21	28.5	−2.62	−0.07	18.7	0.25	28.9
P.-Akhtarsk	−1.75	0.92	5.3	−0.10	13.9	−1.88	0.95	5.5	−0.10	13.9
Temryuk	−0.18	1.03	2.7	−0.14	13.5	−0.18	1.07	3.1	−0.14	13.6
Opasnoye	0.32	0.93	1.7	−0.08	13.0	0.37	0.93	2.2	−0.09	13.1
Mysovoye	0.98	−0.20	8.7	0.26	15.4	1.06	−0.22	8.7	0.30	15.6

From the analysis of data, represented in the left part of Tabl. 1, it follows that realistic wind causes maximum stationary surges at Genichesk station (2.02 m) and negative surges at Eysk (2.44 m), Primorko-Akhtarsk (1.75 m) and Taganrog (1.58 m) stations. In comparison with the extrema of level deviation amplitudes caused by the baric field passage, it is obvious that the greatest differences at the mentioned stations make up 14 %.

Using the data given in Tabl. 1 we are to carry out the analysis of seiche-like oscillations obtained at those stations where the greatest surges take place. At Eysk station where the greatest surge takes place (−2.44 m; $t = t_{st}$) the termination of wind effect results in subsequent level rise ($\zeta_1 = -0.06$ m; in 18.3 h). The range of the first oscillation is 2.38 m at that. Hereafter, the level keep on rising and I n 10.2 h it reaches the maximum value of 0.21 m. Second oscillation height (0.27) is 8.8 times smaller than the one of the first oscillation.

Baric front passage leads to the changes of free oscillation heights and periods which significantly differ at Eisk station. At the moment of perturbation effect termination the decrease of level by 2.62 m forms the subsequent oscillations with 2.55 and 0.32 heights. It should be noted that stationary negative surge value at this station is 7 % lower than the one of non-stationary negative surge. The differences of seiche-like oscillation ranges do not exceed 16 % and the differences of their periods – 0.5 h. In the both cases the same wind was wave and current generation basis, so this difference is obviously caused by baric front passage with 100 hPa pressure drop.

Current fields in the Sea of Azov surface layer at regular time intervals (3 h) from the moment of all external effect termination are given in Fig. 3. It is obvious that at different velocities of realistic wind current velocity maxima are biased towards the Taganrog Bay. Current velocity zero values are scattered all over the water area. Opposite direction currents correspond to the same direction of baric perturbation boundary movement over the water area.

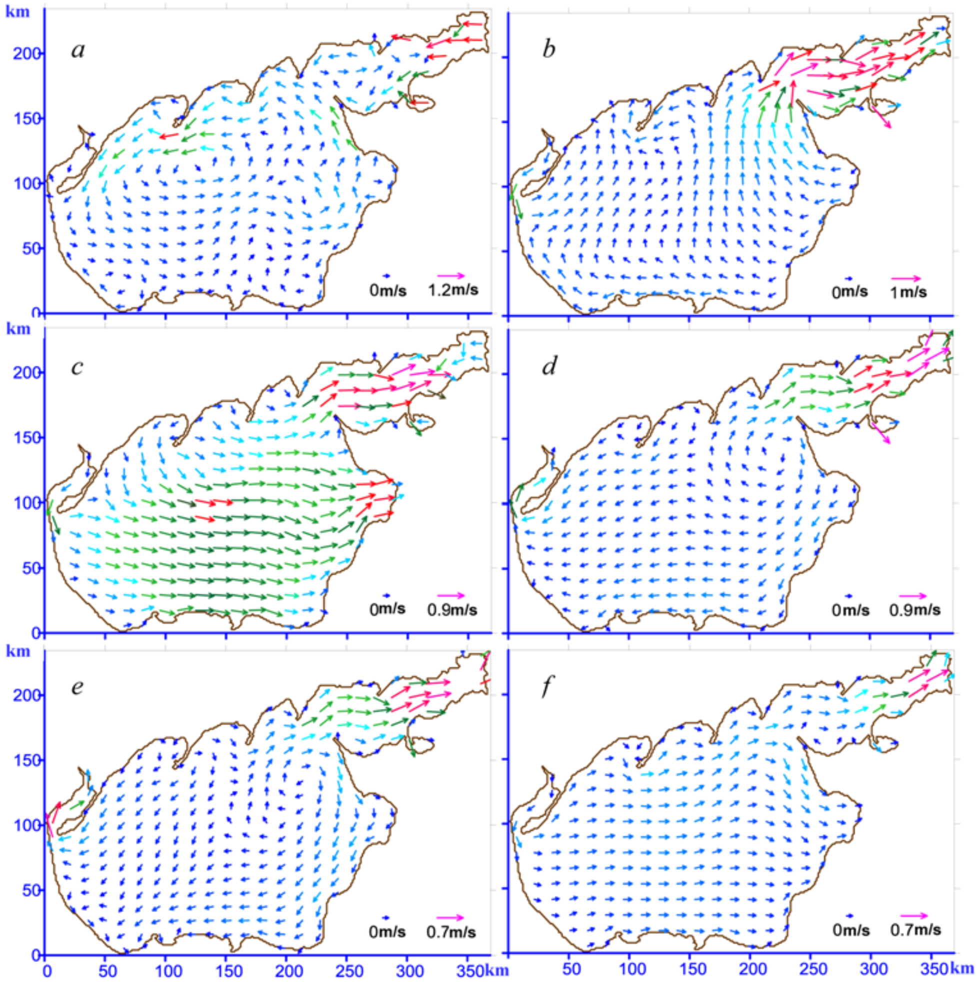

Fig. 3. The Sea of Azov current fields at uniform motion (*a*), at the moment of wind effect termination (*b*), in 3 h (*c*), in 6 h (*d*), in 9 h (*e*), in 12 h (*f*)

2. The next series of experiments was carried out to analyze the effect of resonance characteristics related to the free long wave velocity. The velocity of atmospheric pressure field movement ($|\mathbf{U}_\gamma(H)| = \sqrt{gH}$) above the water area is calculated on the basis of known dispersion relationship and it is a function which depends on natural basin depth.

In Table 2 the dependence of extreme amplitudes of the Sea of Azov level oscillations on the velocity of baric disturbance boundary movement in meridian direction in the field of steady western wind (with 10 m/s velocity) is represented. Baric front velocity, as well as the one of free long wave, varies depending on the selected sea depth values (7 – 14 m).

T a b l e 2

Dependence of extreme characteristics of the wave processes on the velocity of atmospheric pressure field movement ($|\mathbf{U}_\gamma(H)|$) above the Sea of Azov

$\lvert\mathbf{U}_\gamma(H)\rvert$, m/s	ζ_{max}, m	ζ_{min}, m	$\lvert\mathbf{U}\rvert_{max}$, m/s
8.3	0.56	0.40	0.26
8.9	0.66	0.46	0.27
9.4	0.74	0.52	0.30
9.9	0.70	0.50	0.28
10.4	0.68	0.48	0.24
10.9	0.64	0.44	0.23
11.3	0.58	0.40	0.22
11.7	0.58	0.40	0.21

The comparison of the results represented in Tabl. 2 with the ones of calculations carried out at constant value of atmospheric pressure [20] confirms the hypothesis about moving baric formation effect on the oscillations of the Sea of Azov level and current velocities. The increases of level oscillation extreme amplitudes and maximum current velocities (ζ_{max} = 0.56 m, ζ_{min} = 0.4 m, $|\mathbf{U}|_{max}$ = = 0.26 m/s) reach 20, 23 and 14 % in comparison with the constant pressure value (P_{atm}).

From the analysis of data represented in Tabl. 2 it follows that baric disturbance movement velocity affects maximum velocities and sea level deviations. The highest quantities of these values are reached at $|\mathbf{U}_\gamma(H)|$ = 9.4 m/s front velocity corresponding to 9 m sea depth. This baric formation passes from the Sea of Azov westernmost boundary to its easternmost one in 10 h 40 min. It should be noted that the front which moves slower (for instance, with 8.3 m/s velocity (12.8 h)) has lesser effect on wave motion parameters.

On the basis of experiment results we are to investigate free surface change at the moment of fluid motion stationary and atmospheric perturbation passage over the entire area of the sea at fixed time intervals (3 h) from the moment of termination of all external effects.

The results of numerical experiment of baric perturbation passage over the Sea of Azov from the West to the East in the steady wind field (which blows the same direction with 10 m/s velocity) are shown in Fig. 4. The movement of air mass separation boundary with the atmospheric pressure drop takes place with the velocity of free long wave ($|\mathbf{U}_\gamma(H)|$ = = 8.29 m/s) obtained by 7 m mean sea depth. The time of atmospheric perturbation passage is selected to be equal to the half of free oscillation period ($t_f = T_{Merian}/2$ = 12 h).

At the moment of wind effect termination (Fig. 4, *a*) water dynamics is determined by the nodal line, passing through the center of the basin, and by amplitude maximum in the western and eastern parts of the basin.

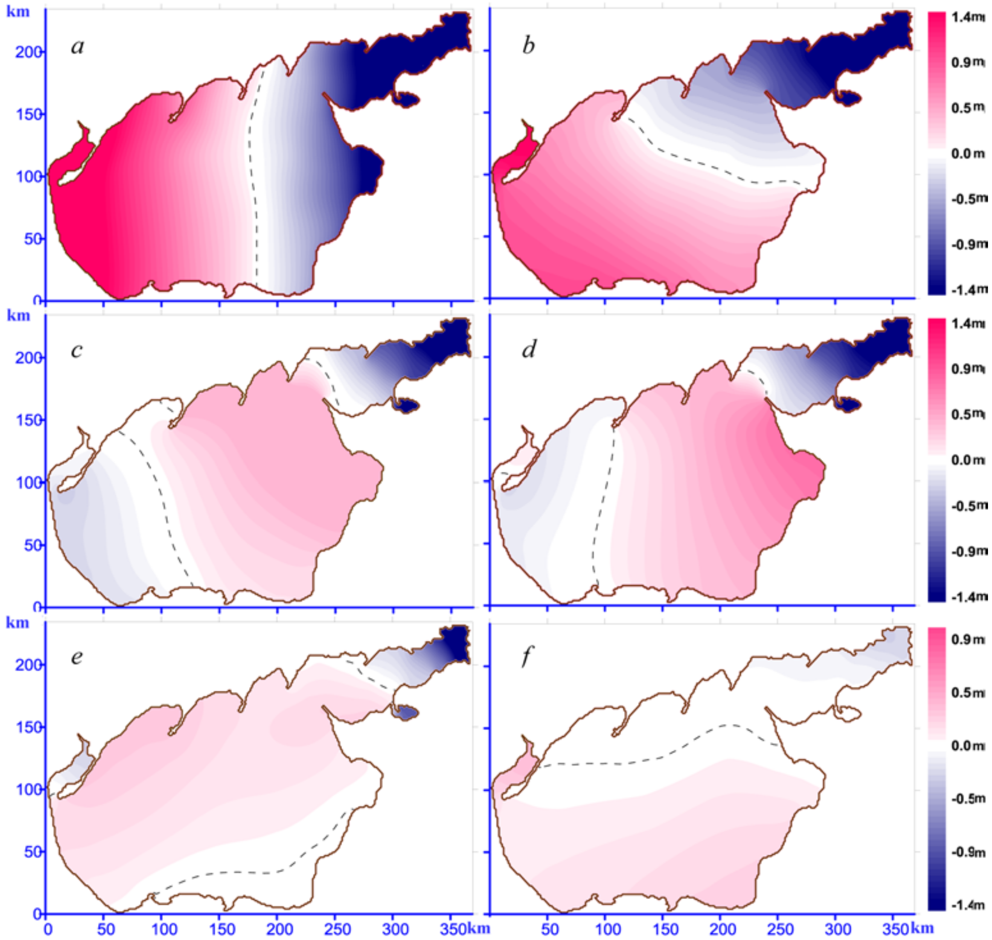

Fig. 4. The Sea of Azov level isolines (m) at the same time moments as in Fig. 3

Future development of free oscillation process leads to the increase of vortex perturbation generation. Nodal line turns asymmetrically anticlockwise taking the longitudinal (Fig. 4, *b*) and diagonal (Fig. 4, *c*) positions. In 11 h after the wind effect termination (Fig. 4, *e*) free oscillations are a bimodal seiche with a central nodal line which repeats its configuration in the initial period of time ($t = = t_{st}$; Fig. 4, *a*). Two shorter nodal lines are symmetrical, and they are the semi-circles whose diameters are perpendicular to the atmospheric front direction.

The lowest intensity of free level oscillations is observed in the central part of the basin. Binodal seiche system moves to the East in 12 h (Fig. 4, *e*). The greatest level deviations take place in the opposite corners of the basin at that. Further development of free oscillation process (Fig. 4, *f*) results in the fact that the sections of small nodal lines are compensated, combining into one line which passes diagonally across the basin. This line divides the basin into the areas of level elevation and lowering.

Principle results. On the basis of analysis of numerical modeling results it was determined that the perturbations, moving at the velocity which is almost equal to the one of free long wave, cause the generation of waves with the amplitudes which are greater than the ones of the waves generated at the same wind and constant atmospheric pressure. Their higher values are reached at 9.4 m/s velocity of baric perturbation boundary movement, corresponding to 9 m sea depth.

Moving baric fields induce (during the time with is equal to half-period the basin self-oscillations) forced and then free oscillations with the amplitudes whose differences from the ones, obtained at constant value of atmospheric pressure and the same wind, are within 14 %.

Atmospheric pressure disturbance plays important but not decisive role in the formation of current structure and the oscillations of the Azov Sea level. The present paper reveals the fact that the currents with opposite directions (which depend on the stationary wind only) may correspond to the same direction of baric disturbance boundary movement over the water area. The important role in the formation of currents belongs to the processes which are caused by prolonged steady wind.

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